Summary of Written Representation
for the
Royal Society for the Protection of Birds

Submitted for Deadline 1
24 October 2022

Planning Act 2008 (as amended)

In the matter of:

Application by Awel y Môr Offshore Wind Farm Limited for an Order Granting Development Consent for the Awel y Môr Offshore Wind Farm

Planning Inspectorate Ref: EN010112
RSPB Registration Identification Ref: 20031695

Contents

1. Introduction

The RSPB

1.1. The Royal Society for the Protection of Birds (the RSPB) was set up in 1889. It is a registered charity incorporated by Royal Charter and is Europe's largest wildlife conservation organisation, with a membership of over 1.1 million[1]. The principal objective of the RSPB is the conservation of wild birds and their habitats. The RSPB therefore attaches great importance to all international, EU and national law, policy and guidance that assist in the attainment of this objective. It campaigns throughout the UK and internationally for the development, strengthening and enforcement of such law and policy. In so doing, it also plays an active role in the domestic processes by which development plans and proposals are scrutinised and considered, offering ornithological and other wider environmental expertise. This includes making representations to, and appearing at, public inquiries and hearings during the examination of applications for development consents.

The RSPB's interest in offshore wind development

1.2. Faced with the threats of climate change to the natural world the RSPB considers that a low-carbon energy revolution to reach net zero is essential to safeguard biodiversity. However, inappropriately designed and/or sited developments can also cause serious and irreparable harm to biodiversity and damage the public acceptability of the necessary low-carbon energy transition technologies. The RSPB recognises the significant role that offshore wind will play in decarbonising our energy systems and the renewed urgency with which this must happen. Installing this technology at the scale and pace needed is no easy task: there are significant challenges rooted in the planning frameworks and the state of our seas which threaten both nature *and* our ability to reach net zero.

1.3. The available evidence suggests that the main risks of offshore wind farms for birds are collision, disturbance/displacement, barriers to movement (e.g. migrating birds, or disruption of access between the breeding areas and feeding areas), and habitat change particularly with associated changes in food availability and the cumulative and in-combination effects of these across multiple wind farms. Such impacts are avoidable, and the RSPB has spent considerable time working with stakeholders in the UK offshore wind industry to ensure that decisions about deployment of renewable energy infrastructure take account of environmental constraints and seek to avoid or minimise impacts wherever possible. The RSPB therefore strongly advocates the use of rigorous, participative environmental assessments to inform the development of projects.

Scope of written submission

1.4. This Written Submission covers the following:

- The nature conservation importance of the seabirds affected by the Awel y Môr Offshore wind farm scheme
- Legislation and policy background
- Offshore ornithology

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[1] [redacted] Accessed 29 March 2022

2. The nature conservation importance of the waterbirds and seabirds affected by the Awel y Môr offshore wind farm scheme

2.1. The UK is of outstanding international importance for its wintering waterbirds including large aggregations of non-breeding red-throated diver (Gavia stellata) in UK coastal areas; and breeding seabirds, including northern gannet (Morus bassanus) for which the UK supports over 50% of the world population and around 78% of the world population of Manx shearwater (Puffinus puffinus). As with all Annex I and regularly occurring migratory species, the UK has particular responsibility under the Birds Directive[2] to secure the conservation of these important waterbird and seabird populations.

2.2. The RSPB considers the project has the potential to impact several Special Protection Areas (SPAs), classified under the EU Birds Directive. It is vital to consider whether the SPAs and their qualifying features meet the attributes and targets set by Natural Resources Wales when considering whether the SPA's conservation objectives to maintain or restore site integrity can be met and the SPAs achieve favourable conservation status throughout the lifetime of the development and any subsequent period where its impacts continue to affect the SPA features.

3. Legislation and policy background

3.1. Energy National Policy Statements (NPSs) set out the Government's approach to considering new energy infrastructure. Consent for energy infrastructure is subject to tests set out in Section 104 of the Planning Act. NPS EN-3, National Policy Statement for Renewable Energy Infrastructure, specifically identifies birds as a biodiversity concern to be taken into account (paragraph 2.6.59 and 2.6.68).

3.2. There is a statutory duty to comply with the Conservation of Habitats and Species Regulations 2017 (the Habitats Regulations, as amended) which offer protection for protected sites (Ramsar, SPA, SAC) and the Conservation of Offshore Marine Habitats and Species Regulations 2017 (Offshore Regulations)(as amended). The Habitats and Offshore Regulations set out a sequence of steps to be taken by the competent authority (here the Secretary of State for Business, Energy and Industrial Strategy (BEIS)) when considering authorisation for a project *likely to have an effect* on a European site and its species before deciding to authorise that project.

3.3. We set out a series of related matters to be considered in this context, including:

- SPA and SAC Conservation Objectives;
- Appropriate assessment;
- In-combination effects and compensation for other schemes;
- Habitats Regulations General Duties;
- Environmental Impact Assessment.

4. Offshore ornithology

4.1. We continue to have significant concerns relating to the project's in-combination and cumulative collision risk and displacement impacts including their assessment. We have significant concerns regarding the findings of some of the impact assessments. As a result of the

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[2] Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds (codified version) (the Birds Directive)

methodological concerns, set out below, the RSPB considers that the impacts have not been adequately assessed and, as such consider that an adverse effect on the integrity (AEOI) on the following qualifying feature of the Liverpool Bay Special Protection Area (SPA) cannot be ruled out:

Project alone – RSPB AEOI conclusions

4.2. Impact on the following feature of the Liverpool Bay SPA:

- The impact of displacement on the red throated diver population

Project in combination with other plans and projects – RSPB AEOI conclusions

4.3. In-combination impacts on the following feature of the Liverpool Bay SPA:

- The impact of displacement on the red throated diver population

4.4. The RSPB's key methodological concerns are with the baseline survey methodology, the scoping out of collision impacts for Manx shearwater, the use of avoidance rates in gannet collision risk modelling, lack of consideration of impacts compounded by highly pathogenic avian influenza (HPAI).

4.5. Due to these methodological concerns the RSPB consider that it is not currently possible to rule out adverse impacts upon Manx shearwater occurring within the study area from the following SPAs:

- Copeland Islands SPA
- Irish Sea Front SPA
- Rum SPA
- St Kilda SPA
- Glannau Aberdaron ac Ynys Enlli/ Aberdaron Coast and Bardsey Island SPA, and
- Skomer, Skokholm and the Seas off Pembrokeshire/ Sgomer, Sgogwm a Moroedd Penfro SPA

4.6. Due to these methodological concerns the RSPB consider that it is not currently possible to rule out adverse impacts upon gannet occurring within the study area from the following SPAs:

- Grassholm SPA
- Ailsa Craig SPA
- Saltee Islands SPA

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The RSPB's interest in offshore wind development

1.2. Faced with the threats of climate change to the natural world the RSPB considers that a low-carbon energy revolution to reach net zero is essential to safeguard biodiversity. However, inappropriately designed and/or sited developments can also cause serious and irreparable harm to biodiversity and damage the public acceptability of the necessary low-carbon energy transition technologies.

1.3. The RSPB recognises the significant role that offshore wind will play in decarbonising our energy systems and the renewed urgency with which this must happen. Installing this technology at the scale and pace needed is no easy task: there are significant challenges rooted in the planning frameworks and the state of our seas which threaten both nature *and* our ability to reach net zero.

1.4. The UK is of outstanding international importance for its breeding seabirds, including northern gannet for which the UK supports over 50% of the world population and around 10% of the world populations of kittiwake and puffin. The UK is also of international importance for its non-breeding seabirds and waterbirds. As with all Annex I and regularly migratory species, the UK has particular responsibility under the Birds Directive[2] to secure the conservation of these birds.

1.5. The available evidence suggests that the main risks of offshore wind farms for birds are collision, disturbance/displacement, barriers to movement (e.g. migrating birds, or disruption of access between the breeding areas and feeding areas), and habitat change particularly with associated changes in food availability and the cumulative and in-combination effects of these across multiple wind farms.

1.6. Such impacts are avoidable, and the RSPB has spent considerable time working with stakeholders in the UK offshore wind industry to ensure that decisions about deployment of renewable energy infrastructure take account of environmental constraints and seek to avoid or minimise impacts wherever possible. The RSPB therefore strongly advocates the use of rigorous, participative environmental assessments to inform the development of projects.

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Scope of written submission

1.7. This Written Submission covers the following:

- The nature conservation importance of the seabirds affected by the Awel y Môr Offshore wind farm scheme
- Legislation and policy background
- Offshore ornithology

1.8. In compiling this Written Representation, the RSPB has considered the application documents, including in particular the following:

Section 4 (offshore ornithology) and Appendix A

- APP-050 6.2.4 Volume 2, Chapter 4: Offshore Ornithology
- APP-095 6.4.4.1 Volume 4, Annex 4.1: Offshore Ornithology Baseline Characterisation Report
- APP-096 6.4.4.2 Volume 4, Annex 4.2: Offshore Ornithology Displacement
- APP-097 6.4.4.3 Volume 4, Annex 4.3: Offshore Ornithology Collision Risk Modelling
- APP-100 6.4.4.6 Volume 4, Annex 4.6: Offshore Ornithology Population Viability Analysis
- APP-027 5.2 Report to Inform Appropriate Assessment
- APP-029 5.2.2 RIAA Annex 2: HRA Screening Update (Ornithology)
- AS-022 Response to post-Acceptance s51 advice: 5.2.3 Report to Inform Appropriate Assessment (RIAA) Annex 3: European Site Information
- APP-032 5.2.5 RIAA Annex 5: Ornithology Apportioning Note
- APP-033 5.2.6 RIAA Annex 6: Screening Matrices
- APP-034 5.2.7 RIAA Annex 7: Integrity Matrices
- APP-035 5.2.8 RIAA Annex 8: Abundance and Distribution of Red Throated Diver in Gwynt y Môr Offshore Wind Farm and Wider Area

2. The nature conservation importance of the waterbirds and seabirds affected by the Awel y Môr offshore wind farm scheme

Introduction

2.1. The UK is of outstanding international importance for its wintering waterbirds including large aggregations of non-breeding red-throated diver (Gavia stellata) in UK coastal areas; and breeding seabirds, including northern gannet (Morus bassanus) for which the UK supports over 50% of the world population and around 78% of the world population of Manx shearwater (Puffinus puffinus). As with all Annex I and regularly occurring migratory species, the UK has particular responsibility under the Birds Directive[3] to secure the conservation of these important waterbird and seabird populations.

2.2. The RSPB considers the project has the potential to impact several Special Protection Areas (SPAs), classified under the EU Birds Directive. Below we provide a brief summary of each affected SPA (including one SPA in the Republic of Ireland) and the relevant qualifying features.

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[3] Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds (codified version) (the Birds Directive)

Liverpool Bay/Bae Lerpwl SPA

2.3. The Liverpool Bay/Bae Lerpwl SPA comprises of areas for foraging breeding seabirds, and non-breeding seabirds and waterbirds. The main feature of the Liverpool Bay SPA affected by the Application is the non-breeding red-throated diver population. The SPA was originally classified in 2010 on the basis that it supported an internationally important population of 1,171 individual wintering red-throated divers and the largest aggregation of common scoters (Melanitta nigra) in the UK; the SPA was reclassified in 2017[4] following changes to the designated site boundary and the addition of internationally important populations of little gull (Hydrocoloeus minutus), common tern (Sterna hirundo) and little tern (Sterna albifrons) to its qualifying features. Cormorant (Phalacrocorax carbo) and red-breasted merganser (Mergus serrator) were added to the waterbird assemblage as named species.

2.4. The conservation objectives for Liverpool Bay SPA[5] are as follows:

> *"…to ensure that subject to natural change, the integrity of the site is maintained or restored as appropriate, and ensure that the site contributes to achieving the aims of the Wild Birds Directive, by maintaining or restoring:*
>
> - *The extent and distribution of the habitats of the qualifying features;*
> - *The structure and function of the habitats of the qualifying features;*
> - *The supporting processes on which the habitats of the qualifying features rely;*
> - *The population of each of the qualifying features; and,*
> - *The distribution of the qualifying features within the site."*

Copeland Islands SPA

2.5. The main feature of the Copeland Islands SPA affected by the Application is the breeding Manx shearwater population. The SPA was originally classified in 2010[6] on the basis that it supported an internationally important population of 4800 breeding pairs of Manx shearwater. The site also qualifies by supporting nationally important populations of Arctic tern.

2.6. The Conservation Objectives[7] for the site are:

> *"To maintain each feature in favourable condition. The SPA selection feature objectives are as follows:*
>
> - *To maintain or enhance the population of the qualifying species;*
> - *Fledging success sufficient to maintain or enhance population;*
> - *To maintain or enhance the range of habitats utilised by the qualifying species;*
> - *To ensure that the integrity of the site is maintained;*
> - *To ensure there is no significant disturbance of the species; and*
> - *To ensure that the following are maintained in the long term:*
> - *Population of the species as a viable component of the site;*
> - *Distribution of the species within site;*
> - *Distribution and extent of habitats supporting the species; and*
> - *Structure, function and supporting processes of habitats supporting the species."*

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[4] Liverpool Bay/Bae Lerpwl SPA Citation

[5] Liverpool Bay/Bae Lerpwl SPA Conservation Objectives

[6] Copeland Islands SPA Citation

[7] Copeland Islands SPA Conservation Objectives

2.7. For each feature there are a number of component objectives which are outlined below (Manx shearwater):

- Manx shearwater breeding population – no significant decrease in population against national trends;
- Manx shearwater breeding population – fledging success sufficient to maintain or enhance population.

Irish Sea Front SPA

2.8. The feature of the Irish Sea Front SPA affected by the Application is the population of Manx shearwater. The SPA is a foraging area for the Manx shearwater breeding population across the Irish Sea region, with a population of 12,039 birds during the breeding season (1.1% of the biogeographic population).

2.9. The site Conservation Objectives[8] are as follows:

> *"To avoid significant deterioration of the habitats of the qualifying species or significant disturbance to the qualifying species, subject to natural change, thus ensuring that the integrity of the site is maintained in the long term and makes an appropriate contribution to achieving the aims of the Birds Directive for each of the qualifying species.*

2.10. This contribution would be achieved through delivering the following objectives for each of the sites qualifying features:

A. Avoid significant mortality, injury and disturbance of the qualifying features, so that the distribution of the species and ability to use the site are maintained in the long-term;
B. Maintain the habitats and food resources of the qualifying features in favourable condition.
C. Ensure access to the site from linked breeding colonies

Rum SPA

2.11. The main feature of the Rum SPA affected by the Application is the breeding Manx shearwater population. The SPA was originally classified in 1982, with marine extension classified in 2009 and red-throated diver added to the marine extension in 2020[9].

2.12. The site qualifies under Article 4.2 by regularly supporting populations of European importance of the migratory species Manx shearwater (61,000 pairs, 23% of the world biogeographic population).

2.13. The Draft Conservation Objectives[10] are as follows:

> *"1. To ensure that the qualifying features of Rum SPA are in favourable condition and make an appropriate contribution to achieving Favourable Conservation Status.*
> *2. To ensure that the integrity of Rum SPA is restored in the context of environmental changes by meeting objectives 2a, 2b and 2c for each qualifying feature:*
> *2a. The populations of the qualifying features are viable components of Rum SPA.*

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[8] Irish Sea Front SPA Draft Conservation Objectives and Advice on Operations
[9] Rum SPA citation
[10] Rum SPA Conservation Objectives

> *2b. The distributions of the qualifying features throughout the site are maintained by avoiding significant disturbance of the species.*
> *2c. The supporting habitats and processes relevant to qualifying features and their prey/food resources are maintained, or where appropriate, restored at Rum SPA"*

St Kilda SPA

2.14. The main feature of the St Kilda SPA affected by the Application is the breeding Manx shearwater population. The SPA was originally classified in 1992, with marine extension classified in 2009[11].

2.15. St Kilda SPA qualifies under Article 4.2 by regularly supporting in excess of 20,000 individual seabirds. It regularly supports 600,000 seabirds including nationally important populations of the seabirds including up to 5,000 pairs of Manx shearwater (1% of the GB population).

2.16. The Draft Conservation Objectives[12]are as follows:

> *"1. To ensure that the qualifying features of St Kilda SPA and the Seas off St Kilda SPA are in favourable condition and make an appropriate contribution to achieving Favourable Conservation Status.*
> *2. To ensure that the integrity of St Kilda SPA and the Seas off St Kilda SPA is restored in the context of environmental changes by meeting objectives 2a, 2b and 2c for each qualifying feature:*
> *2a. The populations of qualifying features are viable components of St Kilda SPA and Seas off St Kilda SPA.*
> *2b. The distributions of the qualifying features throughout St Kilda SPA and Seas off St Kilda SPA are maintained by avoiding significant disturbance of the species.*
> *2c. The supporting habitats and processes relevant to qualifying features and their prey/food resources are maintained, or where appropriate restored, at St Kilda SPA and/or Seas off St Kilda SPA."*

Glannau Aberdaron ac Ynys Enlli/Aberdaron Coast and Bardsey Island SPA

2.17. The main feature of the SPA affected by the Application is the breeding Manx shearwater population. The SPA was originally classified in 1992, with marine extension classified in 2015[13].

2.18. The site qualifies under Article 4.2 as it is used regularly by 1% or more of the biogeographical population of Manx shearwater with 6930 pairs in 1996. There are more recent population figures with 20675 apparently occupied burrows (pairs) in 2016.

2.19. The Conservation Objectives for Manx shearwater[14] are:

> *"The vision for this feature is for it to be in a favourable conservation status, where all of the following conditions are satisfied:*
>
> - *Breeding population of Manx shearwater (confined to Ynys Enlli) is stable or increasing;*
> - *Reproductive rates remain stable;*
> - *Deaths from the lighthouse attractions, fencing and other infrastructure are minimal;*
> - *No ground predators are introduced;*

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[11] St Kilda SPA citation

[12] St Kilda SPA Conservation Objectives

[13] Glannau Aberdaron ac Ynys Enlli SPA Citation

[14] Glannau Aberdaron ac Ynys Enlli SPA Core Management Plan (including Conservation Objectives)

- *Nesting birds are not disturbed by restoration works on boundary walls or recreational activities; and*
- *All factors affecting the achievement of these conditions are under control."*

Skomer, Skokholm and the Seas off Pembrokeshire/Sgomer, Sgogwm a Moroedd Penfro SPA

2.20. The main feature of the SPA affected by the Application is the breeding Manx shearwater population. The SPA was originally classified in 1982, with site reclassified and boundary extended to include marine area in 2014. The seaward boundary of the site was extended in 2017[15].

2.21. The site qualifies under Article 4.2 as it is used regularly by 1% or more of the GB or biogeographical population of Manx shearwater with 150,968 pairs in late 1990s (51.3% of the European population). There are more recent population figures with 390,000 apparently occupied burrows (pairs) in 2018.

2.22. The Conservation Objective for Manx shearwater[16] are:

> *"The vision for this feature is for it to be in a favourable conservation status, where all of the following conditions are satisfied:*
> - *During the breeding season the population of Manx shearwater will be at least 150,000 pairs within the SPA (this represents around half of the current breeding population);*
> - *Breeding success will be at least 0.5 chicks per egg laid; and*
> - *The factors affecting the feature are under control."*

Grassholm SPA

2.23. The feature of Grassholm SPA affected by the Application is the breeding gannet population. Grassholm SPA was classified in 1986 and reclassified in 2015[17].

2.24. Grassholm qualifies under Article 4.2 by regularly supporting internationally important numbers of breeding gannet with 33,000 pairs in 1994/95. It is the third biggest gannet colony in the world.

2.25. The Conservation Objectives[18] for gannet are:

> *"The vision for this feature is for it to be in a favourable conservation status, where all of the following conditions are satisfied:*
> - *The population will not fall below 30,000 pairs in three consecutive years.*
> - *It will not drop by more than 25% of the previous year's figures in any one year.*
> - *There will be no decline in this population significantly greater than any decline in the North Atlantic population as a whole."*

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[15] Skomer, Skokholm and the Seas off Pembrokeshire/Sgomer, Sgogwm a Moroedd Penfro SPA citation

[16] Skomer, Skokholm and the Seas off Pembrokeshire SPA Core Management Plan (including conservation objectives)

[17] Grassholm SPA citation

[18] Grassholm SPA Core Management Plan (including conservation objectives)

Ailsa Craig SPA

2.26. The main feature of the SPA affected by the Application is the breeding gannet population. The SPA was classified in 1990 with marine extension classified in 2009[19]. It qualifies under Article 4.2 by regularly supporting populations of European importance of the migratory species, including gannet with 23,000 pairs (8.7% of the world biogeographic population).

2.27. The Conservation Objectives[20] for the site are as follows:

> *"To avoid deterioration of the habitats of the qualifying species or significant disturbance to the qualifying species, thus ensuring that the integrity of the site is maintained; and*
> *To ensure for the qualifying species that the following are maintained in the long term:*
> - *Population of the species as a viable component of the site;*
> - *Distribution of the species within site;*
> - *Distribution and extent of habitats supporting the species;*
> - *Structure, function and supporting processes of habitats supporting the species; and*
> - *No significant disturbance of the species."*

Saltee Islands SPA

2.28. The main feature of the SPA affected by the Application is the breeding gannet population. The SPA was classified in 2011[21]. The Saltee Islands are internationally important for holding an assemblage of over 20,000 breeding seabirds. The qualifying interests include the nationally important gannet colony on Great Saltee which held 2,446 pairs in 2004.

2.29. The Conservation Objectives for Gannet[22] are:

> *"To maintain the favourable conservation condition of Gannet in the Saltee Islands SPA, which is defined by the following list of attributes and targets:*
> - *No significant decline in breeding population abundance: apparently occupied nests (AONs);*
> - *No significant decline in productivity rate;*
> - *No significant decline in distribution: breeding colonies;*
> - *No significant decline in prey biomass available;*
> - *No significant increase in barriers to connectivity;*
> - *No significant increase in disturbance at the breeding site; and*
> - *No significant increase in disturbance at marine areas immediately adjacent to the colony."*

3. Legislation and policy background

Introduction

3.1. The following planning policy and statutory guidance relevant to Wales are to be considered:

- Future Wales[23]

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[19] Ailsa Craig SPA Citation

[20] Ailsa Craig SPA Conservation Objectives

[21] Saltee Islands SPA Site Synopsis

[22] Saltee Islands SPA Conservation Objectives

[23] https://gov.wales/sites/default/files/publications/2021-02/future-wales-the-national-plan-2040.pdf

- Planning Policy Wales[24]
- Future Generations Act[25]
- Denbighshire County Council Local Development Plan[26] (for Landfall)

3.2. The suite of Energy National Policy Statements (NPSs) set out the Government's approach to ensuring the security of energy supplies and the policy framework within which new energy infrastructure proposals are to be considered. The presumption in favour of granting consent, as identified in NPS EN-1, *Overarching National Policy Statement for Energy*[27], is subject to the tests set out below in section 104 of the Planning Act 2008[28] (see NPS EN-1 paragraphs 4.1.2 and 1.1.2).

3.3. Section 104 of the Planning Act provides that an application for development consent for energy infrastructure must be decided in accordance with the relevant NPS except where in doing so it would lead to the UK:

- being in breach of its international obligations;
- being in breach of any statutory duty that applies to the Secretary of State; or would
- be unlawful;
- result in adverse impacts which would outweigh the benefits; or
- be contrary to regulations about how decisions are to be taken.

3.4. The statutory duties include the Conservation of Habitats and Species Regulations 2017[29] (the Habitats Regulations, as amended) (NPS EN-1 paragraph 4.3.1) and the wider objective of protecting the most important biodiversity conservation interests (see NPS EN-1 section 5.3 generally). It notes the Habitats Regulations' statutory protection for important sites including Ramsar sites, listed under the Ramsar Convention[30], SPAs designated under the Birds Directive and Special Areas of Conservation (SACs) designated under the Habitats Directive[31].

3.5. NPS EN-3, *National Policy Statement for Renewable Energy Infrastructure*, specifically identifies birds as a biodiversity concern to be taken into account (paragraph 2.6.59 and 2.6.68). Whilst it is stated that the designation of an area as a protected European site does not necessarily restrict the construction or operation of offshore wind farms (paragraph 2.6.69), the legislative requirements identified above are still to be met. The protection afforded by legislation, to which the 2008 Act and the NPSs refer, are addressed briefly below.

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[24] https://gov.wales/sites/default/files/publications/2021-02/planning-policy-wales-edition-11_0.pdf

[25] https://gov.wales/well-being-future-generations-statutory-guidance

[26] https://www.denbighshire.gov.uk/en/planning-and-building-regulations/local-development-plan/local-development-plan.aspx

[27] Overarching National Planning Policy Statement for Energy (EN-1): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/47854/1938-overarching-nps-for-energy-en1.pdf

[28] Planning Act, 2008: http://www.legislation.gov.uk/ukpga/2008/29/contents

[29] The Conservation of Habitats and Species Regulations 2017: https://www.legislation.gov.uk/uksi/2017/1012/contents. The Conservation of Offshore Marine Habitats and Species Regulations 2017 are also relevant - https://www.legislation.gov.uk/uksi/2017/1013/contents but unfortunately Legislation.gov.uk has not been updated to reflect the changes made due to Brexit

[30] The Convention on Wetlands of International Importance 1971. Para 5.3.9 of the NPS EN-1 confirms that for the purposes of considering development proposals affecting them, listed Ramsar sites should also, as a matter of policy, receive the same protection

[31] Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora

The Conservation of Habitats and Species Regulations 2017 and the Conservation of Offshore Marine Habitats and Species Regulations 2017

3.6. SACs and SPAs are protected as “European sites” in inshore waters (up to 12 nautical miles from the baselines) under provisions within the Conservation of Habitats and Species Regulations 2017 (Habitats Regulations)(as amended); and in offshore waters (i.e. from 12-200 nautical miles) under provisions within the Conservation of Offshore Marine Habitats and Species Regulations 2017 (Offshore Habitats Regulations)(as amended)[32].

3.7. The Habitats & Offshore Habitats Regulations set out the sequence of steps to be taken by the competent authority (here the Secretary of State for Business, Energy and Industrial Strategy (BEIS)) when considering authorisation for a project *likely to have an effect* on a European site and its species before deciding to authorise that project. These are as follows (with references to just the Habitats Regulations):

- Step 1: consider whether the project is directly connected with or necessary to the management of the SPA and its species (regulation 63 (1)). If not –
- Step 2: consider, on a precautionary basis, whether the project is likely to have a significant effect on the SPA and its species, either alone or in combination with other plans or projects (the Likely Significance Test) (regulation 63 (1)).
- Step 3: make an appropriate assessment of the implications for the SPA and its species in view of its conservation objectives with the aims and objectives of the requirements including the National Sites Network management objectives (reg 16A) to also be considered. There is no requirement or ability at this stage to consider extraneous (non-conservation e.g. economics, renewable targets, public safety etc) matters in the appropriate assessment (regulation 63 (1)).
- Step 4: consider whether it can be ascertained that the project will not, alone or in combination with other plans or projects, adversely affect the integrity of the SPA and its species, having regard to the manner in which it is proposed to be carried out, and any conditions or restrictions subject to which that authorisation might be given (the Integrity Test) (regulation 63 (6)).
- Step 5: In light of the conclusions of the assessment, the competent authority shall agree to the project only after having ascertained that it will not adversely affect the integrity of the SPA, alone or in combination with other plans or projects (regulation 63 (5)).
- Step 6: only if the competent authority is satisfied that, there being no alternative solutions and the plan or project must be carried out for imperative reasons of overriding public interest (which, subject to (regulation 64(2)), may be of a social or economic nature), they may agree to the plan or project notwithstanding a negative assessment of the implications for the European site (regulation 64 (1)).
- Step 7: in the event of the no alternative solutions and imperative reasons of overriding public interest tests being satisfied, the Secretary of State must secure that any and all necessary compensatory measures are taken to ensure that the overall coherence of the National Site Network is protected (regulation 68) taking account of the National Site Network management objectives (reg 16A, as set out below).

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[32] The Conservation of Habitats and Species Regulations 2017: https://www.legislation.gov.uk/uksi/2017/1012/contents. The Conservation of Offshore Marine Habitats and Species Regulations 2017 are also relevant - https://www.legislation.gov.uk/uksi/2017/1013/contents but unfortunately Legislation.gov.uk has not been updated to reflect the changes made due to Brexit

3.8. It is important to add that in addition to the requirements set out above, in relation to both inshore marine area and the offshore marine area, any competent authority must exercise its functions so as to secure compliance with the requirements of the Habitats Directive and the Birds Directive as set out in regulations 9 and 10, Habitats Regulations; and in particular to take such steps as it considers appropriate to secure the preservation, maintenance and re-establishment of a sufficient diversity and area of habitat for wild birds[33], having regard to the requirements of Article 2 of the Birds Directive.[34] And for offshore SPAs and SACs regulation 26, Offshore Habitats Regulations requires competent authorities to exercise their functions (as far as possible) to secure steps to avoid the disturbance of species and the deterioration of habitats or habitats of species within those sites.

SPA and SAC Conservation Objectives

3.9. Under the Habitats Regulations, a site's Conservation Objectives are intrinsic to the Integrity Test when considering whether to grant consent for a plan or project – see Habitats Regulations 63(1).

3.10. In order to understand the Conservation Objectives and the Supplementary Advice in the context of Regulation 63(1) it is important to remind oneself of the role of SPAs within these legislative requirements. These protected sites are part of the requirement for special conservation measures in order to ensure that their contribution to national and international "conservation status" of the species[35] is maximised, as set out in the headline words at the start of all Conservation Objectives:

> *"Ensure that the integrity of the site is maintained or restored as appropriate, and ensure that the site contributes to achieving the aims of the Wild Birds Directive, by maintaining or restoring…"*[36]

3.11. The Conservation Objectives are to be an articulation of the contribution that it is appropriate for the SPA to make in an enduring way. It would be inconsistent with the purposes of the protection and the role of SPAs to have SPA Conservation Objectives (or the interpretation of them) aiming for lower populations particularly since so many sites were designated at a time when populations were not in favourable condition.

Appropriate assessment

3.12. As part of the assessment requirements, regulation 63, Habitats Regulations (regulation 28, Offshore Habitats Regulations) require the application of the precautionary principle. Meaning that if it cannot be excluded, on the basis of objective scientific information, that it is likely to have a significant effect on an SPA or SAC and its species an appropriate assessment will be required: see *Waddenzee*.[37]

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[33] As required by Article 3, Birds Directive

[34] See regulation 9(1) and 10(1)(2)(3) and (8) of the Habitats Regulations and regulation 6 of the Offshore Regulations. Article 2 Birds Directive imposes a requirement on Member States to maintain all wild bird populations at a level which corresponds in particular to ecological, scientific and cultural requirements, while taking account of economic and recreational requirements, or if necessary, to restore the population of these species to that level (Article 2)

[35] Please see points below on the management objectives of the National Sites Network and the requirements for SPAs to ensure that the species are maintained and/or restored across their natural range

[36] The SPA generic Conservation Objectives [redacted] Accessed 29 March 2022

[37] CJEU Case-127/02; [2004] ECR-7405 at [45]

3.13. Following that appropriate assessment, a project may only be granted consent if the competent authority is convinced that it will not have an adverse effect on the integrity of the European site(s) and their species of concern, having applied the precautionary principle and taken account of the conservation objectives for those European sites and their habitats and species. *Waddenzee* confirmed that where doubt remains as to the absence of adverse effects on the integrity of the European site, approval should be refused[38] (subject to the considerations of alternative solutions, imperative reasons of overriding public interest and the provision of compensatory measures as set out in regulations 64 and 68).

3.14. An appropriate assessment requires all aspects of the project which could affect the European site, its species and its conservation objectives to be identified in the light of the best scientific knowledge in the field.[39] The competent authority,

> *"taking account of the conclusions of the appropriate assessment of the implications…for the site concerned, in the light of the conservation objectives, are to authorise such activity only if they have made certain that it will not adversely affect the integrity of the site. That is the case where no reasonable scientific doubt remains as to the absence of such effects"*[40]*.*

3.15. Defra Circular 01/2005 states at page 20, that the 'integrity of the site' should be defined as 'the coherence of the site's ecological structure and function, across its whole area, or the habitats, complex of habitats and/or populations of species for which the site is or will be classified'.[41] An European site can be described as having a high degree of integrity where the inherent potential for meeting site conservation objectives is realised, the capacity for self-repair and self-renewal under dynamic conditions is maintained, and a minimum of external management support is required. When looking at the 'integrity of the site', it is therefore important to take into account a range of factors, including the possibility of effects manifesting themselves in the short, medium and long-term".[42]

3.16. As is clear from the requirements of the Habitats and Offshore Habitats Regulations, the assessment of integrity is to be considered by reference to the impact of the project alone and in-combination with other plans and projects, taking account of the European site(s) conservation objectives. As clearly set out in *Waddenzee*, para 61:

> *"61 In view of the foregoing, the answer to the fourth question must be that, under Article 6(3) of the Habitats Directive, an appropriate assessment of the implications for the site concerned of the plan or project implies that, prior to its approval, all the aspects of the plan or project which can, by themselves or in combination with other plans or projects, affect the site's conservation objectives must be identified in the light of the best scientific knowledge in the field. The competent national authorities, taking account of the appropriate assessment of the implications of mechanical cockle fishing for the site concerned in the light of the site's conservation objectives, are to authorise such an activity only if they have made certain that it will not adversely affect the integrity of that site. That is the case where no reasonable scientific doubt remains as to the absence of such effects."* (emphasis added)

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[38] [56]-[57]

[39] [61]

[40] [59]

[41] Please note the Defra Circular 01/2005 is also titled ODPM Circular 6/2005

[42] See too the European Commission Guidance; Wind Energy Developments and Natura 2000, 2011, page 82-83, paragraph 5.5.3

In-combination effects and compensation for other schemes

3.17. Compensatory measures only enter the equation when it has been determined that there will be adverse effects on the integrity of the site (under regulation 63) or there is a lack of certainty as to the absence of adverse effects and the need for the competent authority to decide whether consent should be granted under regulation 64.

3.18. It therefore follows that if compensation measures have been required for a project then that project has been identified as giving rise to potential adverse impacts on the integrity of a protected site. Therefore, potential adverse effects from that project are also relevant when considering whether a later project is:

- likely to have a significant effect on a designated site, whether on its own or in combination with other plans and projects, and subsequently
- whether the competent authority can be satisfied that there will not be adverse effects on the integrity of the European site whether taken alone or in combination with other projects.

3.19. It is difficult to see on what basis the fact that compensation has been provided for potential adverse effects of the first scheme should mean that the effects of that scheme should be removed from the equation when carrying out the assessments required by regulation 63 for a later scheme, although it may well be relevant when considering whether consent should be granted under regulation 64 for the second scheme and/or what compensation measures should be required at that stage. There are two points we would stress in that context:

- Firstly, the admonition of AG Sharpston in *Sweetman (No 1)* at AG47 (cited above). To exclude the adverse effects of scheme one when considering whether a later scheme would be likely *to* have significant effects / would not have an adverse effect on the integrity of a protected site in combination with other projects would seem to risk perpetuating the "death by a thousand cuts" phenomenon discussed in that case;[43] and
- Secondly, the uncertainty as to the effectiveness of measures that are designed to compensate for (for example) loss of habitat rather than to mitigate the harm which might otherwise be *caused*: see C-164/17 *Grace v Sweetman* at 52-3.

3.20. Such an approach would also seem inconsistent with the clear ruling of the CJEU in C-164/17 *Grace v Sweetman* that *compensatory* measures should not be taken into account at the Article 6(3) stage when carrying out an appropriate assessment for a particular project. It is difficult to see why the compensatory measures associated with an earlier scheme could, therefore, be taken into account (by effectively removing the adverse effects of scheme 1 from consideration) where the competent authority is deciding on a later scheme whether it was likely to have significant effects or would / would not have adverse effects on the integrity of the site in combination with other projects. We set out the material passages from that decision out below for ease of reference:

> *"50 In that regard, the Court has previously ruled that the measures provided for in a project which are aimed at compensating for the negative effects* of the project cannot be

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[43] For the avoidance of doubt, we would stress that the starting point would always need to be the scheme itself – and there would need to be some effect from the scheme which when combined with effects from the earlier scheme could give rise to likely significant effects / outcome

> taken into account in the assessment of the implications of the project provided for in Article 6(3) of the Habitats Directive…[44].
>
> *51 It is only when it is sufficiently certain that a measure will make an effective contribution to* avoiding harm, guaranteeing beyond all reasonable doubt that the project will not adversely affect the integrity of the area, that such a measure may be taken into consideration when the appropriate assessment is carried out[45].
>
> *52* As a general rule, any positive effects of the future creation of a new habitat, which is aimed at compensating for the loss of area and quality of that habitat type in a protected area, are highly difficult to forecast with any degree of certainty or will be visible only in the future[46].
>
> *53 It is not the fact that the habitat concerned in the main proceedings is in constant flux* and that that area requires 'dynamic' management that is the cause of uncertainty. In fact, such uncertainty is the result of the identification of adverse effects, certain or potential, on the integrity of the area concerned as a habitat and foraging area and, therefore, on one of the constitutive characteristics of that area, and of the inclusion in the assessment of the implications of future benefits to be derived from the adoption of measures which, at the time that assessment is made, are only potential, as the measures have not yet been implemented. Accordingly, and subject to verifications to be carried out by the referring court, it was not possible for those benefits to be foreseen with the requisite degree of certainty when the authorities approved the contested development.
>
> *54 The foregoing considerations are confirmed by the fact that Article 6(3) of the Habitats Directiv*e integrates the precautionary principle and makes it possible to prevent in an effective manner adverse effects on the integrity of protected areas as a result of the plans or projects being considered[47]."

Habitats Regulations General Duties

3.21. We would like to also highlight, in particular, the requirements in regulation 9(3)[48]:

> *"9.— Duties relating to compliance with the Directives*
>
> *(1) The appropriate authority, the nature conservation bodies and, in relation to the marine area, a competent authority must exercise their functions which are relevant to nature conservation, including marine conservation, so as to secure compliance with the requirements of the Directives.*
>
> …
>
> *(3) Without prejudice to the preceding provisions, a competent authority, in exercising any of its functions, must have regard to the requirements of the [Birds and Habitats] Directives so far as they may be affected by the exercise of those functions.*[49]

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[44] Judgments of 15 May 2014, Briels and Others, C-521/12, EU:C:2014:330, paragraph 29, and of 21 July 2016, Orleans and Others, C-387/15 and C-388/15, EU:C:2016:583, paragraph 48

[45] See, to that effect, judgment of 26 April 2017, Commission v Germany, C-142/16, EU:C:2017:301, paragraph 38

[46] See, to that effect, judgment of 21 July 2016, Orleans and Others, C-387/15 and C-388/15, EU:C:2016:583, paragraphs 52 and 56 and the case-law cited

[47] See, to that effect, judgment of 15 May 2014, Briels and Others, C-521/12, EU:C:2014:330, paragraph 26 and the case-law cited

[48] https://www.legislation.gov.uk/uksi/2017/1012/regulation/9

[49] The terms of regulation 9(3) are not amended by the Conservation of Habitats and Species (Amendment) (EU Exit) Regulations although it needs to be read with the amended definitions of the relevant Directives and with the new regulation 9(4A) – regard must be had to any Secretary of State guidance – currently we do not believe this has been fully produced

3.22. And the further duties in Regulation 10[50]:

> *10.— Duties in relation to wild bird habitat*
>
> *(1) Without prejudice to regulation 9(1), the appropriate authority, the nature conservation bodies and, in relation to the marine area, a competent authority must take such steps in the exercise of their functions as they consider appropriate to secure the objective in paragraph (3), so far as lies within their powers.*
>
> *…*
>
> *(3) The objective is the preservation, maintenance and re-establishment of a sufficient diversity and area of habitat for wild birds in the United Kingdom including by means of the upkeep, management and creation of such habitat, as appropriate), having regard to the requirements of Article 2 of the new Birds Directive (measures to maintain the population of bird species).*
>
> *…*
>
> *(7) In considering which measures may be appropriate for the purpose of securing or contributing to the objective in paragraph (3), appropriate account must be taken of economic and recreational requirements.*
>
> *…*
>
> *(8) So far as lies within its powers, a competent authority in exercising any function in or in relation to the United Kingdom must use all reasonable endeavours to avoid any pollution or deterioration of habitats of wild birds"*[51]

3.23. As mentioned above following the UK's departure from the EU these regulations have been changed to include (amongst other changes) management objectives for the National Sites Network. Although these requirements already existed, it is helpful to have them clearly within our domestic legislation.

3.24. In summary regulation 16A[52], Habitats Regulations sets out the requirements for the Network jointly and separately recognising the differences between SPAs and SACs (as set out above).

3.25. Authorities with relevant responsibilities must manage the National Site Network with a view to contributing to the achievement of the management objectives of it, namely (focusing just on SPAs):

3.26. For SPAs to contribute, in their area of distribution, to ensuring the survival and reproduction of:

- the species of birds listed in Annex I to the new Wild Birds Directive;
- regularly occurring migratory species of birds; and
- to contribute, to securing compliance with regulation 9(1) (as set out above).

3.27. Overall, take account of:

- the importance of SACs and SPAs;
- the importance of the sites for the coherence of National Site Network;
- the threats of degradation or destruction (including deterioration and disturbance of protected features) to which the sites are exposed; and

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[50] https://www.legislation.gov.uk/uksi/2017/1012/regulation/10

[51] Again the terms of regulation 10 are not amended by the Conservation of Habitats and Species (Amendment) (EU Exit) Regulations although it needs to be read with the amended definitions of the relevant Directives

[52] https://www.legislation.gov.uk/uksi/2017/1012/regulation/16A Accessed 29 March 2022

- in the case of migratory bird species, the importance of their breeding, moulting and wintering areas and staging points along their migration routes.

3.28. The RSPB believes it is essential both during the appropriate assessment and consideration of compensation measures stages for these management objectives to be taken into account.

Environmental Impact Assessment

3.29. The Infrastructure Planning (Environmental Impact Assessment) Regulations 2017[53] state that development consent cannot be granted for Environmental Impact Assessment (EIA) development unless the decision-maker has taken into account environmental information including an environmental statement which describes the significant effects, including cumulative effects, of the development on the environment. This will include effects on all wild bird species whether SPA species or not.

3.30. Offshore wind farms have the potential to impact on birds through collision with rotating blades, direct habitat loss, disturbance from construction activities, displacement during the operational phase (resulting in loss of foraging/roosting area) and impact on bird flight lines (i.e. barrier effect) and associated increased energy use by birds for commuting flights between roosting and foraging areas. This is acknowledged in NPS EN-3[54]. These potential impacts have been taken into account by the RSPB and its remaining concerns with the applications are set out below, in the context of the legislative provisions summarised above, in particular those relating to appropriate assessment.

Summary

3.31. Energy National Policy Statements (NPSs) set out the Government's approach to considering new energy infrastructure. Consent for energy infrastructure is subject to tests set out in Section 104 of the Planning Act. NPS EN-3, National Policy Statement for Renewable Energy Infrastructure, specifically identifies birds as a biodiversity concern to be taken into account (paragraph 2.6.59 and 2.6.68).

3.32. There is a statutory duty to comply with the Conservation of Habitats and Species Regulations 2017 (the Habitats Regulations, as amended) which offer protection for protected sites (Ramsar, SPA, SAC) and the Conservation of Offshore Marine Habitats and Species Regulations 2017 (Offshore Regulations)(as amended). The Habitats and Offshore Regulations set out a sequence of steps to be taken by the competent authority (here the Secretary of State for Business, Energy and Industrial Strategy (BEIS)) when considering authorisation for a project *likely to have an effect* on a European site and its species before deciding to authorise that project.

3.33. We set out a series of related matters to be considered in this context, including:

- SPA and SAC Conservation Objectives;
- Appropriate assessment;
- In-combination effects and compensation for other schemes;

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[53] The Infrastructure Planning (Environmental Impact Assessment) Regulations 2017: http://www.legislation.gov.uk/uksi/2017/572/contents/made Accessed 29 March 2022

[54] Paragraph 2.6.101; see paragraphs 2.6.100-110 and 2.6.58-71 generally. Effects on foraging areas outside a SPA are to be taken into account when assessing the effects on bird populations of the SPA: see *Hargreaves v Secretary of State for Communities and Local Government* [2011] EWHC 1999 (Admin), which concerned effects on pink-footed geese which commuted inland from their roosting sites in the SPA to feed on grain and winter cereal crops on fields adjacent to the proposed development site

- Habitats Regulations General Duties;
- Environmental Impact Assessment.

4. Offshore ornithology

Introduction

4.1. The RSPB supports the deployment of renewable energy projects, providing that they are sited in appropriate places and designed to avoid potential adverse impacts on wildlife. We are grateful for the constructive pre-application discussions that have taken place with Awel y Môr Offshore Wind Farm Limited in respect of this proposal, particularly through the Evidence Plan process.

4.2. While methodological concerns remain, progress towards resolving a number of issues was made during the pre-application discussions for this project. We continue to have significant concerns relating to the project's in-combination and cumulative collision risk and displacement impacts including their assessment.

Offshore ornithology impacts - summary of RSPB position

4.3. We have significant concerns regarding the findings of some of the impact assessments. As a result of the methodological concerns, set out below, the RSPB considers that the impacts have not been adequately assessed and, as such consider that an adverse effect on the integrity (AEOI) on the following qualifying feature of the Liverpool Bay Special Protection Area (SPA) cannot be ruled out:

Project alone – RSPB AEOI conclusions

4.4. Impact on the following feature of the Liverpool Bay SPA:

- The impact of displacement on the red throated diver population

Project in combination with other plans and projects – RSPB AEOI conclusions

4.5. In-combination impacts on the following feature of the Liverpool Bay SPA:

- The impact of displacement on the red throated diver population

4.6. We also have methodological concerns and consider that it is not currently possible to rule out adverse impacts upon other SPA species occurring within the study area, in particular:

- Manx shearwater
- Gannet

Red throated diver displacement

4.7. Red throated diver is a migratory waterbird that breeds in fresh water lakes but winters in coastal marine waters, often in groups of considerable size. The Liverpool Bay Special Protected Area is designated, in part, due to the important its population of wintering red throated diver. The conservation objectives for the Liverpool Bay SPA are:

> *"Ensure th*at the integrity of the site is maintained or restored as appropriate, and ensure that the site contributes to achieving the aims of the Wild Birds Directive, by maintaining or restoring;

- *The extent and distribution of the habitats of the qualifying features*
- *The structure and function of the habitats of the qualifying features*
- *The supporting processes on which the habitats of the qualifying features rely*
- *The population of each of the qua*lifying features, and,
- *The distribution of the qualifying features within the site."*

4.8. Red throated divers are one of the most sensitive species to displacement effects from offshore windfarms, ranked as having the highest species concern value (along with black-throated diver) in relation to displacement of all the species considered in an assessment of vulnerability of seabirds to offshore windfarms (Furness *et al.,* 2013[55]). Similarly, a review of attraction and avoidance of offshore windfarms by seabirds clearly demonstrated that divers showed strong avoidance of turbines (Dierschke *et al.,* 2016[56]). This strong displacement effect has been shown in studies in the German North Sea to be significant at 15km from the wind farm, based on before and after studies on a long term data set (Mendel *et al.,* 2019[57]), a finding confirmed by satellite tracking and digital aerial surveys (Heinänen et al. 2020[58]). Recent analysis by the Centre for Research into Ecological and Environmental Modelling of aerial surveys carried out in Liverpool Bay also showed a strong effect whereby, in all cases, the presence of a wind farm decreased the estimated number of birds compared to the absence of a wind farm. This effect was apparent up to 3.8km from the centre of the wind farm (Burt *et al.,* 2022[59]).

4.9. As such, there is clear evidence of the displacement of red-throated diver from offshore wind farms with a significant effect detectable in some cases at considerable distance from the wind farm. The Awel y Môr proposed development directly abuts the Liverpool Bay SPA, and so these displacement effects will act upon the wintering red throated diver population of the SPA. The numbers of red throated diver, their distribution within the SPA and their ability to use all suitable habitat contained in the SPA are relevant to the SPA conservation objectives but are not considered by the Applicant. If, as the evidence suggest, red throated diver will be displaced from part of the SPA which would otherwise be suitable for them the effect will be to reduce the functional size of the SPA, directly contravening the conservation objectives. The RSPB therefore cannot rule out the impact of displacement on the integrity of the Liverpool Bay SPA, arising through the project alone and in combination.

4.10. Therefore, and as set out in paragraphs 4.4 and 4.5 above, the RSPB's position on adverse effect on integrity in respect of the permanent displacement of red-throated diver in the Liverpool Bay SPA is as follows:

- Adverse effect on integrity cannot be ruled out due to displacement from Liverpool Bay SPA alone; and

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[55] Furness, R. W., Wade, H. M., & Masden, E. A. (2013). Assessing vulnerability of marine bird populations to offshore wind farms. *Journal of environmental management*, *119*, 56-66

[56] Dierschke, V., Furness, R. W., & Garthe, S. (2016). Seabirds and offshore wind farms in European waters: Avoidance and attraction. *Biological Conservation*, *202*, 59-68

[57] Mendel, B., Schwemmer, P., Peschko, V., Müller, S., Schwemmer, H., Mercker, M., & Garthe, S. (2019). Operational offshore wind farms and associated ship traffic cause profound changes in distribution patterns of Loons (Gavia spp.). *Journal of environmental management*, *231*, 429-438

[58] Heinänen, S., Žydelis, R., Kleinschmidt, B., Dorsch, M., Burger, C., Morkūnas, J., ... & Nehls, G. (2020). Satellite telemetry and digital aerial surveys show strong displacement of red-throated divers (Gavia stellata) from offshore wind farms. *Marine environmental research*, *160*, 104989

[59] Burt, M.L., Mackenzie, M.L., Bradbury, G. and Darke, J. 2022. Investigating effects of shipping on common scoter and red-throated diver distributions in Liverpool Bay SPA. NECR425. Natural England

- Adverse effect on integrity cannot be ruled out due to displacement from Liverpool Bay SPA in-combination with existing plans and projects.

Other SPA species of concern present on site

4.11. Manx shearwater are BoCC5 Amber listed (Stanbury et al., 2021[60]) and are a Birds Directive Migratory Species. Awel y Môr is within the mean-max foraging range (1,347 km, Woodward et al., 2019) of six SPAs of which they are a qualifying feature (Copeland Islands, Irish Sea Front, Rum, St Kilda, Glannau Aberdaron ac Ynys Enlli/ Aberdaron Coast and Bardsey Island, and Skomer, Skokholm and the Seas off Pembrokeshire/ Sgomer, Sgogwm a Moroedd Penfro).

4.12. Gannet is Amber listed in BoCC5 (Stanbury et al., 2021). Gannet is a qualifying feature of Grassholm SPA and also known to breed in Ireland's Eye SPA and Lambay Island SPA, all of which are within mean-max foraging range of Awel y Môr (Woodward et al., 2019).

Impact assessment – methodological concerns

4.13. The RSPB's key concerns are with the baseline survey methodology, the scoping out of collision impacts for Manx shearwater, the use of avoidance rates in gannet collision risk modelling, lack of consideration of impacts compounded by highly pathogenic avian influenza (HPAI).

Baseline surveys

4.14. The RSPB are content that digital aerial surveys can provide useful data in order to provide baseline characterisation of an offshore wind farm footprint. However full methodological detail needs to be provided alongside the outputs and the details the Applicant has provided are scant. In particular, but not exclusively there is

- insufficient consideration of potential biases in the survey and analysis methods. For example these could be biases arising from both the camera system, such as imperfect detection of smaller species, or from the imperfect identification by the surveyor of the digital images. Any biases such should have been carefully described
- there is no consideration of potential response of birds to disturbance arising from the survey e.g. from aircraft shadow. This could be behavioural responses such as flight take off rate or diving rate, that would have implications for the accuracy of the assessment
- there is no detail provided as to how spatial autocorrelation has been evaluated and if necessary accounted for. Spatial autocorrelation in this instance is the correlation among values of a count variable strictly attributable to their relatively close locational positions, introducing a deviation from the assumption of independent observation. The assessment should explicitly demonstrate an analysis of the data showing whether spatial auto-correlation is present or not
- there is no rationale provided as to why a grid rather than transect survey design has been used. Both survey designs are commonly used in the assessment of the impacts of offshore wind farms, and both have strengths and weaknesses. Detail is required as to why a grid design was used for this assessment.
- there is no detail given of any independent validation of identification and detection rates. While it is clear that this validation is carried out as part of the *internal* quality assurance

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[60] Stanbury, A., Eaton, M., Aebischer, N., Balmer, D., Brown, A., Douse, A., Lindley, P., McCulloch, N., Noble, D. and Win, I., 2021. The status of our bird populations: the fifth Birds of Conservation Concern in the United Kingdom, Channel Islands and Isle of Man and second IUCN Red List assessment of extinction risk for Great Britain. *British Birds*, *114*, pp.723-747

procedures of the survey providers, no detail of any independent *external* quality assurance appears to have been carried out.

Manx shearwater

4.15. The Applicant has scoped out Manx Shearwater as being a receptor at risk of collision impacts. We disagree with this approach and consider there to be risk of collision. Fundamental to the consideration of collision risk for this species is the extent to which nocturnally active seabirds, such as Manx shearwaters, may be attracted to the illuminations required for turbines, support vessels and the construction or expansion of ports. Such attraction will cause behaviour change, which could in turn increase collision risk, for example if birds fly higher when attracted to lights.

4.16. There is also abundant evidence of light-induced disorientation of Manx shearwaters. This evidence includes the grounding of fledglings in lit areas (Miles et al., 2010[61]) and collision with lighthouses and other illuminated structures (Guilford et al., 2019[62], Archer et al., 2015[63]). If light-induced disorientation leads to individual birds circling the navigation lights on the nacelle or tower of turbines for protracted periods (as has been reported for birds disorientated by lighthouses or gas flares) the probability of collision with turbine blades or other surfaces is vastly increased.

4.17. Such light induced behavioural change invalidates the simplistic assumptions of bird behaviour in the vicinity of turbines of the Band Collision Risk Model. For example, the model assumes that birds will fly at a fixed height and speed once through the rotor swept area, in a direction perpendicular to the turbine blades. Light-induced changes in flight height, disorientation and circling flight behaviour mean that this assumption would not be met.

4.18. Currently in assessment, there is an assumption that Manx shearwater are not at risk of collision because of their low flight height. However, current flight height data for this species is based on aerial or vessel-based at-sea surveys, which can only take place during daylight and in relatively calm weather and may not be representative of the behaviour of Manx Shearwaters under all conditions. The species rarely uses level, flapping flight, but usually engages in slope-soaring, which leads to constant variation in flight height, although generally birds will remain low to the sea surface where the shear is strongest (Spivey et al., 2014[64]). Furthermore, flight heights may increase in stronger winds (Spear and Ainley, 1997[65], Ainley et al., 2015[66]). As such, the assumption of low flight height, and consequent low collision risk, is likely to be unsafe.

4.19. Manx shearwater can be active throughout the day and night and with different levels of activity at different times. For example for birds tracked from Skomer, diving occurred during the day

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[61] Miles, W., Money, S., Luxmoore, R., & Furness, R. W. (2010). Effects of artificial lights and moonlight on petrels at St Kilda. *Bird Study*, *57*(2), 244-251

[62] Guilford, T., Padget, O., Bond, S., & Syposz, M. M. (2019). Light pollution causes object collisions during local nocturnal manoeuvring flight by adult Manx Shearwaters Puffinus puffinus. *Seabird*, *31*

[63] Archer, M., Jones, P. H., & Stansfield, S. D. Departure of Manx Shearwater Puffinus puffinus fledglings from Bardsey, Gwynedd, Wales, 1998 to 2013

[64] Spivey, R. J., Stansfield, S., & Bishop, C. M. (2014). Analysing the intermittent flapping flight of a Manx Shearwater, Puffinus puffinus, and its sporadic use of a wave-meandering wing-sailing flight strategy. *Progress in Oceanography*, *125*, 62-73

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and peaked in the evening (Shoji et al., 2016[67]), while nocturnal foraging was observed from tracking of birds from High Island, Ireland (Kane et al., 2020[68]). These diel variations in activity mean that the somewhat limited amount of time aerial surveys were carried out, restricted to the hours of full light are unlikely to properly characterise the activity of Manx shearwater at the Application site. these have generally taken place between mid-morning and mid-afternoon. For these reasons the RSPB does not have confidence in the baseline densities of Manx shearwater presented, and therefore it is impossible to make any conclusions as to the significance of impacts.

4.20. The concerns around the impact of offshore wind have been highlighted in a recent Offshore Wind Strategic Research and Monitoring Forum (OWSMRF) workshop which identified these species as of growing importance and a potential future consent risk to the Offshore Wind sector as there is currently limited understanding of key aspects of the life history, distribution and interaction of these species with offshore wind[69].

Gannet

4.21. In order to assess the mortality that could arise from avian collisions with turbine blades, the Applicant has used the stochastic version of the Band Collision Risk Model (sCRM)[70,71] and presented this in ES Volume 4 Annex 4.3 Offshore Ornithology Collision Risk Modelling[72] This approach is welcomed by the RSPB. This method combines a series of parameters describing the turbine design and operation with estimates of a bird's size and behaviour to generate a predicted number of birds that would collide with a turbine over a given time period. The stochastic formulation was initially developed by Masden (2015)[73] and then produced in an easier to use interface by McGregor et al, (2018)[74]. The stochastic version allows for some account of uncertainty and variability in parameters to be made.

4.22. The input parameters related to bird size and behaviour include a parameter known as "Avoidance Rate". This is defined by Band (2012)[75] as the inverse of the ratio of the number of actual collisions to number of predicted collisions. As such "Avoidance Rate" is a misnomer; it is a catch all term for the inconsistency between predicted and actual mortalities, an inconsistency that can be derived from a variety of sources, including avoidance behaviour per se, survey error and model misparameterisation.

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[74] McGregor, R.M., King, S., Donovan, C.R., Caneco, B. and Webb, A. (2018) A Stochastic Collision Risk Model for Seabirds in Flight. Report to Marine Scotland Science

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4.23. The Applicant has used Avoidance Rates (see above) in the sCRM, as recommended by the Statutory Nature Conservation Bodies (SNCBs 2014[76]) including Natural England. Whilst the RSPB agree with the majority of the advised rates including the use of a 98.9% avoidance rate for non-breeding gannets, in our opinion, a 98% avoidance rate is more appropriate for breeding gannets. This is because the figures used for the calculation of avoidance rates advocated by the SNCBs are largely derived from the non-breeding season for gannet[77’78]. During the breeding season, gannets are constrained to act as central placed foragers meaning they return to the colony after feeding in order to maintain territories, incubate eggs and provide for chicks. Once chicks have fledged adult gannets remain at sea and no longer visit the colony. Differences in behaviour between the breeding and non-breeding season are likely to result in changes in avoidance behaviour.

4.24. There is evidence that the foraging movements and behaviour of gannets will vary in relation to stage of the breeding season in response to changes in the distribution and abundance of prey and changing constraints as they progress from pre-laying to chick-rearing[79]. GPS tracking of gannets breeding on the Bass Rock between 2010 and 2021 has shown variation in the two-dimensional foraging behaviour of birds across the breeding season (prior to chick-rearing and during chick-rearing), between sexes, and between years[80,72,81]. Three-dimensional tracking of gannets during chick-rearing has also revealed that flight height and flight speed both vary according to behaviour, sex and wind conditions[82,83,84] and similar patterns have been recorded in other seabirds[85] Because any error in the use of flight height and flight speed as input parameters in the sCRM should be corrected for in the use of the Avoidance Rate, any seasonal variation in these parameters should also be reflected in variation in the Avoidance Rate, in the absence of any actual evidence from the breeding season.

4.25. Further to advice from Natural England, the Applicant has applied a reduction of 60-80% to the baseline densities inputted into the gannet collision risk modelling in order to account for macro-avoidance in Appendix 4 of ES Volume 4 Annex 4.3[86]. This approach follows suggestions in Cook

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[76] Joint Nature Conservation Committee (JNCC), Natural England (NE), Natural Resource Wales (NRW), Northern Ireland Environment Agency (NIEA), Scottish Natural Heritage (SNH) 2014, Joint Response from the Statutory Nature Conservation Bodies to the Marine Scotland Science Avoidance Rate Review

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[85] Masden, E.A., Cook, A.S.C.P., McCluskie, A., Bouten, W., Burton, N.H.K, Thaxter, C. 2021. When speed matters: the importance of flight speed in an avian collision risk model. Environmental Impact Assessment Review, 90

[86] APP-097 6.4.4.3 Volume 4, Annex 4.3: Offshore Ornithology Collision Risk Modelling

(2021[87]), the recommendations from which have not yet been formally adopted by the SNCBs. Cook (2021) is currently being reviewed and revised by two projects, one funded by JNCC and one by Natural England. Until these projects have reported, the RSPB do not accept this approach.

4.26. The current evidence of a strong macro avoidance of wind farms by gannets, established from observed behaviour, is almost entirely derived from non-breeding birds28. The evidence for macro avoidance during the breeding season is limited with the exception of a study of gannets breeding on Helgoland[88] in the German North Sea. However, it is unclear from this study what the breeding status of the tracked birds was, or how their behaviour differed from what would have been expected pre-construction as two of the three wind farms were already operational during the first year of tracking. What the study does clearly show is that breeding gannets do fly through offshore wind farms, often showing no avoidance behaviour at all. Below we reproduce Figure 2 from this paper showing tracked gannets' movements in respect to wind farms. While some show clear avoidance others do not and may even be attracted to the wind farm.

4.27. In the Cook (2021) report that suggests the application of macro avoidance to baseline densities, the suggestion is based on reviews that do not include this German tracking study, although it does acknowledge that it shows clear differences between individuals in relation to their response to wind farms. The previous gannet recommended avoidance rate was based on 'all gulls' data because no gannet data were available. The evidence of macro avoidance of gulls in response to wind farms is equivocal, so this rate was only calculated from 'within wind farm' avoidance. As gannets can show macro avoidance it therefore was suggested that this was applied to the baseline densities, and then collision risk modelling was carried out using the 'all gull' avoidance rate, so effectively applying avoidance twice. In response to this suggestion Natural England commissioned a further review of gannet avoidance rates, including whether macro avoidance should be incorporated in this way but this has not yet been reported. In the absence of having this report, the recommendations from it should not be acted upon, and the suggestions in Cook (2021) should not be taken up without the context of this review.

4.28. Notwithstanding the above, the RSPB does not agree with the approach for two reasons. Firstly, it does not take into account the likely seasonal variation in macro avoidance as described above. Secondly, by basing the 'within wind farm' avoidance rate on the 'all gull' rate, it assumes that gannets will have the same 'within wind farm' reactive flight response as gulls. This assumption is very unlikely to be met, as gannets have much lower flight manoeuvrability than gulls[89]. This will result in a lesser ability to make rapid reactions and consequently have a greater risk of collision. This should be reflected in the 'within wind farm' avoidance rate if any further changes are to be made.

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[87] Cook A.S.C.P. (2021) Additional analysis to inform SNCB recommendations regarding collision risk modelling. BTO research report 739

[88] Peschko, V., Mendel, B., Mercker, M., Dierschke, J., & Garthe, S. (2021). Northern gannets (Morus bassanus) are strongly affected by operating offshore wind farms during the breeding season. *Journal of Environmental Management*, *279*, 111509.

[89] Furness, R. W., Wade, H. M., & Masden, E. A. (2013). Assessing vulnerability of marine bird populations to offshore wind farms.Journal of environmental management,119, 56-66

4.29. Any evidence of macro avoidance should also be seen in the context of recent work in Belgian offshore windfarms that has shown potential habituation to the presence of turbines. This effectively results in lower macro avoidance[90] and so an elevated risk of collision. It is also important to acknowledge that corpses of Northern Gannets with injuries consistent with collisions with offshore wind farms have been recovered (Rothery et al., 2009[91]), and the imperfect detection of these corpses indicate that there may be many more.

4.30. Subsequent to carrying out the collision risk modelling for gannet, the Applicant has not fully apportioned the gannet collision impacts to any of the SPAs that are within foraging range of the site only providing a “worked example”, nor have they carried out an assessment of the implications of the mortality arising from collisions on these SPAs populations via population viability analysis. Due to these methodological concerns the RSPB consider that it is not currently possible to rule out adverse impacts upon gannet occurring within the study area from the following SPAs:

- Grassholm SPA
- Ailsa Craig SPA
- Saltee Islands SPA

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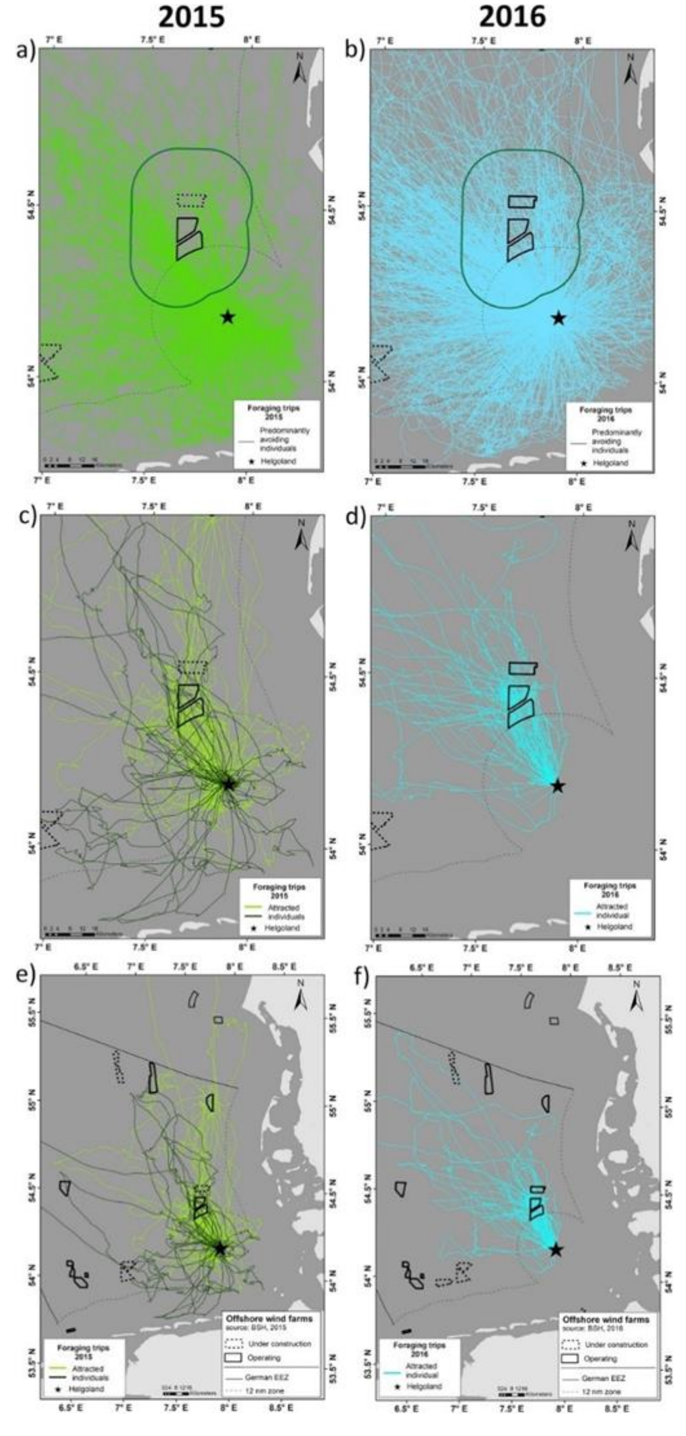
[90] Vanermen, N.; Courtens, W.; Van de walle, M.; Verstraete, H.; Stienen, E. 2021. Macro-avoidanceof GPS-tagged lesser black-backed gulls and potential habituation of auks and gannets. In Degraer, Brabant, Rumes & Vigin (eds) 2021. Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea, avoidance and habitat use at various spatial scales.Brussels: Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management

[91] Rothery, P., Newton, I., & Little, B. (2009). Observations of seabirds at offshore wind turbines near Blyth in northeast England.Bird Study,56(1), 1-14

"Figure 2": from Peschko et al 2021[92] showing flight of tagged birds from Heligoland (indicated by a star) in the vicinity of wind farms (outlined in black). Original figure legend is: "Flight behaviours of gannets tagged in 2015 (n = 10) (a) and 2016 (n = 15) (b) that 'predominantly avoided' the OWFs (all individuals shown in the same colour). Gannets tagged in 2015 (n = 2) (c) and 2016 (n = 1) (d) that were classified as 'attracted individuals' (individuals shown in different colours). (e) & (f) Large-scale movements of individuals shown in (c) and (d). OWFs: dashed black = under construction, solid black = operating, dark green line = 15 km buffer applied for PPM analysis."



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Highly Pathogenic Avian Influenza (HPAI)

4.31. A new virulent form of bird flu, Highly Pathogenic Avian Influenza (HPAI), that originated in poultry in east Asia has now killed tens of thousands of wild birds in the UK and around the world. First confirmed in Britain during winter 2021/22, it has had major impacts on populations of seabirds across Scotland, and there have been an increasing number of confirmed cases appearing across England, including east coast seabird colonies. At the Farne Islands in Northumberland, thousands of seabirds have died. Confirmed cases have also been recorded in Wales. At Grassholm SPA gannetry it has now been confirmed in a number of specimens from dead gannets and birds are continuing to die.

4.32. It is currently unclear what the population scale impacts of the outbreak will be, but it is likely that they will be severe. This scale of impact means that seabird populations will be much less robust to any additional mortality arising from offshore wind farm developments. It also means that there may need to be a reassessment of whether SPA populations are in Favourable Conservation Status. With such uncertainty as to the future of these populations, there is the need for a high level of precaution to be included in examination of impacts arising from the proposed development.

Population Viability Analysis

4.33. The Applicant did not carry out Population Viability Analysis for gannet. The RSPB would prefer that this was now carried out, to considering the likely mortality arising from the outbreak of Highly Pathogenic Avian Influenza on the local and regional populations

4.34. Finally, the RSPB reserves the right to add to and/or amend its position in light of changes to or any new information submitted by the Applicant.

Written Representation: References for the Royal Society for the Protection of Birds

Submitted for Deadline 1
24 October 2022

Planning Act 2008 (as amended)

In the matter of:

Application by Awel y Môr Offshore Wind Farm Limited for an Order Granting Development Consent for the Awel y Môr Offshore Wind Farm

Planning Inspectorate Ref: EN010112
RSPB Registration Identification Ref: 20031695

Written Representation: References

Index

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30. Copeland Islands SPA Citation
31. Copeland Islands SPA Conservation Objectives
32. Irish Sea Front SPA Draft Conservation Objectives and Advice on Operations
33. Rum SPA citation
34. Rum SPA Conservation Objectives
35. St Kilda SPA citation
36. St Kilda SPA Conservation Objectives
37. Glannau Aberdaron ac Ynys Enlli SPA Citation
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39. Skomer, Skokholm and the Seas off Pembrokeshire SPA citation
40. Skomer, Skokholm and the Seas off Pembrokeshire SPA Core Management Plan (including conservation objectives)

41. Grassholm SPA citation
42. Grassholm SPA Core Management Plan (including conservation objectives)
43. Ailsa Craig SPA Citation
44. Ailsa Craig SPA Conservation Objectives
45. Saltee Islands SPA Site Synopsis
46. Saltee Islands SPA Conservation Objectives

SEABIRD FLIGHT BEHAVIOR AND HEIGHT IN RESPONSE TO ALTERED WIND STRENGTH AND DIRECTION

DAVID G. AINLEY[1], ELIZABETH PORZIG[1,2], DAVID ZAJANC[1] & LARRY B. SPEAR[1]

[1]*H.T. Harvey & Associates Ecological Consultants, 983 University Avenue, Bldg D, Los Gatos, CA 95032, USA*
(dainley@penguinscience.com)
[2]*Current address: Point Blue Conservation Science, 3820 Cypress Dr. #11, Petaluma, CA 94954, USA*

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SUMMARY

AINLEY, D.G., PORZIG, E., ZAJANC, D. & SPEAR, L.B. 2015. Seabird flight behavior and height in response to altered wind strength and direction. *Marine Ornithology* 43: 25–36.

The ocean is swept by winds in regionally and seasonally predictable ways, and seabirds have been exploiting these patterns for millennia. Seabird use of wind energy is an under-appreciated aspect of seabird ecology. Using data from 114 cruises spanning the Southern Ocean, Peru Current, California Current and Equatorial Pacific from 1976 to 2006, we evaluate the effect of wind speed and direction on two key characteristics of seabird behavior, flight height and flight behavior. We used cluster analysis to partition 104 seabird species into morphological groupings based on degree of divergence in morphology from Pennycuick's "standard seabird," with subgroups evident among and within flappers, glide-flappers, and flap-gliders. Gliders, sea-anchor soarers and soarers showed no such divergence in morphology within their respective groups. Morphological grouping was in accord with foraging ecology, facilitating foraging behavior. Seabird flight height and behavior varied among groups and subgroups and changed as a function of wind speed and direction relative to travel, with the probability of more gliding and flying above 10 m increasing as wind speed increased. Most of the glide-flappers, flap-gliders and gliders, especially, would be highly vulnerable to offshore wind-generating facilities, as their flight heights bring them well within the blade-swept zone of typical turbines when winds are strong, and their more prevalent gliding makes them less maneuverable than flappers.

Key words: seabird flight behavior, flight height, offshore wind energy development

INTRODUCTION

Understanding the relationship between seabirds and wind has both ecological and practical application, being useful in further understanding resource partitioning (Pennycuick 1987, Spear & Ainley 1998), mobility (Pennycuick *et al.* 1984), and flight behavior as a clue to species' identities, as observed over a range of wind conditions in ocean-going surveys (e.g. Harrison 1983, Howell 2012). Flight behavior (i.e. prevalence of gliding, flapping, some combination of the two behaviors, and soaring) changes with wind speed for a given species (Pennycuick 1982, 2002). We can use this understanding to conduct fatality modeling for specific sites being evaluated for offshore wind energy development (e.g. Garthe & Hüppop 2004). Specifically, flight height information can be used to help predict potential impacts to seabird species from offshore wind farms, because flight heights >10 m would be within the rotor-sweep zone for most wind turbines — the typical turbine array used in Europe, where almost all research on seabird flight height has been conducted to date, has a propeller hub 70 m above the sea and a blade diameter of 100 m (Cook *et al*. 2012 and Johnston *et al*. 2013 use 20 m as the lowest flight height that would be a risk to seabirds). Given this context, the current paper provides evidence of seabird species' vulnerability by summarizing observed flight heights and behaviors and by modeling seabird flight height and behavior with respect to wind speed for several areas outside of Europe, although some species analyzed are found in Europe as well.

Ecological aspects of seabird flight

In a biophysical characterization, the way seabirds use or cope with the wind can be deduced by applying the laws of physics and aerodynamics (Pennycuick 1987a). Key properties of seabird morphology give clues to how a species will behave in long-distance flight; these properties are its mass (m), wing span (b), wing area (S) and disc area (the area of a circle with a diameter equal to the wing span). From these properties, *wing loading* (weight per unit wing area), *disc loading* (weight per disc unit area), and *wing aspect ratio* (length versus width) can be estimated. The *cross-sectional area* of the body (A) is also useful for evaluating capacity to use wind. As discussed in detail by Pennycuick (1987a), wing loading affects gliding speed and therefore the amount of flapping needed; disc loading affects the muscle power required for horizontal flight; wing length affects wing-beat frequency; and disc area and cross-sectional area affect the effective lift:drag ratio (Pennycuick 1987a).

The above properties and the derived properties (for example, mass and wing loading, respectively) can be combined to describe the flight capabilities of the "standard seabird," which resides midway in the geometric progression scaled to size among Procellariiformes, from storm-petrels (20 g) to the largest albatrosses (9 000 g; Pennycuick 1987a). Flight behavior of other species can be described by divergences from this progression, as a function of change in body mass, wing shape and size, wing length (aspect ratio or area remaining constant), and wing area (wing span remaining constant). Flight behavior also varies among species in accordance with aspects of foraging (for instance, prey size and mobility), and, thus, it may constitute an often-ignored element of niche separation (Pennycuick 1982, 1983, 1987b; Spear & Ainley 1998). Flight behavior also affects how far a species might range (Pennycuick 1982, 1987a), and what direction a bird may take in migrations or long-range movements (e.g. Spear & Ainley 1999, Adams & Flora 2010).

Flight behavior, the observed behavior at any given moment, is described by these terms: soaring, gliding, flap-gliding (more gliding than flapping), glide-flapping (more flapping than gliding), and flapping. Previous work has shown that flight behavior is affected by wind vector and that flight speed is affected by wind speed and direction (Spear & Ainley 1997 a, b). Flight style is a grouping of birds that most commonly exhibit certain flight behaviors. For example, a flapper (a style or group of birds) would generally undertake flapping flight, but may exhibit gliding behavior under certain conditions.

Flight behavior and flight height are related to variation in wind speed, as a seabird exploits the wind gradient, or wind boundary layer, over the ocean. Owing to surface friction, the wind speed over the ocean is significantly lower at its surface than it is about 10 m higher — most of the wind speed change occurs in the first 1–2 m above the ocean surface. Above 10 m, surface friction has little effect and wind speed changes are minimal with greater height (Bethwaite 2007). As an example of how the wind gradient affects flight, when flying into the wind, flappers would stay low to be in the zone where winds are lighter but, conversely, when flying with the wind, they would fly higher. Gliders and flap-gliders, in "gust soaring," use the wind gradient to maintain or increase flight speed — each rise above a wave crest is followed by banking and acceleration against the wind. The exceptions among seabird flight groups to the flight style progression (from flapping to flap-gliding to glide-flapping to gliding) are the true soaring flights of pelicans and frigatebirds (Pelecanidae, Fregatidae; Pennycuick 1983), and the sea-anchor flying of frigate and oceanitid storm-petrels (Hydrobatidae; Withers 1979).

Applied aspects of seabird flight

The demand for renewable energy is increasing worldwide. Since winds over the ocean are typically substantial and regionally and seasonally predictable, it is not surprising that over-ocean wind has become an increasingly more important part of the global renewable energy portfolio (e.g. Köller *et al*. 2006). Therefore, in addition to shipping and other industrial uses of the ocean, humans now plan to install wind-energy technology in the seabird realm.

Environmental effects of offshore wind-energy development are poorly known, as this human effort in coastal waters is new. Nevertheless, energy developers and resource agency staff will be required to quantify the effects. Consequently, in recent years, considerable progress has been made in understanding the nature of these effects (Köller *et al*. 2006, Drewitt & Langston 2006), particularly in regard to seabirds. Potential effects on seabirds include habitat loss and fragmentation due to avoidance of turbines, as well as increased injury or mortality due to collisions (e.g. Lapeña *et al.* 2010, Cook *et al.* 2012).

This paper provides information that can be used to help evaluate the potential risk of injury or mortality due to turbine collision, based on the relationships of flight height and flight behavior to wind speed. Models have been developed to predict possible effects on seabird groups as a function of flight height, but rarely is wind speed and how it affects flight height considered. This is due to constraints of data gathering: to ensure observer safety, data are rarely collected when winds are more than "moderate" (e.g., Garthe & Hüppop 2004, Johnston *et al*. 2013).

We analyze 30 years of data on flight behavior and flight height of 104 seabird species or species groups that were investigated on cruises in the Southern Ocean, Peru Current, California Current and Equatorial Pacific between 1976 and 2006. The data were not collected with any specific hypothesis in mind, other than for an eventual comparison of how seabirds use wind energy, but, since their collection, have been used to characterize seabird flight behavior (Spear & Ainley 1997a, b, 1998) and to correct estimates of seabird density (Spear *et al.* 1992, Clarke *et al.* 2003). We test *a posteriori* hypotheses developed to assess seabird flight height and wind speed: (1) groups of species are evident based on the degree to which they diverge in morphology from Pennycuick's "standard seabird;" (2) higher flight heights and changes in flight behavior are associated with increases in wind speed; and (3) species or species groups might be sorted by flight behavior in the same way that they might be sorted by bill size in their acquisition of food (e.g., Ashmole & Ashmole 1967). Foraging and flight behavior are closely linked and could be used to define niche space of a seabird species (Spear & Ainley 1998).

METHODS

Data collection

Data were obtained while conducting strip surveys to estimate seabird abundance at sea in five regions: (1) Antarctic/Southern Ocean, hereafter called the Antarctic (14 cruises; Ribic *et al.* 2011 for more details and cruise tracks), (2) Peru Current (17 cruises; Spear & Ainley 2007), (3) Panama Bight (12 cruises; Spear & Ainley 1999c), (4) California Current (59 cruises; Ainley *et al.* 2009, Ainley & Hyrenbach 2010), and (5) eastern Equatorial and subtropical Pacific, hereafter referred to as ETP (24 cruises, including Hawaii; Spear *et al.* 1999). The strip surveys occurred from 1976 to 2006 (Fig. 1). For this study, the data from the Panama Bight are included in those for the ETP, resulting in four regions.

During summer, surveys close to the coast could include a higher proportion of breeding and therefore commuting birds, which could affect their flight behavior. That is, commuting birds would fly into the wind more than they would normally, depending on where their colony is located relative to where the birds are encountered and relative to the wind direction. In that regard, the majority of cruise

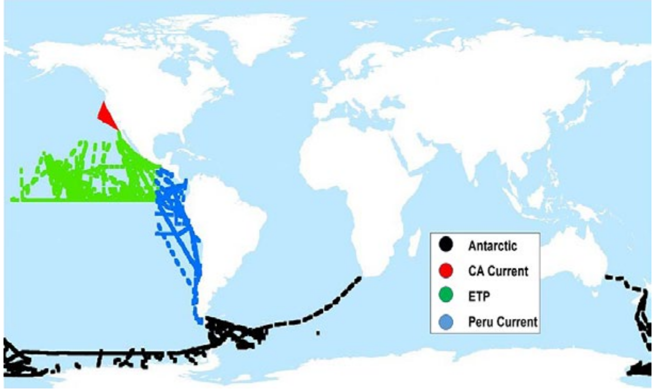

Fig. 1. Location of cruise tracks for seabird strip surveys from 1976 to 2006.

points (58%) were >50 km from shore, although the percentage varied by location: 25% of the cruise points in the California Current were collected at points >50 km from shore, compared with 74% for the Antarctic, 99% for the EPT, and 78% for the Peru Current.

Once underway, two bird monitors aided by binoculars searched one forequarter on the side with least glare, out to 300 m on most cruises, or to 600 m in equatorial/subtropical waters where larger ships offered greater height above the sea surface and ocean waves were generally lower (see Spear *et al*. 1992, 2004 for further details). All vessels were ocean-going, at least 50 m in length, and underway in all conditions, although we rarely collected data when winds were >18 m/s (>35 knots). Each seabird sighting included species identification, direction of travel and behavior (sitting on surface, flapping, flap-gliding or glide-flapping, and gliding). We did not include sightings during which birds were foraging, milling around a food source, flying to a known food source, or attracted to or following the ship. We estimated flight height by comparing our height above the sea surface (generally 12–25 m) with the bird's height, or by comparing the bird's wing span (see Pennycuick 2002 for a similar approach) or by both methods. Height was recorded in three categories: <3 m, 3–10 m and >10 m.

Wind speed and direction were determined from the ship's anemometers, which were placed on the instrument mast at least 20 m above the sea surface. We adjusted wind speeds according to the prospective wind gradient. We designated flight direction (i.e. headwinds, crosswinds, or tailwinds) for birds based on Spear & Ainley (1997a, b), and added a categorical version of wind speed, using the following six categories: <5.1 m/s (<18.4 km/h), 5.1–7.7 m/s (18.4–27.7 km/h), 7.7–10.3 m/s (27.7–37.1 km/h), 10.3–12.9 m/s (37.1–46.4 km/h), 12.9–15.4 m/s (46.4–55.4 km/h) and ≥15.4 m/s (>55.4 km/h).

Data analysis

We defined our database to include a reasoned selection of seabird species. The original seabird strip survey database included over 250 species, but we narrowed the list to those 104 species having at least 20 observations within groupings relative to major wind directions, i.e., headwind, crosswind or tailwind.

We conducted cluster analyses of seabird morphology measurements to define morphological clusters of seabird species. The analyses were conducted on morphological data (i.e. wing span, loading, aspect, wing area and mass), as summarized in Spear & Ainley (1997a), which were obtained by direct measurement of specimens as well as from the literature. We used a partitioning approach to subdivide the flight styles of flappers, glide-flappers, and flap-gliders into morphological groups (referred to hereafter as "clusters;" Table 1). We did not include gliders (small albatrosses and large gadfly petrels), soarers (pelicans and frigatebirds), and sea-anchor soarers (frigate and oceanitid storm-petrels) in the cluster analyses because the morphology of species within these flight styles was homogeneous and the samples of these species were small.

TABLE 1
First two principal components in the clustering analyses, and strongest associations with morphological attributes

Flight style	First principal component	Second principal component
Flappers	Wing loading, $r = -0.922$	Wing span, $r = 0.900$
Glide-flappers	Wing span, $r = 0.889$	Aspect ratio, $r = 0.935$
Flap-gliders	Wing span, $r = 0.747$	Wing loading, $r = -0.807$

We looked at correlations in the dataset to eliminate redundant morphological variables; those such as wing area and mass were eliminated in this step, leaving wing span, loading, and aspect ratio as the variables for the cluster analysis. We used R software (R Development Core Team 2012) to conduct the analyses, and employed the "cluster" package (Maechler 2012). The function "pam" allowed us to assess the most efficient numbers of clusters based on (1) the average dissimilarity between observations within a cluster, and (2) the dissimilarity between observations and their nearest neighbor cluster. We plotted clustering results for the two best clustering options based on these criteria, using the R functions "clara" and "clusplot." Approximately one-third of the seabird species (30 of the 104 species analyzed) did not have associated morphological data, so we assigned them to newly defined clusters based on professional judgment. That is, we based an assignment on known morphological similarities to other species. For example, members of the "Manx shearwater" group were clustered together, although they have long since been divided into separate species. These designations were also used in subsequent modeling.

In order to evaluate the effect of wind speed on flight height, we used generalized linear mixed models, with morphological group as the random variable. We chose a mixed model approach because of the lack of independence within a group as well as our interest in extending inference beyond the species sampled here to seabirds more generally (Faraway 2006). Our response variable was a binary term representing flying below 10 m or above 10 m, in part because of the way the data were collected (by height category). The fixed predictor variables included location (Antarctic, California Current, ETP, or Peru Current), wind speed (m/s), relative wind direction (headwind, crosswind, tailwind), and the interaction between wind speed and relative wind direction. Following Zuur *et al.* (2009) and Bolker *et al.* (2009), we first identified the best random structure by comparing three models using likelihood ratio tests: the models were identical with respect to the fixed terms (each contained the full set of fixed terms), but they differed in their random structure, with the first model containing morphological group as a random intercept, the second containing morphological group as a random slope, and the third model containing morphological group as a random slope and intercept. Based on these tests, we used a random intercept and slope in all candidate models moving forward. Once the random structure was identified, we evaluated the contribution of the fixed effects using an information theoretic approach. We calculated Akaike information criteria corrected for small sample sizes (AICc), including values and weights of 10 candidate models, and calculated evidence ratios for the two models with the lowest AICc scores. We did not model-average because the model with the lowest AICc value had a weight of 1. Mixed models were fit by maximum likelihood using Laplace approximation in the lme4 library in R (Bates *et al*. 2014, R Core Team 2014).

We used linear regression analysis to evaluate the effect of wind speed on flight behavior. We divided flying behavior into five categories that typically characterize a species: (1) flapping, (2) flapping, few glides, (3) flap-gliding, (4) gliding, few flaps, and (5) gliding. We were interested in how wind speed might affect a species' typical behavior, e.g. at what wind speed would a gull transition from mostly flapping to exercise more gliding (flapper to flap-glider)? For each group, we scaled the number of birds

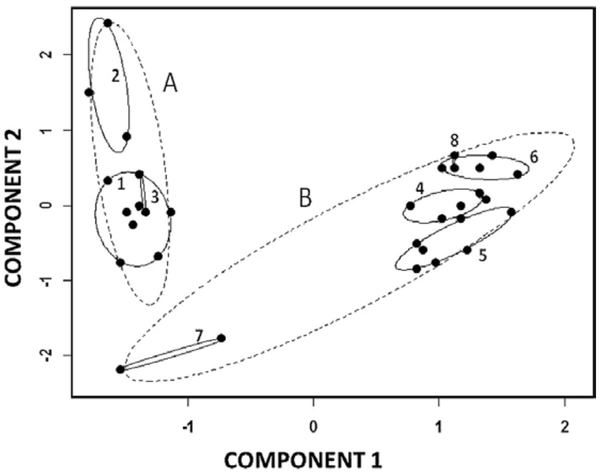

Fig. 2. Cluster analysis of flappers: 1, small alcids and diving petrels; 2, large alcids and loons; 3, cormorants; 4, medium gulls; 5, terns; 6, large gulls; 7, phalaropes; 8, tropicbirds. See Appendix 1, available on the Web site, for a complete list of species in each cluster.

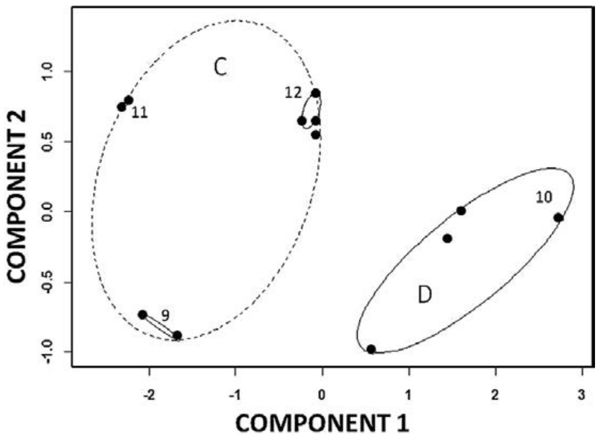

Fig. 3. Cluster analysis results for glide-flappers: cluster 9, boobies; cluster 10, small petrels and storm-petrels; cluster 11, pelicans; and cluster 12, large skuas. See Appendix 1, available on the Web site, for a complete list of species in each cluster.

exhibiting each behavior by the number of birds observed in each wind category. We then evaluated the change in proportion as a function of wind speed category. We tested for statistical significance of a linear trend in behavior as a function of wind speed using *t*-tests at a significance level of 0.05.

Interpretation of modeling results

The practical application of these data and models is to identify seabird clusters that are most vulnerable to being in the rotor-swept zone of typical offshore wind turbines currently used and to flying in a way that decreases maneuverability (i.e. >10 m high and mostly gliding). Therefore, we wanted to interpret the results of our flight

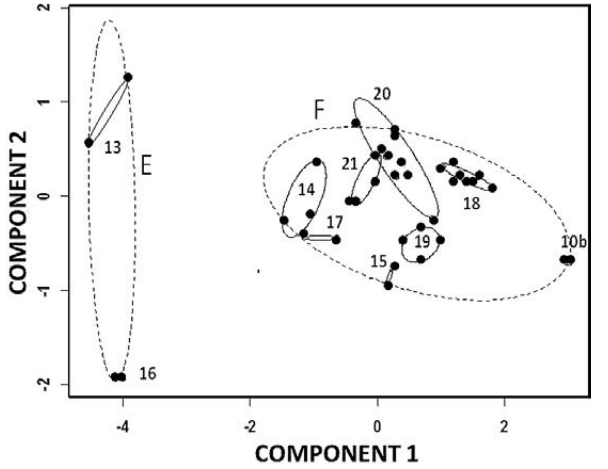

Fig. 4. Cluster analysis results for flap-gliders: 13, small albatross; 14, long-ranging boobies and *Procellaria*; 15, fulmars; 16, giant fulmars; 17, large aquatic shearwaters; 18, small gadflys; 19, small aquatic shearwaters; 20, large gadflys; 21, medium gadflys and large aquatic shearwaters. See Appendix 1, available on the Web site, for a complete list of species in each cluster. Note that Cluster 10b appeared to be an outlier but, upon inspection of modeling results, it was placed among the glide-flappers (and with Cluster 10, Fig. 3).

TABLE 2

Effect of wind speed on flight height: 10 candidate models showing AICc values and weights[a]

Fixed Predictors	Modnames	K	AICc	ΔAICc	AICcWt	LL
Wind + RelDir + Location + Wind*RelDir	m1	12	34 321.50	0	1	-17 148.7
Wind + RelDir + Location	m2	10	34 463.77	142.277	0	-17 221.9
RelDir + Location	m6	9	34 486.19	164.694	0	-17 234.1
1 [null model]	m10	4	39 091.66	4 770.162	0	-19 541.8
Location	m9	7	35 832.82	1 511.319	0	-17 909.4
RelDir	m8	6	37 914.43	3 592.929	0	-18 951.2
Wind	m7	5	39 088.01	4 766.514	0	-19 539.0
Wind + Location	m5	8	35 825.11	1 503.610	0	-17 904.6
Wind + RelDir	m4	7	37 901.84	3 580.344	0	-18 943.9
Wind + RelDir + Wind*RelDir	m3	9	37 799.9	3 478.404	0	-18 890.9

[a] All models had the same random predictor (cluster group [intercept and slope]) and cumulative weight (= 1); among fixed predictors, RelDir = relative direction (bird vs. wind). AICc = corrected (for sample size) Akaike's information criterion; Modnames = model names, using a number for convenience; K = number of estimated parameters; **ΔAICc** = difference in AICc of present model to the model with the lowest AIC score (m1); AICcWt = AICc weight; and LL = Log Likelihood.

TABLE 3
Summary of parameter estimates of fixed effects of the best model

Parameter	Estimate	Standard error	z value	Pr (>|z|)
(Intercept)	-1.5120	0.6057	-2.5	0.0125
Wind speed	0.1794	0.0187	9.58	$< 2 \times 10^{-16}$
Headwind	-0.7670	0.0593	-12.94	$< 2 \times 10^{-16}$
Tailwind	-0.3481	0.0605	-5.75	8.80×10^{-9}
California Current	-1.6391	0.0543	-30.17	$< 2 \times 10^{-16}$
ETP	-3.2725	0.0739	-44.26	$< 2 \times 10^{-16}$
Peru Current	-3.1522	0.0875	-36.04	$< 2 \times 10^{-16}$
Wind speed:Headwind	-0.1049	0.0115	-9.11	$< 2 \times 10^{-16}$
Wind speed:Tailwind	-0.0099	0.0114	-0.87	0.3831

height analysis to make statements about how these factors might contribute to the vulnerability of seabirds to offshore wind turbines. Conservatively, we defined vulnerability to flying within the rotor-swept zone if the probability of flying at a height >10 m is greater than 0.5. We plotted predicted flight heights as a function of wind speed for each geographical region, and identified the wind speeds at which the predicted probability of flying above 10 m is >0.5. We also performed a qualitative assessment of the relative vulnerability of morphological clusters by comparing slopes of the random effects; however, formal between-group comparisons are not appropriate for levels within a random effect. For a given flight style (but increasing with the amount of gliding), we identified which clusters are vulnerable over the range of any of the observed wind speeds for any of the flight directions. For the vulnerable clusters, we determined the wind speeds and flight directions at which they are vulnerable.

TABLE 4
Generalized linear mixed model analysis of flight height and wind speed with the random effect morphology/flight style groups ranked lowest to highest by degree of slope

Group	Intercept	Slope	Antarctic, n	California current, n	ETP, n	Peru current, n
Large gulls	3.255189	-0.06581	88	6 335	0	0
Small gulls	2.854298	-0.06572	0	393	0	55
Skuas	3.03459	-0.06148	216	480	305	302
Phalaropes	-0.50362	-0.05618	0	1 129	144	158
Oceanites	-3.47945	-0.04602	734	0	0	741
Medium-sized gulls	3.236653	-0.0427	0	2 126	0	213
Cormorants	-0.07102	-0.03735	0	959	0	27
Frigate petrels	-3.01924	-0.03717	309	0	21	804
Oceanodroma	-4.67778	-0.03021	0	3 279	6470	3 588
Tropicbirds	5.115913	-0.01523	0	0	28	0
Small alcids	-3.73632	-0.01516	206	1 125	0	0
Frigatebird	7.795711	-0.00994	0	0	0	30
Small albatrosses	0.052342	-0.00796	153	1 109	0	225
Large gadfly petrels	-1.43934	-0.00711	164	0	4 299	1 163
Medium-sized alcids	-2.53977	-0.00168	0	595	0	0
Prions	-1.0231	-0.00121	3 046	0	0	78
Manx-type shearwaters	-4.07447	0.000922	35	113	386	71
Pelicans	2.038491	0.00166	0	334	0	325
Loon grebe	1.029396	0.007822	0	254	0	0
Giant petrels	-0.96771	0.018279	99	0	0	0
Small gadfly petrels	-0.176	0.018574	3 748	137	3 647	884
Surface-feeding shearwaters	-1.18405	0.036555	345	1 673	2 350	566
Boobies	2.240037	0.040926	0	0	329	1 136
Fulmars	-1.02046	0.060311	1 278	1 633	0	139
Large alcids	-2.03463	0.087591	0	5 933	0	0
Terns	2.119291	0.09448	490	211	1 802	151
Diving shearwaters	-1.27113	0.142368	2 728	10 991	886	543

RESULTS

Cluster analysis based on morphology

We used the cluster analysis to subdivide flappers, glide-flappers, and flap-gliders into two coarser clusters (indicated by letter) and numerous finer-scaled clusters (indicated by numbers) (Figs. 2–4, Appendix 1 available on the Web site). The coarse scale clustering revealed two major groups for each of the flight styles (A&B, C&D, E&F). The finer-scaled clustering revealed two to eight clusters within the coarse scale groups. A complete list of all species, as divided into these clusters, is presented in Appendix 1 (available on the Web site), including those that were part of the analysis and those that were not (i.e. those that were classified based on known morphological similarities to clustered species; see Methods). The fine-scale cluster results allowed us to proceed with the initial modeling runs to investigate flight behavior and height as a function of wind speed and flight direction.

Flight height

The full model, composed of location, wind speed, relative wind direction and the interaction between relative wind direction and wind speed, as well as a random intercept and slope for morphological groups, resulted in the best-supported model, with an AIC weight of 1 (Table 2). The ΔAICc between this and the second-best model (without the fixed interaction term) is 142. The evidence ratio between the top two models is 2.893032×10^{30}. Table 3 shows the fixed effects used in the modeling.

The slopes and intercepts for the random effects related to flight height are consistent with flight styles and morphological groups, and particularly with wing loading (Table 4, Fig. 5). Those groups with high wing loading and the diving shearwaters (Procellariidae), in particular – see Kuroda (1954) for separation of diving from surface-feeding shearwaters – flew higher as wind speed increased. Other groups with high wing loading that tend to fly by flapping, specifically terns (Sternidae) and large alcids (Alcidae), ranked next. However, these groups may not have been strictly comparable to the shearwaters, because they were commuting between breeding and feeding grounds (as indicated by their location) and were coping with high winds rather than using them (see Discussion). The next highest-ranked groups, fulmars (Procellariidae), boobies (Sulidae, especially long-distance species) and surface-feeding shearwaters (Procellariidae), also tended to fly especially high as winds increased. The groups of lowest rank were all flappers, e.g. gulls (Laridae), skuas (Stercorariidae), phalaropes (Scolopacidae), storm-petrels, tropicbirds (Phaethontidae), cormorants (Phalacrocoracidae) and small alcids (Alcidae), and tended to fly lower with stronger winds. Many have a small body size. The large gulls and cormorants, almost all sampled in the California Current, were commuting.

With respect to region, seabirds on the whole tended to reach higher heights with stronger winds in the Southern Ocean and to a lesser extent the California Current (Fig. 6). Height increased at lower wind speeds in those areas, as well, compared with heights achieved at those wind speeds in the ETP and Peru Current regions. In the higher wind speed categories, the confidence intervals around the regression coefficients broadened with stronger winds, likely reflecting the differing responses of flight groups.

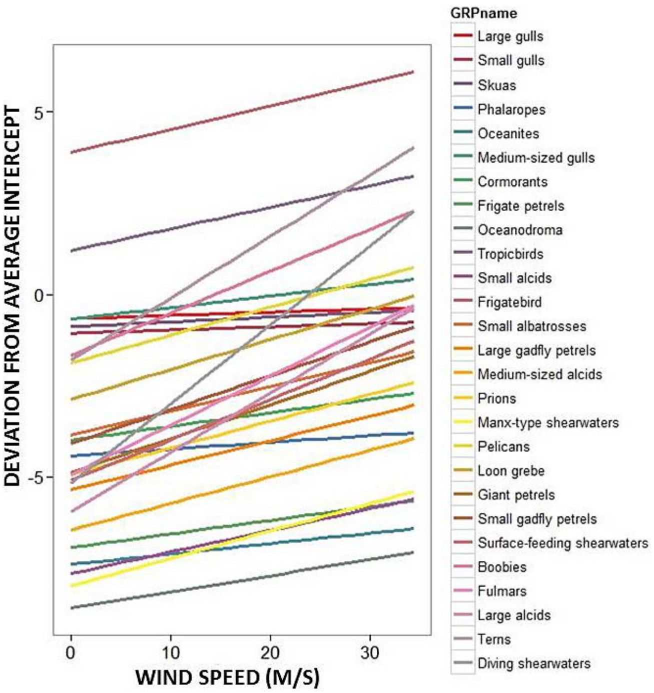

Fig. 5. Slopes and intercepts for the random effect in the relationship between flight height and wind speed compared among morphological groups.

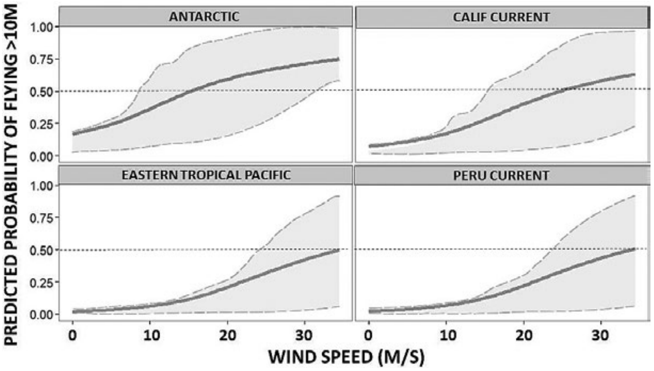

Fig. 6. Model predictions (with upper and lower quartiles) of the probability of seabirds flying higher than 10 m as a function of wind speed. Each region includes all species groups found in that region.

TABLE 5
Proportion seen flapping or gliding by flight style

Flight style	Proportion seen flapping	Proportion seen gliding
Flappers	0.71 to 0.92	0.01 to 0.10
Glide-flappers	0.14 to 0.44	0.02 to 0.15
Flap-gliders	0.03 to 0.12	0.21 to 0.53
Gliders	0.00 to 0.09	0.73 to 1.00
Sea-anchor soarers	0.14 to 0.45	0.00 to 0.21

Flight behavior

For the most part, species that are flappers showed an increase in prevalence of flapping with increasing wind: loons/grebes, cormorants, large and medium alcids, large and small gulls (but not medium-sized gulls), terns, and tropicbirds (Tables 5, 6). Glide-flappers, such as pelicans and boobies, showed this tendency as well. Flap-gliders, such as diving and surface-feeding shearwaters, small and large gadfly petrels (Procellariidae), small albatrosses (Diomedeidae), giant petrels (Procellariidae) and fulmars, exhibited an increase in the preponderance of gliding with higher wind speeds. *Oceanodroma* storm-petrels exhibited slightly increased glides with stronger winds but *Oceanites* storm-petrels did not. A number of species, such as the latter, frigatebirds, phalaropes, prions (Procellariidae), and perhaps small alcids, showed little change in flight style with increased wind speed.

DISCUSSION

Clustering

Morphology is often greatly confounded by phylogeny, and a quick glance at our modeling results shows a strong influence of phylogeny. However, what we find interesting is that our clustering was based on morphology related directly to flight capability, which is almost never measured by seabird researchers, who are quite familiar nevertheless with wing chord, tail, tarsus and bill length (e.g. Brooke 2004). While we did not intend to compare our results with a phylogenetic species array, it is clear that many closely related species use or cope with the wind similarly, but so do some not-so-closely related species. In general, changing the morphology of Pennycuick's (1987a) "standard seabird" produces the diversification of flight styles and capabilities shown in our

TABLE 6
Results of regression analyses of change in flight style with increasing wind speed[a]

	Flapping	Flap, few glides	Flap-gliding	Glide, few flaps	Gliding
Boobies	+	NS	-	NS	NS
Cormorants	+	NS	NS	-	NS
Diving shearwaters	NS	NS	-	-	+
Frigate petrels	NS	NS	-	NS	NS
Frigatebird	NS	NS	NS	NS	NS
Fulmars	+	NS	-	NS	+
Giant petrels	NS	NS	-	NA	+
Large alcids	+	NS	NS	-	NS
Large gadfly petrels	NS	NS	NS	-	+
Large gulls	+	-	NS	NS	NS
Loon/grebe	+	NS	NS	-	NS
Manx-type shearwaters	NS	-	+	-	NS
Medium-sized alcids	+	NS	NS	-	NS
Medium-sized gulls	-	NS	NS	NS	NS
Oceanites	NS	NS	NS	NS	NS
Oceanodroma	-	+	NS	NS	NS
Pelicans	+	NS	NS	NS	NS
Phalaropes	NS	NS	NS	NS	NS
Prions	NS	NS	NS	NS	NS
Skuas	NS	-	NS	NS	NS
Small albatrosses	NS	NS	-	-	+
Small alcids	NS	+	NS	NS	NS
Small gadfly petrels	NS	NS	-	NS	+
Small gulls	+	-	NS	NS	NS
Surface-feeding shearwaters	NS	NS	-	NS	+
Terns	+	NS	-	NS	-
Tropicbirds	+	NS	-	NS	NS

[a] A positive symbol indicates a significant positive relationship (e.g. more flapping with increased wind) and a negative symbol indicates the opposite (NS indicates no significant relationship).

cluster analysis. In a variation on Pennycuick's discussion, at the coarse scale of clustering (the lettered groups A&B, C&D and E&F) and staying close to the standard, our clustering reveals the flap-gliders have a range of body sizes (Fig. 4). Much of the clustering at this level has to do with phylogeny. Increasing wing length and aspect ratio from the "standard seabird" produces the gliders; shortening the wings and increasing wing loading results in the flappers (Fig. 2). Lengthening the wings without changing aspect ratio but reducing wing loading results in the soarers (frigatebirds); broadening the wings results in the glide-flappers (Fig. 3); and adding long legs and large feet results in the sea-anchor soarers (frigate and oceanitid storm-petrels).

Considering the flight-speed groupings of Spear & Ainley (1997b; Appendix 1 available on the Web site) allows us to understand the array of finer-scale clusters (numbered groups). Relative flight speed and the morphological characteristics that affect speed appear to play a role in seabird wind energy use. This is indicated in part by the fact that a number of species with high aspect ratios remain on the water when there is no wind (data not shown). While the soarers ride thermals, seabirds without the lift provided by thermals need to maintain air speed or take advantage of higher wind speed for effective flight. Thus, slight variations among close-to-the-standard flap-gliders (Fig. 4) separate small albatross and giant fulmars (Clusters 13 and 16) that need faster flight speed because of their increased wing loading (flight speed groups 1 and 3) from the remaining seven clusters of flap-gliders (not including Cluster 10b), i.e. various petrels plus long-ranging boobies (see flight speed groups 2, 4 to 9, some of 15). Coarse-scale clustering of the glide-flappers separated slow-flying small petrels/aerial storm-petrels (flight speed groups 6, 12) from heavier, faster-flying boobies, pelicans and large skuas (flight speed groups 14, 15, 17). Finally, all the flappers can be found among flight speed groups 16 and 18–25. Among these clusters, as wings become smaller and more adapted to underwater flight, aerial flight speed (and wing-beat frequency) needs to become faster for them to stay aloft and make horizontal progress. Thus, the heavy-body, high wing-loading, diving species (flight speed groups 22–25) are separated from the non-diving flappers (flight speed groups 13, 16 [small skuas], 18–21).

There were some anomalous groupings in the clustering (Appendix 1 available on the Web site). For instance, Franklin's Gull was grouped with terns (coarse and fine Cluster B-5) but seemingly should have been grouped with medium gulls (Cluster B-4); Short-tailed Shearwater was grouped with somewhat divergent small gadfly petrels (Cluster F-21) but seemingly should have been grouped with large aquatic shearwaters (Cluster F-17). The explanation for these anomalies is likely to do with sample size. In the specimens or published measurements available to Spear & Ainley (1997a), there was only one Franklin's Gull, and thus the measurements may not have been representative of the species. Likewise, there were only two Mottled Petrels and three Kerguelen Petrels in the sample, and, given they were measured during winter and in some stage of wing molt, their wings were shaped more like those of the similar-sized, aquatic Short-tailed Shearwater. Not including the two petrels, the Short-tailed Shearwater would have been clustered with the other aquatic shearwaters (Cluster 17). On the other hand, since its sample sizes seemed adequate, why the Leach's Storm-Petrel (Cluster 10b) was not grouped with the other *Oceanodroma* storm-petrels is perplexing. The other *Oceanodroma* storm-petrels have far narrower ranges than the Leach's. The latter breeds at high latitudes but winters in the tropics, whereas the other *Oceanodroma* measured are found in the same general respective regions year-round. Thus, in fact, the clustering may have identified a real difference: longer wings for the Leach's Storm-Petrel. Power & Ainley (1986) found that Leach's Storm-Petrel populations that nest farther from the tropics (where they wintered) had longer, thinner wings than those nesting closer to breeding areas, a pattern similar to migratory land birds and consistent with wing shape and ranging behavior in other seabirds (Pennycuick 1987a). Finally, we placed Hornby's Storm-Petrel among the sea-anchor soarers on the basis of our observations and the fact that their legs are longer and feet larger than other *Oceanodroma*; it is possible that investigation of this little-known species would reveal that it is not of that genus.

Flight height and behavior

When we began to log flight height and behavior during our at-sea cruises, we put observations into one of four height categories: <1 m, 1–3 m, 3–10 m, >10 m, but we now believe we should have estimated actual height for each bird sighting. Once we experienced the full range of wind conditions that can be encountered, even hurricane-force winds, it became clear that in winds >18 m/s (>35 knots), many seabirds attain heights far greater than 10 m, e.g. to 50 m or more. Thus, our range of categories has resulted in an understatement with respect to height, especially among gliders and flap-gliders, and to a lesser degree among glide-flappers.

Much has been said about seabirds flying to avoid the high winds of fast-moving low pressure systems (e.g. Blomqvist & Peterz 1984, Abrams 1985). However, gale-force winds of 18–21 m/s (35–40 knots) are common in the eastern boundary current regions where much of our data were collected (the same may be true for trade winds in the ETP region); winds often reach those levels in the afternoons in response to sea-land pressure differences, as the sun heats the land. With these strong winds, the seabirds present could travel hundreds of kilometers in a short period, although they may want to remain where they are, having found a particularly productive foraging "hot spot." In these conditions, most seabirds, except for the flappers and especially the heavy-body aquatic ones (and heavily molting, aquatic shearwaters), do not sit on the water. It would seem that on water they would be continually rolled by breaking waves, with danger of injury. The small species, such as storm-petrels, hide from the wind by remaining in wave troughs where wind speeds are low, as shown by their decreasing flight height in higher winds. The larger species are aloft; they likely fly so high in strong winds not only to stay out of the raging water but also to remain in the general vicinity until the winds subside to a level more manageable for feeding (or resting). In other words, they are flying but not really going anywhere, either making high loops or swoops or repeatedly returning to the same locales. Moreover, since they increase gliding and decrease flapping, they are likely expending little energy.

The heavy-body flappers (high wing-loading, e.g. loons, scoters) but also sea-anchor soarers stay low, especially with strong head- or crosswinds. This behavior is consistent with use of the wind gradient, i.e. the lower wind speeds found close to the sea surface. As wind speed increases, species exhibiting these behaviors also flap less, which is not surprising, as the wind is neutralizing their generally heavier wing loading. When flying with the wind, they fly higher, although rarely higher than 10 m. Employing more gliding and less flapping as wind speeds increase, thus decreasing flight energy, was characteristic of almost all seabirds studied.

While strong winds could blow a seabird a long way quickly, as a general rule seabirds, or at least the non-flappers, avoid flying with tailwinds (Spear & Ainley 1997a). Seemingly, seabirds have much less control in a tailwind. If they are in long-distance flight mode, they do so most efficiently with crosswinds (Pennycuick 1987a), even if using such winds takes them on a longer route (Spear & Ainley 1999a, Shaffer *et al*. 2006, Gonzales-Solis *et al*. 2009, Adams & Flora 2010). In crosswinds, the gliders, flap-gliders and glide-flappers use what is known as "gust soaring" (Pennycuick 2002), in which they use the pulses of strong winds that occur between wave crests to climb sufficiently high, without effort, to extract the wind's energy and maintain flight speed attained in the down-swoop. Pennycuick (2002) further theorized that petrels use their tubenose to sense the subtle but rapidly changing pressure gradients in order to be able to take full advantage of the narrow, between-crest wind gusts. Attaining heights of 15 m or higher in this process, at winds of 20 m/s, is not unusual. In stronger winds, the larger seabirds, and especially those with a high aspect ratio, rise even higher, perhaps looping more to minimize the horizontal distances covered, as discussed above. During migration, they take advantage of the wind energy to cover long distances quickly and somewhat effortlessly (see Shaffer *et al.* 2006: shearwaters covering approximately 1 000 km/d).

Regional differences

In our analyses, seabirds of the same flight groups tended to fly higher in either the California Current or the Antarctic compared with the ETP and Peru Current. Given that the ability to employ gust soaring is very much related to the characteristics not only of wind but of the waves as well, the difference in flight height at different locations could be related to wave height. Unfortunately, we did not collect consistent data on wave height, but, informally, we were aware of clear regional differences in wave height and behavior. The long-period swells and large waves of the Southern Ocean are legendary, and result from the unencumbered globe-circling fetch (DeBlieu 1998, Huler 2004). Without much in the way of local winds, using those swells, the larger seabirds of the Southern Ocean would be employing "slope soaring" rather than gust soaring. Slope soaring is employed by most seabirds, even those with the highest wing loading, when they ride up-currents of air along bluffs at breeding colonies; seabirds use the same principle to ride updrafts on the windward side of large ocean swells (Pennycuick 1987a). In the Antarctic (and likely the Arctic, although we have no experience there), a number of species (especially the Snow Petrel) slope-soar along the edges of ice floes (and well as icebergs), although the free-board of an ice floe is often less than a meter. Given these flight behaviors, we should expect differences in seabird flight behavior among regions with substantial differences in wave and wind conditions.

Why seabirds would fly higher in winds over the California Current than in those over the Peru Current is a more perplexing question. These two wind-current systems are completely analogous, being eastern boundary currents generated by steep pressure differentials between large offshore high pressure systems and low pressures over the adjacent land. The fetch should be about the same, as should the resulting wave regime. In both cases, we collected data during both the upwelling and the non-upwelling portions of the year. One explanation for the difference is that it could be an artifact of the locations where we sampled flight height, relative to the respective coasts. In the California Current, significant portions of cruises were close to the land (1–2 km) and especially headlands, where local wind is stronger, affecting wave conditions and gust soaring behavior. In the Peru Current, owing to the politics of national clearance, vessels were rarely closer than 20 km (12 nautical miles) from the coast, except for when entering and leaving port. Therefore, we would not have passed through the steeper local waves near the coast where gust soaring behavior would have been more prevalent.

Vulnerability of flying within the rotor-swept zone of wind generators

We defined vulnerability of flying within the rotor-swept zone as exceeding an estimated probability of 0.5 for flying at >10 m high (Table 4, Fig. 6). In general, for most flight styles, birds tended to reach this vulnerability criterion at lower wind speeds when flying into crosswinds compared with either headwinds or tailwinds. There was considerable variation in vulnerability, however, based on cluster, location, and flight direction. We considered distance offshore as a potential variable influencing vulnerability, although recent research indicates that distance offshore influences concentrations of birds, especially non-breeders, less than prey availability (e.g. Ainley *et al*. 2009).

Any of the species groups with a slope >0 in the relationship between wind and flight height (i.e. the bottom eight groups in Table 4) would be vulnerable to entering the rotor-sweep zone of most of the currently used wind turbines at the wind speeds normally prevalent in eastern boundary currents, such as the California and Peru currents or the trade winds experienced in Hawaii. These winds, typically 15–18 m/s (30–35 knots), surpass the "moderate" velocities detailed by Garthe & Hüppop (2004) and Johnston *et al*. (2013) that are used to assess seabird vulnerability for coastal Europe (see also Bradbury *et al*. 2014). It is these stronger winds that appear to have a significant effect on flight height. Those species at the top of the rank list tend to fly lower with increased wind and so would be much less vulnerable.

The relative positions of many species groups in Table 4 are consistent with the propensity of equivalent species to occur within rotor sweep zones as identified by Cook *et al*. (2012). However, there are notable exceptions, the reason for which is not clear. For example, Cook *et al*. indicate that large gulls that occur in European coastal waters are very vulnerable, where as in our analysis they are not. The reason for the difference could result from the conditions under which respective surveys were made. In our study, the large gull category is based almost entirely on sightings in the California Current of Western Gulls, and almost all of the gulls seen were commuting, often against gale-force winds, to reach their breeding colony from coastal foraging areas. During the non-breeding season, these same gulls would just sit tight on a day of strong winds, and they would not be counted in at-sea surveys. The same would be true of large alcids, deemed by Cook *et al.* (2012) not to be vulnerable. In our study, a large proportion of alcids involved were breeding Common Murres fighting very strong headwinds to return to the colony to feed chicks. The lesson here is that certain local situations need to be considered when applying our results. Presumably Cook *et al*. (2012) and others devising vulnerability indices use data amassed from widespread sources or surveys (e.g. Bradbury *et al*. 2014).

CONCLUSIONS

This study provides much-needed support for future seabird investigations of relationships between foraging ecology, behavior, morphology and wind conditions, thus increasing our understanding of natural history. In addition, this study's findings can likely contribute to the need for better information concerning potential seabird mortality of planned offshore wind energy development, although factors other than the two we studied (flight height, behavior) need to be considered (see below). Especially by location, the propensity to fly at heights >10 m (thus reaching the height of operating wind turbine rotors) and the propensity for gliding with minimal flapping were evaluated. We found that wind speed and flight direction have an important effect on flight style.

Seasonal variation in flight behavior could greatly influence where wind generators would most likely be situated. For instance, during migration in the Atlantic Flyway (not investigated herein), most waterbirds tend to use the corridor within several kilometers from shore; however, during breeding, the use of the coastal areas near breeding habitat is more predominant (Watts 2010). However, this would not apply to the Pacific Coast of North America, where seabird use, including year-round and seasonal residents and migrating species, is spread over waters covering the entire shelf and slope (Briggs *et al.* 1987, Mason *et al.* 2007). This is because bird concentration areas are associated with where prey tend to concentrate (Ainley *et al.* 2009), or biological "hot spots" (Nur *et al*. 2011), and these are not necessarily close to shore along the Pacific Coast. Seasonal ocean trends, such as differences in sea-surface temperature, wind speed and thermocline depth, which are factors that affect prey distribution, can also influence how close to shore certain species such as Sooty Shearwater, Common Murre, and Cassin's Auklet move (Oedekoven *et al*. 2001).

Avoidance behavior can considerably affect estimates of fatality risk, as several different species, particularly waterfowl (Desholm & Kahlert 2005, Fox *et al*. 2006, Masden *et al*. 2012), have been observed to avoid wind turbines. Waterfowl, however, are obligate flappers (high wing loading) and, as such, are among the least affected by winds in terms of flight height and behavior. The high speeds of swooping (flap-gliding, glide-flapping) petrels and albatross, on the other hand, with the final direction and altitude of a swoop determined by physics well in advance of its execution, probably render them incapable of avoiding structures unless they have made adjustments well in advance.

Otherwise, seabirds' responses to ocean winds have been much under-appreciated by seabird biologists, who have instead studied the more tractable aspects of direct food acquisition (e.g. depth of diving, foraging range). For example, much is known about how El Niño-Southern Oscillation (ENSO) affects food availability, but little is known about seabird shifts in response to the dramatic changes in wind and wave patterns that also occur during those events. The resulting disruption of "normal" movement patterns can be significant, and so an ENSO effect on seabirds is likely far more complex than simply an effect on food supply. As seabird biologists increasingly use telemetry and remote sensing, we may acquire new information and better appreciate seabirds' relationships to winds and waves (e.g. Suryan *et al*. 2008, Adams & Flora 2010), including interannual shifts. Pennycuick *et al.* (1984) provided initial insights into how flight behavior (and flight morphology) should be considered an important foraging niche dimension, an insight that has been appreciated rarely (e.g. Ballance 1993, Spear & Ainley 1998, Gaston 2004, Navarro *et al.* 2013). In part, this under-appreciation of at-sea bird science has been affected by biologging and instrumentation of single species, leading toward "aut-ecology" and away from community ecology.

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Departure of Manx Shearwater *Puffinus puffinus* fledglings from Bardsey, Gwynedd, Wales, 1998 to 2013

Mike Archer[1*], Peter Hope Jones[2] and Steven D. Stansfield[2]

** Correspondence author. Email: mikearcher@care4free.net*
[1] *14 Fulwood Park Mansions, Chesterwood Drive, Sheffield S10 5DU, UK;*
[2] *Bardsey Bird and Field Observatory, Cristin, Bardsey, off Aberdaron, via Pwllheli, Gwynedd LL53 8DE, UK.*

Very little has been published about how soon Manx Shearwater *Puffinus puffinus* fledglings leave the area around the natal colony, clearly because of the difficulty of re-catching them after they are first ringed and of knowing whether or not recaptured birds had flown (Perrins *et al*. 1973; Perrins 2014). Fledglings are thought to depart southwards promptly after they finally leave the natal burrow because the food supply near the colony is deteriorating as the breeding season draws to a close, as suggested by the earlier departure of the adults and the lighter weights of later fledglings, and also as evidenced by the paucity of recoveries immediately after fledging, gale-wrecked birds apart (Brooke 1990). Catching Manx Shearwaters on Bardsey, Gwynedd, Wales at lighthouse attractions within the perimeter of the lighthouse complex, and re-catching them there and on the ground elsewhere on the island, showed that not all fledglings left the area immediately, with a few remaining for up to five/six days. The data published here relate to the numbers initially attracted to the lighthouse and later re-attracted or otherwise caught again in late August and September, between 1998 and 2013.

Bardsey (52°76'N 4°78'W) is three km long from north to south and a little over one km at its widest point (Figure 1). A small colony of breeding Manx Shearwaters has been known on the island since early in the 20th century (Cramp *et al*. 1974) and the species currently breeds in burrows, mainly in soil on the steeper slopes, but also in or by the earth-covered stone boundary walls in the low-lying areas. The island's Manx Shearwater colony is perhaps the fifth largest in Britain and Ireland (Newton *et al*. 2004) and the most recent whole-island surveys in 2001 (Leaper 2001; Newton *et al*. 2004) and in 2008, 2009 and 2010 (Else 2009, 2010, 2011) estimated the breeding population at between 9,000 and 16,000 pairs. The productivity mean for the ten-year period 2001–10 was 0.77 (Brown & Stansfield 2011). In 2008–10 the island was subdivided into three survey areas for censusing the population: Area A on the steep east side cliffs held 9,610 apparently occupied burrows (AOB), Area B held 4,071 AOB, and Area C held 2,178 AOB (Else 2009, 2010, 2011). The lighthouse stands in Area C towards the southern tip of the southern promontory (Figure 2), at a point where burrow densities are low, there being probably fewer than 50 AOB within a radius of 100 m.

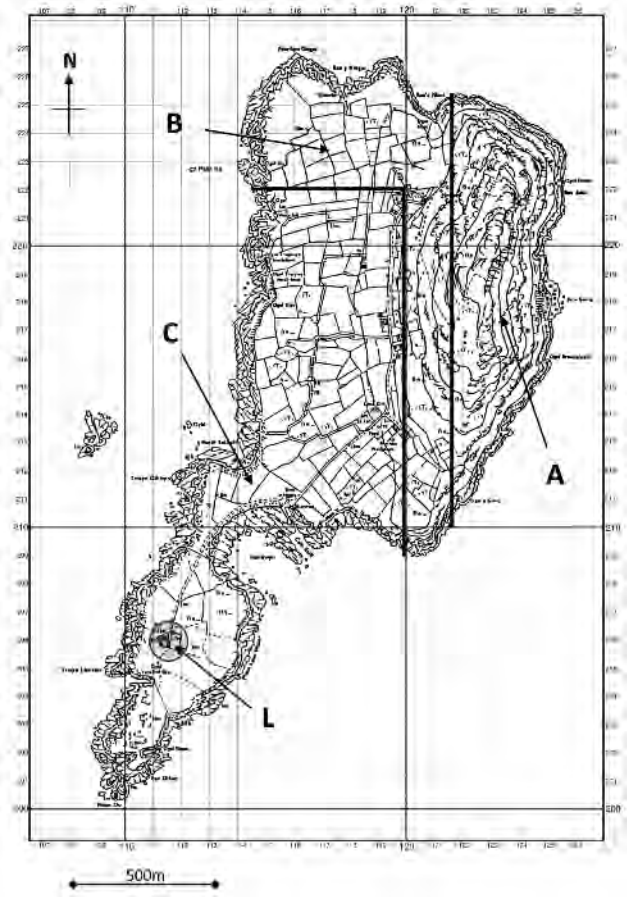

Figure 1. Map of Bardsey showing the position of the lighthouse (L) and the extent of the three survey areas (A, B and C).

Juvenile shearwaters exercise their wing muscles vigorously outside the burrows during the final nights before fledging (Brooke 1990), but very few of these on Bardsey were observed to fly, and those that did flew no more than 20–30 m in level flight nor to a height of more than one metre. The lighthouse lantern light is at about 30 m above ground level, and during 1998–2013 birds were attracted to the light in numbers in weather conditions involving very poor visibility and general mistiness, with rain and a cloud ceiling not far above the upper part of the lighthouse; very small numbers were also attracted from time to time on clearer nights. The attracted birds usually circled in the revolving beams of the light for several minutes and often much longer before colliding with the light and falling to the ground or escaping its attraction and flying off (Stansfield 2010). Birds found on the ground within the lighthouse complex can be assumed to have been free-flying, as a substantial perimeter wall prevented fledglings from wandering into the complex area on foot (Figure 3). Further, 27 of the fledglings attracted, but not re-attracted, were retraps, of which 23 had been ringed as juveniles at least 600 m and as much as 2,500 m from the lighthouse, and between two and 13 nights earlier (mean = 4.91). Thus juveniles attracted to the light were assumed to be fledglings and on their maiden or a subsequent flight. Trinity House altered the light in 2014, precluding the likelihood of any further attractions and gathering further like data.

Regular checks were made at night by Bardsey Bird Observatory staff for attracted birds, which were later ringed. Juveniles were distinguished from adult birds, often by retained down on the crown and/or belly, but also by a combination of fresh, unworn primaries with no bleaching on the tips of the primaries or secondaries, unworn and hence sharp claws, and more subjectively, the soft juvenile feel and, on occasion, the characteristic earthy burrow-smell. None showed any sign of injury.

Whilst the precise time of capture at attractions was not recorded, the post-midnight date was ascribed by convention to the ringing procedures, regardless of whether a bird was picked up before or after midnight. These birds were usually ringed, if not previously ringed at the burrow, (processed) and released by manual launching into the wind, to fly away over the sea and out of sight, in mid/late afternoon or in the evening before dusk, and therefore possibly up to 20 hours after capture, and possibly within four hours of re-capture on the 'following night'. The birds picked up elsewhere and subsequent to the initial attraction were processed there and then and the date and time were usually recorded to the nearest hour.

Accepting that the attracted fledglings were almost certainly reared on Bardsey, at least 21 of those first attracted did not permanently leave the immediate vicinity of their natal colony for between one and six days, 16 being re-captured at lighthouse attractions and five on the ground elsewhere on the island (Table 1). Of those five, three were at least 750 m distant from the lighthouse at the West Coast (1) and in the Lowlands (2), one was c. 600 m distant at Solfach, and the fifth was at the South End, between 50–400 m distant. These 21 fledglings were part of a cohort of 220 fledglings caught at attractions on ten nights. To complete the picture, a further 628 fledglings, caught below the lighthouse on 177 nights at other very minor attractions and usually in twos and threes, were not caught again. The attracted birds were assumed to be Bardsey-fledged. Whilst the possibility of catching a fledgling from a colony elsewhere cannot be ruled out entirely, only a single fledgling ringed elsewhere has been controlled on Bardsey since 1953, compared with 140 adults. Furthermore, the likely minimum number of fledgling shearwaters departing Bardsey in any of the subject years would be about 6,900, calculated by multiplying the likely minimum number of breeding pairs (say 9,000) by the likely productivity mean (0.77).

Figure 2. View of Bardsey, looking southwest towards the lighthouse from the slopes of Mynydd Enlli, May 2015. © *Connor Stansfield*.

Figure 3. Bardsey Lighthouse and the perimeter wall that surrounds it, viewed from the south, May 2015. © *Connor Stansfield*.

Table 1. Numbers of fledgling Manx Shearwaters *Puffinus puffinus* attracted (A) at the Bardsey lighthouse and re-captured at a subsequent attraction or elsewhere on the island shortly afterwards, 1998–2013 and (B) captured and ringed on the ground on Skokholm and re-captured there afterwards, 1967, and the interval in days between captures.

Number of days from first to last capture	A. Number of Bardsey recaptures	Total days: product of first and second columns	B. Number of Skokholm recaptures	Total days: product of first and fourth columns
1	6	6	22	22
2	11	22	23	46
3			14	42
4	2	8	5	20
5	1	5	3	15
6	1	6	2	12
7			2	14
8			1	8
Totals	21	47	72	179
		Mean = 2.24		Mean = 2.49

The Skokholm numbers given here are slightly at variance with those in Perrins *et al.* (1973); of the 72 birds, 39 were weighed on both first and last recapture, covering a total of 104 'days' with a mean loss per day of 14.4 g.

Further, the birds caught at the first attractions may or may not have been on their maiden flights and there is no sure means of telling. As the majority of Welsh birds go overland to the sea on fledging (Brooke 1990), rather than flying, those scrambling to the sea might not have had time, or been able to fly well enough, to be attracted to the lighthouse light on their first night at sea, thus extending the post-fledging periods before the recapture attractions or other recapture for at least another 24 hours and perhaps longer.

So infrequent were the closely-spaced nights of double attractions that only 16 fledglings were both attracted and re-attracted to the lighthouse, while five originally-attracted birds were subsequently recaptured on the ground elsewhere on the island during occasional general ringing activities. The recapture of these five attracted fledglings, away from the lighthouse, indicates that some birds return to land after maiden fledging or other flights and before final departure.

Similar, but larger, samples of data arise from the capture, ringing and recapture of Manx Shearwaters on the ground outside the burrow on Skokholm Island, Pembrokeshire, Wales in 1967 (Table 1). The date of ringing on the surface was taken as indicative of the date of fledging in respect of birds not assumed to have ever flown (Perrins 2014).

Acknowledgements

Thanks are due to Professor Chris Perrins, the Wildlife Trust for South & West Wales (its current name) and Skokholm Bird Observatory for providing the Skokholm data in Table 1 with commentary. Members of the Bardsey Bird Observatory staff and visitors caught, re-caught, ringed and processed the fledglings at attractions and elsewhere on the island. Martin Heubeck, Professor Chris Perrins and another, anonymous, referee greatly improved the manuscript with their comments.

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USING A COLLISION RISK MODEL TO ASSESS BIRD COLLISION RISKS FOR OFFSHORE WINDFARMS

MARCH 2012

Bill Band

This guidance has been prepared for The Crown Estate as part of the Strategic Ornithological Support Services programme, project SOSS-02. It provides guidance for offshore wind farm developers, and their ecological consultants, on using a collision risk model to assess the bird collision risks presented by offshore windfarms.

The guidance has been extended in this March 2012 version to make use of flight height distribution data, where that data is available and robust; and to include a methodology for considering birds on migration, for which survey data on flight activity may be limited.

The guidance is accompanied by

- a Collision Risk Spreadsheet, which enables the calculations required to be undertaken and presented in a standardised manner
- a Worked Example, to illustrate the process
- a Tidal Variation spreadsheet, for use only when tidal effects may be significant

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The SOSS steering group includes representatives of regulators, advisory bodies, NGOs and offshore wind developers (or their consultants). All SOSS reports have had contributions from various members of the steering group. However the report is not officially endorsed by any of these organisations and does not constitute guidance from statutory bodies. The following organisations are represented in the SOSS steering group:

SOSS Secretariat Partners:	The Crown Estate
	British Trust for Ornithology
	Bureau Waardenburg
	Centre for Research into Ecological and Environmental Modelling, University of St. Andrews
Regulators:	Marine Management Organisation
	Marine Scotland
Statutory advisory bodies:	Joint Nature Conservation Committee
	Countryside Council for Wales
	Natural England
	Northern Ireland Environment Agency
	Scottish Natural Heritage
Other advisors:	Royal Society for the Protection of Birds
Offshore wind developers:	Centrica (nominated consultant RES)
	Dong Energy
	Eon (nominated consultant Natural Power)
	EdF Energy Renewables
	Eneco (nominated consultant PMSS)
	Forewind
	Mainstream Renewable Power (nominated consultant Pelagica)
	RWE npower renewables (nominated consultant GoBe)
	Scottish Power Renewables
	SeaEnergy/MORL/Repsol (nominated consultant Natural Power)
	SSE Renewables (nominated consultant AMEC or ECON)
	Vattenfall
	Warwick Energy

Extended model taking account of flight height

PURPOSE OF GUIDANCE

1. Offshore windfarms may have a number of effects on bird populations:
    - **Displacement** – birds may partially or totally avoid a windfarm and hence be displaced from the underlying habitat.
    - **Barrier effects** – birds may use more circuitous routes to fly between, for example, breeding and foraging grounds, and thus use up more energy to acquire food.
    - **Habitat effects** – birds may be attracted or displaced by changes in marine habitats and prey abundance as a consequence of the windfarm.
    - **Collision risk** – birds may be injured or killed by an encounter or collision with turbines or rotor blades.

    This guidance relates to the last of these, collision risk.

2. **An environmental statement for an offshore windfarm should include a quantitative estimate of collision risk for all bird species present on the site for which the level of risk has the potential to be important. The environmental statement should provide a view on the significance of that collision risk on the respective bird populations.**

3. The aim of this guidance is to promote a standardised approach to collision risk assessment for offshore windfarms, to increase the transparency of calculations, and hence promote greater confidence in the results; to enable estimates from different windfarms to be more easily compared and combined so as to facilitate cumulative assessment; and hence enable collision risk assessment to be used as a tool in selecting the best areas for offshore windfarm development.

4. The guidance describes the information needed, and how to use that information, to arrive at an estimate of collision risk. It is accompanied by a spreadsheet which enables the necessary calculations to be performed in a standardised way.

INFORMATION NEEDED

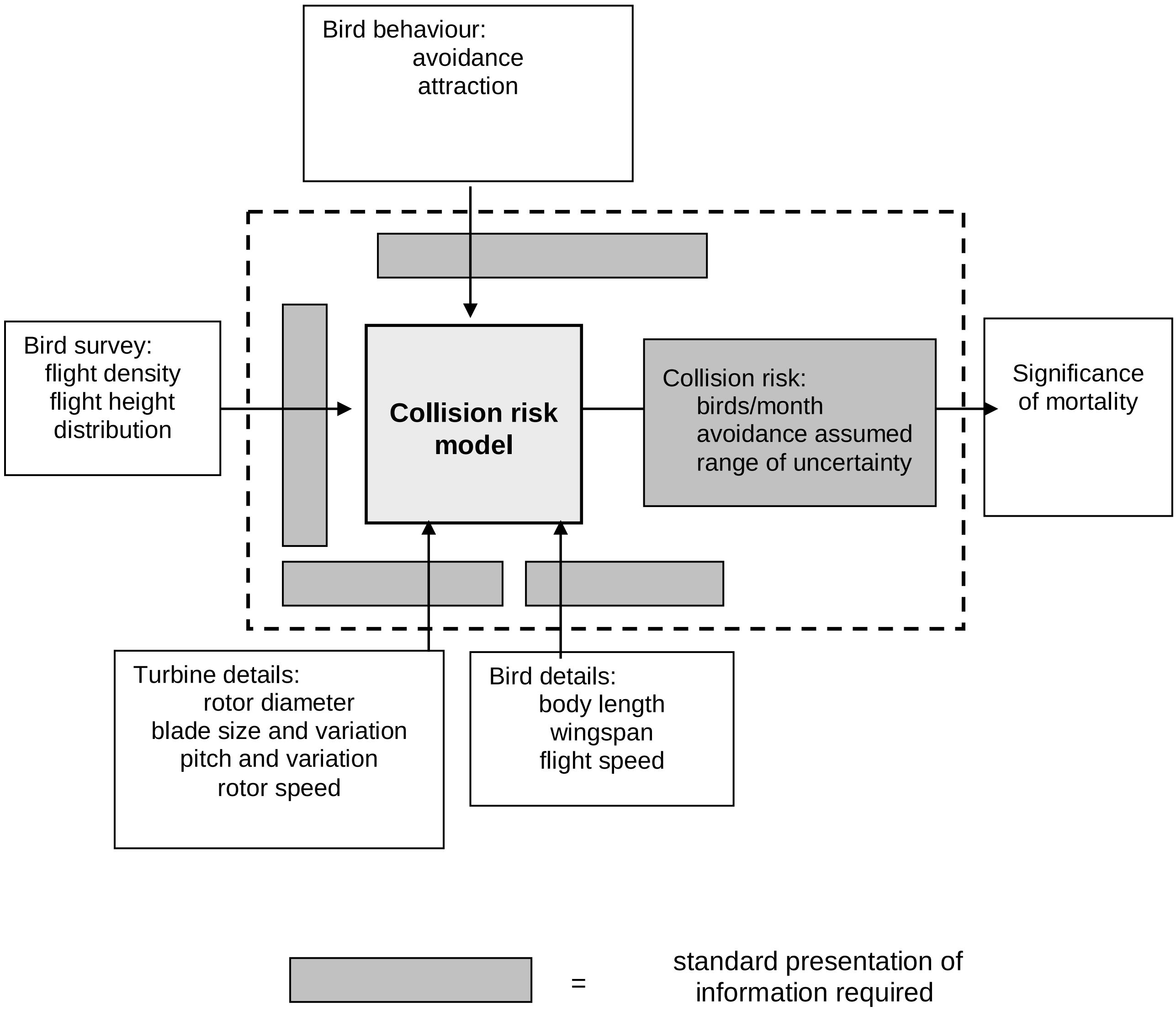
5. Figure 1 shows the information needed to estimate collision mortality:
    - **information derived from bird survey** - on the number of birds flying through or around the site, and their flight height
    - **bird behaviour** - prediction of likely change of behaviour of birds, eg in avoiding, or being attracted to, the windfarm
    - **turbine details** - physical details on the number, size and rotation speed of turbine blades
    - **bird details** - physical details on bird size and flight speed

6. This guidance sets out how that information should be presented and used within a collision model, and how the outputs from that model should be expressed – ie the components in the dashed 'box' in Figure 1. The guidance does not cover:
    - bird survey methods - for which there are various advisory sources.
    - bird behaviour - while it outlines how an avoidance rate factor should be used in the collision risk calculation, the guidance leaves it to other sources, where possible based on actual monitoring of bird collisions at windfarms, to advise on what avoidance rates should be used.

    Figure 1 also indicates the key outputs from the collision model – the collision risk, expressed in terms of the likely number of birds per month or per year which will collide with the windfarm, and the range of uncertainty surrounding that estimate. These should be accompanied by a clear statement of the assumptions on avoidance made in arriving at that estimate, as such assumptions are often be critical to the magnitude of the collision estimate. This guidance includes advice on how these outputs should be presented.

7. Note that the collision risk model stops at an assessment of collision risk. Where collision risk is not negligible, a developer will need to further consider the significance of the predicted mortality - which will depend on the sensitivity of the bird population, and the degree of protection afforded by legislation and any protected sites in the vicinity which may be designated for that species.

Fig 1: Role of collision risk model



COLLISION RISK MODEL

8. The approach adopted follows in general terms that developed by Band (2000)[i] and Band et al (2007)[ii] and promoted in guidance published by Scottish Natural Heritage, but it has been updated to facilitate application in the offshore environment. The offshore approach differs from onshore mainly in the methods used to gather and present information on flight activity, given that direct observations of birds from key vantage points are not usually possible in the marine environment. The approach is described below in six stages:

Stage A	assemble data on the number of flights which, in the absence of birds being displaced or taking other avoiding action, or being attracted to the windfarm, are potentially at risk from windfarm turbines;
Stage B	use that flight activity data to estimate the potential number of bird transits through rotors of the windfarm;
Stage C	calculate the probability of collision during a single bird rotor transit;
Stage D	multiply these to yield the potential collision mortality rate for the bird species in question, allowing for the proportion of time that turbines are not operational, assuming current bird use of the site and that no avoiding action is taken;
Stage E	allow for the proportion of birds likely to avoid the windfarm or its turbines, either because they have been displaced from the site or because they take evasive action; and allow for any attraction by birds to the windfarm eg in response to changing habitats; and
Stage F	express the uncertainty surrounding such a collision risk estimate.

9. The basic model has recently (March 2012) been extended to make use, where it is available, of data on the distribution of bird flight heights; in particular to enable use of the data on flight heights of birds at sea compiled for SOSS by Cook et al[iii]. This 'extended model' is described following Stage D, as within that model Stages B, C and D become merged in a single calculation. Another addition is Annex 6, which describes use of the model when assessing the collision risk to birds on migration, where there may be limited bird survey information on flight activity.

General features

10. Risk is turbine-based. Risk in this model is calculated directly from the rotor parameters and the flight activity in the airspace surrounding each turbine. Some practitioners have used an approach which considers the risk to each bird passing through a windfarm, taking account of the layout and spacing of turbines to calculate the likelihood of encountering one or more turbines and the resulting risk. This is unnecessary if one focuses, as in this guidance, on the risk resulting from each turbine operating within its own airspace within which there is a known (or projected) level of flight activity.

11. Relationship to previous guidance. The approach to quantifying and expressing flight activity in this guidance differs from that set out in the earlier Band papers. These papers offered two alternative approaches for calculating the likely number of flights through turbines: the first using observations of bird flux passing through a vertical 'risk window' enveloping the turbines; and the second assessing the 'bird occupancy' of the volume of airspace occupied by the windfarm as a whole. Both these methods are mathematically equivalent to the method described below and in the attached spreadsheet, in which the core measures of flight activity used are the density of flying birds per unit horizontal area of the windfarm, and the proportion flying at turbine height. The current approach leads to the same results and avoids the need to identify arbitrary risk windows or to define an arbitrary windfarm boundary. The basic model and spreadsheet used to calculate the risk for a single bird flight through a rotor are also as in the earlier papers (though subject to minor refinement). Thus, collision

risk estimates resulting from application of the basic model in this guidance should not differ substantively from those deriving from correct application of the earlier Band papers.

12. Oblique approach simplified. There is a simplification involved in separating out Stages B and C, in assuming that the probability of collision for any bird passing through a rotor is the same regardless of the direction of flight. In fact, the collision risk depends to some extent on a bird's angle of approach, determined by the direction of its flight and the orientation of the turbine blades. A bird approaching a turbine at an oblique angle is exposed both to a reduced probability of flying through the rotor, because the rotor presents an elliptical rather than circular cross-section, and an increased risk of collision if it does so. The model adopted for use here assumes that these two factors exactly offset each other, such that all bird transits can be treated as if making perpendicular approach to the rotor. This enables Stages B and C to be undertaken sequentially. A more exact approach would require estimating the number of flights from each direction, applying the collision probability for that direction, and summing the probability over all directions. Annex 1 provides a fuller explanation of this issue and the justification for adopting the simplified approach. It should be recognised that this simplification leads to some underestimation of collision risk, which may be as much as 10% for large birds.

13. Taking account of bird flight height distribution. Seabirds mostly fly at relatively low heights over the sea surface. The height distribution varies from species to species and may depend on the site and its ecology and related bird behaviour. The basic model considers the risk only to birds flying at risk height (above the minimum and below the maximum height of the rotors) and of these, only those which pass through the rotors. However within these limits it assumes a uniform distribution of bird flights. There are three consequences of a skewed distribution of flights with height:

    - the proportion of birds flying at risk height decreases as the height of the rotor is increased;
    - more birds miss the rotor, where flights lie close to the bottom of the circle presented by the rotor; and
    - the collision risk, for birds passing through the lower parts of a rotor, is less than the average collision risk for the whole rotor.

    This guidance now includes, in addition to the basic model, an extended model (March 2012) which enables flight height distributions to be incorporated in the calculation, for use in circumstances where flight height data is available and adequately robust.

14. Best estimate not worst-case. This guidance does not recommend use of 'worst case' assumptions at every stage. These can lead to an overly pessimistic result, and one in which the source of the difficulty is often concealed. Rather, it is recommended that 'best estimates' are deployed, and with them an analysis of the uncertainty or variability surrounding each estimate and the range within which the collision risk can be assessed with confidence. In stating such a range, the aspiration should be to pitch that at a 95% confidence level, that is, so that there is 95% likelihood that the collision risk falls within the specified range. However, given the uncertainties and variability in source data, and the limited firm information on bird avoidance behaviour, it seems likely that for many aspects the range of uncertainty may have to be the product of expert judgement, rather than derived from statistical analysis.

15. Spatial exploration of risk. While this guidance, and the attached spreadsheet, is written around quantifying the collision risk from an entire windfarm, it can equally well be applied at the level of a subgroup of turbines or even an individual turbine. If the data on flight activity is sufficiently robust to allow such discrimination, this facilitates the examination of risk on a spatial basis. Collision risk is directly proportional to flight activity which is dependent on bird density at rotor risk height. Siting windfarms, or groups of turbines, in areas of lower bird density is likely to yield a proportionately lower collision risk.

16. Use for onshore windfarms. The approach described here could equally well be applied to onshore as to offshore windfarms, using vantage point or other land-based survey or radar to generate the required data on bird density (see paragraph 19).

STAGE A - FLIGHT ACTIVITY

17. The aim of this stage is to estimate the number of flights which, in the absence of birds being displaced or taking other avoiding action, or being attracted to the windfarm, would potentially be at risk from the windfarm turbines. This requires field data to determine levels of flight activity within the proposed windfarm.

How flight activity is expressed

18. Flight activity may be expressed in a variety of ways.

- Bird density is a measure of how many birds (of any given species) are in flight at one time. It may be expressed in terms of birds per m^3 (cubic metre) of air space (the 'true density' D_v). However, more commonly, reflecting the use of boat-based or aerial survey techniques, it may be expressed on an area basis as the total number of birds in flight at any height at a given point of time, per m^2 (square metre) or per km^2 (square kilometre), as viewed from the air, D_A.

- Bird occupancy applies to a given volume of airspace, and is simply the number of birds on average occupying that volume. Thus, in a volume of air for which the bird density is uniform, bird occupancy (birds) = true density (birds/ m^3) x volume (m^3). The concept of 'bird occupancy' is not used in this guidance, but is referred to here to facilitate comparison with the Band (2000) model[1].

- Bird flux is the number of birds crossing an imaginary surface within the airspace, expressed as birds/sec or birds/sec per m^2 of that surface. It is commonly measured in the field in terms of a Mean Traffic Rate which is the number of birds flying per hour across an imaginary horizontal line of length 1km. If all birds crossing that imaginary line, as viewed from above or below, are recorded at any flight height up to height h metres, then the Mean Traffic Rate is the total number of birds N birds/km/hour crossing that line. MTR must be divided by 3600 (seconds in an hour) and 1000 (metres in a km) to express bird flux in birds/sec per metre of baseline, and divided further by the height h to get the bird flux in birds/ sec /m^2.

  Bird flux is directly related to bird density, but depends on the speed of the birds (if they were stationary, there would be no flux). If the total bird flux (flights at any height, in either direction) across the baseline is F_L birds/sec per metre of baseline, then the bird density D_A per m^2 is

$$D_A = (\pi/2)\, F_L \;/\, v$$

  where v is the speed of the birds in m/sec: see Annex 2 for the derivation of this formula and fuller information on converting between flux and bird density.. Flux is directional – for a given density of birds moving in random horizontal directions, a vertical 'window' will intercept more birds flying perpendicular to the area than birds flying at an oblique angle, to which the window will appear narrower. The (π/2) factor takes account of this angle-dependence.

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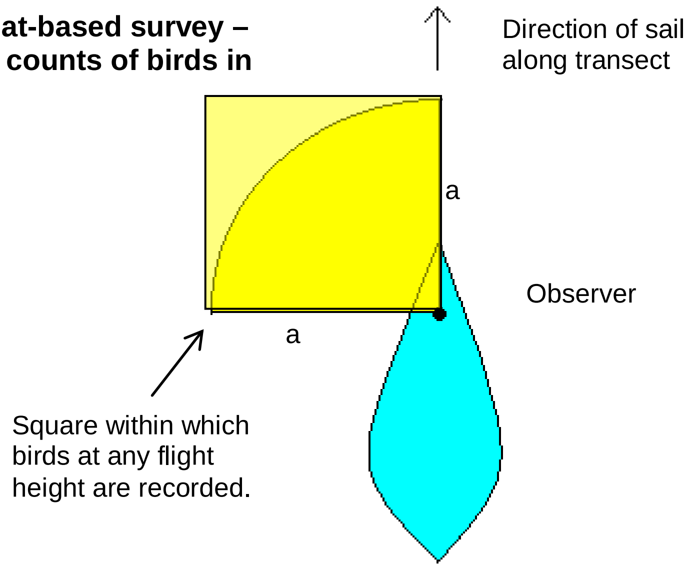
[1] In the Band (2000) model, bird occupancy is expressed in 'bird-seconds per year' as a convenient way of expressing low levels of bird occupancy. An occupancy of 31.6 x 10^6 bird-seconds per year means that on average, within the specified volume, there is one bird throughout the year, 31.6 x 10^6 being the number of seconds in a year.

Fig 2: Boat-based survey – snapshot counts of birds in flight



19. How flight activity is expressed in output from surveys often reflects the type of survey method deployed:

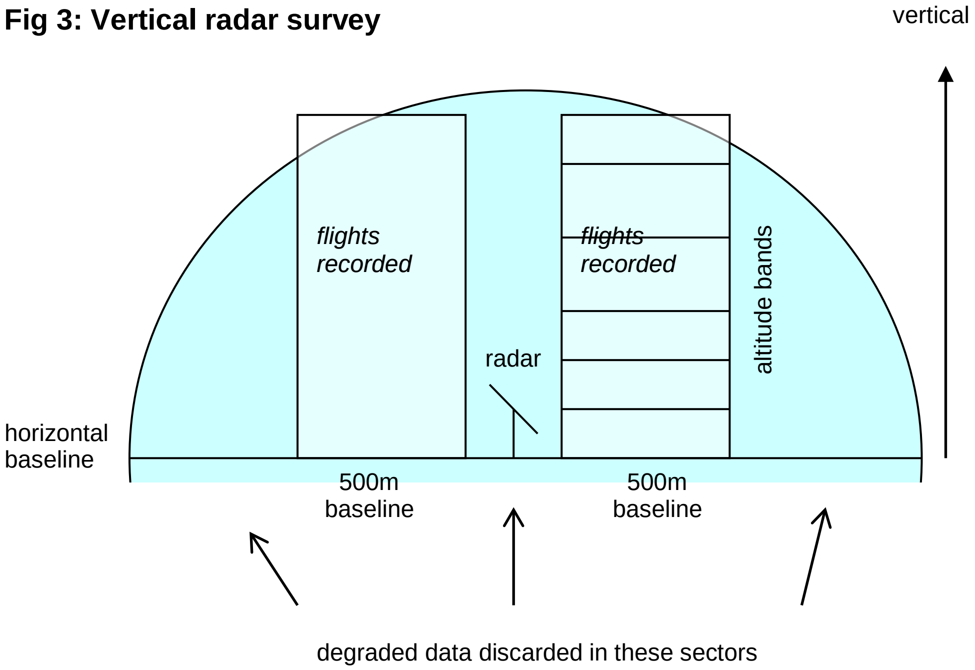
- <u>Boat-based surveys</u>, where the boat follows a transect through the site, and records are taken at intervals of birds in flight, provide a ‘snapshot’ of the number of birds in flight within the range of observation (see diagram) which is usually 300m. If a snapshot has N birds (at any flight height) within an observation square of side a from the boat then the bird density per unit area of sea is N / a^2 (see Fig 2). Some surveyors record flights on both sides of the boat, thus covering two such squares, such that the density is $N / (2 a^2)$. Other surveyors record flights over a quadrant area of sea of radius a, in which case the density is $N / (\pi a^2/4)$.

  Boat-based survey can also provide information on flight heights, such as to enable an estimate of the proportion of flights which fall within the rotor risk height (from the lowest point to the highest point of a rotor, a height equal to twice the rotor radius. Cowrie guidance on boat-based survey methods is provided in Camphuysen et al (2004)[iv].

- <u>Aerial survey methods</u>, whether photographic or not, provide a direct sampling measure of the density of birds in flight per unit area of sea, provided that birds in flight can be discriminated from those on the sea surface, and that species can be identified at an adequate level.

- Radar survey methods which observe bird transits across a radar platform provide a measure of bird flux, ie the number of birds crossing an imaginary vertical surface, defined by a horizontal line between two points and the vertical surface extending from the sea upwards through that line. In practice, vertical radar typically allows most effective scanning of birds crossing two vertical windows of base around 500m, which may be divided into altitude bands (see diagram). Observations both at close range and at large distances, where detection rates degrade, are discarded. Adding the birds crossing each of these windows gives the bird flux across an imaginary baseline of 1km length (eg see report for Bureau Waardenburg, Krijgsveld et al. (2008)[v]).

Fig 3: Vertical radar survey



- Vantage point survey methods which record all bird flights in a defined volume of the windfarm airspace from a key vantage point lead to a measure of bird occupancy in that volume. Such survey is not normally practicable at sea unless a semi-permanent observation platform is installed, or if the relevant sea area can be observed in its entirety from shore. Bird occupancy is readily converted to bird density (per m^2) by dividing by the area scanned from the vantage point (see paragraph 18).

Density of birds in flight and at risk

20. For the purpose of estimating collision risk, this guidance starts from measurements, derived from survey information, of bird density, and of the proportion of birds flying at risk height (ie between the lowest and highest points of the rotors) or, if more detailed observations are available, of the distribution of bird density with height. The calculations set out later use that information to calculate the flux of birds through each rotor (using the simplifying assumption that flight direction is perpendicular to the rotors).

21. The most useful way to present information on bird density is on an area basis, ie the total number of birds in flight at any height at a given point in time, per square kilometre (km^2). Stating the bird density per unit area provides a better basis for comparison of risk assessments, and for cumulative risk assessment, than would be the case if only bird flight density at rotor height were stated. It also provides a level of data which can be re-interpreted

in the future, for example if a new generation of larger turbines came available. Such overall bird density information does not embody assumptions or uncertainties relating to flight height distribution. Where survey information is based directly on measurements of flux (eg from use of radar survey methods) then these should be translated, using the formula in paragraph 18, to estimates of bird density.

22. **An Environmental Statement should clearly state the bird density used in collision calculations, expressed in terms of birds per km^2 across the site, counting birds flying at all heights. It should also state the proportion of birds estimated to be flying within the risk height band – ie between the lowest and highest points of the rotors. Where a bird flight height distribution is used in the calculation, the Environmental Statement should state the distribution used and its source.** Where survey information leads to a range of perspectives on bird density (eg including or excluding data for buffer areas), the Environmental Statement should make clear which survey data has been used, and why. Paragraphs 25-31 describe how information on flight heights should be presented.

23. The number of birds of any one species passing through a rotor is, among other factors, proportional to the density of flying birds in the vicinity of the rotor, and hence so too is the collision risk to which they are exposed. Therefore, where one of the aims of a collision risk assessment is to choose a windfarm location and design so as to minimise bird collision risks, the starting point should be to select those areas with the lowest density of the bird species vulnerable to collision. For large sites, or for consideration of collision risks at a strategic level, it may be possible to discriminate between different zones of the site or areas with different bird densities. Such information will be helpful in identifying preferred zones for development. However care should be taken to ensure that any differences are statistically significant. For most development sites, the statistical variation in the data derived from survey is likely to mask any within-site variations in bird density.

24. While the approach to collision risk in this guidance does not require definition of a windfarm boundary, and the area of the windfarm area does not feature in the calculations, it is important to be clear as to the boundary within which an estimate of bird density applies. Survey recommendations usually recommend survey wider than the windfarm itself so as to ensure that any bird density estimates for the wind farm site are adequately representative of the marine area as a whole.

Flight heights

25. There is only a risk of collision with turbine blades at flight heights between the lowest and highest points of the rotors, a total height 2R, twice the length of a blade. Therefore an important parameter to estimate is the proportion Q_{2R} of birds flying within that risk height band. The data on bird density should be accompanied by an estimate of the proportion of birds flying within the risk height band for the proposed windfarm.

26. If data is available on the distribution of bird flight density with height, that enables the calculation to be refined to allow for the fact that most flights within this risk height are at a height where the chance of passing through the rotor is low, and the actual risk of collision if they do is also lower than for an average rotor transit. Most seabirds spend a high proportion of their flight time quite close to the sea surface, and therefore any collision risk tends to be concentrated in the lower parts of the rotor[vi].

27. Accurate data on flight heights is difficult to capture. In boat-based surveys, it relies on observers being able to estimate flight heights, and the accuracy of such estimates decreases with height. While aerial survey in the past has not normally yielded flight height information, high definition digital photography systems are now available which provide increasingly accurate information on flight height.

28. For some species, survey information at a site may be insufficient to provide a reasonably precise figure for the proportion of birds flying at risk height. Where this is the case, it may be

better to use a generic view of flight height behaviour, obtained by combining flight height information gathered from surveys at different sites – for which a detailed report has been compiled by Cook et al (BTO) for SOSS[iii]. In combining results from different surveys, care is needed to place greatest weight on those with the most robust data, which may imply discarding data with poor levels of precision. The generic information should be reviewed, assessing whether it provides more precise information than the site-based data, and whether the site-based data, if limited, is nonetheless compatible with the generic information. If so, then the generic information should be used. Care must however be taken not to mask any feature of flight behaviour at the site in question which could reflect a genuine difference of behaviour due to environmental variables or the specific use of the site made by the birds. For some species typical flight heights are dependent on the season, and in such a case it will be best to use seasonally dependent typical flight heights in assessing collision risk for each month, rather than average flight heights across the year.

29. Often, at the time of undertaking field survey, the actual turbines to be used have not been selected, and turbine models may vary in their risk height. Estimates of the proportion of birds flying at risk height should reflect the range of turbine heights which potentially may be used. Survey methods should be designed to ensure that data are available to inform all potential turbine options. Guidance on the extent to which the details of a scheme may be kept flexible during the environmental assessment process is published by the Infrastructure Planning Commission (2011)[vii].

30. The central estimate of the proportion of birds flying at risk height should be based on a straightforward analysis of flight height survey data, without any ‘margin of uncertainty’ added to the risk height range. In addition, alternative +/- estimates should also be presented, reflecting the possibility of a higher or lower proportion of birds flying at risk height. Confidence intervals on flight height data should be used where these are available from the survey information. Otherwise, a realistic view should be taken of the potential for mis-estimation and error in flight height observations by field observers. Confidence intervals should be aimed at around 95% confidence that the true result lies within that range. In some circumstances, this may be no more than an expert view based on an understanding of the limitations of the survey techniques.

31. **For the purpose of estimating collision risk, the ES should state**

- **the proportion of birds estimated to be flying within the risk height band – ie between the lowest point of the rotors and the highest point of the rotors – based on survey information at the site;**
- **any flight height distribution derived from combining wider survey data for the species in question, and the proportion of birds thereby assumed to fly at a height exposed to collision risk;**
- **which of the above is used in the collision risk estimate, and why.**

Daylight hours and nocturnal activity

32. For obvious reasons, most bird survey is undertaken by day, and it is generally assumed that such sampled levels of flight activity persist throughout daylight hours. Daylight hours depend both on time of year and on latitude. Forsythe et al (1995)[viii] provide a ready reckoner for daylight hours which is reproduced in Sheet 7 (Daylight and night hours) of the attached spreadsheet. Input of the latitude of the site in Sheet 1 (Input data) triggers the calculations in Sheet 7 (Daylight and night hours) which in turn populates Sheet 2 (Overall collision risk) with the appropriate number of daylight and night hours in each month.

33. There is considerable uncertainty about levels of bird flight activity by night. Garthe and Hüppop (2004) [ix]offer an expert view on levels of nocturnal flight activity for a range of marine bird species, expressed in terms of a 1-5 ranking of the likely level of nocturnal activity in comparison with observed levels of daytime activity. A rating of 1 represents hardly any flight activity at night, and 5 much flight activity at night. King et al (2009) (Appendix 7)[x] provides a

more comprehensive table with rankings on a similar expert basis for a wider range of seabirds.

34. Figures used in the collision model should take both day and night flights into account. Where there is no night-time survey data available, or other records of nocturnal activity, for the species in question, (or for other sites if not at this site), it should be assumed that the Garthe and Hüppop/ King et al 1-5 rankings apply. These rankings should then be translated to levels of activity f_{night} which are respectively 0%, 25%, 50%, 75% and 100% of daytime activity. These percentages are a simple way of quantifying the rankings for use in collision modelling, and they may to some extent be precautionary. For some species, there are no such expert rankings available. Levels of activity may vary from season to season, and activity at sea may in any case differ from the levels of activity in breeding colonies for which the rankings have been formulated. Some species are particularly active during dawn and dusk or extended twilight periods, or in locations where there is ambient windfarm lighting. When expressing the output of the collision risk assessment, the uncertainty surrounding flight activity should reflect the degree of confidence (or lack of confidence) in the flight activity information.

35. **Flight activity estimates should allow both for daytime and night-time activity. Daytime activity should be based on field survey. Night-time flight activity should be based if possible on night-time survey; if not on expert assessment of likely levels of nocturnal activity.**

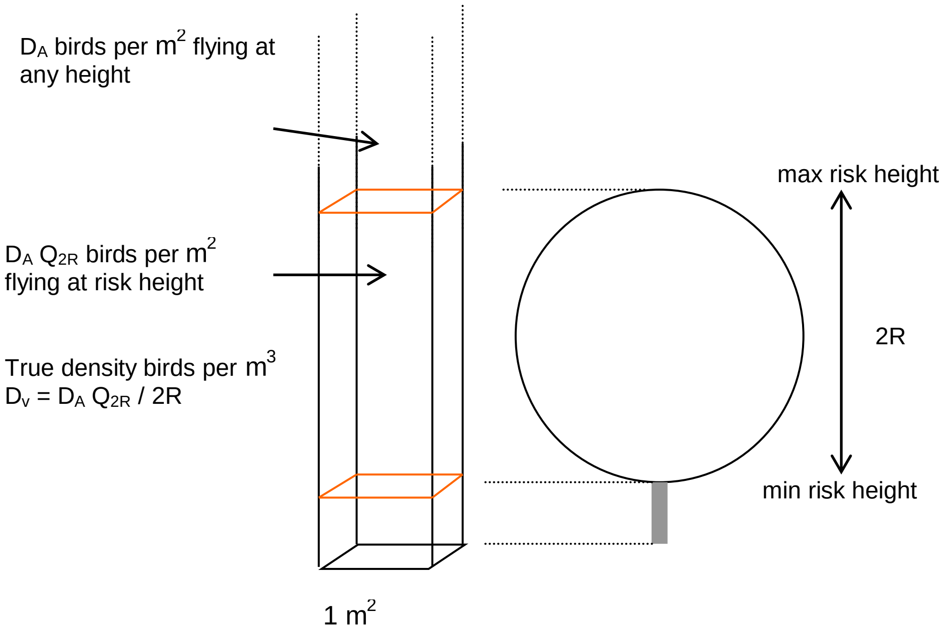
STAGE B - ESTIMATING NUMBER OF BIRD FLIGHTS THROUGH ROTORS

36. In the basic model, this stage is straightforward, but one which often causes some difficulty. It can be addressed in the following steps:

    (i) Start with the observed bird density on an area basis, expressed per unit area, D_A. Convert if needed to units of birds/ m^2. If the survey data is expressed in birds/km^2 then divide by 10^6.

    (ii) Multiply by the proportion Q_{2R} of birds flying at risk height to get only those birds at risk in a column of air of unit area base and 2R high (ie from bottom to top of the rotor) – see Figure 4.

Fig 4: Birds flying at risk height

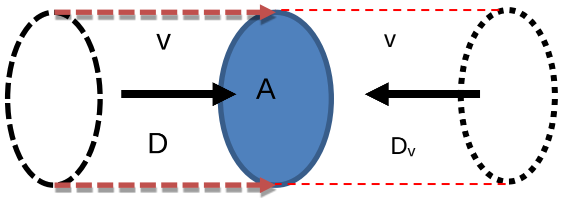


(iii) Calculate the true bird density per unit volume $D_V = (D_A Q_{2R})/2R$, expressed in birds per m^3 (birds per cubic metre).

(iv) Now calculate the flux of birds through a rotor within an airspace of true bird density D_V, noting that we are making the simplifying assumptions that all birds are flying perpendicular to the rotor, and that they are all flying with a single flight speed v. Also, the rotor may be assumed to face the wind at all times. It is also, for simplicity, assumed that there are equal numbers of birds flying upwind as are flying downwind, which is important as the collision risk when flying upwind is greater than for downwind flight[2].

Consider the area of the rotor $A = \pi R^2$. If the birds fly at speed v m/sec, then within one second, all birds within a distance v on one side and flying towards the rotor will pass through the area A. At any one time, half the birds will be travelling upwind and half downwind. Thus, referring to Figure 5, at any time there will be $\frac{1}{2} D_v A v$ birds flying downwind towards the rotor and, on the other side of the rotor, $\frac{1}{2} D_v A v$ birds flying upwind towards the rotor.

Fig 5: Bird flux due to bird density



Thus bird flux $F = \frac{1}{2} D_v (\pi R^2)\, v$ upwind plus $\frac{1}{2} D_v (\pi R^2)\, v$ downwind

$= \quad v\, D_v (\pi R^2)$ in total $= v\, (D_A/2R)\ (\pi R^2)\ Q_{2R}$ .. (1)

This is expressed in birds/second passing through the rotor.

(v) Now multiply by the appropriate number of seconds during which the birds are potentially active – usually the daylight hours in the month t_{day} plus an allowance if appropriate for nocturnal activity $f\, t_{night}$, multiplied by 3600 to convert to seconds.

(vi) Multiply by the number T of turbines. Each turbine in a windfarm, if it is surrounded by an airspace with the same bird density, and if all turbines are of the same size, will experience the same number of bird transits and will therefore contribute the same collision risk to the overall total. If the windfarm includes turbines of different sizes, or zones of differing bird densities, then the calculation should be broken down into subgroups of wind turbines where turbine size and bird density is constant within each subgroup.

37. The result is an estimate of the total number of bird transits through rotors of the wind farm in the specified period. In the spreadsheet provided, the entry for ‘bird transits’ calculates the total number of bird transits for each month, taking account of the proportions of flights deemed to be upwind and downwind. It calculates the result on the basis of the values entered for D_A, Q_{2R}, R, v, T , time for which birds are active, ie the calculation includes all of stages (i) to (vi) above.

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[2] If the collision model is applied specifically to migration flights, or to flights in adverse weather conditions, it may be that a majority of flights will be downwind, in which case the proportions of bird flux should be altered as appropriate from the ½ upwind and ½ downwind assumption made here.

Total number of bird transits =

$$\underbrace{\boxed{v\ (D_A / 2R)\ \ (T\ \pi R^2)\ \ (t_{day} +\ f_{night}\ \ t_{night})}}_{\text{flux factor}}\ \ \times\ \ \underbrace{\boxed{Q_{2R}}}_{\text{proportion at risk height}} \qquad ..\ (2)$$

38. **A key output within the collision risk assessment should be a clear statement of the potential number of bird transits per month, and per year, through the windfarm turbines, assuming birds take no avoiding action. The collision risk is directly proportional to the potential number of bird transits.**

Box 1: Converting from bird density to rotor transits (basic model)

Worked example:

v	Bird flight speed		10.5	m/sec
D_A	Bird density per unit area		0.1128	birds/km^2
	50% upwind, 50% downwind	=	0.1128×10^{-6}	birds/ m^2
R	Rotor radius		63	m (metres)
T	Number of turbines		150	
$T\pi R^2$	Frontal area of all rotors		1870345	m^2
t	Hours active in June		480	hours
	$(t_{day} + f_{night}\ t_{night})$	=	1.728×10^6	seconds
F	Flux factor $v\ (D_A / 2R)\ \ (T\ \pi R^2)\ \ t$		30380	
Q_{2R}	Proportion flying at risk height		28.1%	
	Total bird transits through turbines in June		8537	50% upwind, 50% downwind

STAGE C – PROBABILITY OF COLLISION FOR A SINGLE ROTOR TRANSIT

39. This stage begins with the model described in the earlier Band (2000) and Band et al (2007) papers which uses information on the size and speed of the turbines, and physical details on the size and speed of the bird, to compute the risk of collision for a bird flying through a rotating rotor. Annex 3 is an extract from Band (2000) outlining the core of the model and its derivation.

40. A bird is simplified in shape to a flying cross with length, wingspan, and speed, and always flying perpendicularly towards the rotor. A bird may be 'gliding' ie with the arms of the cross fixed, or 'flapping' ie with the arms of the cross flapping so as to occupy a space similar to that of a spinning top, with the length of the bird being the axis of spin. 'Gliding' flight has a marginally lower collision risk than 'flapping' flight – notably for passage at points level with the rotor hub, where the wings lie parallel with potentially colliding blades. However the difference is rarely sufficient to warrant detailed consideration of different bird behaviours; the flight type used should be that which best typifies most flights for the species in question.

41. Rotor blades are assumed to be laminar (ie with zero blade thickness) but they have length, a chord width which varies along the length of the blade tapering towards the tip, and a pitch angle (the angle between the blade and the rotor plane) which also varies along the length of the blade. Due to commercial sensitivities by blade manufacturers, some of this detailed information may not be readily available for each make/model of blade and hence generic information may have to be used.

42. With these simplifications, the model calculates the risk of actual collision between the bird and the rotor blades. Such a model has a number of important limitations:

    - <u>Stationary infrastructure</u> - it is assumed that birds can avoid stationary infrastructure, so no account is taken of the turbine towers, nor the blades when stationary; While this may be a valid assumption in clear daylight conditions it may not be wholly true at night or in conditions of poor visibility. Onshore, for example, there are records of gamebird species colliding with turbine towers. In this respect, the model may underestimate collision risk.

    - <u>Turbulence</u> - no account is taken of the effects on a bird's flight of turbulence in the wake of a blade. Observers have seen birds 'knocked out of the sky' by turbulence, and there is potential for this to increase mortality through disorientation or impact with the sea surface. The model only takes account of the potential for physical contact between the bird and the turbine blades. In this respect, the model may underestimate collision risk.

    - <u>Slipstream</u> - however, it is also the case that the model does not take account of any 'slipstream' effects whereby the air rushing over the surface of a blade may carry a bird clear of the blade when otherwise it was on a collision course. In this respect, the model may over-estimate collision risk.

    - <u>Bird shape</u> - real birds are larger than represented by a flying cross, though a cross should represent the main extremities. In this respect, the model may underestimate collision risk.

    - <u>Flight height distribution</u> - the basic collision model evaluates the probability of a bird colliding if it passes at random at any point through the rotor disk on a flight path perpendicular to the rotor plane. In practice, the points of passage of seabirds through the rotor are not distributed uniformly across the rotor. Survey data for seabirds has made clear that typical flight heights for many species are relatively low, such that much of the bird flux through a rotor, and the associated collision risk, will relate to the lower parts of the rotor plane. Since it averages risk over the entire rotor including higher-risk areas close to the hub, the basic model will overestimate the collision risk for seabirds whose flight passages are more concentrated towards the lower part of the rotor plane. Where data are available on the distribution of bird density with height, an extended calculation may be undertaken which takes account of this variation with height. This extended model is described following stage D, in paragraphs 61-75.

- Perpendicular approach assumption – as outlined in Annex 1, the model used assumes that the collision probability for oblique angles of approach is the same as for perpendicular approach. In fact, some increase in collision risk should be expected, which, taking account of both upwind and downwind flight, may be of order 10% for large birds. In this respect, the model may underestimate collision risk.

43. The model uses a probability p of collision for a bird flying through a rotor, at a point in the rotor plane defined by coordinates r, φ :

$$p(r, \varphi) = (b\Omega/2\pi v) \; [\quad | \pm c \sin\gamma + \alpha\, c \cos\gamma \,| \quad + \quad \max (L,\; W\alpha F) \quad] \qquad \ldots \qquad (3)$$

where

r = radius of point of passage of bird
φ = angle within rotor plane (relative to vertical) of point of passage of bird
ie $\varphi=0$ is top, $\varphi=\pi$ is bottom, etc

b = number of blades in rotor
Ω = angular velocity of rotor (radians/sec)
c = chord width of blade
γ = pitch angle of blade
R = outer rotor radius

L = length of bird
W = wingspan of bird
β = aspect ratio of bird ie L / W
v = velocity of bird through rotor
α = $v/r\Omega$
F = 1 for a bird with flapping wings (no dependence on φ); $F = \cos\varphi$ for a gliding bird

This probability is then averaged, by integrating over the entire rotor area, to yield the average collision risk for a bird making a single flight through the rotor at any point through the rotor.

44. By way of explanation, there are three terms in equation (3) within the square brackets.

- The first [$c \sin\gamma$] relates to the time taken for the bird to clear the depth of the blade, which increases with pitch γ.
- The second [$\alpha\, c \cos\gamma$] relates to the probability of the bird striking the front face of the blades. Note that the appearance of α cancels any dependence of this term on rotor angular velocity Ω and bird speed v.
- The final term [the greater of L, or $W\alpha F$] relates to the time taken for the full length and wingspan of the bird to clear the sweep of the rotors, for which the geometry depends on the relative speed of bird and blade. Where the bird's aspect ratio $\beta > \alpha$, the bird length is the limiting parameter. However if $\beta > \alpha$ the wingspan is the limiting parameter. For a flapping bird, p(r) not dependent on φ and F is set to 1. For a gliding bird, the effective wingspan depends on φ, reducing to zero at $\varphi = \pi/2$ or $3\pi/2$ where the wings lie parallel to the rotor blade; thus $F = \cos\varphi$.

45. Because of the geometry of the blades in relation to the flight direction, the collision risk for upwind flight is higher than for downwind, even if the bird's flight speed v relative to the ground is taken to be the same. This is expressed in the alternate sign in the first term, which is + for upwind flight, - for downwind. In practice, birds will fly more slowly in upwind flight

than downwind, further widening the difference in risk between upwind and downwind flight (see paragraph 51). If both upwind and downwind flights are equally likely, it is appropriate to take an average of upwind and downwind collision probabilities.

46. The basic model assumes that bird flights may occur with equal probability at any point through the rotor disc. Having ascertained the collision risk p(r,φ) at different points r,φ of the rotor, the basic model then calculates an average of p(r,φ) over the entire area of the rotor disc, firstly summing over φ, then summing (integrating) over successive concentric rings, taking account of the area of each ring which increases with radius (= ring circumference $2\pi r$ times thickness of ring dr). Finally this sum is divided by the overall disk area to get the average collision probability:

$$p_{average} = \int_0^R p(r)\,(2\pi r)\,dr \,/ \int_0^R (2\pi r)\,dr \quad = \int_0^R p(r)\,(2\pi r)\,dr \,/\, \pi R^2 \;=\; 2\int_0^1 p(r)\,(r/R)\,d(r/R) \qquad \ldots(4)$$

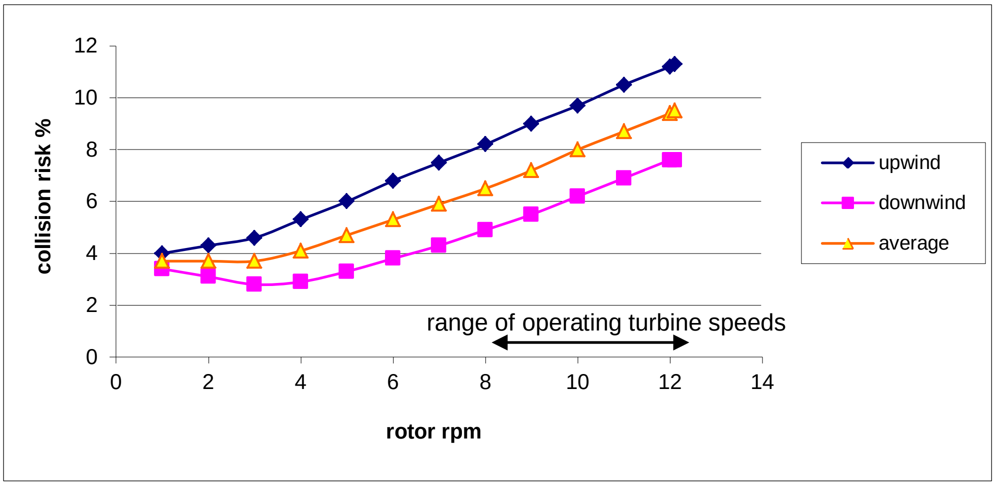
47. Sheet 3 (Single transit collision risk) of the spreadsheet accompanying this guidance provides a collision risk calculator for a single passage through the rotor, evaluating p(r) for a series of twenty radii from r/R=0.05 to r/R=1, and undertaking the above integration numerically to evaluate $p_{average}$, the average collision risk for a passage at any point across the rotor. This is essentially the same as the spreadsheet referred to in Band (2000)[i] but with refinements to the numerical integration[xi].

Wind turbine speed

48. Wind turbines currently available are designed to operate at a range of speeds. Typically they do not operate below a cut-in speed (usually between 3 and 4 m/sec), then increase in speed with wind speed up to an operating wind speed (which may be around 12 m/sec). Thereafter, they maintain a constant operating speed by altering the pitch of the blades until, in extreme conditions, the turbine is shut down for safety.

49. **Collision risk should be evaluated using the turbine rotational speed for an operating turbine. Where turbines operate with a range of rotational speeds, the calculation should be done using a mean operational turbine speed. The mean used should be a mean over time, using an analysis of wind data to enable the likely frequency distribution of turbine speeds to be determined.** Allowance is made elsewhere in the calculation (at Stage D) for the proportion of time that a turbine is non-operational, either because of low wind speeds or for maintenance. The mean turbine speed should thus be a mean over operational time only, not including times when the turbine is idling or stationary. Within the typical range of operating turbine speeds, collision risk varies almost linearly with turbine speed, so that use of a mean turbine speed is adequate in order to yield a mean collision risk – see Fig 6 for a turbine with a maximum operating speed of 12.1rpm. If a frequency distribution of turbine speeds is not available, then collision risk may be evaluated using the maximum operating turbine speed, but acknowledging that this will result in a collision risk which is an upper bound rather than a mean.

Fig 6: No-avoidance collision risk as a function of turbine speed for a 5MW turbine and bird (gannet)



Accuracy of model

50. Having regard for the various simplifications in the model, and the potential sources of under- and over-estimation described above, it is judged that this stage of the model, calculation of no-avoidance collision risk for a single transit, should be regarded as indicative of collision probability within around ±20%. If the flight height distribution is strongly skewed towards the low edge of the rotor, the basic model is likely to overestimate collision risk by more than this margin, while there should be no such overestimation if the extended model is used. These uncertainties are in addition to any uncertainty due to variance in flight activity and other input data (Stage A), or due to uncertainties in avoidance rates (Stage E).

Possible refinements

51. The spreadsheets are set up so that the average collision risk from the ‘Single transit collision risk’ calculation is copied over to the ‘Overall Collision Risk’ sheet and used, as described in the next section, to calculate projected collision mortality. However two refinements may be made at this stage.

    - The ‘Single transit collision risk’ sheet assumes that the bird speed for both upwind and downwind flight is the same, derived from standard references. In fact, it is likely that ground speed downwind will be greater, and ground speed upwind, less than this value. If good data are available, either from field survey or from the literature, to support the use of different up/downwind ground speeds, then this spreadsheet may be run once for each, taking the average of the respective ‘upwind’ and ‘downwind’ outputs to copy over to the ‘Overall Collision Risk’ sheet.
    - In taking an average for upwind and downwind flights, the ‘Single transit collision risk’ sheet uses the relative proportion of upwind and downwind flights to weight the respective collision probabilities. By default the proportion should be set to 50% upwind (and thus 50% downwind). However there are some circumstances, eg migration flights, in which downwind flights may dominate, though flight directions are often far from regular. If field data support the use of differing proportions of upwind and downwind flight, then the proportions may be changed by altering the ‘Proportion of flights upwind’ field in the Input Data sheet.

STAGE D – MULTIPLYING TO YIELD EXPECTED COLLISIONS PER YEAR

Basic model – assuming uniform flight density

52. If the basic model is used, multiplying by the number of bird flights through the rotor is nearly trivial. Stage A has estimated the level of flight activity at potential risk; Stage B has estimated the likely number of flights through rotors across the windfarm; Stage C has calculated the risk of collision for a single bird transit through a rotor. In the present stage, Stage D, these are multiplied together to yield an estimate of total potential collision risk, including a factor to allow for the proportion of time that the wind turbines are operational (before considering avoidance behaviour, which is stage E).

$$\text{Expected collisions} = \underbrace{\boxed{\text{Flux factor} \times Q_{2R}}}_{\text{No of transits}} \times \underbrace{\boxed{\text{Average probability of collision}}}_{\text{Single transit collision risk}} \times \underbrace{\boxed{Q_{op}}}_{\text{Proportion of time operating}} \quad \ldots(5)$$

Units

53. Whichever model is used, there is a need for care with units. In the spreadsheet, flight activity becomes expressed as rotor transits per month and hence the collision risk is in predicted collisions per month.

Non-operational time

54. Turbines do not operate all of the time. Typically a turbine may be at rest or idling for a considerable proportion of time, eg 20%, because the wind is too weak to generate power, or (exceptionally) because the turbines have been closed down to avoid damage in high wind. There is also a requirement for some downtime for maintenance. This non-operational time is accounted for in equation (5) by the factor Q_{op} representing the proportion of time the turbine is operational. If data is available, this factor may be stated on a monthly basis to reflect the different proportions of non-operational time at different times of year – for example reflecting differing wind conditions across the year and increased access for maintenance during the summer.

Large turbine arrays

55. The model assumes that risks are additive, ie that a windfarm with 200 turbines will have 200 times the risk of a single turbine. Where a bird passes successively through two or more turbines, it is exposed to the same risk for each rotor transit. While it is possible that a bird encountering its first turbine may deviate so as to pursue a safer course through (or above or around) the windfarm, this is avoidance behaviour and therefore properly taken into account at Stage E rather than here. Stages A - D simply work out the consequences of birds taking no avoiding action[3]. Thus, if two turbines 'overlap' in the sense that the bird passes through both turbines in a single passage, no allowance is made for that overlap, the collision risk is the sum of the risk from each rotor passage.

56. More strictly, for large windfarms where the overall probability of a bird colliding is relatively high, it may be appropriate to take account of the fact that a declining proportion of the birds will survive passage through early rows of turbines and will thus be exposed to collision risk in later rows. This adjustment is only likely to be of any significance for large arrays of turbines.

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[3] This position was somewhat confused by a reference in Band et al (2007) to making a 50% allowance for overlapping turbines. It is now preferred that any amendment to collision risk resulting from avoidance behaviour should be built into the avoidance rate applied at the end of the calculation.

57. Annex 4 sets out how such a correction may be made for a windfarm with approximately n rows of turbines. Very often the layout of a windfarm is not known at the time of collision risk assessment, so an exact value for n is not known; and in any case the collision risk has to account for birds entering the windfarm from all directions. Sometimes the layout of the windfarm is irregular, lacking in clearly defined rows; but the principle remains that a declining number of birds will be exposed to collision risk if a proportion have already been killed by collision with earlier rotors as they pass through the windfarm. A reasonable and simple approximation is to use $n = \sqrt{T}$ ie the square root of the total number of turbines.

58. If the probability of collision for a single bird passage through the windfarm is C, based on the purely additive approach elsewhere in this guidance, then it may be adjusted to allow for depletion of bird density in later rows of the windfarm by multiplying by a 'Large array correction factor'

$$C_{LA} / C = 1 - ((n-1)/ 2n)\, C + ((n-1)(n-2) / (6 n^2)\, C^2 \ldots \qquad \ldots(6)$$

plus further negligible terms of powers of C

59. If realistic avoidance rates have been taken into account in the collision model, such 'large array corrections' are typically small and can be ignored; typically it is only worth making corrections for values of $C > 0.1$.

60. See Annex 4 for a derivation of this 'large array factor', and a worked example. Sheet 8 – 'Large array correction' in the spreadsheet provides a calculator for this factor. The spreadsheet applies this correction factor to the output of Sheet 2 – 'Overall collision risk' by multiplying each projected collision rate, for each of the various avoidance rates, by the correction factor. In most circumstances it will be evident that the difference is minimal.

EXTENDED APPROACH TAKING ACCOUNT OF FLIGHT HEIGHTS

Effects of taking flight height into account

61. Seabirds tend to fly at relatively low altitude over the sea surface. If the flight height distribution is skewed towards low heights in this way, there are three ways in which taking account of flight height is important to the calculation of collision risk:

    (i) The proportion Q_{2R} of birds flying at risk height will decrease with the height of the rotor above the sea surface. This is accounted for in the basic model if the parameter Q_{2R} is adjusted, but the way in which Q_{2R} changes with height can only be known if a flight height distribution for the species in question is available.

    (ii) If most of the birds flying at risk height (ie above the minimum level of the rotor) do so at a level not far above the bottom edge of the rotor, the probability of passing through the rotor disc is relatively small, simply because the rotor circle occupies less width at that level than, for example, at the midpoint of its diameter. Therefore the expected number of rotor transits is reduced. For some species the reduction may be 50% or more, reducing the collision risk in proportion.

    (iii) Finally, if the birds flying through the rotor do so close to the extremity of the blades, the single-transit probability of collision there is rather less than for passages closer to the hub. This is a smaller effect, but may typically account for a reduction of around 10%.

    For these reasons, if the data is adequate to support an extended analysis taking account of flight heights, it is well worth doing so.

When to use generic flight height distribution data

62. Normally, the bird survey data available for a particular site is insufficient to provide a full flight height distribution. However it may provide some insight into typical flight heights at the site, and it should provide information on the proportion of birds flying at risk height ie above minimum rotor height. The Crown Estate SOSS group has commissioned a compilation of flight height data from windfarm sites across the UK (Cook et al 2012[iii]). That paper contains generic flight height distributions for a number of seabird species.

63. Caution is needed in deploying this generic data. It is entirely possible that the ecological circumstances of a particular site differ from those in the sites used to generate the generic data, and hence bird behaviours and flight heights may not be well represented by the generic data. Before using generic data, consideration should be given to whether

- is the site survey data compatible with the generic data? Does it indicate that the generic data reasonably represents the observations at this site?
- are there particular ecological circumstances which might be expected to lead to non-standard behaviour, eg proximity to breeding sites?

64. A collision risk assessment for a specific site should not be based solely on the use of generic data. Where generic data is used, it is recommended that the collision risk for three different options is stated:

    - Option(i) - using the basic model, ie assuming that a uniform distribution of flight heights between lowest and highest levels of the rotors; and using the proportion of birds at risk height as derived from site survey.
    - Option (ii) - again using the basic model, but using the proportion of birds at risk height as derived from the generic flight height information.
    - Option (iii) - using the extended model, using the generic flight height information.

    The spreadsheet supporting this guidance provides for the calculation of all three options. If site survey information is sufficient to generate a flight height distribution, this should be used as an Option (iv) as well.

    Supporting text should then discuss and justify which of the options is most likely to characterise the collision risks at this site.

The hard stuff (ie maths)

65. This section extends the basic model, and the calculations in Stages B-D, to enable the distribution of flight heights to be taken into account. The basic model calculates the number of transits through rotors, then multiplies these by the average collision probability for a single transit (see equation (5) in paragraph 52):

    No of collisions = number of transits x probability of collision

    The extended approach is underlain by this same equation. However, in this extended model, both bird flux and the probability of collision may vary over the area of the disc, such that their product must be summed over the whole area of the rotor disc.

66. The bird flux through an element of rotor area δA is

    $$v\ D_v\ \delta A$$

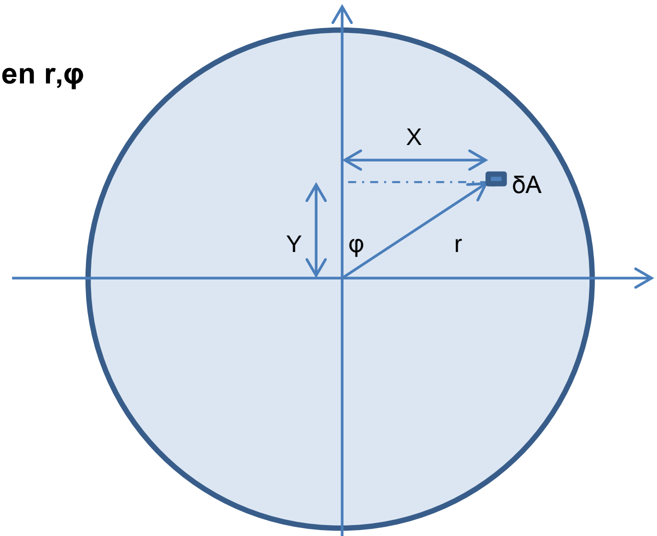
    as in equation (1) in paragraph 36, but applying it to a small area δA rather than the full rotor area A. As before there is a need to consider the proportions of flights upwind and downwind; we shall assume (for example) 50% upwind, 50% downwind.

    In this extended model, D_v may vary with height Y – this is the flight height distribution $D_v(Y)$ in birds/m^3 at height Y metres.

67. The collision risk for a single transit through this element δA is p(X,Y), which is the same as p(r,φ) except that X-Y coordinates, with origin at the rotor hub, are used to reference the point of transit instead of r-φ coordinates; the relationship between these two coordinate sets are

$$X = r \sin \varphi, \quad Y = r \cos \varphi \quad \text{or conversely} \quad r = \sqrt{(X^2+Y^2)}\,, \quad \varphi = \tan^{-1}(X/Y)$$

Fig 7: Relationship between r,φ and X,Y coordinates



The collision rate through this small element δA (take it as a small rectangle of width dX and height dY) is thus

$$v \; D_v(Y)\; p(X,Y)\; dX\, dY$$

The total collision rate for flights through the whole rotor disc is then obtained by integrating this over the whole area of the disc:

$$\text{Collision rate} \; = v \int_{\text{Min rotor height}}^{\text{Max rotor height}} D_v(Y) \int_{-\sqrt{(R^2-Y^2)}}^{+\sqrt{(R^2-Y^2)}} p(X,Y)\; dX\, dY \qquad \ldots (7)$$

The limits $\pm\sqrt{(R^2-Y^{2)}}$ to the integration over X define the outer limits of the rotor circle, and the limits to the integration over Y are the minimum and maximum rotor heights respectively.

68. With this approach, it is not easy to think in terms of there being a defined bird flux, and an average probability of collision, which are then multiplied. The bird flight density varies with height Y, the breadth of the circle (and therefore the number of birds flying through the circle) varies with height Y, and the collision risk too depends on height Y, as it varies with both r and φ. Hence all these factors are expressed and multiplied within the integral, and the integration yields the collision rate.

69. As with the basic model, to translate this into collisions per month in the windfarm, this must be multiplied by the number of seconds the birds are active, and the number of turbines, and by the factor making allowance for non-operational time.

70. For computational purposes, it is best to translate the factors into dimensionless units, within which the rotor has a radius of 1, by using the parameters x = X/R, y=Y/R; and using a dimensionless flight height distribution $d(y) = R\, D_v(Y)/D_A$. Using these factors, and adding in the other factors (number of turbines, etc), equation (6) becomes

$$\text{Collisions} = v\, D_A\, R \int_{-1}^{1} \int_{-\sqrt{(1-y^2)}}^{+\sqrt{(1-y^2)}} d(y)\;\; p(x,y)\, dx\, dy \;\; \times \;\; \text{No of turbines } T \;\times\; \text{Time active } t \;\times\; \text{Proportion of time operational} \qquad \ldots (8)$$

$$= \boxed{v\,(D_A/2R)\, T\pi R^2\, t} \;\times\; \boxed{(2/\pi) \int_{-1}^{1} \int_{-\sqrt{(1-y^2)}}^{+\sqrt{(1-y^2)}} d(y)\;\; p(x,y)\, dx\, dy} \;\times\; \boxed{Q_{op}} \qquad \ldots (9)$$

Flux factor Collision integral Proportion of time operational

It is written in this way for comparability with equation 5 above; the ‘flux factor’ and Q_{op} are the same as used in the basic model. The ‘Collision integral’ is a dimensionless quantity. If we apply this to the earlier scenario in which a proportion Q_{2R} of birds fly at risk height, and are distributed uniformly at all heights within that zone, we then have $d(y) = Q_{2R}/2$, a constant. The Collision integral is then Q_{2R} times the average of p(x,y) over the rotor disc; in that case equation (9) reproduces equation (5).

71. The total bird flux passing through the rotors is similar to equation 9 but with p(x,y) set to 1, ie

$$\text{Flux} = \boxed{v\,(D_A/2R)\, T\pi R^2\, t} \;\times\; \boxed{(2/\pi) \int_{-1}^{1} \int_{-\sqrt{(1-y^2)}}^{+\sqrt{(1-y^2)}} d(y)\;\; dx\, dy} \;\times\; \boxed{Q_{op}} \qquad (10)$$

Flux factor Flux integral Proportion of time operational

72. The average collision probability is just the ratio Collisions /Flux. However it should be noted that this ‘average probability’ is conditioned both by the shape of the circle (more flux at greater height) and by the skewed distribution of flights (ie more flux at lower height), so it is not a very meaningful parameter.

73. Note that the factor Q_{2R} does not appear explicitly in the above equations, as the proportion of birds flying at various levels is included within the distributional data d(y). However, for comparison with the basic model, a value Q'_{2R} is readily calculated from the distribution data, as

$$\int_{-1}^{+1} d(y).\; dy \;=\; Q'_{2R}$$

The symbol Q'_{2R} is used to differentiate this calculated figure from the figure for Q_{2R} input earlier based on bird survey data.

Annex 5 provides a more detailed derivation of these equations.

The easy stuff (how to do the calculation)

74. Calculating a collision estimate using equation (9). and the number of transits through rotors using equation (10), can be done simply using Sheet 4 ‘Extended model’ which computes both the Collision integral and the Flux integral, if an appropriate flight height distribution is input. The flux factor remains as calculated in Stage B for the basic model, and Q_{op}, the proportion of time turbines are operational, as in Stage E.

(i) Start, as in Stage B of the basic model, with the observed bird density on an area basis, expressed per unit area, D_A. Convert if needed to units of birds/ km^2; the spreadsheet divides this by 10^6 so as to work in birds/m^2. As with the basic model, multiply by the total cross-sectional area of the rotors $T\pi R^2$, and the number of seconds t during which birds are active, to get the Flux factor. There is no need however to deploy Q_{2R}.

(ii) Data on the flight height distribution must be available as a table showing the relative frequency of bird flights at different heights. This data should be normalised, that is the sum of all the relative frequencies across all heights should be 1. Relative frequency is $D_v(Y) / D_A$, and the sum of $D_v(Y)$ across all heights is just D_A, the total bird density per km^2 ,so the sum of all relative frequencies is 1. Frequency is in units of 'per metre of height'.

(iii) Sheet 5 of the spreadsheet 'Flightheights' contains generic data from Cook et al[iii] for a number of species. These give flight height relative frequencies at 1m intervals; only the data up to 150m height is shown in the spreadsheet. Columns A and B are the 'master data' ie these columns contain the data which are used in the calculations of Sheet 3. To use a new data table (eg for other species, copy the appropriate flight height column for this species and paste the column into column B (note, don't cut and paste, just copy, so as to leave intact a copy of the data outwith the master columns. The entire column should be copied and pasted, as it includes the name of the species and the number of points in the table, as well as the table of frequencies itself.

(iv) Normally, the hubheight of wind turbines is measured from Highest Astronomical Tide (HAT), to help ensure navigational clearance requirements are satisfied. However, bird flight heights are measured relative to sea level, which may be 2-3 metres or more lower. Mean sea level (Z_0) and HAT are normally stated relative to Chart Datum (CD). The calculation allows for a tidal offset to be added to the hubheight, to allow for this additional height above mean sea level. The tidal offset should be entered in the Input Data sheet. This offset can make a substantive difference to the calculated collision risk, reducing the estimate of risk by 25-30% for some species.

(v) Sheet 4 'Extended model' then does the necessary work in calculating the Collision and Flux integrals. The sheet undertakes a numeric integration of p(x,y), first across x for each horizontal chord of the rotor, and secondly across all heights y, factoring in the flight distribution d(y).

(vi) Following equation (9), multiply the Collision integral by the Flux factor and by the proportion of time Q_{op} for which the turbines are operational, to get the expected collisions assuming no avoidance. Sheet 2 'Overall collision risk' draws on the Collision integral calculated in Sheet 4, and does this multiplication. It also draws on the Flux integral in Sheet 4, to provide a view on the total number of rotor transits in each month. These calculations are presented as 'Option 3'

(vii) In this extended model, the distribution of bird flights with height already includes the information on the proportion flying at risk height. It is valuable nonetheless to evaluate Q'_{2R} from the flight height data and check that it is consistent with survey findings and other sources of data. Sheet 4 shows the value of Q'_{2R} derived in this way directly from the flight height distribution, using the formula

$$Q'_{2R} = \int_{-1}^{+1} d(y)\, dy$$

75. Adding a tidal offset as at stage (iv) takes account of the height of the rotors above mean sea level, but not of the variation of the tides. If the distribution of bird flight heights relative to the sea surface is independent of the level of the tide, then at times of high tide there will be an increased bird density at rotor level, and reduced at times of low tide. As the flight height distribution is non-linear with height, these two effects do not balance out. The 'tidal asymmetry correction' factor is generally small and may be ignored, but a method of calculating it is nonetheless provided, in Annex 7, for use at sites with a particularly large tidal range (eg > 5metres).

STAGE E – AVOIDANCE AND ATTRACTION

Avoidance

76. The preceding stages of the model assume that birds take no avoiding action whatsoever in response to wind turbines. In reality, birds mostly do take effective avoiding action so as to avoid collision with wind turbines. Birds may avoid the area of the windfarm altogether, or they may use more indirect flight routes to bypass the windfarm – referred to as 'macro' or 'far-field' avoidance or 'displacement'. Alternatively, birds may continue to fly within or close to the windfarm, but exhibiting 'micro' or 'near-field' or 'behavioural' avoidance in which birds choose routes which pass between rotors; or fly higher or lower to avoid the rotors; or take emergency action in-flight to escape an approaching blade.

77. Monitoring of windfarms onshore is generating some useful information on levels of avoidance of some land-based bird species. Some of that data derives from collision monitoring, based on regular site scans for bird corpses, and some of it from observations of habitat use in the vicinity of windfarms. For many bird species, avoidance rates of 98% or higher have been observed, implying that the collision risk is less than 2% of that calculated from stages A-D alone. **Avoidance is included in the collision risk model simply by multiplying the before-avoidance collision estimate by (1 - A) where A is the appropriate overall avoidance rate (see Scottish Natural Heritage 2010[xii] for a review).**

78. In general the information for onshore species is not sufficient to discriminate in a quantitative way between macro avoidance (ie displacement or far-field avoidance) and micro (near-field) avoidance, though some Dutch studies are yielding useful data. Offshore, a number of studies have examined macro and micro avoidance behaviour for some seabirds (see Cook et al (2012)[iii]). As monitoring data builds up from constructed offshore windfarms, it may be possible to make more definitive predictions than at present on rates of both macro and micro avoidance. The overall avoidance rate $A_{overall}$ is simply related to macro and micro avoidance rates:

$$(1 - A_{overall}) = (1 - A_{macro}) \times (1 - A_{micro})$$

To obtain an overall avoidance rate in this way, information is needed on both macro and micro avoidance rates, each of which will be less on its own than the overall avoidance rate. In particular, if information on likely displacement is used to conclude that a proportion of birds will not use the windfarm site, that is in effect an application of the $(1 - A_{macro})$ factor. The avoidance rate then applied to those birds not displaced would then have to be a micro-avoidance rate A_{micro}, derived from monitoring observations solely of birds actually flying through windfarms. A micro-avoidance rate will be considerably lower than a rate for overall avoidance which includes displacement effects.

79. Where detailed information on macro and micro avoidance is not available then overall avoidance rates are best estimated by using monitoring data from existing windfarms, comparing actual mortality to that predicted if pre-construction levels of flight activity were maintained:

$$A_{overall} = 1 - \left\{ \frac{\text{Actual collision rate}}{\text{Predicted collision rate if pre-construction levels of flight activity were maintained}} \right\}$$

Care should be taken to ensure that the data on which such avoidance rates are based are on a consistent basis, having regard for example to the potential for changes in turbine model and flight risk heights as between those modelled in a collision risk assessment at the time of preparing an environmental statement, and those actually built.

80. In particular, if the extended model taking account of flight height distribution is used, **it is important that the calculations on which avoidance rates are based also start with a no-avoidance collision rate derived using the extended model.** Where the bird flight

density is skewed towards low altitude, a greater proportion of birds above the minimum risk height will miss the rotor, simply because, at a level close to rotor minimum height, the rotor circle intercepts relatively few flights. This is taken into account through the limits to the x integration in equations (9) and (10). This propensity to miss the rotor must not be confused with avoidance, which requires a behavioural response by a bird. Put another way, if an avoidance rate is calculated by comparing collision rate observations with a calculated avoidance rate using the basic (uniform flight density) model, then that avoidance rate will already include for the fact that low-flying birds will more often miss the rotor. Using such an avoidance rate in conjunction with the extended model would double-count that factor.

81. **All current flight activity should be included within a windfarm collision risk estimate, and the avoidance rates used for collision risk estimates should be characteristic of overall avoidance, ie they should include both macro avoidance (displacement or far-field avoidance) and micro (near-field or behavioural) avoidance.** In particular the likelihood of displacement should be included as an aspect of overall avoidance. Elsewhere in the bird impact assessment the potential direct impact of displacement on the bird population, in terms of reduction in available habitat, should also be assessed.

82. The lack of firm evidence surrounding avoidance rates will almost certainly dominate the uncertainty inherent in the collision risk estimate. For a few land-based bird species there is now substantial international experience on levels of avoidance from long-standing monitoring studies, such that some confidence can be placed in the assumption of high levels of avoidance. However for marine species there is limited firm data as yet on which to base predictions. It should be noted that avoidance behaviour may vary seasonally, and between groups of birds of the same species.

83. **The collision risk estimate should conclude with a table showing potential collision mortality using a range of assumed avoidance rates.** The text relating to this table should point to any evidence from existing post-construction monitoring on the respective or similar bird species which might indicate what levels of avoidance are best supported by evidence. As a default in the absence of specific avoidance information for the species in question, it is recommended that collision risks be evaluated assuming avoidance rates of 95%, 98%, 99% and 99.5%.

Attraction

84. Offshore windfarms may create new habitat which encourages aggregation of fish, and as a result birds may be attracted into the windfarm for foraging. Lighting on wind turbines may also have an effect in attracting birds at night. Where such attraction occurs, it follows that collision risk may be enhanced as a result of increased flight activity through the windfarm. Attraction is in effect a form of ‘negative displacement’ and could in principle be included in the collision risk assessment by including an appropriate negative component in macro avoidance. However, in most circumstances there is not enough definitive evidence to make quantitative predictions on attracting birds with any certainty.

85. **Where, as part of an overall bird impact assessment, attention is drawn to the potential for a wind farm to attract birds, the potential for additional collision risk should also be considered.**

STAGE F - EXPRESSING UNCERTAINTY

86. In a collision risk estimate following the above method, there are a large number of sources of variability or uncertainty in the output. The main sources of uncertainty are:

    - survey data is sampled, often both in time and space, and usually exhibits a high degree of variability. Mean estimates can only be representative of flight activity
    - survey data is unavailable for certain conditions, including night time and storm conditions
    - natural variability in bird populations, over time and space, for ecological reasons
    - flight height information may be subject to observer bias
    - the collision risk model uses a simplified geometry for turbine blades and bird shape
    - it does not include any risk of collision with turbine towers
    - details of blade dimension and pitch may be unavailable at the time of making the estimate
    - turbines deployed may differ from those used in the collision risk analysis
    - bird parameters (length, wingspan, flight speed) have a distribution, they are not fixed
    - bird speed is not a constant but is dependent on wind speed
    - insufficient knowledge about bird displacement and attraction effects
    - there is limited firm information on bird avoidance behaviour at sea

87. Perhaps the most important issue is to keep these uncertainties in proportion. For some of these uncertainties (eg bird density from survey data) the range of variability may be fairly clear from the variability between different survey days. Observer bias in flight height estimates may be tested, for example, by duplicating observers on occasion and comparing results. There are uncertainties in using the collision model itself, for example in using a single bird speed, or if the calculation is made for only one turbine speed rather than deriving an average over all turbine speeds. However these uncertainties are probably less significant than the errors introduced by variability in the survey data input.

88. Then there is uncertainty over avoidance behaviour. At present there is only a handful of bird species for which collision mortality at onshore windfarms has been sufficiently monitored to enable an avoidance rate to be used with confidence. For marine bird species, there is as yet limited information upon which to base a judgement on an appropriate avoidance rate to use. The uncertainty here ranges over an order of magnitude. If an avoidance rate of 98% is used, for example, that may be judged subject to uncertainty covering a range from 95% to 99.5%, representing non-avoidance behaviour between 5% and 0.5%. For the foreseeable future, it seems likely that the uncertainties surrounding bird avoidance behaviour are likely to dwarf the errors and uncertainties arising from an inexact collision model or variability in survey data.

89. A similar position relates to the extent to which birds may respond to habitat changes caused by the windfarm. Here also there is insufficient experience yet to be able to predict with confidence likely levels of displacement or attraction in response to new habitats, or indeed whether these patterns of behaviour will persist or change over time.

90. For these reasons it is proposed that uncertainty due to avoidance behaviour, and uncertainty over response to habitat changes, should be handled differently from uncertainties elsewhere in the calculation.

91. **The output should convey the uncertainty in the collision risk estimate, by indicating, in addition to a 'best estimate', a range of confidence around that estimate. Though it is unlikely (with the exception of the survey data) that these can be subject to detailed statistical analysis, the aim should be to express the range of uncertainty at around the 95% confidence level.**

92. The range of uncertainty should reflect
    - uncertainty or variability in flight activity data (including imprecision on flight height estimates and lack of knowledge about night-time behaviour)
    - uncertainty due to the limitations of the collision model, including the variability of bird dimensions and flight speed, the simplification in shape of a bird and turbine blades. As an expert guesstimate, the uncertainties arising from the collision model, if all required turbine parameters are fully available, may be of order ± 20**%.**
    - uncertainty arising from turbine options yet to be decided, in number, size and speed, where that is consistent with the 'Rochdale envelope' flexibility described in guidance by the Infrastructure Planning Commission (2011)[vi]. These options should include a 'worst case' in terms of the option likely to present greatest bird collision risk.

The range of uncertainty due to each of these three sources should be separately identified and, as the three uncertainties are of independent origin, they may be combined to give an overall uncertainty of $\sqrt{(u_1^2 + u_2^2 + u_3^2)}$ where u_1, u_2 and u_3 are respectively the percentage uncertainties from each of these sources.

Box 2: Example of presentation of uncertainty

(Note that the asterisked figures are chosen for example only and should be derived or judged from detailed consideration of the accuracies and uncertainties inherent in the input data.)

Best estimate of annual collision risk (birds per annum) assuming 98% avoidance rate	147 *	
Range of uncertainty		
due to variance and uncertainty in flight activity	± 50% *	
due to simplifications in collision model	± 20%	
due to design options yet to be finalised	± 15% *	
overall $\pm \sqrt{(0.5^2 + 0.2^2 + 0.15^2)} = 0.56$	± 56%	range 65 - 230

93. Where the extended model is applied using the generic height data from Cook et al[iii], that paper provides confidence intervals around the median data points. The range of uncertainty relating to flight height can be estimated by replacing the median set of data (as shown in Sheet 5: Flightheight) by, respectively, the upper and lower 95% confidence levels, and noting the corresponding uncertainty in the collision risk.

94. **Finally, the output should state the effect on the collision risk of a range of assumptions on avoidance. This should be covered by a statement conveying the status of current information on avoidance behaviour of the bird species in question, noting any variability in this behaviour, and drawing conclusions about the likely collision risk.**

Box 3: Example of presentation of uncertainty on avoidance

Species: XXXXXXX

Best estimate of annual collision risk (birds per annum)

assuming	95% avoidance	367	}	
	98% avoidance	147	}	all subject to ± 56%
	99% avoidance	73	}	
	99.5% avoidance	37	}	
	99.75% avoidance	18	}	

Information on avoidance for this species suggests 99% is most appropriate (refer to text in ES) but the lack of data means that the confidence interval may extend from 95% to 99.9%.

95. The collision risk estimate should also outline qualitatively the possible likelihood and scale of any further collision risks which might result from the wind farm attracting birds (see paragraphs 84/85).

FOOTNOTE

96. One risk of prescriptive guidance is that it could stifle innovation in improved methods. Developers and their advisors are encouraged where appropriate to go beyond the core requirements set out in this guidance; but where they do so, the standard approach of this guidance should also be pursued so as to make clear how the results of any improved methods differ from that of the standard approach.

NOTES ON USING THE SPREADSHEET

The Excel spreadsheet which accompanies this guidance is intended to take the user easily through the first five stages of the process.

Sheet 1: Input data is provided so that all input data is input on this sheet. There are no calculations or calculated fields on this sheet. The user should not input data on any of the three following sheets 2-4, other than (if desired) to replace the blade profile in Sheet 3 with a more specific one for the actual turbine blades used. Sheet 1 is organised with blocks of input data on the bird species; on flight activity from bird survey; on migrant birds (to be used if relevant); on the windfarm; on the turbines to be used in the windfarm; and finally on the avoidance behaviour used in presenting the results.

The source data used for each input should be identified for easy reference on the spreadsheet, and the sources should be listed in full within the Environmental Statement.

Sheet 2: Overall collision risk is the master sheet bringing together all the calculations of Stages A through E, and concluding with overall collision estimates, given a range of assumptions on rates of avoidance:

- Stage A states the information on the density of flying birds, the proportion flying at risk height, and the time over which such bird activity persists.
- The sheet then presents the basic model (Option 1), giving
  - Output from Stage B - the estimated number of potential bird transits through rotors of the windfarm.
  - Output from Stage C - the probability of collision during a single bird rotor transit.
  - Output from Stage D - the potential collision mortality for the bird species in question, assuming current use of the site and no avoiding action is taken
- The sheet then re-applies the basic model, only using the value of Q'_{2R}, the proportion of bird flying at risk height derived from the flight height distribution (Option 2). For this purpose flight height distribution data must be loaded in the first two columns of the Flightheight sheet.
- Finally the sheet applies the extended model allowing flight height distribution to be taken into account (Option 3).
- Output from Stage E is the potential collision mortality for the bird species in question, taking avoidance and other likely behaviour change into account. The user must choose to which of the above set of results (Options 1, 2 or 3) the avoidance factors should be applied.

Sheet 2 draws in turn from Sheets 3-8. Sheet 2 will not display the results from the Extended model until Sheet 4 (Extended model) has been activated by clicking on that sheet, when it will automatically calculate. Once it has done so, Sheet 2 will display the appropriate results.

Sheet 3: Single transit collision risk. This sheet covers stage C of the process, calculating the probability of collision for a bird making a single passage through a rotor at each radius r, in increments from r/R=0.05 out to r/R=1. The collision probability is then averaged over the entire area of the rotor disc, by summing the probability over successive concentric rings each of width 0.05R, multiplying by the area of the successive concentric rings, and dividing by the total area πR^2 of the rotor disk (see paragraphs 46/47). The method used is essentially a trapezoidal numerical integration. The calculation is undertaken separately for upwind and downwind flight, and an average taken.

Sheet 4: Extended model. It should be noted that this sheet requires macros to be enabled, as much of the functionality of this sheet is based on function routines programmed in Visual Basic. If at any stage calculations are not triggered automatically, press Shift-F9 to force recalculation.

This sheet repeats, in the panel at top right, the calculations of the basic model[4]. In the lower panel, this sheet carries out the calculations of the extended model, based on the flight height distribution data in the following sheet 'Flightheight'. The key calculated outputs are Q_{2R}, the flux integral, and the collision integral (for upwind and downwind flight and average of both). The sheet allows input of xinc and yinc, the increments used in the numerical integration. By default these are set to 0.05, ie one twentieth of a rotor radius. For increased precision these may be set to a smaller value like 0.01, but the worksheet calculation time may become significant.

This sheet also shows a table and a set of graphs derived from the table. The table shows the height y from rotor minimum to rotor maximum; the corresponding bird density d(y) (interpolated from the Sheet 5 data); the contribution of that horizontal strip of rotor at height y to risk (up and downwind), and the product of bird density and contribution to risk (up and downwind). The chart then presents these as line graphs. These calculations are all based on a value of 0.05 for xinc and yinc, the increments used in integration. The graphs are included to provide a live illustration of the effect of a skewed flight distribution. They show how the reduction of collision risk towards the rotor minimum height at y=-1, and the reduction in bird density due to the rapidly falling bird density with height, combine to squeeze the zone in which most collisions occur to an area just above y=-1.

Note that the table and graph are calculated entirely separately from the calculation of the Collision and Flux integrals, which make use of the user-input values of xinc and yinc.

Sheet 5: Flight Height. This sheet contains, in the first two columns, the flight height distribution used by Sheet 4 to calculate collision risk. Data is also shown for a number of other species, simply for ease of copying the data and pasting in to the first two columns. The standard form for this flight height distribution data is in 1m height intervals, with values of $D_v(Y)/D_A$ such that the column totals to 1.0. A frequency distribution with a wider height interval may be used, but then D(Y) must be divided by the interval, such that the values properly represent relative bird density per metre of height, and the column will total to (1.0/interval).

Sheet 6: Migrant collision risk. This sheet undertakes a similar calculation of collision risk to Sheet 2, but makes use of information in a different form on the density of birds passing through the windfarm, such as may be available for migrating bird species - see Annex 6 for a full description.

Sheet 7: Daylight and night hours. Given the input latitude, this sheet computes the daylight and night hours in each month within which there could potentially be bird activity.

Sheet 8: Large array correction. This is an add-on, which enables a correction to be made for large arrays where the collision rate is such that bird density might significantly decline as birds pass through the windfarm. These correction factors are then applied to the collision rate estimates in Sheet 2 'Overall collision risk'. In most circumstances the results will demonstrate that a large array correction is not significant and can be ignored.

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[4] There are small differences in the output values for gliding flight, as this sheet avoids a simplification in the earlier model

Notes on input data

Care is needed throughout to use the correct units as specified below and in the spreadsheet. In the main standard SI units are used. However some of the inputs (eg bird density) use units which developed in use as a matter of common practice – as indeed are the outputs in terms of collisions per month.

All the following input data should be entered using Sheet 1 – 'Input data', unless information is available to use a blade chord profile specific to the turbine being used in the relevant columns of Sheet 3 – 'Single transit collision risk'.

Bird data			
Symbol	**Description**	**Units**	**Notes**
	Species name		to help identify this spreadsheet
L	Length of bird	m (metres)	these should be drawn from standard reference works, eg Cramp & Simmons (1983)[xiii] or from BTO Bird Facts[xiv].
W	Wingspan of bird	m (metres)	
v	Flight speed	m/sec	
F	Flight type		'flapping' or 'gliding' - the spreadsheet then applies the relevant factor F = 0 for flapping flight, or +1 for gliding flight
	Nocturnal activity factor	1-5 ranking from Garthe and Hüppop/ King et al	the spreadsheet converts this factor to 0%/ 25%/ 50%/ 75%/100% daytime activity

For flight speed, usually a typical mean flight speed as given in such standard references will be adequate. However, where there is a need to explore the collision risk arising from different types of bird behaviour involving very different flight speeds (eg pursuit, or foraging), then the collision risk calculation should separate out the risk for those birds engaged in each behaviour, and sum the collision risk, as this varies with flight speed in a non-linear way.

Flight activity data			
Symbol	**Description**	**Units**	**Notes**
D_A	Bird density (day)	birds/km^2	Average number of birds in flight in daytime at any height, per square kilometre, as derived from field observation
Q_{2R}	Proportion at rotor height	%	% derived from bird survey, in the light of the projected rotor diameter and rotor hub height. The extended model also computes a figure for this, termed Q'_{2R} to distinguish it
	Proportion of flights upwind	%	This should be set to 50% unless survey indicates a predominant direction relative to wind, eg for large-scale migration flights

Flight activity data – additional for migrants see Annex 6 for details

Windfarm data			
Symbol	**Description**	**Units**	**Notes**
	Latitude of windfarm	degrees latitude (including decimal places)	include degrees and minutes in degrees with decimal places; this data is used to work out daylight hours in each month
T	Number of turbines		
Q_{op}	Proportion of time turbines are operational	%	This includes down-time for maintenance as well as time inactive because of low-wind or storm conditions
	Width of windfarm		optional; this is used only in the large array correction

Turbine data			
Symbol	**Description**	**Units**	**Notes**
R	Rotor radius	m (metres)	measured from the axis of rotation to blade tip. (This differs from the blade length, which is the length of the blade itself from where it is attached to the hub to the blade tip.)
H	Hub height	m (metres)	This is the height in metres of the rotor hub, ie the axis around which it rotates, above the sea surface taken as the Highest Astronomical Tide. In conjunction with the rotor radius and tidal offset, this determines the flight altitudes at risk. In the basic model this parameter is not used in the calculation but it is desirable to state it, as the proportion of birds flying at risk height is strongly dependent upon it. It is however a key parameter in the extended model.
	Tidal offset	m (metres)	This is the difference in metres between HAT (from which hub height is measured) and mean sea level Z_0. The difference is typically 2-3m but may be up to 5m or more in estuarine locations
Ω	Rotation speed	rpm (revolutions per minute)	The spreadsheet converts to radians/sec as required in the underlying formulae
c	Blade chord width (along length)	m (metres)	see below
γ	Average blade pitch	degrees relative to rotor plane	see below

Rotation speed when generating of most contemporary turbines is variable within a pre-determined range. A time-averaged mean of operational rotor speeds should be used, taking account of the expected frequency of different wind speeds and the resulting projected operational speeds (see paragraphs 48-49).

Note that the Band 2000 version of this spreadsheet requires input of the Rotation Period, ie the time required for one full rotation of the rotor, which is the inverse of Rotation Speed: *Rotation period = 1/ (Rotation speed in rpm)*

The underlying formulae make use of rotation speed Ω expressed in radians per second. One complete revolution is 2π radians, and there are 60 seconds in a minute, so $\Omega = (\text{rpm}/60) \times 2\pi$, a conversion undertaken by the spreadsheet.

Chord width. The model considers a blade to be a twisted lamina, ie of zero thickness. It has a chord width, which varies along the length of the blade as it tapers towards the tip. The chord profile in the spreadsheet is typical of a modern 5MW turbine used for offshore generation.

Pitch. The blade also has a pitch angle – the angle between the blade surface and the axis of the rotor. Pitch angle varies along the length of the blade, from a high angle close to the hub, to a low pitch angle towards the blade tips, ie the blade is twisted. Pitch angle also varies as the pitch is controlled to alter the rotation speed of the turbine. In the model, an average angle is used, representing an average pitch along the blade length. 25-30 degrees is reasonable for a typical large turbine.

Note that it is the total cross-sectional area of all the rotors ($T\,\pi R^2$) which is used to calculate the number of bird transits through a rotor. If the size and number of turbines is not known, a figure may be entered directly in Sheet 2 (Overall collision risk) for the ‘total rotor frontal area’: which may be amenable to a better estimate than either the turbine number or size.

Avoidance data

These are the range of avoidance rates to be used when presenting the collision risk conclusions (see paragraphs 76-83). Use avoidance rates if possible which have been established from previous monitoring studies for this species, and an appropriate range to cover the uncertainties involved.

Spreadsheet protection

To protect against unintentional overwriting of formulae, or the entry of input data other than in the ‘Input data’ sheet, each of the worksheets is ‘protected’, and the spreadsheet is fully usable in this state. Should there be a need to change or add to the spreadsheet, the protection can be turned off for any worksheet by going to ‘Tools’ – ‘Protection’ and setting to ‘off’ - there is no password protection in place.

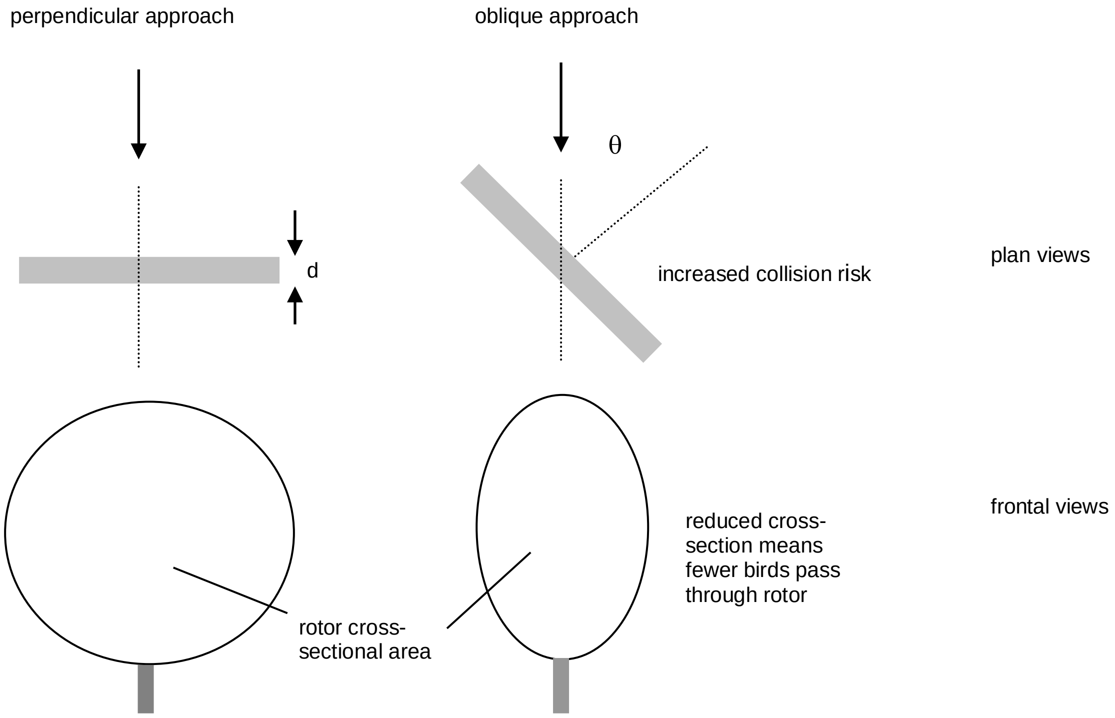
Notes on spreadsheet programming

The functionality of Sheet 4 (Extended model) is entirely based on computations programmed as user-defined functions in Visual Basic. Macros must be enabled. The programme code may be viewed using the ‘Developer’ tab and ‘Visual Basic’ icon. The user-defined functions are listed for reference in Annex 8.

Annex 1 Oblique approach

The collision risk of a bird passing through a turbine is dependent on the angle of approach. If it approaches obliquely, the cross-sectional area presented by the rotor disk will be reduced, as the rotor presents an elliptical rather than circular cross-section to the bird.

Fig A1-1: Effect of oblique approach



If the rotor has radius R and cross-sectional area πR^2 , then to a bird incoming at an oblique angle θ with respect to perpendicular approach, it presents a cross section $\pi R^2 \cos\theta$, thus reducing with $\cos\theta$.

However, if a bird approaching obliquely does pass through a rotor, its collision risk is greater than for a bird approaching perpendicularly, in part because of the increased time the bird takes to clear the full depth of the rotors from back to front, and in part because of the changes in speed of blade approach relative to a bird flying across (as well as towards) a rotor.

In relation to the first of these, a bird making a perpendicular approach has to clear a distance d + L in order not to collide with the blades, d being the depth of the rotor from front to back, and L being the length of the bird. A bird making an oblique approach has to clear a distance $(d+L) / \cos\theta$. The collision risk thus increases, in a first approximation, with $1/\cos\theta$. This 'oblique factor' thus cancels the reduction with $\cos\theta$ due to the reducing cross-section presented by the rotor.

On this basis this guidance considers all bird flights as if they were perpendicular to the rotor plane, and uses the collision risk relevant to flights perpendicular to the rotor. With this simplification stages B and C can be followed sequentially.

However, this does not take account of the second of the above factors, the changes of blade approach relative to a bird flying across a rotor. This leads to a dependence on θ of the collision risk for a bird making an oblique transit which is more complex than $1/\cos\theta$. In particular, an oblique approach leads to the wingspan rather than the length of the bird becoming the dominant element in determining the time it takes for the bird to pass through the rotor plane. Holmstrom et al (2011)[xv] have explored the dependence of collision risk on angle of approach, using a bird modelled as a flat rectangle, building on the original analysis by Tucker (1996a and 1996b)[xvi]. They demonstrate that for large raptors flying downwind through a rotor, collision risk increases with an increasingly oblique angle of approach, reaching a maximum at around 30 degrees from perpendicular approach, then tailing off as the effect of the reduced cross-sectional area presented by the rotor begins to dominate. At the maxima, the collision risk is calculated to be between 10% and 31% higher than for perpendicular approach, dependent on bird parameters and wind speed. Averaged across all angles of approach, the increases for downwind flight may be of order 10-15%, though likely to be less for upwind flight. It is also probable that at values of θ close to $\pi/2$ (ie for flight nearly parallel with the rotor) collision risk rises steeply for birds passing through the rotor, though the likelihood of such an encounter is low because of the edge-on cross-section presented.

The spreadsheet approach accompanying this guidance does not deal with the complexity of oblique angled approaches. If a model for oblique approach were to be used, a stricter approach would require calculation of the number of flights *from each direction* passing through the swept area of the windfarm turbines, applying the probability of collision applying *for that direction*, and *summing these probabilities* for birds flying in all directions.

This guidance makes the simplifying assumption that all flights can be treated as perpendicular to the rotor plane (ie parallel to the rotor axis). This is equivalent to assuming a $1/\cos\theta$ dependence of collision risk for a bird flying through a rotor at angle θ, thus exactly cancelling the $\cos\theta$ dependence of the number of birds flying through the rotor. In the light of the Holmstrom et al (2011) results, it should be recognised that this simplification may underestimate collision probabilities by a factor which, taking account of both upwind and downwind flights, may be of order 10% for large birds.

Annex 2 Relationship between bird flux and bird density

There is a direct relationship between bird density and flux, which is involves a dependence on the speed of the birds (if they were stationary, there would be no flux).

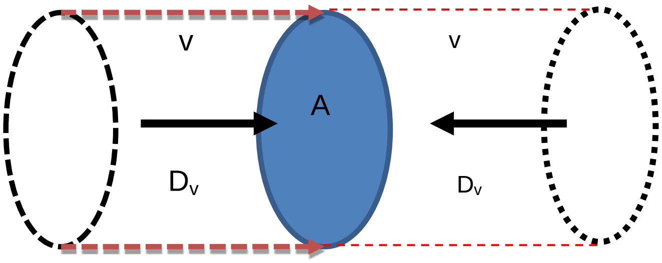
Simplified approach – treating all flights as perpendicular to rotor

First, take a simplified approach in which birds fly either downwind or upwind through a circular rotor area A, but not at oblique angles. Within one second, all birds within the cylinder of base area A and length v will pass through the area A. So the flux F is

$$F = ½ D_v \ A \ v \quad \text{downwind} \quad \text{and} = ½ D_v \ A \ v \quad \text{upwind}$$

where F is the bird flux per unit area, D_v is the bird density (true density) per m^3 and v is the speed of the birds.

Fig A2-1: Bird flux due to bird density (copy of Fig 5)

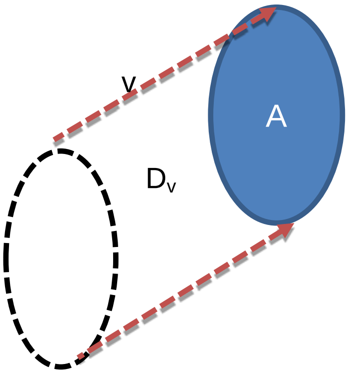


General approach - random horizontal directions

More generally, if one assumes that the birds fly in a horizontal plane, but may fly in random horizontal directions, the flux is

$$F = (1/\pi) D_v \ A \ v \quad \text{downwind} \quad \text{and} = (1/\pi) D_v \ A \ v \quad \text{upwind}$$

Fig A2-2: Bird flux due to bird density – oblique approach



This takes account of the fact that at an approach angle θ, the area A now looks like an ellipse, not a circle, and thus the volume of the squashed cylinder of length v containing the birds which will reach area A within one second is now $A \ v \cos\theta$ rather than simply A v for the perpendicular approach. The proportion of birds flying at an approach angle between θ and $\theta + d\theta$ is ($d\theta/2\pi$). Total flux from this upwind side is then

$$F = \int_{-\pi/2}^{\pi/2} (D_v / 2\pi) \ A \ v \cos\theta \ d\theta = (1/\pi) D_v \ A \ v \qquad \text{… (A2-1)}$$

where F is the bird flux across the area A, D_v is the bird density (true density) per m^3 and v is the speed of the birds.

It should be noted that a flux measurement is directional – for a given density of birds moving in random horizontal directions, a unit area will intercept more birds flying perpendicular to the area than birds flying at an oblique angle, to which the unit area will appear narrower. The $(1/\pi)$ factor accounts for this angle-dependence.

Total bird flux, counting both upwind and downwind flights, is then

$$F_{tot} = (2/\pi)\, D_v\, A\, v \qquad \text{(A2-2)}$$

To convert from a bird flux measurement to a measurement of bird density, use the converse expression

$$D_v = (\pi/2)\, F_{tot} \;/\; (A\, v) \qquad \text{(A2-3)}$$

Using areal bird density

The above refers to bird flux crossing an area such as a rotor disk, and relates it to the bird density D_v surrounding the rotor.

Flux is often referred to as the number of birds F_L flying across a horizontal line, per metre length of that line, at any altitude (as observed, for example, in vertical radar surveys). Taking an aerial view, that is the sum of birds crossing in each 1m band of height, for which the flux is given by equation A2-3:

$$F_L = \sum_{h=0}^{h\ =\ \text{max height}} (2/\pi)\, D_v\, v$$

$$= (2/\pi)\ v\ \Sigma\ D_v$$

But summing the bird density within each successive metre height gives the areal bird density $D_{A.}$. So we have

$$F_L = (2/\pi)\, D_A\, v \quad \text{birds/sec (per metre length of horizontal line)} \qquad \text{(A2-4)}$$

This equation is the equivalent, using areal density, of equation (A2-2) which uses true density.

The converse is the equivalent of equation (A2-3):

$$D_A = (\pi/2)\, F_L / v \quad \text{birds / m}^2 \qquad \text{(A2-5)}$$

Annex 3 - Probability of bird being hit when flying through the rotor

The following text is extracted from the Band (2000) guidance published on the Scottish Natural Heritage website. Text in italics has been updated to reflect changes in the accompanying spreadsheet.

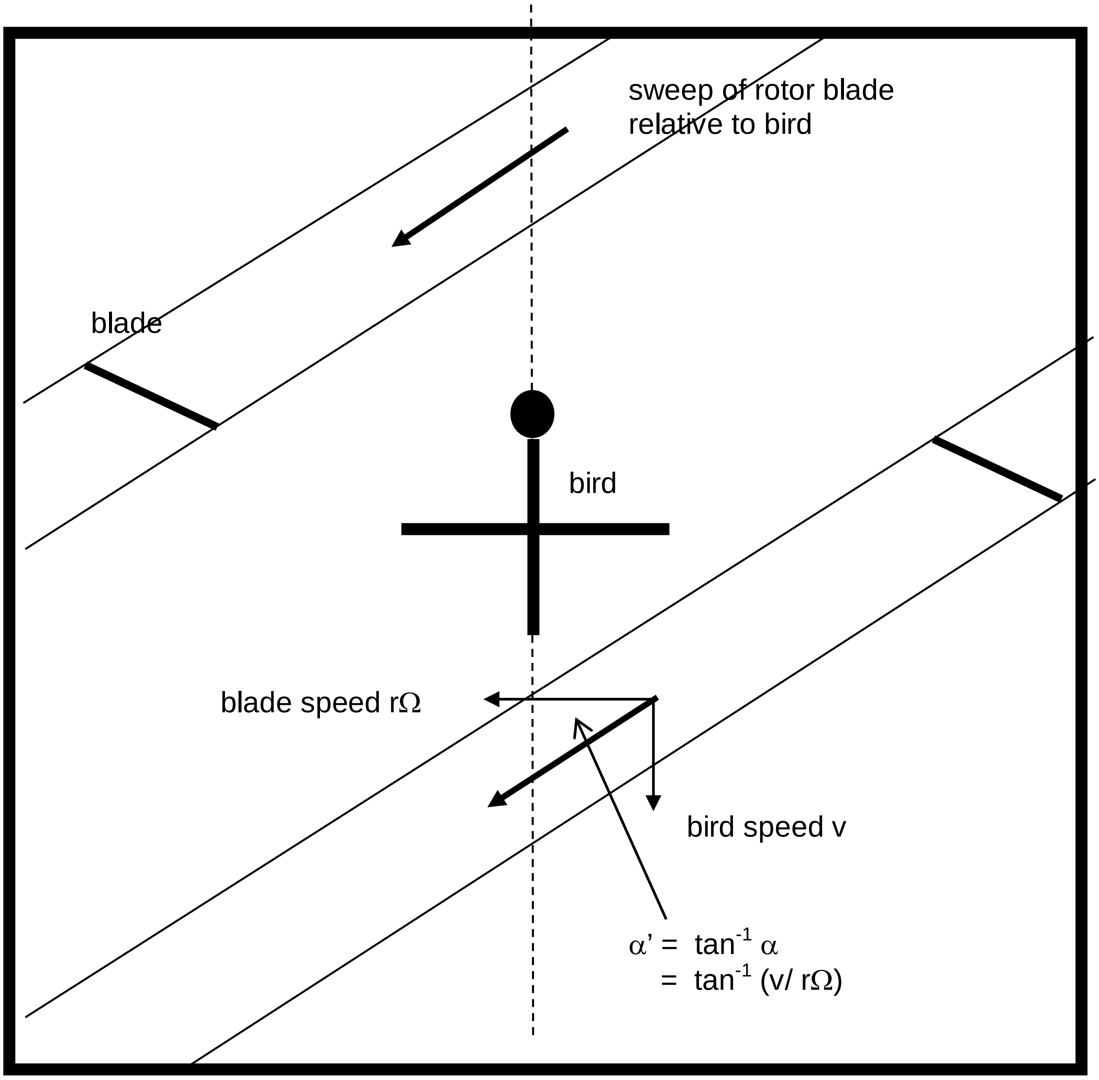
This stage computes the probability of a bird being hit when making a transit through a rotor. The probability depends on the size of the bird (both length and wingspan), the breadth and pitch of the turbine blades, the rotation speed of the turbine, and of course the flight speed of the bird. *The calculation assumes that a bird has an equal probability of passing at any point through the rotor.*

To facilitate calculation, many simplifications have to be made. The bird is assumed to be of simple cruciform shape, with the wings at the halfway point between nose and tail. The turbine blade is assumed to have a width and a pitch angle (relative to the plane of the turbine), but to have no thickness.

It is best to visualise this as in Fig A3-1, looking vertically down on the flying bird in a frame which is moving with the bird. In this moving frame, each rotor blade is both moving from right to left (say) and also progressing towards the bird. Each blade cuts a swathe through the air which depends both on the breadth of the blade and its pitch angle. Successive blades cut parallel swathes, but progressively closer to the bird. The angle of approach of the blade α, in this frame, depends on both bird speed and blade speed. At the rotor extremity, where blade speed is usually high compared to bird speed, the approach angle α' is low, ie the blades approach the bird from the side. Close to the rotor hub, where the blade speed is low and the bird is therefore flying towards a slow-moving object, the approach angle α' is high.

The probability of bird collision, for given bird and blade dimensions and speeds, is the probability, were the bird placed anywhere at random on the line of flight, of it overlapping with a blade swathe (since the bird, in this frame, is stationary). It may therefore be calculated from simple geometric considerations. Where the angle of approach is shallow, it is the length of the bird, compared to the separation distance of successive swathes, which is the controlling factor. Where the angle of approach is high, it is the wingspan of the bird compared to the physical distance between blades, which is the controlling factor.

Fig A3-1: Collision risk from flying through the rotor



The calculation derives a probability p(r, φ) of collision for a bird at a radius r from the hub, and at a position along a radial line which is an angle φ from the vertical. It is then necessary to integrate this probability over the entire rotor disc, assuming that the bird transit may be anywhere at random within the area of the rotor disc:

Total probability

$$= (1/\pi R^2) \int\int p(r, \varphi)\, r\, dr\, d\varphi$$

$$= 2 \int p(r)\, (r/R)\, d(r/R) \qquad \ldots\ldots \quad \textbf{(A3-1)}$$

where p(r) now allows for the integration over φ.

Probability p of collision for a bird at a radius r from hub

$$p(r) = (\, b\Omega/2\pi v\,)\ [\ K\ |\pm c \sin\gamma + \alpha\, c \cos\gamma\,|\ + \begin{array}{ll} L & \text{for } \alpha < \beta \\ W\alpha F & \text{for } \alpha > \beta \end{array}\ ]$$

$$\ldots\ldots \quad \textbf{(A3-2)}$$

where b = number of blades in rotor

Ω = angular velocity of rotor (radians/sec)

c = chord width of blade
γ = pitch angle of blade
R = outer rotor radius

L = length of bird
W = wingspan of bird
β = aspect ratio of bird ie L / W
v = velocity of bird through rotor

r = radius of point of passage of bird
α = $v/r\Omega$

F = 1 for a bird with flapping wings, or = $(2/\pi)$ for a gliding bird

K = 0 for one-dimensional model (rotor with no zero chord width)
= 1 for three-dimensional model (rotor with real chord width)

The chord width of the blade c and the blade pitch γ, ie the angle of the blade relative to the rotor plane, vary from rotor hub to rotor tip. The chord width is typically greatest close to the hub and the blade tapers towards the tip. The pitch is shallowest close to the tip where the blade speed is highest. The apparent width of the blade, looked at from the front, is $c \cos\gamma$, and the depth of blade from back to front is $c \sin\gamma$.

The factor F is included to cover the two extreme cases:

(i) F=1: where the bird has flapping wings. In this case ($p(r, \varphi)$ has no dependence on φ); or

(ii) $F = 2/\pi$: where the bird is gliding, $p(r, \varphi)$ is dependent on φ, with a maximum above and below the hub, and a minimum at the sides when the wings are parallel with a passing rotor blade.

The sign of the $c \sin\gamma$ term depends on whether the flight is upwind (+) or downwind (-).

The factor K is included to give a simple option of checking the effect of real blade width in the result: K=0 models a one-dimensional blade with no chord width.

As α, c and γ all vary between hub and rotor tip, a numerical integration is easiest when evaluating equation (A3-1).

For ease of use these calculations are laid out on a spreadsheet. (*This is reproduced in an updated form in Sheet 3 'Single transit collision risk' in the spreadsheet accompanying this guidance. However the input data must now be entered through Sheet 1 'Input data'.*)

The spreadsheet calculates p(r) at intervals of 0.05 R from the rotor centre (ie evaluating equation (A3-2)), and then undertakes a numerical integration from r=0 to r=R (ie evaluating equation (A3-1). The spreadsheet is set out as follows:

1 The input parameters are in the first two columns. Bird aspect ratio β is calculated.

2 Collision probabilities are then calculated for radii at intervals of 0.05 R from the hub to the tip. Each radius is represented by a row in the table, with the value of the radius r/R in the first column..

3. The second column of the table is the chord width at radius r as a proportion of the maximum chord width. The taper will differ for different turbine blades. *The taper profile in the updated spreadsheet circulated with this guidance is based on the blade of a typical 5 MW turbine used for offshore generation.*

4. Factor α is calculated.

5. The 'collide length' is the entire factor within square brackets within equation (2) above, using the upwind case.
6. p(collision) is p at radius r, as calculated by equation (A3-2). It is however limited to a maximum value of 1.
7. 'contribution from radius r' is the integrand of equation (A3-1) (including the factor 2) prior to integration.
8. The total risk is then the sum of these contributions.
9. The calculation is then repeated for the downwind case.
10. The spreadsheet then shows a simple average of upwind and downwind values. (Note that in a real case it may be important to add in the effect of wind to the bird's ground speed, and flight patterns may not be such that upwind and downwind flights are equally frequent.)

The result is an average collision risk for a bird passing through a rotor.

Note that there are many approximations involved , for example in assuming that a bird can be modelled by a simple cruciform shape, that a turbine blade has width and pitch but no thickness, and that a bird's flight will be unaffected by a near miss, despite the slipstream around a turbine blade. *Thus the calculated collision risks should be held as an indication of the risk - say to around ± 20%, rather than an exact figure*[5]*.* It is also simplistic to assume that bird flight velocity is likely to be the same relative to the ground both upwind and downwind. Ideally, separate calculations should be done for the upwind and downwind case, using typical observed flight speeds.

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[5] In the 2000 version, the uncertainty was judged to be ±10%. In the light of the possible effect of skewed flight distributions and the effects of oblique angle approach, as well as the various simplifications in the model, this advice is updated to ±20% in the present guidance.

Annex 4 - Large turbine arrays

The overall approach in this guidance calculates the rate of collision arising from each turbine independently operating in an airspace with a projected density of flying birds, and sums up the risk from all T turbines in the windfarm. In this approach, the size and layout of the windfarm are unimportant, if the density of flying birds is the same for all turbines.

For large turbine arrays where the overall probability of a bird colliding is relatively high, it may be appropriate to take account of the declining proportion of the birds surviving passage through early rows of turbines and thus exposed to collision risk in later rows. In effect, the density of flying birds surrounding turbines in later rows may be reduced as a consequence of collisions in earlier rows. (While it is convenient to think in terms of successive rows of turbines, the same principle applies within any array of turbines, even if located in a disordered array.)

For this, the overall size and layout of the windfarm are relevant. Here we need to consider the risk to a bird flying through the windfarm as a whole, which depends on how widely spaced the turbines are. Again maintaining the assumption of perpendicular approach to rotors, the collision risk for a single bird due to any one turbine (ie disregarding the risks to the bird presented by other turbines) is

$$c = (\pi R^2 / 2Rw)\ p\ Q_{op}\ (1-A)$$

where πR^2 is the cross-sectional area of a single turbine, 2Rw is the overall cross-sectional area of the windfarm of width w and risk height 2R, p is the collision risk for a bird passing through a rotor, Q_{op} is the proportion of time the turbine is operational, and A is the avoidance rate assumed.

Imagine an array of turbines with n rows of t turbines, each of which on its own would present a collision risk c. The overall collision risk for a single bird passage, if bird density depletion effects are ignored, would be simply C = ntc.

To take account of depletion, consider that the probability of incoming birds surviving a passage across the first row is (1-tc), and the proportion attempting to pass through row 2 is therefore (1-tc). The proportion surviving row 2 is $(1-tc)^2$ and so on until:

after row n the proportion surviving is $(1-tc)^n$ … (A4-1)

which may be expanded as a convergent binomial series

$$(1-tc)^n = 1 - ntc + (n(n-1)/2)\ (tc)^2 - (\ n(n-1)(n-2) / 6\ )\ (tc)^3 + \ldots\ldots$$

where the terms are successively smaller.

The 'large array collision risk' C_{LA} is (1 – proportion surviving) ie

$$C_{LA} = ntc - (n(n-1)/2)\ (tc)^2 + (\ n(n-1)(n-2) / 6\ )\ (tc)^3 - \ldots\ldots$$

The first term here is ntc = C, the risk from a single turbine multiplied by the number of turbines. The subsequent terms provide a correction to that value which takes account of bird density depletion.

Dividing throughout by C we get

$$C_{LA} / C = 1 - ((n-1)/ 2n\ )\ C + (\ (n-1)(n-2) / 6\ n^2\ )\ C^2 - \ldots\ldots \qquad \ldots\ (A4\text{-}2)$$

Thus a first order correction to the value C given by the collision model can be made by subtracting ((n-1)/2n) C. The C^2 and subsequent terms are most likely to be insignificant.

Box 4: Example of large array correction

Take an array of $T = 144$ turbines, rotor radius 50m, in an array of width 6km.

Assume input data

Probability of collision for single rotor transit	= 0.15
Proportion of time operational	= 90%
Avoidance rate assumed	= 97.5%

$$C = T\,(\pi R^2 / 2Rw)\ p\ Q_{op}\ A$$

$$= (\pi \times 50 \times 50)/(2 \times 50 \times 6000) \quad \times 144 \times 0.15 \times 0.9 \times 0.025 = 0.00636$$

Take number of rows $n = \sqrt{T} = 12$

$$C_{LA} / C = 1 - ((n-1)/ 2n)\ C + ((n-1)(n-2) / 6 n^2)\ C^2 - \ldots\ldots$$

$$= 1 - 0.0029 + 0.0000051 \ldots\ldots.$$

$$= 0.997 \quad \text{ignoring terms of order } C^3 \text{ and higher}$$

Thus ‘Large array correction factor’ = 99.7%

Very often the layout of a windfarm is not known at the time of collision risk assessment, so an exact value for n is not known; and in any case the collision risk has to account for birds entering the windfarm from all directions. A rough approximation is to use $n = \sqrt{T}$ ie the square root of the total number of turbines. If a more analytic approach is necessary, with discrimination between flight directions, then the model of Bolker et al (2006)[xvii] may be used.

If realistic avoidance rates have been taken into account in the collision model, such ‘large array corrections’ are likely to be small and can be ignored. However if the overall risk to a single bird passage is of order 0.1 or above, the large array correction will be significant. A spreadsheet is provided at sheet 8 ‘Large Array Correction’ to enable the correction to be calculated easily. The output from this sheet is then applied in the final set of collision estimates in the ‘Overall Collision Risk’ spreadsheet.

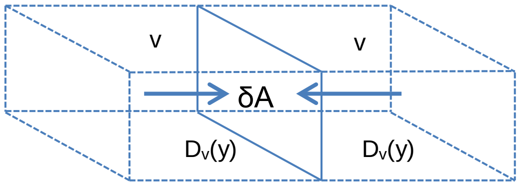
Annex 5 - Using flight height distributions – derivation of equations

Take a rotor disc of radius R, perpendicular to incoming bird flights at various heights Y. Assume that bird density $D_v(Y)$ (in birds per m^3) is a function of flight height; $D_v(Y)$ is the 'flight height distribution'.

Using the same approach as in Figure 5 and equation (1) (paragraph 36) of the main text, consider the bird flux through a small element δA of the disc. Within one second all birds within a distance v on one side and flying towards the rotor will pass through the area δA, as in Figure A5-1. At any time there will be ½ v $D_v(Y)$ δA flying towards the rotor in each direction. Total bird flux is

$v\, D_v(Y)\, \delta A$ where v is the bird flight speed
and $D_v(Y)$ is the bird flight density, per m^3, at this height Y

Fig A5-1: Bird flux through small element of rotor disc



Take δA to be a small rectangle of width dX and height dY. If p(X,Y) is the probability of collision for a bird flying through the rotor at point (X,Y), the collision rate through this small element δA at that point is

$$v\; D_v(Y)\, p(X,Y)\, dX\, dY$$

The total collision rate for flights through a single rotor disc (while the turbine is operational) is then obtained by integrating this over the whole area of the disc:

$$\text{Collision rate} \quad = \quad v \int_{\text{Min rotor height}}^{\text{Max rotor height}} D_v(Y) \int_{-\sqrt{(R^2-Y^2)}}^{+\sqrt{(R^2-Y^2)}} p(X,Y)\; dX\, dY \quad \ldots. \qquad (A5\text{-}1)$$

This is equation (7) (paragraph 67) of the main text. The limits $\pm\sqrt{(R^2-Y^2)}$ to the integration over X define the outer limits of the rotor circle, and the limits to the integration over Y are the minimum and maximum rotor heights respectively.

Translate the factors into dimensionless units, within which the rotor has a radius of 1, by using the parameters x = X/R, y=Y/R; thus dX =Rdx, dY=Rdy. Use the dimensionless relative frequency flight height distribution

$$d(y) = R\, D_v(Y)/D_A$$

D_A, the areal bird density, is just the sum of D_v over all flight heights from sea level upwards, ie

$$D_A = \int_{\text{sea level}}^{\infty} D_v(Y)\, dY$$

Hence d(y) is normalised, ie

$$\int_{\text{sea level}}^{\infty} d(y)\, dy \quad = \quad \int R\, D_v(Y)/\, D_A \;\; (dY\,/\,R) \quad = \quad \int D_v(Y)\, dY\,/\,D_A \quad = \quad 1$$

Using these factors, equation (A5-1) becomes

$$\text{Collision rate} \quad = \quad v\,(D_A/R) \int_{-1}^{+1} d(y) \int_{-\sqrt{(1-y^2)}}^{+\sqrt{(1-y^2)}} p(x,y)\;\; R\,dx\;\; R\,dy$$

$$= \; v\,D_A\,R \int_{-1}^{+1} d(y) \int_{-\sqrt{(1-y^2)}}^{+\sqrt{(1-y^2)}} p(x,y)\,dx\,dy \qquad\qquad (A5\text{-}2)$$

which when multiplied by the total number of turbines T, the time birds are active in a month t, and the proportion of time the turbines are operational Q_{op}, is equation (8) (paragraph 70) of the main text.

This can be rearranged in the form of equation (9) (paragraph 70) of the main text, so as to use the same ‘flux factor’ as in the basic model:

$$\mathbf{Collisions} = \underbrace{\boxed{v\,(D_A/2R)\,T\pi R^2\,t}}_{\text{Flux factor}} \times \underbrace{\boxed{(2/\pi) \int_{-1}^{1} \int_{-\sqrt{(1-y^2)}}^{+\sqrt{(1-y^2)}} d(y)\;\; p(x,y)\,dx\,dy}}_{\text{Collision integral}} \times \underbrace{\boxed{Q_{op}}}_{\text{Proportion of time operational}} \qquad \ldots\;(A5\text{-}3)$$

The total count of birds passing through the rotors is given by the same equation but with p(x,y) set to 1, ie such that every bird is counted, as in equation (10) (paragraph 71) of the main text:

$$\mathbf{Flux} = \underbrace{\boxed{v\,(D_A/2R)\,T\pi R^2\,t}}_{\text{Flux factor}} \times \underbrace{\boxed{(2/\pi) \int_{-1}^{1} \int_{-\sqrt{(1-y^2)}}^{+\sqrt{(1-y^2)}} d(y)\;\; dx\,dy}}_{\text{Flux integral}} \times \underbrace{\boxed{Q_{op}}}_{\text{Proportion of time operational}} \qquad \ldots\;(A5\text{-}4)$$

<u>Comparison with basic model</u>

In the case where flight heights are assumed to be uniformly distributed across the risk height, ie from lowest to highest point of the rotor, then d(y) is a constant over the range y=-1 to y=+1 and can be taken in front of the integrals. Moreover, if all flights take place within this height band then d(y) takes the value ½, because d(y) is normalised, ie $\int_{-1}^{+1} d(y)dy = 1$. The Flux integral then reduces to

$$(2/\pi)\;(½) \int\!\!\int dx\,dy \;=\; (2/\pi)\;(½)\;(\pi) \;=\; 1$$

as the integral is just the area π of a circle of unit radius. The Collision integral is simply the average of p(x,y) over the area of the disc.

More generally, if a proportion Q_{2R} of flights take place between minimum and maximum rotor heights, and the distribution is uniform within these limits, d(y) takes the value $Q_{2R}/2$, the Flux integral = Q_{2R}, and the Collision integral is Q_{2R} times the average of p(x,y) over the area of the disc.

The average of p(x,y) over the area of the disc is the ‘single transit collision risk’ in the basic model. Hence equation (A5-3) above becomes

$$\text{Collisions} = \text{Flux factor} \;\times\; Q_{2R} \;\times\; \text{Single transit collision risk} \;\times\; Q_{op}$$

This reproduces equation (5) (paragraph 52) of the main text, which describes the collision rate in the basic model.

Annex 6 – Assessing collision risks for birds on migration

(DRAFT Extension to Collision Risk Guidance – Bill Band March 8 2012)

Birds on migration are often of particular interest in collision risk assessment, as the birds may be coming from or be heading for a distant site with conservation designations which imply special legal responsibilities in avoiding adverse impacts on the bird population. It will therefore be important to understand the impact of a given windfarm on such a bird population if its migration routes are through the windfarm. Report SOSS-05 by BTO on 'Assessing the risk of offshore wind farm development to migratory birds designated as features of UK Special Protection Areas'[xviii] describes the issues and uncertainties involved in such an assessment.

Calculating collision risk for migrants is little different from the process for other birds, and may make use of the Collision Risk Spreadsheet provided with this Guidance[xix]. The main difference arises in estimating the number of migrant birds passing through the windfarm, and how that data is input to the spreadsheet. The data is usually in terms of the number of birds passing through a migration corridor, rather than starting with bird density, as does the normal process in following the Collision Risk Guidance. To facilitate this, an additional sheet 'Migrant Collision Risk' has been added to the suite of spreadsheets, and to make use of this sheet, additional data on migrants is required in the 'Input Data' sheet.

Estimating total bird flux over the migration period

Report SOSS-05 outlines a number of different methods which may potentially be used to estimate the number of birds flying through a windfarm. Each of these leads directly to information on bird flux density F – the number of birds passing through a tall window of unit width (a metre, or a kilometre) during each migration period.

- In the simplest approach, it may be assumed that an entire bird population uses a migratory corridor twice each year. Report SOSS-05 provides data on the total GB (also international) populations of a range of migratory species. Documentation for individual conservation sites often provides information on the typical occupancy of the sites by species during migration. The maps in the SOSS-05 report may then be used to estimate the width W (km) of the corridor used for migration – the 'migratory front', and the assumption may be made that the entire population of N birds passes through this migratory front, with an even distribution across the front. Thus the bird flux density is N/W birds km^{-1}.

- Instead of assuming an even distribution of birds over the migratory front, tracking studies can help indicate the proportion of a bird population likely to cross a wind farm (or different parts of a wind farm) during an average migration period.
- Migrant birds may be counted along with other birds in the snapshot counts in boat-based surveys. As boat based surveys are usually undertaken on a 1- or 2-days a month sample basis, they are generally unsatisfactory as a means of counting birds on migration: whether or not a flock of migrating birds is observed on sampling occasions, and the size of that flock, is likely to be a matter of chance. However, where the sampling is sufficiently frequent it may be used to generate an estimate of the total number of birds flying across the site during the migration period.
- Finally, the flux of migrant birds may be recorded by visual observation from shore or from a sea platform, or by radar, where the observation period covers a high proportion of the possible migration period. Such data will be measured directly in birds crossing an imaginary baseline, eg of 1km length, ie in birds km^{-1} $hour^{-1}$, and can be grossed up for the complete migration period. If this measurement is of birds approaching the baseline from all directions, the result should be multiplied by $\pi/2$ to convert to the equivalent 'perpendicular flux' (see Annex 2). This allows for the fact that the 'tall window' through which birds may pass – defined by the baseline and extending to all heights - presents a reduced cross-sectional area to birds approaching from an oblique angle.

Calculating the Flux factor

Equation (2) (paragraph 37) of this Guidance indicates:

Total number of bird transits =

$$\underbrace{\boxed{v\,(D_A / 2R)\ \ (T\,\pi R^2)\ \ (\text{time active})}}_{\text{flux factor}} \quad \text{x} \quad \underbrace{\boxed{Q_{2R}}}_{\text{proportion at risk height}}$$

where v is the bird flight speed, D_A the areal density of birds (ie flying at any altitude), $T\pi R^2$ is the total cross-sectional area of all rotors, and Q_{2R} is the proportion of birds flying at risk height.

The data assembled above for birds on migration is on flux density F - the number of birds passing through a tall window of unit width (a metre, or a kilometre) during each migration period. To relate that to bird density, note that if all birds were flying perpendicularly to the window[6], in any second the number flying through the window would be those within a distance v where v is the flight speed. As the total density of birds, summing over all heights, is D_A birds m^{-2}, the number within distance v of a window one metre wide, and hence about to pass through that in the next second, is just $D_A v$. Over a period of time t, the total number of birds passing through this window is thus $D_A v\, t$. So, over a full migration period, $v\ D_A$ (time active) may be replaced in the above equation by F, in units of birds m^{-1}:

Total number of bird transits through rotors

$$\underbrace{\boxed{F\ \ (T\,\pi R^2)\,/\,2R}}_{\text{flux factor}} \quad \text{x} \quad \underbrace{\boxed{Q_{2R}}}_{\text{proportion at risk height}} \qquad .. \quad (\text{A6-1})$$

Note that F is commonly expressed in birds km^{-1} and if so must be divided by 1000 (as the spreadsheet does) for use in this formula.

Flight height

Cook et al 2012[iii], in their SOSS-02 report, have documented the typical flight heights of many bird species at sea, as recorded in wind farm surveys around the UK and elsewhere. However, data on flight heights of birds on migration is patchy, as described by Wright et al in their SOSS-05 report. The proportion of birds on migration $Q_{2R\text{-}m}$ flying at risk height is likely to be different from the Q_{2R} proportion for non-migrants. Table 3 of the SOSS-05 report makes recommendations on the values to be used for $Q_{2R\text{-}m}$ for various species groups, ranging from 100% for raptors to 50% for passerines. For seabirds, divers, gulls and terns use is recommended of the values listed in the SOSS-02 report.

Flight speed

The single transit collision risk uses the bird flight speed as a factor, so if a different flight speed v_m is available for migrating birds, this should be used.

Migration period

Usually, the collision risk of interest will be over a full year, ie over outward and return migration periods. The spreadsheet is arranged, like the 'Overall collision risk' sheet, on a monthly basis. If data is available to support a monthly subdivision, the migration fluxes should be apportioned out over the relevant months. As the proportion of time that the wind farm is operational varies from month to month, this is the most accurate approach. However, if the distribution of migration passages over months is not known or highly variable, any two convenient months (eg April and September) may be used as the assumed migration periods.

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[6] in accord with the assumption of perpendicular approach – see paragraph 12 of main text

Calculating collision risk

Subject to the modified approach outlined above in calculating the Flux factor, the calculation of collision risk follows exactly the same methodology as for other birds. As in the usual approach, the Collision Risk Spreadsheet offers three options for calculating collision risk:

(1) Option 1 - using the assumption that flights at risk are evenly distributed across all rotor heights;

(2) Option 2 - ditto, but using the proportion of birds flying at risk height as derived using flight height distribution data; and

(3) Option 3 - making use of the flight height distribution data to calculate risk in each part of the rotor, and summing that risk.

For some species groups, Table 3 of the SOSS-05 report indicates that a simple percentage should be entered for Q_{2R-m} . This indicates that the flight height distributions documented in Cook et al[iii] are not likely to be characteristic of migrating birds. Only Option (1) should be used, unless good data is available indicating the flight height distribution of migrating birds.

For those species groups where Table 3 indicates the Cook et al data may be used, then Options (2) and (3) may be used. As in the usual approach, it is recommended that for these species the calculations for all three Options should be presented, so as to note the effect of taking an assumed flight height distribution into account.

Use of options to take account of flight height distribution

		SOSS-05 Table 3 recommendation	
Calculation option		Percentage	Use figure from Cook et al
Option 1	assume flights uniformly distributed across risk height	●	o
Option 2	use species flight height distribution to generate Q_{2R-m}		●
Option 3	use species flight height distribution in full to calculate collision risk		●

Uncertainties

One of the main uncertainties is likely to be the uncertainty in flight activity, due to uncertainty and year-to-year variation in the number of birds migrating, and in the precise flight corridor used. Realistic assessments should be made, even if this is no more than an expert view, on the limits within which 95% confidence can be assured for the value of flux density input to the model.

Supplementary notes on using the spreadsheet

The ‘Input data’ sheet now includes:

- ‘bird survey data’, which includes data on bird density. This drives the ‘Overall collision risk’ sheet which provides the overall collision risk calculation for the birds described in terms of bird density.
- ‘birds on migration data’, which includes the number of migration passages, the width of the migration corridor, the proportion of migrants flying at risk height, and the proportion of migratory flights which are upwind. This drives the ‘Migrant collision risk’ sheet which provides the collision risk calculation for the birds included in this ‘birds on migration’ block.

Therefore, to avoid double-counting collisions, the ‘bird density’ figures should exclude any migrants for which collision risk is calculated using the ‘Migrant collision risk’ sheet.

The spreadsheet does not add the two collision elements together, as they are likely to be used for different purposes.

The ‘Migrant collision risk’ spreadsheet only differs from the ‘Overall collision risk’ spreadsheet in the data used on flight activity (as above) and in the resulting calculation of the Flux factor. All other parameters – Bird data, Windfarm data, Turbine data and Avoidance rates – are common to both spreadsheets.

Notes on additional input data

Flight activity data – additional for migrants			
Symbol	**Description**	**Units**	**Notes**
N	Bird population	birds	This is the total number of birds migrating through the migration corridor in question. May be subdivided by month if there is data to support that.
W	Width of migration corridor	km	
Q_{2R-m}	Proportion at rotor height	%	Based on recommendations in Table 3 of Report SOSS-05, unless bettered by new data.
	Proportion of migratory flights upwind	%	This is set at 50% by default, but for migration flights it may be appropriate to assume some bias towards downwind.

Annex 7 - Taking account of tidal variation

This section considers how to take account of changing tidal levels in calculating bird collision risks. It is assumed that the extended collision model – taking account of flight height distribution – is being used.

The flight height distribution D(Y) describes the relative density of bird flights at different heights above the sea surface. However (other than for floating wind turbines) the height of the rotor above the sea surface varies with the tide. The issue to be addressed is how to take account of that variation in the calculation of collision risk.

Height above Mean Sea Level

In order to satisfy navigational clearance requirements, turbine hub heights are usually expressed in metres above Highest Astronomical Tide (HAT), which is the maximum sea height theoretically possible, excluding waves and surges and other sea conditions due to meteorological conditions. To use bird flight height distributions, these heights need to be adjusted to the height above actual sea level.

Tidal information is normally presented in metres above Chart Datum (CD), with mean tidal level Z_0 and a tidal variation which oscillates around that level. If turbine height is H relative to HAT, then it becomes $H + (HAT – Z_0)$ relative to mean sea level. Thus a tidal offset has been added to the height:

Tidal offset = Highest Astronomical Tide (HAT) – Mean Sea Level (Z_0)

Typically this offset is in the range 2.5 - 4 metres. A new 'tidal offset' field has been included (in the extended version Mar 2012) as an input field in the 'Input Data' sheet in the Collision Risk Spreadsheet. The extended model then includes this adjustment to rotor heights when making use of a bird flight height distribution.

This adjustment in expressing turbine height can make a significant difference to collision risk, for some species reducing the estimated risk by around 25% to 30%. The size of the change depends on both species and turbine details, depending on the rate at which the flight height distribution curve varies around the minimum height of the rotor.

Allowing for sea level rise

Current predictions on sea level rise due to climate change are described in UKCP09[xx] . By 2060 the predictions are typically for a rise of order 0.25 – 0.3 metres for a global high emissions scenario.

The aim as far as possible should be for bird collision risk assessment to be valid for the full operational period of the project. Therefore the height of the rotor relative to sea level should be reduced by an amount to take account of the likely increase in sea level over the lifetime of the windfarm. It is recommended that this reduction should be of order 0.25 – 0.3 metres. This should be done by amending the tidal offset, so that it becomes

Tidal offset = Highest Astronomical Tide – Mean Sea level – Climate change adjustment

Tidal variation

The above takes account of the height of the rotors above mean sea level, but it does not take account of the variation of the tides. Assuming that the distribution of bird flight heights relative to sea level is independent of the state of the tide (which may not be the case in estuarine or near-shore locations), at times of high tide there will be increased bird density at rotor level, and at low tide decreased. If the flight height distribution were linear with height, then the increases at high tides would exactly offset the decreases at low tides. But flight height distributions are typically highly non-linear, and there is a 'second-derivative' effect, dependent on the degree of curvature in the flight height distribution, with the increases at high tides more than outweighing the decreases at low tides. Only the section of the flight height distribution above rotor minimum height is relevant to collision risk, so it is the curvature of the distribution at those heights which matters.

This non-linear effect – the ‘tidal asymmetry correction’ - is in general small, but a method for calculating it is set out here.

Calculation of tidal asymmetry correction factor

Take all heights Y as measured with respect to mean sea level. At height Y above mean sea level, the flight density takes the value D(Y) only briefly, twice each tide as the tidal level passes the mean sea level. More generally, the flight density is D(Y-h) when the tide is h metres above mean sea level. The time-averaged flight density is

$$D\sim(Y) = \Sigma f(h)\, D(Y-h) \qquad \text{(A7-1)}$$

where the sum is over all tidal height bands from lowest to highest, and f(h) is the proportion of time that the sea level is within each height band h.

Figure A7-1 shows the frequency of sea levels f(h) at one site (Cromer in East Anglia), ranging from --2.3m to + 2.3m, and banded within 0.2m height bands. Commercial tidal prediction software is available, such as the POLPRED Offshore tidal computation software available from the National Oceanographic Centre, which can generate such a sea level frequency chart with a high level of accuracy for any point in and around the UK [xxi]. For coastal sites near to ports, the ‘Notes on using the spreadsheet’ below describe how an approximate frequency chart can be generated, given basic tidal data published by the National Oceanographic Centre[xxii] on their Website, using the ‘Sea Level Frequency’ spreadsheet provided with this guidance. For Figure A7-1, tide level was calculated at 12 min intervals over 1 year and allocated to 0.2m wide bins. The curve shows symmetrical peaks at around mid-tide levels ±0.9m – not only do all tides pass through that level, but neap tides have their ‘high tide’ turning point in mid-range. In contrast, relatively few tides approach the maximum of the tidal range. Tides are changing most rapidly as they pass the mean sea level, so the curve is characterised by a dip in the middle.

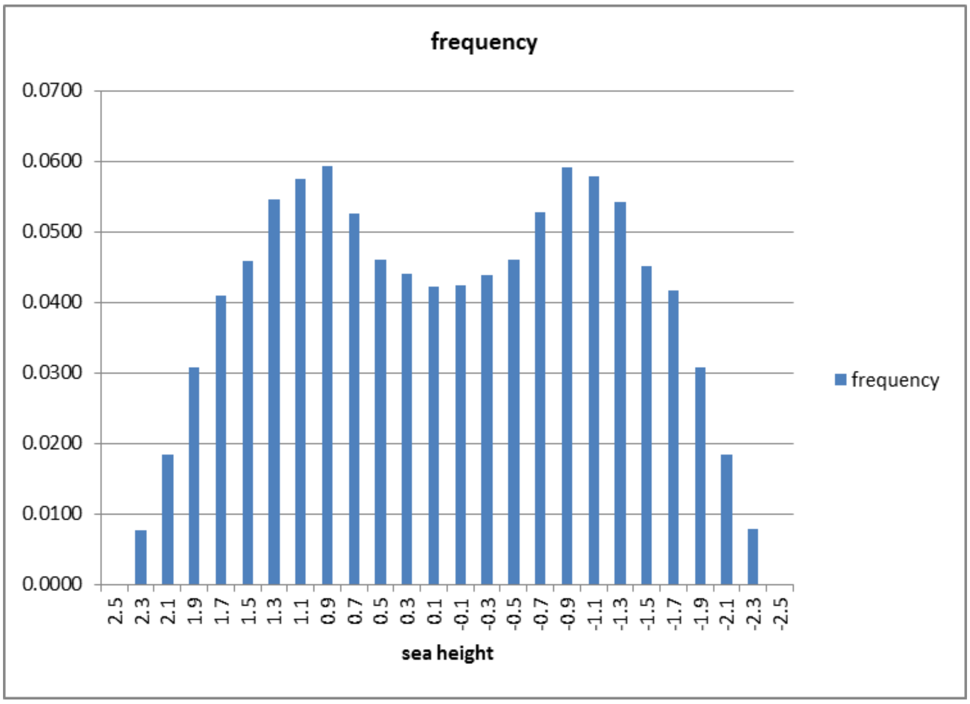

Figure A7-1: Sea level frequency at Cromer, East Anglia

The effect of applying the distribution of tides f(h) to the flight height distribution, ie applying equation (1), is to ‘smear’ the flight height distribution, drawing from a range within ±2.3 metres (for this site) higher or lower, to yield a time-averaged flight height distribution D~(Y). D~(Y) may now be used in place of the original flight height distribution D(Y) in the collision calculation, pasting it in place of D(Y) as the 'current data' in column B of the Flightheight sheet of the Collision Risk Spreadsheet.

Table A7-2 shows sample output for the time-averaged flight density of kittiwake, under the tidal regime at Cromer. The original flight height distribution is from the work by Cook et al SOSS[iii], and the sea level frequency distribution is that in Figure A7-1.

Effects of smearing height distribution

Table A7-1 shows the effects of applying such smearing to flight height data for gannet, kittiwake and fulmar at a sample of five sites around the coast of the UK. The tidal data given is for ports, that for offshore sites may differ.

Table A7-1: Effects of using a tidally-smeared flight height distribution

Base tidal information:

	tidal range (springs)*	**HAT**	**Z_0**	**tidal offset**
Stornoway	4.14	5.53	2.893	2.64
Aberdeen	3.62	4.85	2.557	2.29
Heysham	8.49	10.76	5.176	5.58
Cromer	4.23	5.74	2.920	2.82
Avonmouth	12.27	14.65	6.955	7.69

The data below is calculated using the same 4MW turbine scenario as in the Worked Example: 3 blades, 9.9rpm, 57.5m rotor radius, 80m hub height, 4.21m max chord, 15 degree pitch.

***** tidal range in metres, taken as difference between mean high water spring tides and mean low water spring tides

Gannet	**tidal range**	**collision integral x 10^3**		
		without tidal smear	**with tidal smear**	**change**
Stornoway	4.14	**1.288**	**1.309**	**+1.6%**
Aberdeen	3.62	**1.347**	**1.363**	**+1.2%**
Heysham	8.49	**0.931**	**0.989**	**+6.2%**
Cromer	4.23	**1.259**	**1.284**	**+2.0%**
Avonmouth	12.27	**0.784**	**0.860**	**+9.7%**

bird length 0.94, wingspan 1.72, flight speed 14.9, flight style flapping, 50% upwind

Kittiwake	**tidal range**	**collision integral x 10^3**		
		without tidal smear	**with tidal smear**	**change**
Stornoway	4.14	**1.131**	**1.139**	**+0.7%**
Aberdeen	3.62	**1.176**	**1.184**	**+0.7%**
Heysham	8.49	**0.816**	**0.847**	**+3.8%**
Cromer	4.23	**1.108**	**1.118**	**+0.9%**
Avonmouth	12.27	**0.649**	**0.697**	**+7.4%**

bird length 0.39, wingspan 1.08, flight speed 14.9, flight style flapping, 50% upwind

Fulmar	**tidal range**	**collision integral x 10^3**		
		without tidal smear	**with tidal smear**	**change**
Stornoway	4.14	**0.059**	**0.059**	-
Aberdeen	3.62	**0.061**	**0.060**	-
Heysham	8.49	**0.049**	**0.049**	-
Cromer	4.23	**0.058**	**0.058**	-
Avonmouth	12.27	**0.043**	**0.043**	-

bird length 0.48, wingspan 1.07, flight speed 14.9, flight style flapping, 50% upwind

The effects of the smearing are highly dependent on the species. This is to be expected as the concave-upwards curvature of the flight height distribution, in the lower height range of range of the rotors, differs markedly for different species. Both gannet and kittiwake distributions have strong curvature in this height range, while the fulmar height distribution has flattened off at these heights above the sea surface.

The effects also depend on the tidal range, reflecting in particular the separation of the two peaks in the sea level distribution curve. The effects are generally small (less than 5% of collision risk) except at the two high-tidal range sites, Heysham and Avonmouth. The latter has among the most extreme tides in the UK. For gannet at Avonmouth, the effect is 9.7% of collision risk. That means that the collision risk is increased by 9.7% due to the asymmetry of the flight height distribution. (It should be stressed that these are proportional changes – ie if predicted collisions were 50 per month this effect would raise that estimate to 54.85.)

While for most potential offshore windfarm sites such effects may be judged minimal, at sites with tidal range in excess of 5 metres it may be sufficiently significant to warrant incorporation of use of a ‘tidal asymmetry correction’.

The correction increases with tidal range, more than just linearly. As it depends on the curvature of the flight distribution curve, ie its second derivative, it should be expected to depend on the square of the breadth of the distribution (which is characterised by the tidal range). Making this assumption and using the data in Table A7-1 yields very approximate ‘rule of thumb’ factors:

Correction factors (percentage adjustment of collision risk):

Gannet	0.08 x (tidal range)^2
Kittiwake	0.05 x (tidal range)^2
Fulmar	0

Thus, for gannet at Cromer where the collision integral is 1.259 x 10^{-3}, one should apply a tidal asymmetry correction of 0.08 * (4.23^2) = 1.43%, raising the collision integral to

Adjusted collision integral = 1.259 x 1.0143 x 10^{-3} = 1.277 x 10^{-3}

Where species other than the above three are involved, there will be a need to undertake a comparable analysis to establish the 'rule of thumb' factors.

It should be noted that these rule-of-thumb factors have been evaluated for one particular (fictitious) turbine model. However it may be expected to apply to any large turbine with a similar height clearance above the sea surface: the crucial factor is the degree of curvature of the flight height distribution curve for the species in question, in the vicinity of the lower reaches of the rotor.

Conclusion

Given the additional data processing required to take account of this adjustment, it is not recommended that the effects of tidal asymmetry should be taken into account routinely in collision risk assessment. However, where the tidal range exceeds 5m, the adjustment is significant enough to warrant use of a correction, using the 'rule of thumb' factor if the species is one for which such a factor has been established, and if not, by undertaking the analysis outlined above.

Summary of recommendations

The following recommendations only apply to turbines which are fixed relative to the seabed (ie not floating turbines)

1. For the purposes of collision risk assessment, turbine hub and blade heights should be adjusted so they are relative to mean sea level, by including the height of Highest Astronomical Tide above Mean Sea Level as a 'tidal offset'.

2. A reduction of around 0.25 – 0.3 metres in that offset should be made to allow for the likelihood of increasing sea levels over the period to 2060.

3. The skewed distribution of seabird flight heights means that tidal variation affects bird densities in an asymmetric way, ie the increases at higher sea levels are greater than the decreases at lower sea levels. The changes to collision risk are typically small (<5%). However at sites with a high tidal range (> 5 metres) the effects for some species may be significant. A 'rule of thumb' correction factor is provided for gannet, kittiwake and fulmar. For other species there will be a need to apply the methodology outlined above to establish the correction. Tools are provided in spreadsheet form to assist this process.

Spreadsheet support

A spreadsheet 'Tidal smear' is provided which contains a routine to 'tidally smear' data, ie using D(Y) as input and calculating D~(Y) as output.

Two ancillary spreadsheets 'Tidal height' and 'Sea level frequency' are also included which enable an approximate sea level frequency distribution to be generated for near-coastal sites, if software such as POLPRED is not available.

These are intended for users conversant with spreadsheets and with an understanding of the transformation required; the process involves cutting and pasting data between worksheets. Notes on using these spreadsheets are provided below.

Notes on using the spreadsheets

These spreadsheet tools involve some cut-and-pasting and use of macros so should be undertaken by someone with adequate spreadsheet skills. There are three sheets in the 'Tidal variation' workbook.

Tidal height uses published tidal data to generate tidal predictions. Tidal data for ports around the UK is published by the National Oceanography Centre at [redacted]

Sea level height, ignoring any meteorological effects such as surges or waves, is governed by a series of cycles with different frequencies, relating to the position of the moon and sun in relation to the earth and the location in question. Sea level height is given, where t is the time in hours elapsed from a reference start time, by the formula

$$\Sigma H_i \cos(\sigma_i \; t - g_i)$$

where for each cyclical component i, H_i is the amplitude, σ_i its angular frequency, and g_i its phase.

Based on observations over the period 1989 – 2007, the National Oceanography Centre publishes information on amplitude H_i and phase g_i – the 'harmonic constants' - for the four largest cyclical constituents, termed M_2, S_2, K_1 and O_1 respectively. Their associated frequencies σ_i are drawn from a description of the Doodson numbers [redacted] (see w0, w1, w2 and w3 in the sample programme).

The spreadsheet uses these four principal harmonic constants and their associated phases and frequencies to calculate sea level at times t which increases in steps in successive rows. 'Step' sets the period in hours between successive rows.

This tidal calculation is not used directly, but provides a graph showing alternation of tides and springs and neap tides, which will help explain the shape of the sea level frequency distributions produced next.

It is stressed that this is a very approximate tidal series. More precise prediction involves the addition of a long series of harmonic components, not just four. If greater precision is required, then tidal predictions from various commercial systems may be used. However, these four harmonic components are sufficient to generate the broad pattern of spring and neap tides, and the daily alternation of tide heights, which should be adequate as a basis for a sea level frequency distribution.

Sea level frequency runs exactly the same routine as a time series. As it runs, it categorises each output in a tide height bin, building up a frequency distribution of sea level heights. As input it requires the same table of tidal constants for the location in question as the Tidal height sheet. The programme is initiated as a macro 'Sealevel frequency' - click on 'Developer' then 'Macros' and 'Run' the macro 'Sealevelfrequency'. The programme requires three further inputs:

bin width – use 0.2 for east coast or north coast, use 0.4 or 0.5 for estuarine locations. The distribution matrix is 13 times this bin width both + and -, so 0.2 bin width runs from -2.6m to + 2.6; 0.5 bin width runs from -6.5m to +6.5m.

interval – a value of 0.2 (meaning 0.2 hours or 12 minutes) seems satisfactory,. remembering that the aim is to sample sea level heights.

number of data points – the system should be tested with only 100 or 1000 points, but once working, run it for 45000 which at 12 minute intervals is a little over a year.

The output is a sea level frequency table, which is then normalised in the next column (divided by the total to give a frequency set which adds to 1). This normalised frequency distribution can then be copied then pasted into the Tidal smear spreadsheet.

Tidal smear uses the sea level frequency data as input, and applies it to the flight height distribution (eg that in the SOSS report by Cook et al[iii]), as described above, to produce a 'smeared' output, in which D~(Y) is the time-averaged value of the bird density at height Y. The programme uses two named ranges 'tidefreq' which contains the sea frequency data, and 'gannetdata' (for example) which contains the bird flight height distribution. Both ranges must be two columns wide, the left one with the height in metres, and the right one with the normalised frequency data. The ranges must start at the first data point (ie not including column titles). The sea level data ranges must be 26 rows deep, and the bird data tables 150 rows deep. The output column then uses the function 'tidesmear' to compute the result for each height y. Note that if the sea level frequency distribution runs from say -5m to +5m, then at height y metres the programme will draw from distribution data from y-5 to y+5 metres. So omit the output formula for heights 0-5m and 145-150 metres to avoid the programme going out of range.

The output tide-smeared distribution may then be copied and pasted into the main Collision Risk Assessment spreadsheet, in the 'Flightheights' sheet.

Table A7-2: Sample output of tide-smeared flight distribution Kittiwake, using tides at Cromer

height (m)	original flight height distribution	tide-smeared flight height distribution
0	0.08571	
1	0.07850	
2	0.07175	
3	0.06526	
4	0.05987	0.06039
5	0.05499	0.05548
6	0.05095	0.05100
7	0.04680	0.04686
8	0.04263	0.04299
9	0.03907	0.03938
10	0.03590	0.03606
11	0.03293	0.03302
12	0.02997	0.03022
13	0.02747	0.02763
14	0.02505	0.02530
15	0.02305	0.02317
16	0.02118	0.02122
17	0.01929	0.01940
18	0.01765	0.01760
19	0.01587	0.01584
20	0.01398	0.01419
21	0.01247	0.01264
22	0.01115	0.01127
23	0.00999	0.01009
24	0.00895	0.00902
25	0.00801	0.00805
26	0.00710	0.00718
27	0.00631	0.00639
28	0.00565	0.00568
29	0.00496	0.00504
30	0.00444	0.00447
31	0.00391	0.00395
32	0.00345	0.00350
33	0.00305	0.00309
34	0.00271	0.00273
35	0.00238	0.00242
36	0.00213	0.00214
37	0.00185	0.00189
38	0.00164	0.00166
39	0.00145	0.00147
40	0.00128	0.00130
41	0.00113	0.00115
42	0.00101	0.00103
43	0.00092	0.00092
44	0.00081	0.00081
45	0.00071	0.00072
46	0.00063	0.00063
47	0.00055	0.00056
48	0.00048	0.00049
49	0.00042	0.00043
50	0.00038	0.00038
51	0.00033	0.00034
52	0.00030	0.00030
53	0.00026	0.00027
54	0.00023	0.00024
55	0.00021	0.00021
56	0.00018	0.00019
57	0.00016	0.00017
58	0.00015	0.00015
59	0.00013	0.00013
60	0.00012	0.00012
61	0.00010	0.00010
62	0.00009	0.00009
63	0.00008	0.00008
64	0.00007	0.00007
65	0.00007	0.00007
66	0.00006	0.00006
67	0.00005	0.00005
68	0.00005	0.00005
69	0.00004	0.00004
70	0.00004	0.00004
71	0.00003	0.00003
72	0.00003	0.00003
73	0.00003	0.00003
74	0.00003	0.00003
75	0.00002	0.00002
	etc	

This bracket shows the range of data drawn upon in calculating the smeared distribution for height 4m

Annex 8 Notes on spreadsheet Visual Basic functions

The functionality of Sheet 4 (Extended model) is entirely based on computations programmed as user-defined functions in Visual Basic. Macros must be enabled. The programme code may be viewed using the 'Developer' tab and 'Visual Basic' icon to view 'Module 1'. The user-defined functions are as follows:

interpolate (N,a,y)

Assumes a set of points and associated values in a two-column named range A. It compares y with the set of points and performs a linear interpolation to provide an appropriate intermediate value. It is used twice in the programme: once to extract intermediate values of the chord c/C, using the data table in the Single Transit Risk sheet; and to extract appropriate values of bird density using the table of flight height data in sheet 'Flightheights'. If N is greater than the length of the named range A, an error message appears, but N is allowed to be less than the range length.

pcoll (r, φ, updown)

Calculates the single transit collision risk at point (r, φ) in the rotor, using equation (3). The parameter updown may be either 'up' or 'down'. r is in dimensionless form, ie r= actual radius/rotor radius. φ is in degrees, where φ=0 is the top of the rotor.

pcoll_rav (r, updown)

Calculates the average of pcoll (r, φ, updown) over angles φ, in 10-degree increments.

pcollxy (x,y,updown)

Calculates the single transit collision risk at point (x,y) in the rotor, by converting (x,y) to (r,φ) and calling pcoll (r, φ, updown) . x and y are in dimensionless form ie x=X/R, y=Y/R (see Fig 7).

xareasum (y)

Calculates the length of a horizontal chord at height y

xrisksum (y,xinc,updown)

Integrates the collision risk times bird density along a horizontal chord at height y, using the interpolate function to evaluate the bird density at this height. The parameter xinc is the increment used for integration along the x-axis.

ydistsum (xinc,yinc,updown,flag)

When flag=0, integrates the collision risk times bird density over all heights from y= -1 to y= +1. This is the double integral within the 'collision integral' box in equation (9). The Collision integral is $(2/\pi)$ ydistsum.

When flag=1, integrates bird density only over all heights from y=-1 to y=+1. This is the double integral within the 'Flux integral' box in equation (10). The Flux integral is $(2/\pi)$ ydistsum .

The parameter yinc is the increment used for integration along the y axis.

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Three-dimensional tracking of a wide-ranging marine predator: flight heights and vulnerability to offshore wind farms

Ian R. Cleasby[1,2], Ewan D. Wakefield[1,3,4], Stuart Bearhop[2], Thomas W. Bodey[2], Stephen C. Votier[5] and Keith C. Hamer[1]*

[1]School of Biology, University of Leeds, Irene Manton Building, Leeds LS2 9JT, UK; [2]Centre of Ecology and Conservation, University of Exeter, Cornwall Campus, Falmouth TR10 9EZ, UK; [3]RSPB Centre for Conservation Science, Sandy SG19 2TL, UK; [4]UK and Institute of Biodiversity, Animal Health and Comparative Medicine, University of Glasgow, Glasgow G12 8QQ, UK; and [5]Environment & Sustainability Institute, University of Exeter, Cornwall Campus, Falmouth TR10 9EZ, UK

Abstract

1. A large increase in offshore wind turbine capacity is anticipated within the next decade, raising concerns about possible adverse impacts on birds as a result of collision risk. Birds' flight heights greatly influence this risk, yet height estimates are currently available only using methods such as radar- or ship-based observations over limited areas.

2. Bird-borne data-loggers have the potential to provide improved estimates of collision risk and here, we used data from Global Position System (GPS)-loggers and barometric pressure loggers to track the three-dimensional movements of northern gannets rearing chicks at a large colony in south-east Scotland (Bass Rock), located < 50 km from several major wind farm developments with recent planning consent. We estimated the foraging ranges and densities of birds at sea, their flight heights during different activities and the spatial variation in height during trips. We then used these data in collision-risk models to explore how the use of different methods to determine flight height affects the predicted risk of birds colliding with turbines.

3. Gannets foraged in and around planned wind farm sites. The probability of flying at collision-risk height was low during commuting between colonies and foraging areas (median height 12 m) but was greater during periods of active foraging (median height 27 m), and we estimated that ˜1500 breeding adults from Bass Rock could be killed by collision with wind turbines at two planned sites in the Firth of Forth region each year. This is up to 12 times greater than the potential mortality predicted using other available flight-height estimates.

4. *Synthesis and applications*. The use of conventional flight-height estimation techniques resulted in large underestimates of the numbers of birds at risk of colliding with wind turbines. Hence, we recommend using GPS and barometric tracking to derive activity-specific and spatially explicit flight heights and collision risks. Our predictions of potential mortality approached levels at which long-term population viability could be threatened, highlighting a need for further data to refine estimates of collision risks and sustainable mortality thresholds. We also advocate raising the minimum permitted clearance of turbine blades at sites with high potential collision risk from 22 to 30 m above sea level.

Key-words: climate change, collision risk, environmental impact, foraging, *Morus bassanus*, offshore renewables, population model, wildlife telemetry

Introduction

The number of offshore wind turbines is predicted to increase tenfold over the next decade, particularly in the shallow seas of Europe, making predicting the likely ecological impacts of these developments a conservation priority (Infield 2013). The impact of offshore wind farms on the internationally important populations of seabirds that forage in the seas around the UK is of particular concern (Masden *et al*. 2012; Furness, Wade & Masden

*Correspondence author. E-mail: k.c.hamer@leeds.ac.uk

2013). Evidence from both onshore and offshore wind farms shows that, for some birds, both direct mortality due to collisions and indirect disturbance could have significant negative impacts (Marques *et al.* 2014). However, estimates of mortality from collisions with turbines are frequently based on partial or subjective data (Ferrer *et al.* 2012). Moreover, accurate data on spatial, temporal and activity-specific variability in flight heights are lacking, especially for seabirds (Johnston *et al.* 2014).

To date, seabird flight heights have largely been estimated using ship-based surveys involving surveyors' subjective assessment by eye, the accuracy of which remains unquantified (Cook *et al.* 2012; Johnston *et al.* 2014). Radar can quantify flight heights and tracks much more accurately (Desholm *et al.* 2006), but provides data over only a limited area (maximum range typically 6 km) and is costly. An additional limitation of both ship-based surveys and radar is that the provenance, breeding status and in many cases age and sex of birds cannot be determined, yet these parameters are needed to model population-level consequences of predicted mortality more accurately.

A recent review of the vulnerability of marine bird populations to wind farms identified northern gannets *Morus bassanus* (Linn.) as a species of particular concern (Furness, Wade & Masden 2013). Britain and Ireland hold ~65% and 85% of the world and European breeding populations of gannets, respectively (Wanless, Murray & Harris 2005; Murray, Harris & Wanless 2015). Planning consent for several major offshore wind farms has just been granted in close proximity to major North Sea Gannet colonies (Furness & Wanless 2014). Tracking studies suggest that gannets typically travel at heights below 10 m but may ascend to above 20 m during foraging, as they search for prey and attain height, and therefore potential energy, prior to plunge-diving (Garthe *et al.* 2014). Foraging gannets may thus be at significant risk of colliding with wind turbine blades, which may sweep an area from 22 m above sea level at highest astronomical tide (the lowest blade clearance currently permitted; UK Maritime and Coastguard Agency 2008) to around 160 m above sea level or higher (Rothery, Newton & Little 2009; Furness, Wade & Masden 2013). However, collision risk is currently difficult to estimate because accurate data on flight heights and behaviour in proposed wind farm sites are lacking.

Global Position System (GPS) loggers are increasingly used to record the movements of birds (e.g. Wakefield *et al.* 2013), and can provide information on height as well as latitude and longitude. However, whilst they are accurate to <10 m in the horizontal plane, vertical measurement errors may be an order of magnitude greater (Ladetto *et al.* 2000). Alternatively, height may be estimated by recording atmospheric pressure and comparing it to that at sea level using the barometric formula (Berberan-Santos, Bodunov & Pogliani 1997; Wallace & Hobbs 2006). For example, the flight heights of tropical seabirds have been estimated by assuming that atmospheric pressure recorded at a reference location, such as a bird's breeding colony, is representative of that at tracking locations (Weimerskirch *et al.* 2005). Errors incurred using this approach are tolerably small in tropical regions, where atmospheric pressure usually varies little over wide areas, but at temperate latitudes, surface atmospheric pressure is much more labile in time and space, potentially introducing large errors. To obtain more accurate estimates of flight height in these areas, pressure loggers must therefore be calibrated frequently against pressure at sea level in their vicinity (Li, Harvey & Gallagher 2013). The reliability of such barometric altitude estimates can be assessed by examining the correlation with GPS altitude because, whilst individual GPS altitudes are unreliable, errors have a Gaussian distribution with a mean of zero (Whang & Ra 2008). Hence, a reliable pressure-logger-based estimate should correlate with GPS-derived altitude.

The Bass Rock (56°6′N, 2°36′W) supports the world's largest breeding population of gannets (~75 000 breeding pairs in 2014; Murray, Harris & Wanless 2015), yet several large wind farms have been scheduled for construction in its vicinity within the next 5 years (Marine Scotland 2014; Fig. 1). Taking this system as an example of one in which the potential effects of offshore wind farms on seabirds are of concern, we aimed to assess how the use of different flight-height estimation methods affects the predicted risk of birds colliding with turbines and hence the potential impact on seabird population viability. We combined GPS tracks of gannets breeding at the Bass Rock in three consecutive years (2010–2012) with data from bird-borne pressure loggers in 2011 and 2012 to estimate the foraging ranges and densities of birds at sea, their flight heights during different activities, and spatial variation in flight height and potential collision risk during foraging trips. We then compared these results to collision risks predicted using flight heights reported from ship-based and radar-based studies.

Materials and methods

STUDY SITE AND SAMPLING

Fieldwork took place at Bass Rock between mid-June and mid-August over three consecutive breeding seasons (2010–2012). Adult gannets raising chicks (n = 49 in 2010, 25 in 2011, 33 in 2012) were caught at the nest using a 6-m telescopic pole fitted with a wire crook (n = 55 birds in total; most were sampled in >1 year). Upon initial capture, birds were fitted with a metal British Trust for Ornithology ring and an individually numbered plastic colour-ring (Wakefield *et al.* 2013). An i-gotU 200/600 GPS logger (Mobile Action Technology, Taipei, Taiwan) weighing ~30 g was attached to the upper side of the central three tail feathers of each bird using Tesa© tape (Milton Keynes, UK). In addition, a subset of these birds caught in 2011 (n = 11) or 2012 (n = 5) was equipped with a pressure logger (MSR-145; MSR Electronics, Seuzach, Switzerland) weighing 18 g and taped to the underside of the central tail feather. Air pressure and temperature were logged at 1 Hz, which resulted in a pressure logger battery life of ≥7 days. GPS-loggers, programmed to record at either high

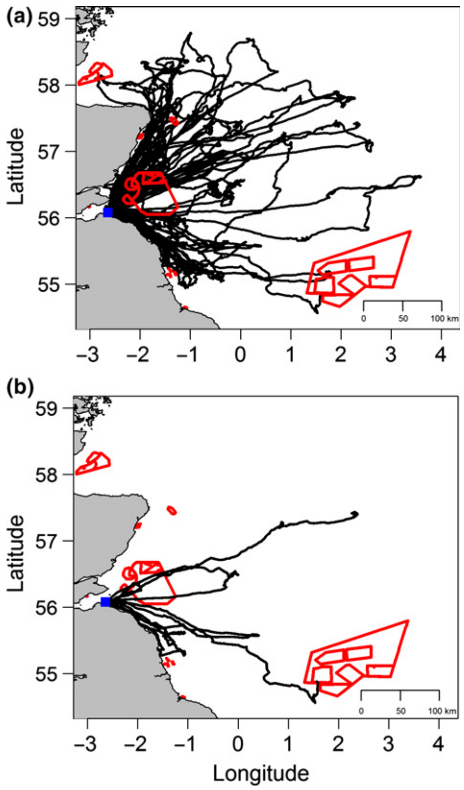

Fig. 1. Foraging tracks of chick-provisioning northern gannets from Bass Rock during June–August in 2010–2012 (black) and locations of proposed wind farms: (a) all tracks for birds equipped with Global Position System-loggers and altitude loggers (n = 54 trips by 16 birds); (b) tracks recorded at high resolution (1 Hz; n = 7 trips by 7 birds). For details of wind farm sites, see Marine Scotland (2014). Square shows location of Bass Rock.

resolution (1 Hz; i.e. once per second) or standard resolution (2-min intervals), were deployed along with pressure loggers. We collected high-resolution GPS data to discriminate behaviours over very short time intervals, allowing us to assess flight heights during different activities accurately. However, GPS battery life was ~20 h at this resolution, which is less than the average trip duration in some years (Hamer *et al.* 2007; Wakefield *et al.* 2015). Standard-resolution data were not used to examine activity-specific heights but covered much longer time periods, allowing us to track individual birds for up to 7 days and examine broad-scale spatial variation in flight heights during trips. Birds were recaptured and loggers retrieved after ≤10 days (total handling time ~15 min on each capture). After release, birds returned immediately to their nest and resumed normal behaviour. The maximum weight of loggers deployed on birds (48 g) was <2% of body mass (3 kg). Trip durations of instrumented birds were very similar to those of non-instrumented birds observed via a remote radio link using a Mobotix© (Uxbridge, UK) surveillance camera installed in the same area of the colony (Cleasby *et al.* 2015b), and previous studies (e.g. Hamer *et al.* 2000) found that similar devices had no discernible effects on trip durations or body mass.

BAROMETRIC ESTIMATION OF HEIGHT

We used the barometric formula (Berberan-Santos, Bodunov & Pogliani 1997; Wallace & Hobbs 2006) to estimate height z (m) above sea level:

$$z = -\frac{kT}{mg}\ln\left(\frac{P}{P_0}\right), \qquad \text{eqn 1}$$

where P_0 and P are the atmospheric pressures (Pascals) at sea level and at height z (m), respectively; k is the universal gas constant for air (8·31432 N m mol^{-1} K^{-1}); m is the molar mass of air (0·0289644 kg mol^{-1}); g is the acceleration due to gravity (m s^{-1}); and T is the temperature of the atmospheric layer between z_0 and z. Validation of this method using loggers placed at different known heights (see Appendix S1 in Supporting Information for details) indicated that the mean absolute error of height estimated by recording pressure was 0·88 m (range 0·32–1·92 m). Precision of height estimates (σ_z) decreased linearly as the interval, Δt, between observations of P_0 and P increased (Fig. S1). At Δt = 11·5 min (the median value used in our study), σ_z was 1 m.

For both the high-resolution and standard-resolution data sets, we used GPS data to categorize the behaviour of birds based on their location and speed of travel as (i) at the colony, (ii) in flight or (iii) on the water (Wakefield *et al.* 2013). Dives were identified by a rapid increase in pressure above ambient. To calculate birds' heights during periods of flight, pressure data P were smoothed using a running median calculated using a moving window of 11 observations (i.e. over a period of 11 s), centred on each successive location. Prior to smoothing, estimates of pressure ≤5 s before and ≤3 s after dives were removed, as there was typically high variation in pressure within these periods due to acceleration and turbulence. Similarly, following smoothing, we discounted short periods of flight (<3 min) and both the initial and final 60 s of each flight period. For the remaining cases, P_0 was defined where we had high-resolution GPS data as the value of P measured 5 s after the current flight period began. We assumed that whilst at this point the bird would still be flying at low altitude, initial Bernoulli effects associated with increasing airspeed during take-off (Chanson 2009) would have subsided. However, this degree of behavioural discrimination was not possible using the standard-resolution GPS data, so we defined P_0 in these cases as the value of P 10 s before the end of the previous period spent on the water. At the onset of a foraging trip, during the initial bout of flight, P_0 was defined as the pressure at the colony reduced to sea level using eqn. 1 (the height of the colony was known). We also assessed the accuracy of a simpler calibration method in which this value of P_0 was used to estimate height throughout foraging trips.

DATA ANALYSIS

Density of birds at sea

The utilization distribution (UD) of breeding birds from Bass Rock was estimated by calculating the kernel density of bird locations (data sets pooled across all 3 years). Kernel density was estimated on a 1-km^2 grid using the R package adehabitatHR (Calenge 2006). Following Wakefield *et al.* (2013), we then estimated the density of birds within each grid-square (d) as:

$$d = \hat{u}_{i,x}N, \qquad \text{eqn 2}$$

where $\hat{u}_{i,x}$ is the empirical probability density of use of cell x by bird i and N is the size of the colony (75 000 breeding pairs in 2014; Murray, Harris & Wanless 2015). The number of breeding pairs was used as a measure of N, rather than the number of breeding individuals, because one member of a pair usually remains at the colony attending the chick (Lewis *et al.* 2004). This approach generated an estimate of the number of breeding gannets expected in each grid cell during the peak chick-rearing period (June–August) each year.

Discrimination of foraging and commuting behaviour

Gannets primarily forage by plunge-diving during daylight (Hamer *et al.* 2009). Following Wakefield *et al.* (2013), we assumed therefore that daytime GPS locations characterized by slow flight speeds and high turning rates indicated foraging (excluding periods when birds were on the water; details and validation of discrimination criteria in Appendix S3). We used the 50% and 95% UDs of foraging locations to represent the core and wider foraging areas, respectively.

Variation in flight heights

We used high-resolution tracking data to examine flight heights during periods of commuting and foraging, and standard-resolution data (i.e. locations at 2-min intervals) to examine spatial variation in flight height (high-resolution data were more precise but included incomplete trips, which could have biased any spatial analysis of heights because birds seldom forage on the return legs of trips; Hamer *et al.* 2009). Flight height was modelled as a log-transformed response variable using a generalized additive mixed model (GAMM) with Gaussian errors in the R package mgcv (Wood 2006). There were some estimated heights ≤ 0 m (2·7% of values), and these were included in the analysis by adding the minimum estimated height (absolute value) to all cases (to permit log-transformation); data are then presented following back-transformation including subtraction of minimum estimated height in each case. The model included an isotropic spatial smooth of longitude and latitude, permitting spatial predictions of flight height (Wood 2003). Trip identity, nested within bird identity, was included as a random effect. To assess the decay in precision of pressure calibrations over long periods of flight, we also modelled the residual variance in flight height as a function of time elapsed since the most recent calibration of P_0 using the varPower variance function in the nlme R package (Pinheiro & Bates 2000). Flight-height estimates (including negative values) are quoted as medians plus interquartile ranges (IQR).

In addition, we used a binomial GAMM to examine spatial variation in the probability of a bird flying at collision-risk height, that is within the height envelope swept by wind turbine rotors. For this analysis, flight heights between 30 and 160 m above sea level (asl) were scored as 1 (at risk of collision) and all other observations were scored as 0 (not at risk of collision). The risk envelope used here represents a general case rather than a specific turbine design. Fixed and random explanatory covariates were as for the flight-height model described above.

Modelling collision risk

We used a mechanistic collision-risk model (Band 2012; the de facto standard in UK wind farm impact assessments) to assess the potential impact on gannets from Bass Rock of the two closest proposed wind farms within the Firth of Forth area (sites A and B in Fig. 2). Other wind farm developments are also planned, but our aim was to investigate the importance of accurate flight-height assessments for collision-risk modelling rather than to predict the potential cumulative impact of all proposed wind farms in the region. For comparison, we used both 'basic' and 'extended' versions of the model, treating flight-height data as categorical and continuous, respectively (see Appendix S2 for details).

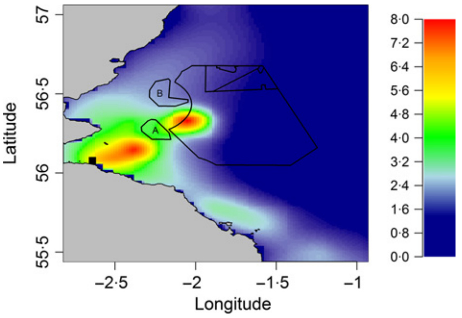

Fig. 2. Estimated density of chick-provisioning northern gannets (birds km^{-2}) in the vicinity of Bass Rock (black square) and the proposed wind farms close to the Firth of Forth (solid lines; sites A and B labelled). Based on all birds equipped with Global Position System-loggers ($n = 516$ trips by 55 birds).

We ran the models for putative turbine avoidance rates of 98·5% and 99%; a recent comprehensive review of behavioural responses to turbines by different species of seabirds (Cook *et al.* 2014) recommended an avoidance rate of 99% for use with gannets in the basic collision-risk model but considered there were insufficient data to derive a rate for use with the extended model. However, for species with more reliable data on turbine avoidance rates at different spatial scales, the recommended avoidance rate for use in the extended model was consistently 0·5–0·6% lower than that for use in the basic model (Table 7·2 in Cook *et al.* 2014). Hence, taking a precautionary approach, we considered that the lower avoidance rate may be more appropriate for the extended model, although further data are needed to confirm or refute this. To account for the fact that birds do not fly continuously at sea (Hamer *et al.* 2000), we multiplied collision-risk estimates in each case by the proportion of occasions when birds were classified as in flight at each site (average of 82%).

To examine how different methods of recording flight height affected collision-risk estimates, we also ran collision-risk models using published gannet flight heights estimated subjectively by human observers (Cook *et al.* 2012; Johnston *et al.* 2014) in conjunction with our spatial distribution data. Cook *et al.* (2012) modelled gannet flight heights, allowing estimation of the proportion of flights within different collision-risk envelopes, based on ship-based, land-based and radar-based surveys, whilst Johnston *et al.* (2014) presented a continuous gannet flight-height distribution estimated using observer data from 32 wind farm sites. In summary, we compare collision risks estimated: using altimeter data collected during this study in (i) the basic and (ii) the extended models; (iii) using data from Cook *et al.* (2012) in the basic model; and (iv) using data from Johnston *et al.* (2014) in the extended model.

Results

FORAGING TRACKS AND DENSITIES OF BIRDS AT SEA

The foraging ranges of birds extended up to 536·5 km from the colony (mean ± SD = 180·9 km ± 106·0,

$n = 516$ trips by 55 individuals) and encompassed proposed wind farm sites close to the Firth of Forth and elsewhere in the North Sea (Fig. 1). Gannet densities during 2010–2012 were high not only close to the Bass Rock but also within proposed wind farm sites close to the Firth of Forth (Fig. 2). Moreover, the foraging UD indicated that the core area of foraging activity (50% foraging UD) overlapped extensively with proposed wind farm sites close to the colony (Fig. 3).

FLIGHT HEIGHTS

High-resolution data

Data collected using GPS and pressure loggers allowed us to reconstruct the three-dimensional movements of birds (Fig. 4). Estimates of height obtained using pressure loggers were significantly positively correlated with GPS-estimated heights ($r = 0{\cdot}58$, $P < 0{\cdot}01$), with a median precision of ±1 m (see Materials and methods section). We are therefore confident that they accounted appropriately for spatiotemporal variation in atmospheric pressure at sea level. In contrast, using P_0 values recorded at the colony at the beginning of each trip gave estimates that were about 40% higher on average and poorly correlated with GPS-estimated heights ($r = 0{\cdot}23$, n.s.). We therefore deemed this technique unreliable and did not consider it further.

Flight height was bimodal, with significantly lower heights during commuting bouts (median = 11·5 m, $n = 738$, IQR = 6·1–21·7 m) than during foraging bouts (median = 26·5 m, $n = 464$, IQR = 9·7–46·1 m; randomization test, $P < 0{\cdot}001$; see Appendix S4 for details). Hence, foraging birds tended to be at or around collision-risk height (Fig. 5). Although the second peak was discernible across all locations visited by birds (Fig. 5a), it was more prominent within the locations of proposed wind farms (Fig. 5b), where a risk envelope of 20–120 m

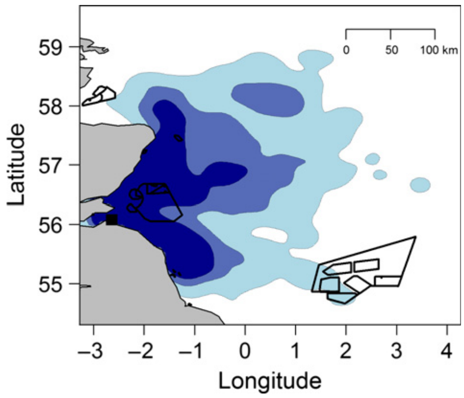

Fig. 3. Foraging utilization distribution (UD) of chick-provisioning northern gannets tracked from Bass Rock (black square) during June–August in 2010–2012, together with locations of proposed wind farm sites. Contours show 50% (darkest), 75% (intermediate) and 95% (palest) UDs.

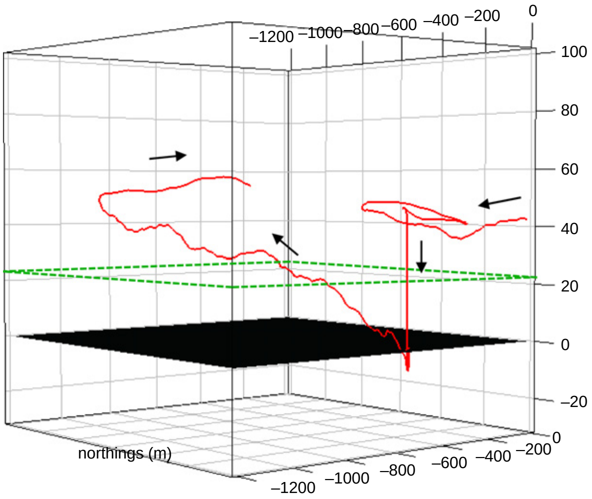

Fig. 4. Five-minute section of a three-dimensional foraging track of a gannet breeding at Bass Rock, recorded using Global Position System (x, y) and pressure difference (z). The bird moves from right to left, circling once, before plunge-diving to 6 m below sea level. On returning to the surface, it takes off and again begins circling. The dotted green line indicates that the bird spent most of this time above the minimum collision-risk height (22 m above sea level).

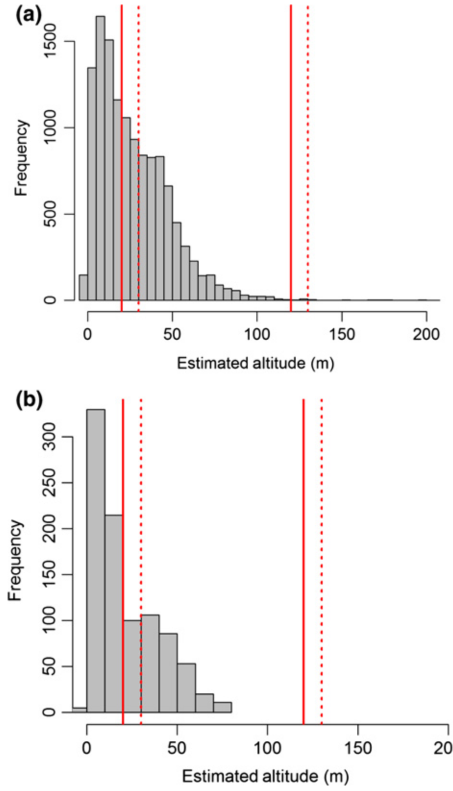

Fig. 5. Distribution of estimated flight heights for (a) all locations visited by birds ($n = 16$ birds, 12989 observations) and (b) area encompassed by proposed wind farms close to the Firth of Forth ($n = 11$ birds, 962 observations; five birds equipped with altitude loggers never visited this area). Vertical lines denote two potential collision-risk envelopes (solid lines, 20–150 m above sea level; dashed lines, 30–160 m above sea level).

asl contained ~10% more observations than one of 30–130 m asl. There was no significant difference between flight heights determined using high-resolution GPS data (median = 13·3 m, n = 1202 height estimates, IQR = 6·9–34·6 m) and those determined using the much larger standard-resolution data set (median = 22·0 m, n = 12621 height estimates, IQR = 10·1–40·0 m; randomization test, P = 0·5; see Appendix S5).

Spatial analysis

There was significant spatial variation in flight heights of birds (Table 1) and in the probability of flying at collision-risk height (Table 2). Areas of high average height were all >100 km from the colony, with lower average heights occurring mainly, though not entirely, inshore and closer to the colony (Fig. 6). There was also significant variation among individuals in flight height (Table 1) and in the probability of flying at collision-risk height (Table 2). Although the precision of our height estimates decreased linearly as the interval between observations of P_0 and P increased (Fig. S1), the time elapsed since measuring P_0 had no effect on the variance of flight-height estimates and including this term in the model of flight height did not improve its performance (Table 1).

COLLISION-RISK ESTIMATES

Mortality predicted using combined altimeter and GPS data was 11·6 times that obtained using the overall distribution of flight heights estimated by observers at sea combined with GPS data (cf. extended models, Table 3) and 5·9 times that obtained by assuming that 5% of birds fly at collision-risk height, based on observer and radar data (cf. basic models, Table 3). Using combined altimeter and GPS data, the basic model with 99% avoidance, which we consider the most reliable estimate, suggested that ~300 breeding adults could be killed per month during the chick-rearing period each year as a result of collisions with turbines at the two planned wind farm sites included in the model (Table 3).

Table 2. Generalized additive model of the probability of gannets flying within a collision-risk envelope of 30–160 m)

Variable	Estimate	Lower 95% CI	Upper 95% CI	*P*-value	ΔAICc
Fixed effects					
Intercept	−0·78	−1·13	−0·42	<0·001	NA
Isotropic smoothers					
s (Lon, Lat)	d.f. = 26·29			<0·001	+948
Random effects					
Trip ID	0·72	0·55	0·94		+98
Bird ID	0·53	0·29	0·96		+592

Discussion

DATA COLLECTION

We found that standard-resolution and high-resolution GPS data (recorded at intervals of 2 min and 1 Hz, respectively), combined with pressure data collected at 1 Hz, resulted in similar gannet flight-height estimates. The use of the standard-resolution GPS-tracking may resolve changes in behavioural state less finely but allows birds to be tracked for longer periods. Time since last calibration had little effect on the precision of our flight-height estimates, perhaps because atmospheric conditions were relatively quiescent during our study. However, it would be desirable to establish how precision decays with this parameter in more dynamic weather conditions, for which further study would be required. Our data show that calibration using pressure recorded in the colony at the beginning of the trip resulted in biased and unreliable estimates of height, so we do not recommend this method, at least in temperate regions or for species that range widely.

The data presented here were all obtained in relatively calm periods, during mid-summer, in years of near-average prey availability (inferred from relative foraging distances; median ± IQR = 175 ± 70 km in 2010, 109 ± 110 km in 2011, 160 ± 145 km in 2012, compared

Table 1. Generalized additive model of gannet flight height (n = 12989 locations from 54 foraging trips by 16 birds)

Variable	Estimate	Lower 95% CI	Upper 95% CI	*P*-value	ΔAICc
Fixed effects					
Intercept	3·02	2·80	3·24	<0·001	NA
Isotropic smooths					
s (Lon, Lat)	d.f. = 21·98			<0·001	+508
Random effects					
Trip ID	0·36	0·23	0·57		+640
Bird ID	0·38	0·30	0·48		+1360
Variance functions					
Time elapsed since P_0 measured	−0·001	−0·004	0·004		−136

ΔAICc is the change in the Akaike Information Criterion (corrected for finite sample sizes) associated with deleting a term from the best fitting model; +ΔAICc indicates that the model fit is worse after deleting a term; ΔAICc <2 indicates that removing the term has little effect on the model. d.f., estimated degrees of freedom for the isotropic smooth, reflecting sinuosity.

to long-term average of 155 km, range of annual medians = 105 ± 133–238 ± 193 km; Hamer *et al.* 2007; Wakefield *et al.* 2015). The foraging ranges of gannets vary with population size and per capita prey availability (Hamer *et al.* 2007; Wakefield *et al.* 2013), and their foraging behaviour also varies in relation to weather conditions and feeding opportunities including potential prey species (Amélineau *et al.* 2014; Cleasby *et al.* 2015b). Hence, the potential occurrence of gannets in the turbine envelope of different proposed wind farm sites will also vary with these factors resulting in both spatial and temporal variability in collision risk. Moreover, foraging ranges of breeding birds are frequently longer during incubation than chick-rearing, and the movement patterns of juvenile and immature birds, non-breeding adults and failed breeders are only poorly understood but could also encompass much larger foraging areas than those of breeding birds (Votier *et al.* 2011). Foraging ranges and behaviour also differ between males and females (Cleasby *et al.* 2015b), potentially resulting in an asymmetry in male–female collision risks. In addition, we found that flight heights varied significantly among individuals, in keeping with consistent individual variation in foraging locations, movements, diets and diving behaviour (Patrick *et al.* 2015; Wakefield *et al.* 2015), producing likely marked differences among individuals in collision risk. Further data are needed on all of these factors in order to make a full assessment of the collision risks posed to gannets and other potentially vulnerable species by offshore wind farm developments.

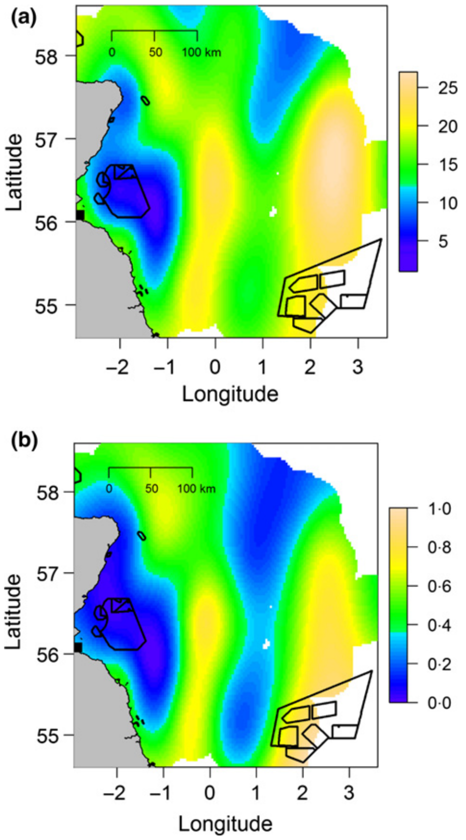

Fig. 6. Variation in (a) mean flight height (m) and (b) the probability of flying within a collision-risk envelope of 30–160 m, across the sampled foraging distribution of gannets breeding at Bass Rock (black square). Locations of proposed wind farms within the foraging range are also shown.

Table 3. Predicted potential collisions per month with wind turbines at two recently consented offshore wind farms, for gannets rearing chicks at Bass Rock

	Flight-height data			Avoidance rate	
Model	Type	Recording method	Source	98·5%	99%
Basic	Categorical*	Ship-/ shore-based observers and radar	Cook *et al.* (2012)	80	**53**
	Continuous	Pressure loggers	This study	467	**311**
Extended	Continuous	Ship-based observers	Johnston *et al.* (2014)	**26**	16
	Continuous	Pressure loggers	This study	**304**	203

Figures in bold indicate rates considered most appropriate based on data in Cook *et al.* (2014).
*Taking the proportion of flights within the modelled collision-risk envelope (29–159 m asl) to be 5%; estimated from height distribution of survey data (figure 3·6 in Cook *et al.* 2012).

FORAGING AREAS AND FLIGHT HEIGHTS

Using high-resolution (1 Hz) data, we estimated that gannets flew at a median height of 12 m whilst commuting and 27 m during foraging bouts, which corresponds reasonably well with a previous estimate of 37 m whilst foraging (Garthe *et al.* 2014). In contrast, flight heights estimated from ship-based surveys are much lower, with fewer than 10% of flights exceeding 20 m (Cook *et al.* 2012). This discrepancy may partly reflect a high proportion of survey data from sites in the southern North Sea where gannets are mainly seen during migration, when they may spend little time foraging. Radar-based estimates were also low (mean height *c.* 10 m; Parnell *et al.* 2005), probably because they were site-specific with a maximum range within *c.* 6 km of land, meaning that these estimates are likely to represent a high proportion of birds commuting along the coast.

In keeping with spatial density estimates from ship-based surveys, areas with the highest density of gannets at sea were close to the colony (Camphuysen *et al.* 2012) and overlapped proposed wind farm sites close to the Firth of Forth. Many of these birds were apparently commuting to or from foraging areas further from the colony, at heights typically below 15 m, resulting in a relatively low probability of flying at collision-risk height. However, gannets also forage during the outward portions of trips (Hamer *et al.* 2009), increasing their potential collision risk. Combined with the high density of birds close to the colony, this resulted in a large number of potential collisions within proposed wind farm sites despite a low average flight height. Further from the colony, average heights were greater as a result of relatively little commuting flight in the distal sections of trips, probably combined with spatial variation in foraging behaviour; birds rely on momentum to attain depth during V-shaped dives and these were significantly deeper in stratified water offshore than in mixed inshore waters close to the colony (Cleasby *et al.* 2015b), suggesting that birds were diving from greater heights offshore.

POTENTIAL POPULATION-LEVEL EFFECTS

Using our data on flight heights, the basic Band (2012) collision-risk model with 99% avoidance and the extended model with 98·5% avoidance yielded very similar estimates for the two sites in our analysis, predicting that during chick-rearing, 311 and 304 breeding adults, respectively, could be killed each month. There is great uncertainty over actual avoidance rates (Cook *et al.* 2014), but taking a figure of ~300 collisions per month and assuming similar foraging behaviour during incubation and chick-rearing, the cumulative predicted mortality during the breeding season (mid-April to mid-September) each year would be ~1500 adults.

To put these data into perspective, a population model for gannets at Bass Rock, based on a population of 48 000 breeding pairs in 2004, suggested that additional mortality of 2000 birds per year, estimated to comprise 1400 adults and 600 immature birds, would be sufficient to cause a sustained decrease in breeding population size (WWT Consulting 2012). This threshold may have been underestimated, since the breeding population at Bass Rock has apparently increased by an average of 2700 pairs per year since then (Murray, Harris & Wanless 2015). Nonetheless, our estimate of predicted adult mortality due to collision with turbines is sufficiently high to cause concern. Moreover, it may be conservative: adults are present at the colony for 9 months each year (Nelson 2002), they may be killed at other proposed wind farms not considered in our study, and we assume a minimum blade clearance of 30 m, whereas this may be to be up to 8 m lower (Marine Scotland 2014). Hence, there is an urgent need for further data, both for gannets and for other high-priority species such as large gulls, to refine collision-risk estimates and mortality thresholds for long-term population viability, and for strategic monitoring at key sites to determine whether predicted collision mortality is realized and has significant effects on population trajectories. We also strongly recommend that, at sites with high potential collision risk, the minimum permitted clearance of turbine blades should be raised from 22 to 30 m above sea level.

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Data accessibility

GPS logger and barometric logger data are available free of charge via Birdlife International's Seabird Tracking Database (http://seabirdtracking.org/mapper/contributor.php?contributor_id=204) and the Dryad Digital Repository doi: 10.5061/dryad.1ds1q (Cleasby *et al.* 2015a).

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Appendix S1. Validation of barometric altitude estimates.

Appendix S2. Discrimination of foraging and commuting behaviour.

Appendix S3. Statistical comparison of foraging and commuting flight heights.

Appendix S4. Statistical comparison of flight heights calculated using high-resolution and standard-resolution data.

Appendix S5. Modelling collision risk.

Table S1. Data used in mechanistic collision-risk models.

Fig. S1. Precision of height estimates based on pressure recorded at the Bass Rock vs. interval between pressure observations.

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FEATURE ARTICLE

Sexual segregation in a wide-ranging marine predator is a consequence of habitat selection

Ian R. Cleasby[1,2,*], Ewan D. Wakefield[1,7], Tom W. Bodey[2], Rachel D. Davies[1], Samantha C. Patrick[3,4], Jason Newton[5], Stephen C. Votier[6], Stuart Bearhop[2], Keith C. Hamer[1]

[1]School of Biology, University of Leeds, Leeds LS2 9JT, UK
[2]Centre of Ecology and Conservation, University of Exeter, Cornwall Campus, Penryn TR10 9EZ, UK
[3]School of Natural and Social Sciences, University of Gloucestershire, Swindon Road, Cheltenham GL50 4HZ, UK
[4]Department of Zoology, South Parks Road, University of Oxford, Oxford OX1 3PS, UK
[5]NERC Life Sciences Mass Spectrometry Facility, SUERC, East Kilbride G75 0QF, UK
[6]Environment and Sustainability Institute, University of Exeter, Cornwall Campus, Penryn TR10 9EZ, UK

[7]*Present address:* Institute of Biodiversity, Animal Health and Comparative Medicine, University of Glasgow, Glasgow G12 8QQ, UK

ABSTRACT: Sexual segregation, common in many species, is usually attributed to intra-specific competition or habitat choice. However, few studies have simultaneously quantified sex-specific foraging behaviour and habitat use. We combined movement, diving, stable isotope and oceanographic data to test whether sexual segregation in northern gannets *Morus bassanus* results from sex-specific habitat use. Breeding birds foraging in a seasonally stratified shelf sea were tracked over 3 consecutive breeding seasons (2010–2012). Females made longer trips, foraged farther offshore and had lower $\delta^{13}C$ values than males. Male and female foraging areas overlapped only slightly. Males foraged more in mixed coastal waters, where net primary production (NPP) was relatively high (>3 mg C m^{-2} d^{-1}) and sea-surface temperature (SST) was relatively low (<10°C). Males also tended to use areas with higher SSTs (>15°C) more than females, possibly as a consequence of foraging in productive mixed waters over offshore banks. Females foraged most frequently in stratified offshore waters, of intermediate SST (12–15°C), but exhibited no consistent response to NPP. Sex-specific differences in diving behaviour corresponded with differences in habitat use: males made more long and deep U-shaped dives. Such dives were characteristic of inshore foraging, whereas shorter and shallower V-shaped dives occurred more often in offshore waters. Heavier birds attained greater depths during V-shaped dives, but even when controlling for body mass, females made deeper V-shaped dives than males. Together, these results indicate that sexual segregation in gannets is driven largely by habitat segregation between mixed and stratified waters, which in turn results in sex-specific foraging behaviour and dive depths.

Male gannet *Morus bassanus* about to depart on a foraging trip.
Photo: Keith Hamer

KEY WORDS: Competition · Foraging behaviour · Oceanography · Wildlife telemetry · Northern gannet · *Morus bassanus*

*Corresponding author: i.r.cleasby@gmail.com

INTRODUCTION

Segregation of males and females occurs in a wide range of animal species and over a wide variety of spatiotemporal scales (Ruckstuhl & Neuhaus 2005, Wearmouth & Sims 2008, Alves et al. 2013, Levin et al. 2013). It is particularly common in marine central-place foragers during the breeding period, when foraging ranges are restricted by the need to return repeatedly to the breeding site to care for offspring (Page et al. 2005, Weimerskirch et al. 2009). Segregation is thought to reflect niche specialisation or competitive exclusion by the dominant sex (Phillips et al. 2004) but could alternatively be a consequence of differing parental roles (Thaxter et al. 2009, Elliott et al. 2010) or differences in the nutritional requirements of males and females as proposed by Lewis et al. (2002).

In many species, between-sex differences in isotopic signatures suggest that males and females exploit different prey species or habitats (Bearhop et al. 2006, Phillips et al. 2011). However, while sex-specific habitat use has been widely documented in terrestrial species (Ruckstuhl & Neuhaus 2005), between-sex differences in habitat use in relation to dynamic oceanographic features have rarely been quantified (but see Pinet et al. 2012). Moreover, in the marine environment, sexual segregation may occur in the vertical as well as horizontal dimension, especially in diving species (Kato et al. 2000, Lewis et al. 2002). Such vertical niche segregation may result from between-sex differences in diving capabilities mediated by morphology or physiology or as a consequence of habitat choice (Le Boeuf et al. 2000). Thus, a detailed understanding of sex-specific differences in foraging behaviour requires a combination of horizontal tracking and dive data with environmental data (Takahashi et al. 2008, Thaxter et al. 2009).

Many air-breathing diving species perform dives with 2 distinct profiles: V-shaped and U-shaped. V-shaped dives tend to be shallower and of shorter duration than U-shaped dives, which typically involve underwater propulsion (Garthe et al. 2000, Ropert-Coudert et al. 2009a). Both the dive type and depth attained may be influenced by intrinsic factors such as an individual's mass as well as extrinsic factors, including the type of prey and its depth distribution, which in turn may be influenced by the presence of other predators and the structure of the water column (Elliott et al. 2008, Machovsky Capuska et al. 2011). In addition, recent work demonstrates that dive type is determined before birds enter the water (Machovsky Capuska et al. 2013), suggesting that gannets use visual cues pre-dive in order to optimize their foraging performance. Therefore, sex-specific differences in diving behaviour should arise as a consequence of habitat segregation as individuals adjust their foraging technique for different prey or habitats (Garthe et al. 2000).

Northern gannets *Morus bassanus* (henceforth gannets) are medium-range foragers, typically travelling tens to hundreds of kilometres from their colonies to obtain food for themselves and their offspring (Hamer et al. 2000, Wakefield et al. 2013). Adults exploit a wide range of prey but feed predominantly by plunge-diving for shoaling fish within the upper 30 m of neritic waters (Garthe et al. 2000). In addition, gannets also scavenge for discards from fishing vessels (Hamer et al. 2007, Votier et al. 2010, 2013). Gannets tracked from a large colony at Grassholm (~40 000 breeding pairs) in the Celtic Sea showed marked sexual divergence in spatial distribution and diet (Stauss et al. 2012). Males made greater use of discards from fishing vessels and foraged closer inshore than females, although it was not clear whether females fed in different areas from males as a consequence of habitat selection or whether they were displaced from fishing vessels by competition with males. In addition, time-depth recorder (TDR) data from birds breeding at Bass Rock (~60 000 pairs) in the North Sea showed that females dived to greater depths than males, suggesting that they may have been selecting different prey than males or that heavier females were able to dive deeper (Lewis et al. 2002). Gannets from both colonies forage in relatively shallow regimes (i.e. <200 m), shelf regions in which the oceanography is dominated by tidal processes (Simpson et al. 1981). In the summer months, deeper waters become thermally stratified, while coastal waters and those overlaying shallow banks remain mixed due to tidal stirring. These 2 regimes are separated by tidal mixing fronts (Simpson et al. 1981, Barnes & Hughes 1988). Birds from Bass Rock forage in association with one such front, located ~50 km offshore (Skov et al. 2008, Hamer et al. 2009), which we term the East Scotland tidal mixing front. The sex-specific behaviour of marine predators with respect to tidal mixing regimes has rarely been investigated. However, the foraging behaviour of many marine predators, including gannets, differs between mixed and stratified waters (Takahashi et al. 2008, Hamer et al. 2009, Camphuysen et al. 2012). Consequently, sexual niche segregation across tidal regimes may shape sex-specific differences in diving behaviour and optimal foraging strategies.

Here, we aimed to quantify sexual differences in the foraging behaviour and habitat use of gannets foraging in the North Sea. We use a combination of horizontal and vertical tracking, stable isotope and environmental data, collected over 3 consecutive breeding seasons at Bass Rock, to address the hypotheses that during foraging: (1) sexual segregation is driven by sex-specific habitat selection; (2) habitat segregation occurs across tidal mixing regimes; and (3) sex-specific foraging behaviour arises as a consequence of habitat segregation as birds adapt their foraging behaviour to the local foraging environment.

MATERIALS AND METHODS

Study site and sampling

Fieldwork took place on Bass Rock, UK (56° 6′ N, 2° 36′ W), between mid-June and mid-August in 2010 to 2012. We used a 6 m telescopic pole fitted with a wire crook to catch adult gannets attending young chicks at the nest. Upon capture, we fitted birds with a metal British Trust for Ornithology ring and an individually numbered plastic colour ring. We then recorded their body mass to the nearest 25 g using a spring balance and took 1 ml of blood from the tarsal vein. Shortly after sampling, blood samples were separated into red blood cells (RBCs) and serum by centrifuging and stored frozen prior to stable isotope analysis and genetic sexing.

Instrumentation

A GPS logger (i-gotu 200 or 600; Mobile Action Technology) weighing 30 g was attached to the upper side of the 3 central tail feathers of each bird (n = 55 birds in total; see Table S1 in the Supplement at [redacted] using Tesa© tape. GPS loggers were programmed to record location data at 2 min intervals. In addition, a subset of birds caught in 2011 and 2012 was fitted with a TDR (Table S1), which was taped to the underside of the central tail feathers. TDR models were either G5 (CEFAS Technology) or MSR145 (MSR Electronics), weighing 2.5 g and 18 g, respectively). G5 loggers recorded pressure at 10 Hz when the bird was submerged (>1.5 m depth), whilst MSR145 loggers recorded pressure continuously at 1 Hz. Total handling time was ~15 min, and after release, birds returned almost immediately to their nest and resumed normal behaviour. Birds were tracked for 4 to 7 d (Fig. S1 in the Supplement at [redacted] which time they were recaptured and the loggers retrieved. The maximum weight of loggers deployed on birds (48 g) was <2% of body mass (3 kg), and previous studies (Hamer et al. 2007, 2009) recorded that such loggers had no discernible effects on trip durations or body masses of birds. Similarly, we found that trip durations of instrumented birds in 2010 (mean ± SD = 23.9 ± 12.6 h, n = 211 trips from 52 birds) were very similar to those of non-instrumented birds observed via a remote radio link using a Mobotix© surveillance camera installed in the same area of the colony (mean = 23.5 ± 14.4 h, n = 636 trips from 27 birds).

Trip metrics and spatial usage

We modelled trip duration (h), total distance travelled during each trip (km) and time spent at the colony between trips using Bayesian linear mixed effects models (BLMM) with the R package MCMCglmm (Hadfield 2010, R Core Team 2012). All variables were log-transformed prior to analysis to ensure normality. Sex and year, and their 2-way interactions, were included as explanatory covariates, and a random intercept was specified for each bird. Minimum adequate models were selected according to their deviance information criterion scores (Lunn et al. 2013).

For each year and sex, we estimated 95 and 50% utilization distributions (UDs) using kernel analysis conducted with the R package adehabitatHR (Calenge 2006). The extent of within-year overlap between male and female home ranges was estimated using Bhattacharyya's affinity (BA; Bhattacharyya 1943), which ranges from 0 (no overlap) to 1 (complete overlap). Using BA as our measure of spatial overlap, we used a randomization procedure to test the null hypothesis that there was no difference in the spatial distribution of males and females each year (see the section 'Using BA and randomization to test for overlap' in the Supplement for additional information).

Stable isotope analysis

To examine sex-specific dietary niches during the breeding season, we analysed stable carbon ($\delta^{13}C$) and nitrogen isotope ratios ($\delta^{15}N$) RBCs. Avian erythrocytes have a lifespan of 28 to 45 d (Rodnan et al. 1957) and hence represent assimilated prey over the previous 4 to 6 wk. In general, δ^{15}N increases by 3 to 5‰ with each trophic level, whereas δ^{13}C typically reflects differences between water masses. Isotope analysis was conducted at the Natural Environment Research Council (NERC) Life Science Mass Spectrometry Facility, East Kilbride, UK. We modelled δ^{15}N and δ^{13}C as response variables in a Bayesian multivariate analysis including year and sex as well as their 2-way interaction as predictors; bird identity was included as a random intercept (further details in the 'Stable isotope analysis' section of the Supplement).

Habitat selection

Environmental covariates

The distribution of forage fish in the North Sea cannot currently be measured simultaneously over all scales at which we tracked gannets in this study (seconds to weeks and metres to 100s of km). However, foraging seabirds show marked associations with particular habitats that concentrate prey in relatively large or predictable aggregations (Wakefield et al. 2009, 2014). Previous studies have shown that northern gannets associate with shelf sea fronts and areas of high primary production (Skov et al. 2008, Votier et al. 2010). We therefore described gannet habitat using sea surface temperature (SST, °C, Fig. 1a, and see Fig. S2 in the Supplement) and net primary production (NPP, mg C m^{-2} $d^{-1,}$ Figs. 1b & S2). Monthly NPP data were estimated on a 1 km^2 grid using data from the Aqua-MODIS sensor. Monthly mean SST data were supplied on a 4 km^2 grid from the AVHRR sensor. All environmental data were supplied by the Natural Environment Research Council Earth Observation Data Acquisition and Analysis Service, Plymouth, UK.

Habitat selection functions

We used habitat selection functions (HSFs) to test whether males and females differed in their habitat usage. HSFs compare habitat usage to availability using a logistic-regression based approach with a case-control design (Aarts et al. 2008). The case-control design generates a binomial response ($\hat{u}_i$) which takes the value 1 for the i^{th} data point if it belongs to the tracking dataset or 0 if belongs to the control dataset. Tracking locations ($\hat{u}_i = 1$) were generated by selecting animal locations that were associated with putative foraging behaviour defined on the basis of movement indices such as speed, acceleration and track tortuosity (see Wakefield et al. 2013 for further details). The control dataset comprised 5 pseudo-

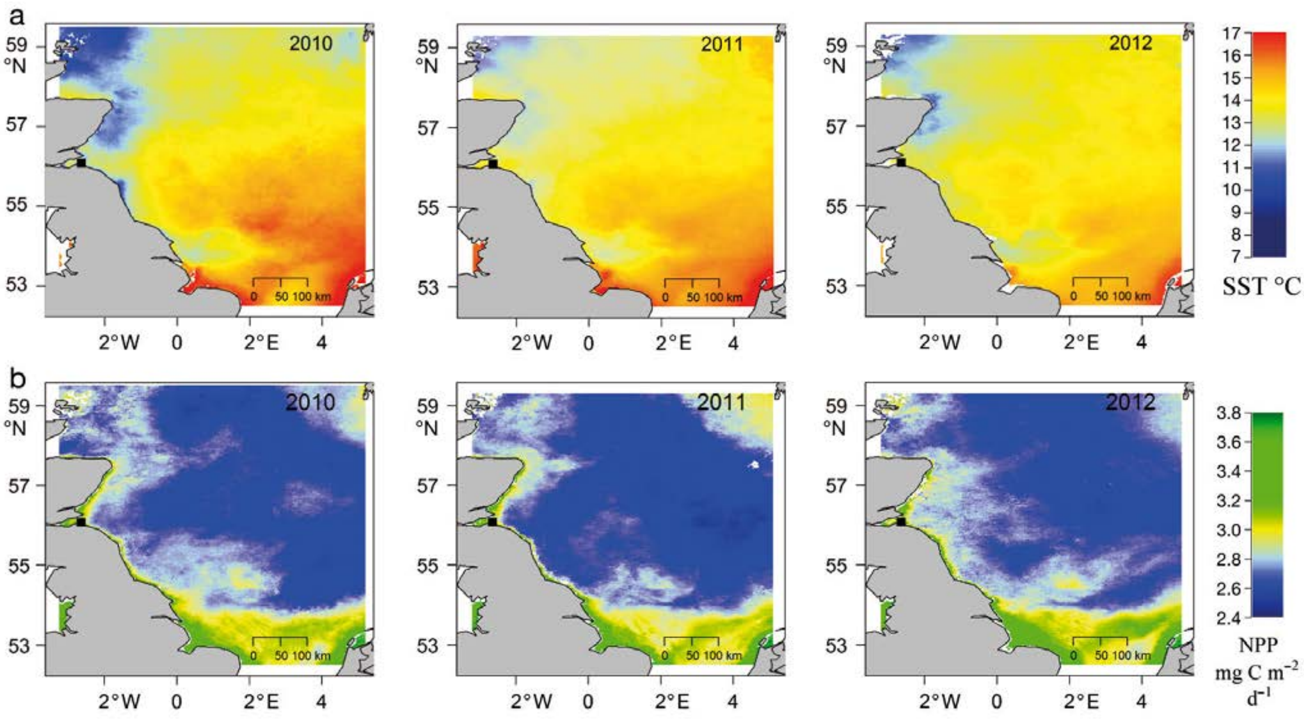

Fig. 1. Plots of the average (a) sea surface temperature (SST) and (b) net primary production (NPP) recorded during the breeding season in the foraging range of northern gannets *Morus bassanus* from Bass Rock, Scotland, UK (■) for each study year

absence locations ($\hat{u}_i = 0$) for each observed foraging location. Pseudo-absences were assigned to the same month as the foraging location with which they were paired and were generated randomly within the boundaries of the population's 95% UD (i.e. the UD for both sexes combined, calculated separately for each year) using a uniform spatial Poisson process.

Foraging HSFs were modelled using a binomial generalized additive mixed model (GAMM) in the mgcv R package (Wood 2006). To facilitate biological interpretation and to keep computer running time within reasonable limits (~2 h to fit each model), we fitted separate models for each study year. Environmental covariates were fitted either as parametric variables, a single smoother for both sexes or as separate smoothers for each sex. The inclusion of smoothers allows for the possibility of non-linear responses to environmental covariates, and fitting separate smoothers for each sex allowed the response of males and females to differ. A random intercept was specified for each bird. In order to account for residual spatial auto-correlation, we also included a thin-plate regression spline based upon the spatial coordinates of each data point (further details in the 'GAMM analysis' section of the Supplement).

Diving behaviour

Using the TDR data, we categorised dives as either V-shaped (bottom time ≤2.7 s) or U-shaped (bottom time >2.7 s; Garthe et al. 2000; see Fig. S3 and the 'TDR dive data' section of the Supplement for details). Dive locations were estimated by combining TDR and GPS data. We used a binomial GAMM to model the probability of dives being U- or V-shaped and a Gaussian GAMM to model maximum depth attained during either V- or U-shaped dives. The maximum depth of U-shaped dives was log-transformed to increase normality (no transformation was required for V-shaped dive depth). In each model, we considered sex, body mass and the interaction between them as explanatory variables. In addition, each model included a smoother for time of day to explain diurnal variation in behaviour and a spatial smoother to account for spatial auto-correlation. Random intercepts were specified for year and for trip identity nested within bird identity. A continuous-time correlation structure was included to account for temporal auto-correlation between dives. Throughout our analysis, minimum adequate models for all GAMMs were selected by backwards selection, using *K*-folds cross-validation (where $K = 5$ equal-sized subsamples of the data; more details in the 'GAMM analysis' section of the Supplement).

RESULTS

Female gannets were ~200 g heavier than males on average (mean ± SD; female: 3021 ± 315 g; male: 2810 ± 190 g; Student's *t*-test = 3.71, df = 47, $p \leq 0.001$).

Spatial distribution of males and females

Males made significantly shorter trips than females, both in duration ($\beta_{\text{SEX}} = -0.14$ log (h), 95% Bayesian credible interval, CRI = −0.24 to −0.041, p = 0.0081, n = 493 trips from 55 birds; Table 1 and see Table S2 in the Supplement) and total distance travelled per trip ($\beta_{\text{SEX}} = -0.19$ log (km), 95% CRI = −0.34 to −0.035 p = 0.046; Table 1). Thus, the duration of male trips was 13% (95% CRI = 4–21%) shorter than that of females, and the distance males travelled was 17% (95% CRI = 3–28%) less than that travelled by females. In general, females foraged more frequently in offshore waters to the east of the colony, whereas males foraged most frequently in coastal waters to the north-east and south-east of the colony (Figs. 2 & S1). Consequently, the overlap between male and female 50 and 95% UDs was significantly lower than the null expectation each year, except for the 50% UD in 2011, which was marginally significant (p = 0.052) and the 95% UD in 2012 (p = 0.083; Table 2).

Table 1. Summary of foraging trip and dive metrics for northern gannets *Morus bassanus* at Bass Rock, Scotland, UK; n: number of trips or dives

Variable	Sex	Mean (SD)	Range	n
Trip duration (h)	Male	21.40 (12.02)	0.91–69.76	493
	Female	24.14 (12.77)	3.71–95.11	
Trip length (km)	Male	454.63 (277.79)	27.32–1265.72	493
	Female	512.56 (262.74)	69.64–1461.62	
Time at colony between trips (h)	Male	10.31 (8.53)	1.07–24.76	379
	Female	10.11 (8.59)	1.07–48.51	
Maximum V-dive depth (m)	Male	4.40 (1.92)	1.52–11.03	4274
	Female	6.69 (2.01)	1.52–9.25	
Maximum U-dive depth (m)	Male	7.23 (4.06)	1.64–27.75	2036
	Female	7.59 (3.78)	1.70–25.96	

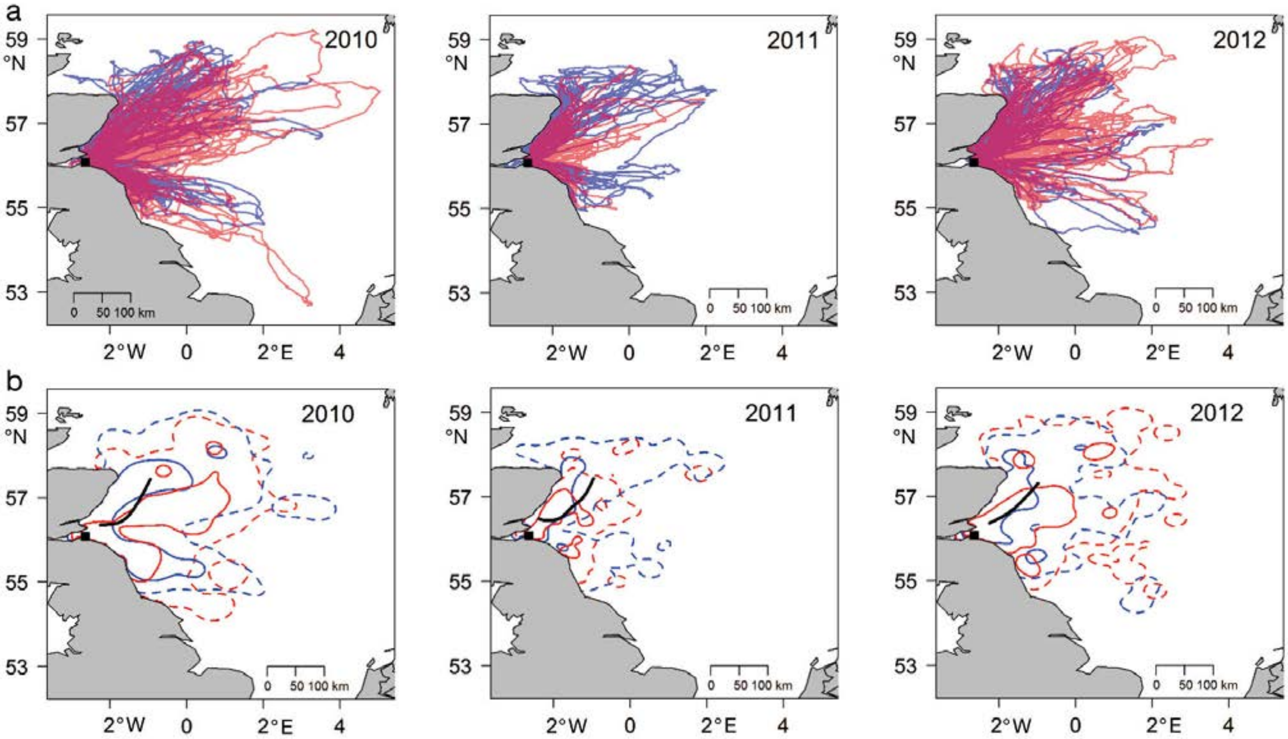

Fig. 2. Foraging ranges of male (blue) and female (red) northern gannets *Morus bassanus* during the breeding season in each study year. (a) Raw location data; (b) kernel density based utilization distributions at 95% (dotted lines) and 50% (solid lines). Bass Rock, Scotland, is shown as a square (■), and the approximate position of the tidal mixing front each year is shown as a solid black line in (b)

HSFs

In each year, the best fitting model contained a sex-specific smoother for SST and NPP (Tables S3 & S4). Both random intercepts for bird identity and spatial smoothers (Fig. S4) were retained in the final models. Females foraged mainly over waters with a temperature between 10 and 15°C. In contrast, males foraged relatively little over such waters, tending to forage in significantly cooler (8–12°C) or warmer waters (>15°C, Fig. 3a). In addition, males made greater use than females of areas with high NPP (>3 mg C m^{-2} d^{-1}; Fig. 3b).

Table 2. Estimated overlap (Bhattacharyya's affinity, BA) in utilization distributions (UD) between male and female northern gannets *Morus bassanus* from Bass Rock, Scotland; p: the proportion of randomized overlaps that were smaller than the observed overlap

UD(%)	Year	BA	p
50	2010	0.22	0.046
	2011	0.25	0.052
	2012	0.22	0.022
95	2010	0.75	0.011
	2011	0.65	0.027
	2012	0.76	0.083

Stable isotope ratios

Male RBCs had significantly higher δ^{13}C values than those of females in each study year and significantly higher δ^{15}N values than females in 2010 and 2011, but not during 2012 (Fig. 4, Table 3).

Diving behaviour

V-shaped dives were more frequent than U-shaped dives across both sexes (total number of V-dives = 4784; total number of U-dives = 2151), but males were more likely than females to make U-shaped dives (males: 38% of 3904 dives classed as U-shaped; females: 22% of 3031 dives classed as U-shaped; β_{SEX} = 0.92, 95% confidence interval, CI = 0.35–1.48, p = 0.0012, n = 6310 dives from 23 birds; Table S5). Body mass did not affect the probability of a dive

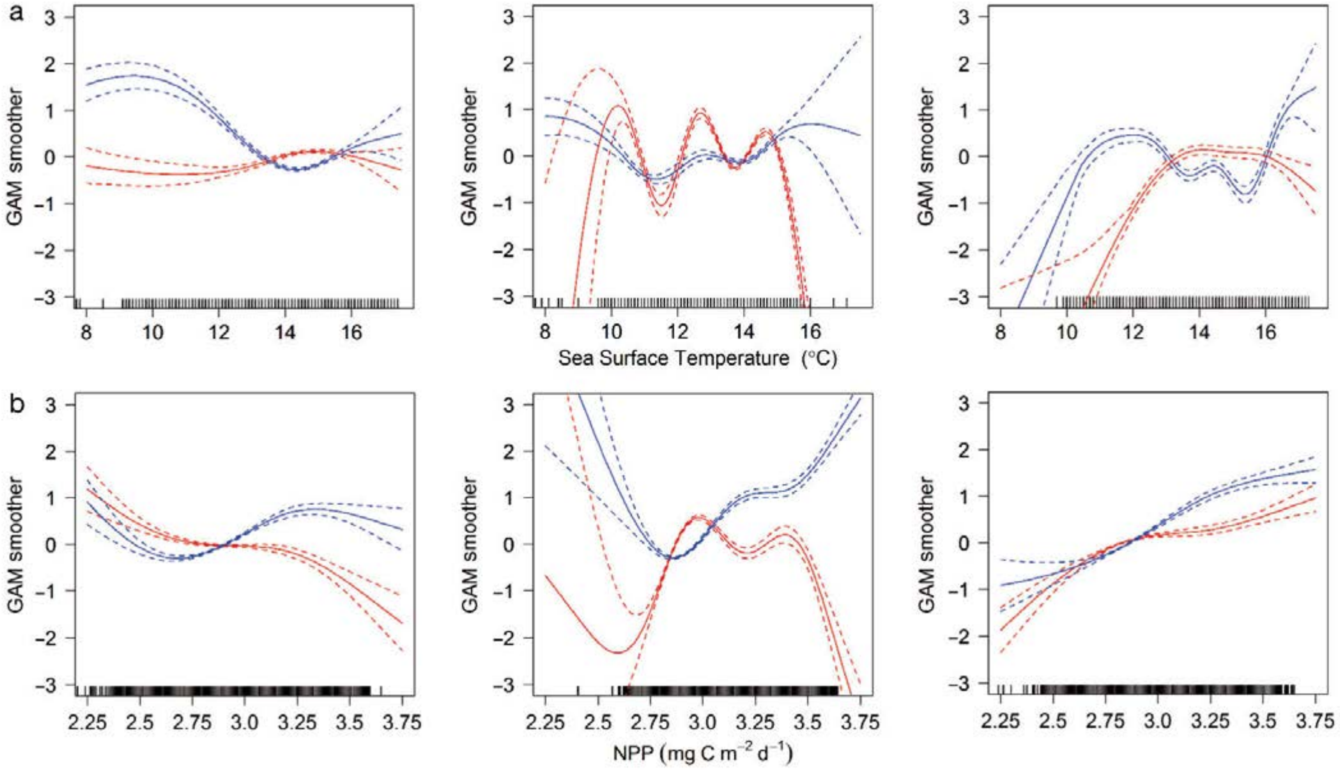

Fig. 3. Habitat selection functions for (a) sea surface temperature (SST) and (b) net primary production (NPP). Plots show the predicted curve from the model (solid line) and 95% confidence intervals (dashed lines) for male (blue) and female (red) northern gannets *Morus bassanus*. GAM: generalized additive model

being U-shaped or V-shaped (β_{MASS} = −0.024, 95% CI = −0.29 to +0.25, p = 0.90; Tables S5 & S6). Plots of dive locations and the spatial smoother from the dive type model indicate that in both sexes, U-shaped dives were more likely to occur close to the colony and inshore of the East Scotland tidal mixing front (Fig. 5). Dives at dawn or dusk were more likely to be V-shaped than U-shaped (Fig. S5).

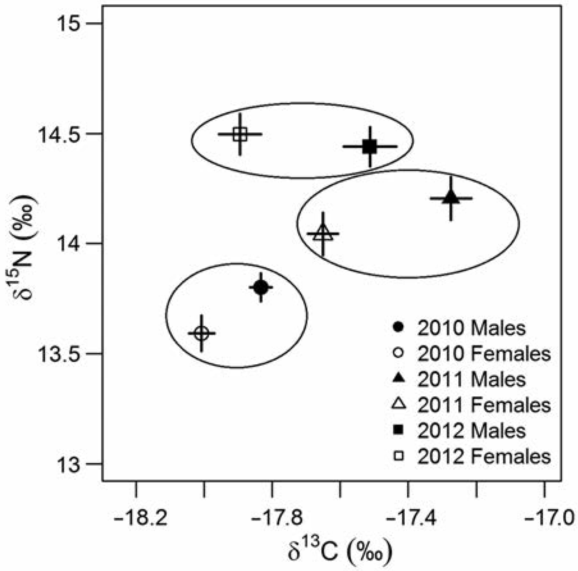

Fig. 4. Mean ± SE δ^{13}C and δ^{15}N values in red blood cells of breeding northern gannets *Morus bassanus* from Bass Rock, Scotland. Ellipses show values from the same year

The maximum depth achieved during V-shaped dives was positively associated with body mass (β_{MASS} = 0.52, 95% CI = 0.31–0.91, p = 0.019). In addition, after controlling for body mass, the maximum depth attained during V-shaped dives was greater in females than males (Table 1; β_{SEX} = −0.81, 95% CI = −1.55 to +0.11, p = 0.021, n = 4272 dives, 23 birds; Tables S7 & S8). In both sexes, the deepest V-shaped dives tended to occur in offshore waters (Fig. 6a), and V-shaped dives were shallowest at dawn and dusk (Fig. S6a). There was little difference in the maximum depth reached by males and females during U-shaped dives (β_{SEX} = 0.11, 95% CI = −0.086 to +0.31, p = 0.28, n = 2036 dives, 23 birds; Tables 1, S9 & S10), nor was there a significant association between maximum depth and body mass (β_{MASS} = 0.073, 95% CI = −0.026 to +0.17, p = 0.16). The maximum depth of U-shaped dives generally increased closer to the colony (Fig. 6b), and U-shaped dives were also shallower at dawn and dusk (Fig. S6b).

Table 3. Bayesian multivariate mixed effects model of $\delta^{15}N$ and $\delta^{13}C$ in northern gannets *Morus bassanus* from Bass Rock, Scotland (n = 138 observations of 66 birds)

Variable	$\delta^{15}N$				$\delta^{13}C$			
	β	Lower 95% CI	Upper 95% CI	p	β	Lower 95% CI	Upper 95% CI	p
Intercept	13.55	13.40	13.67	<0.001	−18.04	−18.11	−17.95	<0.001
Sex	0.27	0.09	0.46	0.007	0.19	0.08	0.31	0.001
Year 2011	0.48	0.29	0.68	<0.001	0.38	0.24	0.52	<0.001
Year 2012	0.90	0.72	1.09	<0.001	0.11	−0.02	0.24	0.100
Sex × Year 2011	−0.10	−0.36	0.17	0.480	0.20	0.02	0.48	0.022
Sex × Year 2012	−0.31	−0.59	−0.02	0.022	0.21	0.03	0.41	0.036

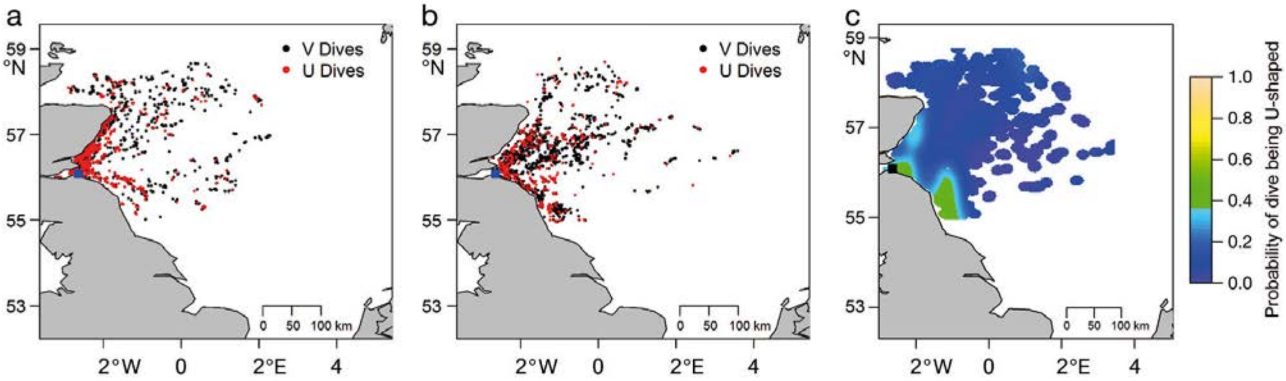

Fig. 5. Locations of U-shaped (red) and V-shaped (black) dives by (a) male and (b) female northern gannets *Morus bassanus*. (c) Plot of the spatial smoother from the generalized additive mixed model dive-type analysis showing the predicted probability that a dive will be classed as U-shaped. The square in all panels denotes the position of Bass Rock, Scotland

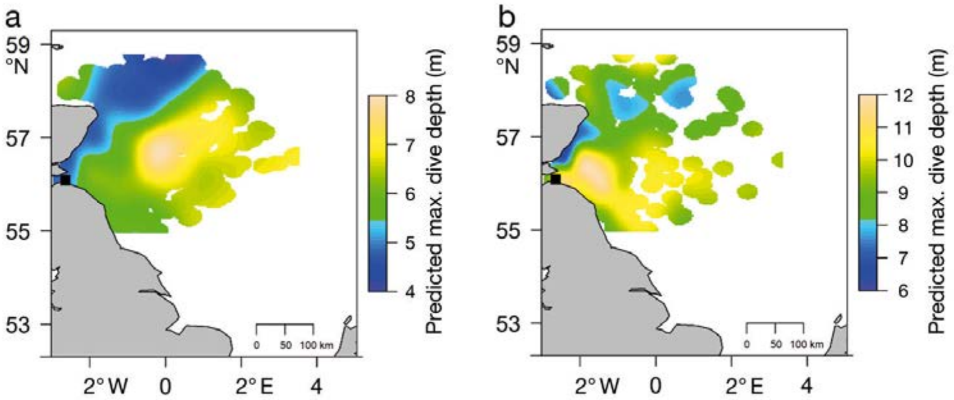

Fig. 6. Spatial smoothers from the models of dive depth for (a) V-shaped dives and (b) U-shaped dives of northern gannets *Morus bassanus*. (■) Bass Rock, Scotland

DISCUSSION

This study provides clear evidence of sexual segregation in northern gannets in both horizontal and vertical planes. Males and females differed in their usage of mixed and stratified waters, providing evidence for sex-specific habitat segregation across tidal mixing regimes. Moreover, our results highlight the association between sex-specific foraging behaviour and spatial and habitat segregation.

Differences in habitat usage

Males foraged predominantly in mixed waters to the north-east of Bass Rock inshore of the tidal mixing front, whereas females foraged predominantly in offshore stratified waters. These results are consistent with previous work showing that chick-provisioning males from Bass Rock departed on more north-easterly bearings than females (Lewis et al. 2004) and that chick-provisioning females from Grassholm foraged farther offshore than males in the Celtic Sea (Stauss et al. 2012). RBC δ^{13}C values were lower in females than in males at Bass Rock, which also indicates that females foraged farther offshore than males, because inshore habitats characteristically have higher δ^{13}C values (Hobson et al. 1994). Lower blood δ^{13}C values in females have also been observed at other gannet colonies (Stauss et al. 2012), suggesting that our results reflect a general feature in gannets. Males made greater use than females of areas with high NPP, as would be expected given that NPP is generally higher in mixed, coastal waters where males foraged (Fig. S2). NPP is often used as a proxy for food availability farther up the food chain (Barnes & Hughes 1988, Wakefield et al. 2014), suggesting that males foraged in a more productive environment than females. However, potential mismatches between productivity towards the bottom of the food web and at intermediate trophic levels (pelagic fish) means that this interpretation should be treated with caution (Grémillet et al. 2008).

Male gannets from Bass Rock had higher δ^{15}N values than females in 2010 and 2011, but not in 2012. Higher δ^{15}N in males from Grassholm may occur if males consume a higher proportion of whitefish fishery discards than females (Stauss et al. 2012). However, at Bass Rock, the between-sex differences in δ^{15}N each year were small and could have arisen from the observed habitat segregation between males and females (as a consequence of variation in isotopic baselines in the areas where individuals foraged; Woodcock et al. 2012) or from lower body condition among males (as a consequence of variation in physiological processes affecting fractionation; Lee Cruz et al. 2012) or both.

Sex-specific responses to SST were generally consistent across years, with males foraging more in cold mixed waters and females foraging in seasonally stratified offshore waters. As well as using colder waters more often than females, males also made greater use of areas with high SSTs (>15°C). This was a consequence of males travelling south-east to forage at the Dogger Bank, where SST was relatively high. The Dogger Bank is a productive shallow offshore bank, which is also targeted by other wide-ranging higher predators (de Boer 2010). Due to benthic–pelagic coupling, such features may lead to elevated prey abundance in the epipelagic waters accessible to gannets (Wakefield et al. 2012). In 2011, differences between male and female responses to SST were smaller (Figs. 1 & 2), probably because the East Scotland tidal mixing front was located closer to shore and the extent of cold mixed waters (SST < 10°C) was relatively limited (Fig. 1a). Between 2010 and 2012, there was also variation in climatic conditions in the North Atlantic as indicated by the North Atlantic Oscillation index which varied from −4.64 in 2010 to 3.17 in 2012 (https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based). Effects of climate on lower levels of the food web may, in turn, have influenced both the locations where gannets foraged and the prey species they targeted. Thus, our results highlight the importance of inter-annual variation in oceanic and climatic conditions in shaping the spatial and trophic ecology of marine predators (Garthe et al. 2011).

Sex-specific diving behaviour

Males and females may adopt different diving tactics as a consequence of intrinsic constraints, competition, habitat segregation or prey preferences (Le Boeuf et al. 2000, Machovsky Capuska et al. 2011). At Bass Rock, male gannets made a greater proportion of U-shaped dives than females. Moreover, U-shaped dives were more frequent in coastal habitats, whilst V-shaped dives were more frequent offshore. Therefore, the different dive types may represent tactics for foraging in different environments, with males making more U-dives as a consequence of their inshore distribution and the prey they encounter.

The higher frequency of U-dives in the vicinity of Bass Rock, and the greater depth of U-dives close to the colony, may arise due to the high density of gannets in these areas. In particular, when large aggregations of gannets form during feeding events, prey may descend to deeper depths to escape predation, forcing gannets to dive deeper (Elliott et al. 2008, Machovsky Capuska et al. 2011). However, this would not explain why U-shaped dives are also more frequent in coastal areas farther from the colony, where the density of conspecifics is lower (Camphuysen et al. 2012). Instead, diving behaviour may reflect the environment and prey encountered (Garthe et al. 2000, 2011), as observed in other marine predators which dived deeper in mixed waters than in stratified waters (Takahashi et al. 2008). In particular, the location of the deepest U-shaped dives corresponds with the location of sandeel (*Ammodytes* spp.) habitat within the Firth of Forth (Wanless et al. 1998), thus deeper U-shaped dives could result from birds feeding on sandeels. Alternatively, the shallower waters in coastal areas may prevent prey escaping to deeper depths, enhancing prey capture and making longer U-shaped dives more profitable than in deeper waters.

Females attained greater depths than males during V-shaped dives, which supports similar findings in gannets and other Sulidae (Lewis et al. 2002, Zavalaga et al. 2007, Weimerskirch et al. 2009). Gannets initially attain depth by plunge-diving from height; therefore, the greater mass of females may give them greater dive momentum and allow them to dive deeper (Kato et al. 2000). However, even when accounting for body mass in our models, females were still predicted to reach deeper depths during V-shaped dives than males. Such a difference may reflect the vertical distribution of prey that males and females target when foraging or assessing prey densities (Wilson 2003, Machovsky Capuska et al. 2011, 2013). For example, because females tend to forage more in offshore stratified waters than males, deeper V-shaped dives may be required to reach the thermocline, which influences the distribution of biomass in the water column (Mann & Lazier 2006) and can play a role in shaping dive profiles (Takahashi et al. 2008, Ropert-Coudert et al. 2009b).

Body mass had no effect on the depth of U-shaped dives, probably because extra depth can be achieved during U-shaped dives by underwater swimming after the initial momentum phase (Ropert-Coudert et al. 2009a).

Factors underlying segregation

Sex-specific differences in foraging behaviour are usually ascribed to the influence of body size on foraging efficiency and intra-specific competition (Shaffer et al. 2001, Wearmouth & Sims 2008, Phillips et al. 2011). Competition may play a greater role in segregating birds from the same colony than it does in between-colony segregation (Wakefield et al. 2013) because the rate at which indirect competition varies with colony distance will be equal for all individuals at the colony. Because males made shorter trips than females, it is possible that females were excluded from areas close to the colony via indirect competition and were pushed into offshore, stratified waters as a result. However, this would not explain why females did not appear to be pushed into inshore sites farther from the colony in a similar fashion. Moreover, when the tidal mixing front was less well-defined and occurred closer to the coastline in 2011, the 50% UD of females shifted inshore, suggesting that females are not excluded from this area.

Alternatively, the greater mass of females may make them more efficient at foraging in offshore environments because they can reach deeper prey. Greater mass appears to be advantageous when performing V-dives, and as the deepest V-dives occurred in stratified waters, this may give females an advantage in this environment. Nevertheless, the slight sexual size dimorphism (~5–10%) seen in gannets suggests that differences in body mass alone will not create large asymmetries in either competitive ability or foraging efficiency. Therefore, other aspects of morphology not measured here, such as wing loading and agility (Weimerskirch et al. 2006), may be important. Finally, the fact that in addition to Bass Rock, females breeding at Grassholm also foraged farther offshore than males (Stauss et al. 2012), despite differences between regions in the arrangement of mixed and stratified waters, suggests that sexual segregation is driven primarily by habitat selection.

Sex-specific niche divergence and habitat segregation can also arise from a difference between sexes in parental roles (Thaxter et al. 2009), but the roles of male and female gannets do not appear to differ during chick-rearing (Nelson 2002, Redman et al. 2002). However, males and females could forage in different areas in order to ensure that their chicks receive the optimum blend of prey species (Elliott et al. 2010). Sex-specific differences in nutritional requirements related to egg production, incubation costs or feather moult could also result in sexual segregation (Carey 1996, Lewis et al. 2002), particularly if key prey items are found in specific habitats. However, gannets lay only a single, small egg, so it seems unlikely that this would cause temporary sex differences in dietary need. It is not known whether there are sex-specific differences in moult in gannets, but such differences do occur in other seabirds (Weimerskirch 1991) and could potentially create temporary sex differences in dietary needs and/or foraging abilities (Lewis et al. 2002).

Overall, our results suggest that sexual segregation in gannets is mediated by habitat segregation across tidal mixing regimes. Males foraged more in mixed coastal waters inshore of the tidal mixing front whereas females foraged more offshore. Hence, while tidal mixing regimes have been identified as important habitat features for marine predators (Skov et al. 2008), males and females may respond differently to such features. In addition, sex-specific diving behaviour may result from males and females adapting their behaviour to suit the differing habitats in which they forage, particularly in relation to whether they are foraging in mixed or stratified waters.

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Additional analysis to inform SNCB recommendations regarding collision risk modelling

Aonghais S.C.P. Cook

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Report to Natural England.

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BTO, The Nunnery, Thetford, Norfolk IP24 2PU
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EXECUTIVE SUMMARY

Collision Risk Models are widely used in order to predict potential impact of collisions with turbines on bird populations but, are known to be sensitive to the parameter referred to as the avoidance rate. The most widely used Collision Risk Model is the Band Model, updated in 2012 for use in the offshore environment. Previous studies have estimated suitable avoidance rates for use in the Band model. However, given ongoing data collection, there is a need to update these estimates to ensure they reflect the best available evidence. Drawing from the data presented in Cook et al. (2014) and more recent studies, notably the ORJIP Bird Collision Avoidance study, this report presents updated estimates of avoidance rates for gulls and terns and makes recommendations about suitable avoidance rates for gannets. It further sets out recommendations and considerations for future revisions to avoidance rates as more data become available.

BACKGROUND

Collision Risk Models are widely used in order to predict the potential impact of collisions with turbines in both the onshore and offshore environments on bird populations (Masden & Cook, 2016). However, these models are known to be sensitive to the parameter referred to as the avoidance rate (Chamberlain *et al.*, 2006). The avoidance rate is assumed to reflect the proportion of birds that take action in order to avoid collision with turbines. However, it is typically calculated by comparing estimates of the number of birds colliding to those that would be expected to collide in the absence of avoidance action (Band, 2012; Chamberlain *et al.*, 2006; Cook *et al.*, 2018; Cook *et al.*, 2014) (Eq. 1)

Eq. 1

$$\textit{Avoidance Rate} = 1 - \left(\frac{\textit{Observed Collision Rate}}{\textit{Collision Rate Predicted In Absence Of Avoidance}}\right)$$

The collision rate predicted in the absence of avoidance is a function of i) the number of birds estimated to pass through the turbine rotor swept areas of a wind farm over any given time period (referred to as the flux rate), and ii the probability of a bird passing through the turbine rotor swept area and colliding with a blade (referred to as the Probability of Collision or, PColl). This means that, in addition to capturing the rate at which birds may take action to avoid collision, the avoidance rate also incorporates error in the estimates of both PColl and the flux rate. However, the estimation of both of these parameters is based on a simplified set of assumptions relating to the movement and behaviour of the birds, and the operation of the turbines. This means that estimates of avoidance rates are sensitive to many of the parameters that CRMs are sensitive to, including flight height, flight speed and turbine rotation speed (Cook *et al.*, 2014; Masden *et al.*, in review).

Flight speed and turbine rotation speed contribute to the estimation of PColl. An increase in turbine rotation speed will result in an increase in the probability of collision and, hence, the collision rate predicted in the absence of avoidance. An increase in flight speed will result in a decrease in PColl as it reduces the probability that the bird and turbine blade will occupy the same point at the same time. However, as flight speed is also used in the estimation of the flux rate, this does not translate to a reduction in the collision rate predicted in the absence of avoidance. The model guidance suggests that whilst the impact of flight speed on the two parameters may act in opposite directions, the error associated with each should cancel this effect out (Band, 2012). However, subsequent analysis suggests this may not be the case, and that the influence of flight speed on the flux rate swamps its influence on PColl (Masden *et al.* in review). Similarly, an increase in the proportion of birds at collision risk height will increase the number of birds available to collide and, hence, the collision rate predicted in the absence of avoidance. Following Eq. 1, an increase in turbine rotation speed, flight height or flight speed will all result in an increase in the collision rate predicted in the absence of avoidance and, therefore, also increase the avoidance rate. This highlights the importance of ensuring that robust estimates of these parameters are used when calculating avoidance rates.

Related to the above point, there are differences in the approaches used by models in order to estimate the number of birds predicted to collide in the absence of avoidance. For example, the basic Band model (options 1 & 2) assumes a uniform distribution across the turbine rotor swept area, whilst the extended Band model (option 3) accounts for variation in this distribution. This allows a more precise estimate of predicted collisions, given that for most species birds will be much more likely to be present at the lower edges of the rotor sweep, where they are less likely to collide, than at higher altitudes within the rotor sweep. As a result, the number of birds predicted to collide in the absence of avoidance using the extended Band model will be lower than that for the basic Band model. This means that, following Eq. 1, the avoidance rate estimated using the extended Band model will be lower than is the case for the basic Band model. This example highlights that avoidance rates are not transferable between different models.

Given the sensitivity of CRMs to avoidance rates and, the challenges posed to industry by current estimates of collisions (Brabant *et al.*, 2015; Broadbent & Nixon, 2019; Busch & Garthe, 2017), there has been considerable interest in generating more accurate estimates of avoidance rates. This has resulted in a number of reviews of the topic (Cook *et al.*, 2018; Cook *et al.*, 2014; Cook *et al.*, 2012) and large-scale, industry-funded projects in order to quantify avoidance behaviour (Skov, *et al.*, 2018). As our understanding of collision risk improves as a result of more projects being built, and an increased appreciation for the scale of potential cumulative impacts, it is necessary to update past estimates of avoidance rates. As part of this, key changes will include the incorporation of data from new studies (including Skov *et al.* 2018), accounting for the imperfect detection of corpses, and incorporating data from sites at which bird activity was recorded but no collisions detected. As a consequence of these changes, the recommended avoidance rates for key species are also likely to be changed.

An important additional data set is likely to be that collected as part of the Offshore Renewables Joint Industry Programme (ORJIP) funded Bird Collision Avoidance (BCA) project. Previous analysis, reported in Bowgen & Cook (2018), considered how the data collected could be used to parameterise avoidance rates for CRMs. Bowgen & Cook (2018) estimated avoidance rates for use in the deterministic Band model as follows:

0.990 for Black-legged Kittiwake (option 1)

0.995 for Northern Gannet and large gulls (option 1)

0.980 for Black-legged Kittiwake (option 3)

0.993 for large gulls (option 3)

Bowgen & Cook (2018) also undertook further analyses in order to derive median avoidance rates suitable for use in the stochastic collision risk model i.e.

0.994 (95% CIs 0.976 – 0.998) for Black-legged Kittiwake (option 1)

0.997 (95% CIs 0.992 – 0.999) for large gulls (option 1)

0.970 (95% CIs 0.871 – 0.989) for Black-legged Kittiwake (option 3)

0.990 (95% CIs 0.974 – 0.995) for large gulls (option 3)

The median values were recommended for use in the stochastic collision risk models and these differ from the values estimated by Bowgen & Cook (2018) for use in the deterministic model, due to differences in the way in which flight height distributions are incorporated into the avoidance rate calculations (which are based on comparing expected with observed collisions). These rates were not adopted into guidance as they were based on the outputs from a single study and lacked the contemporary density data required in order to give more context to the observed collision rates. To support the development of SNCB advice in relation to CRMs, there is a need to consider how the data collected as part of the ORJIP BCA project and analysed by Bowgen & Cook (2018) should be combined with existing estimates of avoidance rates (e.g. Cook *et al.*, 2018; Cook *et al.*, 2014). There is a further need to consider the extent to which avoidance rates may differ according to the model used, with particular reference to the basic and extended Band (2012) model and, the basic and extended stochastic CRM (sCRM) (McGregor *et al*., 2018).

This report will:

1. Combine ARs from various sites as presented in Cook et al. (2014) where appropriate, with those derived from the ORJIP study (Bowgen & Cook, 2018), and any additional sites where the appropriate data are available, to provide avoidance rates based on data across a range of sites where possible. These would be species-specific ARs where data allow, but in some cases these may need to be based on data across functional groups (e.g. gulls) or informed by rates for other species (e.g. Northern Gannet). Where data allow, provide a SD for the recommended avoidance rates.

2. Where a meaningful SD estimated across sites (or from other appropriate source of variability) this should incorporate variation between sites (for the deterministic Band model) and variability in the input parameters (for the sCRM).

3. Production of a set of principles that could be used when making decisions on which avoidance rate is most appropriate in different circumstances. This would need to consider species-specific data availability (for example Cook *et al*. 2014 recommend avoidance rates (with SD) for Gannet which is based on all gulls data because no Northern Gannet data were available) and how variability is estimated and can be applied to both the Band (2012) spreadsheet and the McGregor *et al*. (2018) sCRM tool.

4. Advise on appropriate Avoidance rate and SD to use for Sandwich Tern, given available data.

METHODS

Data

In order to estimate avoidance rates suitable for use in collision risk models we need information describing the number of collisions recorded, and a passage rate for birds through the study area over the period in which collision data were recorded. Ideally, information on the flight heights of birds within the study area, and any corrections applied to account for imperfect detection of corpses, should also be reported. In addition to the data collated as part of Cook *et al.* (2014) and collected by Skov *et al.* (2018), I identified reports from seven additional sites (Bloodgate Hill, Blyth Harbour, Deflzijl-Zuid, Goole Fields, Red House Farm, Sabinapolder and Slufterdam and Distridam) which included the necessary data to estimate avoidance rates (Figure 1).

Collision data presented in Skov *et al*. (2018) were collected using a combined camera-radar system mounted on two offshore wind turbines; all other data were collected during carcass searches as part of post-construction monitoring at onshore wind farms. Bird and wind farm parameters used in this analysis are presented in tables 1 and 2.

Figure 1 Location of windfarms from which data were obtained in order to calculate avoidance rates. 1. Bloodgate Hill; 2. Blyth Harbour; 3. Goole Field; 4. Haverigg; 5. Hellrigg; 6. Red House Farm; 7. Avonmouth; 8. Kessingland; 9. Gneizdzewo; 10. Bouin; 11. Ooseterbierum; 12. Thanet; 13. Zeebrugge; 14. Boudwijnkanaal; 15. Kleine Pathoweg; 16. De Put; 17. Delfzijl-zuid; 18. Sabinapolder; 19. Slufterdam & Distridam.

Table 1 Values for bird parameters (± standard deviation) used to estimate avoidance rates

	Length (m)[1]	Wingspan (m)[1]	Flight speed (m/s)	Flight mode	Nocturnal activity[2]
Common Gull	0.36 (0.005)	1.05 (0.04)	11.9 (1.6)[3]	Flapping	0.25
Black-headed Gull	0.41 (0.005)	1.20 (0.04)	13.4 (2.9)[3]	Flapping	0.25
Black-legged Kittiwake	0.39 (0.005)	1.08 (0.04)	13.1 (0.4)[3]	Flapping	0.25
Lesser Black-backed Gull	0.58 (0.005)	1.42 (0.04)	13.1 (1.8)[3]	Flapping	0.25
Herring Gull	0.60 (0.005)	1.44 (0.04)	12.8 (1.8)[3]	Flapping	0.25
Great Black-backed Gull	0.71 (0.005)	1.58 (0.04)	13.7 (1.8)[3]	Flapping	0.25
Sandwich Tern	0.38 (0.005)	1.00 (0.04)	12.9 (0.9)[4]	Flapping	0
Common Tern	0.33 (0.005)	0.88 (0.04)	10.9 (0.9)[5]	Flapping	0
Little Tern	0.23 (0.005)	0.52 (0.04)	10.9 (0.9)[5]	Flapping	0

[1] (Robinson, 2017), SDs based on guidance issued alongside (McGregor *et al.,* 2018). The default values in the sCRM have subsequently been updated. However, these changes do not have an impact on the estimated avoidance rates. [2] (Garthe & Hüppop, 2004) [3] (Alerstam *et al*., 2007) [4] (Wakeling & Hodgson, 1992) [5] Flight speed for Arctic Tern presented in (Alerstam *et al*., 2007).

Table 2 Values for wind farm (± standard deviation) parameters used to estimate avoidance rates

	Location	Latitude	Turbine Model (MW)	Number of Turbines	Hub Height (m)	Blades	Rotor Diameter (m)	Blade Width (m)	Rotor Speed (rpm)	Rotor Pitch (°)	Width Survey window (m)	Height Survey Window (m)	References
Bloodgate Hill	Coastal	52.87	0.225	10	30	3	27	0.66	43 (0.05)	10 (0.01)	1500	43.5	(Percival *et al.*, 2008)
Blyth Harbour	Coastal	55.13	3.4	1	76	3	104	4.3	13.8 (0.05)	15 (0.01)	400	128	(Percival *et al.*, 2017)
Goole Fields	Inland	53.66	2.05	16	79	3	92	4.4	17.5 (0.05)	10 (0.01)	3200	150	(Percival *et al.*, 2018b, 2018a, 2018c)
Haverigg	Coastal	54.23	0.6	8	41.5	3	42	2.2	13.7 (0.05	15 (0.01)	1800	62.5	(Arcus Consultancy Services, 2019; Percival, 2020)
Hellrigg	Coastal	54.84	2.3	4	80	3	82	4.4	18 (0.05)	10 (0.01)	4000	121	(Percival, n.d., 2015)
Red House Farm	Coastal	52.81	2	6	59	3	82	4.4	18 (0.05)	10 (0.01)	3000	59	(Percival *et al.*, 2015)
Avonmouth	Coastal	51.50	2.05	2	80	3	92	4.4	17.5 (0.05)	10 (0.01)	1300	160	(The Landmark Practice, 2013)
Kessingland	Coastal	52.41		2	80	3	92	2.5	15 (0.05)	10 (0.01)	92	92	(Wild Frontier Ecology, 2013)
Gneizdzewo	Coastal	54.70	2	19	80	3	80	4.4	18 (0.05)	10 (0.01)	3700	120	(Zielinski *et al.*, 2008, 2010, 2011, 2012)
Bouin	Coastal	46.95	2.5	8	60	3	80	4.4	18 (0.05)	10 (0.01)	4000	100	(Dulac, 2008)
Oosterbierum	Coastal	53.20	0.3	18	35	3	30	0.66	43 (0.05)	10 (0.01)	1430	60	(Winkelman, 1992)
Thanet	Offshore	51.50	3	8	70	3	90	3.5	16.1 (0.05)	15 (0.01)	2709	115	(Skov, Heinänen, *et al.*, 2018)
Zeebrugge	Coastal	51.36	0.4	6	34	3	34	0.66	43 (0.05)	10 (0.01)	720	80	(J. Everaert, 2008; J. Everaert *et al.*, 2002; Joris Everaert & Stienen, 2007)
Boudwijnkanaal	Coastal	51.28	0.6	7	55	3	48	1.1	43 (0.05)	10 (0.01)	1539	79	(J. Everaert, 2008; J. Everaert *et al.*, 2002; Joris Everaert & Stienen, 2007)
Kleine Pathoweg	Coastal	51.28	1.8	7	85	3	70	4.4	18 (0.05)	10 (0.01)	1820	120	(J. Everaert, 2008; J. Everaert *et al.*, 2002; Joris Everaert & Stienen, 2007)
De Put	Coastal	51.15	0.8	2	75	3	48	1.1	43 (0.05)	10 (0.01)	300	100	(J. Everaert, 2008; J. Everaert *et al.*, 2002; Joris Everaert & Stienen, 2007)
Delfzijl-Zuid	Coastal	53.28	2	34	85	3	70	4.4	18 (0.05	10 (0.01)	2700	120	(Brenninkmeijer & van der Weyde, 2011)
Sabinapolder	Coastal	51.66	0.85	6	48	3	52	1.1	43 (0.05)	10 (0.01)	1500	84	(Verbeek *et al.*, 2012)
Slufterdam & Distridam	Coastal	51.92	1.5	21	67	3	83	4.4	18 (0.05)	10 (0.01)	3200	500	(Prinsen *et al.*, 2013)

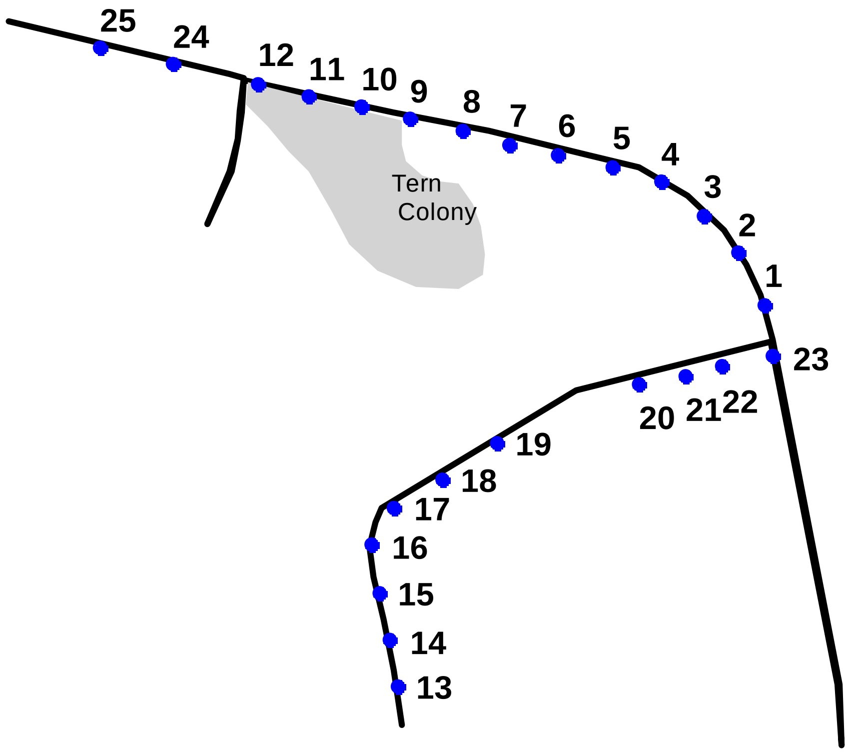
Estimation of avoidance rates

As highlighted above (Eq. 1), avoidance rates can be estimated by comparing predicted and observed collision rates. The predicted collision rate can be estimated by multiplying the number of birds passing through the turbine rotor sweeps by the probability of any individual bird colliding. The number of birds estimated to pass through the rotor sweep is estimated by scaling up the flight activity recorded during surveys to cover the total period over which searches for collision victims were carried out. However, as a result, the final estimated avoidance rate is highly sensitive to the number of flights estimated to occur during the period over which carcass searches are carried out (see p101 of Cook *et al.* (2014) for example).

In some instances, flight activity may not be spread evenly across a site. For example, at Zeebrugge flight activity is likely to be greatest around the turbines closest to the tern breeding colony (Figure 2). As part of monitoring at this site, searches for collision victims were carried out on a weekly or twice weekly basis around all turbines between 2001 and 2007 (Everaert, 2008). Reflecting likely spatial patterns in flight activity, the greatest number of corpses were recovered from beneath the turbines closest to the breeding colony (Everaert, 2008; Everaert & Stienen, 2007). To complement the monitoring of corpses, flight activity surveys were carried out to assess the number of birds passing through the turbine lines in June 2001, September 2001, June 2002, June 2004, and June 2005. In 2001 and 2002, birds were counted passing turbines 9–12, and in 2004 and 2005 birds were counted passing turbines 7–12 (Fig. 2). Extrapolating activity levels from these turbines to turbines elsewhere in the wind farm may lead to an overestimate of the flux rate across the wind farm as a whole and, in turn, the predicted collision rate. Given equation 1, where the predicted collision rate is overestimated, this will lead to an overestimate of the final avoidance rate. Consequently, where possible I assessed avoidance rates in relation to individual turbines (Zeebrugge, Slufterdam and Distridam, Kessingland) before summarising these across the wind farm concerned. Elsewhere, I restricted analyses to carcasses collected from the areas in which flight activity surveys were carried out; though, in the majority of cases, this reflected the wind farm as a whole.

In addition to estimates of flight activity and mortality, estimating avoidance rates requires information describing turbine size (hub height and rotor diameter) and operational parameters (rotor speed and pitch), together with bird flight speed, flight height and nocturnal activity. Turbine information was described within the monitoring reports reviewed or inferred from turbines of a similar size and capacity, following Cook

Figure 2 Turbines on Zeebrugge harbour wall with location of Tern breeding colony shown (recreated from Everaert & Stienen, 2007).



et al. (2014). Data describing bird flight speed and nocturnal activity were drawn from standard references (Alerstam *et al.*, 2007; Garthe & Hüppop, 2004; Pennycuick *et al*., 2013). Where available, estimates of the number or proportion of birds at collision risk height were extracted from the monitoring reports. Where these data were not available, or were felt to be unreliable (e.g. subject to unknown biases), flight height estimates from Johnston *et al*. (2014) were used. The resulting data were used to estimate avoidance rates suitable for use in the basic and extended Band (2012) Model, and the basic and extended sCRM (McGregor *et al.*, 2018).

Basic Band Model

To estimate an avoidance rate for the Basic Band model I followed the approach set out in Cook *et al.* (2014) using the following steps:

Firstly, estimate the passage rate of birds through turbine rotor sweeps:

1. As a first step, I estimated the hourly number of birds passing through the wind farm. In most cases, this was achieved by dividing the total number of birds recorded during surveys by the total duration of these surveys. However, in the case of Skov *et al.* (2018) data were available as density estimates rather than counts – though it is important to note that, in contrast to the data from onshore sites, these estimates were not contemporaneous with the collection of collision estimates. These were converted into an hourly passage rate following the approach set out in Band (2012).

2. I then estimated the total number of birds passing through the wind farm over the duration of each survey: multiplying the hourly passage rate by the total number of hours covered by each survey period and correcting for nocturnal activity (Eq. 2). I estimated the total number of hours daylight and night over each survey period following the approach of Forsythe *et al.* (1995).

Eq. 2

$$N\ Birds\ passing\ through\ wind\ farm = (hourly\ passage\ rate \times n\ hours\ daylight) + (hourly\ passage\ rate \times n\ hours\ night \times correction\ for\ nocturnal\ activity)$$

3. This was then corrected by an estimate of the proportion of birds at collision risk height.

4. I then estimated the area of the total survey frontal area at collision risk height by multiplying the width of the survey window by the rotor diameter (table 2).

5. This was then multiplied by the total turbine frontal area as a proportion of the total survey frontal area at collision risk height (Eq. 3) to give an estimate of the total number of birds passing through the turbine rot or swept area.

Eq. 3

$$Avoidance\ Rate = \left(\frac{N\ turbines \times (\pi \times (0.5 \times rotor\ diameter)^2)}{width\ survey\ window \times rotor\ diameter}\right)$$

To get the number of collisions expected in the absence of avoidance, this figure was multiplied by the probability of collision estimated following Band (2012). For each species and species group ('terns', 'large gulls', 'small gulls' and 'all gulls') I followed the process set out in Cook *et al.* (2014) using ratio estimators (Cochran, 1977) to estimate an avoidance rate across all years and sites, and the Delta method (Powell, 2007) to estimate the standard deviation and 95% confidence intervals around this figure, reflecting variability in the avoidance rates between sites and years. The resulting values reflect within-wind farm avoidance; **in order to estimate total avoidance, macro-avoidance must also be incorporated.**

Extended Band Model

A first step in estimating an avoidance rate for the extended Band model is to estimate the proportion of birds passing through the turbine rotors. This follows steps 1–4 (above) but does not include a correction for the proportion of birds at collision risk height (step 5). That is because species flight height distributions are accounted for in the estimation of the collision integral, which I applied following the approach set out in Band (2012). I based flight height distributions on the values presented in Johnston *et al.* (2014). I then multiplied the number of birds passing through the turbine rotor swept areas by the collision integral to get an estimate of the number of collisions in the absence of avoidance. As above, avoidance rates were then estimated across all sites and years using Eq. 1, and combined using ratio estimators and the Delta method (Cochran, 1977; Powell, 2007). As above, the reported standard deviations reflect variability in the avoidance rates between sites.

Basic Stochastic Collision Risk Model

In contrast to the approach for the Basic Band model, where I estimated a single avoidance rate for each site in each year during which data collection had taken place and then combined these to give an overall avoidance rate with associated uncertainty, for the basic sCRM I used a Monte Carlo simulation approach to estimate avoidance rates. This approach means that I was able to estimate a mean, median, standard deviation and 95% CIs for each year, and for all years and sites combined. Using this approach, avoidance rates were estimated over 1,000 iterations. Within each iteration, the steps set out above for the basic Band model were followed with random values for turbine rotor speed and pitch, bird flight speed, wingspan and length drawn from a normal distribution based on the mean and standard deviations presented in Table 2, and average hourly passage rates drawn from a Poisson distribution based on the mean average hourly passage rates estimated following steps 1–4 above. As above, I then estimated avoidance rates across each site and year, and combined these using ratio estimators (Cochran, 1977). Following these simulations, I had 1,000 estimated avoidance rates for each species and group. From these, I extracted the median values, standard deviations and 95% CIs. In addition to reflecting variability between sites and years, as with the basic and extended Band model, the standard deviations reported here reflect variability in the input parameters.

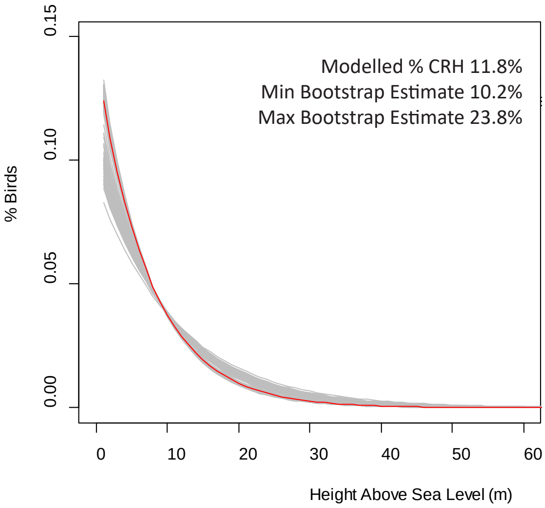
Extended Stochastic Collision Risk Model

The approach to estimating an avoidance rate for use with the extended stochastic collision risk model broadly entailed a Monte Carlo simulation approach, as described for the basic stochastic collision risk model, applied to the steps set out for the extended Band model. However, there is a key difference in relation to how flight height distributions are accounted for.

The extended stochastic collision risk model makes use of 200 random realisations of flight height distributions generated when estimating the distributions presented in (Johnston *et al.*, 2014). Each of these random realisations will have a slightly different shape, reflecting different proportions of birds at any given height. Logically, a difference in the proportion of birds at any given height between distributions will lead to differences in the proportion of birds at other heights. We can examine this more closely by plotting the 200 bootstrapped random realisations of Sandwich Tern flight height distributions and comparing these to the maximum likelihood "best fit" distribution (Figure 3). Here we can see that the "best fit" line does not pass perfectly through the middle of the random realisations. At lower heights, the "best fit" distribution reflects some of the higher proportions of birds at any given height. However, around 10 m above sea level this switches and the "best fit" distribution now has some of the lower proportions of birds at any given heights. We can see this reflected in the minimum and maximum proportions of birds predicted to be flying at collision risk height in relation to turbines of the dimensions present at Zeebrugge.

The proportion of birds at collision risk height is a key component of the number of collisions expected in the absence of avoidance behaviour, and hence the final estimated avoidance rate. Given the range of estimated proportions of birds at collision risk height from these random realisations and the proportion of birds at collision risk height in the "best fit" modelled distribution, it is clear that the mean and median estimates of the number of collisions expected in the absence of avoidance behaviour from the bootstrap data will exceed that estimated using the best fit data within the extended Band model. As a consequence of this the avoidance rates will differ between the extended Band model and, the extended sCRM.

Figure 3 Bootstrapped estimates (grey lines) of the proportion of Sandwich Terns at collision risk height from the data underpinning (Johnston *et al.*, 2014) in comparison to the maximum likelihood distribution (red line).



Northern Gannet Avoidance Rate

Whilst corpses of Northern Gannets which have apparently collided with offshore wind farms have been recovered (Rothery *et al*., 2009), concerns over the imperfect detection of these corpses mean that it is not possible to estimate an avoidance rate for this species following the methodologies described above. Instead, we must rely on comparison with other species and make inferences based on our knowledge of the species' ecology. Unlike the other species considered in this analysis, Northern Gannets are known to strongly avoid wind farms (V. Dierschke *et al*., 2016). We can use this information to estimate a range of potential total avoidance rates by combining plausible macro-avoidance rates with plausible within-wind farm avoidance rates following Eq. 4.

Eq. 4

$$\text{Total Avoidance} = 1-((1-\text{macro avoidance}) \times (1-\text{within wind farm avoidance}))$$

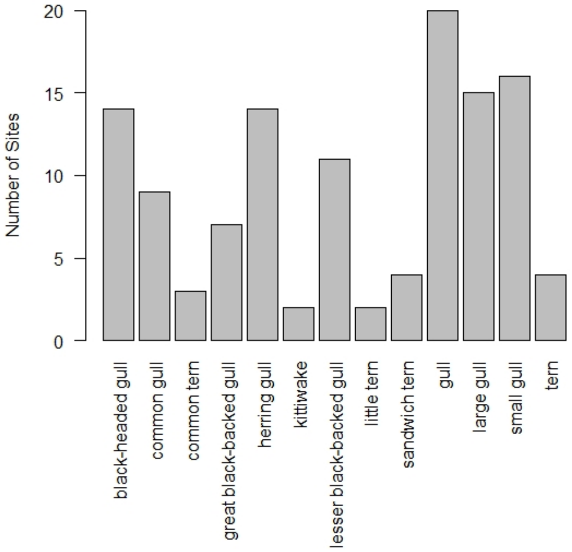
To achieve this, I simulate a range of total avoidance rates based on macro avoidance rates ranging from 0.5–1.0 and within-wind farm avoidance rates ranging from 0.9–1.0. I then compare these to the values of within-wind farm avoidance estimated for the species above, and published estimates of Northern Gannet macro-avoidance, in order to make inferences about plausible values for Northern Gannet total avoidance.

RESULTS

Gull and tern avoidance rates

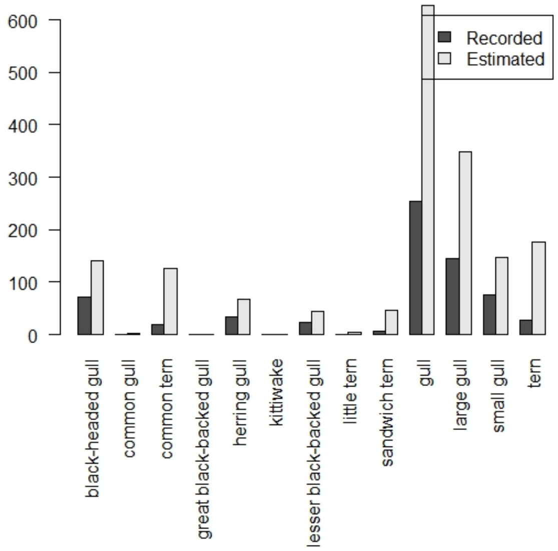
Data were obtained from 19 sites (Table 2, Figure 1). The number of sites from which data were available to estimate avoidance rates varied from two for Little Tern and Black-legged Kittiwake, to 13 for Black-headed Gull and Herring Gull (Figure 4). There were also data from a significant number of sites for Lesser Black-backed Gull (10) and Common Gull (9). Across groups, data were available from 19 sites for all gulls, buT only four sites for terns.

Figure 4 The number of sites from which data were available to estimate avoidance rates for each species and species group.



Across the studies, a total of 282 collisions involving gulls and terns was recorded. However, once corrections were applied to account for the proportion of the search area covered, observer efficiency and scavenger activity, this number increased to 805 estimated collisions. Black-headed Gulls were the most commonly reported victims with 71 recorded collisions, increasing to 140 once correction factors were applied (Figure 5). In total 255 gull collision victims were reported (628 after applying correction factors) and 27 tern collision victims (176 after applying correction factors).

Figure 5 The number of collision victims recorded during collision monitoring and estimated once corrections had been applied for corpse detection and scavenger activity



Generally, estimated avoidance rates for use with the basic sCRM are consistent with those estimated for use with the basic Band model. However, there are noticeable differences for a number of species in the rates estimated using the two extended Band models. As highlighted above, this relates to differences in the way that flight height distributions are considered by the two models.

Table 3 Estimated rates (Standard deviations; 95% Confidence Intervals) for use with different Collision Risk Models

	Basic Band (2012) Model	Extended Band (2012) Model	Basic sCRM	Extended sCRM
Sandwich Tern	0.9722 (0.0016; 0.969–0.9753)	0.9645 (0.0019; 0.9609–0.9682)	0.9723 (0.0005; 0.9714–0.9732)	0.9706 (0.0028; 0.9644–0.9753)
Common Tern	0.9201 (0.0036; 0.9129–0.9272)	0.8558 (0.0074; 0.8413–0.8703)	0.9204 (0.0016; 0.9174–0.9236)	0.8538 (0.0076; 0.839–0.8683)
Little Tern	0.9982 (0.0003; 0.9977–0.9987)	0.9901 (0.0014; 0.9874–0.9929)	0.9982 (0.0001; 0.9981–0.9983)	0.99 (0.0006; 0.9888–0.9911)
All Terns	0.9712 (0.0007; 0.9697–0.9726)	0.9344 (0.0016; 0.9313–0.9375)	0.9713 (0.0004; 0.9704–0.9722)	0.9399 (0.0033; 0.9333–0.946)
Black-legged Kittiwake	0.9970 (0.0015; 0.994–1)	0.9924 (0.0038; 0.9848–0.9999)	0.9979 (0.0013; 0.9954–0.9993)	0.9947 (0.1316; 0.4098–0.998)
Black-headed Gull	0.9873 (0.0009; 0.9856–0.989)	0.8978 (0.0086; 0.8809–0.9147)	0.9874 (0.0008; 0.9859–0.9888)	0.9047 (0.0204; 0.8536–0.9351)
Common Gull	0.9997 (0.0001; 0.9996–0.9998)	0.9976 (0.0005; 0.9967–0.9985)	0.9997 (0; 0.9997–0.9998)	0.9979 (0.0003; 0.9973–0.9984)
Lesser Black-backed Gull	0.995 (0.0003; 0.9944–0.9956)	0.9789 (0.0012; 0.9766–0.9813)	0.995 (0.0003; 0.9943–0.9956)	0.9801 (0.0022; 0.9762–0.9847)
Herring Gull	0.9953 (0.0002; 0.9948–0.9957)	0.9825 (0.0008; 0.981–0.9841)	0.9953 (0.0003; 0.9947–0.9959)	0.9497 (0.0088; 0.9317–0.9651)
Great Black-backed Gull	0.9991 (0.0002; 0.9986–0.9995)	0.9965 (0.0009; 0.9948–0.9983)	0.9991 (0.0002; 0.9985–0.9993)	0.9969 (0.0009; 0.9946–0.9982)
Small gulls	0.9919 (0.0004; 0.9911–0.9927)	0.9354 (0.0034; 0.9288–0.942)	0.9921 (0.0004; 0.9913–0.9928)	0.9426 (0.0081; 0.9229–0.9559)
Large gulls	0.9860 (0.0007; 0.9846–0.9874)	0.9448 (0.0028; 0.9393–0.9503)	0.9861 (0.0006; 0.9849–0.9873)	0.9104 (0.0082; 0.8935–0.9259)
All gulls	0.9874 (0.0003; 0.9868–0.9879)	0.9532 (0.001; 0.9512–0.9553)	0.9879 (0.0005; 0.987–0.9889)	0.9261 (0.0066; 0.9128–0.9382)
All gulls & terns	0.9856 (0.0002; 0.9852–0.9860)	0.9501 (0.0007; 0.9486–0.9515)	0.9861 (0.0005; 0.9851–0.9871)	0.9295 (0.0047; 0.9204–0.9387)

Sandwich Tern Avoidance Rate

Data to estimate avoidance rates for Sandwich Terns came from four sites (Blyth Harbour, Bouin, Zeebrugge and Slufterdam & Distridam). Across these four sites, recorded activity levels varied from 0.004 birds hour^{1} to 884 birds hour^{1}, with 45 collisions estimated across these sites once corrections for search area, searcher efficiency and predator activity had been applied. However, the majority of these collisions occurred within the wind farm in Zeebrugge (Table 4). The avoidance rates estimated here differ from those estimated previously (Cook *et al*., 2014 and Natural England guidance note). In part this is due to the inclusion of data from additional sites. However, restricting analyses to data collected from Zeebrugge in 2004 and 2005 only also highlights differences that must be accounted for. For these data, the analysis presented here generates an avoidance rate of 0.952 in 2004 and 0.984 in 2005. For reference, the equivalent values in Cook *et al.* (2014) were 0.989 and 0.994, while the previous Natural England guidance estimated an average of 0.989 across both years. These differences highlight the role that seemingly minor decisions in how to treat the data can have in the estimation of avoidance rates, and the importance of transparency in these calculations. In Cook *et al.* (2014) a decision was made to base calculations on observed rather than recorded collisions to ensure consistency with the analyses for other species. In relation to Eq. 1, this meant a lower observed collision rate than was included here, resulting in a higher avoidance rate. In relation to the previous Natural England guidance, a collision risk factor (presumed to be equivalent to PColl) of 0.253 was used. In contrast, the estimate of PColl for this study was 0.097. It is unclear how the collision risk factor used in the previous analysis was derived. However, in the context of Eq 1., the higher value would result in a higher estimate of the number of collisions expected in the absence of avoidance and, consequently, a higher avoidance rate.

Table 4 Summary of bird data contributing to avoidance rates for Sandwich Tern

Site	Surveys Start Date	Surveys End Date	Total Count	Hours Of Survey	Passage Rate (Birds Hr^{1})	% Flights At Rotor Height (Site Specific Or Generic)	Observed Collisions	Correction Factor			Corrected Collisions
								Predation	Efficiency	Area	
Blyth Harbour	01/09/2016	31/03/2017	4	54	0.07	0.50	0.00	1.00	1.00	1.00	0.00
Bouin	01/01/2003	31/12/2006	2	370	0.00	0.20*	0.00	1.23	1.32	1.00	0.00
Slufterdam & Distridam	13/06/2012	04/07/2012	18	15	1.20	0.12	1.00	1.00	1.00	1.00–3.23	1.00
Zeebrugge**	01/06/2000	31/07/2000	11	16	0.69	0.18	0.00	1.10	1.16	4.17–9.09	0.00
Zeebrugge**	01/06/2001	31/07/2001	11	16	0.69	0.18	0.00	1.10	1.16	4.17–9.09	0.00
Zeebrugge	01/09/2001	31/10/2001	24	16	1.50	0.38	0.00	1.10	1.16	4.17–9.09	0.00
Zeebrugge	01/06/2004	30/06/2004	15032	17	884.24	0.06	3.00	1.10	1.16	4.17–9.09	28.52
Zeebrugge	01/06/2005	30/06/2005	12320	17	724.71	0.13	3.00	1.10	1.16	4.17–9.09	15.96

*20% of all birds recorded at rotor height; **Data are averaged across the 2000 and 2001 breeding seasons

The low activity levels at the remaining sites mean that if the Zeebrugge data are excluded from the analysis then the estimated avoidance rates are substantially reduced (Table 5), indicating that that these data are exerting a strong influence on the final estimated avoidance rates. For the extended models this includes negative avoidance rates, which would imply a higher number of collisions recorded than would have been expected given activity levels at the site. However, this is likely to be an artefact of incorporating data from Slufterdam & Distridam, where a single collision was recorded despite low levels of activity. Whilst counter-intuitive, this highlights the importance of incorporating data from a range of sites in the analysis. Collisions are chance events and can occur at sites with low levels of activity. Indeed, past analyses have highlighted that recorded collisions do not always correlate with activity levels (Manuela de Lucas *et al*., 2008; Ferrer *et al*., 2012). To ensure that the variation in avoidance rates is accurately captured, it is important to include data from high and low activity sites where available. However, it is also important to consider how well the available data reflect variation in the sites where the species occurs. In this instance there is a strong influence of data from Zeebrugge on the final estimated rate.

Table 5 Estimated rates (Standard deviations; 95% Confidence Intervals) for use with different Collision Risk Models for Sandwich Tern excluding data from Zeebrugge

Basic Band (2012) Model	Extended Band (2012) Model	Basic sCRM	Extended sCRM
0.7144 (0.0631; 0.5907 – 0.8382)	-3.3669 (0.9245; -1.5548 – -5.1790)	0.5477 (0.1557; 0.2744 – 0.9460)	-2.6516 (1.3098; -5.8493 – -0.6090)

Common Tern Avoidance Rate

Data to estimate avoidance rates for Common Terns came from three sites (Bouin, Zeebrugge and Slufterdam & Distridam). Across these three sites, recorded activity levels varied from 0.065 birds hour^{1} to 599 birds hour^{1}, with 126 collisions estimated across these sites once corrections for search area, searcher efficiency and predator activity had been applied (Table 6).

As with Sandwich terns, the majority of these collisions occurred within the wind farm in Zeebrugge. However, in this instance, the exclusion of data from Zeebrugge led to an increase in the estimated avoidance rate for the basic Band Model and basic sCRM and, a reduced avoidance rate for the extended models (Table 7). These changes were not as extreme as those recorded for Sandwich tern and, confidence intervals around the reported rates were smaller, indicating that these data may better reflect a realistic range of behaviour than is the case for Sandwich tern. However, estimated avoidance rates are still based on limited sample size and, an all tern rate may better reflect the variation expected for common terns.

Table 6 Summary of bird data contributing to avoidance rates for Common Tern

Site	Surveys Start Date	Surveys End Date	Total Count	Hours Of Survey	Passage Rate (Birds Hr^{-1})	% Flights At Rotor Height (Site Specific Or Generic)	Observed Collisions	Correction Factor			Corrected Collisions
								Predation	Efficiency	Area	
Bouin	01/01/2003	31/12/2006	24	370	0.06	0.20*	0.00	1.23	1.32	1.00	0.00
Slufterdam & Distridam	13/06/2012	04/07/2012	2564	15	170.93	0.12	4.00	1.00	1.00	1.00–3.23	8.10
Zeebrugge**	01/06/2000	31/07/2000	498	16	31.13	0.07	0.00	1.10	1.16	4.17–9.09	0.00
Zeebrugge**	01/06/2001	31/07/2001	498	16	31.13	0.07	0.00	1.10	1.16	4.17–9.09	0.00
Zeebrugge	01/09/2001	31/10/2001	86	16	5.38	0.21	0.00	1.10	1.16	4.17–9.09	0.00
Zeebrugge	01/06/2004	30/06/2004	10198	17	599.88	0.06	6.00	1.10	1.16	4.17–9.09	44.88
Zeebrugge	01/06/2005	30/06/2005	4216	17	248.00	0.27	9.00	1.10	1.16	4.17–9.09	73.57

*20% of all birds recorded at rotor height; **Data are averaged across the 2000 and 2001 breeding seasons

Table 7 Estimated rates (Standard deviations; 95% Confidence Intervals) for use with different Collision Risk Models for Common Tern excluding data from Zeebrugge

Basic Band (2012) Model	Extended Band (2012) Model	Basic sCRM	Extended sCRM
0.9738 (0.0038; 0.9663 – 0.9813)	0.7263 (0.0400; 0.6479 – 0.8048)	0.9737 (0.0009; 0.9727 – 0.9770)	0.7231 (0.0222; 0.6822 – 0.7280)

Little Tern Avoidance Rate

Data to estimate avoidance rates for Little Terns came from two sites (Zeebrugge and Slufterdam & Distridam). Across these three sites, recorded activity levels varied from 0.333 birds hour^{1} to 116 birds hour^{1} with five collisions estimated across these sites once corrections for search area, searcher efficiency and predator activity had been applied, all at Zeebrugge (Table 8).

Table 8 Summary of bird data contributing to avoidance rates for Little Tern

Site	Surveys Start Date	Surveys End Date	Total Count	Hours Of Survey	Passage Rate (Birds Hr^{-1})	% Flights At Rotor Height (Site Specific Or Generic)	Observed Collisions	Correction Factor			Corrected Collisions
								Predation	Efficiency	Area	
Slufterdam & Distridam	13/06/2012	04/07/2012	5	15	0.33	0.12	0.00	1.00	1.00	1.00–3.23	0.00
Zeebrugge*	01/06/2000	31/07/2000	1860	16	116.25	0.45	0.00	1.10	1.16	4.17–9.09	0.00
Zeebrugge*	01/06/2001	31/07/2001	1860	16	116.25	0.45	1.00	1.10	1.16	4.17–9.09	5.32
Zeebrugge	01/09/2001	31/10/2001	1605	16	100.31	0.50	0.00	1.10	1.16	4.17–9.09	0.00
Zeebrugge	01/06/2004	30/06/2004	1724	17	101.41	0.13	0.00	1.10	1.16	4.17–9.09	0.00
Zeebrugge	01/06/2005	30/06/2005	370	17	21.76	0.65	0.00	1.10	1.16	4.17–9.09	0.00

*Flight Activity Data are averaged across the 2000 and 2001 breeding seasons

All terns Avoidance Rate

Data to estimate avoidance rates for terns came from four sites (Blyth Harbour, Bouin, Zeebrugge and Slufterdam & Distridam). Across these four sites, recorded activity levels varied from 0.07 birds hour^{1} to 1585 birds hour^{1} with 176 collisions estimated across these sites once corrections for search area, searcher efficiency and predator activity had been applied (Table 9).

Excluding data from Zeebrugge from the analysis resulted in avoidance rate for the basic models that were broadly in line with those estimated using all the data, but substantially reduced estimates for the extended models (Table 10).

Table 9 Summary of bird data contributing to avoidance rates for all terns

Site	Surveys Start Date	Surveys End Date	Total Count	Hours Of Survey	Passage Rate (Birds Hr^{-1})	Observed Collisions	Correction Factor			Corrected Collisions
							Predation	Efficiency	Area	
Blyth Harbour	01/09/2016	31/03/2017	4	54	0.07	0	1.00	1.00	1.00	0.00
Bouin	01/01/2003	31/12/2006	26	370	0.07	0	1.23	1.32	1.00	0.00
Slufterdam & Distridam	13/06/2012	04/07/2012	2587	15	172.47	5	1.00	1.00	1.00–3.23	9.10
Zeebrugge*	01/06/2000	31/07/2000	2369	16	148.06	0	1.10	1.16	4.17–9.09	0.00
Zeebrugge*	01/06/2001	31/07/2001	2369	16	148.06	1	1.10	1.16	4.17–9.09	5.32
Zeebrugge	01/09/2001	31/10/2001	1715	16	107.19	0	1.10	1.16	4.17–9.09	0.00
Zeebrugge	01/06/2004	30/06/2004	26954	17	1585.53	9	1.10	1.16	4.17–9.09	73.00
Zeebrugge	01/06/2005	30/06/2005	16906	17	994.47	12	1.10	1.16	4.17–9.09	89.54

Table 10 Estimated rates (Standard deviations; 95% Confidence Intervals) for use with different Collision Risk Models for all terns excluding data from Zeebrugge

Basic Band (2012) Model	Extended Band (2012) Model	Basic sCRM	Extended sCRM
0.9709 (0.0021; 0.9666 – 0.9752)	0.6954 (0.0229; 0.6505 – -0.7404)	0.9707 (0.0011; 0.9696 – 0.9744)	0.6933 (0.0248; 0.6470 – 0.7469)

Black-legged Kittiwake Avoidance Rate

Data to estimate Black-legged Kittiwake avoidance rates come from two sites, Thanet, and Blyth Harbour, with a single collision recorded at Thanet. An additional collision was noted at Zeebrugge in September 2001, but without an estimate of the species' activity levels, it was not possible to use this to estimate an avoidance rate (Everaert *et al*., 2002).

With no birds recorded at collision risk height and no collisions recorded at Blyth Harbour, estimates of Black-legged Kittiwake avoidance rate rely on the data collected as part of the ORJIP BCA study at Thanet (Bowgen & Cook, 2018). In contrast to the other studies considered in this analysis, these data were collected in the offshore environment and consequently make use of density estimates, rather than passage rates derived from visual surveys, in order to estimate the total flux through the wind farm. Estimated avoidance rates presented here are based on generic values for speed rather than the straight line and actual speed values used in those derived as part of Bowgen and Cook (2018). This is because a single generic value for speed better reflects how collision risk models are used at present. The analysis in Bowgen & Cook (2018) highlights the step-by-step process used to estimate avoidance rates from studies such as that carried out at Thanet, and the decisions that need to be taken at each step in the process and the implications those decisions can have on the final estimated values.

The data collected as part of the ORJIP BCA study offer a valuable insight into bird behaviour in and around offshore windfarms (Skov *et al.* 2018) and the analysis set out in Bowgen & Cook (2018) demonstrates how such data can be used in order to estimate avoidance rates for use in the Band Model. However, for a number of reasons, the avoidance rates estimated in Bowgen & Cook (2018) are unlikely to be as representative as those for other species or groups presented in this report. Firstly, data were collected from an area with relatively low densities of Black-legged Kittiwake, and were restricted to winter only. This means that these data are unlikely to be reflective of the full range of conditions experienced by Black-legged Kittiwakes on an annual basis. Secondly, there is some uncertainty over estimates of the proportion of birds at collision risk height within Thanet wind farm. Data collected as part of monitoring carried out during the ORJIP BCA study suggest a far higher proportion of birds at collision risk height than has been estimated elsewhere. It is unclear as to whether this is a genuine effect or may be the result of some bias in data collection. For example, Borkenhagen *et al.* (2018) found that flight heights estimated using laser-rangefinders may be biased against lower flying birds, which could result in an overestimate of the proportion of birds at risk height. Following Eq. 1, such an overestimate would result in an increase in the estimated avoidance rate. If it is a genuine effect, this may indicate site-specific variations in behaviour, e.g., related to how the birds use the site or the time of year at which they are present (and compounding the need to have data from several sites). For these reasons, a more precautionary and generically applicable approach would be to use the generic values estimated by Johnston *et al.* 2014. Finally, and most importantly, contemporaneous density estimates were not available, meaning total flux had to be estimated using the mean of post-construction density estimates. As a result, the extent to which the avoidance rates here reflect activity levels within the windfarm over the time period in which collision rates were monitored is unclear.

Table 11 Summary of bird data contributing to avoidance rates for Black-legged Kittiwake

Site	Surveys Start Date	Surveys End Date	Density (birds km^{1})	Total Count	Hours Of Survey	Passage Rate (Birds Hr^{-1})	% Flights At Rotor Height (Site Specific Or Generic)	Observed Collisions	Correction Factor: Predation	Correction Factor: Efficiency	Correction Factor: Area	Corrected Collisions
Blyth Harbour	01/09/2016	31/03/2017	NA	74	54	1.37	**0.00**	0.00	1.00	1.00	1.00	0.00
Thanet	01/10/2014	31/03/2015	1.1	Na	NA	NA	*0.10*	1.00	1.00	1.00	1.00	1.00
Thanet	01/10/2014	31/03/2016	1.1	NA	NA	NA	*0.10*	0.00	1.00	1.00	1.00	0.00

Black-headed Gull Avoidance Rate

Data to estimate avoidance rates for Black-headed Gulls came from 13 sites (Bloodgate Hill, Blyth Harbour, Goole Fields, Hellrigg, Red House Farm, Avonmouth, Kessingland, Gneizdzewo, Bouin, Boudwijnkanaal, Kleine Pathoweg, Zeebrugge, Slufterdam & Distridam) with passage rates ranging from 0.50 birds hour^{1} to 174 birds hour^{1} and a total of 140 collisions estimated following corrections for search area, searcher efficiency and predator behaviour. These data have been collected across a range of sites reflecting different habitat types, over a number of different years (Table 12).

Table 12 Summary of bird data contributing to avoidance rates for Black-headed Gull

Site	Surveys Start Date	Surveys End Date	Total Count	Hours Of Survey	Passage Rate (Birds Hr^{1})	% Flights At Rotor Height (Site Specific Or Generic)	Observed Collisions	Correction Factor			Corrected Collisions
								Predation	Efficiency	Area	
Avonmouth	01/10/2007	31/03/2008	NA	NA	4.40	**0.32**	1.00	1.00	1.00	1.00	1.00
Avonmouth	01/10/2008	31/03/2009	NA	NA	7.10	**0.65**	0.00	1.00	1.00	1.00	0.00
Avonmouth	01/10/2009	31/03/2010	NA	NA	2.90	**0.33**	0.00	1.00	1.00	1.00	0.00
Avonmouth	01/10/2011	31/03/2012	NA	NA	12.80	**0.75**	0.00	1.00	1.00	1.00	0.00
Bloodgate Hill	01/10/2007	27/02/2008	4503	36	125.08	**0.18**	0.00	1.00	1.00	1.00	0.00
Blyth Harbour	01/09/2016	31/03/2017	520	54	9.63	**0.07**	2.00	1.00	1.00	1.00	2.00
Boudwijnkanaal	01/05/2001	31/05/2001	49	17	2.88	**0.12**	0.00	1.00	1.00	1.00	0.00
Boudwijnkanaal	01/10/2001	31/10/2001	2960	17	174.12	**0.32**	0.00	1.00	1.00	1.00	0.00
Boudwijnkanaal	01/09/2005	31/12/2005	696	17	40.94	**0.69**	12.00	1.00	1.00	1.00	15.96
Bouin	01/01/2003	31/12/2006	5815	370	15.72	**0.20***	28.00	1.23	1.32	1.00	45.46
Gneizdzewo	15/09/2010	15/11/2010	38	68	0.56	*0.02*	1.00	1.00	1.00	1.00	1.00
Gneizdzewo	15/09/2011	15/11/2011	212	57	3.72	*0.02*	0.00	1.00	1.00	1.00	0.00
Gneizdzewo	15/09/2012	15/11/2012	32	63	0.51	*0.02*	0.00	1.00	1.00	1.00	0.00
Goole Fields	01/04/2017	31/08/2017	1187	45	26.38	**0.20**	0.00	1.00	1.00	1.00	0.00
Goole Fields	01/09/2017	31/03/2018	NA	72	62.10	**0.33**	2.00	1.14	1.00	1.00	2.76
Hellrigg	01/12/2011	31/03/2012	182	38	4.79	**0.25**	0.00	1.00	1.00	1.00	0.00
Hellrigg	01/12/2012	31/03/2013	4799	36.5	131.48	**0.81**	0.00	1.00	1.00	1.00	0.00
Hellrigg	01/12/2014	31/03/2015	2501	36	69.47	**0.68**	0.00	1.00	1.00	1.00	0.00
Kessingland	01/11/2011	31/03/2012	215	18	11.94	**1.00**	0.00	1.79	1.00	1.00	0.00
Kessingland	01/11/2011	31/03/2012	104	18	5.78	**1.00**	0.00	1.79	1.00	1.00	0.00
Kessingland	01/11/2012	31/03/2013	58	18	3.22	**1.00**	0.00	1.79	1.00	1.00	0.00
Kessingland	01/11/2012	31/03/2013	117	18	6.50	**1.00**	1.00	1.79	1.00	1.00	1.79
Kleine Pathoweg	01/09/2005	31/12/2005	345	16	21.56	**0.57**	17.00	1.00	1.00	1.00	59.50
Red House Farm	01/04/2009	31/08/2009	NA	36	54.50	**0.24**	3.00	1.00	1.00	1.00	3.00
Slufterdam & Distridam	13/06/2012	04/07/2012	1659	15	110.60	**0.26**	4.00	1.00	1.00	1.00–3.23	7.56
Zeebrugge	01/06/2000	31/07/2000	17	16	1.06	**0.12**	0.00	1.00	1.00	4.17–9.09	0.00
Zeebrugge	01/06/2001	31/07/2001	17	16	1.06	**0.12**	0.00	1.00	1.00	4.17–9.09	0.00
Zeebrugge	01/09/2001	31/10/2001	94	16	5.88	**0.87**	0.00	1.00	1.00	4.17–9.09	0.00

*20% of all birds estimated to be at collision risk height

Common Gull Avoidance Rate

Data to estimate avoidance rates for common gulls came from nine sites (Bloodgate Hill, Blyth Harbour, Goole Fields, Hellrigg, Red House Farm, Kessingland, Gneizdzewo, Bouin, Slufterdam & Distridam) with passage rates ranging from 0.03 birds hour^{1} to 507 birds hour^{1} and 2 collisions estimated following corrections for search area, searcher efficiency and predator behaviour (Table 13). Whilst there are some sites with significant activity levels, in most cases the number of birds recorded is much lower at 1-5 birds hour^{1}.

Table 13 Summary of bird data contributing to avoidance rates for Common Gull

Site	Surveys Start Date	Surveys End Date	Total Count	Hours Of Survey	Passage Rate (Birds Hr^{-1})	% Flights At Rotor Height (Site Specific Or Generic)	Observed Collisions	Correction Factor			Corrected Collisions
								Predation	Efficiency	Area	
Bloodgate Hill	01/10/2007	27/02/2008	2207	36	61.31	**0.17**	0.00	1.00	1.00	1.00	0.00
Blyth Harbour	01/09/2016	31/03/2017	470	54	8.70	**0.02**	0.00	1.00	1.00	1.00	0.00
Bouin	01/01/2003	31/12/2006	12	370	0.03	**0.20***	0.00	1.23	1.32	1.00	0.00
Gneizdzewo	15/09/2010	15/11/2010	39	68	0.57	*0.05*	0.00	1.00	1.00	1.00	0.00
Gneizdzewo	15/09/2011	15/11/2011	64	57	1.12	*0.05*	0.00	1.00	1.00	1.00	0.00
Gneizdzewo	15/09/2012	15/11/2012	110	63	1.75	*0.05*	0.00	1.00	1.00	1.00	0.00
Goole Fields	01/04/2017	31/08/2017	89	45	1.98	**0.29**	0.00	1.00	1.00	1.00	0.00
Goole Fields	01/09/2017	31/03/2018	NA	72	17.60	**0.24**	0.00	1.14	1.00	1.00	0.00
Hellrigg	01/12/2011	31/03/2012	322	38	8.47	**0.50**	0.00	1.00	1.00	1.00	0.00
Hellrigg	01/12/2012	31/03/2013	18512	36.5	507.18	**0.88**	0.00	1.00	1.00	1.00	0.00
Hellrigg	01/12/2014	31/03/2015	3315	36	92.08	**0.75**	0.00	1.00	1.00	1.00	0.00
Kessingland	01/11/2011	31/03/2012	24	18	1.33	**1.00**	0.00	1.79	1.00	1.00	0.00
Kessingland	01/11/2011	31/03/2012	29	18	1.61	**1.00**	0.00	1.79	1.00	1.00	0.00
Kessingland	01/11/2012	31/03/2013	27	18	1.50	**1.00**	1.00	1.79	1.00	1.00	1.79
Kessingland	01/11/2012	31/03/2013	43	18	2.39	**1.00**	0.00	1.79	1.00	1.00	0.00
Red House Farm	01/04/2009	31/08/2009	NA	36	2.90	**0.06**	0.00	1.00	1.00	1.00	0.00
Slufterdam & Distridam	13/06/2012	04/07/2012	66	15	4.40	**0.26**	0.00	1.00	1.00	1.00–3.23	0.00

*20% of all birds recorded at collision risk height

Lesser Black-backed Gull Avoidance Rate

Data to estimate avoidance rates for lesser black-backed gulls came from 10 sites (Bloodgate Hill, Goole Fields, Haverigg, Hellrigg, Red House Farm, Avonmouth, Kessingland, Bouin, Boudwijnkanaal, Zeebrugge, Slufterdam & Distridam) with passage rates ranging from 0.03 birds hour^{1} to 125 birds hour^{1} and a total of 43 collisions estimated following corrections for search area, searcher efficiency and predator behaviour. These data have been collected across a range of sites reflecting different habitat types, over a number of different years.

Table 14 Summary of bird data contributing to avoidance rates for Lesser Black-backed Gull

Site	Surveys Start Date	Surveys End Date	Total Count	Hours Of Survey	Passage Rate (Birds Hr^{-1})	% Flights At Rotor Height (Site Specific Or Generic)	Observed Collisions	Correction Factor			Corrected Collisions
								Predation	Efficiency	Area	
Bloodgate Hill	01/10/2007	27/02/2008	7	36	0.19	**0.60**	0.00	1.00	1.00	1.00	0.00
Boudwijnkanaal	01/05/2001	31/05/2001	45	17	2.65	**0.76**	0.00	1.00	1.00	1.00	0.00
Boudwijnkanaal	01/10/2001	31/10/2001	9	17	0.53	**0.89**	0.00	1.00	1.00	1.00	0.00
Bouin	01/01/2003	31/12/2006	63	370	0.17	**0.20***	0.00	1.23	1.32	1.00	0.00
Goole Fields	01/04/2017	31/08/2017	851	45	18.91	**0.61**	0.00	1.00	1.00	1.00	0.00
Goole Fields	01/09/2017	31/03/2018	NA	72	45.30	**0.49**	1.00	1.14	1.00	1.00	1.38
Haverigg	01/04/2014	31/07/2014	1411	36	39.19	**0.34**	2.00	1.07	1.12	1.00	2.40
Haverigg	01/05/2019	31/07/2019	1016	36	28.22	**0.89**	1.00	1.07	1.33	1.00	1.42
Hellrigg	01/12/2011	31/03/2012	1	38	0.03	**1.00**	0.00	1.00	1.00	1.00	0.00
Hellrigg	01/12/2012	31/03/2013	15	36.5	0.41	**0.88**	0.00	1.00	1.00	1.00	0.00
Hellrigg	01/12/2014	31/03/2015	54	36	1.50	**0.85**	0.00	1.00	1.00	1.00	0.00
Kessingland	01/11/2011	31/03/2012	15	18	0.83	**1.00**	0.00	1.79	1.00	1.00	0.00
Kessingland	01/11/2011	31/03/2012	25	18	1.39	**1.00**	0.00	1.79	1.00	1.00	0.00
Kessingland	01/11/2012	31/03/2013	17	18	0.94	**1.00**	0.00	1.79	1.00	1.00	0.00
Kessingland	01/11/2012	31/03/2013	57	18	3.17	**1.00**	0.00	1.79	1.00	1.00	0.00
Red House Farm	01/04/2009	31/08/2009	NA	36	3.60	**0.74**	0.00	1.00	1.00	1.00	0.00
Slufterdam & Distridam	13/06/2012	04/07/2012	1876	15	125.07	**0.62**	17.00	1.00	1.00	1.00–3.23	29.74
Zeebrugge	01/06/2000	31/07/2000	81	16	5.06	**0.32**	0.00	1.00	1.00	4.17–9.09	0.00
Zeebrugge	01/06/2001	31/07/2001	81	16	5.06	**0.32**	1.00	1.00	1.00	4.17–9.09	4.17
Zeebrugge	01/09/2001	31/10/2001	1025	16	64.06	**0.69**	1.00	1.00	1.00	4.17–9.09	4.17

*20% of all birds recorded at collision risk height

Herring Gull Avoidance Rate

Data to estimate avoidance rates for Herring Gulls came from 12 sites (Bloodgate Hill, Blyth Harbour, Goole Fields, Haverigg, Hellrigg, Red House Farm, Avonmouth, Kessingland, Gneizdzewo, Bouin, Boudwijnkanaal, Zeebrugge, Slufterdam & Distridam) with passage rates ranging from 0.20 birds hour^{1} to 90 birds hour^{1} and a total of 66 collisions estimated following corrections for search area, searcher efficiency and predator behaviour (Table 15). These data have been collected across a range of sites reflecting different habitat types, over a number of different years.

Table 15 Summary of bird data contributing to avoidance rates for Herring Gull

Site	Surveys Start Date	Surveys End Date	Total Count	Hours Of Survey	Passage Rate (Birds Hr^{-1})	% Flights At Rotor Height (Site Specific Or Generic)	Observed Collisions	Correction Factor			Corrected Collisions
								Predation	Efficiency	Area	
Avonmouth	01/10/2007	31/03/2008	NA	NA	6.80	**0.81**	0.00	1.00	1.00	1.00	0.00
Avonmouth	01/10/2008	31/03/2009	NA	NA	13.00	**0.82**	0.00	1.00	1.00	1.00	0.00
Avonmouth	01/10/2009	31/03/2010	NA	NA	18.80	**0.67**	0.00	1.00	1.00	1.00	0.00
Avonmouth	01/10/2011	31/03/2012	NA	NA	38.20	**0.79**	0.00	1.00	1.00	1.00	0.00
Bloodgate Hill	01/10/2007	27/02/2008	49	36	1.36	**0.90**	0.00	1.00	1.00	1.00	0.00
Blyth Harbour	01/09/2016	31/03/2017	4358	54	80.70	**0.56**	1.00	1.00	1.00	1.00	1.00
Boudwijnkanaal	01/05/2001	31/05/2001	154	17	9.06	**0.25**	0.00	1.00	1.00	1.00	0.00
Boudwijnkanaal	01/10/2001	31/10/2001	812	17	47.76	**0.34**	1.00	1.00	1.00	1.00	1.33
Bouin	01/01/2003	31/12/2006	807	370	2.18	**0.20***	0.00	1.23	1.32	1.00	0.00
Gneizdzewo	15/09/2011	15/11/2011	32	57	0.56	*0.11*	0.00	1.00	1.00	1.00	0.00
Goole Fields	01/04/2017	31/08/2017	34	45	0.76	**0.44**	0.00	1.00	1.00	1.00	0.00
Goole Fields	01/09/2017	31/03/2018	NA	72	2.50	**0.66**	0.00	1.14	1.00	1.00	0.00
Haverigg	01/04/2014	31/07/2014	3273	36	90.92	**0.24**	3.00	1.07	1.12	1.00	3.60
Haverigg	01/05/2019	31/07/2019	1757	36	48.81	**0.89**	5.00	1.07	1.33	1.00	7.12
Hellrigg	01/12/2011	31/03/2012	141	38	3.71	**0.44**	1.00	1.00	1.00	1.00	1.00
Hellrigg	01/12/2012	31/03/2013	2646	36.5	72.49	**0.94**	0.00	1.00	1.00	1.00	0.00
Hellrigg	01/12/2014	31/03/2015	1028	36	28.56	**0.86**	0.00	1.00	1.00	1.00	0.00
Kessingland	01/11/2011	31/03/2012	355	18	19.75	**1.00**	0.00	1.79	1.00	1.00	0.00
Kessingland	01/11/2011	31/03/2012	98	18	5.44	**1.00**	0.00	1.79	1.00	1.00	0.00
Kessingland	01/11/2012	31/03/2013	203	18	11.28	**1.00**	0.00	1.79	1.00	1.00	0.00
Kessingland	01/11/2012	31/03/2013	93	18	5.17	**1.00**	1.00	1.79	1.00	1.00	1.79
Red House Farm	01/04/2009	31/08/2009	NA	36	0.20	**1.00**	0.00	1.00	1.00	1.00	0.00
Slufterdam & Distridam	13/06/2012	04/07/2012	403	15	26.87	**0.39**	17.00	1.00	1.00	1.00–3.23	29.34
Zeebrugge	01/06/2000	31/07/2000	136	16	8.50	**0.25**	1.00	1.00	1.00	4.17–9.09	4.17
Zeebrugge	01/06/2001	31/07/2001	136	16	8.50	**0.25**	2.00	1.00	1.00	4.17–9.09	8.79
Zeebrugge	01/09/2001	31/10/2001	1032	16	64.50	**0.53**	2.00	1.00	1.00	4.17–9.09	8.34

*20% of all birds recorded at collision risk height

Great Black-backed Gull Avoidance Rate

Data to estimate avoidance rates for great black-backed gulls came from 7 sites (Bloodgate Hill, Blyth Harbour, Goole Fields, Hellrigg, Red House Farm, Bouin, Slufterdam & Distridam) with passage rates ranging from 0.05 birds hour^{1} to 31 birds hour^{1} and just 1 collision estimated following corrections for search area, searcher efficiency and predator behaviour (Table 16). Activity levels at most sites were low with <1 bird hour^{1} recorded.

Table 16 Summary of bird data contributing to avoidance rates for Great Black-backed Gull

Site	Surveys Start Date	Surveys End Date	Total Count	Hours Of Survey	Passage Rate (Birds Hr^{-1})	% Flights At Rotor Height (Site Specific Or Generic)	Observed Collisions	Correction Factor			Corrected Collisions
								Predation	Efficiency	Area	
Bloodgate Hill	01/10/2007	27/02/2008	13	36	0.36	**0.77**	0.00	1.00	1.00	1.00	0.00
Blyth Harbour	01/09/2016	31/03/2017	1704	54	31.56	**0.56**	0.00	1.00	1.00	1.00	0.00
Bouin	01/01/2003	31/12/2006	18	370	0.05	**0.20***	0.00	1.23	1.32	1.00	0.00
Goole Fields	01/09/2017	31/03/2018	NA	72	1.30	**0.69**	0.00	1.14	1.00	1.00	0.00
Hellrigg	01/12/2011	31/03/2012	2	38	0.05	**1.00**	0.00	1.00	1.00	1.00	0.00
Hellrigg	01/12/2012	31/03/2013	18	36.5	0.49	**0.93**	0.0	1.00	1.00	1.00	0.00
Hellrigg	01/12/2014	31/03/2015	2	36	0.06	**0.50**	0.00	1.00	1.00	1.00	0.00
Red House Farm	01/04/2009	31/08/2009	NA	36	0.06	**1.00**	1.00	1.00	1.00	1.00	1.00
Slufterdam & Distridam	13/06/2012	04/07/2012	4	15	0.27	**0.62**	0.00	1.00	1.00	1.00–3.23	0.00

*20% of all birds recorded at collision risk height

Small Gull Avoidance Rate

Data to estimate avoidance rates for small gulls (Black-headed Gull, Common Gull, Black-legged Kittiwake) came from 15 sites (Bloodgate Hill, Blyth Harbour, Goole Fields, Hellrigg, Red House Farm, Avonmouth, Kessingland, Gneizdzewo, Bouin, Thanet, Boudwijnkanaal, Kleine Pathoweg, Dr Put, Zeebrugge, Slufterdam & Distridam) with passage rates ranging from 1.13 birds hour^{1} to 638 birds hour^{1} and a total of 146 collisions estimated following corrections for search area, searcher efficiency and predator behaviour.

Table 17 Summary of bird data contributing to avoidance rates for small gulls

Site	Surveys Start Date	Surveys End Date	Density (Birds km^{-1})	Total Count	Hours Of Survey	Passage Rate (Birds Hr^{-1})	Observed Collisions	Correction Factor			Corrected Collisions
								Predation	Efficiency	Area	
Avonmouth	01/10/2007	31/03/2008	NA	NA	NA	4.40	1.00	1.00	1.00	1.00	1.00
Avonmouth	01/10/2008	31/03/2009	NA	NA	NA	7.10	0.00	1.00	1.00	1.00	0.00
Avonmouth	01/10/2009	31/03/2010	NA	NA	NA	2.90	0.00	1.00	1.00	1.00	0.00
Avonmouth	01/10/2011	31/03/2012	NA	NA	NA	12.80	0.00	1.00	1.00	1.00	0.00
Bloodgate Hill	01/10/2007	27/02/2008	NA	6710	36	186.39	0.00	1.00	1.00	1.00	0.00
Blyth Harbour	01/09/2016	31/03/2017	NA	1067	54	19.76	2.00	1.00	1.00	1.00	2.00
Boudwijnkanaal	01/05/2001	31/05/2001	NA	49	17	2.88	0.00	1.00	1.00	1.33	0.00
Boudwijnkanaal	01/10/2001	31/10/2001	NA	2960	17	174.12	0.00	1.00	1.00	1.33	0.00
Boudwijnkanaal	01/09/2005	31/12/2005	NA	696	17	40.94	12.00	1.00	1.00	1.33	15.96
Bouin	01/01/2003	31/12/2006	NA	5894	370	15.93	29.00	1.23	1.32	1.00	47.08
De Put	01/01/2006	28/02/2006	NA	160	18	8.89	2.00	1.00	1.00	1.00	2.00
Gneizdzewo	15/09/2010	15/11/2010	NA	77	68	1.13	1.00	1.00	1.00	1.00	1.00
Gneizdzewo	15/09/2011	15/11/2011	NA	289	57	5.07	0.00	1.00	1.00	1.00	0.00
Gneizdzewo	15/09/2012	15/11/2012	NA	142	63	2.25	0.00	1.00	1.00	1.00	0.00
Goole Fields	01/04/2017	31/08/2017	NA	1276	45	28.36	0.00	1.00	1.00	1.00	0.00
Goole Fields	01/09/2017	31/03/2018	NA	NA	72	79.70	2.00	1.14	1.00	1.21	2.76
Hellrigg	01/12/2011	31/03/2012	NA	504	38	13.26	0.00	1.00	1.00	1.00	0.00
Hellrigg	01/12/2012	31/03/2013	NA	23311	36.5	638.66	0.00	1.00	1.00	1.00	0.00
Hellrigg	01/12/2014	31/03/2015	NA	5816	36	161.56	0.00	1.00	1.00	1.00	0.00
Kessingland	01/11/2011	31/03/2012	NA	372	18	20.67	0.00	1.79	1.00	1.00	0.00
Kessingland	01/11/2012	31/03/2013	NA	245	18	13.61	2.00	1.79	1.00	1.00	3.58
Kleine Pathoweg	01/09/2005	31/12/2005	NA	345	16	21.56	17.00	1.00	1.00	3.50	59.50
Red House Farm	01/04/2009	31/08/2009	NA	NA	36	57.40	3.00	1.00	1.00	1.00	3.00
Slufterdam & Distridam	13/06/2012	04/07/2012	NA	1751	15	116.73	4.00	1.00	1.00	1.00–3.23	7.56
Thanet	01/10/2014	31/03/2015	1.1	NA	NA	NA	1.00	1.00	1.00	1.00	1.00
Thanet	01/10/2015	31/03/2016	1.1	NA	NA	NA	0.00	1.00	1.00	1.00	0.00
Zeebrugge	01/06/2000	31/07/2000	NA	17	16	1.06	0.00	1.00	1.00	4.17–9.09	0.00
Zeebrugge	01/06/2001	31/07/2001	NA	17	16	1.06	0.00	1.00	1.00	4.17–9.09	0.00
Zeebrugge	01/09/2001	31/10/2001	NA	94	16	5.88	0.0	1.00	1.00	4.17–9.09	0.00

Large Gull Avoidance Rate

Data to estimate avoidance rates for large gulls (Herring Gull, Lesser Black-backed Gull, Great Black-backed Gull) came from 15 sites (Bloodgate Hill, Blyth Harbour, Goole Fields, Haverigg, Hellrigg, Red House Farm, Avonmouth, Kessingland, Gneizdzewo, Bouin, Thanet, Kleine Pathoweg, Boudwijnkanaal, Zeebrugge, Slufterdam & Distridam) with passage rates ranging from 0.06 birds hour^{1} to 152 birds hour^{1} and a total of 349 collisions estimated following corrections for search area, searcher efficiency and predator behaviour. The estimated large gull avoidance rate is lower than those estimated for Lesser Black-backed, Herring and Great Black backed Gulls as it includes data from surveys in which the data used to estimate activity levels were drawn from birds identified as large gulls rather than to species level. This includes the data collected at Thanet and the data collected at Boudwijnkanaal and Kleine Pathoweg in autumn/winter 2005.

Table 18 Summary of bird data contributing to avoidance rates for small gulls

Site	Surveys Start Date	Surveys End Date	Density (Birds km^{-1})	Total Count	Hours Of Survey	Passage Rate (Birds Hr^{-1})	Observed Collisions	Correction Factor			Corrected Collisions
								Predation	Efficiency	Area	
Avonmouth	01/10/2007	31/03/2008	NA	NA	NA	6.80	0.00	1.00	1.00	1.00	0.00
Avonmouth	01/10/2008	31/03/2009	NA	NA	NA	13.00	0.00	1.00	1.00	1.00	0.00
Avonmouth	01/10/2009	31/03/2010	NA	NA	NA	18.80	0.00	1.00	1.00	1.00	0.00
Avonmouth	01/10/2011	31/03/2012	NA	NA	NA	38.20	0.00	1.00	1.00	1.00	0.00
Bloodgate Hill	01/10/2007	27/02/2008	NA	69	36	1.92	0.00	1.00	1.00	1.00	0.00
Blyth Harbour	01/09/2016	31/03/2017	NA	6070	54	112.41	1.00	1.00	1.00	1.00	1.00
Boudwijnkanaal	01/05/2001	31/05/2001	NA	199	17	11.71	0.00	1.00	1.00	1.33	0.00
Boudwijnkanaal	01/10/2001	31/10/2001	NA	821	17	48.29	1.00	1.00	1.00	1.33	1.33
Boudwijnkanaal	01/09/2005	31/12/2005	NA	339	17	19.94	28.00	1.00	1.00	1.33	37.24
Bouin	01/01/2003	31/12/2006	NA	891	370	2.41	1.00	1.23	1.32	1.00	1.62
Gneizdzewo	18/08/2008	16/11/2008	NA	15	216	0.07	0.00	1.00	1.00	1.00	0.00
Gneizdzewo	15/09/2010	15/11/2010	NA	117	68	1.72	0.00	1.00	1.00	1.00	0.00
Gneizdzewo	15/09/2011	15/11/2011	NA	32	57	0.56	0.00	1.00	1.00	1.00	0.00
Gneizdzewo	15/09/2012	15/11/2012	NA	67	63	1.06	0.00	1.00	1.00	1.00	0.00
Goole Fields	01/04/2017	31/08/2017	NA	924	45	20.53	0.00	1.00	1.00	1.00	0.0
Goole Fields	01/09/2017	31/03/2018	NA	NA	72	50.84	1.00	1.14	1.00	1.21	1.38
Haverigg	01/04/2014	31/07/2014	NA	4684	36	130.11	5.00	1.07	1.12	1.00	5.99
Haverigg	01/05/2019	31/07/2019	NA	2773	36	77.03	6.00	1.07	1.33	1.00	8.54
Hellrigg	01/12/2011	31/03/2012	NA	144	38	3.79	1.00	1.00	1.00	1.00	1.00
Hellrigg	01/12/2012	31/03/2013	NA	2679	36.5	73.40	0.00	1.00	1.00	1.00	0.00
Hellrigg	01/12/2014	31/03/2015	NA	1084	36	30.11	0.00	1.00	1.00	1.00	0.00
Kessingland	01/11/2011	31/03/2012	NA	493	18	27.39	0.00	1.79	1.00	1.00	0.00
Kessingland	01/11/2012	31/03/2013	NA	370	18	20.56	1.00	1.79	1.00	1.00	1.79
Kleine Pathoweg	01/09/2005	31/12/2005	NA	327	16	20.44	57.00	1.00	1.00	3.50	199.50
Red House Farm	01/04/2009	31/08/2009	NA	NA	36	3.86	1.00	1.00	1.00	1.00	1.00
Slufterdam & Distridam	13/06/2012	04/07/2012	NA	2283	15	152.20	34.00	1.00	1.00	1.00–3.23	59.08
Thanet	01/10/2014	31/03/2015	2.76	NA	NA	NA	2.00	1.00	1.00	1.00	2.00
Thanet	01/10/2015	31/03/2016	2.76	NA	NA	NA	2.00	1.00	1.00	1.00	2.00
Zeebrugge	01/06/2000	31/07/2000	NA	217	16	13.56	1.00	1.00	1.00	4.17–9.09	4.17
Zeebrugge	01/06/2001	31/07/2001	NA	217	16	13.56	3.00	1.00	1.00	4.17–9.09	12.96
Zeebrugge	01/09/2001	31/10/2001	NA	2057	16	128.56	3.00	1.00	1.00	4.17–9.09	12.51

All Gull Avoidance Rate

Data to estimate avoidance rates for all gulls came from 19 sites (Bloodgate Hill, Blyth Harbour, Goole Fields, Haverigg, Hellrigg, Red House Farm, Avonmouth, Kessingland, Gneizdzewo, Bouin, Oosterbierum, Thanet, Kleine Pathoweg, De Put, Delfzijl-Zuid, Sabinapolder, Boudwijnkanaal, Zeebrugge, Slufterdam & Distridam) with passage rates ranging from 1.4 birds hour^{1} to 712 birds hour^{1} and a total of 628 collisions estimated following corrections for search area, searcher efficiency and predator behaviour.

Table 19 Summary of bird data contributing to avoidance rates for all gulls

Site	Surveys Start Date	Surveys End Date	Density (Birds km^{-1})	Total Count	Hours Of Survey	Passage Rate (Birds Hr^{-1})	Observed Collisions	Correction Factor			Corrected Collisions
								Predation	Efficiency	Area	
Avonmouth	01/10/2007	31/03/2008	NA	NA	NA	11.20	1.00	1.00	1.00	1.00	1.00
Avonmouth	01/10/2008	31/03/2009	NA	NA	NA	20.10	0.00	1.00	1.00	1.00	0.00
Avonmouth	01/10/2009	31/03/2010	NA	NA	NA	21.70	0.00	1.00	1.00	1.00	0.00
Avonmouth	01/10/2011	31/03/2012	NA	NA	NA	51.00	0.00	1.00	1.00	1.00	0.00
Bloodgate Hill	01/10/2007	27/02/2008	NA	6779	36	188.31	0.00	1.00	1.00	1.00	0.00
Blyth Harbour	01/09/2016	31/03/2017	NA	7137	54	132.17	3.00	1.00	1.00	1.00	3.00
Boudwijnkanaal	01/05/2001	31/05/2001	NA	248	17	14.59	0.00	1.00	1.00	1.33	0.00
Boudwijnkanaal	01/10/2001	31/10/2001	NA	3781	17	222.41	1.00	1.00	1.00	1.33	1.33
Boudwijnkanaal	01/09/2005	31/12/2005	NA	1035	17	60.88	40.00	1.00	1.00	1.33	53.20
Bouin	01/01/2003	31/12/2006	NA	6785	370	18.34	30.00	1.23	1.32	1.00	48.71
De Put	01/01/2006	28/02/2006	NA	160	18	8.89	2.00	1.00	1.00	1.00	2.00
Delfzijl-Zuid	01/08/2006	30/10/2006	NA	1496	33	45.33	8.00	1.00	1.00	1.14	9.12
Gneizdzewo	15/09/2007	15/11/2007	NA	894	216	4.14	0.00	1.00	1.00	1.00	0.00
Gneizdzewo	18/08/2008	16/11/2008	NA	311	216	1.44	0.00	1.00	1.00	1.00	0.00
Gneizdzewo	15/09/2010	15/11/2010	NA	223	68	3.28	1.00	1.00	1.00	1.00	1.00
Gneizdzewo	15/09/2011	15/11/2011	NA	1018	57	17.86	0.00	1.00	1.00	1.00	0.00
Gneizdzewo	15/09/2012	15/11/2012	NA	1839	63	29.19	0.00	1.00	1.00	1.00	0.00
Goole Fields	01/04/2017	31/08/2017	NA	2200	45	48.89	0.00	1.00	1.00	1.00	0.00
Goole Fields	01/09/2017	31/03/2018	NA	NA	72	130.54	3.00	1.14	1.00	1.21	4.14
Haverigg	01/04/2014	31/07/2014	NA	4684	36	130.11	5.00	1.07	1.12	1.00	5.99
Haverigg	01/05/2019	31/07/2019	NA	2773	36	77.03	6.00	1.07	1.33	1.00	8.54
Hellrigg	01/12/2011	31/03/2012	NA	648	38	17.05	1.00	1.00	1.00	1.00	1.00
Hellrigg	01/12/2012	31/03/2013	NA	25990	36.5	712.05	0.00	1.00	1.00	1.00	0.00
Hellrigg	01/12/2014	31/03/2015	NA	6900	36	191.67	0.00	1.00	1.00	1.00	0.00
Kessingland	01/11/2011	31/03/2012	NA	865	18	48.06	0.00	1.79	1.00	1.00	0.00
Kessingland	01/11/2012	31/03/2013	NA	615	18	34.17	3.00	1.79	1.00	1.00	5.37
Kleine Pathoweg	01/09/2005	31/12/2005	NA	672	16	42.00	74.00	1.00	1.00	3.50	259.00
Oosterbierum	NA	NA	NA	NA	NA	NA	NA	2.40	5.50	NA	NA
Oosterbierum	NA	NA	NA	NA	NA	NA	NA	36.50	1.00	NA	NA
Red House Farm	01/04/2009	31/08/2009	NA	NA	36	61.26	4.00	1.00	1.00	1.00	4.00
Sabinapolder	13/11/2209	03/12/2010	NA	NA	NA	30.00	17.00	1.00	1.00	1.00	17.00
Slufterdam & Distridam	13/06/2012	04/07/2012	NA	4034	15	268.93	38.00	1.00	1.00	1.00–3.23	66.64
Thanet	01/10/2014	31/03/2015	3.86	NA	NA	NA	3.00	1.00	1.00	1.00	3.00
Thanet	01/10/2015	31/03/2016	3.86	NA	NA	NA	2.00	1.00	1.00	1.00	2.00
Zeebrugge	01/06/2000	31/07/2000	NA	234	16	14.63	1.00	1.00	1.00	4.17–9.09	4.17
Zeebrugge	01/06/2001	31/07/2001	NA	234	16	14.63	3.00	1.00	1.00	4.17–9.09	12.96
Zeebrugge	01/09/2001	31/10/2001	NA	2151	16	134.44	3.00	1.00	1.00	4.17–9.09	12.51

All Gulls and Tern Avoidance Rate

Data to estimate avoidance rates for all gulls and terns came from 19 sites (Table 2, Figure 1) with passage rates ranging from 1.4 birds hour^{1} to 712 birds hour^{1} and a total of 804 collisions estimated following corrections for search area, searcher efficiency and predator behaviour.

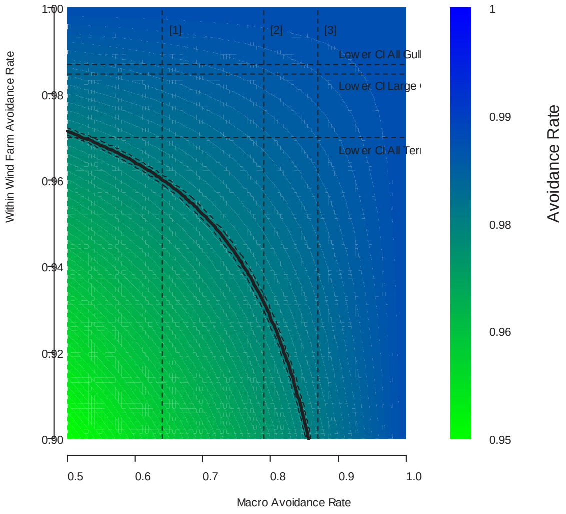
Table 20 Summary of bird data contributing to avoidance rates for all gulls

Site	Surveys Start Date	Surveys End Date	Density (Birds km^{-1})	Total Count	Hours Of Survey	Passage Rate (Birds Hr^{-1})	Observed Collisions	Correction Factor			Corrected Collisions
								Predation	Efficiency	Area	
Avonmouth	01/10/2007	31/03/2008	NA	NA	NA	11.20	1.00	1.00	1.00	1.00	1.00
Avonmouth	01/10/2008	31/03/2009	NA	NA	NA	20.10	0.00	1.00	1.00	1.00	0.00
Avonmouth	01/10/2009	31/03/2010	NA	NA	NA	21.70	0.00	1.00	1.00	1.00	0.00
Avonmouth	01/10/2011	31/03/2012	NA	NA	NA	51.00	0.00	1.00	1.00	1.00	0.00
Bloodgate Hill	01/10/2007	27/02/2008	NA	6779	36	188.31	0.00	1.00	1.00	1.00	0.00
Blyth Harbour	01/09/2016	31/03/2017	NA	7141	54	132.24	3.00	1.00	1.00	1.00	3.00
Boudwijnkanaal	01/05/2001	31/05/2001	NA	248	17	14.59	0.00	1.00	1.00	1.33	0.00
Boudwijnkanaal	01/10/2001	31/10/2001	NA	3781	17	222.41	1.00	1.00	1.00	1.33	1.33
Boudwijnkanaal	01/09/2005	31/12/2005	NA	1035	17	60.88	40.00	1.00	1.00	1.33	53.20
Bouin	01/01/2003	31/12/2006	NA	6811	370	18.41	30.00	1.23	1.32	1.00	48.71
De Put	01/01/2006	28/02/2006	NA	160	18	8.89	2.00	1.00	1.00	1.00	2.00
Delfzijl-Zuid	01/08/2006	30/10/2006	NA	1496	33	45.33	8.00	1.00	1.00	1.14	9.12
Gneizdzewo	15/09/2007	15/11/2007	NA	894	216	4.14	0.00	1.00	1.00	1.00	0.00
Gneizdzewo	18/08/2008	16/11/2008	NA	311	216	1.44	0.00	1.00	1.00	1.00	0.00
Gneizdzewo	15/09/2010	15/11/2010	NA	223	68	3.28	1.00	1.00	1.00	1.00	1.00
Gneizdzewo	15/09/2011	15/11/2011	NA	1018	57	17.86	0.00	1.00	1.00	1.00	0.00
Gneizdzewo	15/09/2012	15/11/2012	NA	1839	63	29.19	0.00	1.00	1.00	1.00	0.00
Goole Fields	01/04/2017	31/08/2017	NA	2200	45	48.89	0.00	1.00	1.00	1.00	0.00
Goole Fields	01/09/2017	31/03/2018	NA	NA	72	130.54	3.00	1.14	1.00	1.21	4.14
Haverigg	01/04/2014	31/07/2014	NA	4684	36	130.11	5.00	1.07	1.12	1.00	5.99
Haverigg	01/05/2019	31/07/2019	NA	2773	36	77.03	6.00	1.07	1.33	1.00	8.54
Hellrigg	01/12/2011	31/03/2012	NA	648	38	17.05	1.00	1.00	1.00	1.00	1.00
Hellrigg	01/12/2012	31/03/2013	NA	25990	36.5	712.05	0.00	1.00	1.00	1.00	0.00
Hellrigg	01/12/2014	31/03/2015	NA	6900	36	191.67	0.00	1.00	1.00	1.00	0.00
Kessingland	01/11/2011	31/03/2012	NA	865	18	48.06	0.00	1.79	1.00	1.00	0.00
Kessingland	01/11/2012	31/03/2013	NA	615	18	34.17	3.00	1.79	1.00	1.00	5.37
Kleine Pathoweg	01/09/2005	31/12/2005	NA	672	16	42.00	74.00	1.00	1.00	3.50	259.00
Oosterbierum	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Red House Farm	01/04/2009	31/08/2009	NA	NA	36	61.26	4.00	1.00	1.00	1.00	4.00
Sabinapolder	13/11/2209	03/12/2010	NA	NA	NA	30.00	17.00	1.00	1.00	1.00	17.00
Slufterdam & Distridam	13/06/2012	04/07/2012	NA	6621	15	441.40	43.00	1.00	1.00	1.00–3.23	75.74
Thanet	01/10/2014	31/03/2015	3.86	NA	NA	NA	3.00	1.00	1.00	1.00	3.00
Thanet	01/10/2015	31/03/2016	3.86	NA	NA	NA	2.00	1.00	1.00	1.00	2.00
Zeebrugge	01/06/2000	31/07/2000	NA	2603	16	162.69	1.00	1–1.1	1–1.16	4.17–9.09	4.17
Zeebrugge	01/06/2001	31/07/2001	NA	2603	16	162.69	4.00	1–1.1	1–1.16	4.17–9.09	18.28
Zeebrugge	01/09/2001	31/10/2001	NA	3866	16	241.63	3.00	1–1.1	1–1.16	4.17–9.09	12.51
Zeebrugge	01/06/2004	30/06/2004	NA	26954	17	1585.53	9.00	1.10	1.16	4.17–9.09	73.00
Zeebrugge	01/06/2005	30/06/2005	NA	16906	17	994.47	12.00	1.10	1.16	4.17–9.09	89.54

Northern Gannet Avoidance Rates

Whilst evidence for macro-avoidance in gulls and terns is equivocal, there is evidence of strong macro-avoidance in Northern Gannet (Dierschke *et al*., 2016). By combining published estimates of macro-avoidance with a range of plausible values for within-windfarm avoidance informed by the above analyses, it is possible to estimate a realistic, precautionary avoidance rate for gannets. A previous review of macro-avoidance in gannets found macro-avoidance rates in excess of 0.5 (Dierschke *et al*., 2016), with several values significantly greater than this reported. Based on this review and subsequent research, we can consider scenarios with low, medium and high levels of macro-avoidance of 0.64, 0.79 and 0.87 (Krijgsveld *et al*., 2011; Vanermen, Onkelinx, Verschelde, *et al*., 2015; Welcker & Nehls, 2016).

Figure 6 Simulations of total avoidance rates for northern gannet in comparison to the published macro-avoidance rates from [1] (Krijgsveld et al., 2011), [2] (Vanermen, Onkelinx, Courtens, et al., 2015) and [3] (Welcker & Nehls, 2016) and, the lower confidence interval surrounding the avoidance rates for use in the basic Band (2012) model for large gulls, all gulls and all terns. Curved line indicates the within-windfarm avoidance rate for all gulls and terns (and 95% Cis) as a proxy for total avoidance.



We can then combine these with the avoidance rates estimated above in order to get an indication of the potential range of overall avoidance. To be precautionary, these calculations can be based on the lower confidence interval estimated for each rate. If we consider that within-windfarm avoidance by Northern Gannets is likely to at least equal to the lower CI of the all terns rate, we can see that, as long as macro-avoidance is greater than 0.535, total avoidance for Northern Gannets is likely to exceed the within-windfarm avoidance rate for all gulls and terns (Figure 6). This figure is well below the low macro-avoidance scenario from Krijgsveld *et al.*, (2011) highlighted above.

Having combined estimates of with-windfarm avoidance from gulls and terns with low, medium, and high estimates of macro-avoidance recorded in Northern Gannets, we can estimate a range of total avoidance of between 0.9891 and 0.9982 (Table 21). Given that avoidance behaviour is likely to reflect a continuum, it is also worth considering whether the all gulls and terns avoidance rate may be a suitable proxy for total avoidance in Northern Gannets. In selecting between these figures there are a number of important factors to consider. Firstly, while it is clear that macro-avoidance in Northern Gannets is likely to be high, data from GPS tracking highlights that there are clear differences between individuals in relation to their response to wind farms (Peschko *et al.*, 2021). Secondly, whilst it is true that no Northern Gannets have been directly observed colliding, collisions are rare events and, to date, studies have been carried out in areas where Northern Gannet densities are relatively low, particularly during the breeding season. Furthermore, it is clear that Northern Gannet collisions do occur, with the recovery of corpses with injuries consistent with having been struck by turbine blades at Blyth (Rothery *et al*., 2009) and in Belgium (E. Stienen pers. comm.). Consequently, a precautionary value is likely to be appropriate.

Sensitivty of Avoidance Rates

Accounting for the imperfect detection of corpses can have a significant impact on the avoidance rates estimated from these data (Figure 7). Generally, the imperfect detection of corpses can have three causes:

- Scavenger or predator activity;
- Searcher efficiency;
- Restricted access to the area around the base of the turbines.

There are a variety of approaches for estimating correction factors to account for this imperfect detection, and the values used are often site-specific and cannot be transferred to other sites (Bernardino *et al.*, 2013; Costantini *et al*., 2017). All studies included in this analysis explicitly state that they have considered imperfect detection in their estimates of mortality. This has been achieved through searcher efficiency trials

Table 21 Avoidance rates for the basic Band (2012) model (and 95% CIs) estimated for Northern Gannet through combining low, medium, and high macro-avoidance rates with the estimated avoidance rates for all terns, small gulls, large gulls, all gulls, and all gulls and terns.

	Low macro-avoidance	Mediun macro-avoidance	High macro-avoidance
All Terns Avoidance Rate	0.9896 (0.9891 – 0.9901)	0.994 (0.9936 – 0.9942)	0.9963 (0.9961 – 0.9964)
Small Gulls Avoidance Rate	0.9971 (0.9968 – 0.9974)	0.9983 (0.9981 – 0.9985)	0.9989 (0.9988 – 0.9991)
Large Gulls Avoidance Rate	0.995 (0.9945 – 0.9955)	0.9971 (0.9968 – 0.9974)	0.9982 (0.998 – 0.9984)
All Gull Avoidance Rate	0.9955 (0.9952 – 0.9956)	0.9974 (0.9972 – 0.9975)	0.9984 (0.9983 – 0.9984)
All Gulls and Terns Avoidance Rate	0.9948 (0.9947 – 0.995)	0.997 (0.9969 – 0.9971)	0.9981 (0.9981 – 0.9982)

Table 22 Avoidance rates for the extended Band (2012) model(and 95% CIs) estimated for Northern Gannet through combining low, medium, and high macro-avoidance rates with the estimated avoidance rates for all terns, small gulls, large gulls, all gulls, and all gulls and terns.

	Low macro-avoidance	Mediun macro-avoidance	High macro-avoidance
All Terns Avoidance Rate	0.9764 (0.9753 – 0.9775)	0.9862 (0.9856 – 0.9869)	0.9915 (0.9911 – 0.9919)
Small Gulls Avoidance Rate	0.9767 (0.9744 – 0.9791)	0.9864 (0.985 – 0.9878)	0.9916 (0.9907 – 0.9925)
Large Gulls Avoidance Rate	0.9801 (0.9781 – 0.9821)	0.9884 (0.9873 – 0.9896)	0.9928 (0.9921 – 0.9935)
All Gull Avoidance Rate	0.9832 (0.9824 – 0.9839)	0.9902 (0.9898 – 0.9906)	0.9939 (0.9937 – 0.9942)
All Gulls and Terns Avoidance Rate	0.982 (0.9815 – 0.9825)	0.9895 (0.9892 – 0.9898)	0.9935 (0.9933 – 0.9937)

Table 23 Avoidance rates for the basic sCRM (and 95% CIs) estimated for Northern Gannet through combining low, medium, and high macro-avoidance rates with the estimated avoidance rates for all terns, small gulls, large gulls, all gulls, and all gulls and terns.

	Low macro-avoidance	Mediun macro-avoidance	High macro-avoidance
All Terns Avoidance Rate	0.9897 (0.9893 – 0.99)	0.994 (0.9938 – 0.9942)	0.9963 (0.9962 – 0.9964)
Small Gulls Avoidance Rate	0.9972 (0.9969 – 0.9974)	0.9983 (0.9982 – 0.9985)	0.999 (0.9989 – 0.9991)
Large Gulls Avoidance Rate	0.995 (0.9946 – 0.9954)	0.9971 (0.9968 – 0.9973)	0.9982 (0.998 – 0.9983)
All Gull Avoidance Rate	0.9956 (0.9953 – 0.996)	0.9975 (0.9973 – 0.9977)	0.9984 (0.9983 – 0.9986)
All Gulls and Terns Avoidance Rate	0.995 (0.9946 – 0.9954)	0.9971 (0.9969 – 0.9973)	0.9982 (0.9981 – 0.9983)

Table 24 Avoidance rates for the extended sCRM (and 95% CIs) estimated for Northern Gannet through combining low, medium, and high macro-avoidance rates with the estimated avoidance rates for all terns, small gulls, large gulls, all gulls, and all gulls and terns.

	Low macro-avoidance	Mediun macro-avoidance	High macro-avoidance
All Terns Avoidance Rate	0.9784 (0.976 – 0.9806)	0.9874 (0.986 – 0.9887)	0.9922 (0.9913 – 0.993)
Small Gulls Avoidance Rate	0.9793 (0.9722 – 0.9841)	0.9879 (0.9838 – 0.9907)	0.9925 (0.990 – 0.9943)
Large Gulls Avoidance Rate	0.9677 (0.9617 – 0.9733)	0.9812 (0.9776 – 0.9844)	0.9884 (0.9862 – 0.9904)
All Gull Avoidance Rate	0.9734 (0.9686 – 0.9778)	0.9845 (0.9817 – 0.987)	0.9904 (0.9887 – 0.992)
All Gulls and Terns Avoidance Rate	0.9746 (0.9713 – 0.9779)	0.9852 (0.9833 – 0.9871)	0.9908 (0.9897 – 0.992)

Figure 7 Avoidance rates estimated for use with the basic Band model with (blue) and without (red) application of correction factors for corpse detection.

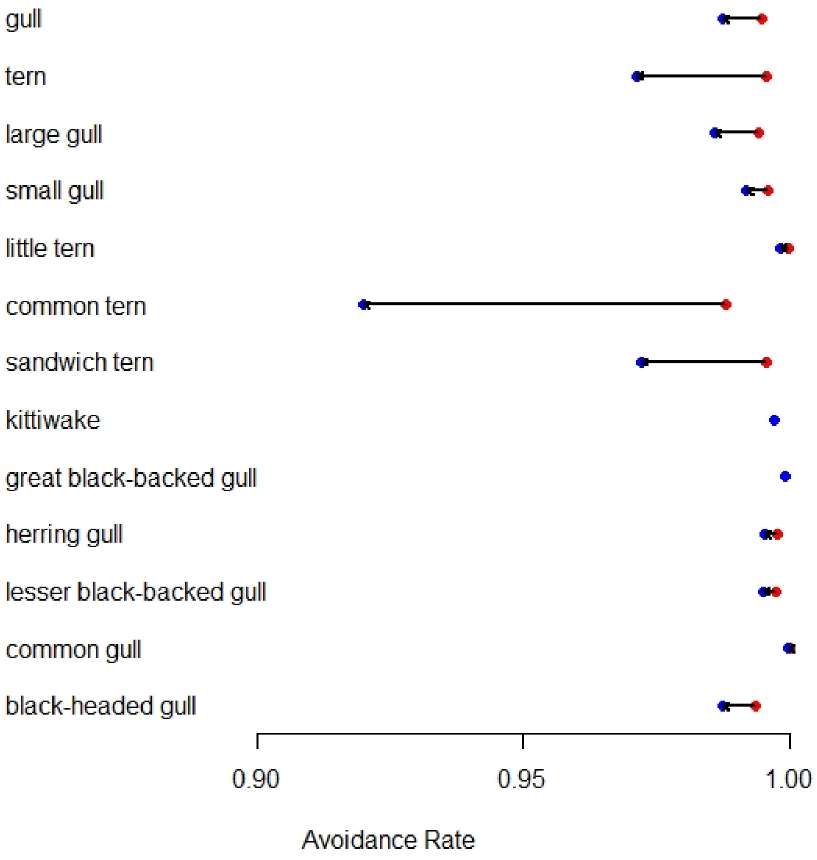
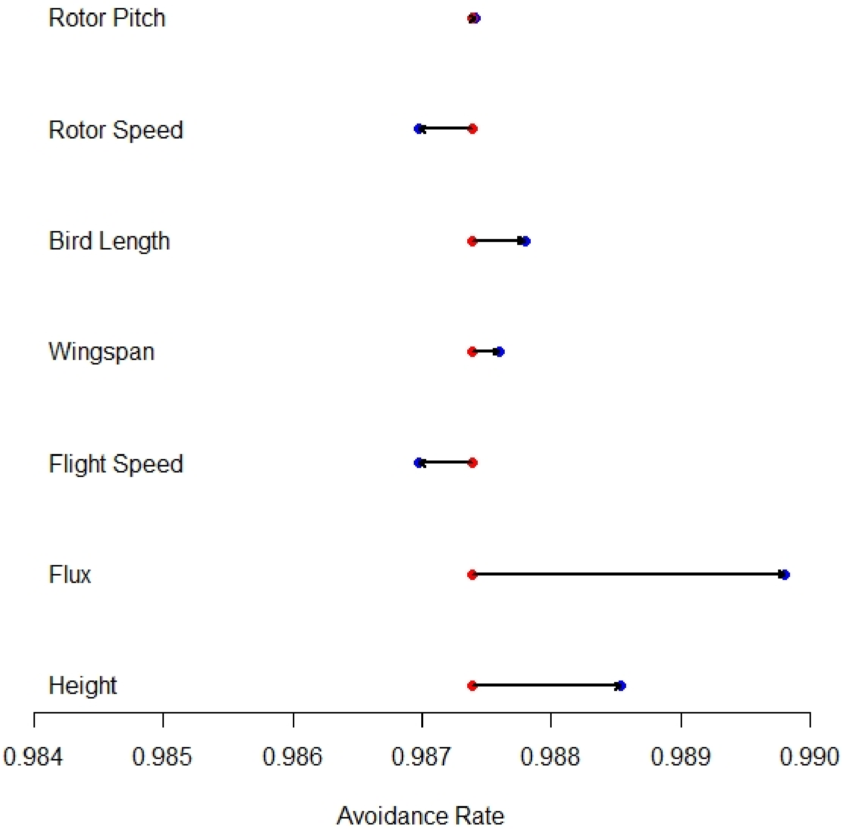


Figure 8 Impact of a 10% error in each parameter used to estimated avoidance rates for gulls using the basic Band model.



and corpse persistence trials. Generally, for the terns and gulls considered here, corrections for these factors have been close to 1 (i.e., there is perfect detection of collision victims, tables 4–20), reflecting both the size of the species concerned and the regularity of searches over the study period. However, in some cases a more significant correction has been applied to account for the area available to search. Where possible we have applied these corrections on a turbine-specific basis. For example, at Zeebrugge, where turbines are on the seawall, in some cases these are adjacent to water and only a small strip either side of the turbine is available to search (Figure 2). The avoidance rates calculated here are based on the collision rates estimated once the corrections for search area, predator activity and searcher efficiency reported in each study have been applied. The impact of applying these correction factors is particularly pronounced in relation to terns, with an estimated avoidance rate for use with the basic Band model of 0.995 reduced to 0.971 after corrections have been applied to account for the imperfect detection of corpses (Figure 7). This is likely to reflect the influence of data from Zeebrugge and Slufterdam & Distridam on the calculated avoidance rates, as both sites applied substantial corrections to account for the area available to search. However, even with gulls we can see a significant reduction in the avoidance rate once imperfect detection of corpses has been accounted for, from 0.994 to 0.987 (Figure 7). Whilst estimates of avoidance rates are sensitive to error in other parameters, notably the flux rate and the proportion of birds at risk height, this sensitivity is not as great as the sensitivity to whether a correction has been applied to account for imperfect corpse detection (Figure 8).

Having applied corrections for corpse detections, in many cases avoidance rates are lower than previous estimates (Table 3) (e.g. Cook *et al*., 2018; Cook *et al.*, 2014). This is particularly noticeable in relation to terns. However, entering the collision rate with corrections applied for corpse detection into the electronic appendix supplied alongside Cook *et al*. (2014) yields a similar estimated avoidance rate for sandwich terns at Zeebrugge to that reported here.

Alternative approaches to estimating avoidance rates

The avoidance rates estimated within this report are based on data collected within the windfarms concerned by comparing predicted and observed collision rates. As such, they account for meso-avoidance, micro-avoidance and error in the model that is used to estimate the predicted collision rates. Given the uncertainty over how applicable avoidance rates derived from onshore sites are to offshore windfarms, and the challenges in collecting collision data in the offshore environment, there is growing interest in approaches to directly measure avoidance behaviour and collision rates. Approaches which have been used to date include boat or digital aerial surveys (APEM Ltd., 2014; Harwood *et al.*, 2018), GPS or boat-based visual tracking (Harwood *et al.,* 2018; Thaxter *et al.*, 2018), radar (Krijgsveld *et al.*, 2011; Plonczkier & Simms, 2012; Skov, Heinanen, *et al*., 2018) and camera systems (Desholm *et al*., 2006; Skov, Heinanen, *et al*., 2018). These studies all provide valuable insights into the behaviour of birds in the offshore environment and context about collision and avoidance rates.

The variability of the marine environment makes it challenging to draw conclusions about the response of birds to windfarms based on changes in their distribution (Maclean *et al*., 2013; Vanermen, Onkelinx, Verschelde, *et al.*, 2015). However, given the expansion of offshore windfarms and the monitoring carried out at these sites, we are in a position to make general inferences about the likely response of different species to a windfarm at a macro scale. For example, species like gannets and divers show a consistent, negative response to windfarms, while gulls may not show any avoidance response (Dierschke *et al*., 2016). Whilst some studies (e.g. Desholm & Kahlert, 2005) show birds strongly responding to the presence of turbines, translating data from these studies into an avoidance rate is challenging as they do not account for birds whose flightpaths would not have intersected with turbines. However, such challenges can be overcome.

Harwood *et al*. (2018) use a data set based on visual tracking of Sandwich Terns from boats in order to investigate their avoidance response to turbines within Sheringham Shoal Windfarm. As data were available from the pre- and post-construction phases, it was possible to analyse how distance to turbine locations changed once the windfarm had been completed. Similarly, (Thaxter *et al.,* 2018) used GPS tracking data in order to analyse the proximity of Lesser Black-backed Gulls to windfarms within the Irish Sea. In this instance no pre-construction data were available, but this challenge was overcome by simulating a series of random tracks and comparing these to the observed distribution. Both of these studies highlighted a strong avoidance response to the presence of turbines. Such responses reflect meso-avoidance, given that they relate to data collected within the windfarms concerned. The resolution of the GPS data and the rarity of birds entering turbine rotor-swept areas mean that it is not possible to make inferences about last-second micro-avoidance from these data. However, the strength of the response to the presence of turbine implies that meso-avoidance rates are likely to be very high.

Such studies highlight how macro- and meso-avoidance rates can be derived as part of ongoing studies. However, in order to estimate an avoidance rate suitable for use in collision risk models it would be necessary to combine these with estimates of micro-avoidance, and account for model error (the term avoidance rates may be misleading, but the avoidance rate as specified in Band 2012 is a way of accounting for error in predicted collisions, widely assumed to be largely due to avoidance behaviour taken by birds). The deployment of camera systems will help with the estimation of last-second micro-avoidance rates. However, the rarity of such events (e.g. Skov, Heinanen, *et al*., 2018) will make it challenging to robustly quantify these rates. Incorporating other sources of model error is likely to be more challenging still.

Principals to guide the selection of appropriate avoidance rates

The sensitivity of collision risk models to the assumed avoidance rates means that it is important that the best available evidence is used in order to select appropriate values. Ideally, we would be able to recommend a series of seasonal-, species-, age-, and activity-specific rates. In practice we lack the data to do so. Given the data available at present we must consider where it is appropriate to use species-specific values and, where we must use generic values. I outline some key considerations below to guide current recommendations about avoidance rates and, the incorporation of additional data in the future.

Has imperfect corpse correction been accounted for?

Estimated avoidance rates are highly sensitive to whether or not corpse corrections have been applied (Figure 5). In incorporating future data into estimates of avoidance rates, it is important to consider whether these have been applied. Even in cases where the correction for imperfect detection is 1 (i.e., perfect detection of collision victims), it is important that this is stated explicitly. Monitoring of collision rates using camera systems is becoming increasingly widespread. It is important to develop methodologies that can account for imperfect detection of collisions (e.g. due to camera malfunctions or limits on the number of birds that can be tracked at any time) with these systems.

Null records

The fact that no collisions have been recorded at a site should not be a reason to exclude data from that site when estimating avoidance rates. Where flight activity for a species of interest has been recorded at a site, it is important that these data are incorporated into analyses. A failure to incorporate these data is likely to result in an underestimate of avoidance rate. Incorporating these data will also help to ensure avoidance rates are based on data from a more representative range of sites; the variability and uncertainty surrounding these estimates will also be better reflected.

Avoidance rates are model specific

A key part of estimating avoidance rates is estimating the number of collisions that would have been expected in the absence of avoidance. Each model does this differently and, hence, each requires the use of a different avoidance rate. The most obvious example of this relates to the basic and extended Band models. By accounting for the vertical distribution of birds, the extended model results in a reduced estimate of the total number of birds at risk of collision. Consequently, the avoidance rate used with the extended model is typically lower than that used with the basic model. A similar logic applies to the Christie & Urquhart (2015) extension to the Band model. However, it also applies to the extended sCRM, and may apply to the basic sCRM. As set out above (Figure 3), the way bootstrapped estimates of species flight height distributions are used by the extended sCRM means that median estimated collision rates in the absence of avoidance may differ from those estimated using the extended Band model. A similar issue is likely to arise for the basic sCRM if site specific estimates of the proportion of birds at collision risk height are not available and must be derived from the generic Johnston *et al.* (2014) distributions.

Avoidance rates for the extended models

At present, the extended models make use of the continuous flight height distributions developed by Johnston *et al.* (2014) in order to account for variation in collision risk across a turbine's rotor-swept area. Where the proportions of birds at risk height were reported by the studies included in the analyses reported above, these were not correlated with the proportion that would be predicted to be at risk height from the Johnston *et al.* (2014) data ($r = 0.3$). This introduces another source of error into the collision rates predicted using the extended models. However, the proportion of birds at risk height were not systematically over or underestimated from the Johnston *et al.* (2014) data. This suggests that, where these generic flight height distributions are used, the avoidance rates estimated here are suitable for use with the extended models. This is because the error in estimating the proportion of birds at risk height will be present in the avoidance rates and the data feeding into the collision risk model. However, where site-specific flight height distributions are available, this error will not be present in both sources of data, meaning the avoidance rates estimated here should not be used.

Species-specific or group-specific values?

The avoidance rates estimated above are derived from a broad range of sites with varying levels of bird activity. In determining whether to use species-specific or group-specific values, it is useful to consider whether data have been collected across a range of sites that capture variability in bird activity levels. In relation to offshore windfarms, there may be a desire to focus on data that have been collected from offshore sites. However, this should be balanced against consideration of how representative those data are, particularly in circumstances when monitoring of bird movements is not concurrent with monitoring of collisions. It may be useful to consider rules of thumb (e.g. data from a minimum of 10 sites) when considering whether to use species-specific avoidance rates in preference to group-specific estimates.

Site specific and generic values for bird parameters

At present, the avoidance rate captures both the avoidance behaviour of the bird and error arising as a result of simplifications of the models. A key part of this is the estimate of the total number of birds likely to pass turbine rotor swept areas and being exposed to the risk of collision. This is a product of the total number of birds in the windfarm at any given time (in the case of an offshore windfarm, the density of birds), the speed at which each bird moves through the windfarm, and the proportion of birds at collision risk height. The total number of birds within the windfarm and the proportion at collision risk height are both estimated using site-specific values, and are consequently representative of the sites under consideration. This means that elements of model error associated with site-specific estimates of these parameters are accounted for in the calculation of avoidance rates. In contrast, flight speed is usually based on generic values (e.g. Alerstam *et al.*, 2007). Flight speed is used to estimate the total number of birds likely to pass through a windfarm over any given time period. A higher flight speed means that a greater number of birds will pass through a windfarm and be at risk of collision.

If we consider an example whereby the generic estimate of speed is greater than the site-specific estimate, the generic speed would estimate a greater number of birds moving through the windfarm than the site-specific speed and, consequently, the collision rate predicted in the absence of avoidance would be greater using the generic speed. When compared to the observed number of collisions, this would lead to a higher avoidance rate than if the site-specific value was used. In such an example, the error associated with assumptions around flight speed would not be properly accounted for. As more robust estimates of parameters, such as flight speed, become available (e.g. through GPS tracking), careful consideration is needed in relation to how these should be incorporated into analyses of collision risk and avoidance.

Avoidance rates for species or groups for which collision data are unavailable

Estimating avoidance rates following the approach set out above relies on data describing both collisions and the movements of birds through a windfarm. For some species, such as Northern Gannet, whilst we know collisions do occur, despite extensive monitoring, we lack the necessary data to estimate avoidance in this way. As an alternative, we could consider a gradient of values drawing from published estimates of macro-avoidance behaviour and a plausible range of within windfarm avoidance rates, as set out above (Figure 8). Based on our understanding of macro-avoidance behaviour of the species concerned, and its ecology relative to other species, we could make inferences about suitable total avoidance rates for use in collision risk models.

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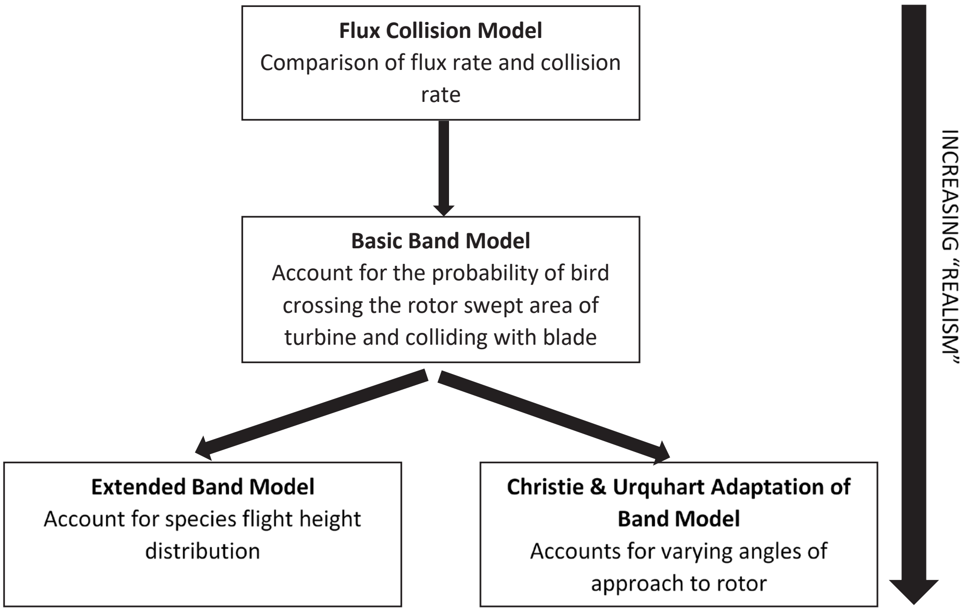
Appendix 1 Alternative Collision Risk Models

There are a number of CRMs available but, the starting point for most is to estimate the total number of birds likely to pass through the turbine rotor sweeps (Masden & Cook, 2016). The Flux Collision Model (Kleyheeg-Hartman *et al.*, 2018) simply compares this figure to the number of recorded collision victims in order to estimate a collision rate for use in future analyses. The basic Band (2012) model takes this a step further and estimates the probability of a bird colliding with a turbine blade. Further developments of this model then incorporate additional complexity in order to more accurately reflect the movement and behaviour of birds through accounting for the flight height distribution of the species concerned (Band, 2012), or allowing different angles of approach to turbine blades (Christie & Urquhart, 2015). Each of these steps increases the realism of the model (Figure A1) but also alters the number of collisions expected in the absence of avoidance behaviour and, hence, the avoidance rate to be used.

Figure A1 Collision Risk Models vary in their complexity and incorporate different aspects of bird behaviour and turbine operational parameters in order more realistically estimate collision risk



Christie and Urquhart extension to Band Model

At present, the Band (2012) model assumes that birds have a perpendicular angle of approach to the turbine rotor swept area. However, as demonstrated in figure 39 of Everaert (2008), this is unlikely to be a reasonable assumption, and birds are likely to approach from multiple angles. This is important as birds which do not approach at a perpendicular angle may take longer to cross the turbine rotor sweep and, therefore, be at greater risk of collision. Christie & Urquhart (2015) refined the Band *et al.* (2007) Model to account for different angles of approach. However, as with the basic and extended Band models, this refinement will impact the number of birds predicted to be at risk of collision, and hence the appropriate avoidance rates to be used. In addition to allowing for different angles of approach to the turbine, the refinement of Christie & Urquhart (2015) also accounts for the impact of wind speed on bird flight speed and, therefore, the length of time any individual bird is exposed to the risk of collision. To account for this I assumed a mean wind speed of 5 m/s (± 2.5 m/s) at ground level at each site. I then followed the approach described above for the basic stochastic collision risk model to estimate avoidance rates for the (Christie & Urquhart, 2015) refinement to the Band model using Monte Carlo simulation. In addition to the parameters described above, I also drew estimates for wind speed from a normal distribution defined by the mean and standard deviation presented highlighted above.

Flux Collision Model

In contrast to the previous examples, the Flux Collision model (Kleyheeg-Hartman *et al.*, 2018) uses a collision rate rather than an avoidance rate in order to estimate the number of birds at risk of collision. These collision rates are based on observed estimates of collisions and flux rates at operational windfarms and are corrected to account for differences in windfarm layout and turbine design. These collision rates account for both avoidance behaviour within the windfarm (meso- and micro-avoidance) and the probability of a bird which crosses a turbine rotor-swept area colliding with turbine blades. I used Monte Carlo simulation to estimate the total number of birds passing through the turbine rotor sweep as described above for the basic stochastic collision risk model. For each iteration of the simulations, I then estimated a collision rate by dividing the number of collision victims by the number of birds predicted to pass through the turbine rotor sweeps. As previously, mean, and median collision rates with associated standard deviations and 95% CIs were estimated for 2004, 2005 and both years combined.

Table A1 Estimated rates (Standard deviations; 95% Confidence Intervals) for use with different Collision Risk Models

	Christie & Urquhart extension to Band Model	Flux Collision Model
Sandwich Tern	0.9815 (0.0006; 0.9805 – 0.9828)	0.00025494 (0.00000257; 0.00025017 – 0.0002604)
Common Tern	0.9492 (0.0028; 0.945 – 0.9556)	0.00091548 (0.00001197; 0.00089265 – 0.00093957)
Little Tern	0.9988 (0.0001; 0.9986 – 0.999)	0.00005632 (0.0000014; 0.00005384 – 0.00005918)
All Terns	0.981 (0.0008; 0.9798 – 0.983)	0.00043097 (0.00000377; 0.00042347 – 0.00043839)
Black-legged Kittiwake	0.9984 (0.001; 0.9963 – 0.9994)	0.00001672 (0.00037138; 0.00000602 – 0.00173809)
Black-headed Gull	0.9907 (0.0009; 0.9892 – 0.9926)	0.00044743 (0.00002545; 0.00040279 – 0.00050175)
Common Gull	0.9998 (0; 0.9997 – 0.9999)	0.00001553 (0.00000099; 0.0000137 – 0.00001753)
Lesser Black-backed Gull	0.996 (0.0003; 0.9954 – 0.9967)	0.00031671 (0.00002197; 0.00027959 – 0.00036589)
Herring Gull	0.9963 (0.0003; 0.9957 – 0.9971)	0.00030098 (0.00001722; 0.00026849 – 0.00033611)
Great Black-backed Gull	0.9992 (0.0002; 0.9988 – 0.9995)	0.00005016 (0.00001053; 0.00003754 – 0.00007731)
Small gulls	0.994 (0.0006; 0.9932 – 0.9955)	0.00029785 (0.00002827; 0.00024383 – 0.00035169)
Large gulls	0.9891 (0.0007; 0.9879 – 0.9908)	0.00088817 (0.00003622; 0.00082261 – 0.00095754)
All gulls	0.9908 (0.0006; 0.9898 – 0.9921)	0.00052416 (0.0000377; 0.00045444 – 0.00060334)

Appendix 2 Recommended Avoidance Rates

Based on the analyses described above, suggested avoidance rates for key species are presented in Table A2. For terns and gulls, the rates presented below reflect within-windfarm avoidance rates. They do not incorporate macro-avoidance (e.g., any avoidance or attraction that takes place outside the wind farm). When using these values, consideration should be given as to whether, and how, any macro-avoidance should be incorporated. For Northern Gannets, the presented value is presumed to incorporate both macro and within-windfarm avoidance. The increased availability of data, and our increased understanding of how species respond to offshore wind farms mean that it is now possible to extend suggestions about avoidance rates to the extended models for both Northern Gannet and Black-legged Kittiwake. However, it is important to note that the data under-pinning these suggestions is drawn from other species and subject to significant uncertainty. Consequently, if these values are used, they should be treated with caution, and the uncertainty surrounding them should be clearly highlighted.

Following the previous review of avoidance behaviour (Cook *et al.*, 2014), it was not possible to make recommendations about avoidance rates for the extended Band model for Northern Gannet and Black-legged Kittiwake. Since that review was completed, we have gained a much greater understanding of the behaviour of birds in the offshore environment. This has included GPS tacking studies measuring species flight heights (Cleasby *et al.*, 2015; Ross-Smith *et al*., 2016) and species interactions with wind farms and individual turbines (Peschko *et al*., 2020; Thaxter *et al*., 2017), and the ORJIP Bird Collision Avoidance study at Thanet (Skov, Heinänen, *et al*., 2018). These studies give us greater confidence in extrapolating avoidance rates for the extended model to both Northern Gannet and Black-legged Kittiwake. However, in doing so, it is important to note that the data under-pinning these suggestions is drawn from other species and subject to significant uncertainty. Consequently, if these values are used, they should be treated with caution, and the uncertainty surrounding them should be clearly highlighted.

Avoidance rates for these species were previously presented in Cook et al. 2014 and Bowgen and Cook 2018. The inclusion of additional data has enabled the estimation of avoidance rates has resulted in revisions to suggested values and enabled the estimation of avoidance rates suitable for use with the extended Band Model and extended sCRM for a greater range of species. Key changes are set out in table A3.

Table A2 Recommended avoidance rates by species and groups (Standard deviations; 95% Confidence Intervals)

Species & Groups	Suggested Rates	Basic Band (2012) Model	Extended Band (2012) Model	Basic sCRM	Extended sCRM
Sandwich Tern, Common Tern, Little Tern, and other tern species	**All Gulls and Terns rate** Data are only available for a limited number of sites with low levels of activity for some species. Consequently, pooling data across species and sites may better reflect variation in behaviour than relying on species-specific rates. The influence of data collected at Zeebrugge, where the wind farm is present on the edge of a tern breeding colony, means that the all tern rate may not truly reflect behaviour further offshore. Consequently, the all gulls and terns rate is recommended.	0.9856 (0.0002; 0.9852 – 0.9860)	0.9501 (0.0007; 0.9486 – 0.9515)	0.9861 (0.0005; 0.9851 – 0.9871)	0.9295 (0.0047; 0.9204 – 0.9387)
Black-legged Kittiwake and Little Gull	**All gulls rate** Insufficient data to estimate species-specific avoidance rates. Whilst previous reports have recommended the small gulls rate, data collected at Thanet makes reference to collisions involving "unidentified gulls", and it cannot be ruled out that these involved black-legged kittiwakes.	0.9874 (0.0003; 0.9868 – 0.9879)	0.9532 (0.001; 0.9512 – 0.9553)	0.9879 (0.0005; 0.987 – 0.9889)	0.9261 (0.0066; 0.9128 – 0.9382)
Black-headed Gull, Common Gull and other small gulls species	**Small gulls rate** Insufficient data to estimate species-specific rates for these species. Similarities in wingspan, body length and flight speed suggest they may have similar levels of manoeuvrability. Consequently, the pooling data with other small gulls is likely to be appropriate.	0.9919 (0.0004; 0.9911 – 0.9927)	0.9354 (0.0034; 0.9288 – 0.942)	0.9921 (0.0004; 0.9913 – 0.9928)	0.9426 (0.0081; 0.9229 – 0.9559)
Lesser Black-backed Gull, Herring Gull, Great Black-backed Gull and other large gull species	**Large gulls rate** Whilst robust data are available from the onshore environment to estimate avoidance rates for Herring and Lesser Black-backed Gull, uncertainty over the identification of species involved in collisions at Thanet means it may be more appropriate to use the large gulls rate for these species. Similarly, a lack of robust data suggests the large gull avoidance rates should also be used for Great Black-backed Gull and other large gull species.	0.9860 (0.0007; 0.9846 – 0.9874)	0.9448 (0.0028; 0.9393 – 0.9503)	0.9861 (0.0006; 0.9849 – 0.9873)	0.9104 (0.0082; 0.8935 – 0.9259)
Northern Gannet	**All gulls rate** There is significant uncertainty surrounding the behaviour of birds that enter wind farms. However, data collected at Thanet suggests strong avoidance of turbines once birds are inside the wind far, hence the all gulls rate is likely to reflect a realistic within wind farm avoidance rate for gannets. Post-construction data from operational wind farms also suggests strong avoidance of the wind farms themselves. Consequently, prior to assessing collision risk, macro avoidance should be accounted for. There is some uncertainty surrounding macro-avoidance so, it is recommend a range of a 60-80% reduction in pre-construction densities should be considered.	0.9874 (0.0003; 0.9868 – 0.9879) + macro avoidance of 60-80%	0.9532 (0.001; 0.9512 – 0.9553) + macro avoidance of 60-80%	0.9879 (0.0005; 0.987 – 0.9889) + macro avoidance of 60-80%	0.9261 (0.0066; 0.9128 – 0.9382) + macro avoidance of 60-80%

Table A3 Changes from previous recommended avoidance rates

Species	Model	SNCB Guidance (2014)	Bowgen & Cook (2018)	New Rate (Standard deviations; 95% Confidence intervals)	Justification
Sandwich Tern	Basic Band Model	0.98		0.9856 (0.0002; 0.9852 – 0.9860)	This has been revised through the incorporation of additional data. Furthermore, analyses in Cook et al. (2014) did not account for the imperfect detection of corpses and, it is unclear how the collision risk factor used in the previous Natural England guidance was estimated. Given the influence of data from Zeebrugge, which may not be reflective of offshore behaviour, the all gulls and terns rate, as opposed to species specific or tern-specific rates, is suggested.
Black-legged Kittiwake	Basic Band Model	0.989 (± 0.002)	0.99	0.9874 (0.0003; 0.9868 – 0.9879)	The suggested avoidance rate for kittiwake for use in the basic Band model is based on the all gulls rate. The majority of the data relating to kittiwake came from Thanet, and it cannot be ruled out that the collisions involving "unidentified gulls" related to kittiwakes.
Great Black-backed Gull	Basic Band Model	0.995 (± 0.001)	0.995	0.9860 (0.0007; 0.9846 – 0.9874)	In the absence of robust species-specific data, the suggested avoidance rate for great black-backed gulls is based on the large gulls rate. This has been revised following the incorporation of additional data and, through accounting for imperfect detection of corpses.
Lesser Black-backed Gull	Basic Band Model	0.995 (± 0.001)	0.995	0.9860 (0.0007; 0.9846 – 0.9874)	Uncertainty surrounding the identification of species involved in collisions at Thanet mean the large gulls rather than species specific rates are suggested.
Herring Gull	Basic Band Model	0.995 (± 0.001)	0.995	0.9860 (0.0007; 0.9846 – 0.9874)	Uncertainty surrounding the identification of species involved in collisions at Thanet mean the large gulls rather than species specific rates are suggested.
Lesser Black-backed Gull	Extended Band Model	0.989 (± 0.002)	0.993	0.9448 (0.0028; 0.9393 – 0.9503)	The inclusion of additional data and, accounting for imperfect corpse detection has resulted in the suggested avoidance rates for these species for use in the extended Band model being reduced. Uncertainty surrounding the identification of species involved in collisions at Thanet mean the large gulls rather than species specific rates are suggested.
Herring Gull	Extended Band Model	0.990 (± 0.002)	0.993	0.9448 (0.0028; 0.9393 – 0.9503)	The inclusion of additional data and, accounting for imperfect corpse detection has resulted in the suggested avoidance rates for these species for use in the extended Band model being reduced. Uncertainty surrounding the identification of species involved in collisions at Thanet mean the large gulls rather than species specific rates are suggested.
Great Black-backed Gull	Extended Band Model	0.989 (± 0.002)	0.993	0.9448 (0.0028; 0.9393 – 0.9503)	Uncertainty surrounding the identification of species involved in collisions at Thanet mean the large gulls rather than species specific rates are suggested.
Northern Gannet	Basic Band Model	0.989 (± 0.002)	0.995	0.9874 (0.0003; 0.9868 - 0.9879) + macro avoidance of 60-80%	Data collected from Thanet suggest strong avoidance of turbines, and data collected from post-construction studies of operational wind farms suggest strong avoidance of the wind farms themselves.

Cover image: Dennis Atherton / BTO; Back cover: Edmund Fellowes / BTO

Additional analysis to inform SNCB recommendations regarding collision risk modelling

Collision Risk Models are widely used in order to predict potential impact of collisions with turbines on bird populations but, are known to be sensitive to the parameter referred to as the avoidance rate. The most widely used Collision Risk Model is the Band Model, updated in 2012 for use in the offshore environment. Previous studies have estimated suitable avoidance rates for use in the Band model. However, given ongoing data collection, there is a need to update these estimates to ensure they reflect the best available evidence. Drawing from the data presented in Cook et al. (2014) and more recent studies, notably the ORJIP Bird Collision Avoidance study, this report presents updated estimates of avoidance rates for gulls and terns and makes recommendations about suitable avoidance rates for gannets. It further sets out recommendations and considerations for future revisions to avoidance rates as more data become available.

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BTO
Looking out for birds

Quantifying avian avoidance of offshore wind turbines: Current evidence and key knowledge gaps

Aonghais S. C. P. Cook[a,*$], Elizabeth M. Humphreys[b,$], Finlay Bennet[c], Elizabeth A. Masden[d], Niall H. K. Burton[a]

[a]British Trust for Ornithology, The Nunnery, Thetford, IP24 2PU, UK

[b]British Trust for Ornithology Scotland, Biological and Environmental Science, University of Stirling, FK9 4LA, UK

[c]Marine Scotland Science, Marine Laboratory, 375 Victoria Road, Aberdeen, AB11 9DB, UK

[d]Environmental Research Institute, North Highland College-UHI, University of Highlands and Islands, Ormlie Road, Thurso, Caithness, KW14 7EE, UK

*Corresponding author: [redacted]

[$]ASCPC & EMH contributed equally and should be viewed as joint first authors

Abstract

The risk of collision between birds and turbines is seen as one of the key issues in the planning process for offshore wind farms. In some cases, predictions of collision risk have led to projects either being withdrawn from the planning process, or refused planning consent. Despite this, the evidence base on which collision risk is assessed is extremely limited and assessments rely on models which can be highly sensitive to assumptions, notably about bird collision avoidance behaviour. We present a synthesis of the current state of knowledge about collision risk and avoidance behaviour in seabirds. Evidence suggests species-specific responses to turbines and that in order to avoid collision, most birds adjust their flight paths at some distance from the turbines, rather than making last-second adjustments. We highlight the key gaps in knowledge and make recommendations for future data collection.

Keywords

Collision Risk Model, Environmental Impact Assessment, Offshore Wind Farm, Seabirds

1. Introduction

Offshore wind energy is likely to play a key role in efforts to combat climate change through the production of renewable energy (Kaldellis and Zafirakis, 2011). At present the industry is well-developed in northern Europe, and is expanding globally (Breton and Moe, 2009; Snyder and Kaiser, 2009). However, there are concerns over the potential for offshore wind farms to negatively affect wildlife, with impacts on seabirds frequently cited as a key concern (Furness et al., 2013; Garthe and Huppop, 2004).

The main effects of offshore wind farms on seabirds are thought to be: i) collision mortality ; ii) displacement and attraction effects and; iii) barrier effects (Desholm and Kahlert, 2005; Everaert and Stienen, 2007; Masden et al., 2009; Vanermen et al., 2015). Barrier effects occur when the wind farms physically exclude birds causing extended flight journeys around the development during migration or when commuting between colonies and foraging areas (Masden et al., 2010, 2009). Displacement is regarded as a response that results in a functional loss of the habitat available within a wind farm, as opposed to a change in flight trajectory around the wind farm (Drewitt and Langston, 2006; Furness et al., 2013). Whereas attraction to wind farms is argued to be a consequence of turbines serving as a platform for roosting birds or the base acting as a reef resulting in an increase in food availability (Dierschke et al., 2016). Collision mortality describes birds colliding with turbines and associated infrastructure and has received a significant level of attention by the onshore industry as a result of well documented events (de Lucas et al., 2008; Everaert and Stienen, 2007; Loss, 2016; Thaxter et al., 2017a). However, the feasibility of collecting corpses or observing collision events in the marine environment is challenging and, to date, only two studies have reported birds colliding with offshore turbines (Desholm, 2006; Pettersson, 2005).

In the absence of more detailed information about collision rates, Collision Risk Models (CRM) are routinely used to predict the risk posed by offshore wind farms to seabird populations as part of pre-construction Environmental Impact Assessments (EIAS) in Europe (e.g. Ministry of Economic Affairs, 2015; NIRAS, 2015). CRMs are also being used in a range of countries where the offshore wind industry is in the early stages of development including the USA (Cranmer et al., 2017; Fammler and Kuris, 2010; Jenkins et al., 2018; Stumpf et al., 2011). They have also been used in a post-construction context in order to quantify likely collision rates (Skov et al., 2012) and to help estimate the cumulative impact of collisions at multiple offshore wind farms through extrapolation (Brabant et al., 2015; Busch and Garthe, 2017). A variety of different CRMs are available, but at their core most calculate the probability of a bird colliding based on the likelihood of it occupying the same space as a turbine blade. The collision risk to an individual bird is then scaled up based on the number of birds likely to pass through a wind farm over a given time period. The final stage is the application of an avoidance rate which takes into account the proportion of birds likely to take action to avoid a collision (Masden and Cook, 2016). However, outputs from CRMs are known to be sensitive to assumptions made about the avoidance behaviour of the species concerned, notably flight height and flight speed, which are often based on extremely limited data (Chamberlain et al., 2006; Masden, 2015).

Whilst avoidance behaviour can be seen as a continuum over space and time, there is a need to break this down into different components which correspond to how birds may respond to both the wind farm and to individual turbines. Technological limitations associated with measurement have also influenced the definitions but, currently avoidance behaviour is recognised at three different scales (Figure 1), termed macro, meso, and micro (Cook et al., 2014). May (2015) developed a framework for understanding avian avoidance based on the underlying behavioural mechanisms and set out how this related to these three classifications. Macro-avoidance (avoidance of the wind farm as a whole) can arise through a functional habitat loss and is observed as displacement. May (2015) went on to argue that attraction could be included under the term displacement, resulting in what are in effect negative avoidance rates. However macro-avoidance can also include barrier effects, a type of evasive behaviour which can be classified as being impulsive or anticipatory, the latter of which requires early detection or a prior experience or knowledge. Meso-avoidance is the anticipatory or impulsive evasion of rows of turbines within a wind farm. Micro-avoidance reflects the last-second action taken to avoid collision with the turbine blades and may be thought of as an escape response (May, 2015).

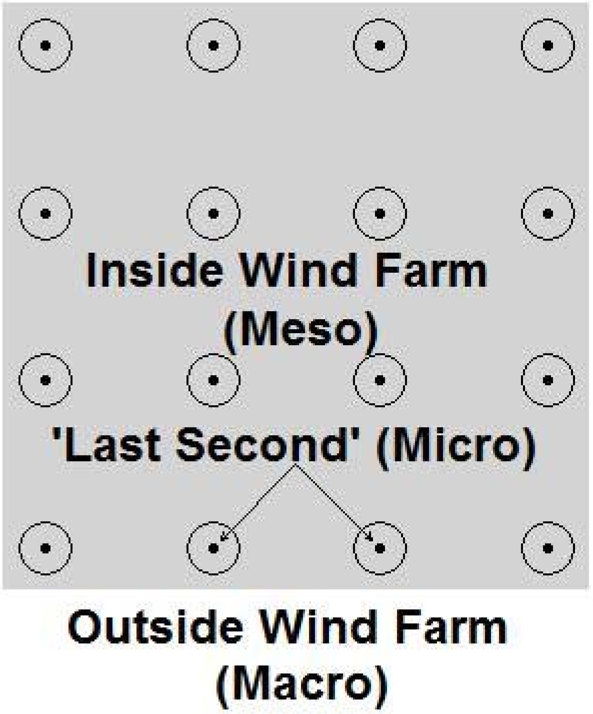

Figure 1 Different scales of avoidance behaviour in relation to an offshore wind farm, turbines indicated by black dots. Macro-avoidance reflects birds either taking action to avoid entering, or birds being attracted to, a wind farm, meso-avoidance reflects birds taking action to avoid individual turbines and micro-avoidance reflects birds taking last-second action to avoid colliding with rotor blades (i.e. within circles surrounding each turbine).

Collisions with turbines may not only have significant conservation implications (Everaert and Stienen, 2007) but important economic consequences as well. In the UK, the Docking Shoal Offshore Wind Farm was refused planning consent over the estimated numbers of Sandwich terns *Thalasseus sandvicensis* predicted to be killed (DECC, 2012), a decision with major implications for both the developer and regulators. Considering the respective economic and conservation concerns, it is vital that decisions about offshore wind farms are made based on the best available evidence. Despite this, there has been no clear agreement about how data describing avoidance behaviour should be collected (Cook et al., 2014; May, 2015). There is a risk that this situation may lead to “decision paralysis” whereby decision-making is constantly postponed whilst additional data are collected (Milner-Gulland and Shea, 2017).

Northern gannet *Morus* bassanus, lesser black-backed gull *Larus fuscus*, herring gull *Larus argentatus*, great black-backed gull *Larus marinus* and black-legged kittiwake *Rissa tridactyla* are viewed as being at a high risk of collision with offshore wind farms due to their flight altitude (Furness et al., 2013; Johnston et al., 2014; Ross-Smith et al., 2016). In northern Europe, the foraging ranges of these species also often overlap with the currently planned offshore wind farm developments (Bradbury et al., 2014; Johnston et al., 2015; Soanes et al., 2013; Thaxter et al., 2015). Here we consider what evidence currently exists to quantify avoidance behaviour for these species. We then describe how these data can be best combined to calculate an overall avoidance rate suitable for use in CRMs for the five key species. In so doing we present an approach which can be adapted for other species and also allows for sufficient flexibility for the inclusion of future data for our example species. Finally, we highlight any gaps in knowledge that we have identified as part of our review.

2. Methods

We focussed our literature search on operational wind farms in northern Europe at which the five key bird species were likely to occur. An online database ([redacted] was used to identify offshore wind farm sites, relevant developers and their environmental consultants in order to obtain available reports and data. Web of Science and Google Scholar were used to search for relevant peer-reviewed papers, reports, conference proceedings and book chapters relating to the impacts of wind farms on the five priority species, following literature trails where appropriate. We also referred to previous reviews on the topic (Marine Management Organisation, 2014; Smartwind/Forewind, 2013) to ensure that all sources of primary literature had been identified. Where appropriate, we also considered data relating to the five key species collected from coastal sites, as currently these may reflect the best or only available data on which to base decisions (potential biases are highlighted in section 4.2-Limitations).

2.1 Macro-avoidance

Methodologies which have been used to look at macro-avoidance may not actually distinguish between birds displaced from a wind farm and those exhibiting barrier effects since both can be manifested as a decrease in the numbers of birds in flight within the wind farm area. For the purposes of this review however, we considered studies according to the effect they were designed to investigate. This was not considered an issue as barrier, displacement and attraction effects collectively describe the overall macro-avoidance rate. The key studies included based boat or aerial surveys or from counts from panoramic scans but supporting information was included from GPS tracking studies or radar studies where species identification had been possible. Rates of macro-avoidance were taken directly from the studies cited or calculated using model coefficients (see Cook et al 2014 for more details).

2.2 Meso-avoidance

To assess evidence for meso-avoidance, we considered studies in which the distribution or movement patterns of birds within a wind farm were assessed. Studies selected for inclusion in the review were those which compared the distribution of bird densities or bird movements in the area surrounding individual turbines to the density elsewhere within the wind farm. Surveys were carried out using either visual observations or with radar in combination with visual observations to identify target birds to species level.

2.3 Horizontal vs vertical macro- and meso-avoidance

We considered both macro- and meso-avoidance to have two components, a vertical component and a horizontal component. For the horizontal component, we considered studies in which the distribution of birds (densities) or flightpaths outside the wind farm were compared to the distribution within the wind farm (macro) or with respect to turbines or turbine rows within the wind farm itself (meso).

A significant proportion of birds are likely to fly below rotor-swept height where no turbines are present (Johnston et al., 2014). Consequently, in order to estimate vertical avoidance, a comparison must be made of the proportion of birds at rotor-swept height pre- and post-construction or, inside and outside the wind farm. We searched for studies which met these criteria. These studies were mainly derived from fairly limited visual observations collected from boats or other observation platforms. Data collected using radar were considered, but were found to be at too coarse a scale to be of use.

2.4 Micro-avoidance

Studies of micro-avoidance require detailed behavioural observations of the interaction between birds and turbines due to the fact that they involve last-second escape responses. Therefore, to assess micro-avoidance we considered studies in which interactions between birds and turbines were recorded visually by observers or remotely using radar or turbine-mounted cameras. There was a lack of information which was identified for this scale however.

2.5 Within-wind farm avoidance

Ideally, micro and meso avoidance could be quantified separately for each species in order to generate robust estimates of avoidance behaviour. However, such data may not be available and, given pressures in the decision making process, decisions often rely on the best available data (Milner-Gulland and Shea, 2017). In these circumstances, it is possible to derive avoidance rates by comparing recorded collision rates with estimates of bird flight activity within a wind farm (Band, 2012). As this approach considers all bird movements within a wind farm, it is effectively a combination of both meso-avoidance and micro-avoidance although, it should be noted that it also incorporates elements of bias introduced by estimates of flight activity from the model itself (Band, 2012). We therefore refer to avoidance rates calculated in this way as within-wind farm avoidance. At present, technologies to record collision rates in the offshore environment are still under development (e.g. Collier, Dirksen, and Krijgsveld 2011). Consequently, avoidance rates derived using this approach rely on data from the onshore environment. However, analysis of GPS data indicates that there are likely to be strong differences between flight behaviour on the coast and in marine areas in comparison to the terrestrial environment (Ross-Smith et al., 2016). Consequently, we limited data considered for this analysis to those collected from coastal locations, where flight behaviour may be more similar to that observed offshore, although there may still be some differences (Ross-Smith et al., 2016).

Records of collisions between birds and turbines are frequently reported as a collision rate per year, or a collision rate per turbine per year (Musters et al., 1996). However, in order to estimate a within-wind farm avoidance rate, these data must be combined with estimates of the number of birds passing through the site i.e. the flux rate. We therefore restricted our analyses to sites where estimates of flight activity were also made. Due to likely seasonal and spatial patterns in flight activity, analyses were restricted to sites in which collision and flight activity data were collected during the same months in order to ensure that collision rates reflected seasonal patterns in flight activity data. For these reasons, reported avoidance rates may not match those presented in the original studies. However, we feel it is important that data across sites should be assessed in a consistent way. In order to ensure transparency, Table S3 includes the data and calculations used to estimate the flux rates and within-wind farm avoidance rates at each site. Within-wind farm avoidance rates at each site were estimated using equation 1 (Scottish Natural Heritage, 2010).

$$Within - wind\ farm\ avoidance\ rate = 1 - \left(\frac{Observed\ Collisions}{Probability\ of\ collision \times Flux\ Rate}\right) \qquad \text{Eq. 1}$$

Probability of collision is the likelihood of the blade and bird occupying the same location in space and time based on simplified geometry and is derived using the Band model (Band, 2012), assuming turbine characteristics presented in Table S1 and bird behaviour and morphology presented in Table S2. The probability of collision for each species at each site is given in Table S3. The flux rate is estimated by calculating the number of birds expected to have passed through the wind farm per m^2 per hour scaled up to cover the total turbine frontal area and the total time period during which corpses were collected, and corrected for the proportion of birds at collision risk height and the level of nocturnal activity. The assumptions made during calculations can have a significant impact on the final estimates, and we therefore include Table S3 in supplementary information which shows the step by step process by which we estimated each within wind farm avoidance rate. We then used ratio estimators (Cochran, 1977) to combine avoidance rates across multiple sites and the delta method (Powell, 2007) to estimate the standard deviation associated with the derived avoidance rates.

2.6 Derivation of recommended total avoidance rates

Collision risk estimates are typically based on pre-construction estimates of the total number of birds within a wind farm (Cook et al., 2014). Consequently, the avoidance rates used in collision risk models must account for changes in the total number of birds within the wind farm between the pre- and post-construction periods as well as any redistribution arising from behavioural responses to turbines within the wind farm. The total avoidance rate can then be estimated by combining the macro-, meso- and micro-avoidance rates as shown in equation 2 (Cook et al., 2014; Krijgsveld et al., 2011), or the macro- and within wind farm-avoidance rates as shown in equation 3 (adapted from Equation 2).

(1 – Total Avoidance Rate) = (1 – Macro-Avoidance) x (1 – Meso-Avoidance) x (1 – Micro-Avoidance) (Eq. 2)

(1 – Total Avoidance Rate) = (1 – Macro-Avoidance) x (1 – Within-wind farm avoidance) (Eq. 3)

Equations 2 and 3 can accommodate situations where birds are attracted at a macro- or meso-scale. Within these formulae, a value of 1 relates to total avoidance, a value of 0 relates to neither avoidance nor attraction and values less than 0 relate to attraction (i.e. -0.1 would relate to a 10% increase), meaning the avoidance rate is reduced when birds are attracted to the wind farm or individual turbines.

3. Results

3.1 Macro-avoidance – barrier effects

Overall there was limited evidence of macro-avoidance as an apparent consequence of barrier effects for the five priority species (Table 1). Systematic panoramic scans of densities of birds in flight within and around the Egmond aan Zee wind farm in the Netherlands revealed a macro-avoidance rate of 0.64 for northern gannet (n=81) and 0.18 for gull spp combined (Krijgsveld et al., 2011). Using a combination of radar and laser range finders at Horns Rev, a macro-avoidance rate of 0.84 was calculated based on the numbers of tracks of migrating gannets (n=74) which did not enter the wind farm (Skov et al., 2012). The same study also reported an avoidance rate of 0.56 for large gulls (n=84) and 0.69 for kittiwakes (n=11). An earlier study at the same wind farm reported that out of 126 tracks representing 268 individual migrating gannets, none of these entered the wind farm. For migrating gulls (herring, great black-backed, little and kittiwake, 442 tracks out of a total of 461 did not enter the wind farm — although as neither species or size of flock were reported, the avoidance rate cannot be estimated (Petersen et al., 2006). However, in these studies data were collected during the post-construction period only and caution should therefore be applied when interpreting their significance in the absence of pre-development data. Furthermore, data collection also tended to be focused on outside the breeding season and the extent to which this information is relevant to birds when they are tied to their colonies is unclear.

3.2. Macro-avoidance – displacement

From studies of displacement, macro-avoidance was estimated for northern gannet using ship based surveys at the Blighbank wind farm in Belgium (Vanermen et al., 2015) – a rate of 0.85 (Table 1) – and at the Alpha Ventus wind farm in Germany – a rate of 0.92 –although this study was based in an area where gannets densities were low (Welcker and Nehls, 2016). As before, whether these data are representative of behaviour during the breeding season is uncertain as the majority of the data were from the non-breeding season(Vanermen et al., 2013). Of the remaining studies, one reported displacement at two wind farms (Leopold et al., 2013) and another three reported no response of northern gannet, possibly as a result of low densities of birds being present pre- and post-construction (Mendel et al., 2014; Natural Power, 2014; Petersen et al., 2006). An aerial based survey at Greater Gabbard in the UK estimated an avoidance rate of 0.95 (APEM 2014) during the autumn passage period and based on the post construction period only. An additional study of three GPS-tagged northern gannets also indicated that they avoided entering wind farms (Garthe et al., 2017).

One study reported great black-backed gulls as being attracted to offshore wind farms (Welcker and Nehls, 2016), whilst the others reported no response (i.e. no attraction to or displacement from). For lesser black-backed gulls the evidence for macro-avoidance was equivocal with studies reporting attraction, displacement and no response to the wind farms. A recent study of GPS-tagged lesser black-backed gulls suggests that while individuals may differ in their response to offshore wind farms, overall the species did not consistently exhibit displacement or attraction (Thaxter, Ross-Smith, et al. 2017). Herring gull largely showed no response to wind farms with the notable exception at Blighbank and Alpha Ventus where attraction effects were reported (Vanermen et al., 2015; Welcker and Nehls, 2016) possibly linked to increased roosting opportunities provided by the wind farm (the same effect was observed for lesser black-backed gulls at the same site). Black-legged kittiwake showed both displacement effects and no response to wind farms.

3.3. Macro-avoidance – combining all effects

For the species considered in this review, there was evidence that northern gannet exhibit macro avoidance. At this stage, we believe the lower of the available values, 0.64 (Krijgsveld et al., 2011), is an appropriate macro-avoidance rate for northern gannet. This is based on a precautionary approach given that estimates were often based on small sample sizes leading to limited power to detect change combined with most data being collected outside the breeding season. In contrast, based on the studies we identified, none of the gull species appear to show a consistent response to wind farms. In the absence of consistent evidence, we are unable to recommend a suitable macro-avoidance rate for gulls.

3.3. Horizontal meso-avoidance

Meso-avoidance is likely to reflect the anticipatory or impulsive evasion of individual turbines. We identified four studies in which the distribution of birds or flight paths within a wind farm were quantified. Using radar, Krijgsveld *et al.* (2011) and Skov *et al.* (2012) found strong evidence of horizontal meso-avoidance of individual turbines. Krijgsveld *et al.* (2011) reported that the density of birds within 50m of a turbine was 66% of the density elsewhere in the wind farm. Assuming that, in the absence of turbines, birds would be expected to be evenly distributed across the area of the wind farm, this reflects a meso-avoidance rate of 0.34. It is likely that this figure reflects an underestimate of total meso-avoidance as it is based on data collected using horizontal radar and will, therefore, include birds flying above or below the turbines thus not at risk of collision. Skov *et al.* (2012) found a stronger response, with none of the 408 large gulls they recorded passing within 50m of a turbine. However, the primary purpose of this analysis was to collect information describing species flight heights rather than their proximity to turbines. Tracks from radar suggested some birds may approach the turbines more closely. Using visual observations, Janoska (2012) recorded only 23 out of 917 gulls passing within 75m of a turbine, reflecting a meso-avoidance rate of 0.975. By contrast, also using visual observations, Everaert (2008) reported no significant difference in the number of gulls passing within 100m of a turbine (or its proposed site) between pre- and post-construction periods, possibly reflecting the location of the site on a flight line between a roost and a foraging/loafing area. These studies suggest that gulls may have a strong horizontal meso-avoidance of turbines, but that this may be site or context specific. Whilst the data in the studies described above are informative, it should be noted that they are not sufficiently robust to allow firm conclusions to be drawn about the likely magnitude of any meso-avoidance.

In addition to the studies described above, several studies reported anecdotal evidence describing how the relative location of the turbines may influence the distribution of birds within a wind farm. Petersen *et al.* (2006) provided evidence to suggest that birds may be more likely to respond to turbines as the number of turbine rows they passed increased, suggesting stronger avoidance towards the middle of the wind farm than at the edge. Similarly, Winkelman (1992) noted that there were fewer collision victims towards the centre of a wind farm. These data suggest that the strength of any horizontal meso-avoidance may vary with distance from the wind farm centre. There was also evidence from three sites – Horns Rev, Alpha Ventus and Egmond aan Zee – to suggest that birds respond to the operational status of turbines, with higher densities recorded when turbines were not operational, although this effect may be more noticeable at night (Krijgsveld et al., 2011; Mendel et al., 2014; Petersen et al., 2006; Schulz et al., 2014).

3.4 Vertical meso-avoidance

We identified three sites at which the proportions of birds of different species at rotor-swept height could be compared pre- and post-construction – Barrow (Barrow Offshore Wind Limited, n.d.), Gunfleet Sands (GoBe Consultants Ltd., 2012; NIRAS Consulting, 2011) and Robin Rigg (Natural Power, 2013) – and a fourth – Egmond aan Zee (Krijgsveld et al., 2011) – where flight heights were compared inside and outside a wind farm (Table 2). Across these sites, there was no consistent pattern indicating an increase or decrease in the proportion of birds at rotor-swept height in response to the presence of a turbine. However, given the extremely limited evidence, no firm conclusions can be drawn about the extent or direction of any vertical meso-response in any species of marine birds. Furthermore, where flight heights are estimated by observers by eye, it should be noted that any comparison may be confounded by the fact that heights are easier to estimate once turbines have been installed as they offer fixed reference points of known height.

3.5. Micro-avoidance

Micro-avoidance reflects a last second action to avoid collision and, may be thought of as an escape response (May, 2015). We identified 17 sites at which visual observations of the interactions between birds and turbines had been reported (Table 3). Over the course of these studies, only two collision events were directly observed, the first involving a flock of four common eider *Somateria mollisima* at a single turbine at the Utgrunden Offshore Wind Farm in Sweden and the second, a passerine or bat at Nysted Offshore Wind Farm in Denmark (Desholm, 2006; Pettersson, 2005). Whilst it should be noted that collisions may have occurred between observation periods, the number of birds observed interacting with turbines without colliding suggests that collisions are likely to be rare events (Table 3).

Of the studies we identified, only six provided sufficiently detailed descriptions of birds' interactions with wind turbines to characterise micro-avoidance (Table 3; Desholm 2005; Krijgsveld et al. 2011; RPS 2011; Schulz et al. 2014; Thaxter, Ross-Smith, et al. 2017; Wild Frontier Ecology 2013), although these reflected significant effort across multiple sites. Despite this effort, there were very few records of birds flying close enough to turbines to require micro-avoidance. Indeed, Desholm (2005) did not record any birds passing within 20m of a turbine. Similarly, a detailed analysis of two GPS-tagged Lesser Black-backed Gulls indicated that these birds significantly avoided entering the turbine rotor-swept area (Thaxter, Ross-Smith, et al. 2017). Across the remaining studies only 59 birds were recorded as passing close to the turbine rotor-swept area, of which 54 were recorded as taking action to avoid the rotor-swept area (Table 3). The data for micro-avoidance would appear to be consistent with those reported above for meso-avoidance, suggesting that a last second escape reflex may be required relatively rarely as, within a wind farm, avoidance behaviour is driven by a high level of anticipatory or impulsive evasion. However, given the differences in the species recorded interacting with turbines and the relatively low number of birds recorded, it is difficult to draw firm conclusions about the extent of micro-avoidance behaviour.

3.6. Within-wind farm avoidance

We identified nine coastal sites (Table 3) from which data describing the recorded number of collisions were available from the same time periods as estimates of the total number of birds passing through turbine rotor-swept areas. Based on the data presented in the studies highlighted in Table 3, it was possible to calculate species-specific within-wind farm avoidance rates for herring gull and lesser black-backed gull, as well as rates for small gulls (e.g. black-legged kittiwake), large gulls (e.g. great black-backed gull) and all gulls (Table 4) but not for northern gannet.

These analyses confirmed that within-wind farm avoidance rates were likely to be very high (> 0.99) (Table 4). Avoidance rates were similar between species with rates of 0.9959 for herring gull and 0.9982 for lesser black-backed gull. We also estimated group-specific avoidance rates of 0.9921 for small gulls (birds identified as little, common or black-headed gulls), 0.9956 for large gulls (those identified as lesser black-backed, herring or great black-backed gull or described as large gull spp.) and 0.9893 for all gulls (those identified to species level or described as large gull, small gull or gull spp.).

Whilst the level of precision expressed by these values may seem excessive, it should be noted that it is the non-avoidance rate (1-avoidance) which is incorporated in the collision risk model. When presented to four decimal places, the non-avoidance rates typically had 2 significant figures (table 4), which we feel reflects a reasonable level of precision. The difference between an avoidance rate of 0.995 and 0.9959 would result in an 18% increase in the collision rate predicted from the CRM. We would also argue that this level of precision is justified given the estimated level of uncertainty surrounding each value (Table 4).

3.7. Recommended total avoidance rates

Evidence suggests that the response of gulls to turbines at a macro scale may be highly variable. Consequently, at present, we consider all gull species (including kittiwake) to have an average macro-avoidance rate of zero. Few studies were available with which to draw conclusions about meso- and micro-avoidance in gulls. Consequently, the total avoidance rates for gulls can be considered to be equal to the within-wind farm avoidance rates. However, the evidence base for macro-avoidance in gulls was limited meaning it was not possible to produce robust estimates of uncertainty surrounding macro-avoidance rates. Therefore, when combining macro- and within-wind farm avoidance rates, we are not able to give an estimate of uncertainty surrounding the total avoidance rate. Additionally, given the limited evidence base for macro-avoidance, we present the total avoidance rate to three, rather than four, significant figures and round down in order to be precautionary. We recommend total avoidance rates of 0.998 for lesser black-backed gull and 0.995 for herring gull. Based on flight behaviour and morphology, we believe it is reasonable to include the great black-backed gull in the large gull spp. grouping, and the black-legged kittiwake in the small gull spp. grouping. We therefore recommend total avoidance rates of 0.995 and 0.992 respectively for these species.

Fewer data were available to support a total avoidance rate for northern gannet. However, given the evidence of strong macro-avoidance of wind farms, it was felt that the total avoidance rate was unlikely to be below that obtained for all gulls. Consequently, a rate of 0.989 is recommended for northern gannet.

4. Discussion

May (2015) suggests that alertness is likely to increase with decreasing distance to turbines, meaning birds are more likely to take action as they get closer to a turbine. We believe our review supports this hypothesis as, despite significant survey effort, we uncovered very little evidence of birds approaching turbines close enough to be at risk of collision. Of those that did, a high proportion were recorded taking last-second action to avoid collision, termed an escape response by May (2015). In a behavioural context, this suggests that most avoidance action is likely to be caused by functional habitat loss or anticipatory or impulsive evasion, rather than a last second escape reflex. There was also evidence to suggest that the avoidance rate may vary in relation to both the position of a turbine in an array and whether or not turbines are operational (Krijgsveld et al., 2011; Mendel et al., 2014; Petersen et al., 2006; Schulz et al., 2014; Winkelman, 1992), a conclusion consistent with the predictions made by May (2015). Such responses highlight the ability of some species, particularly gulls, to adapt to the presence of wind turbines.

4.1. Use of avoidance rates in collision risk models

Previous guidance of the use of avoidance rates in CRMs was that 0.98 should be considered the default value for seabirds (Scottish Natural Heritage, 2010). Whilst significant gaps in knowledge remain, this review highlights that, for the species most likely to be affected by collision, avoidance rates are estimated to exceed 0.99. Whilst this may seem a trivial difference, it will result in the predicted collision rate being more than halved. These avoidance rates are applicable to models such as Band (2012), as well as others including the models of Tucker (1996) and Eichhorn (2012). However, care must be taken when using these avoidance rates in models which account for the vertical distribution of birds when estimating the probability of collision (e.g. the Extended Band Model Band, 2012). Accounting for the vertical distribution of birds will reduce the number of collisions predicted in the absence of avoidance as the number of birds within the central, and more risky part of the rotor-swept area will be reduced (Johnston et al., 2014). Consequently, within-wind farm avoidance rates suitable for use with models such as the extended Band model (Band, 2012), which do account for vertical distribution, are likely to be lower than those suitable for use with simpler models. At present, insufficient data are available with which to estimate robust avoidance rates for use in the extended Band model for most species. However, with ongoing data collection in the offshore environment, for example through the UK Offshore Renewables Joint Industry Project (Davies et al., 2013), it is to be hoped that this review will help inform for the collection of appropriate data in future.

4.2. Limitations

At present, our recommended avoidance rates only consider horizontal avoidance. We identified some evidence suggesting birds may alter their flight altitudes when within a wind farm in order to reduce collision risk (Table 2). However, this evidence was inconclusive and further studies are required in order to fully understand vertical avoidance behaviour. Technological advancements, for example, the availability of radar (Kunz et al., 2007; Skov et al., 2016; Ward et al., 2016) and GPS tags (Corman and Garthe 2014; Garthe et al. 2017; Thaxter, Ross-Smith, et al. 2017) which can collect detailed information about the movement patterns of individual birds may mean these data could be collected in the near future. Combining horizontal and vertical avoidance rates in order to derive a three-dimensional avoidance rate is unlikely to be straightforward as birds may employ both strategies at the same time, meaning simple formulae like equation 2 are unlikely to be appropriate. However, approaches such as that used with GPS tracking data by Thaxter *et al.* (2017) may prove valuable.

Within wind farms (i.e. at meso- and micro-scales) a lack of data from the offshore environment is an issue, particularly in relation to northern gannet. Whilst data from terrestrial sites are informative about how birds may interact with individual turbines, evidence suggests that flight behaviour may differ between onshore and offshore environments (Corman and Garthe, 2014; Ross-Smith et al., 2016) potentially affecting how birds respond to turbines and therefore avoidance rates. Whilst we have attempted to minimise the impact of this by focussing on data collected from coastal locations, some differences may remain, notably in relation to flight height and speed (Corman and Garthe, 2014; Ross-Smith et al., 2016; Spear and Ainley, 2008). Birds tend to fly higher over land than offshore and, there is also a greater tendency for them to fly at altitudes within the rotor-swept area of turbines in the terrestrial environment (Corman and Garthe, 2014; Ross-Smith et al., 2016). This greater potential exposure to turbine blades means that collision rates in the terrestrial environment may be greater than is the case offshore. Seabird flight speed can be strongly influenced by weather conditions, particularly wind strength and direction (Shamoun-Baranes and van Loon, 2006; Spear and Ainley, 2008), potentially affecting their manoeuvrability and ability to respond to obstacles. As wind conditions can differ markedly between the onshore and offshore environments, this is likely to have implications for collision risk. However, at present insufficient data are available to enable us to understand in which direction this may influence collision risk.

The within-wind farm avoidance rates presented here are higher than those derived by Everaert (2014). This may partly reflect the broader range of sites covered by our review, especially as some of the sites covered in Everaert (2014) appear to have particularly high collision rates. In particular Everaert (2014) highlights the proximity of one wind farm to a breeding colony as a key reason for a high collision rate. This highlights the importance of considering site-specific variation in avoidance behaviour, which we have attempted to capture by estimating confidence intervals around our within-wind farm avoidance rates. However, even when we estimate within-wind farm avoidance rates from similar data, the values derived as part of our review differ from those presented by Everaert (2014) (Table S3). A key reason for this is that, in order to ensure data were consistent with those collected elsewhere, we have only considered data where no spatial or temporal extrapolation was required in order to combine collision and flight activity data. We recognise that there are a number of ways in which avoidance rates can be derived, and that small differences in the way some parameters are derived (i.e. passage rate), and biases due to survey technique, can strongly influence the final estimated avoidance rates. This is undesirable as it can increase uncertainty in the consenting process, increasing costs for those involved. For this reason, we strongly suggest that authors provide detailed calculations showing how the rates presented have been estimated in order to enable readers to come to an informed decision about the results (see Table S3).

To date, there has been little consideration of factors which are likely to influence avoidance behaviour and to what extent there is seasonal- or site-specific variation in the offshore context. Avoidance rates for non-seabird species at onshore wind farms have been reported to vary by site and even within wind farms (Garvin et al., 2011), as well as by season, whether birds are resident or migrants and the relative distance to the wind farm from roost sites or nest locations (Campedelli et al., 2014). It is apparent, therefore, that the magnitude of any avoidance behaviour is likely to be linked to the ecological importance of a site to a species at a given point in time, and how it is being used. Seabirds act as central place foragers during breeding (Stephens and Krebs, 1986; Thaxter et al., 2012). This may manifest itself in spatial differences in behaviour, dependent upon whether the area covered by an offshore wind farm is used for active foraging or for commuting between foraging grounds and the breeding colony. Such behavioural differences may be associated with varying levels of collision risk and avoidance behaviour. There may also be a temporal element to avoidance behaviour. Stage-dependent changes in foraging behaviour between the incubation and early chick-rearing period have explained the change in spatial overlap with offshore wind farms (Thaxter et al., 2015). The presence of newly fledged birds in the population towards the end of the breeding season may also affect avoidance rates as these naive individuals may unintentionally engage in riskier flight behaviour (Henderson et al., 1996). Individual seabirds may also show consistency in their preferred foraging areas (Irons, 1998; Soanes et al., 2013) or have limited alternative habitats available. Where wind farms overlap with these preferred foraging areas, displacement may be less likely and macro-avoidance rates therefore lower for these individuals. These studies suggest that there are likely to be both spatial and temporal elements to avoidance behaviour for seabirds, neither of which have yet been properly quantified. There is also some evidence to suggest that group size and social interactions can influence the likelihood of collision and hence by association, the avoidance behaviour of birds (Croft et al., 2013). Other factors which influence collision risk have also been reviewed extensively (Marques et al. 2014; May et al. 2015; Thaxter, Buchanan, et al. 2017; Wang et al. 2015) and include aspects of: species characteristics (morphology, flight behaviour, sensory perception, phenology); site features (landscape, food availability, weather); and wind farm features (type of turbines and design of array).

4.3. Future data collection — displacement and functional habitat loss

Whilst this study has advanced our understanding of avoidance behaviour of seabirds in relation to offshore wind farms, a number of significant gaps in knowledge remain. Collecting the data necessary to quantify avoidance behaviour in relation to offshore wind farms can be extremely costly and therefore requires well designed studies involving both industry and regulators (e.g.

Davies et al. 2013). The cost and challenging nature of these studies means that it is important to utilise robust analytical approaches that make the most of any data collected.

Studies of displacement/attraction have typically used Before-After-Control-Impact (BACI) survey design (Stewart-Oaten et al., 1986) but have been hampered by inadequate survey design notably gaps in spatial or temporal coverage and inappropriate choice of control sites (Marine Management Organisation, 2014). Recently developed approaches, such as Before-After-Gradient (BAG) analyses are increasingly used to assess the impacts of wind farms with the focus on collecting data over much more extensive areas around the wind farm site starting in the pre-construction period (Jackson and Whitfield, 2011; Mackenzie et al., 2013; Marine Management Organisation, 2014; May, 2015). By incorporating environmental covariates (e.g. sea surface temperature, tidal cycles) to help describe spatial and temporal variation in seabird distributions and abundance at sea, further changes associated with the construction and operation of wind farms can be more accurately attributed (Mackenzie et al., 2013), and therefore better inform macro-avoidance rates. Species assumed to be at risk of displacement (Furness et al., 2013), tend to have estimates of avoidance based largely on data collected at the macro-scale. In the case of species for which displacement is not perceived to be a significant issue, for example gulls, there is often less focus on data collection at this scale, meaning the macro level response to wind farms is often less well understood. By focussing data collection on the scale perceived to be most relevant for the species concerned, there is a risk that avoidance behaviour at other spatial scales is overlooked. Whilst this is primarily an issue for data collected using observational surveys, it may also be an issue for data collected using radar depending on the range over which the system operates.

To help to provide a better evidence base for macro-avoidance, future analyses should distinguish between birds in flight and those on the water, as only those in flight are at risk of collision. Ideally, such studies should also incorporate measurements of flight altitude so that birds flying above, or below, the collision risk window can be excluded from subsequent analyses. However, in collecting these data a key consideration needs to be whether the survey has sufficient power to detect change between the pre- and post-construction periods. The power to detect change is related to a variety of factors including the frequency of, and area covered by, the surveys as well as inherent spatial and temporal variability in seabird distribution and relative abundance (Maclean et al., 2013; Pérez Lapeña et al., 2010). This is a particular issue where the pre-construction population of a species is small, and is always likely to be an issue where baseline sampling has not taken account of statistical power for detection of change. This exacerbates the risks of a change in the number of birds using a site either giving the false impression of a significant effect (false positive response) or where no change is found, the results are wrongly interpreted as a lack of response to the presence of the wind farm by the particular species (false negative response). A recent review (Marine Management Organisation, 2014) of post-consent monitoring of offshore wind farms concludes that the power to detect such changes by existing studies is likely to be low and the responses of seabirds to wind farms may have been incorrectly quantified. Careful consideration must also be given to biases associated with survey methodology. In particular, data collected from different platforms (e.g. visual aerial surveys vs digital aerial surveys) can give very different estimates of abundance (Buckland et al., 2012). Consequently, when estimating macro-avoidance based on displacement as functional habitat loss, it is important to ensure that the data used to do so are directly comparable.

Ideally, the effect size and associated confidence intervals should always be reported as standard in the results of ecological studies (Masden et al., 2015; Nakagawa and Cuthill, 2007). However, of the studies we considered, only Vanermen *et al.* (2015) and Natural Power (2014) did so in respect to the studies of displacement and attraction. If these practices were adopted as standard when measuring avoidance behaviour, not only would it make it more straightforward to quantify avoidance rates and compare across studies, it would also give us an understanding of the uncertainty and variability surrounding these rates.

4.4. Future data collection — anticipatory or impulsive evasion

Radar can be deployed in order to investigate anticipatory or impulsive evasion of wind farms or turbines. However, deriving species-specific avoidance rates from data collected in this way can be challenging given the difficulty of identifying species from radar tracks. Where species-specific macro-avoidance rates have been derived using radar, this has been possible because the majority of tracks could be assigned to a single species (e.g. during mass migration events when only a few species are represented; Desholm and Kahlert, 2005; Petersen et al., 2006). However, recent studies have demonstrated effective use of radar monitoring in combination with visual observations in order to be able to identify more complex suites of species moving in and around wind farms (Skov et al., 2012). Ideally these studies should also aim to collect data on the vertical distribution of birds and in-flight changes in behaviour (e.g. flight speed and turning angles).

4.5. Future data collection — escape response

In order to collect data describing micro-avoidance, carefully designed experiments and analyses are required. Approaches such as the use of turbine mounted cameras (Desholm, 2005) may be suitable, but must be capable of detecting abrupt changes in flight direction and/or altitude. Given that micro-avoidance behaviour is likely to be an extremely rare event, careful consideration must be given to ensure that any methods used have the necessary statistical power to estimate robust avoidance rates.

5. Conclusions

Our study assesses the evidence for avoidance behaviour in five key seabird species, perceived to be at particular risk of collision, at three different spatial scales. We have demonstrated how the different types of data which have been collected fit within the framework for describing avoidance behaviour developed by May (2015). Whilst we have done this in the context of offshore wind farms, this approach is also likely to be applicable to other situations where collision risk is likely to be an issue, for example in relation to tidal turbines.

Lack of data on avoidance behaviour has been acknowledged as an issue for some time (Chamberlain et al., 2006). As the wind industry has developed both onshore and offshore, the evidence base has developed. This review summarises the evidence that has been collected to date and represents a significant step forward by presenting estimates of avoidance behaviour for five seabird species. It is important to acknowledge that these values are largely based on data from coastal, rather than offshore locations. However, in our opinion, this remains the best available evidence with which to quantify avoidance behaviour in seabirds. Significant knowledge gaps remain and key areas to be addressed include distinguishing between vertical and horizontal avoidance and gaining a better understanding of how seasonal and spatial processes may influence avoidance behaviour. This is particularly important given the rapid growth of the offshore wind sector and the potential for the cumulative impacts of collisions from multiple wind farms on species and populations of concern (Brabant et al., 2015; Busch and Garthe, 2017).

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Table 1 Summary of key studies of barrier effects, displacement and attraction for the five priority species (B = barrier effects; D = displacement; A = attraction and NR = no response). Black filled cells indicate species which were not covered by that particular study. Where given, estimated rates are either those reported in the study concerned or, derived from published effect sizes.

	Horns Rev (Petersen et al., 2006)	Horns Rev (Petersen et al., 2006)	Nysted (Petersen et al., 2006)	Egmond aan Zee (Krijgsveld et al., 2011)	Horns Rev 2 (Skov et al., 2012)	Egmond aan Zee (Leopold et al., 2013)	Princess Amalia (Leopold et al., 2013)	Alpha Ventus (Mendel et al., 2014)	Robin Rigg (Natural Power, 2014)	Greater Gabbard (APEM Ltd., 2014)	Blighbank (Vanermen et al., 2015)	Alpha Ventus (Welcker and Nehls, 2016)
Northern gannet	D	B (1.00)		B (0.64)	B (0.86)	D	D	NR	NR	D (0.95)	D (0.85)	D (0.92)
Lesser black-backed gull	■	■	■	■	■	D	NR	D	■	■	A (-4.25)	■
Herring gull	A	■	NR	■	■	NR	NR		NR	■	A (-8.4)	A (-1.79)
Great black-backed gull	■	■	■	■	■	NR	NR		NR	■	NR	A (-2.00)
Black-legged kittiwake	■	■	■	■	B (0.69)	NR	D	D	NR	■	NR	NR
Gulls (*Larus spp.)*	■	■	■	B (0.18)	B (0.56)	■	■	■	■	■	■	■

Table 2 Vertical meso-avoidance rates obtained for the five priority species and for birds classified as unidentified gulls from comparisons of the number of birds at rotor height pre- and post-construction, or the number of birds at rotor height inside and outside a wind farm. Values of 0 reflect no increase or decrease in the proportion of birds at rotor height, values >0 reflect a decrease in the proportion of birds at rotor height (avoidance) and values <0 reflect an increase in the proportion of birds at rotor height (attraction).

	Barrow (Barrow Offshore Wind Limited, n.d.)	**Egmond aan Zee** (Krijgsveld et al., 2011)	**Gunfleet Sands 2010/11** (GoBe Consultants Ltd., 2012; NIRAS Consulting, 2011)	**Gunfleet Sands 2011/12** (GoBe Consultants Ltd., 2012; NIRAS Consulting, 2011)	**Robin Rigg** (Natural Power, 2013)
Northern gannet	-0.59	0.49	[redacted]	[redacted]	[redacted]
Black-legged kittiwake	-0.41	0.20	-0.47	0.05	-1.00
Lesser black-backed gull	0.72	attraction	-0.44	0.00	[redacted]
Herring Gull	0.35	No change	-0.02	0.11	-8.00
Great black-backed gull	0.28	avoidance	-0.75	-0.53	-0.67
“small” gulls	[redacted]	-0.26	[redacted]	[redacted]	[redacted]
“large” gulls	[redacted]	no change	[redacted]	[redacted]	[redacted]
Gull *spp.*	-0.85	avoidance	-1.98	-1.13	[redacted]

915 **Table 3** Data sources used to estimate micro-avoidance and within-wind farm avoidance rates for marine species. Rows in bold indicate sites from which
916 data were used to derive within wind farm avoidance rates.

Wind Farm (citation)	Survey Method	N Hours observations	N Turbines Covered	N Birds recorded during point counts	Reported Fatalities (N collisions directly observed)	Behavioural interactions with turbines
Alpha Ventus (Schulz et al., 2014)	Remote Camera	8741	1	241	<1 (0)	Of 14 objects reliably identified as birds, at least 12 had successfully passed through the rotor swept area of the turbine. Whilst collisions were assumed, none were directly recorded by the cameras
Avonmouth (The Landmark Practice, 2013)	**Visual**	**108**	**3**	**5,616**	**1 (0)**	
Blyth (Rothery et al., 2009)	Visual	352	2	8,534	0 (0)	
Blyth Harbour (Newton and Little, 2009)	Visual	93	9	791	1,410-1,838[1] (0)	
Boudwijnkanaal (Everaert, 2014)	**Visual**	**34**	**5-7[2]**	**1,847**	**12 (0)**	
Bouin (Dulac, 2008)	**Visual**	**370**	**8**	**8,243**	**30 (0)**	
De Put (Everaert, 2014)	**Visual**	**18**	**2**	**54**	**2 (0)**	
Egmond aan Zee (Krijgsveld et al., 2011)[3]	Visual		6	1,610	0 (0)	Of 36 birds (2 lesser black-backed gulls, 4 great black-backed gulls, 2 starlings, 28 skylarks) recorded within 50m of a turbine, 33 were recorded as being beyond the reach of the turbine blades
Gneizdzewo (Zielinski et al.,	**Visual**	**620**	**19**	**4,443**	**1 (0)**	

2012, 2011, 2010, 2008)						
Greater Gabbard (RPS, 2011)	Visual	36	7	189	0 (0)	1 kittiwake noted making an evasive manoeuvre to avoid collision, no other birds reported close enough to turbines to require evasive manoeuvres
Groettocht (Krijgsveld et al., 2011)	Radar	39	7	6,825	5 (0)	
Haverigg (RPS, 2011)	Visual	42	8	836	0 (0)	
Hellrigg (Percival, n.d., n.d.)	**Visual**	**74.5**	**4**	**26,638**	**1 (0)**	
Kessingland (Wild Frontier Ecology, 2013)	**Visual**	**36**	**2**	**3,535**	**3 (0)**	**5 black headed gulls, 2 lesser black-backed gulls and 1 herring gull reported taking evasive action within 50m of turbines. No birds observed colliding**
Kleine Pathoweg (Everaert, 2014)	Visual	16	7	672	0 (0)	
Nysted (Desholm, 2005)	Remote Camera	476	1	55	0 (0)	Despite potential to record birds interacting with turbines, no birds were recorded within 20m of a turbine
Oosterbierum (Winkelman, 1992)[3]	**Radar**		**18**	**202,400**	**49 (0)**	
Walney I, Walney II, West of Duddon Sands, Ormonde & Barrow Offshore Wind Farms (Thaxter et al., 2017b)	GPS Tag	2112	270	2	0 (0)	2 lesser black-backed gulls spent 1.2% and 2.7% of their time within a 3-dimensional rotor swept area around turbines, neither collided with the blades
Waterkaaptocht (Krijgsveld et al., 2011)	Radar	39	8	14,430	6 (0)	
Yttre Stengrund (Pettersson, 2005)	Visual	219.5	5	404,146	4 (4)	
Zeebrugge (Everaert, 2014)	**Visual**	**43.7**	**4**	**2,491**	**7 (0)**	

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[1] Extrapolated from mean annual collision rates corrected for corpses lost at sea or undetected by observers. [2] Five turbines covered in 2001, seven turbines in 2005.[3]Total time not stated.

Table 4 Within-wind farm avoidance rates for seabirds

Species	**N birds observed (N collisions recorded)**	**Non-avoidance rate**	**Within-wind farm avoidance rate (± SD)**
Lesser black-backed gull	101,746 (2)	0.0018	0.9982 (±0.0005)
Herring gull	546,047 (9)	0.0041	0.9959 (±0.0006)
Small gull spp.	1,598,953 (42)	0.0079	0.9921 (± 0.0015)
Large gull spp.	639,560 (14)	0.0044	0.9956 (± 0.0004)
Gull spp.	2,567,124 (139)	0.0107	0.9893 (± 0.0008)

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The avoidance rates of collision between birds and offshore turbines

Authors

Aonghais S.C.P. Cook[1], Elizabeth M. Humphreys[2],
Elizabeth A. Masden[3] & Niall H.K. Burton[1]

[1] British Trust for Ornithology, The Nunnery, Thetford, Norfolk IP24 2PU, UK
[2] BTO Scotland, School of Biological Sciences, Stirling University, FK9 4LA
[3] Centre for Energy and the Environment, Environmental Research Institute, North Highland College – University of the Highlands and Islands (UHI), Ormlie Road, Thurso, Caithness, KW14 7EE

Report of work carried out by the British Trust for Ornithology[1]
in collaboration with the Environmental Research Institute[2]
on behalf of the Marine Scotland Science

The British Trust for Ornithology, The Nunnery, Thetford, Norfolk IP24 2PU
Registered Charity No. 216652

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EXECUTIVE SUMMARY

1. The selection of appropriate avoidance rates for use in collision risk models at offshore windfarms is often a key part of the Environmental Impact Assessment process. Ideally, these avoidance rates should reflect the behavioural responses of birds to turbines. However, they are often used as a ‘fudge-factor’ to incorporate aspects of model error. The situation is further complicated by a lack of data for marine birds and offshore windfarms. As a consequence, present guidance is based on values that have been derived for terrestrial species at onshore windfarms. This study reviewed data that have been collected from offshore windfarms and consider how they can be used to derive appropriate avoidance rates for use in the offshore environment. Aims of the study were five-fold:

    - To produce definitions for the types and scales of avoidance;
    - To review current use of avoidance rates;
    - To review and critique existing avoidance behaviour studies and any derived rates;
    - To provide summary avoidance rates and a total avoidance rate for each priority species/species group based on the evidence available at present;
    - To undertake an assessment of the sensitivity of the conclusions reached to inputs and conditions under which they were collected.

    The study focussed on five priority species – northern gannet, black-legged kittiwake, lesser black-backed gull, herring gull and great black-backed gull – whose behaviour and distribution make them particularly prone to collision with offshore turbines.

Definitions (section 3)

2. A key hurdle to defining appropriate avoidance rates for use in the offshore environment has been a lack of clear, agreed definitions of avoidance behaviour. Therefore, the first step of this review was to define the different scales at which avoidance behaviour may occur. Three categories of behaviour were initially defined – macro-, meso- and micro. Micro-avoidance refers to ‘last-second action taken to avoid collision, which is considered to occur within 10 m of the turbine rotor blades. Meso-responses reflect all responses to individual turbines occurring between the base of each turbine and the windfarm perimeter (defined as 500 m from the base of the outermost turbines). Macro-responses reflect all behavioural responses to the presence of the windfarm that occur at distances greater than 500 m from the base of the outermost turbines. Avoidance rates are typically derived by comparing observed collision rates to the number of collisions that would be expected in the absence of avoidance behaviour, considering all bird movements within the perimeter of the windfarm. Consequently, calculations do not usually consider whether any avoidance action takes place at the meso- or micro-scale. It was thus also necessary to consider a fourth category, within-windfarm avoidance, which combines micro-avoidance and meso-responses.

Current use of avoidance rates (section 4)

3. The avoidance rates used with collision risk models have shown substantial variation over time. Initially, very high values, often based on incorrect interpretations of data, were used. Since the earliest environmental impact assessments, there has been a broad tendency to follow standard guidance with avoidance rates of 0.95 and more recently, 0.98 used. However, in light of recent evidence from both on- and offshore windfarms these values are coming under increasing scrutiny from developers and their consultants.

Macro-responses (section 5.1)

4. As with micro-avoidance and meso-responses, the evidence for macro-responses to the presence of a windfarm was typically inconsistent for gulls. Studies designed to look at potential displacement effects reported both evidence for attraction and for displacement and others no significant response at the limited number of sites which were available for consideration. Thus, for gulls, the balance of evidence suggests a macro-response of 0 (i.e. no attraction to or avoidance of the windfarm). However, the response of northern gannet to the presence of windfarms appeared to be more consistent, with strong avoidance evident at several sites, although again it was not always clear whether the macro-response was a result of barrier effects or displacement. Based on the evidence currently available, it is suggested that a macro-response rate of 0.64 is a suitable precautionary value for northern gannet.

Micro-avoidance (section 5.2) and meso-responses (section 5.3)

5. Data for micro-avoidance and meso-responses were extremely limited. No clear and consistent patterns were evident for any of our five priority species. For this reason, it was not possible to derive micro-avoidance or meso-response rates for these species.

Within-windfarm avoidance (section 5.4)

6. A total of 20 sites were identified as having sufficient data to derive within-windfarm avoidance rates by comparing observed collision rates to those expected in the absence of avoidance behaviour. Of these, nine were considered to have data of sufficient quality to estimate robust within-windfarm avoidance rates to be calculated using the Band (2012) collision risk model. Within-windfarm avoidance rates were derived for use with both the basic Band model (Options 1 and 2), that assumes that birds are distributed evenly within the rotor-swept area of a turbine, and with the extended Band Model (option 3) that uses a continuous flight height distribution to estimate collision risk at different points within the turbines rotor-swept area. Based on these data within-windfarm avoidance rates of 0.9959 (± 0.0006 SD) and 0.9908 (± 0.0012 SD) were derived for herring gull for use with the basic Band model and extended Band model respectively. Similarly, within-windfarm avoidance rates of 0.9956 (± 0.0004 SD) and 0.9898 (± 0.0009 SD) were derived for large gulls for use with the basic Band model and extended Band

model respectively, and rates of 0.9921 (± 0.0015 SD) and 0.9027 (± 0.0068 SD) derived for small gulls also for use with the basic Band model and extended Band model respectively. Within-windfarm avoidance rates of 0.9893 (± 0.0007 SD) for the basic Band model and 0.9672 (± 0.0040 SD) for the extended Band model were derived for all gulls. Insufficient data were available to calculate a within-windfarm avoidance rate for northern gannet. (Note, where we report the standard deviation around the derived within windfarm avoidance rates, this relates variability between sites and not to uncertainty in the model input parameters. Estimating the contribution of the model input parameters to the uncertainty associated with the derived avoidance rates requires a more detailed understanding of the real range of values associated with each parameter than is available currently.)

Sensitivity of derived within-windfarm avoidance rates (section 6)

7. The sensitivity of within-windfarm avoidance rate values to model input parameters was also assessed and it was found that the final derived values were most sensitive to assumptions about the proportion of birds at collision risk height. However, it was also found that sensitivity to input parameters declined as the number of flights through a windfarm increased.

Recommended total avoidance rates (section 7)

8. Whilst we have estimated within-windfarm avoidance rates to four decimal places, current guidance from SNH is that expressing avoidance rates to more than three decimal places is unwarranted (SNH 2013). Given the inherent uncertainty in the data we feel that this is a sensible approach to apply to total avoidance rates. For this reason, we round within-windfarm avoidance rates down to three decimal places when deriving recommended total avoidance rates. For gulls the balance of evidence suggests a macro-response of 0 (i.e. no consistent attraction to or avoidance of the windfarm). Consequently, the recommended total avoidance rates for these species are equal to the within-windfarm avoidance rates. Therefore, avoidance rates of 0.995 for herring gull, lesser black-backed gull and great black-backed gull and 0.992 for black-legged kittiwake are recommended for use with the basic Band model. Based on the evidence available, it is suggested that the total avoidance rate for northern gannet is unlikely to be lower than that for all gulls. Assuming a macro-avoidance rate of 0.64, this would reflect a within windfarm avoidance rate of 0.9703. We acknowledge that this is precautionary, but in the absence of more species-specific data, we feel it is appropriate. Hence, an avoidance rate of 0.989 for northern gannet is recommended when using the basic Band model. For the extended Band model, avoidance rates of 0.990 for herring gull and 0.989 for lesser black-backed gull and great black-backed gull were recommended. Based on the evidence available at present, it was not possible to recommend an avoidance rate for use with the extended model for either black-legged kittiwake or northern gannet.

Transferability of avoidance rates between models (section 8)

9. Whilst the basic and extended Band models are the most widely used collision risk models at present, there are a number of alternatives. Based on our assessment of the alternative models which we were able to obtain descriptions of, the definitions and values we present in this report are likely to be broadly applicable to other models.

RECOMMENDATIONS AND LIMITATIONS

Definitions (Section 3)

- **Micro avoidance** should be defined as 'last-second' action taken to avoid collision, occurring within 10 m of the rotor blades.

- **Meso-response** should be defined as all behavioural responses, including attraction, in flight deflection and functional habitat loss, to the presence of a turbine occurring more than 10 m from the rotor blades and within the perimeter of the windfarm (500 m from the base of the outermost turbines).

- **Macro-response** should be defined as all behavioural responses, including attraction, displacement, and barrier effects, to the presence of a windfarm occurring beyond its perimeter (> 500 m from the base of the outermost turbines).

- Where an avoidance rate has been derived by comparing observed collisions to those expected in the absence of avoidance, this should be referred to as **within-windfarm avoidance**, it is a combination of meso-responses and micro-avoidance.

Recommended avoidance rates

- A **macro-avoidance rate of 0.64** is recommended for **northern gannet** (section 5.4). However, no data were available to derive a within-windfarm avoidance rate for this species (section 5.3). Based on the evidence available, there is no reason to suppose that the total avoidance rates for **northern gannet** should be less than those for all gulls. A **total avoidance rate** of **0.989** is thus recommended for use with the basic Band (2012) collision risk model. This would reflect a within windfarm avoidance rate of 0.970. We acknowledge that this is precautionary, but in the absence of more species-specific data, we feel it is appropriate. It was not possible to recommend an avoidance rate for use with the extended Band (2012) collision risk model based on the evidence available at present.

- No consistent evidence of macro-avoidance was found for **black-legged kittiwake** (section 5.4). As it was not possible to derive species-specific within-windfarm avoidance rates for **black-legged kittiwake**, the within-windfarm rates derived for the small gulls group were considered appropriate for use for this species (section 5.3). A **total avoidance rate** of **0.992** is thus recommended for the basic Band model. It was not possible to recommend an avoidance rate for use with the extended Band (2012) collision risk model based on the evidence available at present.

- No consistent evidence of macro-avoidance was found for **lesser black-backed gull** (section 5.4). Whilst it was possible to derive species-specific within-windfarm avoidance rates for lesser black-backed gull, these were based on limited data and thus the within-windfarm avoidance rates for large gulls were considered more appropriate for use for this species (section 5.3). A **total avoidance rate** of **0.995** is thus recommended for use with the basic Band model and a **total avoidance rate** of **0.989** for use with the extended Band model (section 7).

- No consistent evidence of macro-avoidance was found for **herring gull** (section 5.4) and thus total avoidance rates reflect species-specific within-windfarm avoidance rates. A species-specific **total avoidance rate** of **0.995** is thus recommended for use with the basic Band model and a **total avoidance rate** of **0.990** for use with the extended Band model (section 7).

- No consistent evidence of macro-avoidance was found for **great black-backed gull** (section 5.4). As it was not possible to derive species-specific within-windfarm avoidance rates for **great black-backed gull**, the within-windfarm rates derived for the large gulls group were considered appropriate for use for this species (section 5.3). A **total avoidance rate** of **0.995** is thus recommended for the basic Band model and a **total avoidance rate** of **0.989** for use with the extended Band model (section 7).

- Given the multiple ways in which data can be interpreted, it is vital that future studies in which avoidance rates are derived are completely transparent and present their workings as a step-by-step process. Appendix 7 enables the reader to go back to the original source material and fully understand how the values presented in this report have been derived. This also offers an indication of the uncertainty present in the derived values.

- Based on the available data, it was not possible to derive species-specific avoidance rates for three of the five priority species. Of particular concern is the lack of within-windfarm avoidance data for northern gannet given that it is taxonomically distinct from the other four species, all of which are gulls. Future projects should focus on collecting data for northern gannet as a priority. Given the limitations in the data we identified for macro-responses, especially for gulls, there is also a need to collect further data on barrier effects and displacement/attraction rates.

1. INTRODUCTION

The Scottish Government has a target for 100% of Scottish demand for electricity to be met from renewables by 2020 by creating a portfolio of both onshore and offshore technologies (Marine Scotland 2011). However, concern over the environmental impacts of these developments in the UK, and in particular the risk of birds colliding with wind turbines, has contributed to the delay and cancellation of some projects. In order to quantify the risk of birds colliding with wind turbines, a number of collision risk models have been developed (Band 2012, Smales *et al*. 2013). These include an update to the Scottish Natural Heritage (SNH) collision risk model, originally developed for onshore windfarms (Band 2000, Band *et al.* 2007), redeveloped to better reflect data collected in relation to impact assessments for offshore windfarms (Band 2012). This work was undertaken as part of one of the projects undertaken through the Strategic Ornithological Support Service (SOSS) programme, a joint initiative involving industry, statutory nature conservation bodies (SNCBs) and the RSPB. These models combine a series of parameters describing the turbine design and operation with estimates of a bird's size and behaviour in order to predict the number of birds that would be expected to collide with a turbine over a given time period. Of these parameters, detailed analysis has suggested that these models are highly sensitive to variation in the avoidance rate, the proportion of birds which take action to avoid colliding with a turbine (Chamberlain *et al.* 2005, 2006). Despite this, there has been relatively little empirical evidence put forward to support avoidance rates for offshore windfarms, which are likely to vary according to species and weather conditions, in particular visibility.

Whilst avoidance rates can be determined from observed mortality rates or actual observations of birds' behaviour, defining robust values for use in collision risk modelling can be extremely challenging. However, there are concerns that avoidance rates derived from observed mortality rates may act as a 'fudge-factor', incorporating observer biases and model error, as opposed to the actual behaviour of the birds (May *et al.* 2010, Douglas *et al.* 2012). Current guidance from SNH (2010) is that, in the absence of species-specific empirical data, a default avoidance rate of 0.98 should be used for most species in onshore windfarm assessments and this value has been widely used in the offshore environment as well. However, in light of recent evidence (e.g. Everaert & Stienen 2007, Krijgsveld *et al.* 2011) the validity of this approach has been questioned and concerns have been raised by developers that it will lead to an over-estimate of the likely number of collisions (Moray Offshore Renewables Limited 2012, Trinder 2012, Smartwind/Forewind 2013) and, as a consequence, potentially contribute to the delay and cancellation of key projects. In a policy environment where there is limited evidence on which to base decisions it is important to reflect uncertainty, but not to apply unrealistic levels of precaution which will make it difficult to reach informed decisions about where and where not to build windfarms.

There is a strong need for a consensus on the appropriateness of recommended avoidance rate values given the influence they have on collision estimates and, therefore, consenting decisions. However, at present, there is a lack of clarity over the interpretation of studies of avoidance behaviour and the applicability of the resultant avoidance rates to different collision risk models, study sites and species. As a result, details presented in reviews of avoidance behaviour of birds in the marine environment (e.g. Maclean *et al.* 2009, Cook *et al.* 2012) have been subject to confusion. A key reason for this is the lack of consistency in the terminology applied to different spatial scales of avoidance, and the widely varying interpretation of the types of avoidance behaviour occurring. There is therefore, an urgent need for a review of avoidance behaviour in offshore windfarms in order to provide a clear appraisal of the existing evidence base, provide a robust critique of the data available with which to refine recommendations on avoidance rates and offer clear guidance as to how they should be used in future collision risk modelling scenarios. Whilst the focus of this review will be on collision risk modelling and species relevant to the UK context, it will draw on evidence from Europe and beyond.

This work aims to reduce the current level of uncertainty around appropriate avoidance rates for seabird species within collision risk modelling by providing a thorough review of the existing evidence base. The scope of this review is broader than those previously undertaken (e.g. Cook *et al.* 2012) and includes quantitative and qualitative analyses of the data identified with a view to identifying representative avoidance rates for five priority species – northern gannet, black-legged kittiwake, lesser black-backed gull, herring gull and great black-backed gull. The review identifies current knowledge gaps and aims to ensure that future strategic work is targeted at addressing the most appropriate issues. Due to the sensitivity of the work and the importance of its conclusions, the work has been overseen by a steering group of key stakeholders and experts, with a view to gaining widespread acceptance of its conclusions.

2. OBJECTIVES

2.1 Produce definitions for the types and scales of avoidance rates that will be used throughout the review document

It is important to make a distinction between avoidance rates, as used in collision risk models, and avoidance behaviour. Avoidance behaviour refers specifically to the behavioural response of birds to wind turbines. However, at present, in addition to accounting for avoidance behaviour, avoidance rates are often used as a ‘fudge-factor’ to account for error in the model itself and in its input parameters (see May *et al.* 2010, Douglas *et al.* 2012). Whilst SOSS guidance (Band 2012) sets out how these uncertainties should be accounted for in the collision risk modelling process, in practice, this is rarely done. The purpose of this review is to identify suitable avoidance rates for use in collision risk models; these rates will be informed, where appropriate, by recorded estimates of avoidance behaviour.

A lack of clear, working definitions for different avoidance rates has hampered attempts to come up with standardised measures. Present definitions of avoidance rates rely on an ability to collect empirical data with which to compare predicted and observed collision rates (SNH 2010). As this is impractical for the offshore environment, Band (2012) proposes combining estimates of micro- (or near-field) avoidance, where a bird takes action to avoid collision at a point close to the turbine, and macro- (or far-field) avoidance, where a bird takes action to avoid collision at a point distant from the turbine, to generate an estimate of total avoidance. However, the empirical data underpinning such definitions is currently inconsistent and difficult to interpret.

A key problem is often the lack of detail over what spatial scale data have been collected at. For example, radar monitoring has shown that birds may take action to avoid entering a windfarm at distances of up to 6 km (Christensen *et al.* 2004), far further than could be observed by eye. As a result, by relying on visual observations, avoidance rates may be under-estimated as a significant proportion of birds will have taken action to avoid the windfarm before they are visible. Similarly, at present, it is not possible to identify birds to species level on the basis of radar echoes; consequently, by relying on radar, it will not be possible to derive species-specific avoidance rates. This is further complicated by evidence that avoidance can occur in a three-dimensional space, with horizontal avoidance, where a bird alters its heading to avoid collision, and vertical avoidance, where a bird alters its altitude to avoid collision (Krijgsveld *et al.* 2011, Plonczkier & Simms 2012). Such alterations may be relatively subtle and difficult to detect by eye. Where radar is utilised to monitor movements in response to turbines, it requires the use of both horizontal and vertical radar. Evidence describing three-dimensional avoidance behaviour, if it exists, is likely to be extremely limited. In defining different avoidance behaviours, the review therefore gives careful consideration to the methodologies used to collect the necessary data.

Wind turbines are most typically in the order of seven rotor diameters apart (Meyers & Meneveau 2012), based on existing turbine designs, this may vary from 480 m to 1.5 km, depending on the capacity used. Given the variable distances between turbines and the difficulties in obtaining consistent estimates of avoidance behaviour over the relevant spatial scales, the review considers whether it is possible to define micro-and macro-avoidance with reference to distance to turbines, or whether a more pragmatic approach, basing definitions on whether a bird is inside or outside a windfarm would be more appropriate. The review considers whether these definitions are appropriate to all species and groups, or whether a more flexible approach is necessary. This may depend on what evidence is available for different species. For example, avoidance rates for terns have often been derived from observed collision rates (Everaert 2008), whilst for other species, such as northern gannets, avoidance rates may be more reliant on radar data (Krijgsveld *et al.* 2011). The review then considers evidence for avoidance behaviour occurring over horizontal and vertical planes.

The review provides clear and concise definitions for micro-horizontal avoidance, micro-vertical avoidance, macro-horizontal avoidance and macro-vertical avoidance. Definitions are produced based on the behaviour of the birds as opposed to the requirements of a model and offer guidance about how final values can be adapted for use in different models.

Defining the different forms of avoidance behaviour represents a major step forward in collision risk modelling. These definitions are central to the rest of the project, and, as such, have been agreed through discussion with the project steering group of key stakeholders and experts.

2.2 Review the current use of avoidance rates

In order to provide context to this work, it is important to consider how avoidance rates are currently used. With this in mind, the review considers published EIAs and identifies what avoidance rates have been used within the collision risk modelling process and what justifications have been put forward for their selection. This will help us determine how consistently existing guidance has been interpreted and applied, and help refine future guidance in order to minimise discrepancies in its application.

2.3 Review and critique existing avoidance behaviour studies and any derived rates

Avoidance rates have been derived from both observed mortality rates and actual observations of birds' behaviour (Cook *et al.* 2012, Trinder 2012, Moray Offshore Renewables Limited 2012, Smartwind/Forewind 2013, Everaert 2014). In Belgium, at Zeebrugge port breakwater, onshore collision rates in terns and gulls have been used to derive avoidance rates based on recorded movement patterns and assumptions about turbine design (Everaert & Stienen 2007 Moray Offshore Renewables Ltd. 2012, Everaert 2014). However, the difficulties in directly recording collisions in the marine environment mean that studies of avoidance at offshore windfarms have relied on observing behaviour (Desholm *et al.* 2006, Blew *et al.* 2008, Krijgsveld *et al.* 2011). These studies have varied both in the species they have investigated, and also in the potential form of avoidance behaviour reported.

Recognising that appropriate data may be extremely limited, we initially take a broad approach to our review, reviewing evidence for avoidance behaviour in marine birds generally. We demonstrate how this evidence relates to the definitions set out in the previous section of the report. Having done this, we assess whether sufficient evidence exists to draw conclusions about avoidance behaviour in five priority species – northern gannet, black-legged kittiwake, lesser black-backed gull, herring gull and great black-backed gull. If this is not possible, we will consider how to combine evidence within groups of species, on the basis of the ecology of the species concerned. Where this is necessary, we clearly state which species are in each group.

In order to make an assessment of the level of confidence in the reported avoidance rates for each species or species group, we make a detailed qualitative critique of each study. Key questions include:

i. How have avoidance rates been derived?

We consider first whether the avoidance rates reported have been determined from observed mortality rates or actual observations of birds' behaviour. The data collection methods used are summarised, and the limitations of each method discussed. Where avoidance rates have been back-calculated from observed collisions at reference windfarms, they may incorporate error associated with model input parameters including population estimates, flight heights and turbine operational characteristics in addition to the actual avoidance behaviour of the birds. In contrast, direct observations of birds' behaviour in relation to turbines will not incorporate model error. However, these observations may still need careful interpretation given methodological constraints over how data may be collected, for example, the distances over which birds can be observed in comparison to the distances over which they may take avoidance action.

ii. How comparable are the different datasets?

Avoidance rates based on behaviour have typically been derived from a series of visual or radar observations (Desholm & Kahlert 2005, Blew *et al.* 2008), or through a combination of both (Krijgsveld *et al.* 2011, Plonczkier & Simms 2012). The range of distances over which data can be collected varies markedly between these platforms (Cook *et al.* 2012) and it is important to consider whether estimates – particularly of macro-avoidance – are comparable between different studies.

It is also important to consider how and when data have been collected. For example, visual observations from land, or an offshore platform, may differ from those obtained during a boat-based survey, where the movement of the boat may mean that surveyors have a less stable platform or because birds may exhibit a behavioural response to the presence of a boat (although following standard guidance should help to minimise the influence of these factors: Camphuysen *et al.* 2004). Visibility may also strongly influence results from visual observations. Seasonality may influence the results from both radar and visual observations as foraging birds may respond very differently to migrating birds (Blew *et al.* 2008, Krijgsveld *et al.* 2011). This may be particularly important for radar studies, where it is not possible to identify radar echoes to species level and, as a result, it is more difficult to separate observations of migrants from those of local, foraging birds during periods of passage.

iii. Are reported avoidance rates affected by any special factors?

The location of the windfarm may have a strong impact on reported collision rates. If these collision rates are then used to calculate avoidance rates, it may lead to an erroneous assessment of avoidance behaviour. For example, a Belgian study has reported collision rates at a windfarm in Zeebrugge for terns (Everaert & Stienen 2007). The results from this study have been widely used to calculate micro-avoidance rates for terns (e.g. Whitfield 2008). However, as this windfarm was located on a seawall, next to a breeding tern colony, it is unclear whether behaviour around the turbines would be consistent with that of foraging terns, further out to sea. In addition, the size of turbines planned for offshore windfarms is significantly greater than those installed at many of the sites for which collision data are available. For this reason, we will consider whether there is any evidence for a relationship between turbine size and the avoidance rates derived from mortality data.

2.4 Provide summary avoidance rates and a total avoidance rate for each priority species/species group based on the evidence available at present

Based on the information compiled from the above review, we derive avoidance rates based on published evidence for each of the five priority species – northern gannet, black-legged kittiwake, lesser black-backed gull, herring gull and great black-backed gull, and other species as relevant. Where necessary, this involved going back to the source material of the studies concerned and back-calculating avoidance rates following the methodology set out by Band (2000). Where insufficient data were available to make recommendations for individual species, we combine estimates within species groups, based on the ecologies of the species concerned. Based on our critique of the studies from our review we then indicate where our confidence in each reported value is affected by the quality of the data it is based on.

Where possible, we combine avoidance rates collected at different scales, in order to calculate a total avoidance rate for each species. Estimates of micro-avoidance and macro-response can be combined to give an overall avoidance rate following equation 1, if sufficient data are available, we will extend this equation to include horizontal and vertical avoidance, as detailed in equations 2 and 3. Given the limited evidence available, it may be necessary to draw in data from closely related species and derive avoidance rates based on a group, rather than species-specific basis. Where this is necessary, we will clearly state what we have done and indicate our confidence in the derived rate accordingly.

$$A_{rate} = 1 - [(1 - A_{micro}) \times (1 - A_{macro})] \text{ [Eq. 1]}$$
$$A_{micro-} = 1 - [(1 - Mi_{horiz}) \times (1 - Mi_{vert})] \text{ [Eq. 2]}$$
$$A_{macro-} = 1 - [(1 - Ma_{horiz}) \times (1 - Ma_{vert})] \text{ [Eq. 3]}$$

Where A_{rate} *is the total avoidance rate,* A_{micro-} *is the micro-avoidance rate,* A_{macro-} *is the macro-avoidance rate,* Mi_{horiz} *is the micro-horizontal avoidance rate,* Mi_{vert} *is the micro-vertical avoidance rate,* Ma_{horiz} *is the macro-horizontal avoidance rate and* Ma_{vert} *is the macro-vertical avoidance rate. Note that the ability to combine horizontal* *and vertical movements in this way will depend on how data have been collected. It is likely that some birds will make horizontal and vertical movements concurrently, and therefore, it would not be appropriate to combine data in this way.*

This summary is used as the basis for a gap analysis based on our earlier definitions of avoidance behaviour. In combination with the above critique of avoidance rate studies, this gap analysis will help provide a target and possible methodologies for future research on avoidance behaviour of birds in relation to offshore windfarms, for example the Offshore Renewables Joint Industry Project (ORJIP), due to get underway in summer 2014 (Davies *et al.* 2013).

2.5 Undertake an assessment of the sensitivity of the conclusions reached to inputs and conditions under which they were collected

The final avoidance rates are likely to be sensitive to both factors which are directly parameterised within the collision risk model, such as species' flight heights, turbines' operational time and rotation speed, those parameterised in collecting collision data such as corpse collection, and also those which are not directly parameterised, such as seasonality, weather conditions and whether data have been collected during the day or night. Whether estimates of avoidance behaviour have been derived from behavioural observations or recorded collision rates, they are likely to be influenced by the factors which are not directly parameterised. For this reason, we assess how such variables are likely to have influenced the final avoidance rate in each study. For example, avoidance rates based on data only collected during conditions with better than average visibility may be expected to differ from those based on data collected during periods of poor visibility, a potential source of model error. Where avoidance rates have been derived from collision data, there is the also potential for the model input parameters to influence the final values.

These methodologies have typically been restricted to turbines at onshore locations (Everaert & Stienen 2007), where corpse collection is practical. There are concerns that this may lead to an over-estimate of the avoidance rate as some corpses go undetected and correction factors to account for this (Winkelmann 1992, Bernardino *et al.* 2013) may not be correctly applied. With this in mind, we focus on the best quality studies, but also consider how undetected corpses may influence the avoidance rate we derive.

Where a collision rate is available for a site, the avoidance rate (A_{rate}) can be calculated as follows:

$$C_{pred} = (\text{Flux rate} * P_{coll}) + \text{error} \qquad \text{[eq. 4]}$$
$$A_{rate} = 1 - (C_{obs}/C_{pred}) \qquad \text{[eq. 5]}$$

Where C_{pred} is the predicted number of collisions in the absence of avoidance action, C_{obs} is the observed number of collisions, flux rate is the total number of birds passing through the rotor swept area and P_{coll} is the probability of a bird colliding with a turbine. The probability of collision, P_{coll} can be calculated following the formula set out in Band (2012). However, this highlights a second area where the conclusions about avoidance rates may be sensitive to the inputs as values of P_{coll} will be specific to the design of turbines (Cook *et al.* 2011). Consequently, knowledge of rotor speed, radius, chord width and pitch, for the turbine concerned, are required before estimating an avoidance rate from a collision rate. These characteristics can vary considerably, even between turbines of a similar generating capacity (http://www.4coffshore.com). As a result, error is likely to be introduced into the calculation through inaccuracies in estimates of the flux rate and also through inaccuracies in the estimation of P_{coll}.

As detailed in Cook *et al.* (2012), failing to account for turbine design correctly when deriving avoidance rates as described above can lead to erroneous estimates of P_{coll} and, therefore, the avoidance rate. For this reason, where a study reports a collision rate, rather than an avoidance rate, we have attempted to obtain data on these parameters. Where we are unable to obtain this information, we calculate a value of P_{coll} based on the parameters from a range of turbines of a similar size. We then consider whether avoidance rates derived from collision estimates are more sensitive to variation in turbine design or to correction factors that account for failure to detect corpses.

2.6 Applicability of avoidance rates to different collision risk models

We finally consider how the total avoidance rate, and its constituent elements, reflect the values necessary for collision risk modelling. At present, the collision risk model formulated by Band (2012) for use in the offshore environment has three different options which can be used to estimate the total number of birds at risk of collision. These options reflect different ways in which estimates of the proportion of birds at collision risk height can be incorporated into the collision risk modelling process. Band model option 1 assumes that birds are distributed evenly within the rotor-swept area of a turbine. It bases estimates of the proportion of birds at risk of collision on data collected during pre-construction surveys of the site in question. Band model option 2 is mathematically identical to the first option, also assuming an even distribution of birds within the rotor-swept area of the turbine. However, the proportion of birds at collision risk height is estimated from continuous distributions derived from data collected across multiple sites (Cook *et al.* 2012, Johnston *et al.* 2014a,b). Options 1 and 2 of the Band model are collectively referred to as the basic model. In practice, birds are unlikely to be evenly distributed across the rotor-swept area of a turbine (Johnston *et al.* 2014a). Band model option 3, often referred to as the extended Band model, accounts for this by using a continuous flight height distribution to estimate collision risk at different points within the turbines rotor-swept area.

As birds are typically clustered to the lower edges of the rotor-swept area (Johnston *et al.* 2014a), option 3 often results in lower estimates of collision rates. As a consequence, there is intense interest in its use within EIAs for offshore windfarms. However, avoidance rates currently in use that are derived for the onshore environment by combining collision rates with estimates of P_{coll} from the basic Band model are not suitable for use in the extended model, as accounting for a heterogeneous flight height distribution will result in a lower number of collisions predicted in the absence of avoidance. (Although, note that this difference may be partially offset as avoidance rates derived in this way do not account for changes in flight altitude in response to the presence of a windfarm.) As a result estimates of avoidance behaviour based on the basic model are likely to be higher than is appropriate for the extended model (equations 4 and 5) – this is considered as part of the review.

Where estimates of avoidance rates have been derived from behavioural observations, for example displacement from offshore windfarms, rather than recorded collision rates, the applicability to different models is less clear. We consider how our final avoidance rates have been derived and what implications this has for how they are incorporated in collision risk models.

We also offer guidance not just on the applicability of avoidance rates to the basic and extended Band models, but also their transferability of avoidance rates to alternatives including the Biosis model (Smales *et al.* 2013).

The data necessary to derive avoidance rates suitable for use with option 3 of the Band model following the formula given by equation 6 are often unavailable. However, a suitable avoidance rate can be derived by estimating the ratio of P_{coll} from option 2 of the Band model to P_{coll} from option 3 of the Band model and applying this to the inverse of the avoidance rate used for option 1. For the rationale and a full description of this approach see the supplement to the guidance on ‘Using a collision risk model to assess bird collision risks for offshore windfarms’ (Band 2012) provided by Bill Band as Annex 1 to this report.

3. DEFINITIONS OF AVOIDANCE BEHAVIOUR

3.1 Introduction

Chamberlain *et al.* (2005, 2006) demonstrated that, of the parameters used in the Band collision model (Band 2006), the avoidance rate used was among those that the predicted collision rates were most sensitive to. Subsequently, the identification of appropriate avoidance rates has been subject to widespread debate. Guidance produced by Scottish Natural Heritage (SNH 2010) has been largely accepted in the UK for the terrestrial environment, subject to revision as additional data become available (e.g. Pendlebury 2006). Whilst this document references some seabird species, its guidance for offshore windfarms is limited to the suggestion that a range of avoidance rates should be presented. Country agencies have provided advice to developers as necessary, but the lack of guidance produced specifically for the offshore environment, and for the updated Band model for use in the offshore environment (Band 2012), has led to uncertainty amongst developers, regulators and other stakeholders as to what values reflect realistic avoidance rates (e.g. MacArthur Green 2012, MORL 2012) and for which collision risk models they are appropriate. Previous studies have attempted to review avoidance behaviour in offshore species (e.g. Maclean *et al.* 2009, Cook *et al.* 2012) but a failure to gain widespread consensus about the values presented has meant the situation remains largely unresolved.

Deriving avoidance rates for terrestrial windfarm developments has been based largely on the ability to estimate the numbers of birds killed by collisions. Every bird flying through the rotor-swept area of a turbine has a probability of colliding with the turbine blades (P_{coll}), typically in the range of 5-10% for seabirds, depending on species and the design of the turbine concerned (Cook *et al.* 2011). By multiplying the total number of birds expected to pass through the rotor-swept area of a turbine by P_{coll} it is possible to predict the number of collisions that would be expected, should birds take no action to avoid collision. In the case of terrestrial windfarms estimates of the total number of collisions actually occurring, once turbines are operational, can be made by using corpse searches around the windfarm to assess actual mortality rates, or observed collision rates[1]. Band (2000) therefore suggests that the avoidance rate can be thought of as equation 6, where the collision rate expected in the absence of avoidance is the total number of birds (Flux rate) passing through the rotor-swept area of a turbine, multiplied by P_{coll}. However, in practice both P_{coll} and the flux rate are likely to be subject to error – P_{coll} in relation to the model input parameters and flux rate in relation to estimates of the total number of birds passing through the windfarm. Of the two, the error associated with the flux rate is likely to be greatest as a result of the difficulty in recording the number of birds passing through a site over an extended period of time and the need to extrapolate from, often brief, observation periods to estimate a flux rate for the study period as a whole. As a result of the need to incorporate this error, it may be better to think of this in terms of an avoidance correction factor, as opposed to an avoidance rate, which implies it is solely dependent on the behavioural responses of birds:

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[1] Subject to some carcass recovery factor (i.e. the potential to miss carcasses, removal by predators, etc.).

$$Avoidance = 1 - \frac{Observed\ collision\ rate}{Pcoll \times Flux\ Rate} \quad \text{(eq. 6)}$$

However, in the case of offshore windfarms, recording actual collisions, or mortality rates, is not currently practical, although the forthcoming Offshore Renewables Joint Industry Project (ORJIP) will aim to provide additional data to inform avoidance rates using behavioural observations (Davies *et al.* 2013). Therefore, at present, guidance on appropriate avoidance rates for use in the offshore environment draws on the experiences gained in the terrestrial environment, as well as being informed by studies of bird movements, where suitable data are available (e.g. Desholm & Kahlert 2005, Petersen *et al.* 2006, Masden *et al.* 2009, Blew *et al.* 2008, Krijgsveld *et al.* 2011). Where studies have sought to use movement data to inform values for avoidance rates, this has often led to confusion due to uncertainty over the spatial scales involved. Birds have been shown to alter their flight paths in order to avoid entering an offshore windfarm at distances of up to 6 km (Christensen *et al.* 2004). As a result, where avoidance rates have been derived from human observations they may represent a substantial under-estimate of total avoidance, as many birds will have taken action to avoid the windfarm before they become visible to observers. The difficulties caused in attempting to draw firm conclusions from such disparate data sources has led to a variety of terms being used to sub-divide avoidance behaviour at different spatial scales.

At a simple level, Cook *et al.* (2012) and Band (2012) suggest that the total avoidance rate for an offshore windfarm could be considered as (eq. 7):

$$Total\ Avoidance = 1 - (\ 1 - Macro \quad \times \quad 1 - Micro\ ) \quad \text{(eq. 7)}$$

We use this definition as the basis for discussion relating to the different types of avoidance that need to be quantified in order to derive an estimate of total avoidance, and extend it to incorporate meso-avoidance (eq. 8), as defined below.

$$Total\ Avoidance = 1 - (\ 1 - Macro \quad \times \quad 1 - Meso \quad \times \quad 1 - Micro\ ) \quad \text{(eq. 8)}$$

3.2 Defining appropriate spatial scales of avoidance

This section aims to define appropriate spatial scales of avoidance; for detailed review of the evidence for avoidance at these defined scales, see section 5.

A bird may respond to a fixed object, such as a turbine, at any point between the time at which it first observes the object and the time at which it passes or collides with the object, or based on previous experiences of the site. As such, attempts to subdivide avoidance behaviour with reference to spatial scale are largely arbitrary and the different behaviours should be seen as part of a continuum. Nevertheless, such divisions are necessary given the spatial scales over which these behaviours can be recorded. Band (2012) focusses on macro- and micro- avoidance, with a third category, meso-avoidance, fitting in the gap between the two also suggested (Pendlebury, *pers. comm.*). We consider these scales in turn, with each reflecting an increasing distance between the bird and the turbine blades (Figure 3.1). However, the distances over which these categories of behaviour occur are more difficult to define.

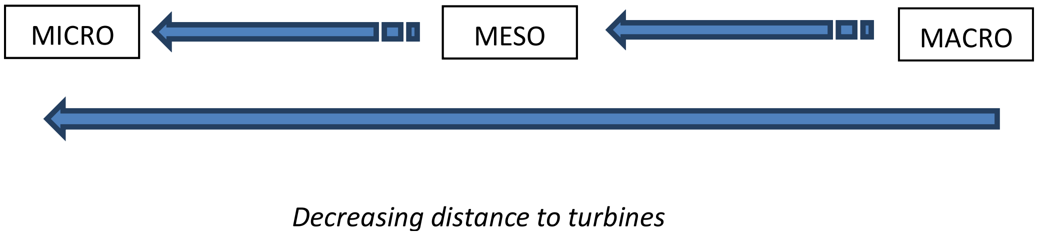


Figure 3.1 Spatial scales over which avian responses to turbines have been recorded

It is also necessary to consider how avoidance rates are applied within the collision risk modelling framework. Expected collision rates (as per eq. 7) are typically derived using estimates of the numbers of birds flying through the windfarm area prior to construction. Therefore, overall avoidance rates need to account for birds no longer entering the windfarm area post-construction (i.e. birds exhibiting displacement and barrier effects) in addition to avoidance of the turbines themselves. As a result, it is necessary to consider how other effects, such as displacement and barrier effects, may contribute to the overall avoidance rates, as part of macro-avoidance.

We consider how each of these scales may be used to inform collision risk modelling below:

Macro- Band (2012) gives the example of displacement as one impact which may contribute to macro-avoidance. Displacement is typically assessed by comparing numbers of birds in the area of the windfarm to those recorded in a baseline period. However, difficulties in quantifying displacement rates – numbers may vary for many reasons in addition to the development of the windfarm, and it is important that this is considered in an appropriate survey design, for example using a BACI-approach (Masden *et al.* 2010) – mean that interpreting these data must be undertaken with caution and careful consideration of the survey design (Maclean *et al.* 2013). Furthermore, published displacement rates can refer to the numbers of birds displaced from the windfarm plus a significant (species-dependent) buffer distance around the windfarm. Consideration must also be given as to whether displacement rates reflect all birds within the windfarm area and buffer, or just those on the water. As collision risk modelling relates only to birds in flight, if displacement rates refer only to birds on the water, they may not reflect macro-avoidance. Relying solely on displacement, as often reported in Environmental Impact Assessments, may therefore underestimate the true scale of macro-avoidance because 1) estimates may not account for birds in flight; and 2) estimates do not account for birds that are displaced from the windfarm area, but remain within the buffer surrounding the windfarm.

In addition to measuring displacement rates, a number of offshore windfarm post construction monitoring studies have used radar to assess the proportion of birds which enter a windfarm area (e.g. Petterson 2005, Petersen 2006, Krijgsveld *et al.*

2011). The potential for windfarms to act as a barrier to birds in this way has been widely discussed, mostly in the context of migrants (e.g. Desholm & Kahlert 2005, Masden *et al.* 2009), although it may also be of relevance to seabirds commuting between breeding colonies and feeding areas – an area of study that needs addressing with some urgency. Such studies would illustrate changes in flight trajectory amongst birds approaching windfarms and would help to determine the spatial scale over which such responses may occur.

In addition to displacement and the windfarm acting as a barrier, several studies have suggested that some species, notably gulls and cormorants, may be attracted to the area of offshore windfarms (e.g. Lindeboom *et al.* 2011, Leopold *et al.* 2011). The macro-avoidance rate needs to capture the change in bird numbers within the windfarm area resulting from the development of the windfarm site. Consequently, the term 'macro-avoidance', may lead to confusion as, conceptually, the idea of a negative macro-avoidance rate (i.e. birds being attracted to a windfarm) may be difficult to communicate to stakeholders. For this reason, use of the more neutral term, **macro-response**, may be preferable as it implicitly covers both attraction and avoidance (Figure 3.2).

Figure 3.2 Range of proportional responses to the presence of an offshore windfarm as they would be incorporated in eq. 2 (above), i.e. a response of -0.1 would reflect an increase in the number of birds present within the windfarm of 10% in comparison to baseline numbers, whilst a response of 0.1 would reflect a decrease of 10% in comparison to baseline numbers, which are sensitive to survey design due to the extent of year on year variation in seabird abundance.

The macro-response of birds to the presence of a windfarm should be defined as the behavioural response taking place outside the windfarm perimeter. It is important that the perimeter of the windfarm is clearly defined. Definitions could be based on characteristics such as turbine rotor diameter, or the inter-array turbine spacing. However, such definitions would vary between sites in relation to the layout and size of turbines used, meaning values for the macro-response rate would be less directly comparable between sites. For this reason, defining the perimeter as extending a fixed distance from the base of the outermost turbines is preferable. The review will define of the perimeter as the boundary of a minimum convex polygon encompassing an area extending from a distance of **500 m from the base of the outermost turbines** (see Figure 3.3).

The term macro-response will be used to refer to changes in bird numbers within the windfarm area resulting from the development of the windfarm site, through processes including, but not limited to, attraction, displacement and barrier effects. Where displacement is used to infer a macro-response rate, it is important to be clear whether this reflects displacement from the windfarm only, or displacement from the windfarm plus a buffer. Buffers considered in the assessment of displacement effects typically extend beyond the 500 m around the windfarm perimeter considered here as some birds may respond to the presence of the windfarm at distances greater than this. Measures of displacement that use such buffers may thus underestimate the macro-response rate considered here. As collision risk models refer to birds in flight only, when using displacement rates to estimate a part of macro-avoidance behaviour, it is also important to lend more weight to studies that distinguish the displacement rates of birds in flight and on the water, or those for which it is possible to estimate the number, or proportion, of birds in flight.

Micro- Blew *et al.* (2008) suggests that micro-avoidance reflects a 'last-second' alteration to a flight path in order to avoid collision with a turbine. Petterson (2005) and Blew *et al.* (2008) both suggest that birds adjust their flight paths to avoid entering the rotor-swept zone of a turbine and that, therefore, birds may only rarely need to take last second action to avoid collision, possibly as a result of adverse conditions, such as poor visibility. This is borne out by empirical evidence presented in Desholm (2005) and Krijgsveld *et al.* (2011) (see section 5.3).

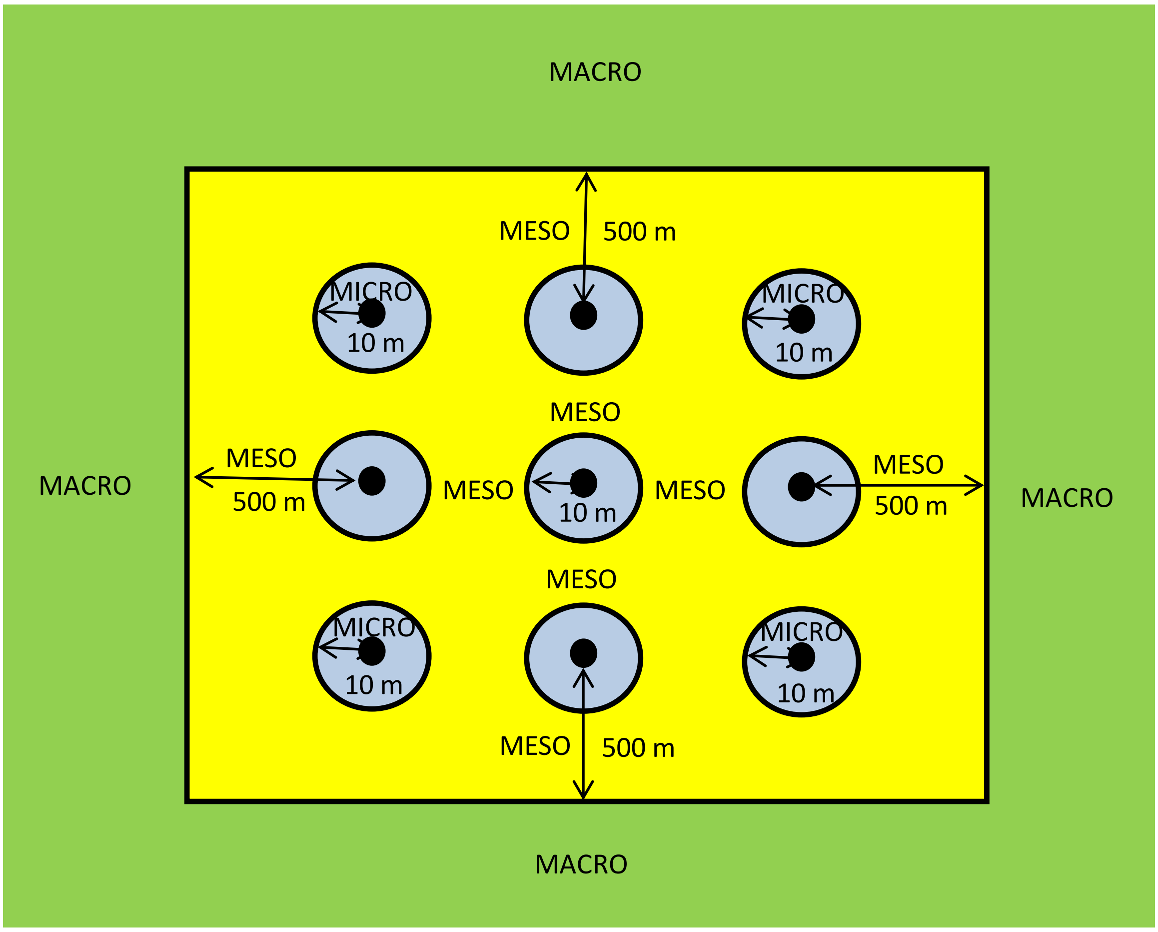


Figure 3.3 Schematic illustrating the spatial scales over which micro-avoidance, meso- and macro- responses operate. Dots refer to turbine tower locations (not to scale).

Therefore, it would seem reasonable to define **micro-avoidance** as a last-second alteration to a bird's flight path in order to avoid collision. For the purposes of observational studies, such last-second avoidance would be expected to occur in a 3-dimensional space **within 10 m of the turbine blades** (i.e. at distances of 10 m horizontally or vertically from edges of the turbine blades) – though note that this distance (and consequently the appropriate definition of micro-avoidance) may be refined based on future advances in the techniques used to collect the necessary data (see Figure 3.3). Such behaviour is likely to be recorded relatively rarely.

Meso- Whilst macro-responses reflect behaviour outside the windfarm and micro-avoidance reflects last-second action taken to avoid collision, there is a need to consider a third category, reflecting species responses to turbines within a windfarm (Figure 3.4). Both Desholm & Kahlert (2005) and Krijgsveld *et al.* (2011) demonstrated that the majority of birds do not pass within 50 m of a turbine. However, some, such as cormorants, may be attracted to structures, which offer potential roosting sites (e.g. Leopold *et al.* 2011). For this reason, as in the case of macro-response, it may be more straightforward to talk about a **meso-response** to turbines than meso-avoidance. The term meso-response should be used to refer to all behavioural responses to the **turbines beyond the 10 m buffer around the rotor blades, covered by micro-avoidance, and within the perimeter of the windfarm** (see Figure 3.3). This may include, for example the attraction of cormorants to turbine bases as a roosting site, as the base of the turbine would be beyond the 10 m buffer around the rotor blades.

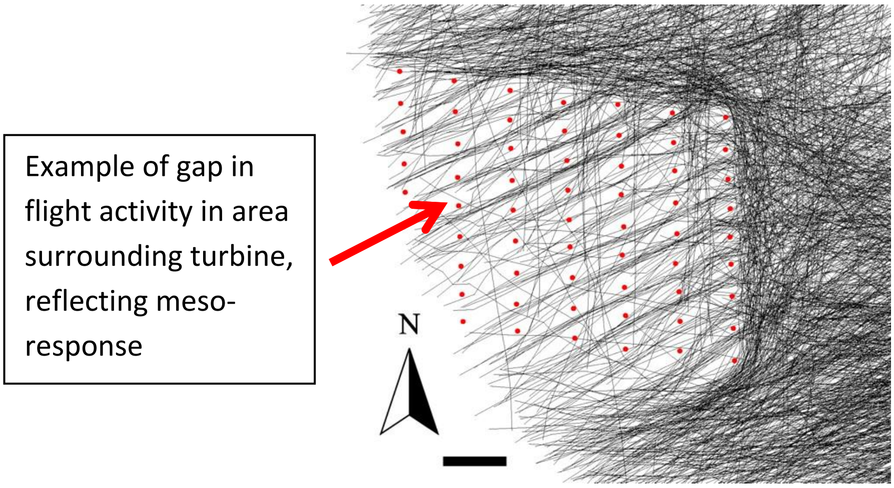

Example of gap in flight activity in area surrounding turbine, reflecting meso-response

Figure 3.4 Flight trajectories of migrating waterbirds within an offshore windfarm, red dots indicate locations of turbines. Reproduced with permission from Desholm & Kahlert (2005) Avian collision risk at an offshore windfarm. *Biology Letters* 1: 296-298.

At present, the scale at which data are collected may make it difficult to differentiate between a meso-response and micro-avoidance. Therefore, it is recommended that the term **macro-response** is used to refer to a response outside the windfarm and within-windfarm response, covering both the meso- and micro-scale, is used to refer to a response occurring inside a windfarm. In response to technological advances, a fuller separation of meso-responses from micro-avoidance is likely to be possible in the near future. For example, it may be possible in future to combine radar monitoring of flight paths through offshore windfarms to capture meso-responses (as in Desholm & Kahlert 2005) with images captured from turbine mounted cameras to capture micro-avoidance (as in Desholm *et al.* 2006).

3.3 Defining the appropriate 3-D level of avoidance

This section aims to define appropriate 3-D scales of avoidance; for detailed review of the evidence for horizontal and vertical meso-avoidance, see section 5.2.

In addition to occurring over a range of different spatial scales, avoidance behaviour may occur in both the horizontal and vertical planes. Below, we describe how observations of horizontal and vertical avoidance may be collected and the spatial scales which may be relevant to each. This distinction is important given that some methodologies for recording avoidance behaviour, such as radar, may not detect both horizontal and vertical movements, meaning that where only one is recorded, the derived avoidance rate is likely to be an underestimate, which may be offset by an inability to record horizontal and vertical movements occurring concurrently. There is also a need to consider the relationships between avoidance and other effects of offshore windfarms on birds, for example barrier effects and displacement.

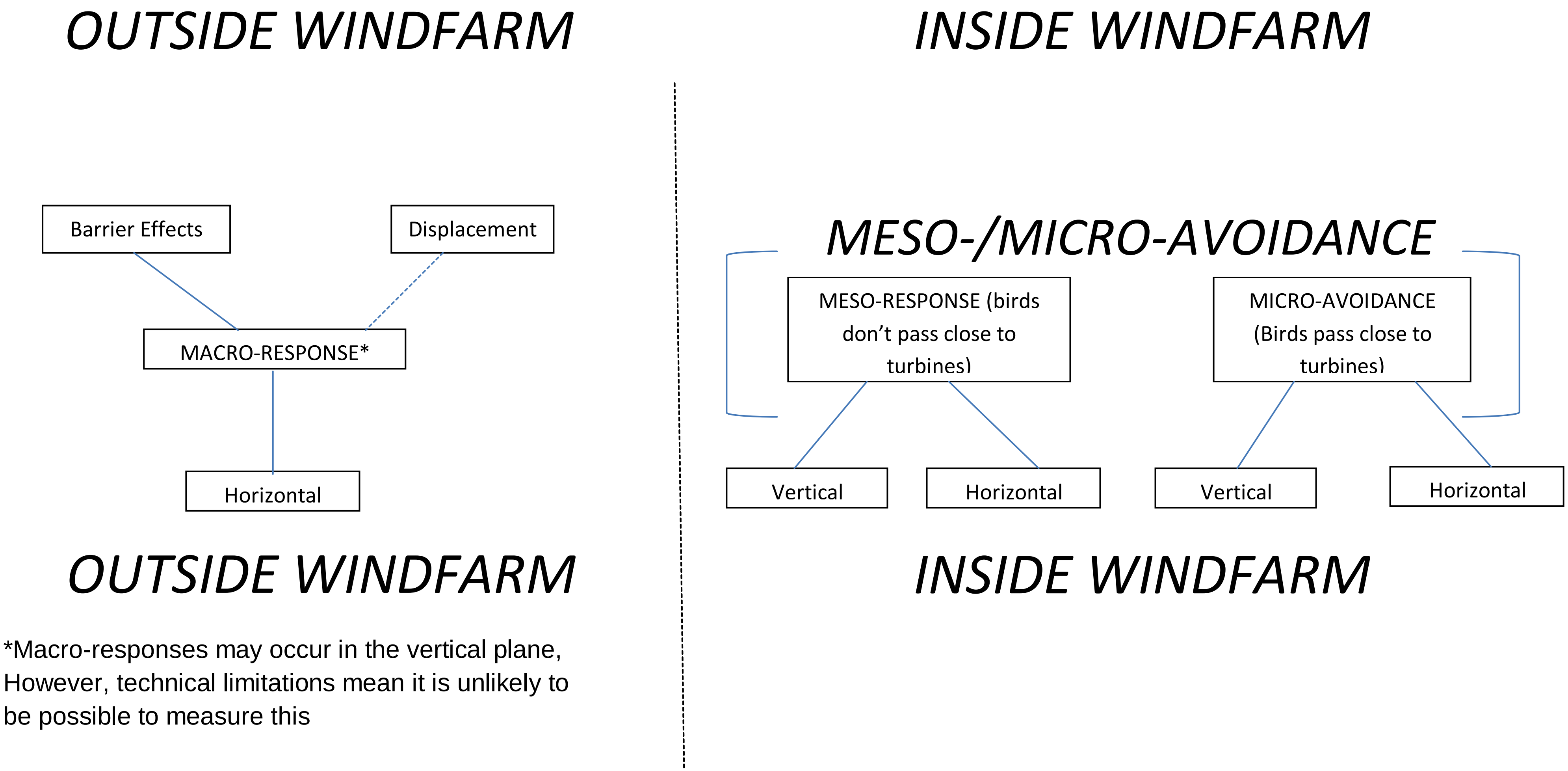
Horizontal Avoidance Much of the research into the avoidance behaviour of seabirds in relation to offshore windfarms has focussed on horizontal avoidance, whereby birds alter their flight paths so that they fly around turbines or do not enter the perimeter of the windfarm (i.e. Desholm & Kahlert 2005, Masden *et al.* 2009). These data have been collected using a variety of methodologies, notably visual observations (i.e. Krijgsveld *et al.* 2011) and radar observations (i.e. Petersen *et al.* 2006). We consider that all 3 spatial scales defined here are relevant in the context of horizontal avoidance.

Vertical Avoidance As technologies and survey protocols for monitoring collisions become more developed (e.g. Desholm *et al.* 2006, Collier *et al.* 2011a, 2011b) monitoring of both horizontal and vertical movements around turbines should become more feasible. For radar, however, at greater distance this may be more challenging as detecting both horizontal and vertical avoidance requires the use of both x- and y-band radar. At present, radar monitoring of bird movements in and around offshore windfarms typically focuses on horizontal avoidance behaviour, using horizontal radar (e.g. Petersen *et al.* 2006). Where changes in flight height amongst birds entering the windfarm have been estimated (e.g. Blew *et al.* 2008) this has been at too coarse a resolution to inform vertical avoidance. However, recent developments in radar technology (e.g. [redacted] may make this a more practical solution to investigate vertical avoidance behaviour amongst birds approaching offshore windfarms.

Krijgsveld *et al.* (2011) demonstrate that a number of species may fly at lower altitudes within-windfarms than outside windfarms and incorporate vertical avoidance behaviour in their estimation of micro-avoidance rates using a combination of visual and radar observations. Their results suggest that a substantial proportion of birds may alter their flight altitudes in order to avoid collision. Given the development of technologies capable of monitoring the movement of birds close to turbines, such as the Thermal Animal Detection System (Desholm *et al.* 2006), these results suggest that focussing on vertical avoidance at a micro-meso, as opposed to macro, scale may be worthwhile. At a micro-scale, it is likely that vertical avoidance would be captured as part of an evasive manoeuvre.

3.4 Total avoidance rates

In this section, we have produced definitions that are considered to work within the constraints of our current understanding of avoidance behaviour and data collection limitations. It is clear, given the multiple potential components of avoidance behaviour that we have identified (Figure 3.5), that equation 7 is an over-simplification of overall avoidance rates. In future studies it is important to consider how each of these components can be quantified. As technological capabilities advance, the definitions outlined above may become obsolete. However, any refinement to these definitions should be based on the behaviour of the species concerned, rather than artificially induced by methodological constraints, for example, the distance over which observations can be made with the use of binoculars or telescopes.



*Macro-responses may occur in the vertical plane, However, technical limitations mean it is unlikely to be possible to measure this

Figure 3.5 Schematic detailing how different behavioural responses to offshore windfarms may combine to give a total avoidance rate. At each different level birds may respond either vertically or horizontally. Outside a windfarm, both displacement and barrier effects are likely to contribute to the macro-response rate. However, the contribution of displacement to macro-avoidance may be hard to quantify as a result of uncertainty associated with estimating its effects. Avoidance behaviour inside a windfarm is often termed micro-avoidance, however, it may be appropriate to split this term further by considering a meso-response, where birds enter a windfarm but do not pass close to turbines, and micro-avoidance, where birds take last minute action to avoid collisions.

3.5 Recommended Definitions

For the purposes of this review, the definitions we will use for bird behaviour in response to offshore windfarms and turbines are (Figure 3.3):

> **MACRO-RESPONSE –** The response of birds to the presence of the windfarm outside its perimeter, defined as a 500 m buffer surrounding the outermost turbines. Responses may include attraction to the windfarm, displacement from preferred foraging habitat or an alteration to flight paths as a result of seeing the windfarm as a barrier. These may occur in either horizontal or vertical planes, although at present technological limitations mean that it is not possible to measure vertical macro-responses. For this reason, for the purposes of this review, we consider only horizontal macro-responses.
>
> **MESO-RESPONSE –** A redistribution of birds, or alteration of flightpaths within a windfarm in response to the presence of the turbines. This may encompass both horizontal and vertical responses. These responses are in contrast to micro-avoidance, see below.
>
> **MICRO-AVOIDANCE** – Last-second action taken by birds flying at rotor height to avoid collision, encompassing both horizontal and vertical movements, within a 10 m buffer surrounding turbine rotor-swept areas.

Due to current methodological difficulties in distinguishing micro-avoidance behaviour from meso-response behaviour, a fourth category is defined for the purposes of this review to act as a proxy for responses to windfarms at these scales:

> **WITHIN-WINDFARM AVOIDANCE –** Encompassing both meso-responses and micro-avoidance to describe how birds within a windfarm respond to the presence of a turbine.

The review focuses on data relating to macro-responses and within-windfarm avoidance. Distinctions between responses at the meso- or micro-scale and horizontal or vertical responses have not been made at this stage as insufficient data are available to support them. Future studies should aim to be able to make such distinctions to improve our understanding of avian avoidance behaviour at offshore windfarms.

4. REVIEW OF AVOIDANCE RATES USED IN COLLISION RISK MODELLING FOR OFFSHORE WINDFARMS

We reviewed the use of avoidance rates in collision risk modelling as part of the impact assessment process for 35 consented or proposed offshore windfarms (Table 4.1). There was considerable variation between assessments in the rates selected, which were as low as 0.87 and as high as 0.9999. In the majority of cases, a single avoidance rate for all species, ranging from 0.95 to 0.99, has been used in the collision risk modelling process to assess the potential impacts for all species considered. However, in some instances, developers and their consultants have felt that sufficient evidence exists to consider higher rates for some species, notably terns, although these values have not always been accepted within the decision process.

The species assessed during the collision risk modelling process vary on a site by site basis. This typically reflects the distribution of these species, for example, with Manx shearwater likely to be assessed at sites on the west coast of the UK. However, some species, such as northern gannet, black-legged kittiwake, lesser black-backed gull and great black-backed gull, are considered in most assessments, reflecting the broad scale distributions of these species. The flight height of birds is also an extremely important factor in determining the likely risk of collision (Johnston *et al.* 2014a). In several early assessments, a screening process was also carried out whereby species for which only a small proportion of individuals (typically <1%) were recorded flying at heights placing them at a risk of collision were excluded from the collision risk modelling process (Table 4.1). As a result of this screening process, the collision risk of some species, such as auks and divers, was assumed to be negligible and therefore not assessed using collision risk models.

In early assessments, the avoidance rates used in collision risk modelling were often very high, typically in excess of 0.99. The use of these rates was largely founded on collision rates reported at onshore windfarms (e.g. Winkelman 1992, Everaert 2003). However, these do not reflect true avoidance rates as they do not account for birds which pass safely through the rotor swept area of the turbines without taking avoidance action, or indeed those which pass through the windfarm without entering the rotor-sweep of the turbines.

In 2005, SNH issued guidance for sensitive bird species commonly identified in (onshore) windfarm environmental statements (SNH 2010) that a default avoidance rate of 0.95 should be used. This figure was based on expert opinion (Andy Douse *pers. comm.*) and acknowledged as being precautionary. It was felt that, as evidence became available, this rate would be revised upwards. Of the 13 assessments for offshore windfarms published between 2005 and the revision of this guidance in 2010 (SNH 2010), seven followed this guidance (see Table 4.1). The remaining assessments which argued that higher avoidance rates were more appropriate, cited as part of their justification empirical data of collision rates collected from sites in Belgium (see Everaert 2003, Everaert and Stienen 2006, Everaert 2008) or assessments of species' manoeuvrability as determined by Garthe and Hüppop (2004) and Maclean *et al.* (2009).

Following evidence obtained from onshore windfarms suggesting avoidance rates were likely to be significantly higher than 0.95 (Fernley *et al.* 2006, Pendlebury 2006, Whitfield and Madders 2006, Whitfield 2009) the default values were revised by SNH (2010). A default rate of 0.98 was recommended for all species considered in this guidance which included gull spp., tern spp, skua spp and diver spp. Exceptions to the default value included geese, hen harrier and golden eagle, for which sufficient evidence was available to support a 0.99 avoidance rate, and kestrel and white-tailed eagle, for which the 0.95 avoidance rate was retained as it was felt they were particularly susceptible to collisions. Again, a significant proportion (12 out of 18) of environmental impact assessments for offshore windfarms published since 2010 follow this guidance. The remaining studies cite evidence from Belgium (Everaert 2003, Everaert and Stienen 2006, Everaert and Kuijken 2007, Everaert 2008) and the Netherlands (Leopold *et al.* 2011, Krijgsveld *et al.* 2011), or again base avoidance rates on assessments of species' manoeuvrability as determined by Garthe and Hüppop (2004) and Maclean *et al.* (2009) in support of higher avoidance rates. As part of our review, we consider the strength of the quantitative evidence put forward in these studies and how qualitative information may be used to support these conclusions.

The evidence base for the revised avoidance rates is largely based on collision mortality observations at onshore / coastal windfarms – although recent behavioural avoidance evidence from Egmond aan Zee (Krijgsveld *et al.* 2011) is also being used – and there are uncertainties around the applicability of these values to offshore windfarms (Trinder 2012). First, whilst some seabird species may be attracted to offshore windfarms, others such as northern gannet show evidence of macro-avoidance (e.g. Krijgsveld *et al.* 2011, Vanermen *et al.* 2013) (see section 5.1). In contrast, while some terrestrial species, such as geese, may also show strong macro-avoidance of offshore windfarms (Plonczkier & Simms 2012), macro-avoidance is often less likely at terrestrial windfarms (e.g. Devereux *et al.* 2008, Garvin *et al.* 2011, Pearce-Higgins *et al.* 2012). As a result, avoidance rates in relation to offshore windfarms need to capture not just avoidance of the individual turbines, as is the case for species at terrestrial sites, but also of the windfarm itself.

Secondly, estimates of avoidance derived from collision mortality rates (rather than direct observations of avoidance – 'behavioural avoidance') follow the formula given in SNH (2010), whereby observed mortality is divided by the mortality expected in the absence of avoidance based on the flux of birds through the rotor-swept area (equation 6).

Surveys for terrestrial windfarms are usually carried from vantage points within 2 km of the area to be observed, ensuring that all observations are within 2 km. However, these methodologies rarely employ distance correction which means that the flux rates of birds (or population estimates) are likely to be underestimated. If the numbers of birds passing through the rotor-swept area of a turbine, and therefore the expected numbers of collisions, are underestimated, the derived avoidance rate will also be an underestimate. In contrast, population sizes within offshore windfarms of each of the five priority species considered as part of this review may potentially be over-estimated, given the attraction of each to boats (e.g. Garthe & Hüppop 1994, Skov & Durinck 2001). Even where population data have been collected from other platforms, for example, by digital aerial survey (e.g. Buckland *et al.* 2012), the potential for underestimating population size is considerably less than for surveys of onshore windfarms. As populations within offshore windfarms are unlikely to be underestimated, it has been argued (Trinder 2012) that an avoidance rate suitable for estimating collisions at an onshore windfarm will lead to underestimation of avoidance behaviour if used for estimating collisions at an offshore windfarm.

This review highlights the reliance of offshore windfarm developers, and their consultants, on guidance from Statutory Nature Conservation Bodies (SNCBs) about the use of appropriate avoidance rates. Of the 35 studies we identified, 19 cited the SNH guidance from either 2005 or 2010 in support of the avoidance rates selected for some, or all of their study species. Of these studies, several have suggested that these avoidance rates are potentially overly-precautionary, citing evidence from Belgium (Everaert 2003, Everaert and Stienen 2006, Everaert 2008), and the Netherlands (Winkelman 1992, Krijgsveld *et al.* 2011). The use of avoidance rates in excess of 0.98 in a number of recent environmental statements may reflect an increasing concern amongst developers that the SNH guidance is overly precautionary and posing an unnecessary risk to the consenting process. Many of the early developments were relatively small scale and consequently, collision risk estimates, even with an avoidance rate of 0.95, were extremely low. However, the scale of many of the developments proposed more recently is significantly greater, with commensurate increases in estimated collision rates. Consequently, it is important the subsequent review of avoidance rates can clarify the situation for developers and SNCBs alike.

Table 4.1 Avoidance rates considered during the collision risk modelling undertaken in assessments for proposed offshore windfarms and the justification for their use. All avoidance rates were used in conjunction with the basic (option 1) Band model and were taken from the final submitted environmental statements.

Offshore windfarm	Year	Avoidance rate(s) used	Species considered	Justification
Kentish Flats	2002	0.9998	Red-throated diver	Collision rate of 0.02% presented in Winkelman (1992)
Burbo Bank	2002	No Collision Risk Modelling	Red-throated diver, common scoter, common tern, wader sp., great cormorant, red-breasted merganser, little gull, common guillemot/razorbill	Sensitive species flew below rotor height and, therefore, were not at risk of collision
North Hoyle	2002	No Collision Risk Modelling	Red-throated diver, great cormorant, common scoter, tern sp., European shag, common guillemot, razorbill	Sensitive species flew below rotor height and, therefore, were not at risk of collision
Teesside	2004	0.9962 for all species	Red-throated diver, northern gannet, great cormorant , waders, Arctic skua, herring gull, great black-backed gull, black-legged kittiwake, Sandwich tern, common tern, common guillemot, geese sp.	Based on calculations from Blyth Harbour (citing Still *et al.* 1996, Painter *et al.* 1999)
Beatrice Demonstration Site	2005	0.95 for all species	Black-legged kittiwake, great black-backed gull, northern fulmar, northern gannet, auk spp, herring gull, tern spp	Follows SNH guidance from 2005 (SNH 2010) and is acknowledged as a conservative value.

Offshore windfarm	**Year**	**Avoidance rate(s) used**	**Species considered**	**Justification**
Thanet	2005	0.99 for all species	Red-throated diver, northern fulmar, northern gannet, common tern, Sandwich tern, black-legged kittiwake, common gull, herring gull, lesser black-backed gull, gull spp, auk spp	In line with previously published estimates of avoidance (Percival 1998, Everaert *et al.* 2002, Henderson *et al.* 1996, Winkelman 1992, Winkelman 1990, Percival 2001, Still *et al.* 1996)
London Array	2005	0.995 and 0.999 for gull spp, tern spp and Northern gannet, and 0.99 and 0.995 for diver sp.	Red-throated diver, black-throated diver, herring gull, lesser black-backed gull, great black-backed gull, common tern, northern gannet, Sandwich tern	Based on vulnerability to collision as assessed by Garthe & Hüppop (2004) and observed collision rates for gulls and terns presented by Everaert (2003)
Greater Gabbard	2005	High (0.9999), Medium (0.9982) and Low (0.87) for all species	Red-throated diver, lesser black-backed gull, great skua	High and Medium rates calculated from data presented in Winkelman (1992) based on total collisions numbers for gulls (High) and nocturnal collisions for gulls (Medium), Low avoidance rate derived from lowest reported avoidance rate of 0.87 found in American kestrel and considered highly unrealistic
Gwynt Y Mor	2005	No Collision Risk Modelling	Diver sp., northern fulmar, Manx shearwater, Leach's petrel, northern gannet, common scoter, small skua spp, great skua, black-legged kittiwake, Sandwich tern, 'comic' tern, common guillemot/razorbill	Sensitive species flew below rotor height and, therefore, were not at risk of collision

Offshore windfarm	Year	Avoidance rate(s) used	Species considered	Justification
Sheringham Shoal	2006	0.98 for all species	Sandwich tern, common tern, northern gannet, little gull, lesser black-backed gull	SNH guidance from 2005 (SNH 2010) guidance felt to be over-precautionary
West of Duddon Sands	2006	0.999	Lesser black-backed gull	Based on vulnerability to collision as assessed by Garthe & Hüppop (2004) and observed collision rates for gulls presented by Everaert (2003)
Humber Gateway	2007	0.95 for all species	Red-throated diver, northern gannet, great skua, Arctic skua, little gull, black-headed gull, common gull, black-legged kittiwake, herring gull, great black-backed gull, lesser black-backed gull, Sandwich tern, common tern, Arctic tern	Follows SNH guidance from 2005 (SNH 2010) and is acknowledged as a conservative value
Lincs	2007	0.95 for all species	Pink-footed goose, red-throated diver, northern gannet, little gull, common gull, lesser black-backed gull, common tern, Common guillemot	Follows SNH guidance from 2005 (SNH 2010) and is acknowledged as a conservative value
Westernmost Rough	2009	0.95 for all species	Northern gannet, black-legged kittiwake, common gull, lesser black-backed gull, herring gull, great black-backed gull, common tern	Follows SNH guidance from 2005 (SNH 2010) and is acknowledged as a conservative value

Offshore windfarm	**Year**	**Avoidance rate(s) used**	**Species considered**	**Justification**
Race Bank	2009	0.996 for Sandwich tern, 0.95 for all other species	Sandwich tern, common tern, northern fulmar, little gull, northern gannet, lesser black-backed gull, black-legged kittiwake, common guillemot, razorbill	Sandwich tern avoidance rate based on data from Zeebrugge, SNH guidance from 2005 (SNH 2010) for other species, but also discussion as to whether higher avoidance rates may be appropriate in some cases (northern gannet and lesser black-backed gull)
Dudgeon	2009	0.996 for Sandwich Tern, 0.99 for lesser black-backed gull, 0.97 Northern gannet	Sandwich tern, lesser black-backed gull, northern gannet	Evidence presented in Everaert & Stienen (2006) & Everaert (2008) for Sandwich tern and recommendations in Maclean *et al.* (2009) for northern gannet and lesser black-backed gull
LID6	2010	0.95 for all species	Black-throated diver, great northern diver, northern gannet, dark-bellied brent goose, little gull	Follows SNH guidance from 2005 (SNH 2010) and is acknowledged as a conservative value
Triton Knoll	2011	0.98 for all species	Northern fulmar, little gull, black-legged kittiwake, Sandwich tern, northern gannet, common guillemot, Arctic skua, lesser black-backed gull, great black-backed gull, common tern	Follows SNH guidance from 2005 (SNH 2010) guidance
Galloper Offshore Windfarm	2011	0.99 for gulls, 0.98 for other species	Red-throated diver, northern gannet, Arctic skua, great skua, common gull, lesser black-backed gull, herring gull, great black-backed gull, black-legged kittiwake	Evidence from ‘vantage point surveys’ for gulls, follows SNH (2010) guidance for all other species

Offshore windfarm	**Year**	**Avoidance rate(s) used**	**Species considered**	**Justification**
Rampion	2011	0.995 for Northern gannet, Gulls sp. , skuas spp and Auks, 0.99 for terns sp. and waterbirds	Brent goose, common scoter, northern gannet, bar-tailed godwit, Eurasian curlew, great skua, Mediterranean gull, common gull, lesser black-backed gull, herring gull, great black-backed gull, black-legged kittiwake, Sandwich tern, common guillemot, barn swallow, meadow pipit	Follows Maclean *et al.* (2009)
Aberdeen Offshore Windfarm	2012	0.98 for all species	Common guillemot, razorbill, Atlantic puffin, northern fulmar, common tern, Sandwich tern, herring gull, black-legged kittiwake, great black-backed gull, common gull, common scoter, common eider, European shag, great cormorant, northern gannet, red-throated diver, Arctic skua	Follows SNH (2010) guidance
Blyth Offshore Demonstration Project	2012	0.98 for all species	Northern gannet, common gull, herring gull, great black-backed gull, little gull, black-legged kittiwake, common tern	Follows SNH (2010) guidance

Offshore windfarm	**Year**	**Avoidance rate(s) used**	**Species considered**	**Justification**
Hornsea Project One	2012	0.98 for all species	Northern fulmar, northern gannet, black-legged kittiwake, little gull, common gull, great black-backed gull, lesser black-backed gull, herring gull, common tern, Arctic tern, common guillemot, razorbill, Arctic skua, great skua	Follows SNH (2010) guidance
Irish Sea	2012	0.98 for all species	Manx shearwater, great black-backed gull, lesser black-backed gull, herring gull, black-legged kittiwake, northern gannet, Greenland white-fronted goose	Follows SNH (2010) guidance
East Anglia One	2012	0.98 for all species	Northern fulmar, northern gannet, black-legged kittiwake, common gull, lesser black-backed gull, herring gull, great black-backed gull	Follows SNH (2010) guidance
Firth of Forth Alpha and Bravo	2012	0.98 for all species	Northern gannet, black-legged kittiwake, lesser black-backed gull, herring gull, great black-backed gull	Follows SNH (2010) guidance
Beatrice Offshore Windfarm	2012	0.99 for all species	Arctic skua, Arctic tern, northern fulmar, great black-backed gull, northern gannet, herring gull, black-legged kittiwake, great skua, common guillemot, razorbill	Review of micro-and macro-avoidance rates and criticism of the transferability of avoidance rates between onshore and offshore windfarms in MacArthur Green (2012)

Offshore windfarm	**Year**	**Avoidance rate(s) used**	**Species considered**	**Justification**
Dogger Bank Creyke Beck A and B	2012	0.99 for northern gannet, 0.98 for all other species	Northern fulmar, northern gannet, great skua, Arctic skua, black-legged kittiwake, lesser black-backed gull, great black-backed gull, common guillemot, razorbill, little auk, Atlantic puffin	Evidence from Egmond aan Zee(Krijgsveld *et al.* 2011) and elsewhere supporting 0.99 for northern gannet and following SNH (2010) guidance for all other species
Moray Firth Offshore Windfarm	2012	0.995 for northern gannet, 0.985 for lesser black-backed gull, 0.99 for black-legged kittiwake	Northern gannet, black-legged kittiwake, herring gull, great black-backed gull	Consideration of micro-and macro-avoidance rates presented for Dutch and Belgian windfarms (Everaert 2008, Krijgsveld *et al.* 2011)
Nearth na Gaoithe	2012	0.998 for northern gannet, 0.995 for gulls spp., 0.98 for Arctic tern	Northern gannet, little gull, lesser black-backed gull, herring gull, great black-backed gull, black-legged kittiwake, Arctic tern	High macro-avoidance rates for northern gannet presented in Leopold *et al.* (2011) suggest that avoidance rates presented in both SNH (2010) guidance and MacLean *et al.* (2009) are likely to be over precautionary for northern gannet. Tern and gull avoidance rates follow Maclean *et al.* (2009)
Bligh Bank Windfarm (Belgium)	2013	0.976 micro-avoidance rate for all species	Common gull, lesser black-backed gull, herring gull, great black-backed gull, black-legged kittiwake	Based on rates estimated at Egmond aan Zee by Krijgsveld *et al.* (2011)
Walney Extension Offshore Windfarm	2013	0.98 for all species	Whooper swan, pink-footed goose, lesser black-backed gull	Follows SNH (2010) guidance

Offshore windfarm	**Year**	**Avoidance rate(s) used**	**Species considered**	**Justification**
Burbo Bank Extension	2013	0.98 for all species	Red-throated diver, Manx shearwater, common scoter, little gull, black-headed gull, herring gull, lesser black-backed gull, common tern, Arctic tern, Sandwich tern, great cormorant, northern gannet, Arctic skua, great skua, black-legged kittiwake	Follows SNH (2010) guidance
Atlantic Array	2013	0.98 for all species	Manx shearwater, northern gannet, black-legged kittiwake, lesser black-backed gull, herring gull, great black-backed gull, common guillemot	Follows SNH (2010) guidance
Inch Cape	2013	0.99 for northern gannet, 0.98 for all other species	Northern gannet, Arctic skua, pomarine skua, great skua, black-legged kittiwake, great black-backed gull, herring gull	Evidence presented from Egmond aan Zee to justify 0.99 for northern gannet, follows SNH (2010) guidance for all other species

5. REVIEW OF PUBLISHED EVIDENCE FOR AVOIDANCE RATES OF MARINE BIRDS

This section provides a review of published evidence for macro-response (section 5.1), meso-response alone (section 5.2), micro-avoidance alone (section 5.3) and overall within-windfarm avoidance (i.e. combined micro-/meso-avoidance; section 5.4). For macro response rates (section 5.1) we consider data collected from the offshore environment only. The more limited evidence base for meso-response and micro-avoidance rates (sections 5.2 and 5.3) meant that it was necessary to include some evidence from the onshore environment. The difficulties in obtaining estimates of collision rates in the offshore environment mean that the majority of the evidence that relates to within-windfarm avoidance rates (section 5.4) originates from the terrestrial environment.

5.1 Review of Published Evidence for Macro-response Rates of Marine Birds

Here we consider macro-responses as including: (i) barrier effects for migrating birds or those commuting between breeding colonies and foraging areas; (ii) displacement effects from the windfarm area leading to an effective loss of habitat; and (iii) attraction. Each of these responses may result in a change in the numbers of birds in flight present within the perimeter of the windfarm between the pre- and post-construction periods. As collision risk modelling is usually based on the number of birds present during the pre-construction period, these changes must be accounted for as part of the collision risk modelling process. All of the studies we consider in this section originate from the offshore environment.

5.1.1 Causes of barrier, displacement and attraction effects

The term barrier effects describes the behavioural response of flying birds to the presence of the windfarm. The windfarm acts as a physical barrier, impeding the most direct route to a bird’s destination, necessitating a change in flight direction in order to avoid entering the windfarm. This will ultimately reduce the numbers of birds recorded in flight within the windfarm area.

The effects of displacement are harder to classify since the habitat within the area of the windfarm may have been used by birds for a variety of purposes, notably foraging, but potentially other essential maintenance behaviours, such as moulting, preening or forming rafts. The availability of alternative foraging habitat may be more restricted, however, and hence for the purpose of this review we consider displacement as the inability of a bird to forage in a particular area due to the presence of the turbines. This may be manifested as a reduction in the number of birds flying into the area of the windfarm to look for food but this does not necessarily mean that birds will no longer enter the windfarm. It is possible, for example, that some species may land outside the windfarm and swim into the windfarm area. Studies of displacement, however, have tended to report the changes in all observed birds within the windfarm’s perimeter relative to the areas outside and have not differentiated between the numbers flying and those recorded on the water. To better inform both studies of displacement and macro-avoidance, it would be prudent in future studies to separate flying birds from birds on the water when reporting displacement rates. Another important consideration relates to the flight height information that may be collected during surveys. This is primarily used to inform collision risk, but could potentially be used to inform on the vertical avoidance of birds over or under the rotor swept area.

Attraction is defined as an increase in numbers of birds within the windfarm area post-construction and can arise though several means. The monopiles of the turbine can act as a useful platform for birds to dry their feathers, rest, and socialise (e.g. great cormorant, Lindeboom *et al.* 2011). There is also evidence that structure of the turbines may also provide feeding opportunities through changes in local hydrography, seabed morphology or by acting as an artificial reef (Inger *et al.* 2009, Wilson & Elliot 2009, Maar *et al.* 2009, Lindeboom *et al.* 2011). Whilst there is the potential for collision risk to increase, as a result of attraction into the windfarm area, this will only occur if birds utilise the space covered by the rotor swept area.

5.1.2 Overall approach to assessing evidence for barrier, displacement and attraction effects

In reality, the ability to differentiate between birds exhibiting barrier and displacement effects may not always be possible since both are manifested as a decrease in the numbers of birds within the windfarm area (as defined both horizontally and vertically). For the purpose of this review, however, we will critique studies carried out at windfarms according to the type of effect they were designed to look at. For each example we present the relevant methods, key results and an overall assessment of the appropriateness of their use in looking at the effect they were designed to measure. Although our brief was to examine the evidence for five key species being considered in this review, we have also included several examples which have been cited as providing supporting evidence of macro-avoidance for seabirds in general (e.g. Desholm & Kahlert 2006 study on common eider and geese spp). We have not included studies carried out solely on migrating terrestrial species, e.g. such as pink-footed geese at Lynn and Inner Downing windfarm (Plonczkier & Simms 2012).

5.1.3 Studies of barrier effects

5.1.3.1 Methodologies used to look at barrier effects

Barrier effects have been measured mostly using (horizontal) radar and/or visual observations from fixed observation points (see Table 5.1 for summary). Radar technology has been used to measure barrier effects directly by quantifying the percentage of bird tracks that are deflected away from the windfarm, and also to look at the distance at which the deflection occurs (e.g. Peterson *et al.* 2006). However, due to technological constraints of horizontal radar (see below), this has been limited to quantifying horizontal macro-responses only. Radar has also been used to look at barrier effects indirectly by comparing the number of flight paths (tracks) inside and outside the windfarms (e.g. Krijgsveld *et al.* 2011), to look at the densities of tracks in relation to distance from the windfarm (e.g. Skov *et al*. 2012) or to look at percentages of flight paths flying towards, away from and parallel to the windfarm (Blew *et al.* 2008). Such indirect measures may not necessarily be able to differentiate between barrier and displacement effects however. Visual observations, whilst also critical for the validation of the results of the radar, in terms of providing species identification and relative abundance, have also been used independently to compare numbers of birds in flight inside and outside the windfarm (e.g. Krijgsveld *et al.* 2011) although again, these methods may not necessarily preclude the possibility of inadvertently measuring displacement effects. Emerging technology in the form of laser range finders has also recently been used (e.g. Skov *et al.* 2012), and there may be scope to apply this approach in the context of barrier effects. There have been examples, notably in the UK, where data collected from boat based surveys have been used to look at barrier effects but this methodology is not considered to adequately provide the quantification needed here (MMO 2014).

There are a number of limitations associated with the use of radar (for further discussion see Krijgsveld *et al.* 2011 and Peterson *et al.* 2006) in terms of deriving avoidance rates: (i) Identification to the species level is not possible without visual validation and even then this information is generally only available as the species composition of birds passing through in a comparable time period – hence the values cited may be considered relevant only to the most commonly recorded birds species; (ii) There can be problems with distinguishing between flocks or individual birds – tracks recorded by radar may therefore not necessarily correspond to individual birds and corresponding avoidance rates could be more representative for flocks (which are likely to vary in size); (iii) Detection issues exist with picking up individual birds or flocks of small birds; (iv) Detection of birds can be affected by environmental conditions such as wave height and rain; (v) Seabirds such as the northern gannet, tubenose spp, sea duck spp and alcid spp tend to fly in the troughs between waves (as a means of flying in the most energetically efficient manner). In conditions where the wave height is sufficiently high, the total number of these birds is likely to be underestimated; (vi) The relative orientation of the radar beam to the flight direction of the birds can also affect detection (flying head on into the beam is the best) – this can present challenges when considering the optimum position for the radar; (vii) Whilst the range of detection for radar exceeds that of visual observations, there is a risk that birds could start to change their flight orientation beyond the range of the radar which would result in birds not being detected at all and hence the relative contribution of barrier effects to macro-responses is underestimated; (viii) Detection rates have been shown to be lower inside the windfarm due to interference caused by the presence of the windfarms (this is covered more extensively under the site accounts). Another considerable limitation of radar is that horizontal radar can only be used to record horizontal displacement (sometimes referred to as lateral displacement) as no information on altitude is collected. It is possible, therefore, that birds may fly over the windfarm at altitudes higher than the rotor swept area but this would not be picked up as avoidance behaviour (Blew *et al.* 2008). In contrast, vertical radar can only be used to determine flight height (altitude) and densities of birds in passage (flux) directly above the radar itself and provides insufficient information either on horizontal change or vertical avoidance that takes place outwith the windfarm perimeter. Radar has been useful, however, in demonstrating the importance of time of day (day versus night time), wind direction (head versus tail wind), season (spring versus autumn) for avoidance rates (e.g. Peterson *et al.* 2006 and Krijgsveld *et al.* 2011).

In terms of data collection issues for visual observations, there are also limitations when compared to radar: (i) Sampling is limited to daylight with reasonably calm conditions and good visibility. Although, under some circumstances, observations at night (e.g. moon watching) or auditory observations (based on bird calls) have been used, these have limited use; (ii) The range of detection is smaller; (iii) Individual observers may differ in assessing the distance and altitudes of birds, although there may be scope to reduce such differences through calibration with other techniques (Mateos *et al.* 2010; Norman *et al.* 2005).

5.1.3.2 Results of studies on barriers effects

Overall there is very little species-specific evidence for the five priority species for macro-avoidance as a consequence of barrier effects (see Appendix 1 for detailed site accounts) as radar was the most commonly used method. Of the studies reviewed all but one study looked at barrier effects during the post-construction period only – the exception being Nysted (Desholm & Kahlert 2005; Peterson *et al.* 2006) which also looked at the pre-construction period. Arguably comparison of the pre- and post-construction periods provides the most robust evidence for barrier effects rather than focussing solely on the post-construction period. Avoidance rates were only derived for three windfarms (see Table 5.1): (i) Egmond aan Zee (Krijgsveld *et al*. 2011); (ii) Nysted (Desholm & Kahlert 2005; Peterson *et al.* 2006); and Horns Rev (Peterson *et al*. 2006). The latter two are not considered further here since the derived values are likely only to be relevant to common eider (and geese) and common scoter respectively. Whilst there has been some additional work carried out at the Alpha Ventus test site to look at barrier effects (BSH 2011 and Mendel *et al.* 2014), the data have not been presented in such a way that would allow the derivation of a macro-avoidance rate and are hence not considered further here.

The only study which has specifically looked at barrier effects for northern gannet was that of Krijgsveld *et al.* (2011) at Egmond aan Zee which derived a macro-avoidance rate of 0.64. This was derived from indirect measure of barrier effects using visual observations made during panoramic scans to calculate the number of birds in flight within, at the edge and outside the windfarm (and by using a factor to correct for relative surface area – see Appendix 1, section A1.1). It is therefore not possible to discount the possibility that the apparent decreases within the windfarm could have included displacement due to the methodology used. These data were based on a total of 405 panoramic scans from spring 2007 to the end of 2009 (see Table 4.2 Krijgsveld *et al.* 2011) with particular emphasis on the spring and autumn periods as a total of 140 and 121 scans were carried out respectively compared to 71 and 73 scans in the summer and winter respectively. Overall, the sample sizes of the numbers of flying birds observed for northern gannet and common scoter were 282 and 123, although these figures were not broken down on a seasonal basis. However, it is also worth highlighting that northern gannets' use of the area – based on the density of flying birds – was highest during the spring, autumn and winter with an order of magnitude less use during the summer (mean density or numbers of birds per km^2 per scan for the periods of spring, summer, autumn and winter were 0.03, <0.005, 0.05 and 0.02 respectively – see Table 8.3 Krijgsveld *et al.* 2011). The extent to which the derived macro-avoidance rate is representative of breeding birds is thus questionable due to the relatively low use of the Egmond aan Zee site at this time and the lower sampling frequency. Therefore until such time that data are collected on northern gannet flights around OWFs specifically during breeding, this value should be applied with caution when considering the breeding season. It is also worth noting that Krijgsveld *et al.* (2011) reported a deflection rate of 0.89 for northern gannet based on the assessment of visual observations of flight paths. However, this result was based on a sample size of 38 birds and these observations were not based on systematic recording methods (c.f. the panoramic scans, which were based on strict protocols and recorded all birds seen). Consequently the authors do not recommend that these values be used as macro-avoidance rates (Karen Krijgsveld *pers. comm.*). Note, however, that these deflection rates have been cited as evidence for macro-avoidance rates by industry (e.g. Natural Power 2013).

There are no species-specific macro-avoidance rates, relating to barrier effects, for any of the four priority gull species of this review. Arguably, the most relevant study is that of Krijgsveld *et al*. (2011) which derived a macro-avoidance rate of 0.18 for the generic group of gull spp. These data were based on the indirect measure of barrier effects of the relative percentage of tracks that were outside the windfarm in winter. This was justified on the grounds that the species composition of bird tracks was heavily dominated by gulls spp (and great cormorants) at that time of year. A deflection rate of 0.4 was reported (based on the flight paths for 78 birds recorded as gull spp) but, as before, this value is not derived from systematic recording methods and the authors do not recommend this as evidence as macro-avoidance.

Table 5.1 Summary of key studies of barrier effects, the stage of data collection, methods used, parameters measured and species or species groups reported. *Italics* indicates species for which values were based on averages of other species (see Appendix 1 for site accounts)

Windfarm site	Study	Stage of data collection	Method used/parameter measured	Species/spp groups (values of macro-avoidance are given in parentheses where available)	Time of year data collected
Egmond aan Zee	Krijgsveld *et al.* (2011)	Post-construction	Radar /Numbers of tracks inside and outside the windfarm	*Gull spp (0.18)* *Grebe spp (0.28)* *Tubenoses spp (0.28)* *Skua spp (0.28)* *Tern spp (0.28)*	Winter All year All year All year All year
			Visual observations /Numbers of birds inside and outside the windfarm	*Northern gannet (0.64)* *Seaducks/scoter (0.71)* *Diver spp (0.68)* *Alcid spp (0.68)*	All year All year All year All year
Horns Rev I	Peterson *et al.* (2006)	Post-construction	Radar / The percentage of tracks that were considered to have a theoretical chance of entering the windfarm Radar / The distance at which deflection occurs	Common scoter (range 0.71-0.86 based on inter-annual variation and the direction at which birds approach the windfarm)	Spring/autumn combined
Horns Rev I	Blew *et al*. (2008)	Post-construction	Radar - Orientation of tracks in relation to the windfarm (% flying towards, away or parallel to the windfarm)	All birds	Spring/autumn combined
Horns Rev I and II	Skov *et al*. (2012)	Post-construction	Radar / Densities of tracks in relation to the radar station and windfarm	Common scoter and all birds	Spring/autumn combined

			Laser range finders / The distance at which deflection occurs (based on peak densities of radar tracks)		
Nysted	Peterson *et al.* (2006) Desholm & Kahlert (2005)	Pre- and post-construction	Radar / The percentage of tracks that were considered to have a theoretical chance of entering the windfarm Radar / The distance at which deflection occurs	Common eider and geese spp (0.78 – inter-annual variation 0.63-0.83)	Autumn
Nysted	Blew *et al*. (2008)	Post-construction	Radar / Orientation of tracks in relation to the windfarm (% flying towards, away or parallel to the windfarm)	All birds	Spring/autumn combined

5.1.4 Studies of displacement/attraction

5.1.4.1 Methodologies (and survey design) used to look at displacement/attraction

Data used to look at displacement effects have tended to be derived from boat and/or visual aerial surveys. Whilst industry guidance (Camphuysen *et al.* 2004) tends to be cited as the basis of the methodologies used, the extent to which guidelines are followed may be unclear (Maclean *et al.* 2009). Although digital aerial surveys are becoming more commonly used by the offshore windfarm industry (MMO 2014, Mackenzie *et al.* 2013), there appears to be a lack of sites where this technology has been used during all phases of the development. Further consideration of the advantages and disadvantages of these methodologies are given in Mackenzie *et al.* (2013). Additional to these, and of relevance to the assessment of displacement, there are concerns that boat surveys may overlook birds flying at higher altitudes and that might, therefore, fly over windfarms (Hartman *et al.* 2012). As is true for most of the studies designed to target barrier effects which may not necessarily exclude displacements effects, the same is true for the reverse situation.

Studies of displacement effects carried out at offshore windfarm sites within the UK have largely been based on the Before and After Control Impact (BACI) design which was viewed as being best practice at the time these sites were being set up (based on Stewart-Oaten *et al.* 1986). The extent to which this approach has been successfully implemented has been hampered by inadequate survey design including: (i) Location of the reference site often situated immediately adjacent to the impact site of the windfarm area – thus any changes as result of the windfarm may be over- estimated e.g. displaced birds could move into the adjacent area resulting in higher numbers recorded than during the pre-construction period; (ii) Insufficient spatial coverage e.g. boat surveys often only covered the windfarm area and a buffer, hence any possible changes that may have occurred in the wider environment cannot be taken account of; (iii) Gaps in temporal coverage e.g. survey periods between the different phases of the development did not always correspond or visual aerial surveys having to be abandoned following construction of the windfarm, due to Civil Aviation Authority flight height restrictions; (iv) The ability to select control sites which are truly comparable to the area impacted by the windfarm area (e.g. in terms of hydrography, seabird populations) has been questioned. For further consideration of these issues see MMO (2014).

A further limitation of displacement studies in their survey design is that little consideration is usually given to the power to detect change, which is related to a number of factors including the frequency of surveys and their relative spatial and temporal coverage (Maclean *et al.* 2013; Vanermen *et al.* 2012; Pérez Lapeña *et al.* 2010). The distribution and relative abundance of seabirds show high levels of both spatial and temporal variability within and between years. Therefore the use of power analyses, particularly at the start of any offshore windfarm development, can be extremely helpful in determining the most appropriate survey design in order to be able to adequately test for whether a windfarm impacts birds through either displacement or attraction effects.

There is also the problem that the post-construction reports, notably those leading up to the final report, have tended not to provide formal statistical analyses and any assessments of changes in species abundance are often based on simple comparisons of changes in absolute numbers or are qualitative (e.g. visual inspection of maps: MMO 2014). Even in instances where the significance of change has been looked at, the focus has been on measuring differences in numbers or densities between the pre-construction and post construction periods and any changes in distribution within the study area may go undetected (MacKenzie *et al.* 2013). Recently, there have been developments in model-based approaches such as density surface modelling (Rexstad 2011) which allow the inclusion of covariates (e.g. environmental factors such as water depth, sea surface temperature) which can help better explain inherent spatial and temporal variability in the abundance and distribution of animal populations. The resulting distribution maps of relative abundance provide a more robust means of assessing whether changes have occurred as a result of the presence of an offshore windfarm. There also appears to be a shift away from using BACI survey design for looking at displacement, with a Before-After-Gradient approach being recommended (MMO 2014, Jackson & Whitfield 2011), and this is highly compatible with density surface modelling approaches.

It is also important to highlight that displacement studies to date have tended to focus on comparing numbers or densities of birds pre-construction and post-construction which, in general, do not distinguish between birds in flight and birds on the water (the former group being more likely to show displacement). Despite ship-based data collection methods being distinct for birds on the water and birds in flight, counts are generally combined and for most studies presented below are not considered separately. Similarly, whilst visual aerial surveys do differentiate between birds on the water and those in flight, estimates are usually collated.

5.1.4.2 Results of studies on displacement/attraction

Of the studies considered, comparisons of pre- and post-construction surveys were carried out in all cases with the exception of Egmond aan Zee (Leopold *et al.* 2011), where it was argued that this was not possible due to considerable annual variation in seabird presence (Appendix 2, section A2.1). Instead analysis of the effect of the windfarm was carried out based on individual surveys (e.g. species monthly counts which were converted into presence/absence data) for which there were sufficient data and the results should therefore be considered with caution (see Table 5.2).

It was only possible to calculate actual values of macro-avoidance for a single study carried out at the Blighbank and Thorntonbank windfarms for which the model co-efficients generated from the Generalised Linear Models were provided (Vanermen *et al.* 2013). Results for Thorntonbank are not considered here, however, as they relate either to the first post-construction phase when only six turbines were operational or during the second phase of construction which was still ongoing at the time of reporting. Other studies have reported evidence for displacement or attraction based on the results of Jacob's selectivity indices (Nysted and Horns Rev - Peterson *et al.* 2006) or density surface maps of the predicted distribution over the different phases of the development (Robin Rigg – Natural Power 2014).

For northern gannet there was strong evidence for displacement effects at Blighbank based on comparisons of pre- and post-construction data. From this study, therefore, it was possible to derive a macro-avoidance rate of 0.84 for northern gannet. Currently the vast majority of monitoring tends not to present a seasonal breakdown of displacement (macro-avoidance) values and this report does not differ in that respect. However, there is notable variation in the seasonal use of the windfarm and the surrounding area (termed the BPNS) by northern gannet – mean numbers across the period of 2001-2007 in winter and autumn were 1,799 and 4,990 respectively compared to spring and summer at 737 and 556 respectively (see Table 2 in Vanermen *et al*. 2013). Therefore, as for barrier effects, the extent to which these data are representative of northern gannet during the breeding season is debateable. It is also worth reflecting that further monitoring work has been carried out since the publication of Vanermen *et al*. (2013) and that these results should be considered as being provisional (Nicholas Vanermen *pers. comm*.). Potential corroboration that northern gannets are displaced by windfarms is also provided by results from Egmond aan Zee (Leopold *et al.* 2011) where it was shown that the presence of northern gannets was significantly negatively related to the presence of the windfarm in two of nine monthly post-construction surveys (no other significant effects were reported for the other seven surveys). However the strength of this evidence is relatively weak as the analyses were based on within survey (monthly) comparisons – a comparison of pre- and post-construction data was not considered feasible (see Appendix 2 – A2.1 for further details). The study at Robin Rigg found no response from northern gannet to the windfarm which tend to use the site mainly during the breeding season, though the pre- and post-construction densities were generally rather low e.g. across the entire study within which the windfarm is located, a total of 352 birds were recorded in flight for the entire pre-construction period compared to 397 in the post-construction period (up to and including year 3 - see Table 3.22 in Natural Power 2014). Similarly at Horns Rev, there were never any birds recorded within the windfarm itself either pre- or post-construction (although an increased avoidance was reported for both the 2 km and 4 km buffers post-construction based on Jacob’s selectivity indices). More recent work carried out at Alpha Ventus was inconclusive as the overall abundance of northern gannet was very low e.g. a total of nine individuals were seen in the pre-construction period (BSH 2011 and Mendel *et al.* 2014).

Lesser black-backed gull was only considered by three of the studies reported in Table 5.2. There was strong evidence of very high levels of attraction at Blighbank (Vanermen *et al.* 2013) – with relative increases in numbers at the windfarm provisionally estimated in the order of 3.81 (see Appendix 2, section A2.3 for further details). Far weaker evidence to support lesser black-backed gulls being attracted to windfarms was provided from Egmond aan Zee (Leopold *et al.* 2011) where the presence of lesser black-backed gulls was significantly negatively related to the presence of the windfarm in at least one out of 12 possible monthly post-construction surveys. However, despite the results being suggestive of displacement, it was concluded by the authors that, given the strong association shown by lesser black-backed gulls to fishing vessels (based on anecdotal observations during the surveys) attraction to the windfarm was apparently being masked by their strong association with boats which were excluded from the windfarm in the post-construction period. Completely contradictory results were derived for Alpha Ventus where comparison of the distribution of birds pre- and post-construction showed a marked decrease in densities (based on maps of 1 km^2 cells) and statistically significantly lower abundances were reported for the 0-2 km, 2-6 km and 6-10 km distance classes from the windfarm (BSH 2011 and Mendel *et al.* 2014). There is also no consistent pattern in the studies summarised in Table 5.2 for either displacement or attraction being shown by herring gulls, great black-backed gulls and black-legged kittiwake (Table 5.2).

Furness *et al.* (2013) developed a scoring system to quantify the vulnerability of marine bird population to offshore windfarms with respect to collision and disturbance/displacement. Northern gannet, lesser black-backed gull, herring gull, great black-backed gull, and black-legged kittiwake all scored very highly with respect to collision risk (within the top seven of all the species considered) and this was largely a result of time spent flying at rotor height (other parameters considered included flight agility, % of time flying, night flight and an overall conservation score). In contrast, with respect to displacement, all five species scored very low (species concern index values were no more than 6 compared to the highest value of 32). This was a result of the species being little affected by the disturbance effects associated with ships/helicopters and not being particularly constrained by foraging habitat (the same overall conservation score used for collision risk was also used with respect to displacement). Given this, it is therefore unsurprising that the majority of priority gull species appeared to show no consistent pattern for displacement.

5.1.5 Evidence for an overall macro-response rate

In terms of assessing whether changes in numbers (e.g. from the pre-construction to post-construction periods) are statistically significant, this has only been possible for displacement /attraction studies and not for barrier studies. The notable exception to this is the work carried out at Nysted windfarm (Desholm & Kahlert 2005; Peterson *et al.* 2006) where it was possible to record the number of flight paths that changed their direction by comparison of the pre-and post- construction periods.

There are also considerable issues in how data are collected in terms of differentiating between barrier and displacement effects. Migratory species, which have a distinct passage period during spring and/or autumn and do not occur in the vicinity of the windfarm outwith these periods (e.g. geese spp and passerine spp), are likely to experience solely barrier effects. In contrast, species which are resident in the vicinity of the windfarm, may be subject to a combination of barrier effects or displacement /attraction effects (e.g. the vast majority of seabird spp, at least in the breeding season). This is certainly the case for all of the five priority species being considered here and to date, there has not been a single study which can be considered as exclusive evidence for either barrier or displacement effects.

It is also worth flagging up that the extent to which impacts of the windfarm actually affects bird populations is likely to be site specific. Therefore it would be reasonable to expect that the barrier effects for migrating birds are far more likely to be pronounced when offshore windfarms are located on major flyways. Similarly, an offshore windfarm that is located within the foraging ranges of breeding seabirds is more likely to be an issue in terms of barrier and displacement/attraction effects compared to one that is not (although the latter scenario is unlikely). Another consideration which has been picked up by this review occurs when the windfarm has relatively low numbers of certain species using the site pre-construction. This may give a misleading impression as to the extent of any changes pre- and post-construction. Whilst an increase or decrease in numbers between these periods may give the impression of a significant effect, the power to detect such a change is extremely low, and, as a consequence, we cannot have much confidence in these results.

Another important caveat related to all studies of barrier and displacement/attraction effects, is that there has been very little attention given to teasing out potential variation over the annual cycle and only a single value of relative change between pre- and post-construction is presented. Yet there may be significant time and energy constraints imposed by the breeding season when birds have to return repeatedly to the nest whereas at other times of year they can move more freely (Stephens *et al.* 1986). In addition to this shift due to the onset of the breeding season, notable changes in foraging behaviour within the breeding season have also been extensively documented in seabirds (e.g. black-legged kittiwake trip duration typically decreases from incubation to the chick rearing period due to the need to feed the young frequently Hamer *et al*. 1993). Hence, the response of foraging and commuting birds to the presence of a windfarm may vary according to the stage of their life cycle e.g. birds which are limited in terms of time or energy may be willing to take more risks by entering the windfarm when otherwise they would simply avoid the area. While, due to the absence of evidence, any such seasonal variation in birds' responses to the impacts of windfarms is hypothetical, when utilising derived macro avoidance rates, the extent to which these values are considered representative for all times of year should be given careful consideration, particularly if they contribute to the collision risk modelling. There may also be further scope in the future for investigating variation in macro-responses between the breeding and non-breeding seasons (although investigating within the breeding season differences may be more problematic).

Among the priority species considered by this review, there is limited evidence, however, to suggest that northern gannet may show a tendency towards a negative macro–response. The study of barrier effects at Egmond aan Zee, Krijgsveld *et al.* (2011) suggests a macro-avoidance rate of 0.64, while the study of displacement at Blighbank, Vanermen *et al.* (2013) suggests a macro-avoidance rate of 0.84. At this stage, the lower and therefore the most conservative of these values is assumed to be a reasonable macro-response rate.

In contrast, there is a lack of species- or even species group-specific evidence for barrier effects relating to gulls. With respect to displacement/attraction, the evidence is equivocal, with some studies suggesting evidence for attraction, others evidence for displacement, and others no significant response. For gulls, the balance of evidence thus suggests a macro-response of 0 (i.e. no attraction to or avoidance of the windfarm).

Table 5.2 Summary of key studies of displacement and attraction studies, the stages of development at which data were collected, main methods used, parameters collected, species reported and responses. Grey indicates species which were not covered by that particular study. For further information see Appendix 2 for site accounts.

Windfarm	**Study**	**Survey/s used**	**Modelling approach**	**Species**	**Response (values are given in parentheses where available)**		
					Displacement	**Attraction**	**None**
Blighbank	Vanermen *et a*l. (2013)	Boat	Generalised linear models with a negative binomial distribution with count data as the response	Northern gannet	✓(0.84)[1]		
				Lesser black-backed gull		✓(-3.81)[6]	
				Herring gull		✓(-51.98)[6]	
				Great black-backed gull			✓
				Black-legged kittiwake			✓
Egmond aan Zee	Leopold *et al.* (2011)	Boat	Presence/absence modelling of individual monthly surveys (Generalised Additive Modelling)[2]	Northern gannet (10/2) [2]	✓		
				Lesser black-backed gull (12/1) [2]	✓		
				Herring gull (14/3) [2]	✓		
				Great black-backed gull (17/6) [2]	✓[4]	✓[5]	
				Black-legged kittiwake (5/1) [2]		✓	
Horns Rev	Peterson *et al.* (2006)	Aerial	Comparison of Jacob's Selectivity Indices Encounter rates per survey km (student's t-test)	Northern gannet			✓
				Lesser black-backed gull			
				Herring gull			✓
				Great black-backed gull			
				Black-legged kittiwake			

Windfarm	Study	Survey/s used	Modelling approach	Species	Response (values are given in parentheses where available)		
					Displacement	Attraction	None
Nysted	Peterson *et al.* (2006)	Aerial	Comparison of Jacob's Selectivity Indices Encounter rates per survey km (student's t-test)	Northern gannet			
				Lesser black-backed gull			
				Herring gull			✓
				Great black-backed gull			
				Black-legged kittiwake			
Alpha Ventus	BSH (2011) and Mendel *et al.* (2014)	Boat and aerial	Comparison of changes distribution patterns (1 km$^{2)}$ Generalised Linear Mixed Models with a Poisson error[7]	Northern gannet			✓
				Lesser black-backed gull	✓		
				Herring gull			
				Great black-backed gull			
				Black-legged kittiwake	✓		
Robin Rigg	Natural Power (2014)	Boat	Generalised Additive mixed effects mixture modelling within a Bayesian framework	Northern gannet -			✓
				Lesser black-backed gull			
				Herring gull	✓		
				Great black-backed gull	✓[3]		
				Black-legged kittiwake			✓

[1] See Appendix 2 for calculations

[2] The total numbers of post-construction monthly surveys for which there were sufficient data for modelling / the number of which the results were significant

[3] Between pre-construction and construction only

[4] Four surveys

[5] Two surveys.

[6] negative values for attraction;

[7] lesser black-backed gull only.

5.2 Review of Published Evidence for Meso-Response Rates of Marine Birds

5.2.1 Studies of meso-avoidance

Within a windfarm, birds may respond to the presence of a turbine either by altering the altitude at which they fly, termed a vertical meso-response, or by altering the flight path they take, termed a horizontal meso-response. This is distinct from micro-avoidance, which occurs as a 'last-second' reaction to avoid collision, as meso-responses may take place at some distance from the turbines but still within the windfarm site.

On entering a windfarm, birds may alter their horizontal flight path so that they fly around, or between, turbines, thereby lowering their risk of collision. Alternatively, they may make no response, or even be attracted to a turbine, as a potential roost or perch. In such circumstances, the risk of collision for each individual bird would remain the same, or increase. Such behaviours can be assessed by examining flight paths within the windfarm and considering whether these show a change in direction as they approach the turbines or considering whether birds approach turbines in the proportions that may be expected if they were randomly distributed within the windfarm.

Birds may also alter their flight heights in response to turbines. They may alter their flight heights so that they fly under, or above, the turbines in order to avoid collision. Alternatively, they may make no alteration to their flight height in response to encountering a turbine, meaning either they make a horizontal alteration to their flight path to avoid collision, or their risk of collision remains the same.

Avian flight heights are commonly assessed during surveys of onshore or offshore windfarms. However, concluding that a certain proportion of birds might fly below the rotor swept area of a turbine does not necessarily imply avoidance behaviour as seabirds commonly fly at low altitudes in the absence of turbines (Cook *et al.* 2012, Johnston *et al.* 2014a). In order to assess the scale of any vertical responses to turbines it is necessary to compare the proportion of birds flying at rotor height within the windfarm to data collected either prior to the windfarm construction, or to the proportion of birds flying at rotor height in control areas adjacent to the windfarm.

5.2.2 Horizontal meso-response conclusions

Evidence for the extent and direction of horizontal meso-responses to turbines is extremely limited (see Appendix 3). We identified two studies with relevant information from the onshore environment (Everaert 2008 and Janoska 2012) and two studies from the offshore environment (Skov *et al.* 2012 and Krijgsveld *et al.* 2011). At De Put in Belgium, no evidence of a response was recorded amongst either black-headed or common gulls (Everaert 2008). Similarly, the data presented for Horns Rev I and II in Denmark only support a meso-response for large gulls, with none of the 402 flight paths recorded passing within less than 50 m of a turbine (Skov *et al.* 2012). The data presented do not make it possible to determine whether meso-responses occur within northern gannet, common scoter or terns although, on average these species passed turbines at a greater distance than large gulls. Data from two terrestrial sites in Hungary also suggest a strong, meso-response for large gulls, with only 2.5% of birds flying within 75 m of a turbine (Janoska 2012). However, confidence in these data is extremely limited given the lack of detail available about the methodology of this survey. The strongest evidence for a meso-response rate from an offshore windfarm comes from Egmond aan Zee in the Netherlands. Here, the number of birds recorded by radar within 50 m of a turbine was 66% of those recorded elsewhere within the windfarm (Krijgsveld *et al.* 2011), reflecting a meso-response rate of 0.34, considerably lower than the meso-response rate reported in the Hungarian study.

However, it should be noted that measurements of the proportions of birds passing within a set distance of a turbine may not be an accurate reflection of the true meso-response rate. To estimate species' meso-response rates it is necessary to consider whether the proportion or density of birds in areas close to turbines is higher or lower than would be expected within the windfarm as a whole. This could, potentially, be assessed either through visual observations during surveys of the area, or with the use of remote tracking technologies, such as radar. At present, however, such data are too limited to reliably quantify the horizontal meso-response rates of birds within a windfarm.

5.2.3 Vertical meso-response rates conclusions

All evidence for vertical meso-response rates which we identified originated from the offshore environment (Table 5.3). The quality of evidence presented by each of these studies varies considerably (see Appendix 4). For example, at Blyth, there was a reported increase in the proportion of birds flying at altitudes of more than 9.1 m above mean sea-level between pre- and post-construction (Rothery *et al.* 2009). However, as the rotor sweep of turbines at this site is between 26.4 and 92.4 m above mean sea level, it is unclear as to whether, despite this apparent increase in flight height post-construction, there was a significant increase in the proportion of birds flying at rotor height. Similarly, data from Nysted and Horns Rev were collected by radar and cover all birds flying below 200 m above mean sea level and are also, therefore, likely to incorporate a significant number of birds flying outside the rotor sweeps at these sites (Blew *et al.* 2008). Due to the significant proportion of birds in both of these studies that are likely to fly outside the turbine rotor sweeps, it is not possible to obtain useful information about the level of vertical meso-responses from either. In addition, at Robin Rigg (Natural Power 2013) concerns have been raised about the power of the available data to detect changes in species' flight heights, and about the methodology used to collect data on species in flight which may have led to the double-counting of individuals. For these reasons, data from these sites are not considered further in this section.

Of the remaining sites, estimates of vertical meso-avoidance rates can be obtained from Barrow (Barrow Offshore Wind Farm Ltd) and Gunfleet Sands (NIRAS 2011, GoBe Consultants Ltd. 2012) by comparing the proportion of birds flying in different height bands pre- and post-construction, and at Egmond aan Zee (Krijgsveld *et al.* 2011) by comparing the proportion of birds at different heights inside and outside the windfarm. Of the species or groups for which data were available, only divers showed a consistent vertical response to turbines, in the form of a reduced proportion of birds at rotor height. Other species appear to show a full range of responses covering a strong vertical avoidance to a strong vertical attraction. For example, the proportion of northern gannet assessed to be flying at heights placing them at risk of collision increased by 59% between pre- and post-construction at Barrow, but the proportion at risk height at Egmond aan Zee within the windfarm was 49% lower than the proportion outside the windfarm. A similarly mixed picture is evident for each of the remaining four priority species. The differences in the methodologies used by each study and the inconsistency in the different results mean it is not possible to draw conclusions about the magnitude or direction of any vertical meso-response to turbines.

Table 5.3 Vertical meso-avoidance rates obtained from reviewed studies – see Appendix 4 for the origin/derivation of these figures. Values of 0 indicate no response, values <0 indicate an attraction response, values >0 indicate an avoidance response.

	Barrow	**Blyth Summer**	**Blyth Winter**	**Egmond aan Zee**	**Gunfleet Sands 2010/11**	**Gunfleet Sands 2011/12**	**Nysted / Horns Rev**	**Robin Rigg**
	Barrow Offshore Wind Farm Limited.	**Rothery *et al.* (2009)**	**Rothery *et al.* (2009)**	**Krijgsveld *et al.* (2011)**	**Niras (2011), GoBe Consultants Ltd, (2012)**	**Niras (2011), GoBe Consultants Ltd, (2012)**	**Blew *et al.* (2008)**	**Natural Power Consultants (2012)**
Diver spp					1.00	1.00		
Red-throated diver					0.39	0.86		
Northern gannet	-0.59	-27.00	*exp**	0.49				*exp**
Common scoter	-0.24	0.00	0.00					
Common eider		0.00	-2.00					
Great cormorant	*exp**	-1.38	-0.61	-0.38				*exp**
Arctic skua	-1.00							
Black-headed gull	0.56	0.07	-7.00	0.49	-10.70	1.00		
Common gull	*exp**			-0.20	-0.25	0.33		
Little gull				-0.65				
Black-legged kittiwake	-0.41	-0.14	-28.00	0.20	-0.47	0.05		-1.00
Small gulls				-0.26				
Lesser black-backed gull	0.72			-1.00	-0.44	0.00		
Herring gull	0.35	-1.16	-1.67	0.02	-0.02	0.11		-8.00

Great black-backed gull	0.28	-1.38	-3.50	0.17	-0.75	-0.53		-0.67
Large gulls				-0.01				
Gull spp	-0.85			0.45	-1.98	-1.13		
Sandwich tern	0.56	-1.94		0.35				
Common guillemot	-1.00							
Auks spp	-1.00							
Daytime migrants <200							0.17	
Night time migrants <200 m							0.18	

*Increase in the number of birds recorded from 0 in pre-construction surveys, meaning it is not possible to calculate a proportional increase.

5.2.4 Meso-response rates conclusions

Data quantifying meso-response rates to turbines within offshore windfarms are extremely limited and of variable quality. Overall, evidence describing horizontal meso-responses appears to be stronger than the evidence for vertical meso-responses. Data from one onshore (Janoska 2012) and one offshore site (Krijgsveld *et al.* 2011) appear to suggest a moderate, negative horizontal meso-response to turbines. Whilst there was a stronger meso-response rate at the onshore site, a lack of methodological detail made it difficult to understand the reasons for this difference. Furthermore, an additional two studies did not offer evidence of a horizontal meso-avoidance rate (Everaert 2008, Skov *et al.* 2012). As all four studies we identified had limitations at this stage it is not possible to be confident about the magnitude of any horizontal meso-response, particularly at a species specific level. Whilst a greater quantity of data were available describing vertical meso-responses to turbines, the variable nature of these data and limitations associated with each study, mean it is not possible to draw firm conclusions about either the magnitude or direction of any vertical meso-response. Particular concerns included the low power of some of the datasets, and a lack of overlap between the height bands assessed and the rotor-swept areas of the installed turbines.

However, some studies do indicate how meso-responses may vary within-windfarms. Data from Horns Rev suggest that as birds travel further into a windfarm, they respond more strongly to turbines, with a greater number of directional changes in response to the third or fourth turbine rows than to the first or second rows (Petersen *et al.* 2006). Similarly, the operational status of turbines may influence species responses. Again at Horns Rev, common scoter, Arctic skua, herring gull, great black-backed gull, kittiwake, common/Arctic tern and Sandwich tern were all found to be less likely to pass by operational than non-operational turbines. This response is even stronger when considering birds passing between two adjacent turbines which are both either operational or non-operational (Petersen *et al.* 2006). Similar results have been found at Alpha Ventus and Egmond aan Zee, where concentrations of birds were higher when turbines were non-operational than when they were operational (Krijgsveld *et al.* 2011, Mendel *et al.* 2014).

5.3 Review of Published Evidence for Micro-Avoidance Rates of Marine Birds

5.3.1 Studies of micro-avoidance

We consider micro-avoidance to be the ‘last-second’ action taken to avoid collision with a turbine. In practice, this can be difficult to measure given the effort required to generate meaningful data. Several strategies have been employed to collect such data including: direct observations of bird interactions with turbines, using radar to track birds as they approach turbines and fitting cameras to turbines to record interactions. Interpretation of these data may be challenging and necessitate subjective judgements in relation to whether a bird is at risk of collision and what behavioural responses reflect a reaction.

5.3.2 Micro-avoidance conclusions

Data describing the ‘last-second’ response of birds to turbines have been collected from 16 individual turbines, of which 14 were offshore and two were onshore, across four sites for in excess of 3,000 hours (Desholm 2005, RPS 2011, Krijgsveld *et al.* 2011, Wild Frontier Ecology 2013; see Appendix 5). Despite this effort, very few birds have been recorded passing close enough to turbine rotors to necessitate micro-avoidance action. In total, 45 birds (excluding those recorded at Nysted in Denmark, which were not recorded passing within less than 20 m of turbines, Desholm 2005) have been recorded passing close enough to turbines to necessitate some form of avoidance action, and at least 42 of these have been recorded as taking some form of avoidance action (RPS 2011, Krijgsveld *et al.* 2011, Wild Frontier Ecology 2013). The remaining three birds were tracked at Egmond aan Zee in the Netherlands, using radar and it is unclear whether or not these may also have taken some form of avoidance action, although they were not recorded as colliding with the turbines (Krijgsveld *et al.* 2011).

These data suggest that last-second action to avoid collision is an extremely rare event. This is not because birds do not respond to turbines, but because most avoidance action takes place at distances from the turbines beyond which the methodologies in the studies above could record (i.e. at the meso- and/or macro scales). Whilst only limited data are available describing micro-avoidance rates, the 45 flights considered in the studies described above suggest that a high proportion of birds, >0.93 based on the data described above, may take last second action to avoid collision.

5.4 Review of Published Evidence for Within-Windfarm Avoidance Rates of Marine Birds

5.4.1 Background

In addition to monitoring behavioural avoidance of birds at windfarms, as described in the micro-avoidance and meso-response sections above, a key part of the post-construction monitoring programmes at onshore windfarms is recording the incidence of collisions between birds and turbines. This is typically achieved through organised searches at regular intervals around turbine bases (e.g. Winkelman 1992, Thelander *et al.* 2003, Everaert 2008). Corrections are then applied to account for factors including searcher efficiency and the removal of corpses by scavengers (e.g. Winkelman 1992). These records are often presented as a collision rate per turbine per year (e.g. Winkelman 1992, Musters *et al.* 1996, Brown & Hamilton 2004, 2006, Grunkorn *et al.* 2009). Whilst such values may provide a useful comparison of collision risk between individual turbines within a windfarm, or between windfarms in general, they do not, by themselves provide useful information about the behavioural responses of birds to the presence of turbines.

In order to use collision rates to derive meaningful information about the behavioural responses of birds to the turbines, it is necessary to combine them with an estimate of the rate at which birds pass through the windfarm. Estimates of the rate at which birds pass through the windfarm can be derived by converting the total number of birds observed over a known period of time into an hourly, or daily rate. These flux rates can then be multiplied by the total length of the study period, taking care to correct for factors such as variable day length, to estimate the total number of birds passing through the windfarm during the period in question – for example, the months over which searches were made for collision victims. It may also be necessary to rescale these estimates, for example if only a proportion of the windfarm was covered during surveys. However, as movement data refer to the windfarm as a whole, it is not possible to separate the meso and micro elements of these mortality derived avoidance rates. For this reason, these are collectively referred to as within-windfarm avoidance rates.

5.4.2 Methodology

5.4.2.1 Deriving within-windfarm avoidance rates

We identified 20 sites at which data were available combining an estimate of the collision rate with an estimate of the rate of flux through the windfarm that made it possible to derive within-windfarm avoidance rates (see Appendix 6). Of these, 17 sites were onshore and three were offshore. Using the methodology set out in Band (2007) it is possible to calculate the number of birds expected to collide with turbines at each of these sites if no avoidance action is taken.

The first step of this process is to estimate the total number of birds likely to have passed through the windfarm during the period in which collisions were recorded. As surveys are not, typically, carried out continuously over the study period, the number of birds recorded must be converted to an hourly rate. The total number of birds passing through the windfarm is then estimated by multiplying the hourly rate by the total number of hours over the study period as a whole, with a correction applied to account for the nocturnal activity level of the species concerned, based on the figures reported in Garthe and Hüppop (2004). However, it should be noted that the difficulty of collecting data on nocturnal activity in seabirds means it is unclear how accurate these figures are.

The next step is to use this value to estimate the total number of birds likely to pass through the turbine rotor sweeps. The total number of birds flying through the windfarm is multiplied by the proportion estimated to fly at rotor height, based on the original survey data. This value is then converted to the number of flying birds per m^2 and multiplied by the total area occupied by the turbine rotors.

A significant proportion of the birds passing through the turbine rotors are likely to do so without colliding (Band 2007). Therefore, a correction, the Probability of Collision (P_{coll}), must be applied to the data to account for this. This is calculated based on the turbine specifications, design of the windfarm array and the flight behaviour and morphometrics of the species of interest and based on the methodology set out in Band (2007). Species morphometric and behavioural data used to estimate P_{coll} are given in Table 5.4, whilst turbine details for each site are given in Table 5.5.

Table 5.4 Bird parameters to estimate P_{coll} for each windfarm. Speed data taken from Pennycuick (1997) and Alerstam *et al.* (2007), morphometric data from Robinson (2005), where species groups are given, data come from a species likely to be representative of that group as a whole, within the offshore wind context.

Species	Length (m)	Wingspan (m)	Speed (m/s)	Flap/glide
Diver (red-throated diver)	0.61	1.11	14.50	flap
Grebe (great crested grebe)	0.48	0.88	18.65	flap
Northern gannet	0.94	1.72	14.90	glide
Arctic skua	0.44	1.18	13.30	flap
Great cormorant	0.90	1.45	14.50	flap
Common eider	0.60	0.94	18.65	flap
Common scoter	0.49	0.84	18.65	flap
Long-tailed duck	0.58	0.88	18.65	flap
Black-headed gull	0.36	1.05	9.50	flap
Common gull	0.41	1.20	9.50	flap
Black-legged kittiwake	0.39	1.08	13.10	flap
Franklin’s gull	0.41	1.20	18.65	flap
Ring-billed gull	0.41	1.20	9.50	flap
Little gull	0.26	0.78	11.50	flap
Lesser black-backed gull	0.58	1.42	13.10	flap
Herring gull	0.60	1.44	12.80	flap
Great black-backed gull	0.71	1.58	13.70	flap
Little tern	0.23	0.52	10.00	flap
Common tern	0.33	0.88	10.00	flap
Sandwich tern	0.38	1.00	10.00	flap
Auk (common guillemot)	0.40	0.67	19.10	flap

Table 5.5 Turbine data used for each site. Figures in red indicate that the parameter was not presented for site in question and had to be estimated from a turbine with a similar design. Row colours indicate confidence assigned to data collected at each site – green indicates highest confidence, where there was both spatial and temporal overlap in the collection of corpse and movement data; yellow indicates moderate confidence where there was temporal overlap in the collection of corpse and movement data, but incomplete spatial overlap, meaning that bird activity had to be extrapolated across the site; red indicates lowest confidence, sites where there was incomplete spatial and temporal overlap in the collection of corpse and movement data, meaning bird activity had to be extrapolated both spatially and temporally; grey indicates studies in which flights through the windfarm were recorded so that collisions could be directly recorded, such studies typically had very little power.

Windfarm	N turbines	Turbine capacity (MW)	Width of survey window (m)	Height of survey window (m)[1]	N blades	Blade width (m)	Rotor diameter (m)	Rotor speed (rpm)	Pitch (degrees)	Hub height (m)
Altamont	685	0.12	7713.624[2]	33.5	3	0.66	19	43.0[25]	10	24.0
Blyth	2	2.00	600[3]	92.4	3	4.40	66	18.0[26]	10	59.4
Blyth Harbour	9	0.30	925[4]	37.5	3	66[32]	25	43.0	10[32]	25.0
Boudwijnkanaal	5/7/14[5]	0.6	1040/1536[6]	79	3	1.10	48	43.0[25]	10	55.0
Bouin	8	2.5	4000[7]	100	3	4.40	80	18.0[26]	10	60.0
Buffalo Ridge	143	0.75	9600[8]	74	3	1.10	48	32.3	10	50.0
De Put	2	0.8	300[9]	100[26]	3	1.10	48	43.0[25]	T10	75.0
Gneizdzewo	19	2.00	3700[10]	120	3	4.40	80	18.0[26]	10	80.0
Greater Gabbard	7	3.6	4000[11]	180[27]	3	4.20	107	15.0[27]	10	77.5
Groettocht	5	1.65	1000[12]	140[28]	3	4.40	66	21.3	10	78.0
Haverigg	8	0.6	920[13]	66	3	1.10	42	43.0[25]	10	45.0
Kauwnee County	31		12247[14]	89	3	1.10	47	43.0[25]	10	65.0
Kessingland	2		800[15]	126	3	2.50	92	15.0	10	80.0

Kleine Pathoweg	7	1.8	1820[16]	120	3	4.40	70	18.0[26]	10	85.0
Oosterbierum	18	0.3	1430[17]	60[18]	3	0.66	30	43.0[25]	10	35.0
Waterkaaptocht	5	1.65	1000[12]	140[28]	3	4.40	66	21.3	10	78.0
Yttre Stengrund	5	2.0	20000[19]	250[29]	3	4.40	72	10.0	10	60.0
Zeebrugge	4/6/23/24/25[20]	0.4[21]	400/720[22]	65/80[23]	3	0.66	34	43.0[25]	10	34.0
Hellrigg	4	2.3	4000[24]	121	3	4.40	82	18.0[26]	10	80.0
Avonmouth	3	2.00	1300[30]	160[31]	3	4.40	83	17.5	10	79.0

[1]Maximum turbine height unless otherwise stated; [2]see Table 2 of Thelander *et al.* 2003, total survey area of 59.5 km^2, width of survey window assumed to be $\overline{59.5} * 1000$; [3]Rothery *et al.* (2009) state 600 m scan area; [4] Lawrence *et al.* (2007) state that observations were carried out between turbines 5-9, turbines separated by 200 m with a rotor diameter of 25 m and arranged in a single line; [5]Collisions were recorded under all 14 turbines in 2002-2006. In 2001, bird activity surveys were carried out around five turbines and avoidance rates derived from collisions around these turbines are also presented. In 2005, bird activity surveys were carried out around seven turbines and avoidance rates derived from collisions around these turbines are also presented; [6]In 2001, only five turbines were present with diameters of 48 m and spacing of 200 m, therefore, the total survey window in 2001 was 1,040 m wide (section 3.3.1 in Everaert *et al.* 2002, Table 27 in Everaert 2008). In 2005, 14 turbines were present, but activity was only monitored around seven of these, therefore in 2005 the total survey window was 1,536 m wide (Table 27 in Everaert 2008). Turbines were all arranged in a single line; [7]Observations carried out along four 1 km linear segments on the edge of the windfarm, see section 5.1 of Dulac (2008); [8] Raptor/large bird surveys carried out through point counts at six locations, each with a radius of 0.8 km, (page 7, Johnson *et al.* 2000); [9]Estimated from Figure 101 in Everaert (2008); [10]Estimated from Google Earth map of windfarm ([redacted] [11]Data collected within viewing arc with a radius of 2 km, covering seven turbines (Galloper Offshore Windfarm Environmental Statement, Appendix 4); [12]Data presented as number of birds/km/hr; [13]Table A.3.13 in Galloper Offshore Windfarm Environmental Statement; [14]Abstract of Howe *et al.* (2002) states that 150 km^2 were surveyed, width taken as $(\overline{150}) * 1000$; [15]Birds recorded were those passing within a 200 m radius around each turbine, Wild Frontier Ecology (2013); [16]Table 32 of Everaert (2008), activity monitored around turbines 3-7 which are each separated by 280 m, arranged in a single line and have a diameter of 140 m; [17]Section 2.1 of Winkelman (1992), turbines have a diameter of 30 m and are 250 m apart and arranged in three lines of six turbines; [18]Birds up to 60 m recorded (Tables 12a-d Winkelman 1992); [19]Movements monitored over four 5 km observation lines (Figure 3, Petterson 2005); [20]Based on Everaert (2008) – 23 turbines were operational and searched for corpses in 2001-2003, 25 turbines were operational and searched for corpses in 2004, and 24 turbines were

operational and searched for corpses in 2005-2007. In addition, collision data for the four turbines monitored for gull activity in 2000 and 2001 (Everaert *et al.* 2002) and the seven turbines monitored for tern activity in 2004 and 2005 (Everaert & Stienen 2007, Everaert 2008) are also analysed in this report; [21]While different turbine types have been used at Zeebrugge, the analysis in this report is based on the assumption that they share the characteristics of those on the eastern wall, where the greatest number of collisions are typically recorded (Everaert 2008); [22]Gull activity was monitored along a 400 m section of the eastern wall in 2000 and 2001 (Everaert *et al.* 2002) and tern activity was monitored along a 720 m section of the eastern wall in 2004 and 2005 (Everaert & Stienen 2007, Everaert 2008); [23]In 2000 and 2001, flight height was estimated up to a maximum of 65 m and in 2004 and 2005 flight height was estimated up to a maximum of 80 m; [24]States that standard SNH vantage point methodology with radius of 2 km from a single point used (Percival 2012, 2013);[25]Based on rotational speed of Blyth Harbour turbines;[26] Based on rotational speed of Enercon E-70 2.3 MW turbine;[27]Similar size to Kessingland turbines; [26]Birds up to 100 m recorded, see Table 37 of Everaert (2008); [27]Birds up to 180 m recorded, see section 1.11 of Appendix 4; [28]Radar monitoring of flight heights up to 140 m, see Krijgsveld *et al.* (2011); [29]Flights monitored up to altitude of 250 m, see figure 11 of Petterson (2005); [30]Estimated from Google Earth map of windfarm ([redacted] [31]Paragraph 2.3 of The Landmark Practice (2013).[32]highlighted grey so red numbering shows up against red background.

The number of birds predicted to collide with the turbines in the absence of any avoidance action can be estimated by multiplying the total number of birds predicted to pass through the rotor sweep of the turbines over the course of the time period in which collision searches were carried out by the probability of those birds colliding with the rotor blades. An avoidance rate can now be derived from these data by dividing the observed collision rate by the predicted collision rate, as in equation 6.

Avoidance rates were derived, as described above, for each species-site combination for which sufficient data were available in the studies identified as part of our literature review. The quality of data presented in each of these reports was highly variable, in particular in the level of spatial and temporal overlap between the periods over which corpses were collected and bird movement data were collected. The feasibility of collecting movement data over the course of the study periods as a whole meant that some extrapolation was inevitable when calculating avoidance rates. However, we sought to minimise this extrapolation and sought to categorise the studies we identified accordingly (Table 5.5).

The first category (green) we identified, which we had greatest confidence in, was that in which activity data were collected at intervals throughout the period in which corpse data were collected, and from around all turbines which were searched for corpses. This meant that no spatial extrapolation was necessary to derive an avoidance rate, and the need for temporal extrapolation was minimised. The second category (yellow) we identified was similar to the first, with the exception that activity data were not collected around all of the turbines which were searched for corpses, for example at Kleine Pathoweg, where bird movements were only monitored around five of the seven turbine where corpse searches were carried out. This meant that spatial extrapolation of movement data was necessary, potentially leading to erroneous conclusions if flights were not to occur evenly throughout the site. The third category (red) also required spatial extrapolation of activity data. In addition, movement data were only collected for a portion of the time in which corpse data were collected, meaning that bird activity had to be extrapolated across seasons or years. Such extrapolation is extremely likely to give a misleading picture of the true level of bird activity at a site over the study period which is likely to vary seasonally, e.g. over breeding or migration periods. The final category (grey) relates to studies in which bird movements through windfarms have been monitored in order to directly observe collisions. Given the relative rarity of birds colliding with turbines, these studies typically have low power to detect a collision.

We consider how each of these categories influences the avoidance rates that are derived. We also consider the influence of other factors, such as turbine size, on avoidance rates in order to assess whether it is appropriate to apply avoidance rates from some of the smaller onshore turbines to the much larger turbines used in the offshore environment.

The estimation of predicted collisions requires assumptions to be made regarding the proportion of birds flying at collision risk height and their flight height distributions. Consequently, we derive avoidance rates appropriate for use with each of the three model options presented in the Band offshore collision risk model spreadsheet (Band 2012):

i. Option 1, where site specific flight height data are used to estimate the proportion of birds flying at collision risk height;
ii. Option 2, where modelled data are used to estimate the proportion of birds flying at collision risk height, based on the distributions presented in Johnston *et al.* (2014a) and the exact rotor dimensions presented in each report;
iii. Option 3, where modelled flight height distributions are used to account for collision risk not being distributed evenly within a turbine's rotor swept area.

It should be noted that different values would be expected for Band model options 1 and 2 because option 2 uses generic distributions from compiled data sources, which may not be directly comparable to data collected from some of the sites included in this review. In some cases, option 2 may also use a better defined risk window, as it reflects the actual turbine dimensions rather than a pre-defined window set during pre-construction surveys.

5.4.2.2

The aim of this review was to derive representative within-windfarm avoidance rates that can be used to inform a total avoidance rate for use in collision risk modelling for each of the priority species. Whilst the above methodology can give us a range of different values for marine birds in general, and some of the priority species in particular, combining them to get a single, representative figure is far from straightforward. This is further complicated as several studies report no collisions, suggesting an avoidance rate of 1 over the study period. However, were the study periods of these studies to be extended indefinitely, it is likely that the avoidance rate would drop to below 1 as some individuals will always fail to take action to avoid collision, given sufficient time and bird flux within the site. Whilst one approach would be to discard studies in which no collisions were recorded, this would be inappropriate as it would risk negatively biasing our dataset and, potentially, result in a within-windfarm avoidance rate which is overly precautionary.

We identified five methodologies – ratio estimators, meta-analysis, proportional hazard models and mark-recapture models, events-trials models and Poisson regression – that could potentially be used to combine collision records and flux rates across sites in order to derive representative avoidance rates (Table 5.6). We then considered the limitations and assumptions associated with each technique, before determining which was likely to be the most effective approach.

Meta-analysis is most appropriate when estimates of variance around effect sizes are available, which was not the case in this instance. The data available from the studies we reviewed fail basic assumptions about perfect detectability required for proportional hazard models. Similarly, as individual birds are recorded only upon their deaths, and not on their entry to the population, mark-recovery models were not appropriate. Collisions between birds and turbines are rare events. As event-trials models are most effective when the probability of an event is moderate, this methodology is also likely to be ineffective. Poisson regression models may be an effective approach. However, such an approach would require time to develop and test using simulated data. It may also be ineffective without access to raw survey data from each site. Whilst this approach may provide a useful framework for future studies it was not considered feasible within the framework of the current project.

Having considered each of the different approaches, we concluded that ratio estimators would be the most appropriate approach to combining the avoidance rate data. Given the limitations of the data, we felt that any of the more complex modelling approaches may result in undue confidence being assigned to the derived values. In the absence of raw data, we feel that any more involved modelling approach is likely to be less than robust and that, in this instance, a simpler approach, such as ratio estimators, is most appropriate.

Ratio estimators divide the total number of collisions across all sites by the total number of collisions predicted in the absence of avoidance behaviour across all sites (equation 9). By dividing the total number of collisions by the predicted collision rate, sites with greater levels of bird activity are given greater weighting than sites at which bird activity is relatively low. Arguably, this approach to weighting is more appropriate than weighting flux rate alone, as it accounts for the fact that a higher flux rate may not necessarily reflect a greater number of birds at risk of collision. For example, a site may have a relatively high flux rate, but only a relatively small proportion of these birds may be at a height which places them at risk of collision. Using equation 9, we derive representative avoidance rates for all species and groups for which sufficient data were available.

$$Within\ Windfarm\ Avoidance = 1 - \frac{Observed\ collisions}{Pcoll \times Flux\ Rate} \quad \text{(eq. 9)}$$

As data come from multiple sites, there is likely to be a degree of uncertainty associated with avoidance rates derived in this manner. The importance of incorporating uncertainty in the Environmental Impact Assessment process is receiving increasing recognition (Masden *et al.* 2014). The variance associated with the avoidance rates derived using ratio estimators can be calculated using the delta method (Powell 2007). The square root of this value will give an estimate of the standard deviation around the avoidance rates derived using ratio estimators (Batschelet 1976). It is important to note that this value will reflect variability between sites, as opposed to uncertainty in the input parameters. At present, many of the input parameters for the Band model are only available as single values (e.g. mean rotor speed), until a realistic range of values is available for the key parameters, quantifying uncertainty from these sources will be challenging.

As we are looking for representative values for the within-windfarm avoidance rates, it is important to ensure that the values we are deriving are not unduly influenced by a single data point (each data point reflecting a single site-year-species combination), or set of data points. For this reason we investigate how different factors may influence the final avoidance rates we derive. As a first step, we explore how much influence (leverage) each data point has on the final, representative avoidance rates. We identify sites which have a high leverage and determine whether there are any common factors linking them, for example, an unusually high or low flux rate or the presence of small turbines.

We then consider how bird flux and turbine size may influence the final derived avoidance rates using a stepwise approach. These analyses are not an essential part of deriving our final avoidance rates, instead, they help us to understand how reliant our values are on the inclusion of all of our data points. Ideally, as we drop data points from our calculations, the avoidance rates derived should remain fairly constant. In the first analysis, we drop sites based on their estimated flux rates. This helps to demonstrate whether our final avoidance rate is dependent on the inclusion of data from a handful of sites with high levels of bird activity. In our second analysis, we drop sites based on maximum turbine height, to identify whether sites with smaller turbines, less typical of the offshore environment are unduly influencing the values we derive. A more detailed analysis of the sensitivity of our derived values is carried out in section 6 (below).

Table 5.6 Methodologies considered for synthesising avoidance rates across multiple data sources.

Method	**Description**	**Used**
Ratio estimators	Ratio estimators provide a relatively simple approach that compares the mean of the number of collisions to the mean of the number of birds at risk of collision (Cochran 1977). The approach does this by combining data across sites prior to any calculation and, therefore, accounting for the differing levels of bird activity at each site. As the number of birds at risk of collision is proportional to the bird flux at a site, this approach effectively weights sites by the level of bird activity recorded. Depending on the data available, such calculations can be undertaken on a species, group or global basis. They have the advantage of offering a single, easily interpretable output. This approach has previously been used to derive avoidance rates for geese from multiple data sources (Pendlebury 2006).	✓
Meta-analysis	Meta-analysis provides a way of combining studies, which may have different uncertainties attached to them, to determine the size and statistical significance of a given effect. The units of meta-analysis are the independent results of studies, rather than the responses of individual subjects (Arnqvist & Wooster 1995), with a strong recommendation from statisticians that they should use weighted combination of effect sizes (Stewart 2010). Meta-analyses are most appropriate when studies present estimates of variance around the effect sizes (Gurevitch & Hedges 1999, Stewart 2010), which were not available from the studies we have reviewed.	✗
Proportional hazard models / mark-recovery models	We considered the possibility of using time to event style models such as proportional hazard or mark-recovery models. In the case of proportional hazard models, the data fail basic assumptions about perfect detectability necessary for such analyses. As each individual bird is recorded only on its death (and not on entry to the population, i.e. when it enters the turbine space), it was not possible to use mark-recovery type models to produce synthesised ARs from the various studies.	✗
Events-	Events-trials models involve combining the number of events	✗

trials models	(in this case, collisions) with the number of trials (in this case, birds passing through the turbines) within a binomial generalised linear model (GLM). However, collisions are rare events and binomial GLMs work best when the probability of an event is moderate (typically in the region of 0.2-0.8). We therefore feel such a methodology is inappropriate in this instance.	
Poisson regression	As collisions are rare events the mean across sites is likely to be low and may be expected to follow a Poisson distribution. We could use bird flux as an offset in such a model to account for the different abundance of birds at each site and incorporate a weighting factor to account for survey effort. Zero-inflation is also likely to be an issue (i.e. many sites record no collisions). Whilst this approach may be possible and provide a useful framework for future analyses, it would require some time to develop and test using simulated data and was thus outside of the scope of this project. It should also be noted that we are uncertain about how effective such an approach would be without access to the raw survey data from each site.	×

5.4.3 Results

5.4.3.1 Derived within-windfarm avoidance rates

Data combining collision rates and passage rates through windfarms were obtained from 20 sites – see Appendix 6 for details of sites and species, and Appendix 7 for full results. However, based on the available data, it was only possible to derive within-windfarm avoidance rates for eider, gulls and terns. Whilst other species had been recorded within the windfarms, these were often present in relatively low numbers, and only a single collision event, involving a flock of four eider, was observed during visual observations of turbines. The range of species reflects the onshore or coastal locations of the study sites, and it should be noted that, among the priority species being considered in this review, no estimates could be derived for northern gannet.

The range of responses estimated from the available data runs from an apparent strong attraction whereby the proportion of birds within the rotor-swept area increases by >1000% in some cases, to strong avoidance, where close to 100% of birds avoid the rotor-swept area.

Multiple years' data were collected from several onshore sites including Avonmouth and Hellrigg in the UK, Boudwijnkanaal and Zeebrugge in Belgium, Gneizdzewzo in Poland, and an offshore site at Yttre Stengrund in Sweden. Multiple years' collision data were also available from Kleine Pathoweg in Belgium. However, bird activity data were not collected concurrently with data on collision rates for this site, meaning the results cannot be used for the purposes of this review. Whilst we have been able to derive a within-windfarm avoidance rate in both study years for this site, this approach is flawed as it involves extrapolating from one year's activity data to the next. The same is true for some of the data collected for both Zeebrugge and Boudwijnkanaal. Whilst multiple years' data were also collected from sites such as Altamont Pass and Buffalo Ridge in the U.S.A. and Blyth Harbour in the UK, these data were summarised across years so it was not possible to examine year to year variation in derived avoidance rates and the resultant avoidance rates should be treated with a high degree of scepticism. Of the sites where it may be possible to compare values between years, only Hellrigg, Gneizdzewo, Boudwijnkanaal, Yttre Stengrund and Zeebrugge provide data that allow this.

We present within-windfarm avoidance rates from all sites for illustrative purposes only (Appendix 7). For the purposes of deriving representative values, we only use what we consider to be the highest quality data (green rows in Appendix 7) where there is both spatial and temporal overlap between the collection of corpses and the collection of bird activity data. Unless otherwise stated the within-windfarm avoidance rates presented in the text from this point refer to those derived using option 1 of the Band model, but these are applicable to option 2.

In the five years for which data were available for Gneizdzewo, only a single collision involving a gull species was recorded (Appendix 7). Similarly, in the years for which data are available from Hellrigg and Yttre Stengrund, collisions were only recorded in a single year at each site. At Boudwijnkanaal, the within-windfarm avoidance rate for herring/lesser black-backed gulls declined from 0.9903 in October 2001 to 0.9556 in October 2005. At Zeebrugge, it was possible to compare within-windfarm avoidance rates for herring and lesser black-backed gulls both between seasons and years. For herring gulls within-windfarm avoidance rates declined from 0.9861 in the 2000 breeding season to 0.9722 in the 2001 breeding season. For lesser black-backed gulls the equivalent figures were 1 in 2000 and 0.9706 in 2001. In 2001, activity data at Zeebrugge were collected in both the breeding season and autumn. The within-windfarm avoidance rates showed an increase for both species during the autumn, to 0.9976 in the case of herring gulls and 0.9990 in the case of lesser black-backed gulls. However, given the limited data available to explore these patterns, more data are required to make firm conclusions about aspects such as seasonal variation in avoidance rates.

Everaert (2014) presents within-windfarm avoidance rates for gulls derived from the same datasets for Zeebrugge, Boudwijnkanaal, Kleine Pathoweg and De Put, using the basic Band collision risk model. The results differ from those we present. The reason for this is likely to be that Everaert (2014) extrapolate bird activity data to cover broader spatial and temporal scales, whilst we focus only on the turbines and months in which bird activity data were specifically collected. The author highlights this extrapolation as a reason why his results should be treated with caution in his discussion of the results. For our purposes, we felt that focussing on the period when activity data were collected when deriving within-windfarm avoidance rates was more consistent with our approach at other sites. A similar issue has been raised in the past in relation to Sandwich tern within-windfarm avoidance rates derived from collision data at Zeebrugge, where rates derived from the same dataset have varied from 0.9664-0.9955 (see NE/JNCC note on subject). This highlights the importance of transparency in the calculations used to derive within-windfarm avoidance rates, enabling people to understand why differences may have arisen and come to an informed position about which values are likely to be most applicable to the situation at hand.

Our analyses of the tern data from Zeebrugge suggest that within-windfarm avoidance rates are likely to be towards the high point of this range. Using only collisions reported in June and around the seven turbines from which activity data were collected, we estimated a within-windfarm avoidance rate of 0.9944 for common tern in 2004 and 0.9948 in 2005. For Sandwich tern, we estimated within-windfarm avoidance rates of 0.9980 in 2004 and 0.9989 in 2005. No collisions involving little terns were recorded around these turbines in either year. These data suggest that tern within-windfarm avoidance rates are very high, and may be consistent year on year.

In addition to estimating collision rates from fatality searches, at four sites – Blyth Offshore Windfarm, Greater Gabbard Offshore Windfarm, Haverigg Windfarm and the Yttre Stengrund and Utgrunden Offshore Windfarms in Sweden – bird activity has been monitored with a view to directly observing collisions. In total, 646 hours of observations have been collected in this manner across the four sites and five windfarms. These surveys documented 3,167,238 bird movements within-windfarms, including at least 5,319 involving gulls. Despite this, these had relatively low power to detect a collision. In the absence of avoidance action, across these sites only 63 collisions would have been expected based on the basic Band model and only 45 based on the extended Band model (Appendix 7). In relation to the priority species covered by this report, 17 of the collisions predicted using the basic Band model and 13 predicted using the extended Band model would have involved gulls. A single collision involving a gull would reflect an avoidance rate of less than 0.95 for both the basic and extended Band model. Such an avoidance rate would be extremely conservative, and it is therefore, unsurprising that no collisions were recorded during visual observations. Indeed, over the course of these studies, only a single collision event, involving four common eider at a single turbine at Yttre Stengrund Offshore Windfarm was observed, reflecting a within-windfarm avoidance rate of 0.1861 for common eider in autumn 2003 or 0.9024 across all seasons and years. Consequently these studies do not provide strong evidence for the behavioural response of our five priority species to turbines.

Deriving within-windfarm avoidance rates using the different Band model options

Whilst the observed number of collisions remains constant, regardless of the model option used, the predicted number of birds at risk of collision varies. As avoidance rates are derived by dividing observed collisions by predicted collisions (eq. 6), avoidance rates derived using different model options will vary. Collision estimates produced using the different Band model options and option-specific avoidance rates will only be identical if the windfarm in question has the same specifications as used to derive those avoidance rates. However, this will not be the case when these avoidance rates are applied to a novel site as a result of differences in model input parameters (e.g. turbine specifications and site-specific estimates of the proportion of birds at collision risk height).

Within-windfarm avoidance rates derived using option 1 of the Band model are higher than those derived using options 2 and 3. The difference in values derived using option 1 and option 2 results from the use of site-specific data on the proportion of birds at risk in option 1, and the use of a generic flight height distribution to inform the proportion of birds at risk in option 2 – in other respects these options are mathematically identical. The difference between option 2 and option 3 lies in how the flux rate and probability of collision are applied across the turbines rotor-swept area. Using option 2, an average collision probability is multiplied by an average flux rate. This introduces error when a species' flight height distribution is not uniform. Option 3 accounts for the non-uniform flight height distribution, common to many species (Johnston *et al.* 2014a), by integrating the flux rate and collision probability over the turbines' rotor-swept area.

5.4.3.2 Representative within-windfarm avoidance rates

The within-windfarm avoidance rates data described above, and presented in Appendix 7 are of extremely variable quality. The final, derived within-windfarm avoidance rates are heavily dependent on the accuracy of the estimated flux rates at each site and on the accuracy of collision estimates. As continuous monitoring of bird activity at these sites was not feasible, some degree of extrapolation to estimate the total flux rate will be inevitable. However, it is desirable to keep this extrapolation to a minimum. For this reason, we only combine data from sites at which it was not necessary to make a spatial extrapolation in order to estimate a flux rate, and for which activity data were collected at intervals throughout the period in which collisions were monitored, to minimise the potential for inappropriate temporal extrapolation. The sites meeting these criteria were Avonmouth (Winter 2007/08, 2008/09, 2009/10, 2011/12), Boudwijnkanaal (October 2001 and October 2005), Bouin, De Put, Gneizdzewo (autumn 2007, 2008, 2009, 2010, 2011, 2012), Hellrigg (winter 2011, 2012), Kessingland, Oosterbierum (autumn 1990, spring 1991) and Zeebrugge (June-July 2000, June-July 2001 and September-October 2001). All of these sites were located onshore.

Across these sites, a total of 3,880,794 seabirds, of which the majority (66%) were gulls, were expected to have passed through the windfarms over the periods in which corpse searches were carried out. We determined that sufficient data were available to derive avoidance rates for four species – black-headed gull, common gull, lesser black-backed gull and herring gull – and four species groups – all gulls, large gulls (lesser black-backed gull, herring gull, great black-backed gull, Caspian gull, yellow-legged gull), small gulls (black-headed gull, common gull, little gull) and all terns.

Black-headed gull

A total of 746,668 black-headed gulls were expected to have passed through seven sites – Avonmouth (four studies), Boudwijnkanaal (one study), Bouin (one study), Gneizdzewo (three studies), Hellrigg (two studies), Kessingland (one study) and Zeebrugge (three studies) – over the course of their respective study periods. After adjustments were made to this total to account for the proportion of birds flying at rotor height, the size of the rotor swept area and the probability of birds passing through the rotor-swept area without colliding, this was predicted to result in 1,839 collisions based on option 1 and 582 collisions based on option 2, and 297 based on option 3. However, in total only 38 black-headed gull collisions were recorded across all sites during their respective study periods. This corresponds to within-windfarm avoidance rates of 0.9795 (± 0.0033 SD) using option 1 of the Band model, 0.9351 (± 0.0031 SD) using option 2 of the Band model and 0.8731 (± 0.0056 SD) using option 3 of the Band model.

We investigated the leverage that each study site had on the final within-windfarm avoidance rates derived for black-headed gull. We identified three sites which had high leverage for the within-windfarm avoidance rates derived using options 1 and/or 2 and/or 3 of the Band model (Figure 5.1). Of these, the exclusion of data from Bouin resulted in an increase in the value derived using option 1. This is likely to be due to the presence of the turbines on the edge of a black-headed gull breeding colony. This may have led to a greater number of flights through the rotor-swept area of turbines by adult birds returning to provision chicks and/or newly fledged chicks less experienced at flying. As a result of the relatively high collision rate at this site, including this site in our analysis reduced the overall within-windfarm avoidance rate derived using option 1. The leverage of data from Hellrigg in 2012/13 was of a similar magnitude, but in the opposite direction. Despite having the highest level of black-headed gull activity and a high proportion of birds flying at collision risk height, no collisions were recorded at this site, in this year. As a consequence, excluding these data from our analysis resulted in a reduction in the overall within-windfarm avoidance rate.

In contrast to option 1, the exclusion of data from Bouin led to a substantial decrease in the overall within-windfarm avoidance rates derived using options 2 and 3. The relative importance of data from Bouin is exaggerated using options 2 and 3 of the Band model as modelled flight height distributions suggest that other sites with high levels of bird activity, such as Hellrigg, should have very low proportions of birds flying at collision risk height. As such, the predicted collision rates at these sites are much lower than when using option 1 and they have much less influence when used to derive overall within-windfarm avoidance rates using ratio estimators. In addition, the within-windfarm avoidance rates derived for Bouin using options 2 and 3 are significantly higher than for other sites at which collisions were recorded meaning, given its importance relative to other sites, excluding data from Bouin from the analysis results in a significant decrease in the overall within-windfarm avoidance rate derived. Excluding data from Boudwijnkanaal from the analysis for options 2 and 3 results in an increase in the overall within-windfarm avoidance rate. As with Bouin, a relatively high number of collisions were recorded at this site. However, as observed data suggest a high proportion (69%) of birds flew at collision risk height, this site did not have particularly high leverage for the within-windfarm avoidance rates derived. However, using options 2 and 3, only 4.5% of birds were predicted to fly at collision risk height, meaning the final within-windfarm avoidance rate derived for this site was relatively low.

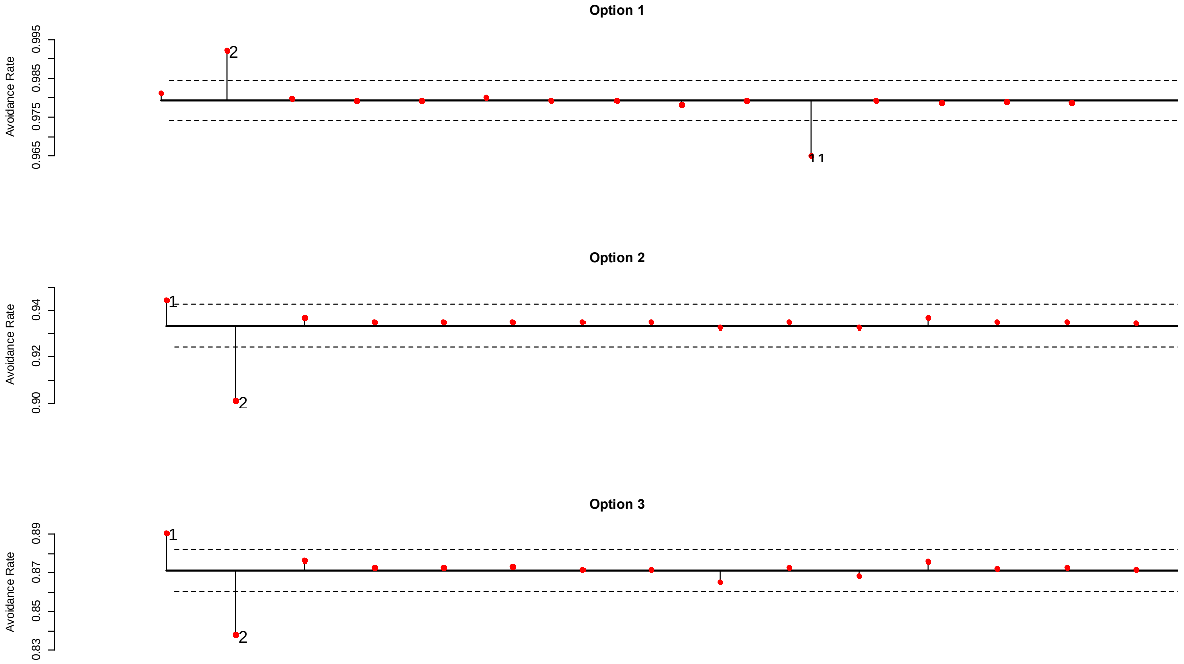


Figure 5.1 Leverage exerted by each site at which within-windfarm avoidance rates were calculated on the overall, mean within-windfarm avoidance rate derived for black-headed gull. Solid line indicates mean within-windfarm avoidance rate across all sites, broken line indicates mean within-windfarm avoidance rate across all sites ± 1 standard deviation, dots indicate mean within-windfarm avoidance rate with each site excluded from analysis. Sites are considered to have high leverage when their exclusion from the analysis leads to a change of more than 1 standard deviation in the overall mean within-windfarm avoidance rate. Sites with high leverage are: 1 – Boudwijnkanaal, 2 – Bouin and 11 – Hellrigg in 2012/13.

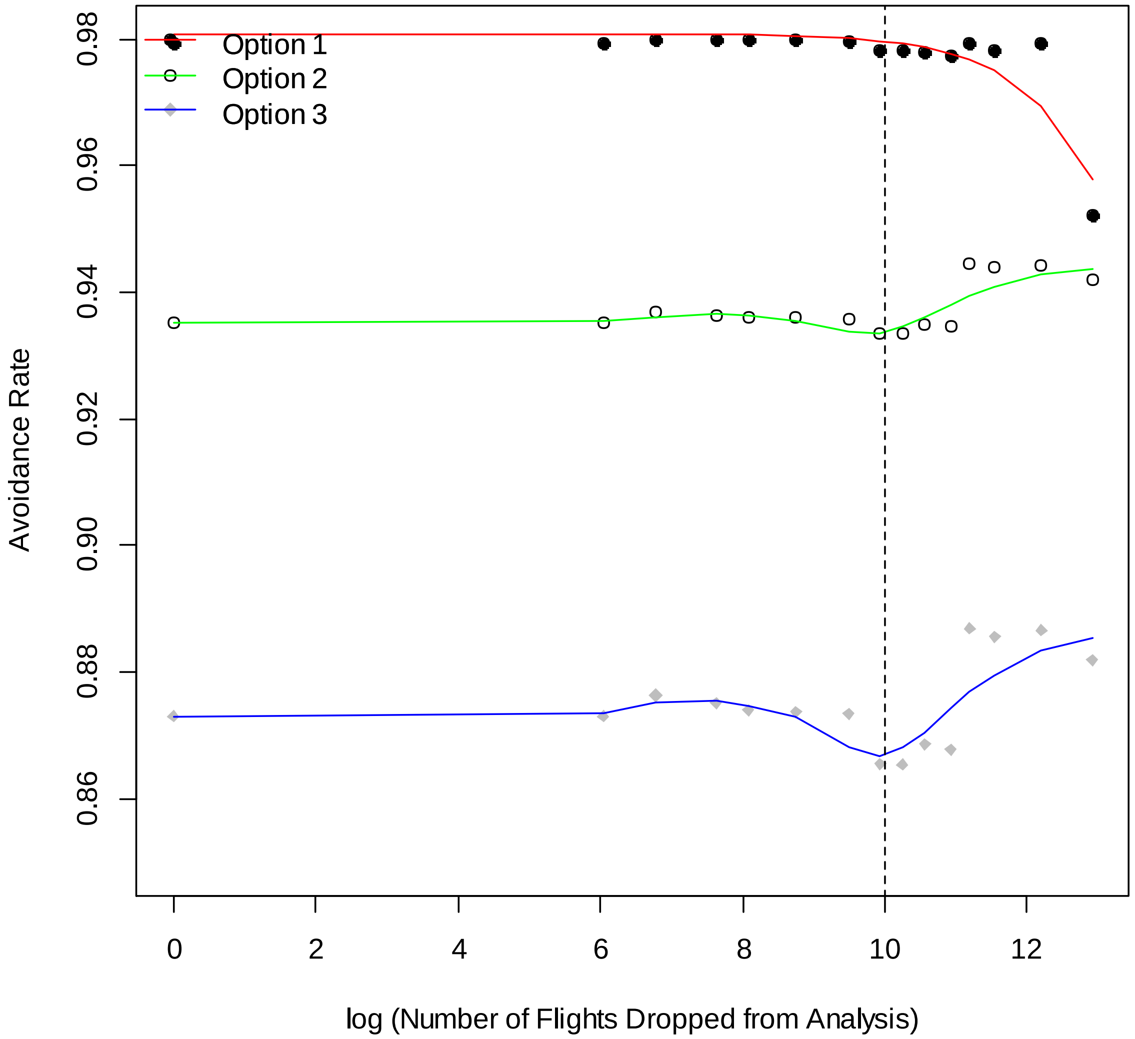


Figure 5.2 Impact of dropping data points (each site-year-species combination) on the within-windfarm avoidance rates derived using ratio estimators for options 1, 2 and 3 of the Band model for black-headed gull.

As might be expected, dropping sites from the analysis can influence the final within-windfarm avoidance rates. Only sites at which there is a relatively limited level of flight activity can be dropped from the analysis before the within-windfarm avoidance rates derived become less stable (Figure 5.1). In all three model options, this is noticeable after around 22,000 of the 746,668 flights through the windfarms have been removed (Figure 5.2).

Using option 1 of the Band model, the derived within-windfarm avoidance rate remains relatively stable at around 0.9795 until Bouin is the only site remaining in the analysis at which point it drops to around 0.9370. As discussed previously, this may reflect the fact that Bouin is located on the edge of a black-headed gull breeding colony, resulting in a higher number of collisions than were recorded elsewhere. In contrast, using options 2 and 3, within-windfarm avoidance rates start to increase after the first 22,000 flights have been dropped. Again, as discussed previously, this is likely to reflect the fact far fewer collisions were predicted at several key sites due to differences in the predicted proportions of birds at collision risk height. As a consequence, as more sites are dropped from the analysis the influence of Bouin, previously identified as having a strong influence on the final derived values for options 2 and 3, becomes stronger.

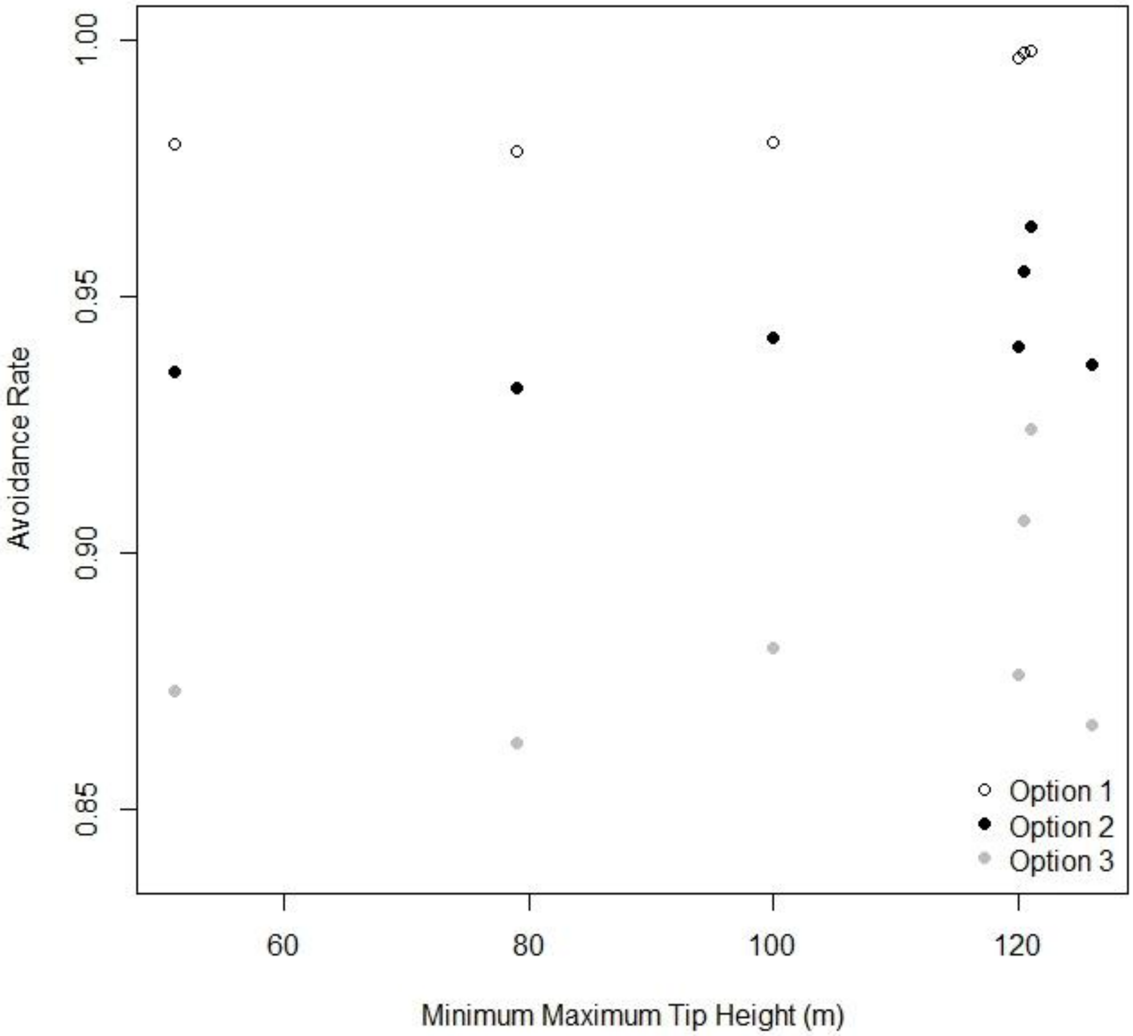


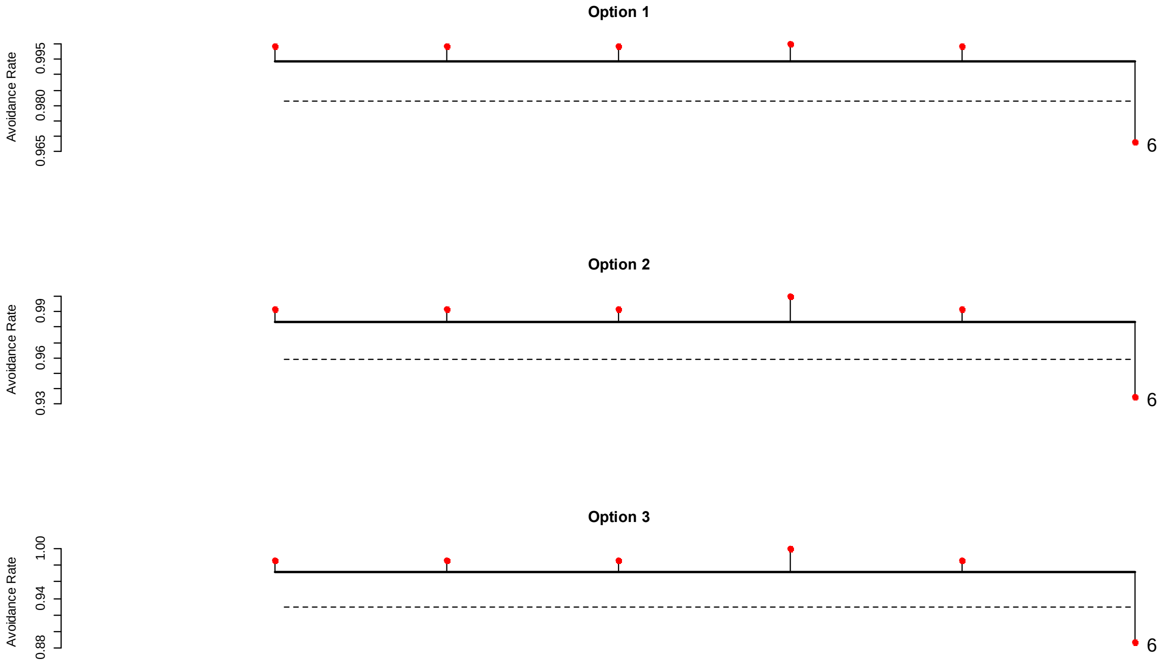
Figure 5.3 Impact of excluding sites with smaller turbines on the within-windfarm avoidance rates derived using ratio estimators for options 1, 2 and 3 of the Band model for black-headed gull.

The inclusion of sites with smaller turbines did not appear to strongly influence the final within-windfarm avoidance rates derived for black-headed gull using any of the three model options (Figure 5.3).

We consider within-windfarm avoidance rates of 0.9795 (± 0.0033 SD) for the basic Band model, and 0.8731 (± 0.0056 SD) for the extended Band model to be realistic, precautionary values given the data available. Whilst we identified several sites as having a strong influence over the final values derived, we do not feel there is sufficient reason to exclude these data from our analysis. It should be noted that the influence of these sites occurs in similar magnitudes in both positive and negative directions. The within-windfarm avoidance rates derived, especially for option 1, remain relatively stable regardless of which sites are included in the analysis. We did not identify any strong impact of turbine size on the final within-windfarm avoidance rate derived.

Common gull

A total of 841,008 common gulls were expected to have passed through three sites – Gneizdzewo (three studies), Kessingland (one study) and Hellrigg (two studies) – over the course of their respective study periods. After adjustments were made to this total to account for the proportion of birds flying at rotor height, the size of the rotor swept area and the probability of birds passing through the rotor-swept area without colliding, this was predicted to result in 3,405 collisions based on option 1 and 218 collisions based on option 2, and 129 based on option 3. However, in total only two common gull collisions were recorded across all sites during their respective study periods. This corresponds to within-windfarm avoidance rates of 0.9995 (± 0.0003 SD) using option 1 of the Band model, 0.9918 (± 0.0046 SD) using option 2 of the Band model and 0.9861 (± 0.0078 SD) using option 3 of the Band model.


Option 1

Option 2

Option 3

Figure 5.4 Leverage exerted by each site at which within-windfarm avoidance rates were calculated on the overall, mean within-windfarm avoidance rate derived for common gull. Solid line indicates mean within-windfarm avoidance rate across all sites, broken line indicates mean within-windfarm avoidance rate across all sites ± standard deviation, dots indicate mean within-windfarm avoidance rate with each site excluded from analysis. Sites are considered to have high leverage when their exclusion from the analysis leads to a change of more than 1 standard deviation in the overall mean within-windfarm avoidance rate. Site with high leverage is 6 – Hellrigg in 2012/13.

For all three model options, Hellrigg in 2012/13 appears to have a strong influence over the final within-windfarm avoidance rate derived (Figure 5.4). This is likely to reflect the fact that of the total number of common gulls estimated to have flown through windfarms, over 94% were estimated to have flown through Hellrigg in this year. Despite this, no collisions were recorded involving common gulls at Hellrigg in 2012/13. As a result, excluding these data from our analyses results in an overall within-windfarm avoidance rate of 0.9680 for option 1 of the Band model, 0.9345 for option 2 of the Band model and 0.8865 for option 3 of the Band model. However, we do not feel it would be appropriate to exclude such a substantial portion of our data from the analysis in this way.

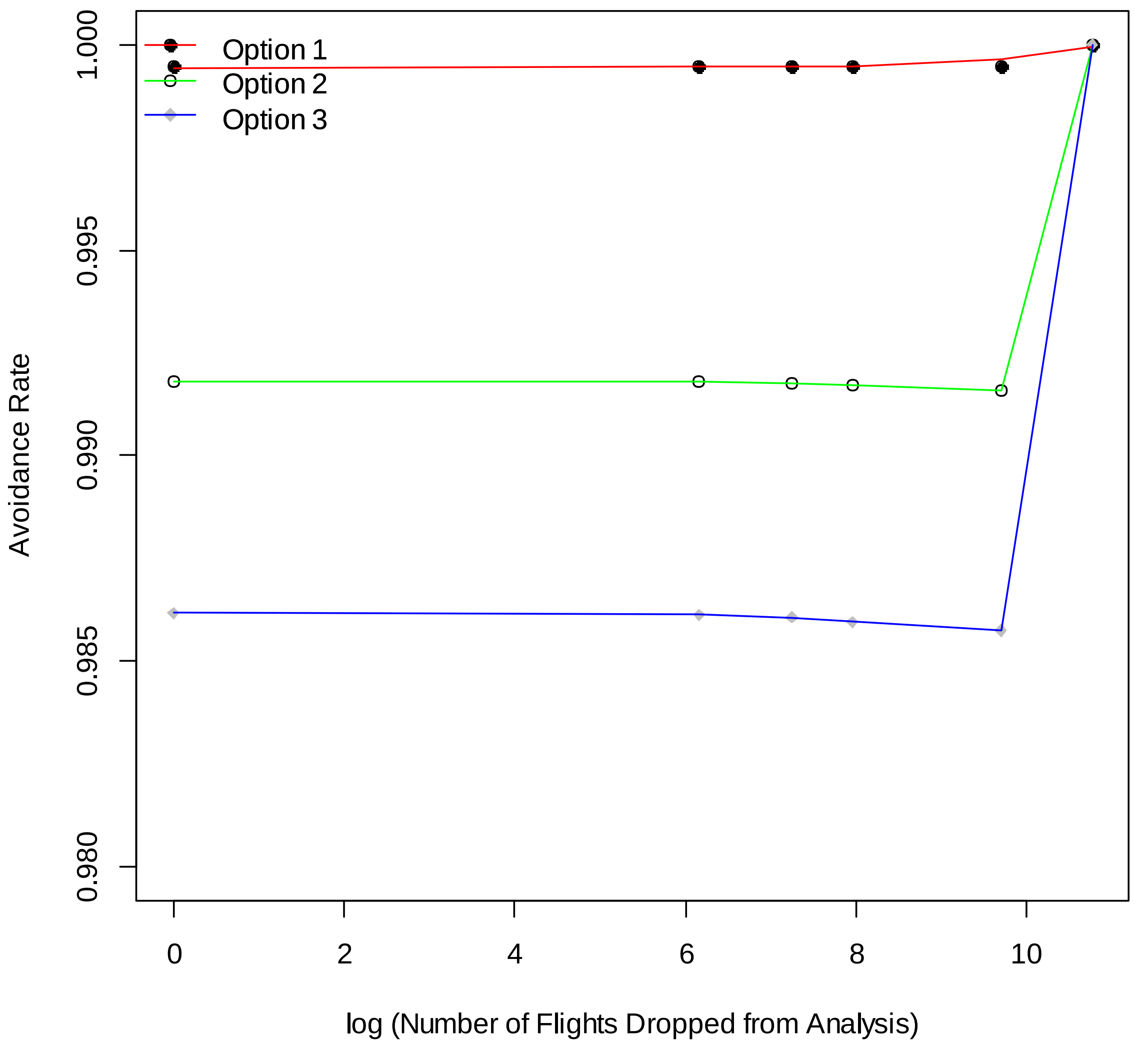


Figure 5.5 Impact of dropping data points (each site-year-species combination) on the within-windfarm avoidance rates derived using ratio estimators for options 1, 2 and 3 of the Band model for common gull.

For all three model options, the within-windfarm avoidance rate derived using ratio estimators remains stable until the only site remaining in the analysis is Hellrigg in 2012/13 (Figure 5.5). As stated above, this is likely to reflect the extremely high leverage of this data point.

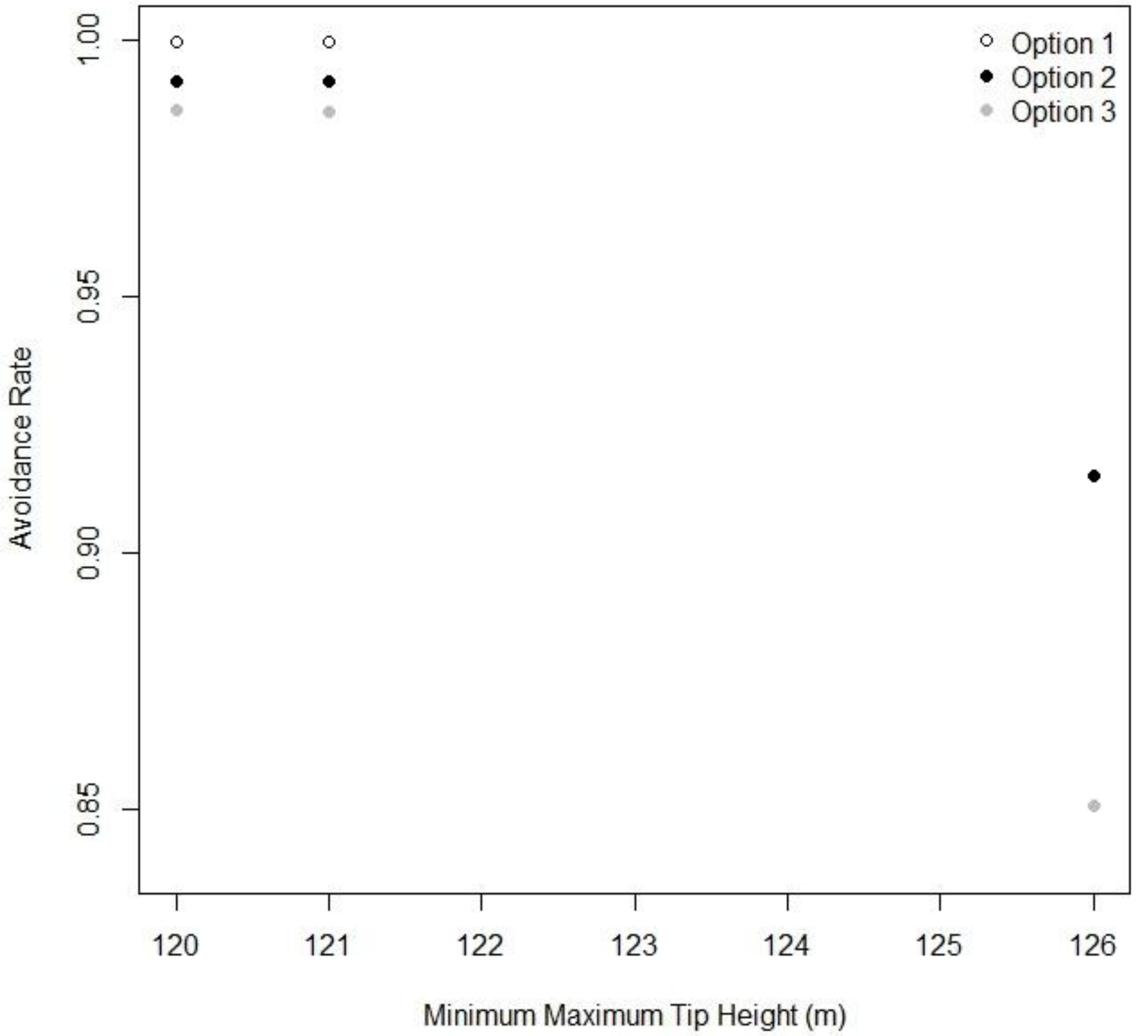


Figure 5.6 Impact of excluding sites with smaller turbines on the within-windfarm avoidance rates derived using ratio estimators for options 1, 2 and 3 of the Band model for common gull.

Maximum tip height appeared to influence the within-windfarm avoidance rates reported, with lower within-windfarm avoidance rates associated with the tallest turbines (Figure 5.6). In reality, this is likely to reflect the fact that collisions were only recorded at Kessingland, the site with the largest turbines, and may, therefore, be coincidence.

Whilst data from Hellrigg in 2012/13 have strong leverage, this must be considered in the context of the sheer number of flights that were estimated at the site in that year, and in combination with the fact that collisions involving common gulls were only recorded at one of the three study sites in a single year. We therefore feel that within-windfarm avoidance rates of 0.9995 (± 0.0003 SD) for the basic Band model and 0.9861 (± 0.0078 SD) for the extended Band model are likely to reflect realistic, precautionary within-windfarm avoidance rates for common gulls. Whilst we feel there is no valid reason to exclude the data from Hellrigg in 2012/13 from our analyses, we feel that its high leverage means that the final within-windfarm avoidance rates derived must be treated with caution.

Herring gull

A total of 526,047 herring gulls were expected to have passed through seven sites – Avonmouth (four studies), Boudwijnkanaal (one study), Bouin (one study), Gneizdzewo (one study), Hellrigg (two studies), Kessingland (one study), Zeebrugge (three studies) – over the course of their respective study periods. After adjustments were made to this total to account for the proportion of birds flying at rotor height, the size of the rotor swept area and the probability of birds passing through the rotor-swept area without colliding, this was predicted to result in 2,157 collisions based on option 1, 1,147 collisions based on option 2, and 957 based on option 3. However, in total only nine herring gull collisions were recorded across all sites during their respective study periods. This corresponds to within-windfarm avoidance rates of 0.9959 (±0.0006 SD) using option 1 of the Band model, 0.9924 (±0.0010 SD) using option 2 of the Band model and 0.9908 (±0.0012 SD) using option 3 of the Band model.

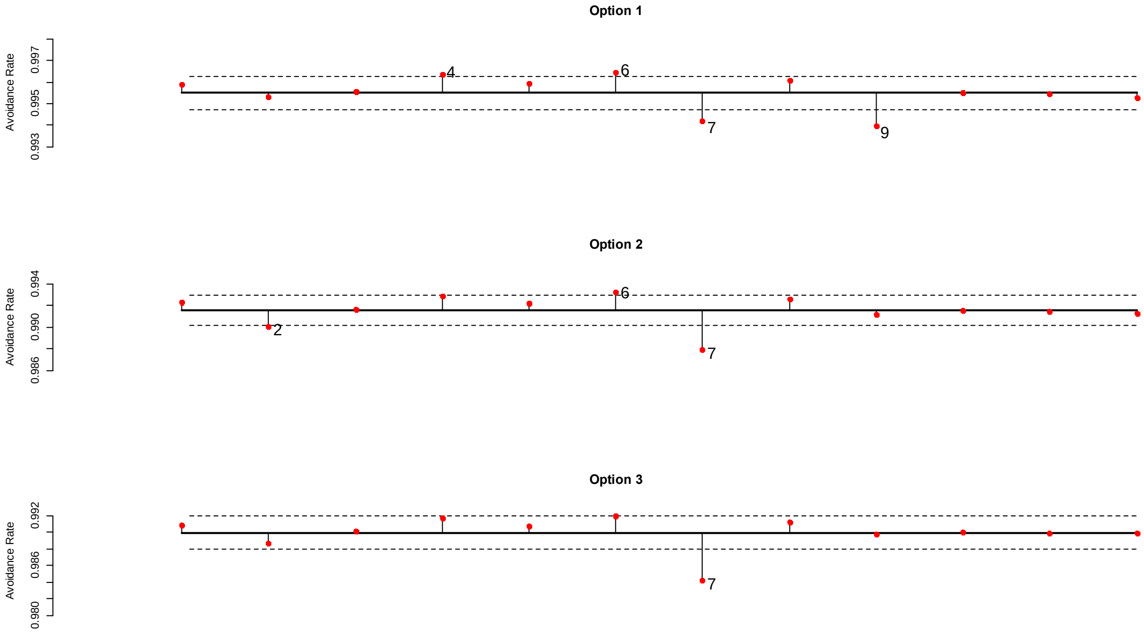


Figure 5.7 Leverage exerted by each site at which within-windfarm avoidance rates were calculated on the overall, mean within-windfarm avoidance rate derived for herring gull. Solid line indicates mean within-windfarm avoidance rate across all sites, broken line indicates mean within-

windfarm avoidance rate across all sites ± 1 standard deviation, dots indicate mean within-windfarm avoidance rate with each site excluded from analysis. Sites are considered to have high leverage when their exclusion from the analysis leads to a change of more than 1 standard deviation in the overall mean within-windfarm avoidance rate. Sites with high leverage are 2 – Bouin, 4 – Kessingland, 6 – Zeebrugge (June-July 2001), 7 – Zeebrugge (September-October 2001) and 9 – Hellrigg (2012/13).

No obvious patterns were evident amongst the sites with high leverage (Figure 5.7). The exclusion of data from Kessingland and Zeebrugge (June-July 2001) from the analysis led to an increase in the overall within-windfarm avoidance rates as both these sites recorded two collisions over the course of their respective study periods. Whilst these were amongst the highest collision rates at the sites we considered, there is no evidence that turbine size played a role. Whilst the turbines at Zeebrugge were the smallest among our study sites, those at Kessingland were the largest. The exclusion of Hellrigg (2012/13) and Zeebrugge (September-October 2001) led to a decrease in the overall within-windfarm avoidance rates. This is likely to reflect the fact that whilst these data points represented the greatest numbers of birds passing through the sites, only two collisions were recorded at Zeebrugge (September-October 2001). It is worth noting that the magnitude of the effect of removing data from Zeebrugge was similar whether data from June-July 2001 or September-October 2001 were removed, although the effect was in opposing directions. Based on these analyses, we did not feel it was appropriate to exclude any data points from our analysis when deriving an overall within-windfarm avoidance rate for herring gull.

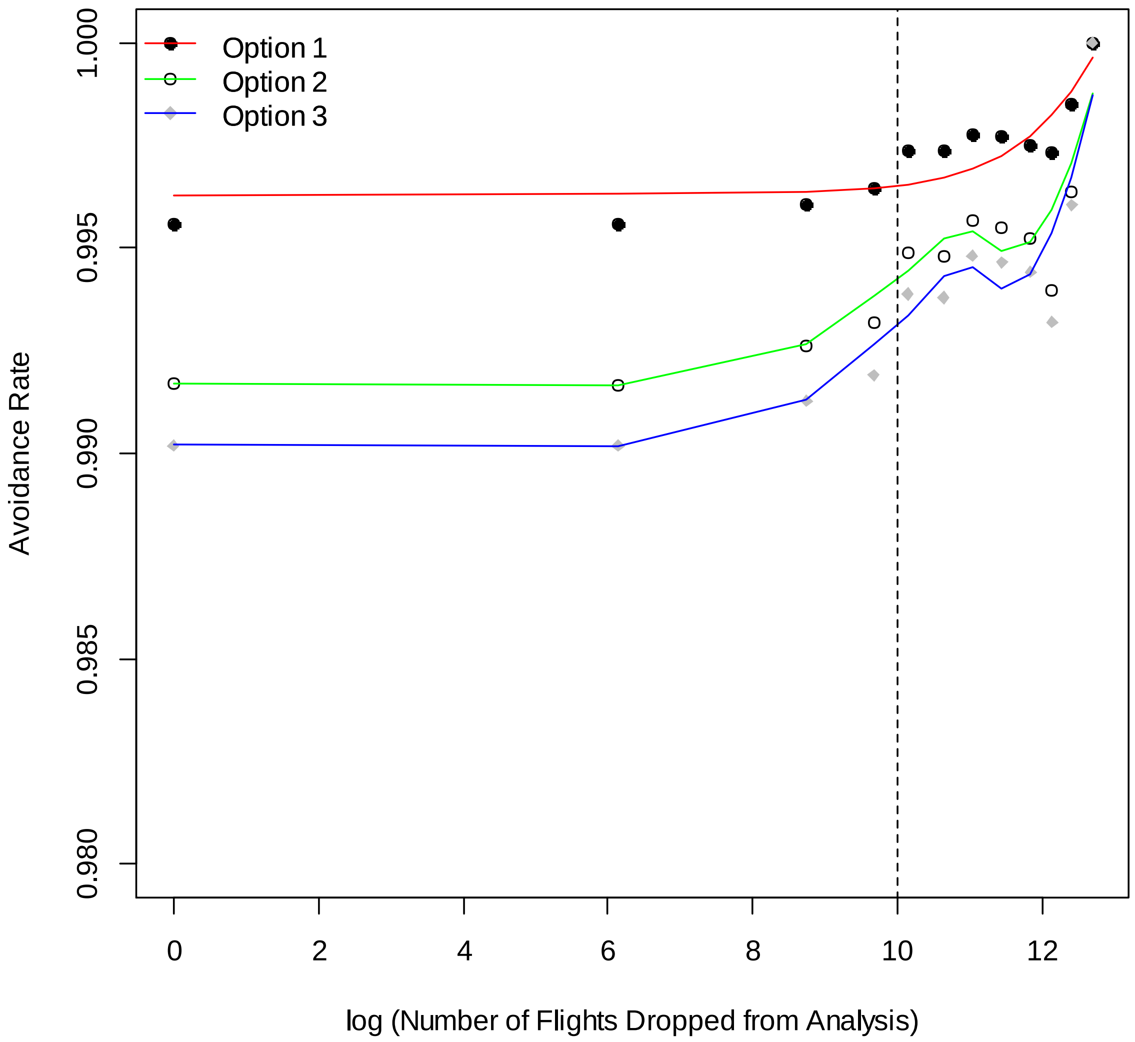


Figure 5.8 Impact of dropping data points (each site-year-species combination) on the within-windfarm avoidance rates derived using ratio estimators for options 1, 2 and 3 of the Band model for herring gull.

Dropping sites with lower levels of flight activity leads to an increase in the within-windfarm avoidance rates derived for herring gull using all three model options (Figure 5.8). Whilst ideally, within-windfarm avoidance rates would remain stable, regardless of the number of flights included in the analysis, it does suggest that the rates derived using the full dataset may be realistic, precautionary values.

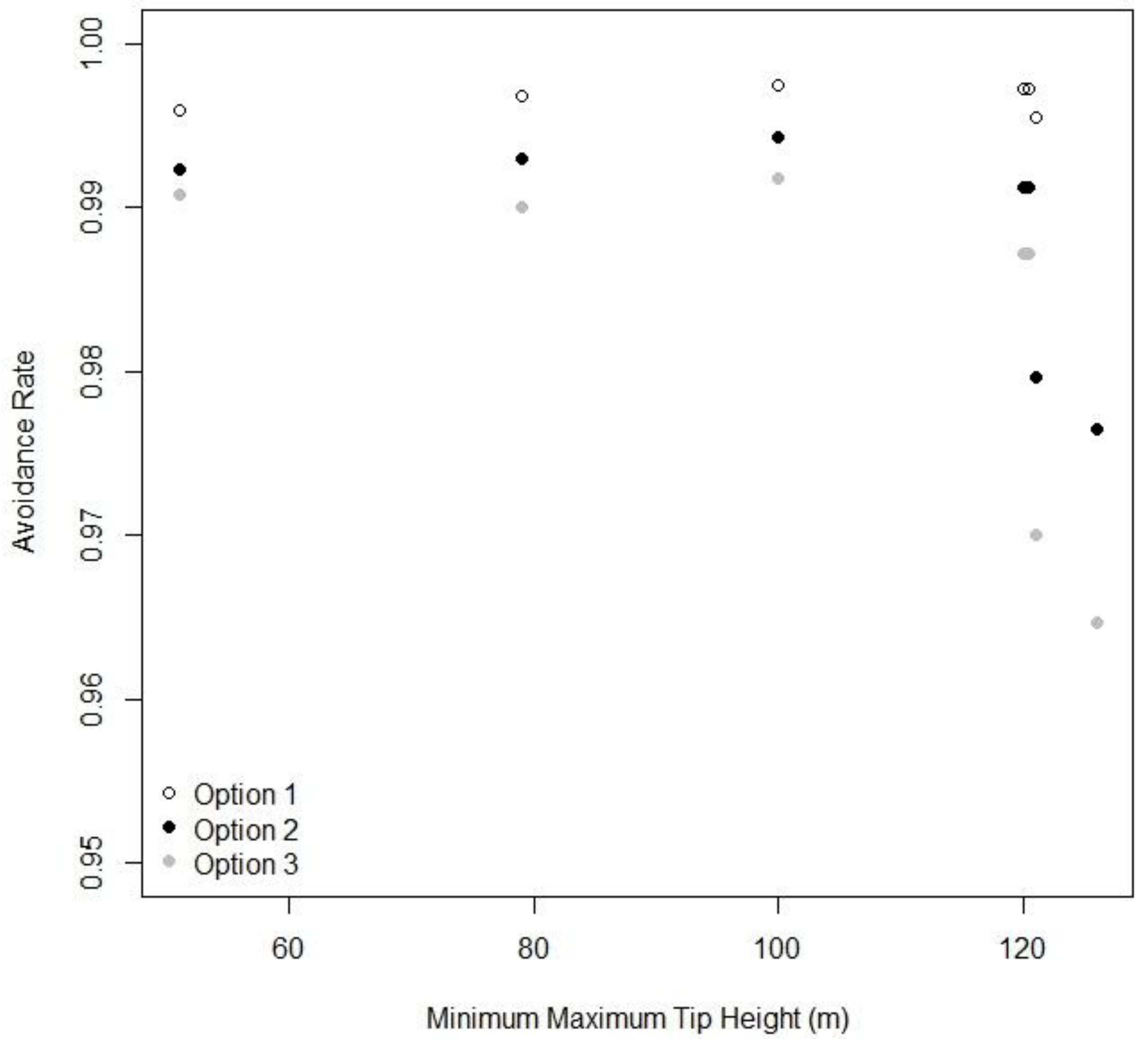


Figure 5.9 Impact of excluding sites with smaller turbines on the within-windfarm avoidance rates derived using ratio estimators for options 1, 2 and 3 of the Band model for herring gull.

Using option 1 of the Band model, there does not appear to be a relationship between turbine size and the within-windfarm avoidance rates derived using ratio estimators (Figure 5.9). However, in the case of options 2 and 3, there is a trend for lower within-windfarm avoidance rates with larger turbines. This apparent discrepancy is likely to reflect differences between the proportion of birds observed flying at collision risk height and the proportion of birds estimated to fly at collision risk height from generic distributions. The generic distributions estimated a lower proportion of birds flying at collision risk height for the larger turbines, meaning the predicted collision rate, and therefore overall within-windfarm avoidance rate, was reduced.

We consider within-windfarm avoidance rates of 0.9959 (±0.0006 SD) for the basic Band model, and 0.9908 (±0.0012 SD) for the extended Band model to be realistic, precautionary values given the data available. Whilst we identified several sites as having a strong influence over the final values derived, we do not feel there is sufficient reason to exclude these data from our analysis. It should be noted that the influence of these sites occurs in similar magnitudes in both positive and negative directions. We did not identify any strong impact of turbine size on the final within-windfarm avoidance rate derived.

Lesser black-backed gull

A total of 101,745 lesser black-backed gulls were expected to have passed through three sites – Hellrigg (two studies), Kessingland (one study) and Zeebrugge (three studies) – over the course of their respective study periods. After adjustments were made to this total to account for the proportion of birds flying at rotor height, the size of the rotor swept area and the probability of birds passing through the rotor-swept area without colliding, this was predicted to result in 1,110 collisions based on option 1,512 collisions based on option 2, and 473 based on option 3. However, in total only two lesser black-backed gull collisions were recorded across all sites during their respective study periods. This corresponds to within-windfarm avoidance rates of 0.9982 (±0.0005 SD) using option 1 of the Band model, 0.9960 (±0.0010 SD) using option 2 of the Band model and 0.9957 (±0.0011 SD) using option 3 of the Band model.

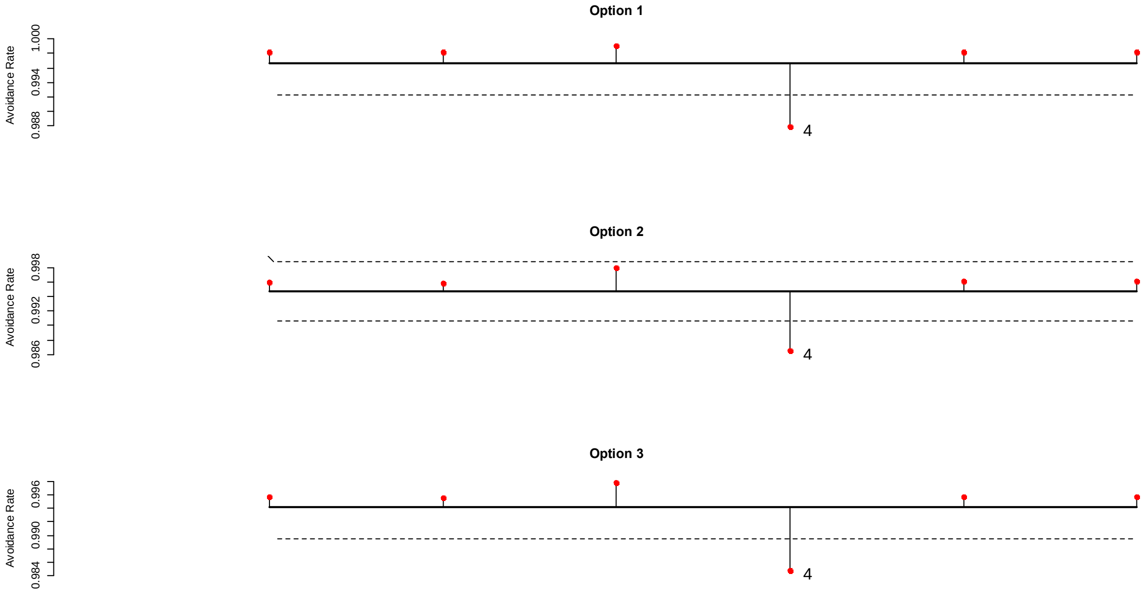


Figure 5.10 Leverage exerted by each site at which within-windfarm avoidance rates were calculated on the overall, mean within-windfarm avoidance rate derived for lesser black-backed gull. Solid line indicates mean within-windfarm avoidance rate across all sites, broken line indicates mean within-windfarm avoidance rate across all sites ± 1 standard deviation, dots indicate mean within-windfarm avoidance rate with each site excluded from analysis. Sites are considered to have high leverage when their exclusion from the analysis leads to a change of more than 1 standard deviation in the overall mean within-windfarm avoidance rate. Site with high leverage is 4 – Zeebrugge (September-October 2001).

Data from all three model options indicated that Zeebrugge in September-October 2001 had a relatively high leverage on the final within-windfarm avoidance rates derived using ratio estimators (Figure 5.10). This is likely to reflect the fact that Zeebrugge in September-October 2001 had the highest levels of bird activity by some distance. Despite this, only a single collision was recorded over the study period. Excluding these data from the analysis results in within-windfarm avoidance rates of 0.9878 using option 1, 0.9865 using option 2 and 0.9847 using option 3. However, we do not feel it is appropriate to exclude data in this way.

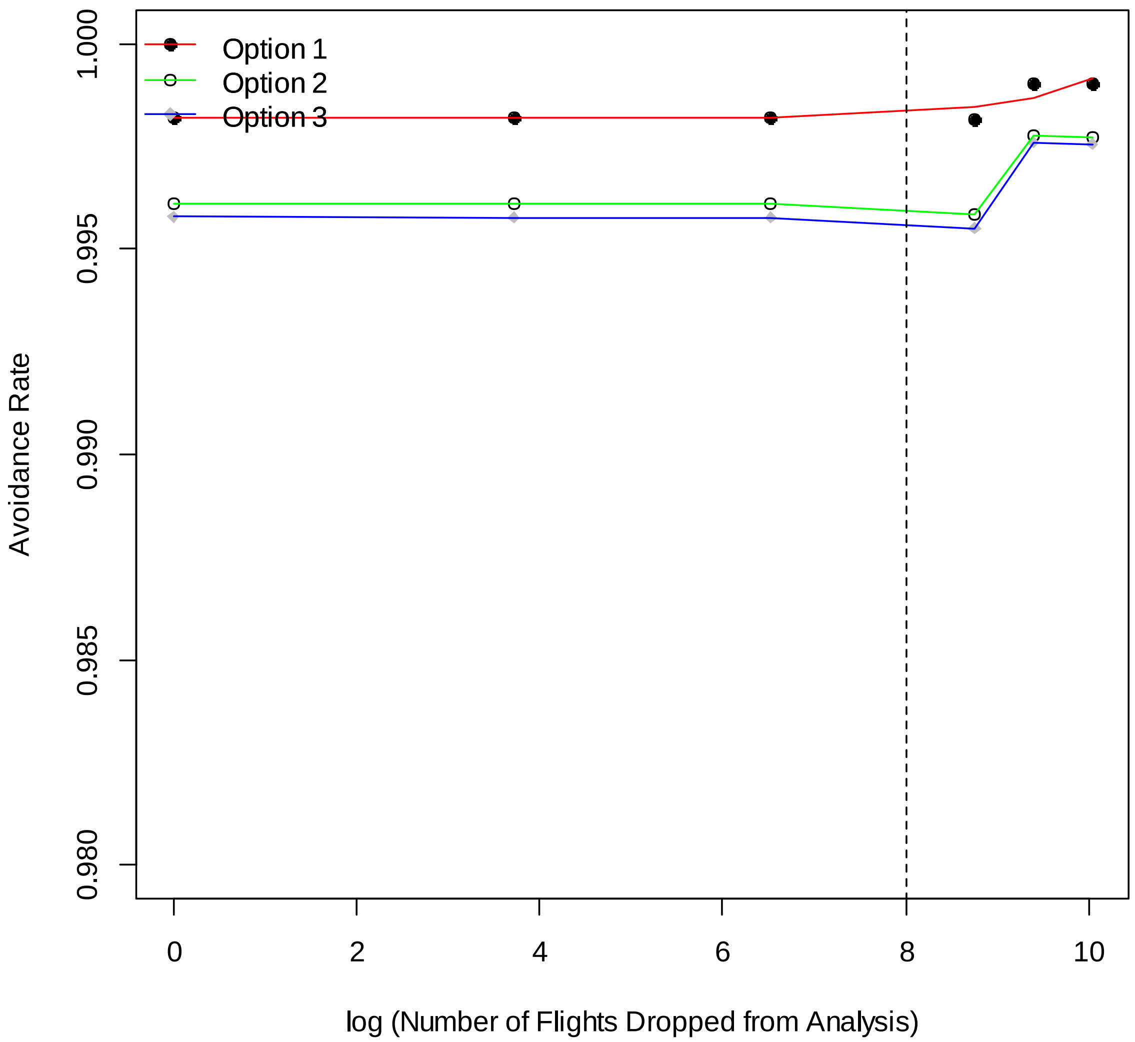


Figure 5.11 Impact of dropping data points (each site-year-species combination) on the within-windfarm avoidance rates derived using ratio estimators for options 1, 2 and 3 of the Band model for lesser black-backed gull.

Using option 1 of the Band model to derive within-windfarm avoidance rates, values remain fairly stable regardless of the number of birds recorded flying through the study sites (Figure 5.11). Using options 2 and 3 the final value remains relatively stable until the first 6,000 flights have been removed. This is likely to reflect that fact that whilst a relatively high number of birds were predicted to have flown through the final two sites, only a single collision was recorded.

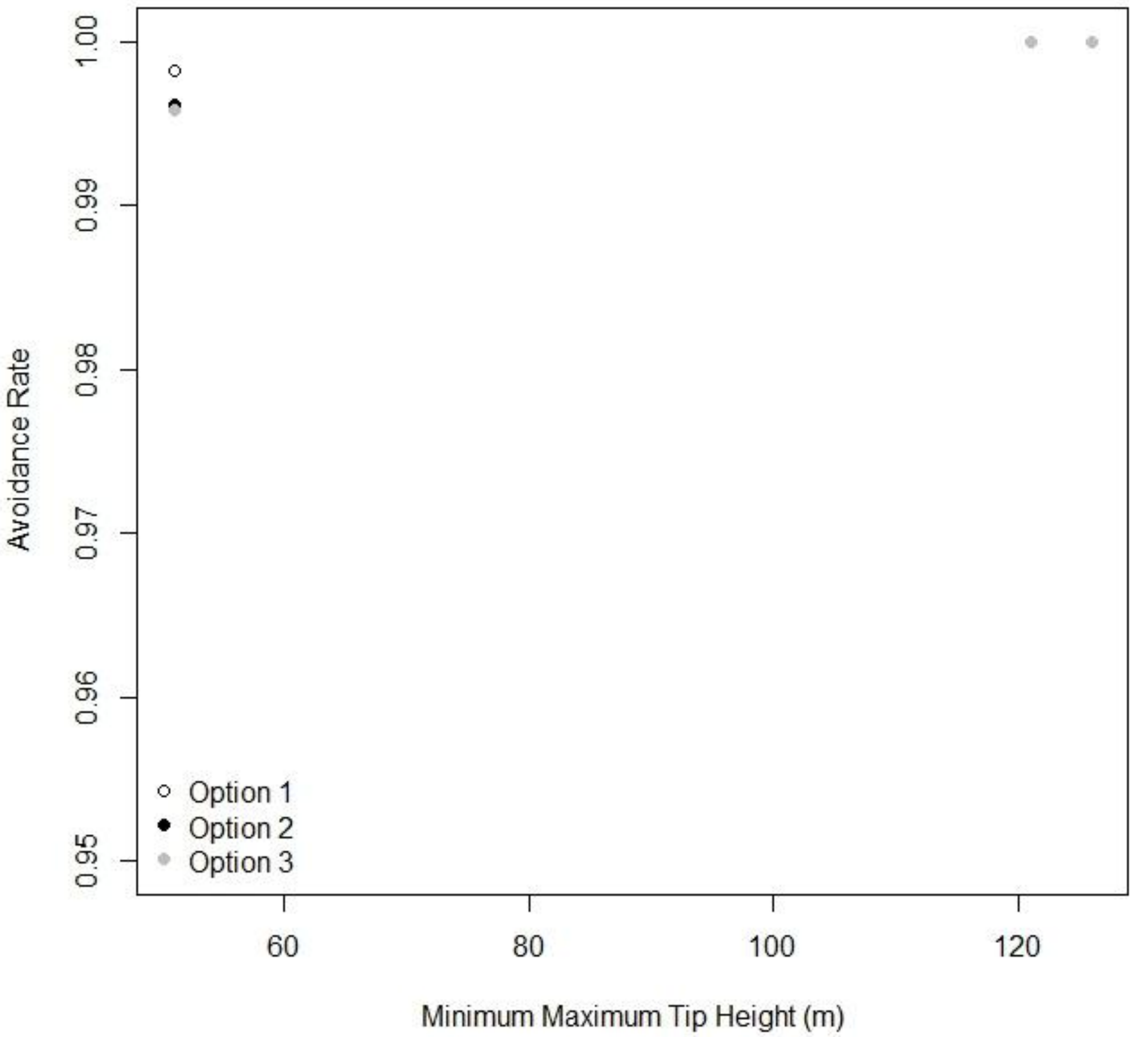


Figure 5.12 Impact of excluding sites with smaller turbines on the within-windfarm avoidance rates derived using ratio estimators for options 1, 2 and 3 of the Band model for lesser black-backed gull.

Excluding smaller turbines did not appear to have a significant impact on the final within-windfarm avoidance rate derived for lesser black-backed gull using any of the three model options (Figure 5.12).

Whilst data from Zeebrugge in September-October 2001 had a relatively high leverage on the final within-windfarm avoidance rates derived, we did not feel there was a compelling reason to exclude these data from our analysis. Based on the data available for lesser black-backed gull, we consider within-windfarm avoidance rates of 0.9982 (±0.0005 SD) for the basic Band model and 0.9957 (±0.0011 SD) for the extended Band model to be realistic, precautionary values given the data available. However, given the data come from only three sites and incorporate a relatively small number of flights through the windfarm, we feel these values should be treated with caution. Whilst we identified several sites as having a strong influence over the final values derived, we do not feel there is sufficient reason to exclude these data from our analysis. It should be noted that the influence of these sites occurs in similar magnitudes in both positive and negative directions. We did not identify any strong impact of turbine size on the final within-windfarm avoidance rate derived.

Small gulls

A total of 1,589,953 small gulls were expected to have passed through eight sites over the course of their respective study periods. After adjustments were made to this total to account for the proportion of birds flying at rotor height, the size of the rotor swept area and the probability of birds passing through the rotor-swept area without colliding, this was predicted to result in 5,263 collisions based on option 1,801 collisions based on option 2, and 427 based on option 3. However, in total only 42 small gull collisions were recorded across all sites during their respective study periods. This corresponds to within-windfarm avoidance rates of 0.9921 (±0.0015 SD) using option 1 of the Band model, 0.9481 (±0.0032 SD) using option 2 of the Band model and 0.9027 (±0.0068 SD) using option 3 of the Band model.

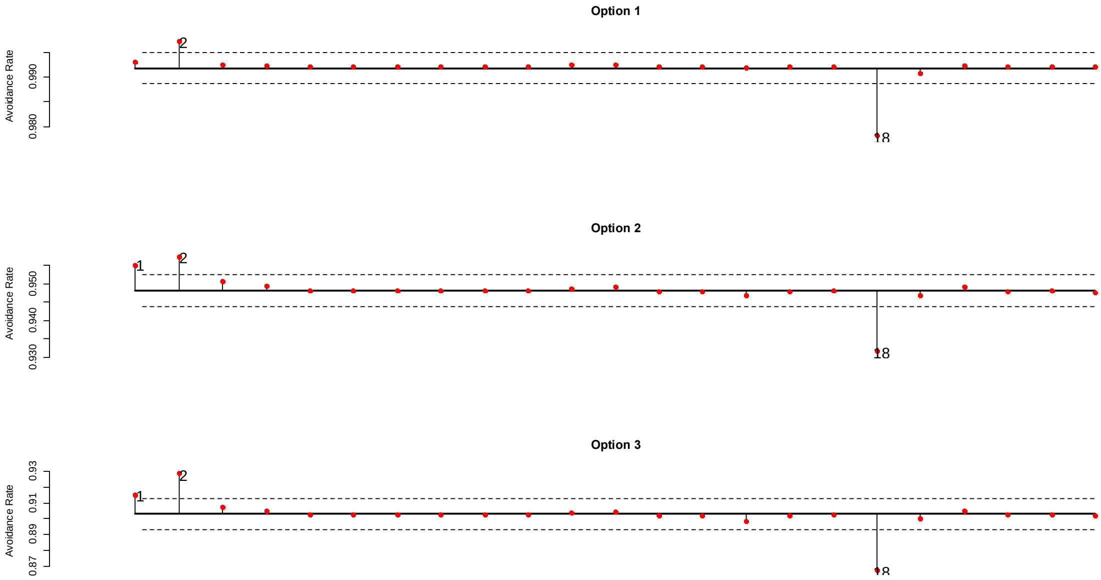


Figure 5.13 Leverage exerted by each site at which within-windfarm avoidance rates were calculated on the overall, mean within-windfarm avoidance rate derived for small gulls. Solid line indicates mean within-windfarm avoidance rate across all sites, broken line indicates mean within-windfarm avoidance rate across all sites ± 1 standard deviation, dots indicate mean within-windfarm avoidance rate with each site excluded from analysis. Sites are considered to have high leverage when their exclusion from the analysis leads to a change of more than 1 standard

deviation in the overall mean within-windfarm avoidance rate. Sites with high leverage are 1 – black-headed gull at Boudwijnkanaal in October 2015, 2 – black-headed gull at Bouin and 18 – common gull at Hellrigg in 2012/13.

For all three model options, the exclusion of data from black-headed gull at Bouin results in an increased within-windfarm avoidance rate (Figure 5.13). This is likely to be due to the presence of the turbines on the edge of a black-headed gull breeding colony. This may have led to a greater number of flights through the rotor-swept area of turbines by adult birds returning to provision chicks and/or newly fledged chicks less experienced at flying. As a result of the relatively high collision rate, including this site in our analysis reduced the overall rate derived using option 1. The leverage of data from Hellrigg in 2012/13 was of a similar magnitude, but in the opposite direction. Despite having the highest level of small gull activity and a high proportion of birds flying at collision risk height, no collisions were recorded at this site, in this year. However, we did not consider there to be a valid reason for excluding these sites from our analysis.

Using options 2 and 3, excluding data for black-headed gull from Boudwijnkanaal in October 2005 also resulted in an increase in the overall within-windfarm avoidance rates. The reason for this differing from the results for option 1 is that the modelled flight height distribution predicts a lower proportion of birds at collision risk height. As a consequence, the predicted collision rate, and therefore the within-windfarm avoidance rate, is reduced.

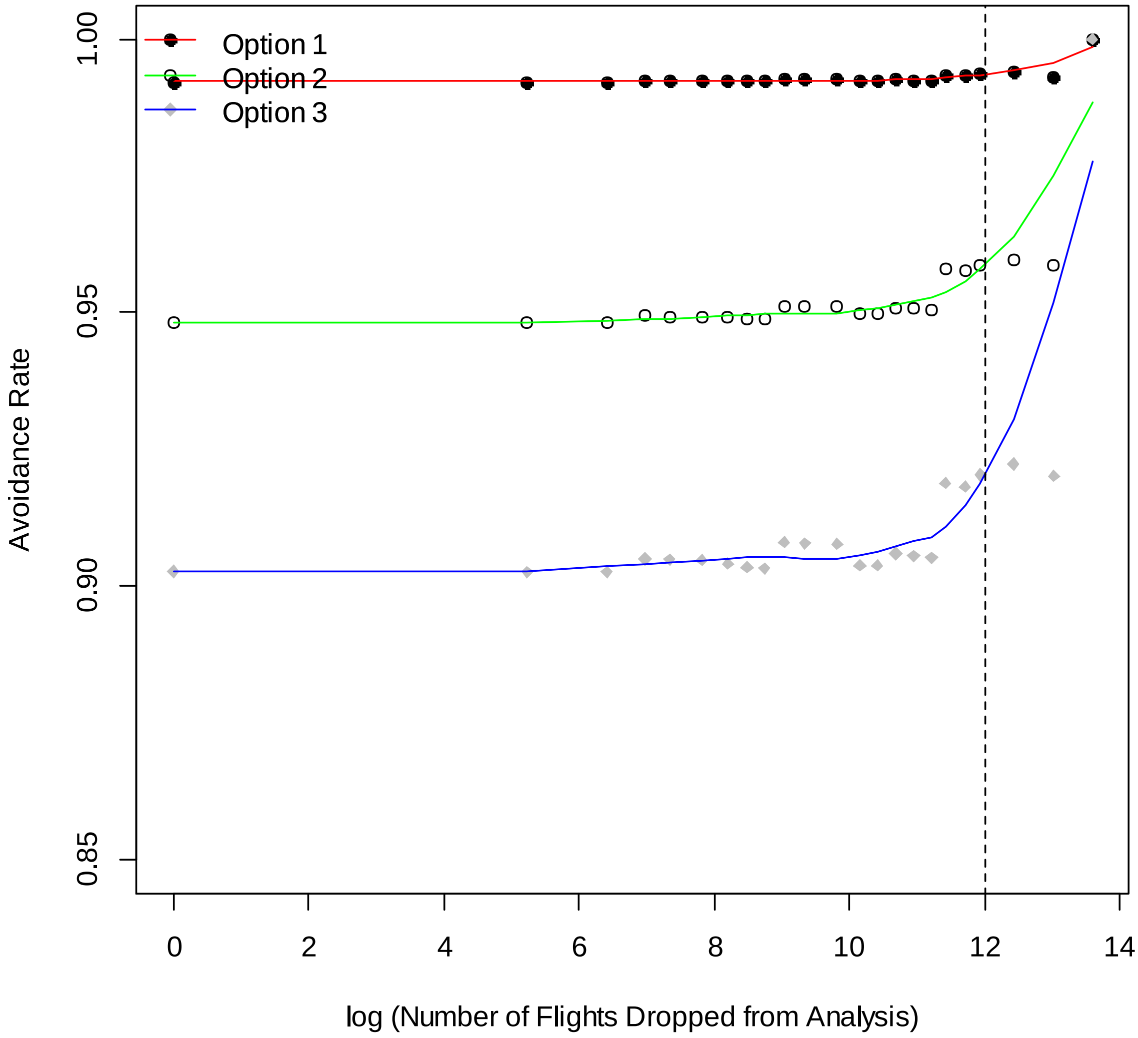


Figure 5.14 Impact of dropping data points (each site-year-species combination) on the within-windfarm avoidance rates derived using ratio estimators for options 1, 2 and 3 of the Band model for small gulls.

Within-windfarm avoidance rates derived using all three model options remain relatively stable as the first 160,000 flights through windfarms were dropped from the analysis (Figure 5.14), before increasing as only the sites with the highest levels of gull activity remain. This reflects the fact that at several of the sites with the highest levels of gull activity, no collisions were recorded, resulting in an overall increase in the within-windfarm avoidance rates as other sites were dropped.

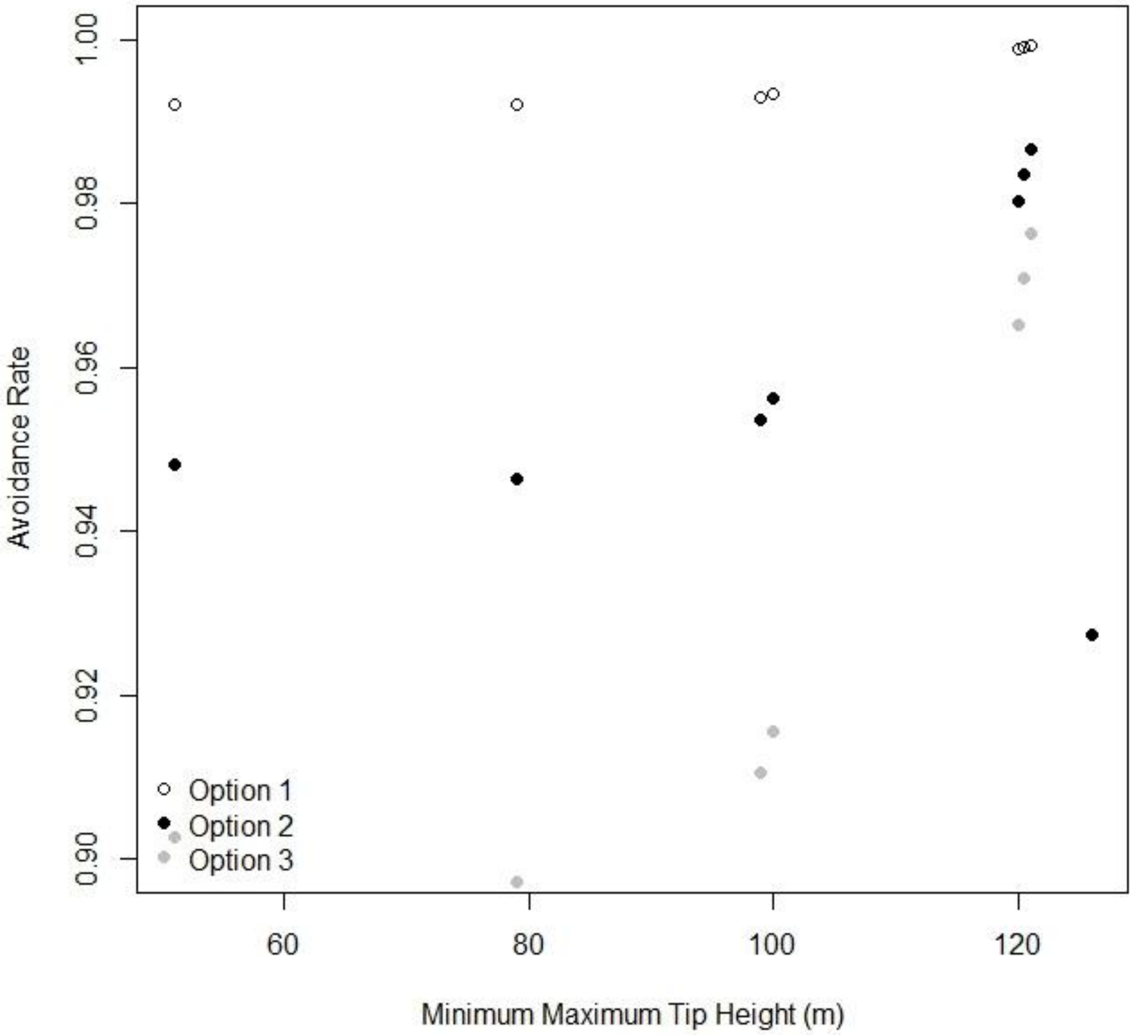


Figure 5.15 Impact of excluding sites with smaller turbines on the within-windfarm avoidance rates derived using ratio estimators for options 1, 2 and 3 of the Band model for small gulls.

Using option 1 of the Band model, there does not appear to be a relationship between turbine size and the within-windfarm avoidance rates derived using ratio estimators (Figure 5.15). However, in the case of options 2 and 3, there is a trend for higher within-windfarm avoidance rates with larger turbines. The reason for this discrepancy is unclear, although it may reflect differences in the proportion of birds at collision risk height between the observed data and modelled distributions.

We consider within-windfarm avoidance rates of 0.9921 (±0.0015 SD) for the basic Band model, and 0.9027 (±0.0068 SD) for the extended Band model to be realistic, precautionary values given the data available. Whilst we identified several sites as having a strong influence over the final values derived, we do not feel there is sufficient reason to exclude these data from our analysis. It should be noted that the influence of these sites occurs in similar magnitudes in both positive and negative directions. We did not identify any strong impact of turbine size on the final within-windfarm avoidance rate derived using option 1 of the Band model.

Large gulls

A total of 639,560 large gulls were expected to have passed through seven sites – Avonmouth (four studies, one species), Boudwijnkanaal (two studies, two species), Bouin (one study, one species), Gniezdzewo (three studies, three species), Hellrigg (three studies, three species), Kessingland (one study, three species) and Zeebrugge (three studies, two species) – over the course of their respective study periods. After adjustments were made to this total to account for the proportion of birds flying at rotor height, the size of the rotor swept area and the probability of birds passing through the rotor-swept area without colliding, this was predicted to result in 3,368 collisions based on option 1, 1,684 collisions based on option 2, and 1,452 based on option 3. However, in total only 42 large gull collisions were recorded across all sites during their respective study periods. This corresponds to within-windfarm avoidance rates of 0.9956 (±0.0004 SD) using option 1 of the Band model, 0.9912 (±0.0007 SD) using option 2 of the Band model and 0.9898 (±0.0009 SD) using option 3 of the Band model.

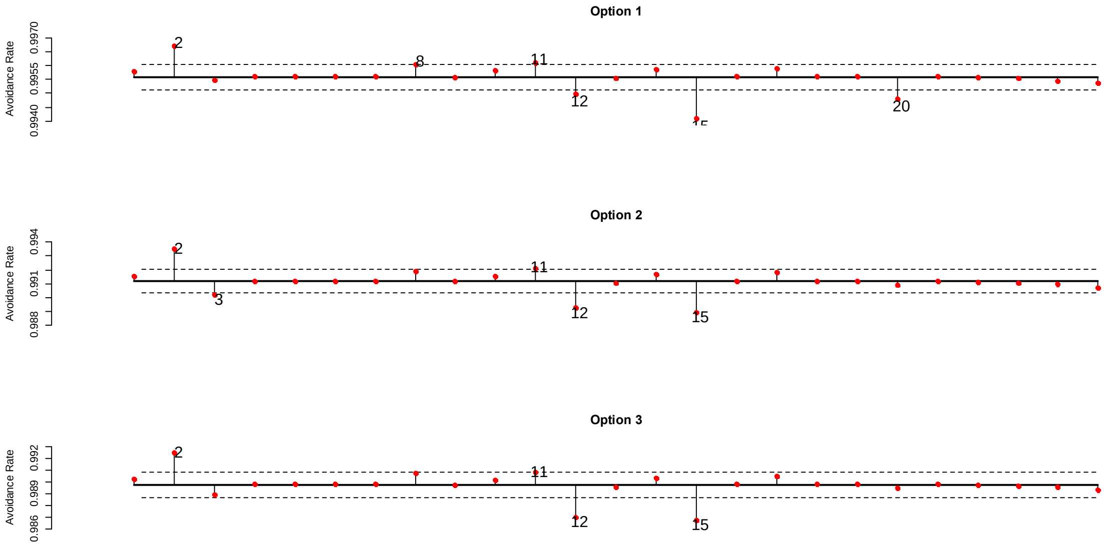


Figure 5.16 Leverage exerted by each site at which within-windfarm avoidance rates were calculated on the overall, mean within-windfarm avoidance rate derived for large gulls. Solid line indicates mean within-windfarm avoidance rate across all sites, broken line indicates mean within-windfarm avoidance rate across all sites ± 1 standard deviation, dots indicate mean within-windfarm avoidance rate with each site excluded from analysis. Sites are considered to have high leverage when their exclusion from the analysis leads to a change of more than 1 standard deviation in the overall mean within-windfarm avoidance rate. Sites with high leverage are 2 – herring/lesser black-backed gull, Boudwijnkanaal (October 2005), 3 – herring gull, Bouin; 8 – herring gull, Kessingland; 11 – herring gull, Zeebrugge (June-July 2001); 12 – herring gull, Zeebrugge (September-October 2001); 15 – lesser black-backed gull, Zeebrugge (September-October 2001); and 20 – herring gull, Hellrigg (2012/13).

There is no obvious pattern to the sites which have high leverage over the final derived within-windfarm avoidance rates (Figure 5.16). Excluding the data for herring/lesser black-backed gull at Boudwijnkanaal in October 2005, herring gull for Kessingland and herring gull for Zeebrugge in June-July 2001 results in an increase in the overall within-windfarm avoidance rate. The size of turbines at these sites varies from small (51 m maximum turbine height at Zeebrugge) to large (126 m maximum turbine height at Kessingland) so the inclusion of different sizes of turbines does not appear to have influenced the within-windfarm avoidance rates derived. In contrast, the inclusion of date for herring gull and lesser black-backed gull at Zeebrugge in September-October 2001 and for herring gull at Hellrigg in 2012/13 results in an increase in the overall within-windfarm avoidance rate derived. In these cases, the increase in the within-windfarm avoidance rates is likely to be linked to the relatively high activity levels at these sites and relatively low collision rates. We do not consider there to be a valid reason for excluding these sites from the analysis.

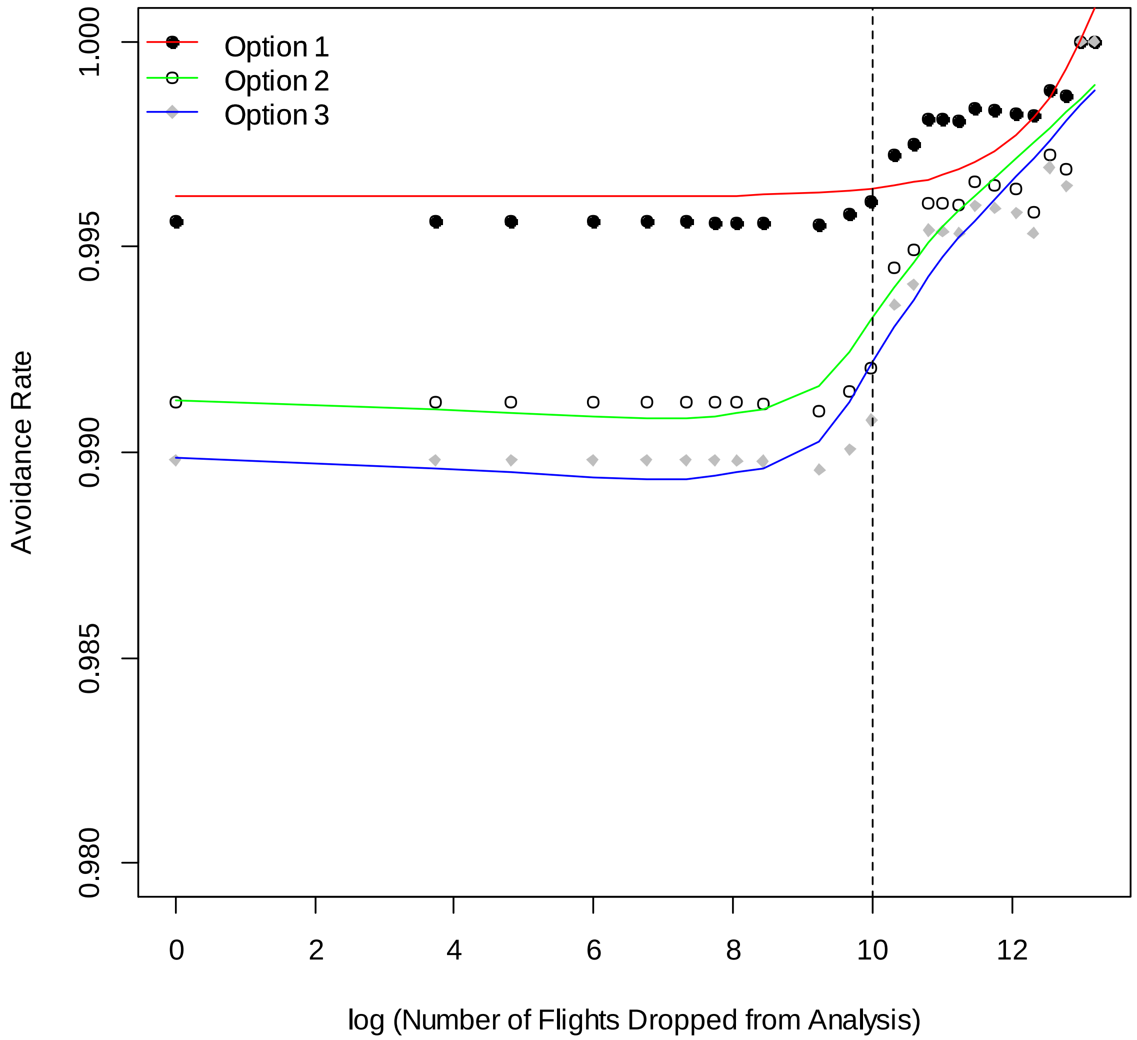


Figure 5.17 Impact of dropping data points (each site-year-species combination) on the within-windfarm avoidance rates derived using ratio estimators for options 1, 2 and 3 of the Band model for large gulls.

Within-windfarm avoidance rates derived using all three model options remain relatively stable as the first 22,000 flights through windfarms are dropped from the analysis (Figure 5.17), before increasing as only the sites with the highest levels of gull activity remain. This reflects the fact that at several of the sites with the highest levels of gull activity, no collisions were recorded, resulting in an overall increase in the within-windfarm avoidance rates as other sites were dropped.

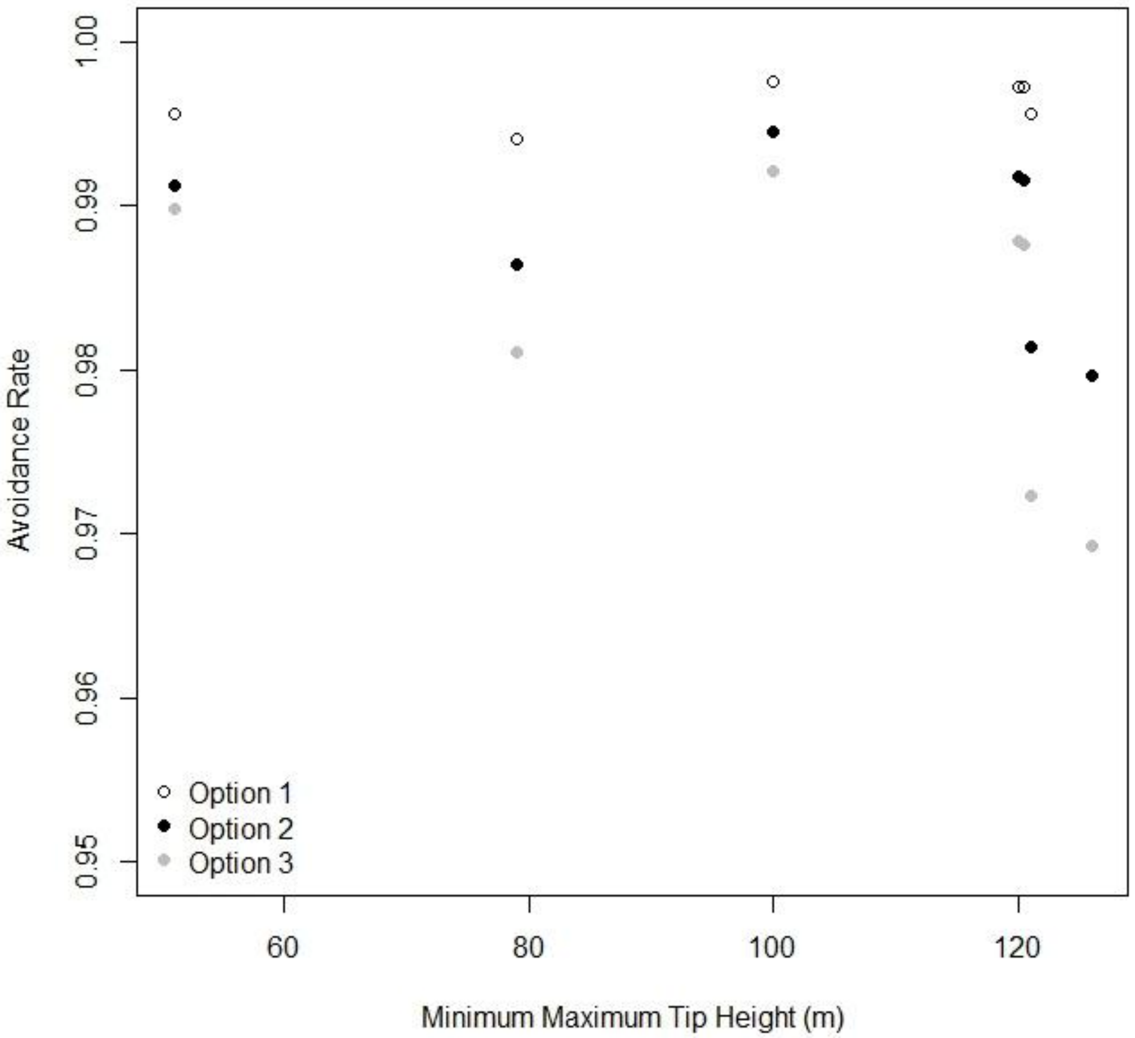


Figure 5.18 Impact of excluding sites with smaller turbines on the within-windfarm avoidance rates derived using ratio estimators for options 1, 2 and 3 of the Band model for large gulls.

Using option 1 of the Band model, there does not appear to be a relationship between turbine size and the within-windfarm avoidance rates derived using ratio estimators (Figure 5.18). However, in the case of options 2 and 3, there is a trend for lower within-windfarm avoidance rates with larger turbines. This apparent discrepancy is likely to reflect differences between the proportion of birds observed flying at collision risk height and the proportion of birds estimated to fly at collision risk height from generic distributions. The generic distributions estimated a lower proportion of birds flying at collision risk height for the larger turbines, meaning the predicted collision rate, and therefore overall within-windfarm avoidance rate, was reduced.

We consider within-windfarm avoidance rates of 0.9956 (±0.0004 SD) for the basic Band model, and 0.9898 (±0.0009 SD) for the extended Band model to be realistic, precautionary values given the data available. Whilst we identified several sites as having a strong influence over the final values derived, we do not feel there is sufficient reason to exclude these data from our analysis. It should be noted that the influence of these sites occurs in similar magnitudes in both positive and negative directions. We did not identify any strong impact of turbine size on the final within-windfarm avoidance rate derived.

All gulls

A total of 2,567,124 gulls were expected to have passed through seven sites over the course of their respective study periods. After adjustments were made to this total to account for the proportion of birds flying at rotor height, the size of the rotor swept area and the probability of birds passing through the rotor-swept area without colliding, this was predicted to result in 10,052 collisions based on option 1, 4,054 collisions based on option 2, and 3,271 based on option 3. However, in total only 107 gull collisions were recorded across all sites during their respective study periods. This corresponds to within-windfarm avoidance rates of 0.9893 (±0.0007 SD) using option 1 of the Band model, 0.9735 (±0.0014 SD) using option 2 of the Band model and 0.9672 (±0.0018 SD) using option 3 of the Band model.

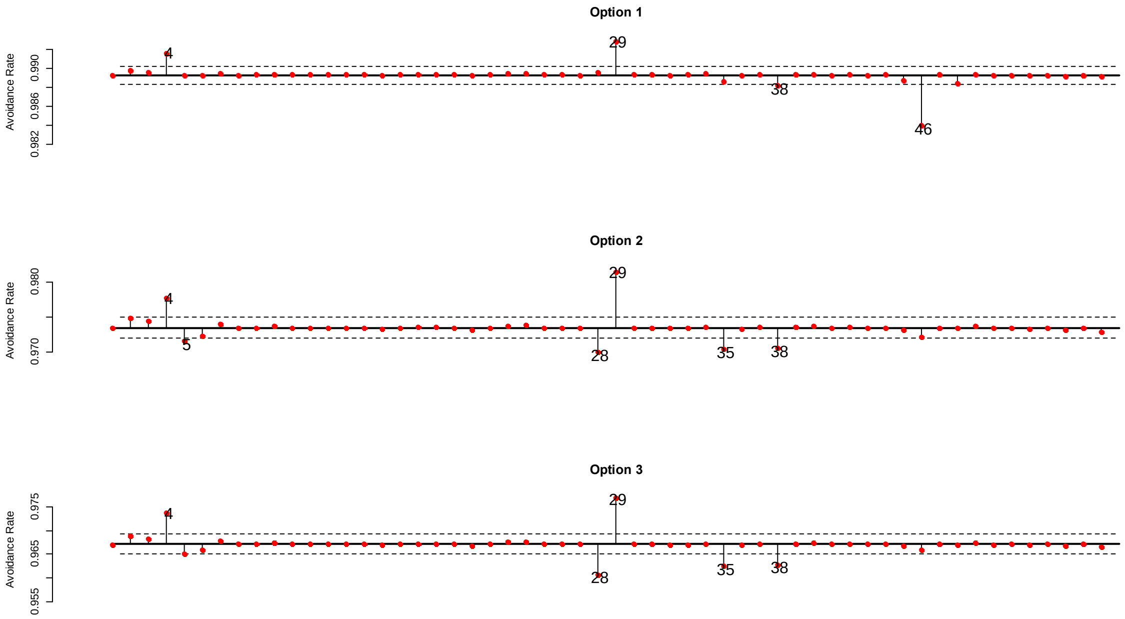


Figure 5.19 Leverage exerted by each site at which within-windfarm avoidance rates were calculated on the overall, mean within-windfarm avoidance rate derived for all gulls. Solid line indicates mean within-windfarm avoidance rate across all sites, broken line indicates mean within-windfarm avoidance rate across all sites ± 1 standard deviation, dots indicate mean within-windfarm avoidance rate with each site excluded from analysis. Sites are considered to have high leverage when their exclusion from the analysis leads to a change of more than 1 standard deviation in the overall mean within-windfarm avoidance rate. Sites with high leverage are 4 – black-headed gulls, Bouin; 5 – gull spp, Bouin; 28 – gull spp, Oosterbierum (autumn 1990); 29 – gull spp, Oosterbierum (spring 1991); 35 – herring gull, Zeebrugge (September-October 2001); 38 – lesser black-backed gull in Zeebrugge (September-October 2001); 46 – common gull, Hellrigg (2012/13).

For all three model options, excluding data for black-headed gulls at Bouin and gull spp at Oosterbierum in autumn 1990, results in an increase in the overall within-windfarm avoidance in the final derived within-windfarm avoidance rates (Figure 5.19). There are no obvious commonalities between these sites. The turbines at Oosterbierum are relatively small with a maximum tip height of 50 m, but those at Bouin are more typical of the sites in our study, with maximum tip heights of 100 m. Using option 1, the exclusion of data from lesser black-backed gull at Zeebrugge in September-October 2001 and common gull at Hellrigg in 2012/13 resulted in decreased within-windfarm avoidance rates. This is likely to reflect relatively high levels of bird activity in combination with very few recorded collisions at these sites, meaning they have a negative bias on the final, derived figures. This pattern was repeated for gull spp at Oosterbierum in spring 1991 and herring gulls and lesser black-backed gulls at Zeebrugge in September-October 2001 using options 2 and 3 and gull spp at Bouin using option 2.

It should be noted that for all three model options, leverage occurred in both directions. We did not feel there was a valid justification for excluding any of these data points from our analysis.

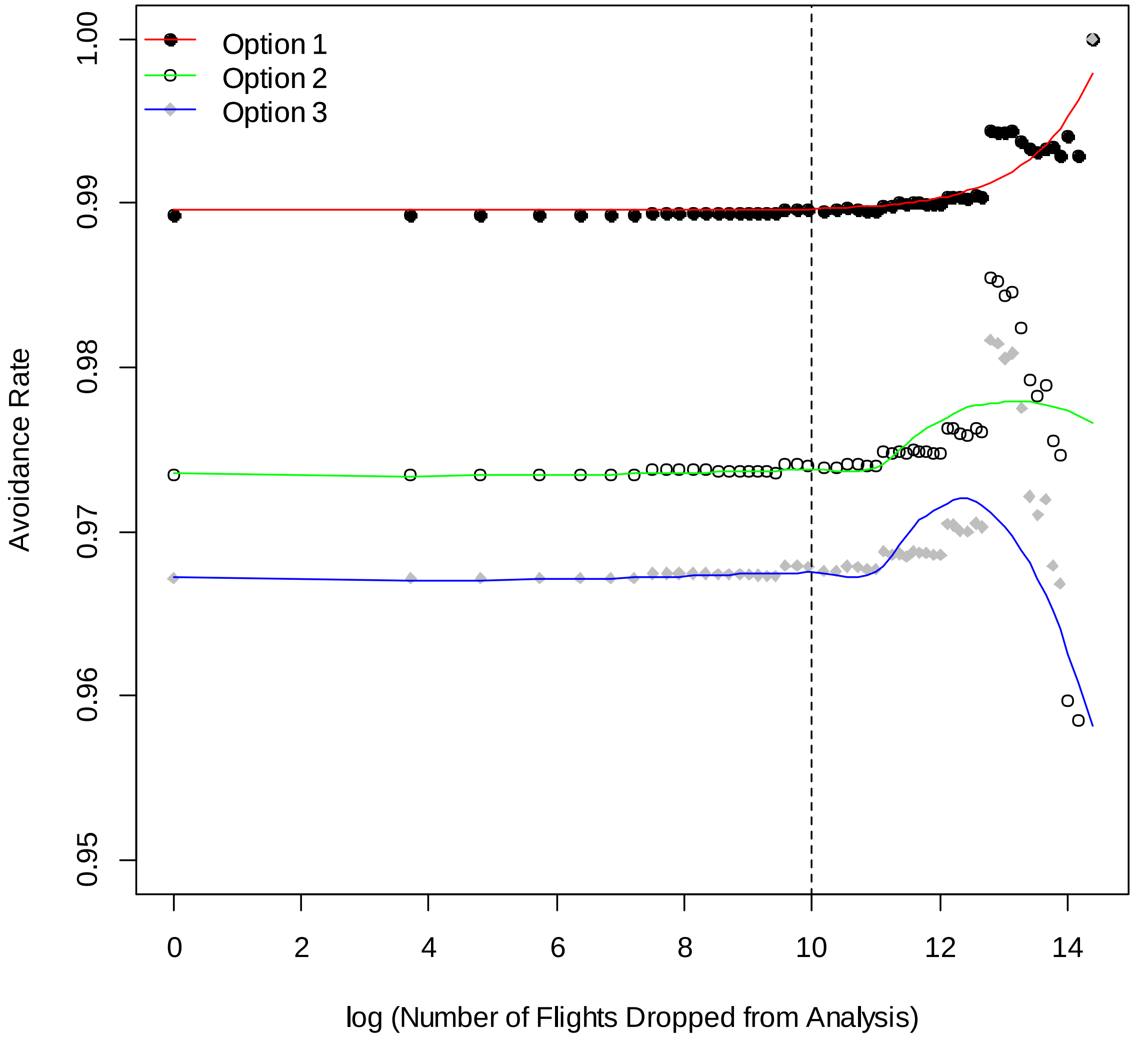


Figure 5.20 Impact of dropping data points (each site-year-species combination) on the within-windfarm avoidance rates derived using ratio estimators for options 1, 2 and 3 of the Band model.

As might be expected, dropping sites from the analysis can influence the final within-windfarm avoidance rates. Only sites at which there is a relatively limited level of flight activity can be dropped from the analysis before the within-windfarm avoidance rates derived become less stable (Figure 5.20). In all three model options, this is noticeable after around 22,000 of the 2,605,681 flights through the windfarms have been removed (Figure 5.20).

Using option 1 of the Band model, dropping sites from the analysis results in an increase in the overall within-windfarm avoidance. This result suggests that, for option 1, a higher flux rate is associated with a higher within-windfarm avoidance rate. Collisions between birds and turbines are relatively rare events, so studies carried out over a month or two may under-estimate mean annual within-windfarm avoidance rates if they are targeted to specific times of year when collisions are more likely. Amongst our datasets, there was a propensity for studies carried out during the breeding season. At Zeebrugge, both herring and lesser black-backed gulls showed a marked increase in their within-windfarm avoidance rates during the autumn than during the breeding season. At present, data are not robust enough to enable detailed analysis of seasonal patterns in within-windfarm avoidance behaviour, but this is an area that would benefit from such analyses as better data become available.

Initially a similar pattern is evident with option 3 of the Band model. However, when only the last few sites are included in the analysis, the final within-windfarm avoidance rates derived using ratio estimators start to fall (Figure 5.20). The decline is driven by breeding season data from Zeebrugge and Bouin, sites where turbines are situated close to the edge of breeding colonies. The reason the pattern is not evident in the within-windfarm avoidance rates derived using option 1 is the variation in the difference between the proportion of birds observed at rotor height in each study and those predicted to occur at rotor height based on the modelled flight height distribution. This is apparent when the differences between within-windfarm avoidance rates derived using options 1 and 2 are considered. Options 1 and 2 differ only in the proportion of birds predicted to fly at collision risk height. The proportion of birds estimated to fly at rotor height tended to be lower than the proportion of birds observed flying at rotor height (Appendix 7). As a result, the predicted collision rate, and therefore mean within-windfarm avoidance rate, was lower using option 2 than option 1. This difference becomes exaggerated under option 3 because, in addition to accounting for a lower proportion of birds flying at rotor height, fewer of these birds are predicted to collide.

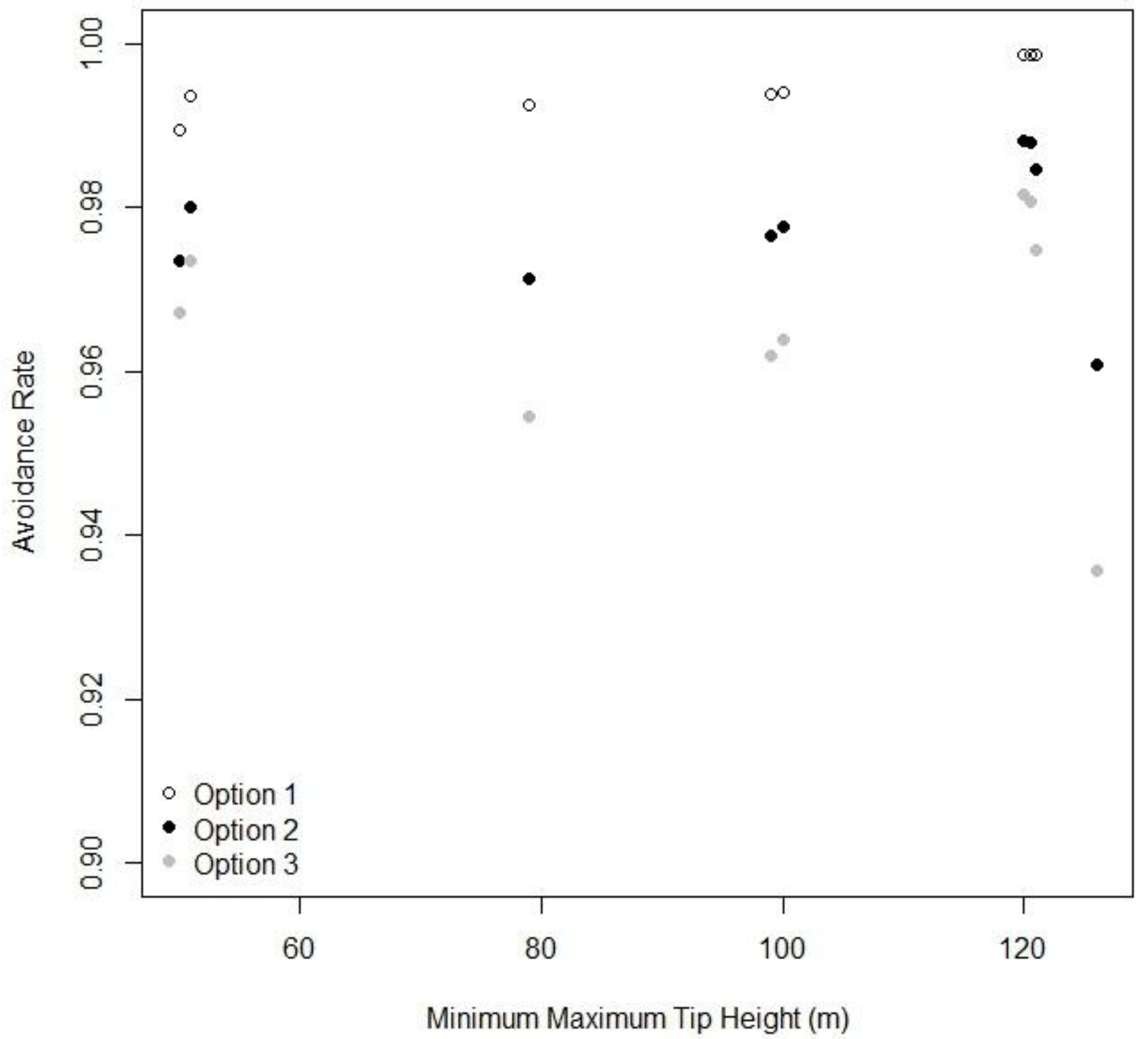


Figure 5.21 Impact of excluding sites with smaller turbines on the within-windfarm avoidance rates derived using ratio estimators for options 1, 2 and 3 of the Band model for large gulls.

Across all three model options there did not appear to be any consistent effect of excluding data collected from sites with smaller turbines on the final within-windfarm avoidance rates derived (Figure 5.21).

We consider that within-windfarm avoidance rates of 0.9893 (±0.0007 SD) for the basic Band model and 0.9672 (±0.0018 SD) for the extended Band model are realistic precautionary within-windfarm avoidance rates given the data available. Whilst we identified several sites as having a strong influence over the final values derived, we do not feel there is sufficient reason to exclude these data from our analysis. It should be noted that the influence of these sites occurs in similar magnitudes in both positive and negative directions. We did not identify any strong impact of turbine size on the final within-windfarm avoidance rate derived.

All terns

A total of 1,286,562 terns were expected to have passed through one site – Zeebrugge – during June 2004 and June 2005. After adjustments were made to this total to account for the proportion of birds flying at rotor height, the size of the rotor swept area and the probability of birds passing through the rotor-swept area without colliding, this was predicted to result in 1,408 collisions based on option 1, 1,299 collisions based on option 2, and 1,011 based on option 3. However, in total only 21 tern collisions were recorded across all sites during their respective study periods. This corresponds to within-windfarm avoidance rates of 0.9851 (±0.0022 SD) using option 1 of the Band model, 0.9838 (±0.0031 SD) using option 2 of the Band model and 0.9792 (±0.0040 SD) using option 3 of the Band model.

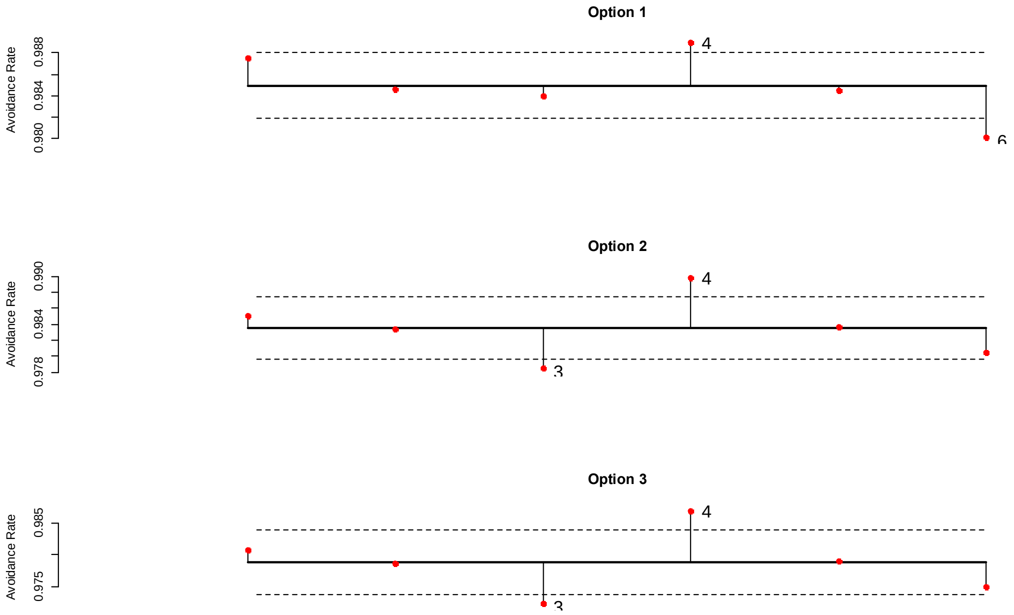


Figure 5.22 Leverage exerted by each site at which within-windfarm avoidance rates were calculated on the overall, mean within-windfarm avoidance rate derived for terns. Solid line indicates mean within-windfarm avoidance rate across all sites, broken line indicates mean within-windfarm avoidance rate across all sites ± 1 standard deviation, dots indicate mean within-windfarm avoidance rate with each site excluded from analysis. Sites are considered to have high leverage when their exclusion from the analysis leads to a change of more than 1 standard deviation in the overall mean within-windfarm avoidance rate. Points with high leverage are 3 – Sandwich tern in June 2004, 4 – common tern in June 2005, 6 – Sandwich tern in June 2005.

There was no obvious pattern in the data points with high leverage. Using all three model options, excluding common tern data from June 2005 was found to result in an increased within-windfarm avoidance rate, reflecting the relatively high collision rate involving this species in this year (Figure 5.22). Using option 1, excluding

Sandwich tern data from June 2005 resulted in a decrease in the within-windfarm avoidance rate derived. Using options 2 and 3 the same was true of Sandwich tern data in June 2004. This is likely to reflect the fact that relatively few collisions were recorded involving this species, despite a high flux rate. Differences between model options are likely to result from differences between the proportion of birds observed at collision risk height during surveys, and that estimated from the modelled distributions. We do not consider there to be a valid reason to exclude any of these data from our analysis when deriving within-windfarm avoidance rates.

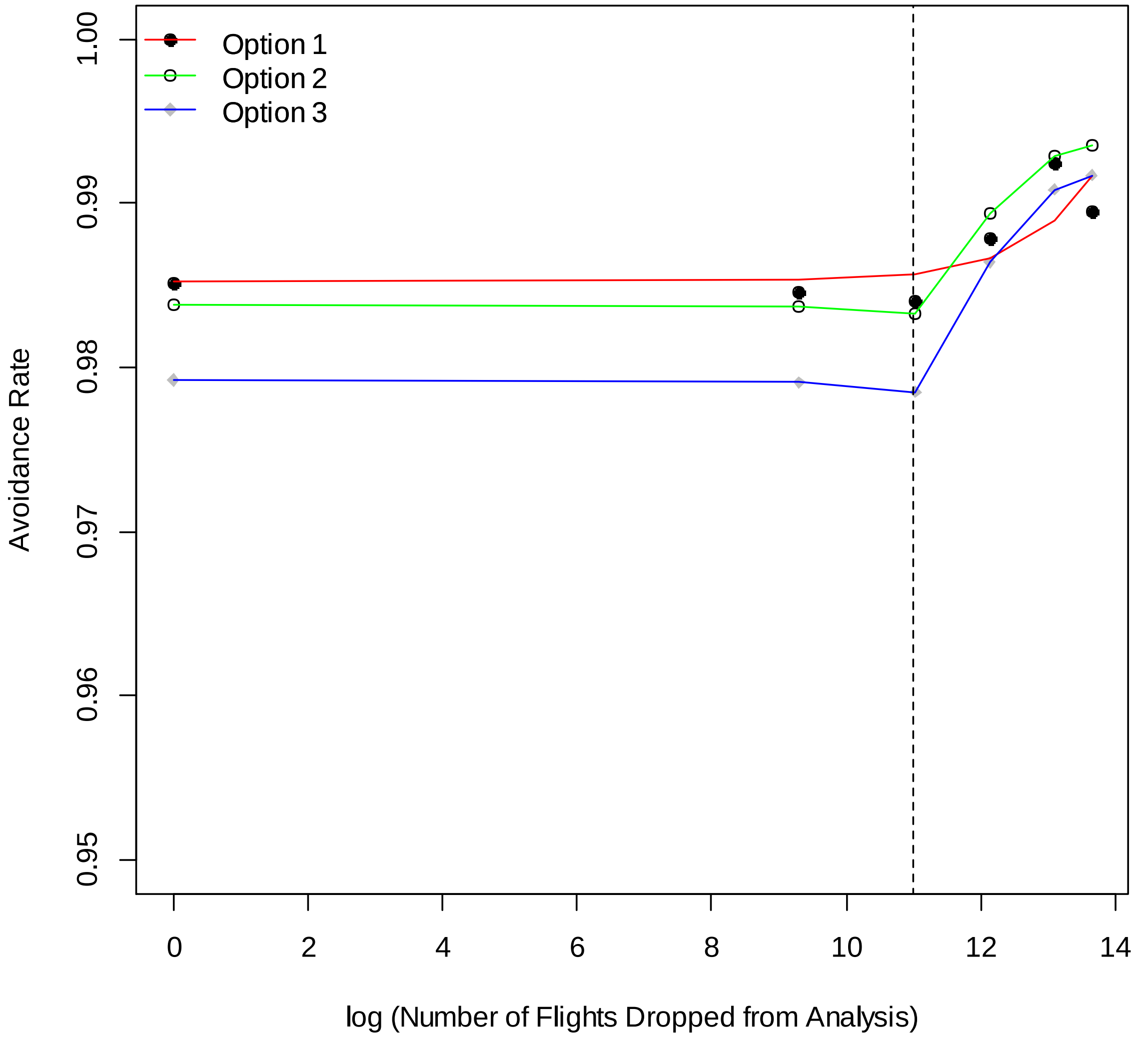


Figure 5.23 Impact of dropping data points (each year-species combination) on the within-windfarm avoidance rates derived using ratio estimators for options 1, 2 and 3 of the Band model for terns.

Within-windfarm avoidance rates derived using all three model options remain relatively stable as the first 660,000 flights through windfarms are dropped from the analysis (Figure 5.23), before increasing as only the species with the highest levels of activity remain. This reflects the fact that Sandwich terns, the species with the highest levels of activity were involved in relatively few collisions, resulting in an overall increase in the within-windfarm avoidance rates as other species were dropped from the analysis.

We consider that within-windfarm avoidance rates of 0.9851 (±0.0022 SD) for the basic Band model and 0.9792 (±0.0040 SD) for the extended Band model are realistic precautionary within-windfarm avoidance rates given the data available. Whilst we determined that some data points had a high level of leverage on the final values derived, we did not feel that there was sufficient justification for excluding them from our analysis. It should be noted that this leverage occurred in both positive and negative directions. However, as data come from only a single site, it is unclear how transferable they are to novel sites.

6. SENSITIVITY ANALYSIS

Within windfarm avoidance rates can be derived from sites at which estimates of collision rates and bird activity are available using the parameters listed in Table 6.1 and following equation 6 (see section 3.1). However, many of these parameters are incorporated into the calculations as mean values, or a range of values, and others must be estimated. Therefore, in order to understand how transferable these values may be between different models and situations, it is important to understand how sensitive the final avoidance rates are to each of the model input parameters. If avoidance rates are found to be highly sensitive to variation in one or more of the input parameters, it may raise questions about whether or not it is appropriate to apply the avoidance rates derived to novel sites.

For this reason, we assess the sensitivity of each of the avoidance rates presented in Appendix 7 to different input parameters. These parameters include corpse correction factors used to correct for the efficacy of corpse searches (observed collision rate in eq. 6), which will be influenced by scavenger behaviour and searcher efficiency, and estimates of the number of birds passing through a windfarm over a given period of time (flux rate in eq. 6). They also include parameters used to calculate collisions in the absence of avoidance behaviour (P_{coll} in eq. 6) including bird behavioural parameters such as flight speed and altitude, and turbine parameters such as rotor speed and pitch.

Avoidance may also be sensitive to a range of additional factors which cannot be easily quantified. These include time of day, weather, proximity to breeding colonies or overlap with migration routes and the size of the turbines concerned. We use a brief literature review to consider how each of these factors may influence the avoidance rates we derive.

6.1 Avoidance rates derived using the basic Band model (options 1 and 2)

The variables used to estimate P_{coll}, the first step to deriving an avoidance rate, are subject to differing levels of uncertainty. Some, such as rotor diameter, blade width and turbine height are fixed and are, therefore, known quantities with very little, if any, uncertainty surrounding them. Others, such as rotor speed and pitch and aspects of bird behaviour, such as flight speed and altitude and the propensity to fly upwind or downwind are subject to a greater degree of uncertainty. As part of the sensitivity analysis, we focus on the parameters which are not fixed and, therefore, subject to varying degrees of uncertainty, in order to determine what influence the inaccurate estimation of each of these parameters has on the final derived avoidance rates. Whilst the focus of much of the interest in collision risk modelling has been on avoidance rates, it is actually 1-avoidance rate, or the non-avoidance rate which is applied in the final step of the Band collision risk model (Band *pers. comm.*, Masden *et al.* in prep). For this reason, we focus our sensitivity analysis on this factor, rather than the avoidance rate.

For each of the sites and species combinations presented in Appendix 7 at which collisions were recorded, we consider the impact that a 10% increase (following Chamberlain *et al.* 2006) in each of rotor speed, rotor pitch, bird flight speed, flux rate and the proportion of flights upwind would have on the avoidance rates derived using option 1. In addition, we also consider the influence of a 10% increase in corpse detection rate.

Table 6.1 Input parameters for the Band (basic and extended model)

Parameter	**Sensitivity assessed**
Species name	No
Bird length	No
Wingspan	No
Flight speed	Yes – 10% increase considered following Chamberlain *et al.* (2006)
Nocturnal activity factor (1-5)	Considered as part of increase in flux rate
Flight type, flapping or gliding	No – Seabirds most likely to engage in flapping flight, which is the higher risk activity
Daytime bird density	Yes – considered as part of increase in flux rate
Proportion at rotor height	Yes – 10% increase in birds flying at risk height considered for basic model, 200 randomly simulated distributions considered for the extended model
Proportion of flights upwind	Yes – 10% increase in the proportion of birds flying upwind considered
Name of windfarm site	No – Fixed parameter
Latitude	No – Fixed parameter
Number of turbines	No – Fixed parameter
Width of windfarm	No – Fixed parameter
Tidal offset	No – Suitable datasets were only available for onshore windfarms
Turbine model	No – Fixed parameter
No. of blades	No – Fixed parameter
Mean rotation speed	Yes – 10% increase considered following Chamberlain *et al.* (2006)
Rotor radius	No – Fixed parameter
Hub height	No – Fixed parameter
Monthly proportion of time operational	Yes – considered as part of increase in flux rate
Max blade width	No – Fixed parameter
Pitch	Yes – 10% increase considered following Chamberlain *et al.* (2006)

6.1.1 Sensitivity to the assumed flux rate at the windfarm

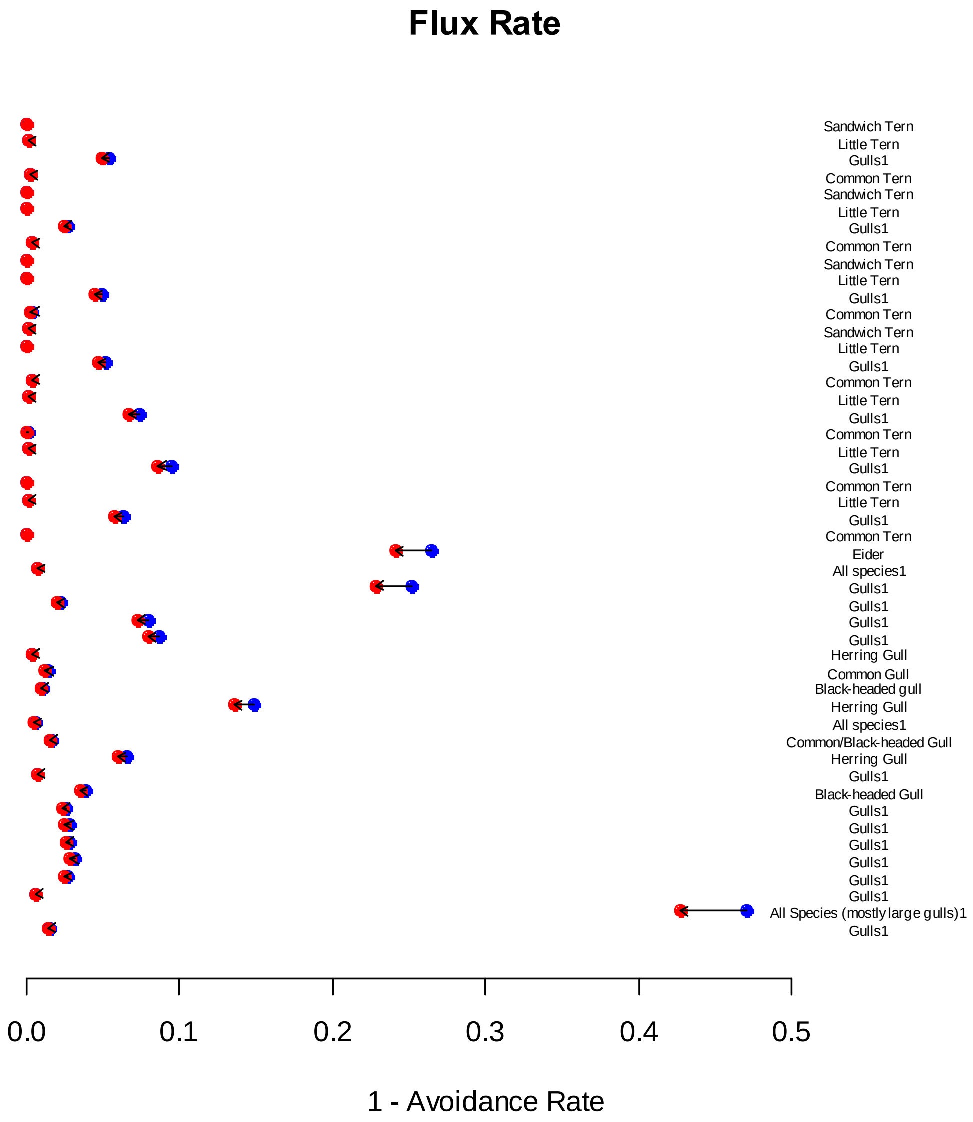


Figure 6.1 Sensitivity of non-avoidance rates for each species and site in Appendix 7 at which a collision was recorded and derived using the basic Band model, to the assumed flux rate at each site. Blue dots indicate the non-avoidance rate derived assuming the flux rate presented in Appendix 7, red dots indicate the non-avoidance rate derived assuming a 10% increase in the flux rate at each site.

Bird flux rate is an estimate of the total number of birds passing through the windfarm when it is operational. As such, it combines estimates of the number of birds recorded within the windfarm, the proportion of birds at collision risk height, corrections for nocturnal activity and an estimate of the monthly proportion of time it is operational. An increase in the flux rate derived at each site results in a decrease in the derived non-avoidance rates (Figure 6.1). This is because, whilst the observed number of collisions remains constant, the number of birds passing through the windfarm increases, meaning that a greater proportion of them are assumed to have avoided collision. These changes are approximately inversely proportional to the increase in the numbers of birds passing through the site. A comparison of the mean non-avoidance rates based on the flux rate presented in Appendix 7, with the mean non-avoidance rates assuming a 10% increase in this flux rate suggests that such an increase may result in a 9.1% decrease in the non-avoidance rate.

6.1.2 Sensitivity to the corpse detection rate at the windfarm

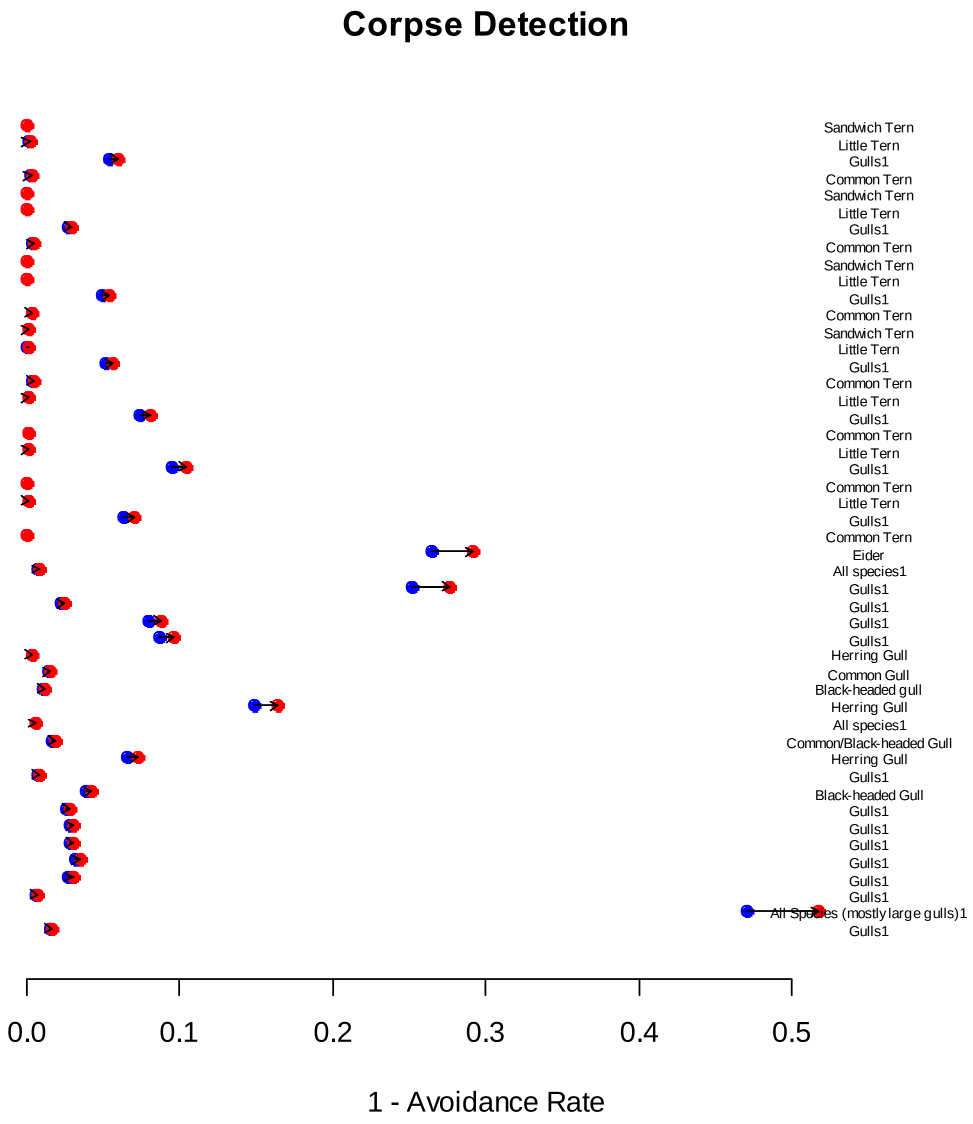


Figure 6.2 Sensitivity of non-avoidance rates for each species and site in Appendix 7 at which a collision was recorded and derived using the basic Band model, to the assumed corpse detection rate at each site. Blue dots indicate the non-avoidance rate derived assuming the

number of collisions presented in Appendix 7, red dots indicate the non-avoidance rate derived assuming a 10% increase in the number of collisions detected at each site.

During the search for collision victims, corpses may be missed either as a result of searcher inefficiency, or through the removal of carcasses by predators (Winkelman 1992). As a result it is often necessary to correct observed collision rates to account for these missing corpses. Assuming an increase in the total number of victims leads to an increase in the derived non-avoidance rate because the total number of birds passing through the windfarm remains constant and it is assumed a higher proportion of them collide with the turbines. These increases in the non-avoidance rate are proportional with the increase in corpse detection (Figure 6.2), with a 10% correction in the number of collisions to account for a failure to detect corpses resulting in 10% increase in the non-avoidance rate.

6.1.3 Sensitivity to the proportion of birds flying upwind

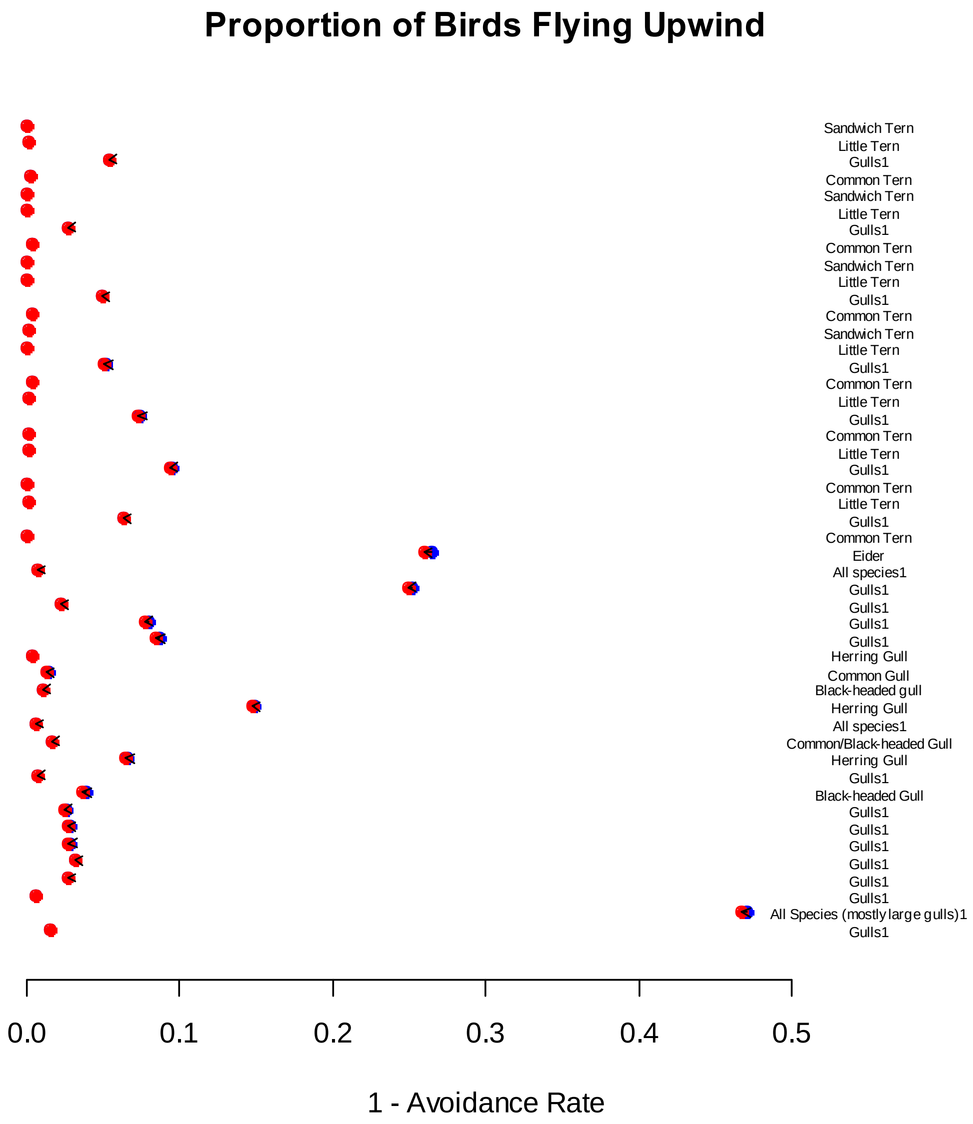


Figure 6.3 Sensitivity of non-avoidance rates for each species and site in Appendix 7 at which a collision was recorded and derived using the basic Band model, to the proportion of birds flying upwind at each site. Blue dots indicate the non-avoidance rate derived assuming the number of collisions presented in Appendix 7, red dots indicate the non-avoidance rate derived assuming a 10% increase in the proportion of birds flying upwind detected at each site.

A 10% change to the proportion of birds flying upwind resulted in a small decrease in the derived non-avoidance rates (Figure 6.3) of 1.17%. These results suggest that the proportion of birds estimated to fly up or downwind has a relatively small effect on the final, derived non-avoidance rate.

6.1.4 Sensitivity to the mean turbine rotor speed

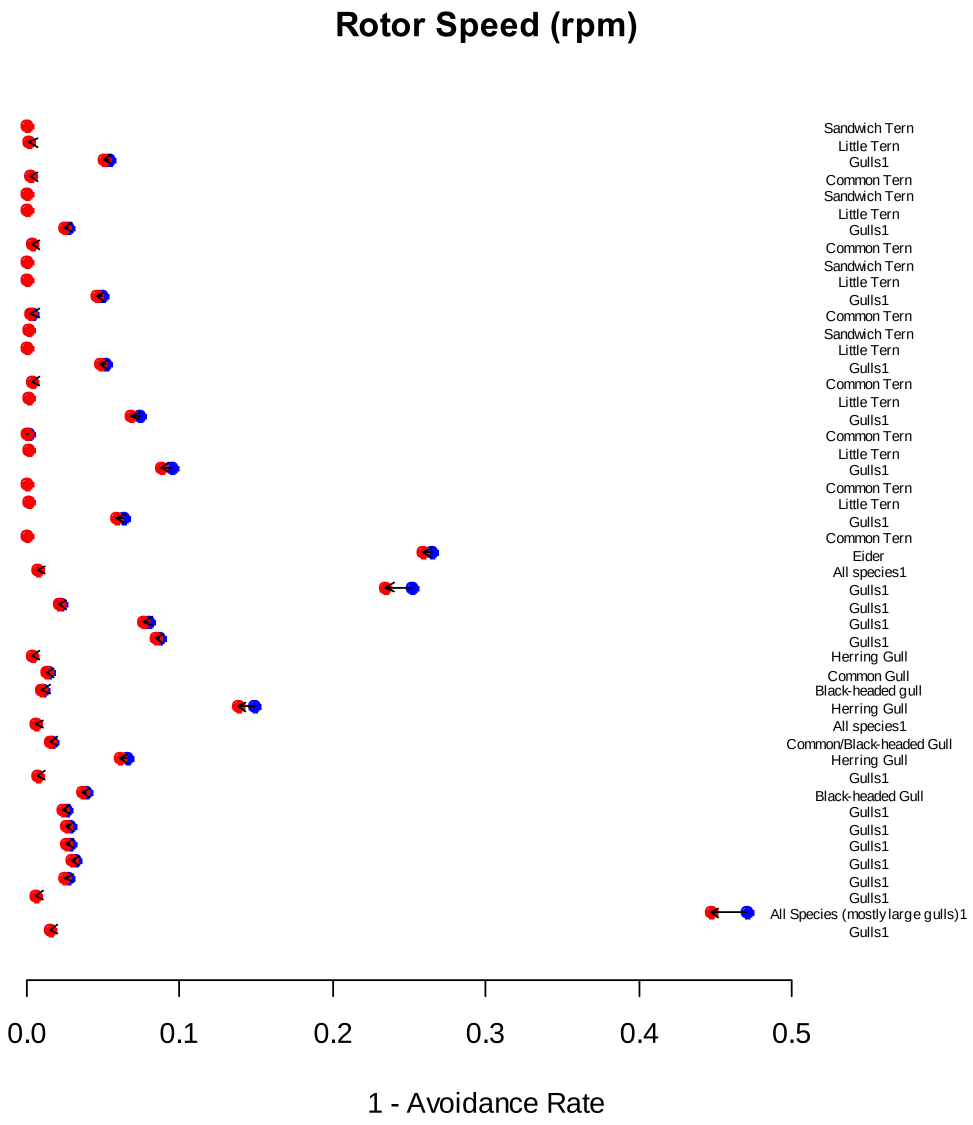


Figure 6.4 Sensitivity of non-avoidance rates for each species and site in Appendix 7 at which a collision was recorded and derived using the

basic Band model, to the turbine rotor speed at each site. Blue dots indicate the non-avoidance rate derived assuming the number of collisions presented in Appendix 7, red dots indicate the non-avoidance rate derived assuming a 10% increase in the turbine rotor speed at each site.

A 10% increase in the mean turbine rotor speed assumed typically resulted in a decrease in the derived non-avoidance rates of approximately 5.5% (Figure 6.4). The reason for this decrease is that as the rotor speed increases, the time available for a bird to pass through unharmed decreases, meaning that the predicted collision rate increases whilst the recorded number of collisions remains constant. Based on the turbines we considered, a 10% increase in mean rotor speed reflects an increase of between 1 and 4 rotations per minute. Published data from turbine manufacturers (http://www.4coffshore.com/) suggests the range of operational speeds for turbines is like to vary by between 5 and 15 rpm. As such, the increase in rotation speed we consider may be somewhat conservative but, without more detailed curves showing the range of operational speeds used by different turbines, assessing this is difficult.

6.1.5 Sensitivity to the turbine pitch

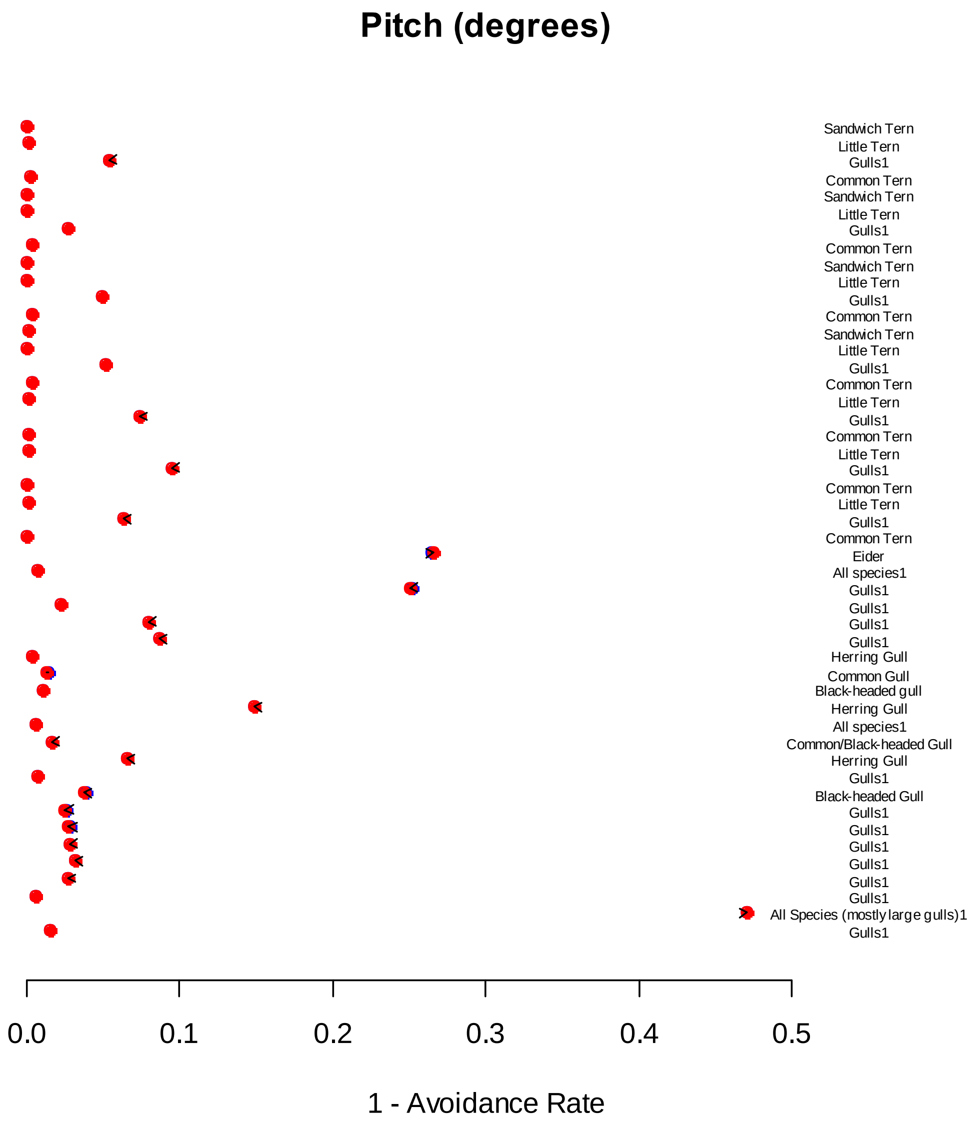


Figure 6.5 Sensitivity of non-avoidance rates for each species and site in Appendix 7 at which a collision was recorded and derived using the basic Band model, to the turbine pitch at each site. Blue dots indicate the non-avoidance rate derived assuming the number of collisions presented in Appendix 7, red dots indicate the non-avoidance rate derived assuming a 10% increase in the turbine pitch at each site.

A 10% change in the assumed turbine pitch resulted in a fairly negligible decrease in the derived non-avoidance rates (Figure 6.5) of 0.2%. Our calculations were based on an assumption of a 10˚ pitch for each turbine, so a 10% increase reflects an 11˚ pitch. Available data describing the pitch of operational turbines are extremely limited. As a consequence, it is not possible to determine how well these values reflect reality at operational turbines.

6.1.6 Sensitivity to the bird flight speed

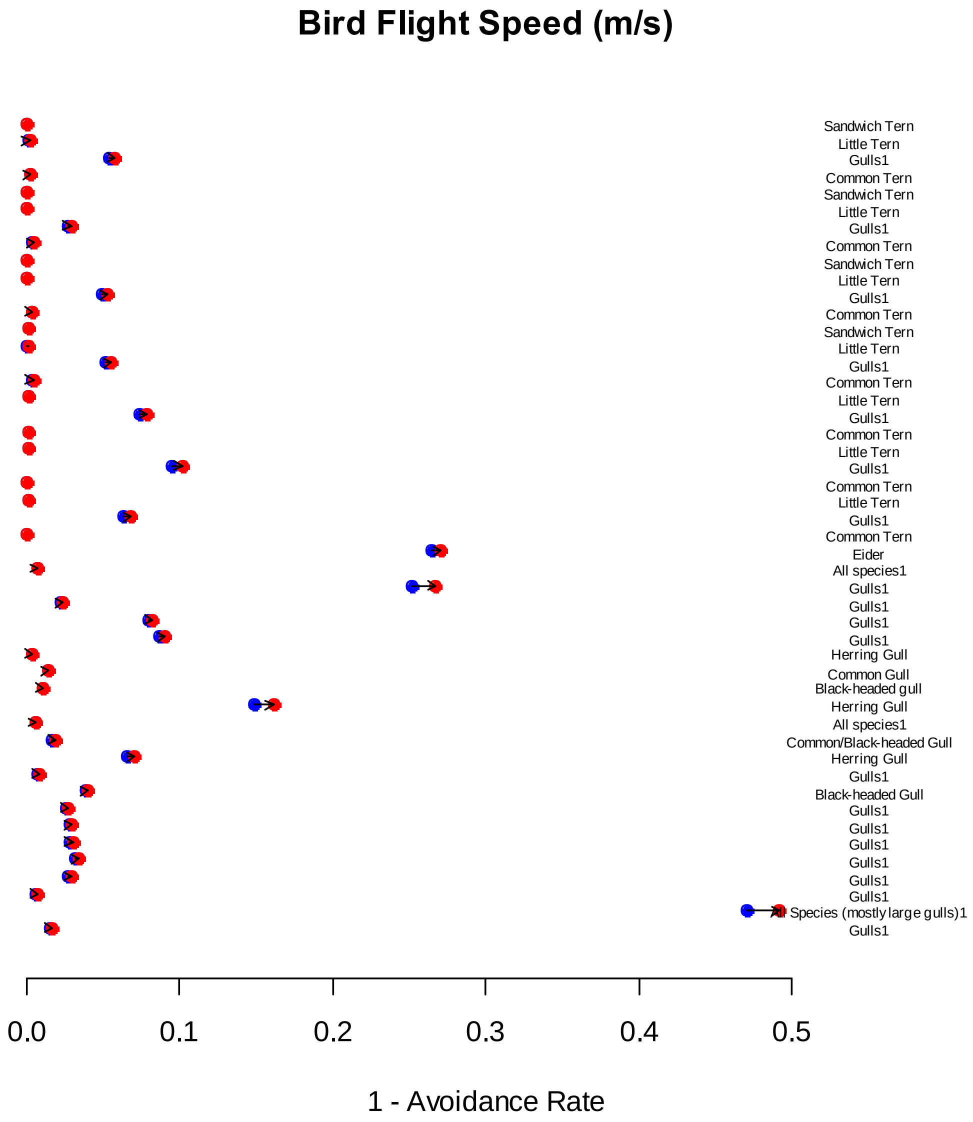


Figure 6.6 Sensitivity of non-avoidance rates for each species and site in Appendix 7 at which a collision was recorded and derived using the basic Band model, to the bird flight speed at each site. Blue dots indicate the non-avoidance rate derived assuming the number of collisions presented in Appendix 7, red dots indicate the avoidance rate derived assuming a 10% increase in the bird flight speed at each site.

A 10% increase in the assumed bird flight speed resulted in an increase in the derived non-avoidance rates (Figure 6.6) of 5.5%. This increase reflects the fact that the faster a bird passes through the rotor swept-area, the less likely it is to be hit. As a result an increase in flight speed results in a decrease in the predicted number of collisions whilst the observed number of collisions remains constant. For our study species a 10% increase in flight speed reflects an increase of 1-1.3 m/s. Alerstam *et al.* (2007) suggest that the standard deviations around the mean flight speeds for our study species are in the region of 1-2 m/s, suggesting that a 10% increase in flight speed may be a realistic, precautionary assumption.

6.1.7 Basic Band model sensitivity conclusions

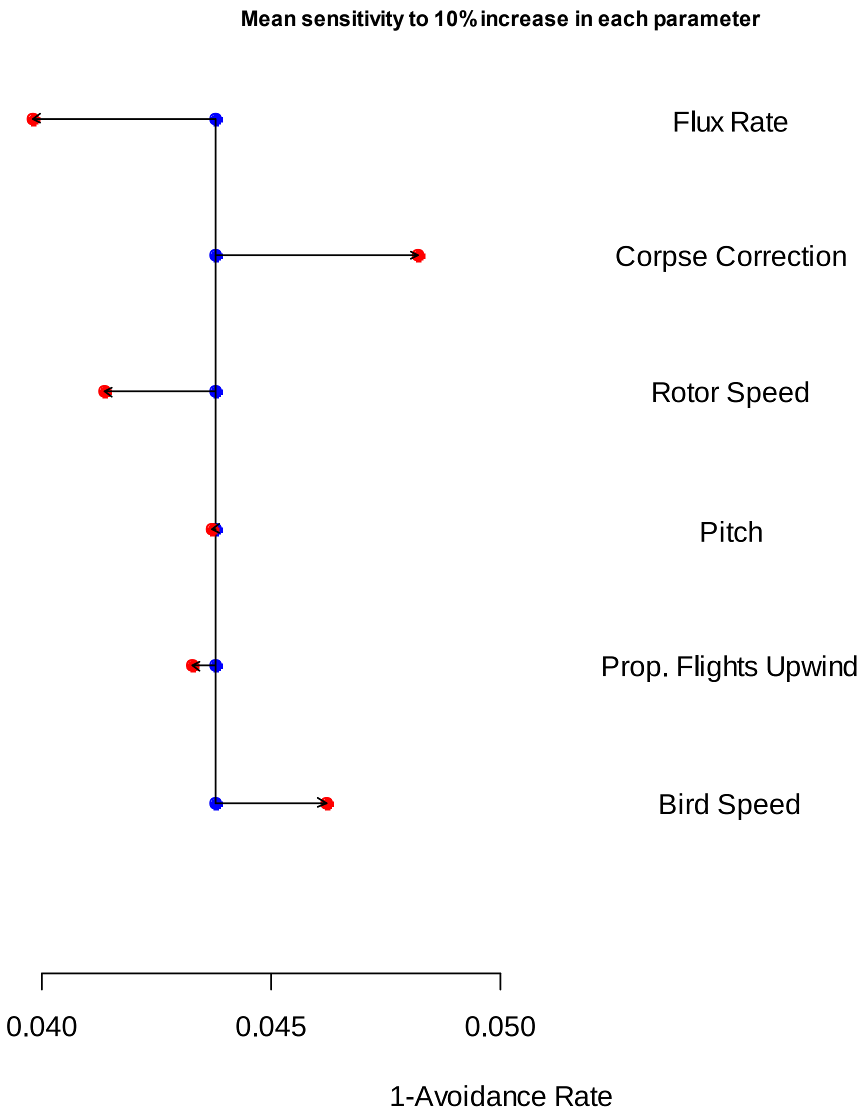


Figure 6.7 Sensitivity of derived non-avoidance rates derived using the basic Band model to a 10% increase in each of the Band model parameters.

Of the parameters considered, the final derived non-avoidance rates were most sensitive to flux rate and the corpse correction (Figure 6.7). An increase in the flux rate meant that the predicted collision rate increased, whilst the observed collision rate remained constant (see eq. 6, section 3.1); as a consequence, the non-avoidance rate decreased in response to an increase in the flux rate. For similar reasons, an increase in the number of corpses detected resulted in an increase in the non-avoidance rate derived. The impacts of assumed rotor speed and bird speed on the derived non-avoidance rates were of a similar magnitude, but in opposite directions. An increased assumed rotor speed results in a decreased non-avoidance rate because faster turbines result in an increased risk of collision. As a consequence, a faster rotor speed would result in an increase in the predicted collision rate, whilst the observed collision rate remains constant. This results in a decrease in the non-avoidance rate. In contrast, an increase in the assumed speed of the birds passing through the rotor swept area of a turbine decreases the risk of collision. As a consequence, the predicted collision rate decreases and, for the reasons stated above, the non-avoidance rate derived increases. Whilst increases in both the assumed pitch and the proportion of flights upwind resulted in decreases in the derived non-avoidance rates, the impact of both parameters was negligible.

6.2 Avoidance rates derived using the extended Band model (option 3)

In addition to the variables described above (section 6.1), non-avoidance rates derived using the extended Band model are also likely to be sensitive to the assumed flight height distributions. Collision risk is not evenly distributed within the rotor swept area of turbines, and is greatest towards the centre of the rotor disk. The extended Band model makes use of flight height distributions, such as those derived by Johnston *et al.* (2014a) to account for this variable risk. However, as these are continuous distributions, it is not appropriate to simply assume, for example, that an additional 10% of birds fly at rotor height as this will have implications for the overall shape of the distribution. Therefore, in addition to the parameters considered for the basic Band model, for each species/site combination we consider, we use 200 random distributions estimated following the methodology of Johnston *et al.* (2014a) to investigate sensitivity to the assumed distribution (Figure 6.8). It is important to note that by comparing between different distributions, the outputs of the sensitivity analysis will not be strictly comparable to the outputs of the sensitivity analyses described above.

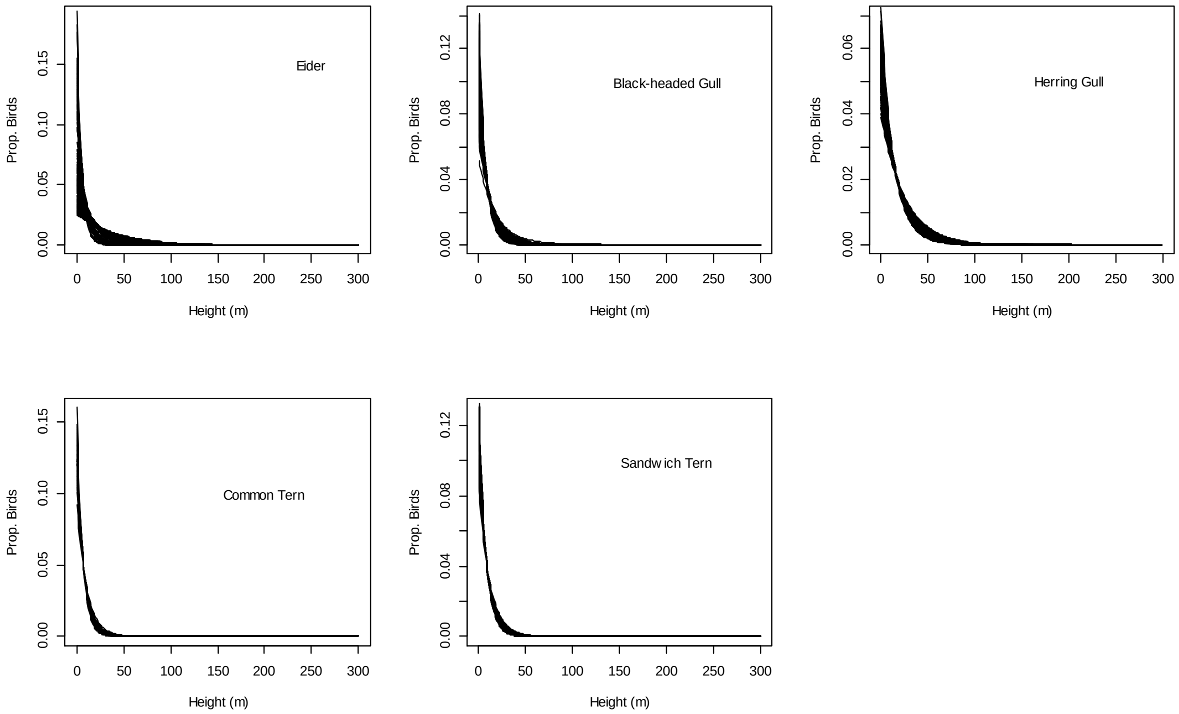


Figure 6.8 200 Random flight height distributions estimated for each of eider, black-headed gull, herring gull, common tern and Sandwich tern, species for which avoidance rates could be derived from a combination of recorded collisions and recorded levels of bird activity, using the methodology set out in Johnston *et al.* (2014a) and used to assess the sensitivity of derived avoidance rates to the assumed flight height distribution.

6.2.1 Sensitivity to assumed flight height distribution

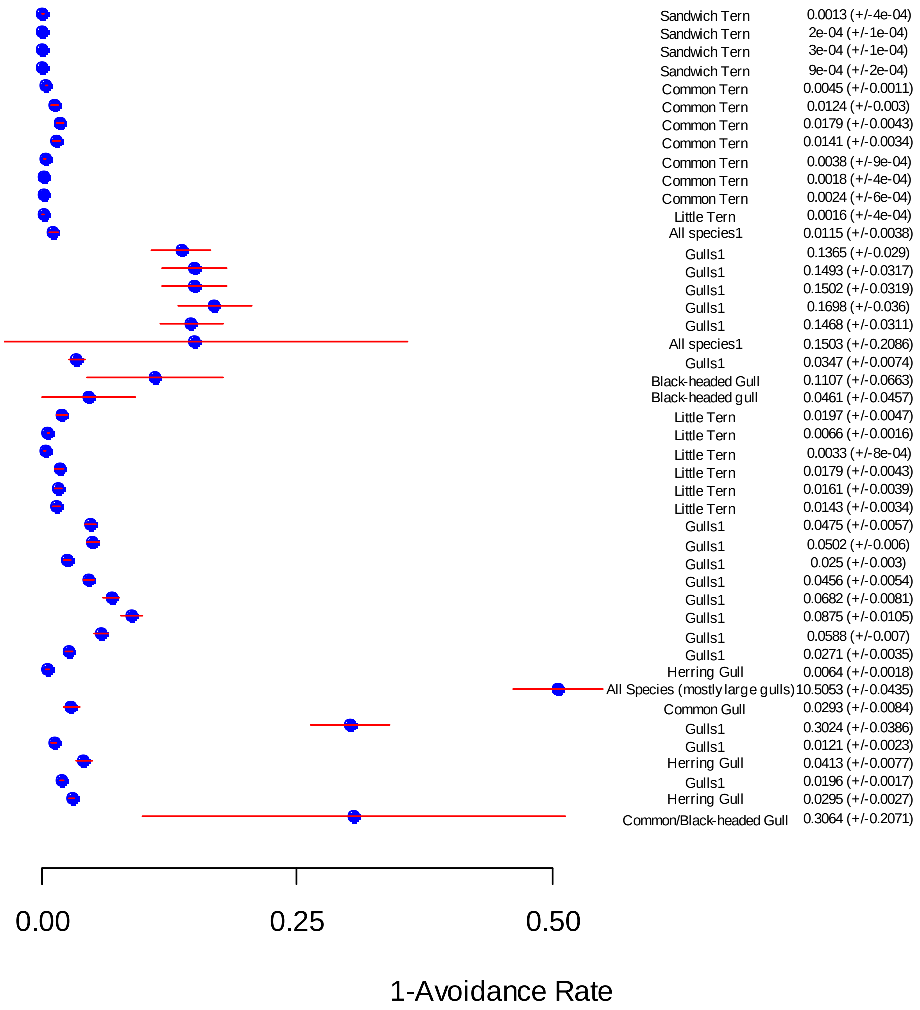


Figure 6.9 Sensitivity of non-avoidance rates derived for each species and site in Appendix 7 at which a collision was recorded and derived using the extended Band model, to the assumed flight height distribution at the site. Blue dots indicate the mean non-avoidance rate values derived from 200 random flight height distributions at each site, red lines indicate the standard deviation around these values, actual values shown alongside plot.

The sensitivity of the derived non-avoidance rates to different flight height distributions appears to be highly variable (Figure 6.9). The greatest sensitivity appears to occur where derived non-avoidance rates are highest. This relationship is likely to reflect the level of activity at any given site. For example, consider two sites, at the first of which 1 flight out of 100 at rotor height results in a collision and at the second of which 1 flight out of 1000 results in a collision. If the estimate of the proportion of birds flying at rotor height increases at each site by 10%, whilst the recorded number of collisions remains constant, this becomes 1 flight out of 110 at the first site and 1 flight out of 1,100 at the second. At the first site the non-avoidance rate decreases from 0.0100 to 0.0091, whilst at the second it decreases from 0.0010 to 0.0009. The overall decrease is therefore greater at the first site, with the lower level of flight activity.

6.2.2 Sensitivity to the assumed flux rate at the windfarm

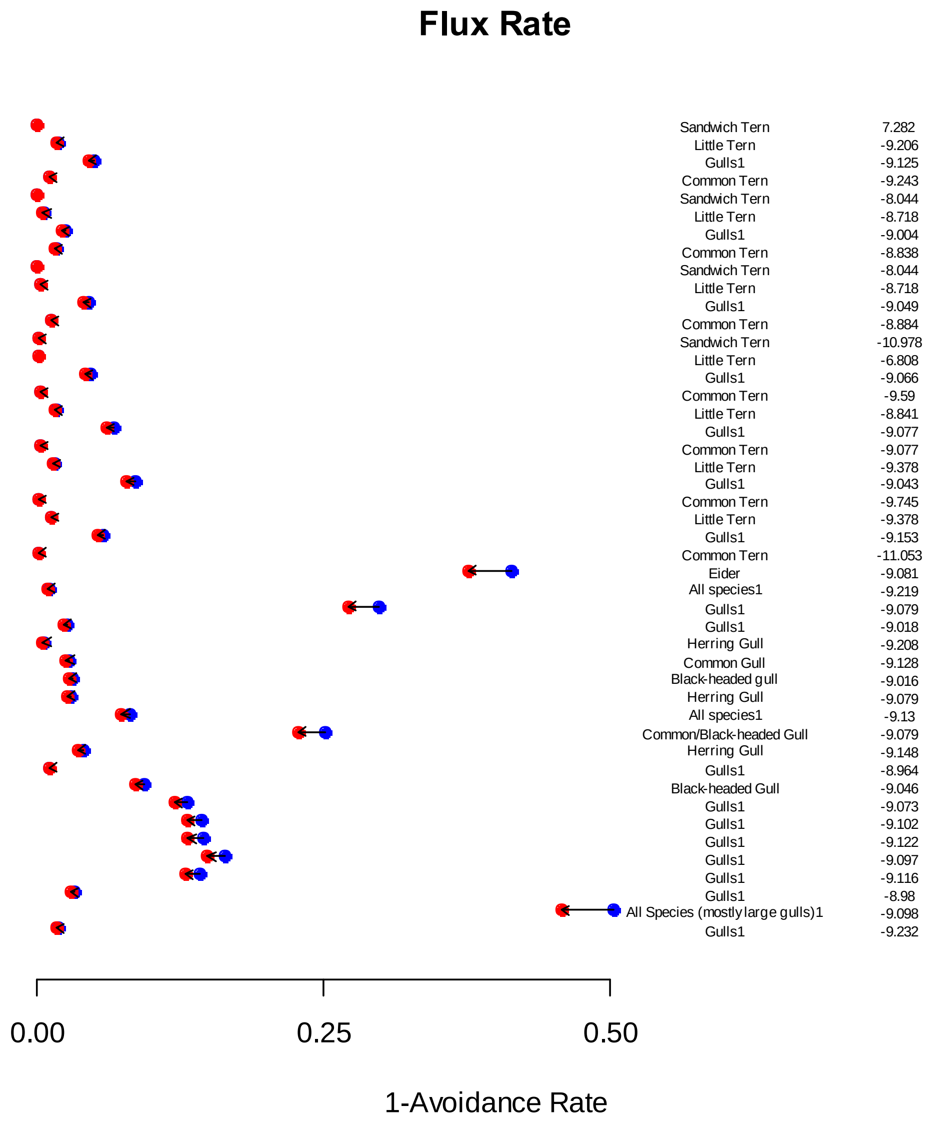


Figure 6.10 Sensitivity of non-avoidance rates derived for each species and site in Appendix 7 at which a collision was recorded and derived using the extended Band model, to the assumed flux rate at each site. Blue dots indicate the non-avoidance rate derived assuming the flux rate presented in Appendix 7, red dots indicate the non-avoidance rate derived assuming a 10% increase in the flux rate at each site. % change in the non-avoidance rates following a 10% increase in flux rate shown alongside graph.

Bird flux rate is an estimate of the total number of bird passing through the windfarm when it is operational. As such, it combines estimates of the number of birds recorded within the windfarm, corrections for nocturnal activity and an estimate of the monthly proportion of time it is operational. An increase in the flux rate derived at each site results in a decrease in the derived non-avoidance rates (Figure 6.10). This is because, whilst the observed number of collisions remains constant, the number of birds passing through the windfarm increases, meaning that a greater proportion of them are assumed to have avoided collision. These decreases are roughly inversely proportional to the increase in flux rate, although in contrast to the case of the basic Band model, this value will vary across sites as a consequence of the different height distributions assumed. A comparison of the mean avoidance rates based on the flux rate presented in Appendix 7, with the mean avoidance rates assuming a 10% increase in this flux rate suggests that such an increase may result in a mean 8.73% decrease in the non-avoidance rate.

6.2.3 Sensitivity to the corpse detection rate at the windfarm

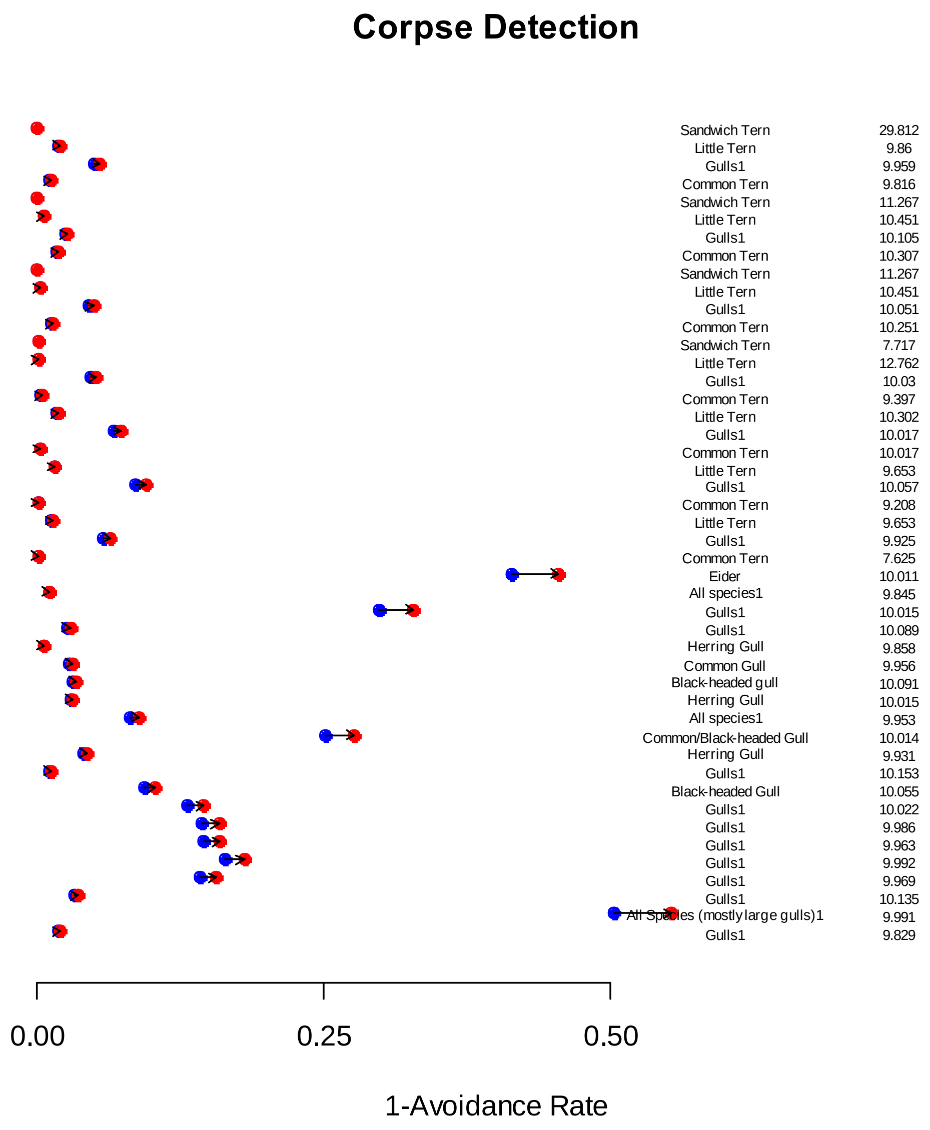


Figure 6.11 Sensitivity of non-avoidance rates for each species and site in Appendix 7 at which a collision was recorded and derived using the extended Band model, to the assumed corpse detection rate at each

site. Blue dots indicate the non-avoidance rate derived assuming the number of collisions presented in Appendix 7, red dots indicate the non-avoidance rate derived assuming a 10% increase in the number of collisions detected at each site. % change in the non-avoidance rates following a 10% increase in the number of collisions detected shown alongside graph.

During the search for collision victims, corpses may be missed either as a result of searcher inefficiency, or through the removal of carcasses by predators (Winkelman 1992). As a result it is often necessary to correct observed collision rates to account for these missing corpses. Assuming an increase in the total number of victims leads to an increase in the derived non-avoidance rate because the total number of birds passing through the windfarm remains constant and it is assumed a higher proportion of them collide with the turbines (Figure 6.11). This increase is broadly proportional with the increase in the flux rate across sites, with a mean 10.43% increase in the non-avoidance rate following a 10% increase in the flux rate.

6.2.4 Sensitivity to the proportion of birds flying upwind

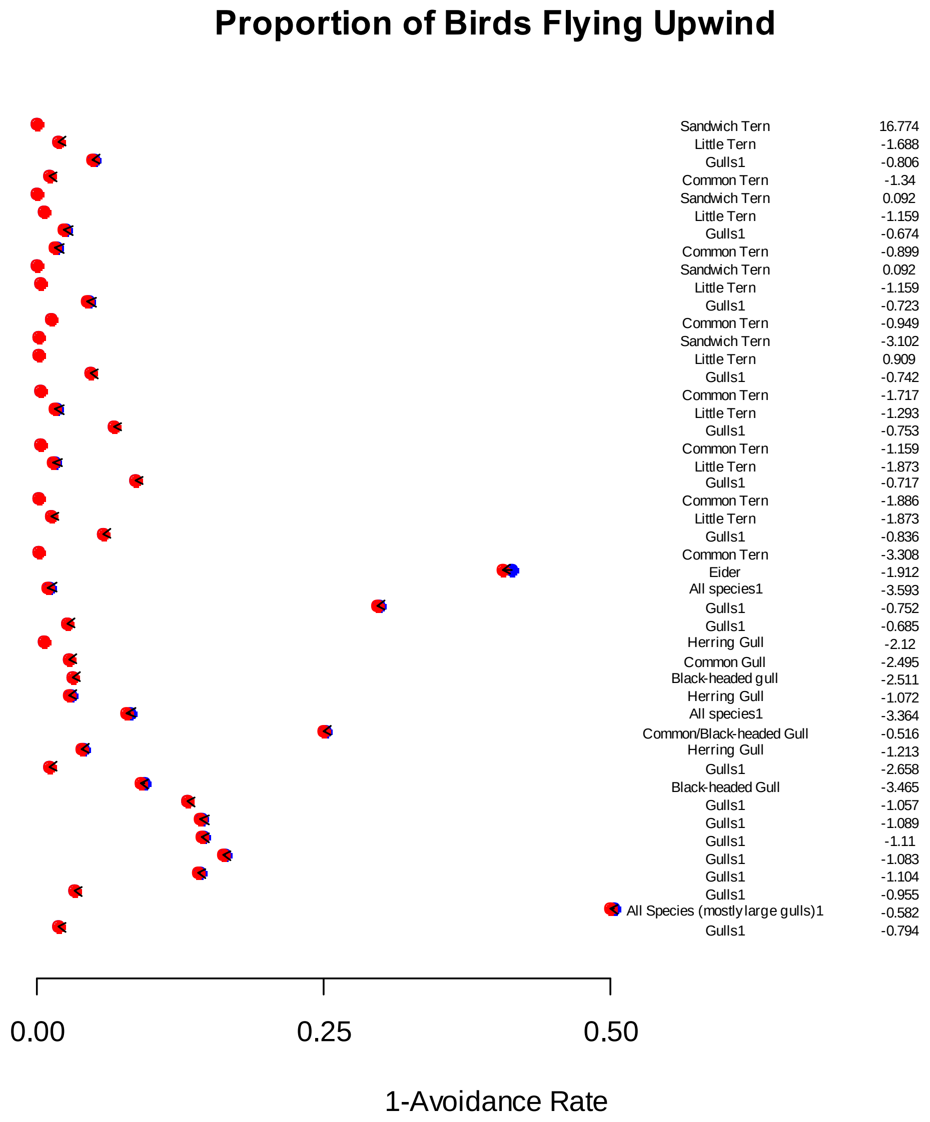


Figure 6.12 Sensitivity of non-avoidance rates derived for each species and site in Appendix 7 at which a collision was recorded and derived using the extended Band model, to the proportion of birds flying upwind at each site. Blue dots indicate the non-avoidance rate derived assuming 50% of birds flying upwind, red dots indicate the avoidance rate derived assuming a 10% increase in the proportion of birds flying upwind at each site. % change in the non-avoidance rates following a 10% increase in the proportion of birds flying upwind shown alongside graph.

A 10% change to the proportion of birds flying upwind resulted in a fairly negligible decrease in the derived avoidance rates (Figure 6.12). The % increases were typically <1%, and across all sites a 10% increase in the proportion of birds flying upwind resulted in a decrease in the non-avoidance rate of approximately 0.97%. These results suggest that the proportion of birds estimated to fly up or downwind has a negligible effect on the final, derived non-avoidance rate.

6.2.5 Sensitivity to the turbine rotor speed

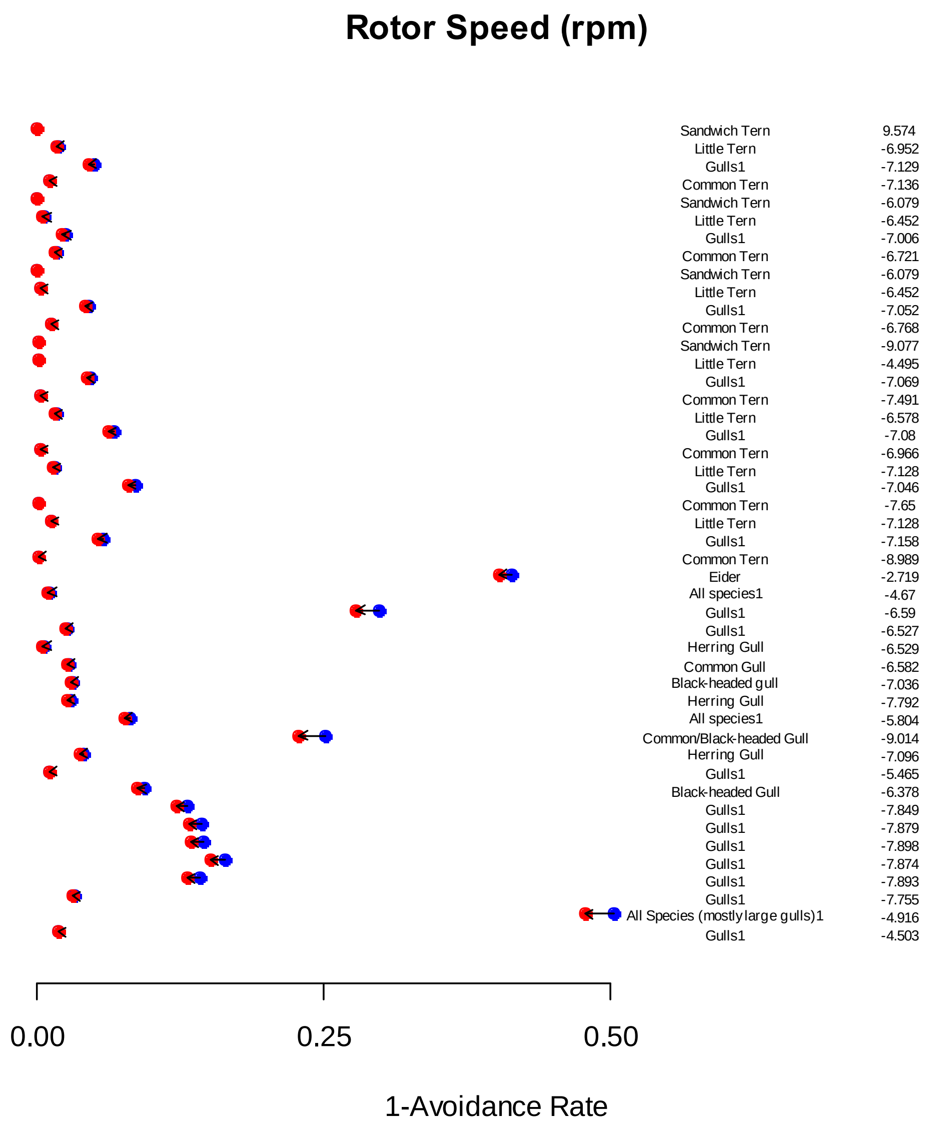


Figure 6.13 Sensitivity of non-avoidance rates derived for each species and site in Appendix 7 at which a collision was recorded and derived using the extended Band model, to the turbine rotor speed. Blue dots indicate the non-avoidance rate derived based on the rotor speed values presented in Appendix 7, red dots indicate the non-avoidance rate derived assuming a 10% increase in these rotor speeds. % change in the non-avoidance rates following a 10% increase in the turbine rotor speed shown alongside graph.

A 10% increase in the assumed turbine rotor speed typically resulted in a decrease in the derived non-avoidance rates (Figure 6.13). Across all sites a 10% increase in the rotor speed resulted in a decrease in the non-avoidance rate of approximately 6.45%.

6.2.6 Sensitivity to the turbine pitch

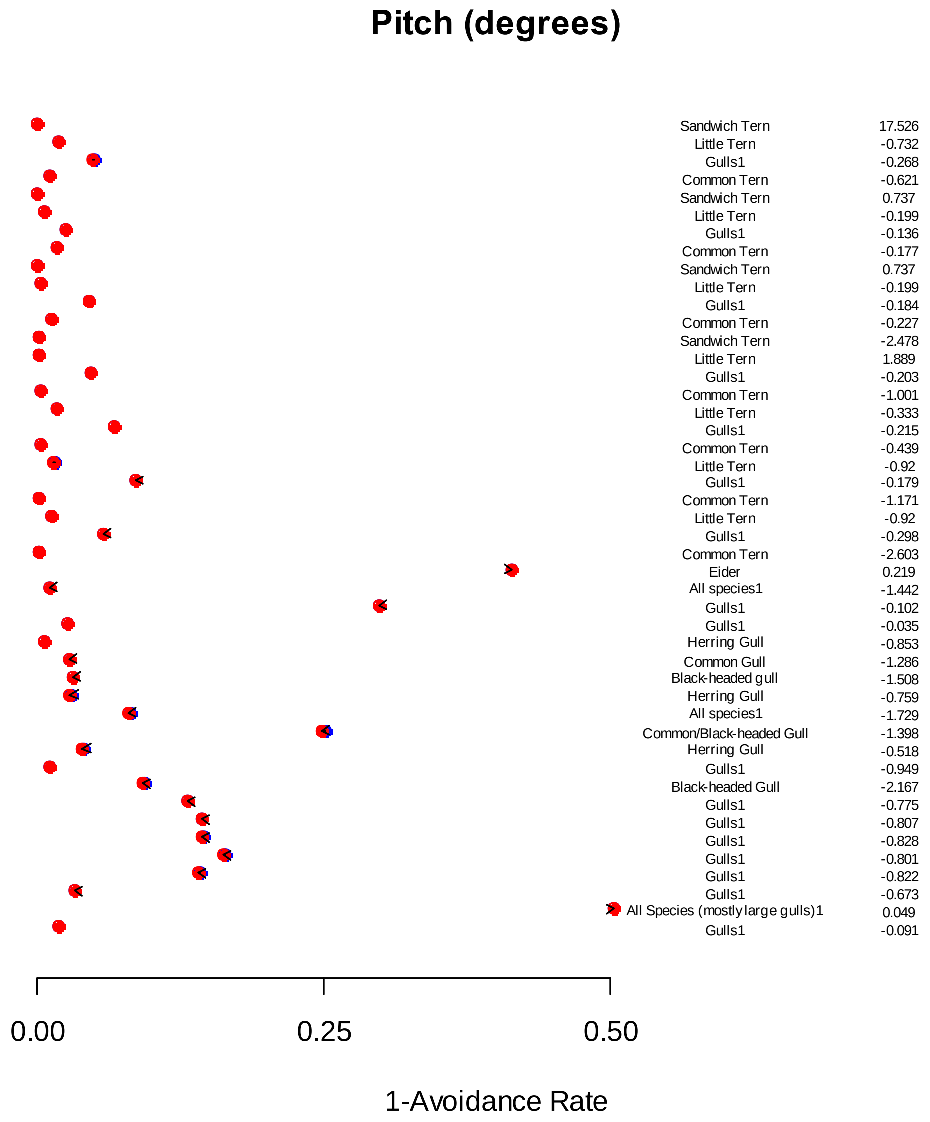


Figure 6.14 Sensitivity of non-avoidance rates derived for each species and site in Appendix 7 at which a collision was recorded and derived using the extended Band model, to the turbine pitch. Blue dots indicate the non-avoidance rate derived based on the rotor speed values presented in Appendix 7, red dots indicate the non-avoidance rate derived assuming a 10% increase in the pitch. % change in the non-avoidance rates following a 10% increase in the turbine rotor speed shown alongside graph.

A 10% change in the assumed turbine pitch resulted in a fairly negligible decrease in the derived non-avoidance rates (Figure 6.14). The % decreases were typically <1%, and across all sites a 10% increase in the turbine pitch resulted in a decrease in the non-avoidance rate of approximately 0.21%.

6.2.7 Sensitivity to the bird flight speed

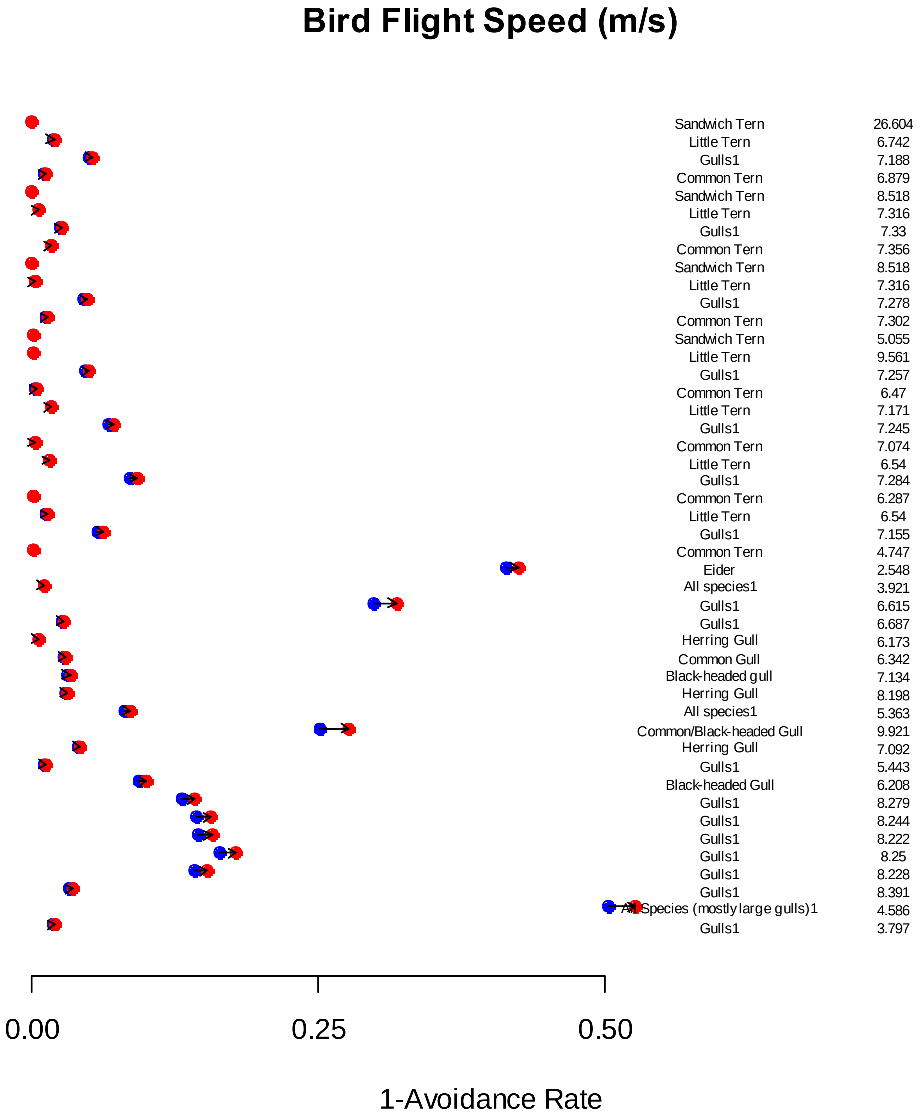


Figure 6.15 Sensitivity of non-avoidance rates derived for each species and site in Appendix 7 at which a collision was recorded and derived using the extended Band model, to the bird flight speed. Blue dots indicate the non-avoidance rate derived based on the bird flight speed values presented in Table 5.4, red dots indicate the non-avoidance rate derived assuming a 10% increase in the bird flight speed. % change in the non-avoidance rates following a 10% increase in the bird flight speed shown alongside graph.

A 10% increase in the assumed bird flight speed typically resulted in an increase in the derived non-avoidance rates (Figure 6.15). Across all sites a 10% increase in the bird flight speed resulted in an increase in the non-avoidance rate of approximately 7.31%.

6.2.8 Extended Band model sensitivity conclusions

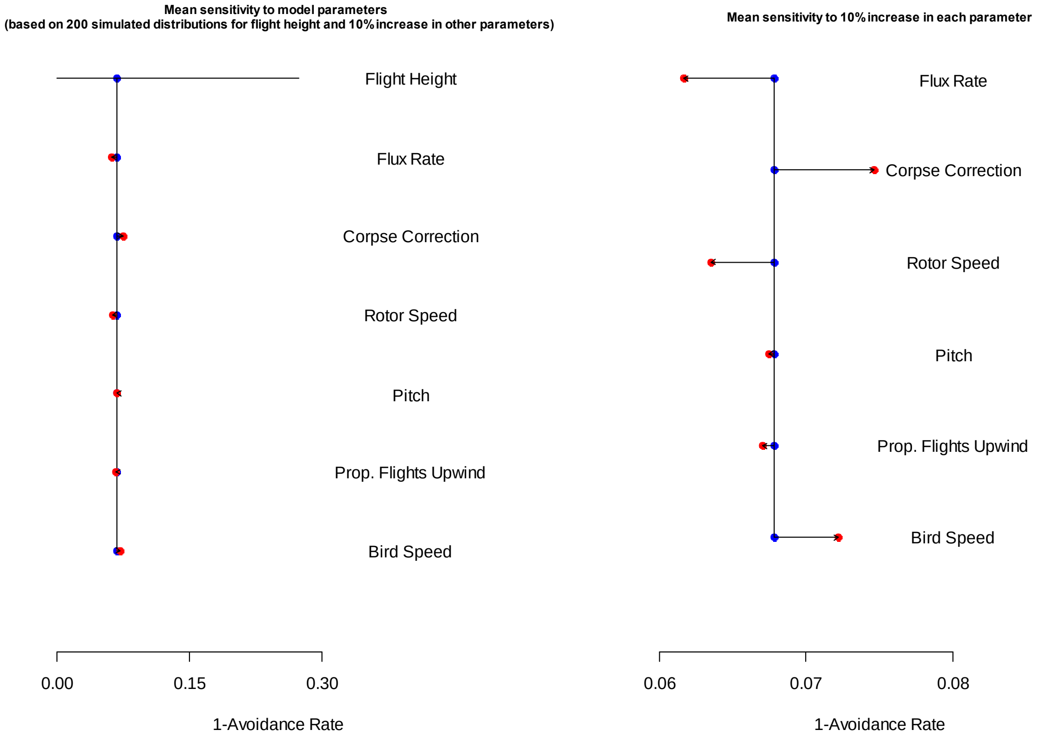


Figure 6.16 Sensitivity of non-avoidance rates derived using the extended Band model to Band model parameters. Sensitivity to flight height distribution is assessed by considering the standard deviation calculated from non-avoidance rates derived using 200 randomly simulated flight height distributions and sensitivity to the remaining parameters is derived from a 10% increase in the values presented in Appendix 7 and Table 5.4.

Of the parameters considered, the derived non-avoidance rates appear to be most sensitive to the assumed flight height distribution (Figure 6.16). However, the assessment of sensitivity for this parameter is not strictly comparable to that for the other parameters as it is not possible to make a simple assumption about a change in a continuous distribution in the same way it is about a change in, for example, rotor speed or bird numbers. Furthermore, the magnitude of the sensitivity in this parameter may be strongly influenced by 11 of the 45 data points, for which there was particularly high variation around the mean values (Figure 6.9). On closer examination, this variation appears to be strongly linked to sites with relatively low levels of bird activity (Figure 6.17).

Of the remaining parameters, the derived non-avoidance rates were most sensitive to changes in the flux rate at the windfarm (the number of birds passing through over the course of the study period) and the accuracy with which corpses were detected.

Both rotor speed and bird speed also appeared to have a moderate influence on the derived non-avoidance rates (Figure 6.18). The sensitivity of the non-avoidance rates to the input parameters appeared to be relatively consistent between option 1 and option 3.

Sensitivity to each parameter also appeared to be strongly linked to the number of birds estimated flying through each monitored windfarm (Figures 6.10 and 6.17). As the number of birds passing through a site increases, the sensitivity of the derived non-avoidance rates to each of the model parameters, including the assumed flight height distribution, drops markedly. This finding is consistent with that of Douglas *et al.* (2012) who found that the sensitivity of predicted collision rates to input parameters dropped as the quantity of observational data increased. In the case of sensitivity to the assumed flight height distributions used, at sites where flight activity is greatest, the derived avoidance rates have a similar level of variability to this and to other parameters. This is because for two sites where similar numbers of collisions are recorded, but at which the levels of bird activity differ, the non-avoidance rate will be higher at the site with the lowest level of bird activity. As a consequence, where an identical change occurs at both sites, the total change in the non-avoidance rate will be greatest at the site with the lowest level of bird activity.

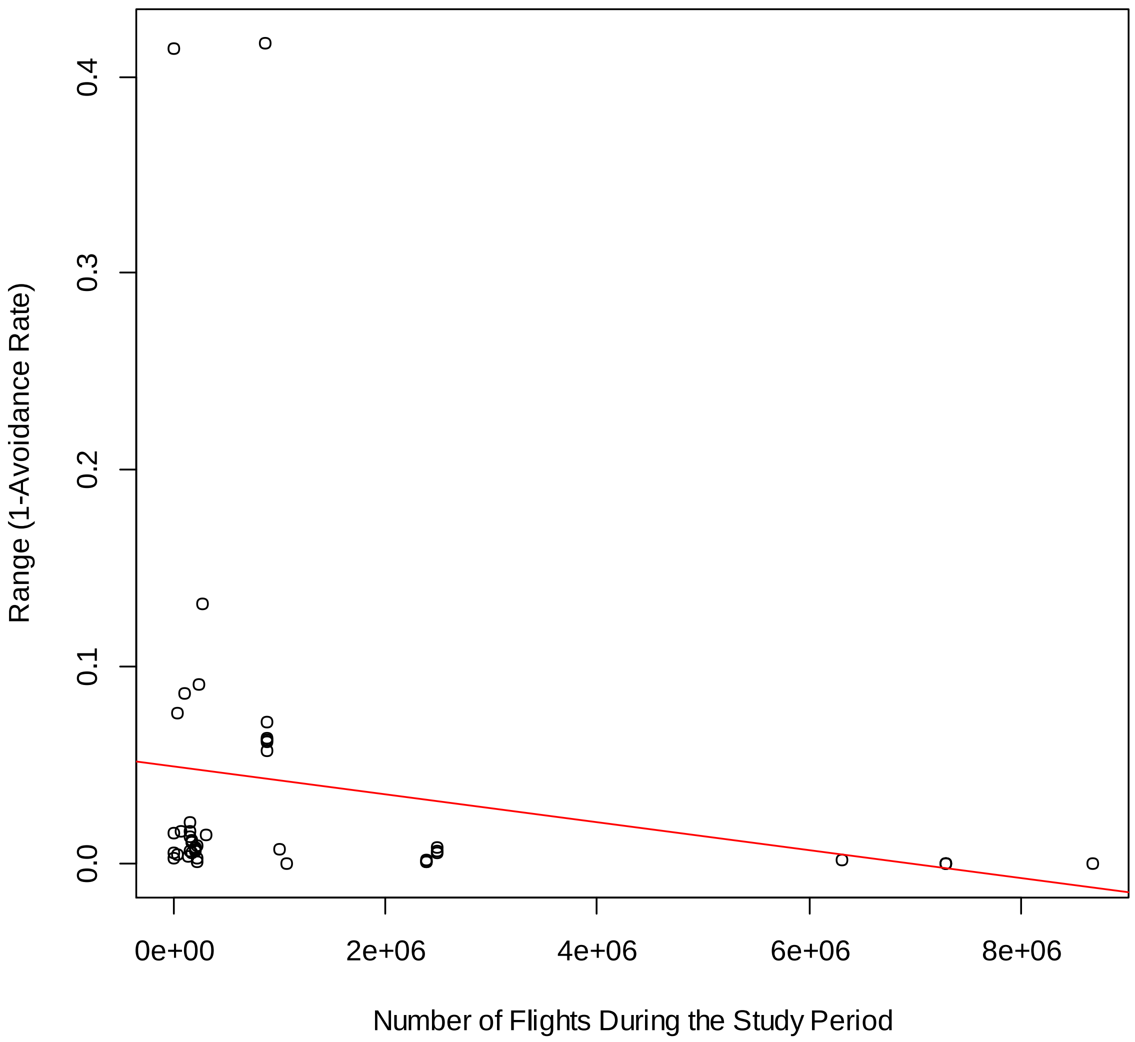


Figure 6.17 Sensitivity of the non-avoidance rate derived using option 3 of the Band model to the assumed flight height distribution.

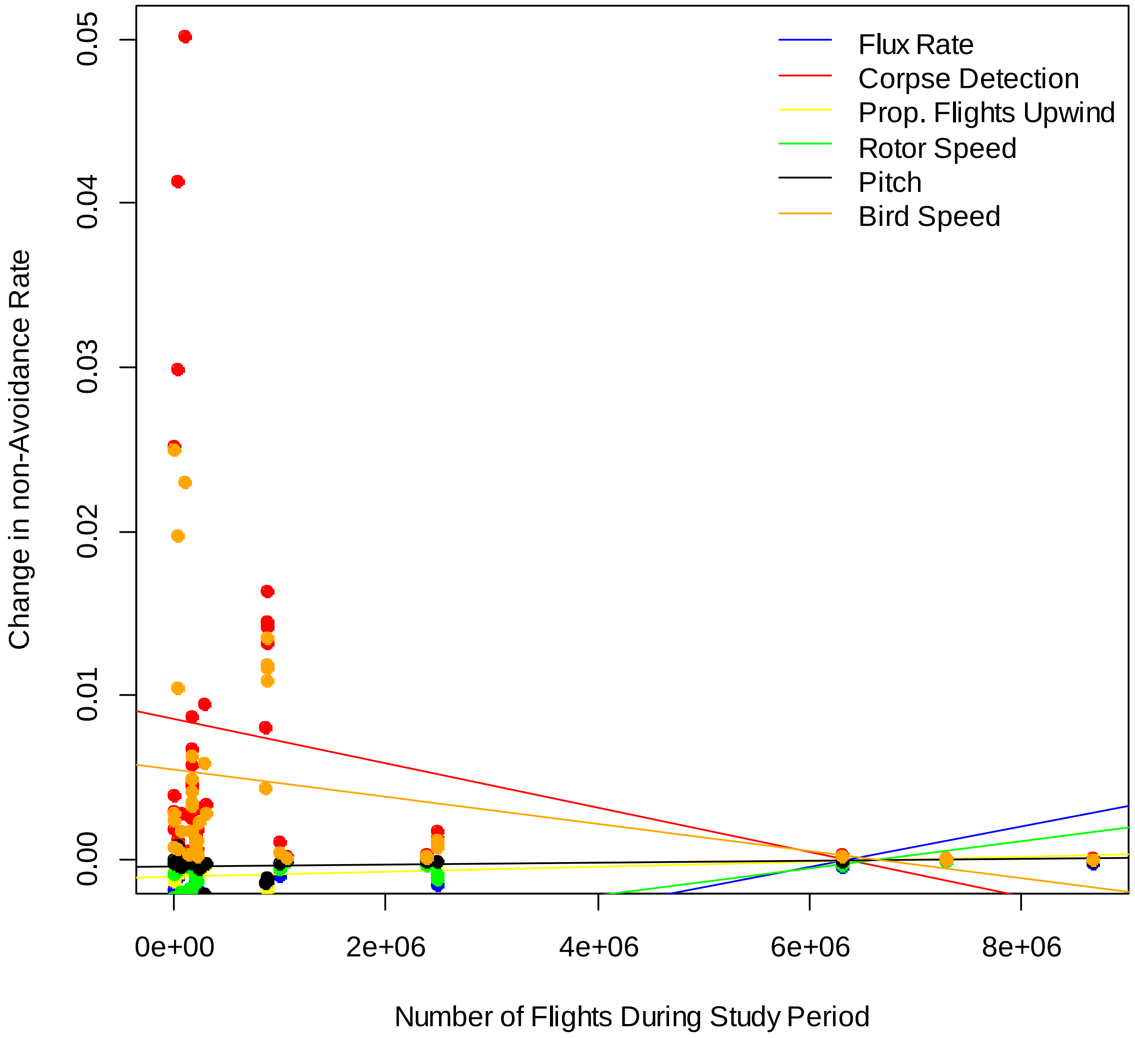


Figure 6.18 Sensitivity of non-avoidance rates derived using option 3 of the Band model to a 10% increase in each of the following parameters – flux rate, corpse detection, proportion of flights upwind, rotor speed, pitch and bird speed.

6.3 Sensitivity analysis conclusions

Avoidance rates derived using both the extended and basic Band models were sensitive to uncertainty surrounding the flux rate, corpse correction factor, rotor speed and bird speed. Whilst we considered a 10% increase in each of these parameter values to test the sensitivity of the models to the underlying assumptions, it would be valuable to consider how this compares to the actual range in each of these parameters experienced at each site. This would enable us to better quantify the uncertainty surrounding the derived avoidance rates. However, such an analysis would be complex, especially given that some parameters may co-vary, or be influenced by factors not included in the model, for example, both rotor speed and bird speed are likely to be influenced by wind speed. Such an analysis would be beyond the scope of this project and has not been considered here.

6.4 Sensitivity to other external factors

6.4.1 Weather

The flight behaviour of birds may be strongly influenced by weather conditions. However, much of the research on this subject has been carried out in relation to migration (e.g. Larkin & Thompson 1980, Gauthreaux 1991, Zehnder *et al.* 2001, Dokter *et al.* 2011). Weather is likely to influence avoidance behaviour in two ways. Firstly, by reducing visibility, making it harder to detect hazards and, therefore, increasing the risk of collision and, secondly, by affecting the manoeuvrability of birds as a result of strong winds or the presence of thermals (Spear & Ainley 1997, Shamoun-Baranes *et al.* 2006, Shamoun-Baranes & van Loon 2006).

Increases in the numbers of recorded collisions between birds and wind turbines, or other man-made objects, have been widely reported following periods of dull, overcast weather (Crawford 1981, Winkelman 1992, Bevanger 1994). This is likely to be because poor visibility reduces the ability of birds to detect turbines, and may lead to them becoming disorientated (Williams *et al.* 1974, Able 1982, Richardson 1990). As a result, the avoidance rates of individual birds are likely to be lower during periods of poor visibility. However, data used for collision risk modelling are based on the abundance of birds in flight within the windfarm, during conditions with good visibility (Camphuysen *et al.* 2004).

In contrast, there is some, limited, evidence that some bird species may be more likely to forage inland, and less likely to fly during periods of poor visibility (Williams *et al.* 1974, Pinder 1989), reducing the number of birds in flight within the windfarm in comparison to baseline survey data used in collision risk modelling. Such a potential reduction in the number of birds in flight needs to be factored into the avoidance rates used in collision risk modelling.

As a result, it is unclear as to the extent to which conditions with poor visibility may affect the avoidance rates necessary for use in offshore windfarms. To understand the potential importance of this, it is necessary to quantify the proportion of birds likely to be in flight, at sea when visibility is poor. Data collected using modern GPS tags has the potential to answer this problem and also inform on nocturnal flight activity.

Wind speed and direction both influence bird flight behaviour (e.g. Spear & Ainley 1997, Safi *et al.* 2013), with potential implications for avoidance rates. At onshore windfarms, birds have been observed to exhibit less risky flight behaviour during periods of increasing wind (Barrios & Rodriguez 2004). During periods of strong winds, Krijgsveld *et al.* (2011) noted a decrease in the number of birds in flight around Egmond aan Zee. However, as these data were collected using radar, they emphasise that these observations may reflect increased clutter from waves, rather than a decrease in the total number of birds.

Studies have demonstrated that birds make use of wind conditions to minimise the energetic cost of flight and optimise the trade-off between the maximum range they can reach and the energy they expend in reaching it (Williams *et al.* 1974, Spear & Ainley 1997, de Lucas *et al.* 2012). They achieve this in two ways. Firstly, birds fly faster into headwinds than tail or crosswinds (Tucker & Schmidt-Koenig 1971, Larkin & Thompson 1980, Wakeling & Hodgson 1992, Spear & Ainley 1997). This would lead to a decrease in the avoidance rates derived above, as the probability of a bird colliding with a turbine would be reduced, reducing the ratio of predicted to observed collisions (see sections 6.1.6 and 6.2.7). Secondly, during stronger winds, birds have a tendency to fly more slowly (Larkin & Thompson 1980, Spear & Ainley 1997). This would lead to an increase in the avoidance rates derived above, as the probability of a bird colliding with a turbine would be increased, increasing the ratio of predicted to observed collisions (see sections 6.1.6 and 6.2.7). As with the influence of visibility, the relative importance of wind direction and speed on avoidance behaviour is hard to quantify. The situation is further complicated as birds may be less likely to fly during periods of heavy wind (Stienen *et al.* 2000). Again, the growth of modern tracking technology has the potential to help address some of these issues.

6.4.2 Habitat use

The avoidance behaviour of birds in relation to an offshore windfarm may relate to how the habitat surrounding the turbines is used – for example, are turbines close to a breeding colony, are turbines situated on a commuting route, or are turbines situated on a key foraging area. Varying responses to the surrounding habitat are likely to manifest themselves in different flight modes, and these different flight modes are likely to have different levels of collision risk associated with them (Martin 2010, 2011). When foraging or searching for roost sites and conspecifics, birds can considerably reduce their detection of obstacles, and therefore increase their risk of collision, by moving their heads vertically (Martin & Shaw 2010). Collision risk at turbines surrounding colonies, as was the case for several of the sites included in our review, may therefore be inflated by birds arriving at the colony searching for their nests. Collision risk at breeding colonies may be further inflated by the display flights undertaken by males at the start of the breeding season (May *et al.* 2013) and by the presence of young birds, whose flight behaviour may place them at greater risk of collision (Henderson *et al.* 1996) at the end of the breeding season.

It is unclear whether foraging may confer a greater collision risk than searching for conspecifics on arrival at breeding colonies. It is, therefore, difficult to say with any certainty whether birds foraging within the area of offshore windfarms may be at lesser or greater risk of collision than those returning to breeding colonies and searching for conspecifics. However, when at sea, species such as northern gannets may restrict their foraging behaviour to relatively discrete areas (Hamer *et al.* 2009, Pettex *et al.* 2010). Therefore, the majority of the area covered at sea is likely to fall within the less risky category of commuting flights. As a consequence, relying on avoidance rates derived from turbines next to breeding colonies, such as those at Bouin and Zeebrugge, for birds at sea is likely to result in an overestimate of the true risk of collision. New technology, for example camera-loggers (e.g. Votier *et al.* 2013), has the potential to help gain a better understanding of collision risk at sea both by revealing more details about activity budgets, and also by allowing quantification of the proportion of flight time spent by birds looking straight ahead, and therefore at less risk of collision, as opposed to looking below.

6.4.3 Turbine Size

Initial analyses suggested that there was no strong relationship between turbine size and the avoidance rates derived for each of the species and groups we considered in our review (see section 5.3.3.2). Plots of avoidance rate against maximum turbine tip height appear to support this conclusion (Figure 6.19).

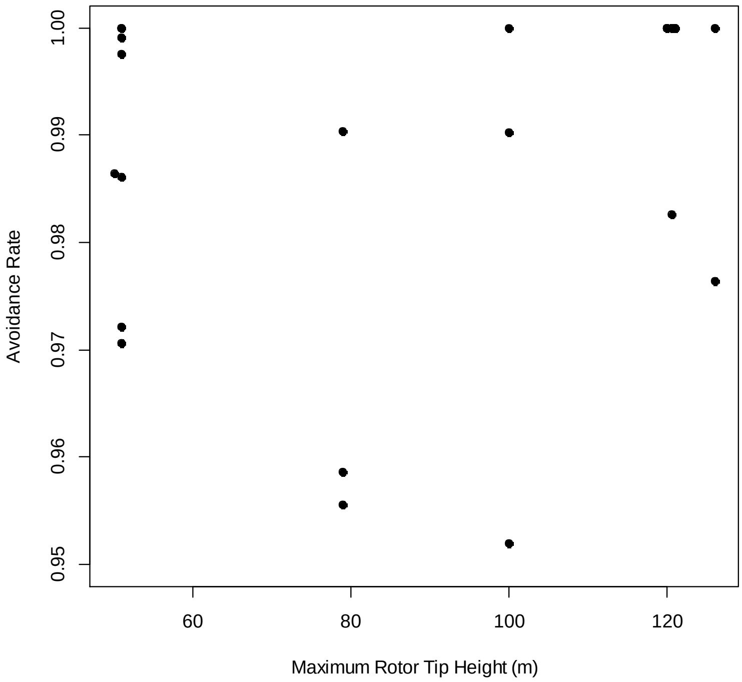


Figure 6.19 Relationship between maximum rotor tip height and the avoidance rate derived using option 1 of the Band model for all gulls.

6.4.4 Seasonality

Our analysis of the data from Zeebrugge present limited evidence that there may be a seasonal aspect to collision risk (see Section 5.1). These data suggest that avoidance rates may be higher in the autumn than in the breeding season. This may be related to two factors. Firstly the presence of younger, inexperienced birds which may have riskier flight behaviour (e.g. Henderson *et al.* 1996). Secondly, given that several of our study sites were located on the edge of breeding colonies, it may be that during the breeding season birds arriving at colonies focus on locating their nests and are therefore less likely to see turbines, increasing the collision risk.

6.4.5 Applicability of avoidance rates between species

Avoidance rates are likely to be linked to a bird’s ability to detect a turbine and perceive it as a potential threat in sufficient time to take action to avoid collision. Whilst we have able to derive a within-windfarm avoidance rate for gulls, we have been unable to come up with a suitable value for northern gannet due to lack of data.

Therefore we consider other supporting evidence to evaluate whether for northern gannet total avoidance rates are likely to be higher or lower than those for gulls.

Total avoidance rates are likely to be a combination of the probability of a bird detecting a turbine and its ability to take last-second action to avoid collision. Ability to take last-second avoidance action is likely to be linked to a species manoeuvrability and a previous review used this as the basis for recommending avoidance rates for different species (Maclean *et al.* 2009). In general, expert opinion suggests that the flight manoeuvrability of northern gannets may be less than that of gulls (Garthe and Hüppop 2004, Furness *et al.* 2013), suggesting that they need more time to react to the presence of a turbine, and may therefore need to detect it earlier. Evidence from our review suggests that a high proportion of northern gannets avoid entering windfarms (Krijgsveld *et al.* 2011, Vanermen *et al.* 2013). In addition, observations undertaken within offshore windfarms suggest that very few northern gannets pass close enough to turbines to be at risk of collision (see section 5.1).

Birds are likely to be better able to detect obstacles, such as turbines, when they are looking straight ahead, as opposed to down, towards the sea-surface (Martin 2010). At sea, it may be reasonable to assume that birds will look downwards when actively foraging, and straight ahead when migrating or commuting between their breeding colonies and foraging areas. Northern gannet typically forage using area-restricted search (ARS) behaviour (based on diving activity) resulting in a relatively small proportion of the total area covered being actively used when at sea (Hamer *et al.* 2009, Votier *et al.* 2013). These ARS zones are found solely on the outbound part of the foraging trip. In contrast, gulls are not likely to limit their foraging area to such restricted zones within foraging trips (Kubetzki and Garthe 2003, Schwemmer and Garthe 2005), and may therefore spend a greater proportion of their time at sea looking towards the sea-surface. The distance over which birds can see is strongly correlated with body size (Brooke *et al.* 1999). As a consequence, northern gannets are likely to be able to detect turbines at a greater distance than gulls. Recent evidence suggests that northern gannets may respond to the presence of fishing vessels over distances of up to 11 km (Bodey *et al.* 2014). These results suggest that, at least theoretically, northern gannets may be capable of responding to the presence of a windfarm over considerable distances.

Whilst insufficient data were available to derive within-windfarm avoidance rates for northern gannets, evidence of strong avoidance of windfarms, in contrast to gulls which appear to show no consistent response, suggests that total avoidance rates for northern gannets are unlikely to be lower than those for gulls.

6.4.6 Comparability of onshore and offshore avoidance rates

The difficulty of recording collisions in the offshore environment has meant that estimates of within-windfarm avoidance rely on data collected from terrestrial windfarms. However, birds may respond differently to onshore and offshore turbines. For example, migrating geese have been found to consistently avoid entering offshore windfarms, demonstrating macro-avoidance, (Plonckzkier & Simms 2012) but may habituate to the presence of onshore turbines (Madsen & Boertmann 2008).

Understanding how avoidance behaviour differs between onshore and offshore environments requires an understanding of how flight behaviour differs between the two. Modern GPS tracking technologies have made such comparisons easier, and it appears that whilst lesser black-backed gulls may spend a similar proportion of their time in flight in both environments (Kolios 2009), there is a tendency to fly lower when offshore (Corman & Garthe 2014, Ross-Smith *et al.* in prep.). As this would result in fewer flights at risk height in the offshore than onshore environment, this would be accompanied by decrease in both the proportion of birds at risk height (and therefore the predicted collision rate) and the actual collision rate of the same proportion. Consequently the avoidance rate would be unchanged between the onshore and offshore environments. However, there remain a number of other possible differences between onshore and offshore flight behaviour. Gulls are capable of adjusting their flight mode in response to airflow patterns which differ between onshore and offshore environments, in order to minimize their energy expenditure (Shamoun-Baranes & van Loon 2006). In the onshore environment they can take advantage of thermals by soaring and wind blowing up slopes or other major topographical features resulting in slope lift soaring. Whereas in the offshore environment a boundary layer can be created as the wind blows over the surface of the sea resulting in differential air wind speeds which some seabirds including gulls can exploit for dynamic soaring (see Alexander 2004). It is unclear how these adjustments between soaring and flapping flight may influence collision risk, though changes in manouverability and flight speed may be important. At present, there are significant gaps in our understanding of how flight behaviour may differ between onshore and offshore environments, though recent technological advances may start to fill these gaps. However, at present, the data describing within-windfarm avoidance rates collected from onshore sites remains our best available evidence.

7 TOTAL AVOIDANCE RATES FOR PRIORITY SPECIES

In this section, we consider total avoidance rates for each of the five priority species – northern gannet, black-legged kittiwake, lesser black-backed gull, herring gull and great black-backed gull.

7.1 Macro-response rates (section 5.1)

For gulls, the present evidence base is equivocal, with some studies suggesting evidence for attraction, others evidence for displacement, and others no significant response. Thus, for these species, the balance of evidence suggests a macro-response of 0 (i.e. no attraction to or avoidance of the windfarm) (Table 7.1).

Northern gannets typically show a strong macro-response to offshore windfarms. However, differences in survey methodologies make it difficult to arrive at realistic macro-response values by combining data from multiple sources. Based on currently available evidence, we believe that 0.64 to be a reasonable value for the macro-response rate (Table 7.1). However, it should be noted that this figure is based on data that are most representative of the non-breeding season.

7.2 Micro-response or meso-response rates (sections 5.2 and 5.3)

The review of existing evidence for avoidance rates in relation to offshore windfarms for the key species considered in this study indicated that insufficient data were available to generate separate micro-avoidance or meso-response rates for any of the species of interest.

7.3 Within-windfarm avoidance rates (section 5.4)

Within-windfarm avoidance rates, representing a combination of meso-responses and micro-avoidance may be derived by comparing observed collisions to those expected in the absence of avoidance (see equation 6 under section 1). Options 1 and 2 of the Band model are mathematically identical (both termed the basic Band model), with the proportion of birds at collision risk height estimated from modelled flight height distributions for option 2 and based on site-specific observational data using option 1. Therefore, it is necessary to use the same avoidance rates for both model options. As the rates derived using option 1 utilise site-specific data, rather than data derived from a generic curve (produced following the methodology of Johnston *et al.* 2013), we feel that these values are the most appropriate to recommend for use with the basic Band model. With respect to the extended Band model, the rate derived should be acknowledged as, potentially, being precautionary as, at several key sites, it is based on an underestimate of the proportion of birds flying at collision risk height (see Appendix 7). As a consequence, when calculating the avoidance rate by comparing the predicted and observed number of collisions, the resulting value is lower than would otherwise be expected. Therefore, where there is a significant difference between the observed proportion of birds at collision risk height and the proportion predicted to be at collision risk height from modelled distributions, the avoidance rates derived for use with the extended model are not considered appropriate as they will be based on an inaccurate assessment of the number of birds at risk of collision.

An alternative methodology with which to derive a within-windfarm avoidance rate for use with the extended Band model is described by in Annex 1 to this report. Following this methodology, the ratio between the number of collisions expected in the absence of avoidance derived using options 2 and 3 of the Band model is used to modify the avoidance rate derived using option 1 of the Band model. However, this requires knowledge of the flight height distribution (e.g. to 1m resolution) at the windfarm concerned – as opposed to the proportions of birds assigned to different flight height categories – in order to separate geometric avoidance (i.e. birds passing the rotor at lower altitudes where the probability of collision is lower) from behavioural avoidance. Whilst it is possible to use this methodology without knowledge of the flight height distribution at the windfarm in question, the result would be that the predicted collision rate using option 3 would be identical to that obtained using option 2. However, this methodology is likely to be of value in the future as data collection techniques improve and detailed flight height distributions are derived on a site-specific basis.

We were able to derive within-windfarm avoidance rates for herring gull and lesser black-backed gull (Table 7.1). Based on a sample of 526,048 predicted flights through windfarms, we derived an avoidance rate of 0.9959 (± 0.0006 SD) for herring gull based on the basic Band model and 0.9908 (± 0.0012 SD) using the extended Band model. For lesser black-backed gull, the derived avoidance rates were 0.9982 (± 0.0005 SD) and 0.9957 (± 0.0011 SD) respectively, based on a sample of 101,746 predicted flights through windfarms. However, the larger sample size and the fact that data originate from a greater number of sites (see Appendix 7) means that the avoidance rates derived for herring gull are more robust than those derived for lesser black-backed gull. We also derived within-windfarm avoidance rates for large gulls as a group. This group includes all birds positively identified as herring gull (this species accounting for 526,048 of the total of 639,560 flights through windfarms), lesser black-backed gull or great black-backed gull, but also those with uncertain species identification (10,638 predicted flights through windfarms), for example those identified as herring/lesser-black backed gull. For the large gulls group, we derived avoidance rates of 0.9956 (± 0.0004 SD) using the basic Band model and 0.9898 (± 0.0009 SD) using the extended Band model. A comparison of the observed and predicted proportions of birds at collision risk height (Appendix 7) shows that whilst there are some notable differences in these values, across most sites they are broadly consistent. For this reason, we feel that the avoidance rates derived using both the basic and extended Band models are appropriate to use.

We also derived within windfarm avoidance rates for small gulls (1,589,953 predicted flights through windfarms) based largely on data collected from common gull (746,668 predicted flights through windfarms) and black-headed gull (841,008 predicted flights through windfarms). For species within the small gulls group, we derived within-windfarm avoidance rates of 0.9921 (± 0.0015 SD) for use with the basic Band model and 0.9027 (± 0.0068 SD) for use with the extended Band model (Table 7.1). However, given significant differences between the proportion of birds observed and predicted to be at collision risk height at a number of key sites, we do not feel that it is appropriate to use the avoidance rate derived for use with the extended Band model for the small gulls grouping. These differences are likely to arise from the fact that the data considered here originate from the terrestrial environment, often close to breeding colonies, whilst the modelled data were collected from the offshore environment.

Finally, we calculated a within-windfarm avoidance rate for all gulls as a group (2,567,124 predicted flights through windfarms). As with the large gull and small gull groups, this incorporated data for individuals with uncertain identification (350,338 predicted flights through windfarms), for example ‘gull spp’. For all gulls, we derived an avoidance rate of 0.9893 (± 0.0007 SD) for use with the basic Band model and 0.9672 (± 0.0040 SD) for use with the extended Band model (Table 7.1). However, as with the small gulls group this includes data for which there were significant differences – due partly to the inclusion of unidentified gulls – between the observed and predicted proportions of birds at collision risk height. For this reason we do not feel that it is appropriate to use the avoidance rate derived for use with the extended Band model for the all gulls groupings.

Insufficient data were available to identify a reliable within-windfarm avoidance rate for northern gannet (Table 7.1).

It is important to note that where we report the standard deviation around the derived within windfarm avoidance rates, this relates variability between sites and not to uncertainty in the model input parameters. Estimating the contribution of the model input parameters to the uncertainty associated with the derived avoidance rates requires a more detailed understanding of the real range of values associated with each parameter than is available currently.

7.4 Total avoidance rates

Total avoidance rates are also provided in Table 7.1. Ideally, total avoidance rates should be calculated using equation 8 (section 3.1). For gulls, the balance of evidence suggests a macro-response of 0 (i.e. no consistent attraction to or avoidance of the windfarm). Consequently, the total avoidance rates for these species are equal to the within-windfarm avoidance rates.

As data describing macro-responses to the windfarm are limited, we are unable to estimate the variability around the macro-response rate. For this reason, whilst we are able to provide an estimate of variability around the within windfarm avoidance rates, we are unable to provide an estimate of variability of uncertainty around the total windfarm rates.

Table 7.1 Derived avoidance rates for priority species and current knowledge gaps based on the review of available data. Empty cells indicate a lack of robust and/or consistent data on which to base conclusions. Colour coding indicates confidence in presented values (based on sample size, representativity of data): green = highest, orange = intermediate, red = lowest (i.e. not suitable for use in CRM). Confidence in total avoidance rates reflects the lower of the confidence ratings given for macro-responses and within-windfarm avoidance rates.

Species/species groupings and sample size for within-windfarm avoidance rate given in parentheses*	**Macro-response[1]**	**Meso-response[2]**	**Micro-avoidance[3]**	**Within-windfarm avoidance basic Band model[4]**	**Within-windfarm avoidance extended Band model[4]**	**Total avoidance basic Band model (1-total avoidance)**	**Total avoidance extended Band model (1-total avoidance)**	**Caveats**
Black-legged kittiwake (0)	None							Whilst data were available for macro-response, no clear patterns were evident across studies. No data available for within-windfarm avoidance.
Lesser black-backed gull (101,746)	None			0.9982 (± 0.0005)	0.9957 (± 0.0011)	0.9982 (0.0018)	0.9957 (0.0043)	Whilst data were available for macro-response, no clear patterns were evident across studies. Within-windfarm rate based on data from only two sites.

Herring gull (526,048)	None			0.9959 (± 0.0006)	0.9908 (± 0.0012)	0.9959 (0.0041)	0.9908 (0.0092)	Whilst data were available for macro-response, no clear patterns were evident across studies. Within-windfarm rate based on a large sample size from seven different sites.
Great black-backed gull (1,128)	None							Whilst data were available for macro-response, no clear patterns were evident across studies. No within-windfarm avoidance rates estimated due to extremely small sample size.

Small gull spp (1,589,953) Comprising: black-headed gull (746,668), common gull (841,008), common/black-headed gull (2,090), little gull (188)	None			0.9921 (± 0.0015)	0.9027 (± 0.0068)	0.9921 (0.0079)	0.9027 (0.0973)	Whilst data were available for macro-response, no clear patterns were evident across studies. Within-windfarm avoidance rates based on large sample size from eight different sites. However, differences between observed and predicted proportions of birds at collision risk height mean it is not appropriate to use value derived for extended model.
Large gull spp (639,560) Comprising: lesser black-backed gull 101,746, herring gull 526,048, herring/Caspian gull 1,417, herring/lesser black-backed gull 8,345, herring/yellow-legged gull 876, great black-backed gull 1,128	None			0.9956 (± 0.0004)	0.9898 (± 0.0009)	0.9956 (0.0044)	0.9898 (0.0102)	Whilst data were available for macro-response, no clear patterns were evident across studies. Within-windfarm avoidance rates based on large sample size from seven different sites.

Gull spp (2,567,124) Comprising: black-headed gull 746,668, common gull 841,008, common/black-headed gull 2,090, little gull 188, lesser black-backed gull 101,746, herring gull 526,048, herring/Caspian gull 1,417, herring/lesser black-backed gull 8,345, herring/yellow-legged gull 876, great black-backed gull 1,128, gull spp. 337,610	None			0.9893 (± 0.0008)	0.9672 (± 0.0018)	0.9893 (0.0107)	0.9672 (0.0328)	Whilst data were available for macro-response, no clear patterns were evident across studies. Within-windfarm avoidance rates based on large sample size from nine different sites. However, differences between observed and predicted proportions of birds at collision risk height mean it is not appropriate to use value derived for extended model.

Northern gannet (0)	0.64							Macro-response rates for northern gannet indicated strong avoidance of windfarms. As data were available from a limited number of sites, the lowest reported value was felt to be most appropriate as a precautionary figure. Note the majority of data comes from the non-breeding season and it is unclear how applicable these findings may be to the breeding season. No data available for within-windfarm avoidance.

[1] See section 5.4; [2] See section 5.1; [3] See section 5.2; [4] see section 5.3.

7.5 Recommended avoidance rates

Please note that these recommendations apply to the five priority species only – northern gannet, black-legged kittiwake, lesser black-backed gull, herring gull and great black-backed gull – they are not intended to be applied to seabirds more generally.

Whilst we have estimated within-windfarm avoidance rates to four decimal places, current guidance from SNH is that expressing avoidance rates to more than three decimal places is unwarranted (SNH 2013). Given the inherent uncertainty in the data we feel that this is a sensible approach to apply to total avoidance rates. For this reason, we round within-windfarm avoidance rates down to three decimal places when deriving recommended total avoidance rates.

- A **macro-response rate of 0.64** is recommended for **northern gannet** (section 5.4). However, no data were available to derive a within-windfarm avoidance rate for this species (section 5.3). Given that there is consistent evidence for high macro-avoidance, and considering the at-sea ecology of northern gannet and gulls (section 6.3.5), we feel that there is no reason to suppose that the total avoidance rates for **northern gannet** should be less than those for all gulls (as opposed to large gulls). A **total avoidance rate** of **0.989** is thus recommended for use with the basic Band (2012) collision risk model. This would reflect a within windfarm avoidance rate of 0.9703. We acknowledge that this is precautionary, but in the absence of more species-specific data, we feel it is appropriate. However, given the evidence available at present, we are unable to recommend an avoidance rate for use with the extended Band (2012) collision risk model.

- No consistent evidence of macro-avoidance was found for **black-legged kittiwake** (section 5.4). It was not possible to derive species-specific within-windfarm avoidance rates for **black-legged kittiwake** (section 5.3)**.** However, as black-legged kittiwake have similar wing morphologies (wingspan, wing:body aspect ratio, wing area: Robinson 2005, Alerstam *et al.* 2007), flight speeds (Alerstam *et al*. 2007) and flight altitudes (Cook *et al.* 2012, Johnston *et al.* 2014b) to black-headed and common gulls, which contribute the majority of records for the small gulls group, the within-windfarm avoidance rates derived for the small gulls group were considered appropriate for this species. A **total avoidance rate** of **0.992** is thus recommended for the basic Band model. However, given the evidence available at present, we are unable to recommend an avoidance rate for use with the extended Band (2012) collision risk model (section 5.3).

- No consistent evidence of macro-avoidance was found for **lesser black-backed gull** (section 5.4). Whilst it was possible to derive species-specific within-windfarm avoidance rates for lesser black-backed gull, these were based on limited data and thus the within-windfarm avoidance rates for large gulls were considered more appropriate for use for this species (section 5.3). A **total avoidance rate** of **0.995** is thus recommended for use with the basic Band model and a **total avoidance rate** of **0.989** for use with the extended Band model.

- No consistent evidence of macro-avoidance was found for **herring gull** (section 5.4) and thus total avoidance rates reflect species-specific within-windfarm avoidance rates. A species-specific **total avoidance rate** of **0.995** is thus recommended for use with the basic Band model and a **total avoidance rate** of **0.990** for use with the extended Band model (section 5.3).

- No consistent evidence of macro-avoidance for **great black-backed gull** (section 5.4). It was not possible to derive species-specific within-windfarm avoidance rates for **great black-backed gull.** Given the taxonomic similarity between species within the large gulls group, the avoidance rates derived for use with this group were considered to be appropriate for great black-backed gull (section 5.3). A **total avoidance rate** of **0.995** is thus recommended for the basic Band model and a **total avoidance rate** of **0.989** for use with the extended Band model.

At present, the evidence available does not enable us to recommend a robust avoidance rate for northern gannet or black-legged kittiwake for use with Band model option 3. This does not imply that option 3 is not suitable for these species, and given the programmes of work currently underway in the offshore environment, it is envisaged that an appropriate rate will be derived in the near future. Note, while it is not possible to recommend a robust avoidance rate for use for these species at this time, this does not preclude presenting a no-avoidance collision estimate using option 3 alongside collision estimates derived using option 1 and/or option 2 (with or without using the avoidance rates recommended here) to inform on likely collision risk.

Table 7.2 Recommended total avoidance rates for use in the basic and extended Band models with each of the five priority species.

Species (rate used)	Basic Band model avoidance rate	Extended Band model avoidance rate
Northern gannet (all gull avoidance rate)	0.989	Not available
Black-legged kittiwake (small gull avoidance rate)	0.992	Not available
Lesser black-backed gull (large gull avoidance rate)	0.995	0.989
Herring gull (species-specific avoidance rate)	0.995	0.990
Great black-backed gull (large gull avoidance rate)	0.995	0.989

8 TRANSFERABILITY OF AVOIDANCE RATES BETWEEN MODELS

There are various collision risk models currently available within the scientific literature to estimate likely collision and mortality of birds due to windfarms (Band 2012; Desholm 2006; Eichorn *et al.* 2012; McAdam 2005; Smales *et al.* 2013; Tucker 1996; Holstrom 2011). The models vary in numerous ways including whether static components such as the tower are included in calculations, if oblique angles of attack are considered and whether single or multiple turbines are assessed, as well as how avoidance behaviour is incorporated. Although the Band model (Band 2012) is the most widely used collision risk model in the UK, it is not the only one available and therefore any developments in our understanding of avoidance behaviour should consider, where possible, these alternative models.

Although described in the literature, avian collision risk models are often not presented in enough detail to reproduce. The majority of models consider avoidance behaviour as an add-on to the process of estimating the probability of collision, separate from the calculation of collision probability for a single rotor transit. From the information available, however, it would seem that the definitions and avoidance rates presented in our report would generally be suitable for use within a range of collision risk models, not only Band (2012). Here we provide examples of how the definitions and rates may align with some of these alternative models.

Desholm (2006) developed a stochastic model analysis of avian collision which included variability in the input parameters and outputs of the model. Although it was a very specific example from an offshore windfarm in the Baltic Sea, the method could be used elsewhere. The definitions used in our project seem suitable for the model. The method considered the different stages at which birds may avoid a windfarm and uses values for the proportion of birds entering the windfarm (1 - macro-avoidance), the proportion within the horizontal/vertical reach of rotor blades (1 - meso-avoidance) and also the proportion trying to cross the area swept by the rotor blades without showing avoidance (1 - micro-avoidance).

Eichorn *et al.* (2012) developed an agent-based, spatially-explicit model of red kite foraging behaviour to assess collision risk related to wind turbines. The model is largely stochastic and combines a spatial model with a collision risk model. Although the study was specific to red kite, the methods could be used more widely. The model uses the method from Band (2007) for calculating probability of collision from a single rotor transit therefore it is likely that any definitions for avoidance behaviour provided by our study will be suitable. The model specifically includes the probability of a bird recognising the threat and actively avoiding, and this avoidance rate is taken from the literature. The value ranges from 0.98 – 0.995 and is therefore likely to be a value for overall avoidance, however the definitions within this study for meso- and micro-avoidance would seem to fit more appropriately because it is a single bird avoiding a single turbine within a 100 m x 100 m grid cell.

Smales *et al.* (2013) describe a collision risk model developed by Biosis Propriety Limited which has been widely used to assess wind energy developments in Australia since 2002. The model uses a deterministic approach and provides a predicted number of collisions between turbines and a local or migrating population of birds. The model uses flight activity data from the windfarm site and applies avoidance rate to the typical number of turbines encountered per flight. Therefore the definitions and rates for within windfarm behaviour should be suitable in this context.

A note of caution when considering avoidance rates and their application within different collision risk models is that although not the intended purpose, avoidance rate may have become a sink for multiple sources of error and uncertainty within a model. Collision risk models rarely state the associated error along with collision estimates. In the process of apportioning overall avoidance into the different components of macro-, meso-, and micro-avoidance, this previous inclusion of model error may need to be considered, and may be model-specific.

9 CONCLUSIONS

We have derived within-windfarm avoidance rates for a variety of species for specific sites. In some cases, these differ from those presented elsewhere using, apparently, the same data (see Natural England/JNCC note). For this reason, we include an appendix (Appendix 7) detailing how each of our values has been derived. Note that the values in Appendix 7 are supplied for illustrative purposes only and that we would recommend the use of the total avoidance rates presented in Table 7.2. Given the variability in the values that have been presented for some datasets, we believe that this level of transparency is crucial to enable readers to come to an informed opinion as to what represents a robust avoidance rate. The derivation of the flux rate through the windfarm is particularly important, as it can have quite a strong influence on the predicted number of collisions, and therefore, the final avoidance rate.

Very little data were available describing separate meso-responses or micro-avoidance. There were limitations in the data from each of the studies we identified. However, observations of flight behaviour around individual turbines indicate that birds very rarely pass close to the rotor blades, suggesting that a significant proportion of avoidance behaviour is likely to occur at a meso-scale. We identified evidence from several sites to suggest that avoidance behaviour may be influenced by both the layout of the windfarm (e.g. the inter-turbine spacing) and the operational status of turbines. There is some limited evidence to suggest that overall avoidance rates may be lower during the breeding season than the non-breeding season, although significantly more data are required to confirm this hypothesis (see section 5.3.3.1).

The availability of suitable data has been a key problem throughout this review. In part, this relates to the difficulty in collecting collision data at sea, leading to gaps in data for key species such as northern gannet and black-legged kittiwake. It is to be hoped that the ongoing ORJIP work will help to address this issue. However, it also relates to the way in which data have been collected as part of post-construction monitoring at offshore windfarms. We identified extremely limited evidence for macro-response rates for our priority species. In many instances, this may be because when impacts which may contribute to macro-avoidance, such as displacement or barrier effects, are considered, the focal species are usually auks, divers and sea-ducks. As a consequence, the impacts on other species, such as northern gannet are less well understood.

Our review highlights that there are still significant data gaps in relation to avoidance rates for marine birds and offshore windfarms, particularly in relation to micro- and meso-responses, as opposed to the correction factors often used as avoidance rates at present. Despite this, we feel that our review represents a significant step forward. We are able to recommend for the first time within-windfarm avoidance rates for gulls using both the basic Band (2012) model (options 1 and 2) and extended Band (2012) model (option 3) based on significantly more data than has been used to make recommendations for geese and raptors in the past (e.g. Pendlebury 2006, Whitfield 2009). Significant data gaps still remain for within-windfarm avoidance behaviour in the northern gannet.

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APPENDIX 1 Evidence review macro-response – barrier effect studies

A1.1 Egmond aan Zee

Location / habitat

Marine, 10-18km offshore

Turbine / array specification

Turbine array consists of 36 Vestas V90 3 MW turbines covering an area of 27 km^2. Distances between turbines are 650 m within rows and 1000 m between rows. Turbine specifications given as hub height 70 m; rotor diameter 90 m; rotor altitude min 25 m (above mean sea level) and max rotor altitude 115 m (above mean sea level).

Case study number 1

Krijgsveld, K.L., Fijn, R.C., Japink, M., van Horssen, P.W., Heunks, C., Collier, M., Poot, M.J.M., Beuker, D. and Dirksen, S. 2011. *Effect studies offshore windfarm Egmond aan Zee: Final report on fluxes, flight altitudes and behaviour of flying birds*. Bureau Waardenburg Report No. 10 - 219.

Lindeboom, H.J., Kouwenhoven, H.J., Bergman, M.J.N., Bouma, S., Brasseur, S., Daan, R., Fijn, R.C., de Haan, D., Dirksen, S., van Hal, R., Hille Ris Lambers, R., ter Hofstede, R., Krijgsveld, K.L., Leopold, M. & Scheidat, M. 2011. Short-term ecological effects of an offshore windfarm in the Dutch coastal zone; a compilation. *Environmental Research Letters* **6,** doi:10.1088/1748-9326/6/3/035101.

Methods

Krijgsveld *et al.* (2011) focussed on the disturbance of flight paths otherwise referred to as barrier effects. Whereas what was termed as the disturbance of locally resting and/or feeding birds were covered by another project (Leopold *et al.* 2011) as birds recorded on the water. Lindeboom *et al.* (2011) reported the impacts of the windfarm on a range of taxonomic groups but with respect to birds focussed on barrier effects, displacement effects and attraction. As the results presented in Lindeboom *et al.* (2011) were based on the preliminary results of Krijgsveld *et al.* (2011), cited as Krijgsveld *et al.* (2010), this paper is not considered further here.

Data collection was carried out during the post-construction period only.

Radar: Horizontal radar was used to record flight paths, with the radar located on a meteorological mast 500 m from the nearest turbine at the south western side of the windfarm). The radar was set to scan up to distances of 5.6 km from the meteorological mast (although it was calculated that gulls could be detected up to shorter distances of 4.5 km). There was no coverage from the angles of 155° to 220° relative to the mast however).

The radar signal was processed and recorded by Merlin (DeTect Inc). Flight paths of birds or groups of birds were visualised in QuantumGIS and grid cells (750 m x 750 m) were set up in order to analyse both the numbers of tracks and flight directions. In order to mitigate for reduced detection of tracks, due to the presence of turbines and decreasing detection rates with increasing distance from the radar, correction factors were applied to the numbers of tracks recorded inside the windfarm.

Visual and auditory observations: Panorama scans from the meteorological mast consisting of hourly 360° scans to record all birds flying within sight of the observation platform. This information was then used to calibrate the radar counts and provided information on species composition, density, flight altitude and flight direction. Additional information was collected at night and included moon watches, call registration by ear, and call registration by an automated bird call recording system. In addition, the opportunistic recording of flight paths of individual birds or bird groups (picked up either visually using a binoculars or a telescope) or on the radar) was carried out.

Study period

Radar: Continuous recording through the period of April/May 2007 to 31 May 2010. Flight path data was obtained for 817 days (out of a possible 918 due to factors such as high winds).

Visual observations: A total of 405 panoramic scans were carried out over 53 days (dawn to dusk) spread throughout the period of Feb 2006 to Dec 2009 and six nights (dusk to dawn) during spring and autumn migration (October 2008 to April 2009). Opportunistic observations of flight paths were carried between and during panoramic scans (n = 666 flight paths of 85 species were recorded with great cormorant (n = 82) and northern gannet (81) being the most commonly observed).

Species

Local seabirds (gull spp, northern gannet, scoter spp, and auks spp); migrating seabirds (diver spp and scoter spp) and migrating non-marine birds (thrushes and geese spp).

Conditions data collected under

Radar: all conditions.

Visual observations: recording carried out in generally dry, relatively calm conditions (all but day had one Beaufort scale of less than 5) and with a range of visibility conditions (0 - 50 km).

Results

Macro-responses (which were regarded by this study as being due to barrier effects), referred to in the report as macro-avoidance rates, were quantified by two methods[2]:

i. Panoramic scans were used to derive the proportion of birds within, at the edge and outside the windfarm. Using the combined values of the first two groupings, it was possible calculate the % of birds that passed through the windfarm[3]. The resulting values were corrected for relative surface area for within and outside the windfarm and then used to derive macro-avoidance rates[4] for northern gannet = 0.64 (n = 282 birds[5]), sea ducks/scoters spp = 0.71 (n = 123 birds), diver spp = 0.68[6] and alcid spp = 0.68[3]. Sample sizes were too small for other species/species groups for values to be derived and, hence, values have to be derived by other means;

ii. Flight path data collected by radar showed that the number of all birds that flew within the windfarm was on average 72% of the numbers outside the windfarm. This was proposed to equate to an average macro-avoidance rate of 0.28 of birds in relation to the windfarm, and when broken down according to time of year, the values ranged from an average of 0.18 (in winter) and 0.34 (in autumn)[7]. For gull spp and great cormorant, the average avoidance rate in winter of 0.18 was used, as the species composition was heavily dominated by those birds at that time of year (as shown by the visual observations). The overall average avoidance value of 0.28 was assumed for grebe spp, tubenoses spp, skua spp, and tern spp (in the absence of other available data or rationale). It was also shown using radar that the percentage of birds flying in the windfarm was significantly higher during the day compared to night (when data from spring was excluded) and these differences were greatest during summer and winter. Hence avoidance was argued to be higher at night.

Results of the opportunistic recording of flight paths indicated deflection rates of 89% for northern gannet and 40% for gulls spp based on sample sizes of 38 and 78 birds respectively[8]. These values were not considered by the authors to provide evidence for macro avoidance (Karen Krijgsveld *pers. comm.*) however.

There was inherent variation in flight direction as recorded by radar with higher variability recorded winter and summer (probably due to the inclusion of locally foraging birds which are less likely to have a consistent flight trajectory than birds migrating through the area) and during the day. Nevertheless, adjustment of flight paths occurred at 750 - 1,500 m from the windfarm when there was a pronounced

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[2] Table 15.1- Krijgsveld *et al.* 2011.

[3] Table 9.3 - Krijgsveld *et al.* 2011.

[4] Macro-avoidance = 100-((x/50)*100). Where x = % of birds that passed through the windfarm and 50 is the correction factor for surface area. Karen Krijgsveld *pers. comm.* Values of x for northern gannet and common scoter were 18 and 14 respectively (sum of the relative abundance inside and at the edge of the windfarm – see Table 9.3).

[5] Taken from Figure 9.25.

[6] Based on the average of northern gannet (0.64) and scoter spp (0.71) which was justified on the grounds of their avoidance behaviour being similar (based on their flight paths).

[7] Figure 9.15 - Krijgsveld *et al.* 2011.

[8] Table 9.6 - Krijgsveld *et al.* 2011

change in flight direction. This was largely based on plots of the mean ± standard errors of flight direction in relation to distance according to season and time of day[9]. The reported changes at 750-1500 m appear to occur before and after midnight in the spring and at dusk during autumn. There were also changes in flight direction at distances further away from the windfarm but these are not highlighted – notably in spring, for most times of day, at distances between 4,500 and 5,250 m.

Numbers of birds were also shown to be highest at 750 - 1500 m, which was taken as evidence of flying birds building up as they were deflected away from the windfarm (also confirmed by visual observations of birds). Moreover, the number of tracks for all seasons in the grid cells circa 750 m from the windfarm was also shown to be significantly higher than the number of tracks for the grids cells containing the adjacent single row of turbines[10].

Assessment of methodology

The values of macro-avoidance derived from the panoramic scans were species specific and were collected in a systematic manner. As for all visual observations, data collection was mostly restricted to days of reasonable visibility and calm conditions.

Macro-avoidance rates (barrier effects) derived using radar were based on mean values across all species and should be interpreted very carefully since there is likely to be variability in response rates between species. Hence this should be borne in mind when citing values derived for gull spp, grebe spp, tubenoses spp, skua spp, and tern spp. It is also unclear whether the actual numbers reported will consist of solely individual birds or whether flocks of birds may have been inadvertently included. Hence as for most radar studies, the avoidance rates cannot be necessarily assumed to correspond to those of individual birds. It is also worth bearing in mind, that the way these data have been collected (comparison of number of flight paths inside and outside the windfarm) could also be potentially considered to be evidence of displacement.

It is also problematic to overlay the arbitrarily selected boundary of 500 m buffer surrounding the outermost turbines used to delineate inside (micro and meso) and outside (macro) the windfarm avoidance (section 3.5) with the grid cell system of 750 km^2 used to analyse the number of tracks.

The grid cell system also does not correspond exactly to the boundaries of the windfarm and hence some cells will overlay areas inside and outside the windfarm which could be an issue for the values cited for % of tracks inside and outside the tracks.

A1.2 Horns Rev

Location / habitat

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[9] Figure 9.28- Krijgsveld *et al.* 2011.

[10] Generalised Linear Model (t_{2228} =3.4, $p < 0.001$) - Krijgsveld *et al.* 2011.

Horns Rev 1: Marine, 14 km offshore.
Horns Rev 2: Marine, 30 km offshore.

Turbine /array specification

Horns Rev 1: Turbine array consists of 80 2.0 MW Vesta turbines. Distance between turbines – north to south (560 m) and east to west (560 m). Turbine specifications given as: hub height 70 m; rotor blade length 40 m (diameter 80 m); and total height 110 m. Height of the lowest tip of rotor blade.

Horns Rev 2: Turbine array consists of 91 turbines. Distance between turbines – north to south (560 m) and east to west (560 m). Turbine specifications given as: hub height 68 m; rotor diameter 93 m; and total height 114.5 m. Height of the lowest tip of rotor blade 21.5 m.

Case study number 1

Petersen, I.K., Christensen, T.K., Kahlert, J., Desholm, M. & Fox, A.D. 2006. *Final results of bird studies at the offshore windfarms at Nysted and Horns Rev, Denmark*. Report commissioned by DONG Energy and Vattenfall A/S. National Environmental Research Institute.

Methods

This report focussed on barrier effects, displacement effects, physical changes to the habitat and collision risk. Work was carried out at the Horns Rev 1 and Nysted offshore windfarms but there were differences in methodology and timing of data collection in relation to the development phase – data collection was carried out during the post-construction period only at Horns Rev 1.

Radar observations*:* Recordings by radar occurred in a circular area of radius ca. 11 km (no coverage in the north east quadrant with the exception of late November 2005). The radar was located on a transformer station located less than 0.6 km from the windfarm. Migration mapped by tracing course of flocks onto a transparency and subsequently digitised. As fewer tracks were recorded both within and beyond the windfarm, due to presence of the turbines and the increasing distance from the radar, densities of tracks were not used to quantitatively to look at barrier effects.

All tracks (n = 468 north of the windfarm and n = 342 east of the windfarm) which were deemed to have a theoretical chance of entering the windfarm were selected using the criteria that they were orientated towards the windfarm at distances between 1.5 and 2 km from the windfarm and had lengths of tracks greater than 2 km.

In order to look at the lateral (horizontal) change in migration route in response (where avoidance occurs) to the windfarm, two sets of transects lines were set up. The first were located east of the windfarm running parallel to the direction of the rows of turbines (from north to south) and were set up at intervals of 50, 100, 150, 200, 250, 300, 400, 500, 1000, 2000, 2500, 3000, 3500 and 4000 m (max. range set by limits of the radar). The second were set up north of the windfarm at 50, 100, 200, 300, 400, 500, 1000, 1500, 2000, 2,500, 3000 m and then at intervals of 1000 m until 7000 m. The orientation of all bird tracks that intersected two adjacent transects were calculated for all of the transects running east and north of the windfarm.

Visual observations: four transects from the transformer station set up, one of which passed diagonally through the windfarm.

Study period

Radar observations: A total of 17 survey periods (shortest = 5 h 30 min, longest = 39 h 30 min) were carried out covering the periods of August to November 2003; March to May 2004; August to September 2004; March to May 2005; and August to November 2005. Total of 243 h 45 min of observations.

Visual observations: 19 surveys (shortest = 7 h 0 min, longest = 29 h 30 min) were carried out covering the periods of April to May 2003; August- November 2003; March to May2004; August to September 2004; March to May 2005; and August to November 2005. Total of 403 h 18 min of observations.

Species

Staging and migrating birds. Based on visual observations of birds during transect counts, likely to consist primarily of diving ducks (by an order of magnitude higher than any other group and consisting almost exclusively of common scoter), gulls (herring gull, little gull, greater back-backed gull and black-legged kittiwake and terns (Sandwich tern and common/Arctic tern)[11].

Conditions data collected under

During day and night, weather conditions not presented.

Results

The annual percentage of bird tracks (based on the years 2003, 2004 and 2005) entering the windfarms from either the northern or the eastern side of the windfarm ranged from 13.6 % (2005, north of windfarm) and 29.3% (2004, east of the windfarm[12]). The number of tracks that these percentages are based upon are relatively small however (ranging from 12 to 39 tracks). These values appear to provide the origins of cited macro-avoidance rates of 0.71 and 0.86. Spring and autumn periods were not differentiated between as it was argued that bird behaviour would be similar regardless of the time of season.

The mean orientation of tracks of migrating birds, as calculated for all intervals between transects, was used as the response variable to look at the lateral deflection of south bound tracks for birds north (n = 2108) and east of the windfarm

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[11] Table 48 - Peterson *et al.* 2006.

[12] Table 55 - Peterson *et al.* 2006.

(n = 1168). For birds north of the windfarm during southbound bird migration, analyses[13] showed that distance to windfarm, wind direction (crosswinds), time of day and the interaction between distance and time of day were significant. Plots of the mean flight orientation with distance to windfarm in relation to time of day wind direction showed that deflections were most pronounced at distances of less than 400 m from the windfarm and that changes at larger distances (<2 km) were more obvious during the daytime compared to the night time period[14]. For birds east of the windfarm analyses[15] found that distance had a significant effect on the orientation of the birds (wind direction, time of day and the interaction between distance to windfarm and wind direction were also significant. Plots of the mean flight orientation with distance to windfarm in relation to time of day wind direction showed that deflections were most pronounced at distances of less than 500 m from the windfarm. Changes in orientation occurred up to 4 km from the windfarm during south bound migrations notably during the day in westerly winds[16].

Assessment of methodology

The derived macro-avoidance rates (based on barrier effects) are a mean value for all birds which occurred during the study and according to visual observations consisted mainly of common scoter. Therefore, these reported avoidance rates may have limited applicability to the less commonly recorded gulls spp and tern spp. In addition these avoidance rates are based on relatively small sample of tracks. Moreover, tracks do not differentiate between individuals or flocks, therefore the reported macro-avoidance rates do not respond to the level of individual birds.

Case study number 2

Blew, J., Hoffman, M., Nehls, G. & Hennig, V. 2008. *Investigations of the bird collision risk and the responses of harbour porpoises in the offshore windfarms Horns Rev, North Sea, and Nysted, Baltic Sea, in Denmark. Part 1: Birds*. Report from the University of Hamburg and BioConsult SH, 145pp.

Methods

The report focussed on the collision risk to migrating birds at Horns Rev 1 and Nysted offshore windfarms and the same methodology was used at both sites.

Blew *et al.* (2008) proposed that avoidance occurred at the three broad scales of: (1) large scale avoidance >2000 m; (2) medium to small scale avoidance 1000 m to 150 m and either horizontally or vertically as measured directly (reactions) or indirectly (comparison of numbers or flight altitudes); (3) last second avoidance. Thus, the

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[13] ANOVA analyses: distance F_{14}=18.93, $p < 0.0001$; wind direction F_1=57.49, $p < 0.0001$; time of day F_1=95.33, $p < 0.0001$; and distance*time of day F_{14} = 3.27 , $p < 0.0001$)- Peterson *et al.* 2006.

[14] Figure 170 - Peterson *et al.* 2006.

[15] ANOVA analyses: distance F_{14}=25.38, $p < 0.0001$; wind direction F_1=13.37, $p = 0.0003$; time of day F_1=132.67, $p < 0.0001$; and distance*wind direction F_{14} = 2.79 , $p = 0.0004$) - Peterson *et al.* 2006.

[16] Figure 172 - Peterson *et al.* 2006.

second category, which was the focus of this report, overlaps with the definitions in section 3 of this report of both macro- and meso-avoidance.

Data collection was carried out during the post-construction period only.

***Radar observations**:* Horizontal radar (Bridgemaster E-series and Pathfinder) was deployed from ships with a range of anchoring sites (three, four and four at the eastern, southern and western edges of the windfarm respectively) at distances of 150 to 300 m to the windfarm. Screenshots were captured using a digital camera for the horizontal radar and the angle of tracks and their length were also registered. The range of the radar was set to 1.5 nautical miles. No manual tracking of signals on the horizontal radar was carried out which meant that changes in flight trajectories for individual tracks could not be looked at.

Radar tracks were categorised according to their direction in relation to the first row of the windfarm; flying towards (± 45° either side of perpendicular to the windfarm; flying away; and flying parallel (more or less).

In order to look at lateral avoidance, four intervals ranging from 0-500 m, 500-1,000 m, 1,000-1,500 m and 1,500-2,000 m in relation to the ship and the relative orientation of tracks were recorded in the range of ± 90° with 0° being perpendicular to the windfarm. Due to sample size issues (insufficient number of tracks), it was not possible to report results for Horns Rev, however.

Visual observations: Visual observations were carried out along a 2 km transect which ran perpendicular to the outer edge of the windfarm, with the ship located halfway along it length. On the windfarm side of the transect, the gap between the edge of windfarm as defined by the row of the outer turbines (approximately 300 m from the ship) to 700 m inside the windfarm (or 1,000 m from the ship) was regarded as being inside the windfarm. On the corresponding non-windfarm side, the transect which was between 300–1,000 m from the ship was regarded as being outside the windfarm (in relation to the windfarm this represents a distance of between 600 and 1,300 m). Collectively these were termed as Class A, whereas the transect up to 300 m either side of the ship was Class B (excluding birds within 30 m either side of the ship which were disregarded). Visual observations of flying birds (optics only used for identification purposes) were carried out every half hour for observation periods of 15 minutes from sunrise to sunset. Distance, flight direction and altitude were recorded (classes were largely defined by the upper and lower limits of the rotor blade: 0-5 m: 5-30 m; 30-100 m; >110 m). The results of this work are not considered further here.

Visual observations were carried out for 219.5 and 238.5 h in 2005 and 2006 respectively.

Study period

March to May to coincide with spring migration (27.5 observation days in 2005 and 2006) and September to November to cover autumn migration (39 observation days in 2005 and 2006).

Radar appeared to have been run continuously.

Species

Seaducks, geese, gulls and terns and wide range of songbird species.
Transect counts showed that gulls (many of which were unidentified to the species level) were the most common group recorded in both spring and autumn (with little gull notably more common in the former time of year). Common scoter were also common but more so in spring.

Conditions data collected under

Horizontal radar observations were limited to calm sea state conditions (wind speed < 2 ms^{-1}) and generally dry weather.

Visual observations were stopped when visibility <1 km but visual and acoustic observations were possible for all observation days

Results

During the day, the overall number of tracks flying parallel to the windfarm was higher (n = 1,045) compared to flying away from (n = 486) or towards (n = 386) the windfarm. This pattern was less pronounced at night with the number of birds parallel to the windfarm (n = 253) being only marginally higher compared to flying away from the windfarm (n = 206) but were higher than towards the windfarm (n = 101).

Although the visual observations were designed primarily to look at the differences in flight height distribution, they were able to provide supporting evidence for macro avoidance occurring. For northern gannet, out of 66 gannets recorded only 2 flew within the windfarm. For both little gull and all gull spp (excluding little gull), significantly less birds were present inside the windfarm.

Assessment of methodology

Results from the observations from horizontal radar were limited as only 5% (9% for Nysted) of the observation time yielded screenshots which could be used and these were biased to daytime periods. There was also the additional problem that detection within the windfarm was considerably lower compared to outside due to the presence of the wind turbines (tracks were observed to disappear and reappear when entering and leaving the windfarm).

There were several limitations with working on a ship compared to from land or a fixed platform, including rough sea conditions, which would likely hamper data collection. There were also issues associated with the tidal cycles (particularly at Horns Rev, less so at Nysted) and strong winds which could result in the ship turning and this affected the radar data collected. Another potentially confounding factor is that the ship could also act as an attractant to some species of seabirds (e.g. gull spp) or potentially act as a disturbance to others (e.g. diver spp and duck spp).

In terms of demonstrating macro-avoidance, horizontal radar was unable to provide quantitative evidence. Avoidance appeared to be implied by the percentage of birds flying parallel being higher than those values reported for birds flying towards and away from the windfarm and this pattern was more pronounced during the day when the windfarm was more visible. The significance of birds tracks running parallel to as opposed to being orientated towards or away from the windfarm was not explained, however, and there was a lack of pre-construction information to make comparisons with. There was also insufficient data to look at potential changes in the orientation of tracks (but enough data was available for Nysted – see section 5.4.4). Similarly the visual observations did not provide quantitative evidence of macro-avoidance rates.

Case study number 3

Skov H., Leonhard, S.B., Heinänen, S., Zydelis, R., Jensen, N.E., Durinck, J., Johansen, T.W., Jensen, B.P., Hansen, B.L., Piper, W. & Grøn, P.N. 2012. *Horns Rev 2 Monitoring 2010-2012. Migrating Birds*. Orbicon, DHI, Marine Observers and Biola. Report commissioned by DONG Energy.

Methods

This report focussed on migrating birds in relation to Horns Rev 1 and 2.

Radar observations: Horizontal radar was used from observation stations located to the north east of Horns Rev 1 (assumed to be the same as used in previous studies at Horns Rev 1, 560 m distance to the windfarm) and to the east of Horns Rev 2 (no distance provided but estimated to be less than 2 km away). Radar range was set at 6.0 km and covered a circular area. Additional information on species identification was possible by use of “a real-time tracking” procedure whereby tracks of individual birds or tracks could be followed on background images to produce videos. Videos were produced using a frame grabber connected to the radar and tailor made software provided the video as a back ground image on the PC screen. Whilst one observer followed the trace on the screen, a second attempted to locate the target in the field using a binocular or telescope to provide names, number of birds and altitude. Identification on tracks was not always possible during busy periods. Track densities were estimated for a 100 m^2 grid system within the radius of the radar.

Laser range finders: Laser range finders (Vectronix 21 Aero) were also used from the observation stations used to collect species-specific data up to distances of 2-3 km for large bird species (depending on the field of view and flight mode of the bird). Positions and altitudes of birds were logged automatically via GPS recorded at intervals of 10-15 sec. Data from the laser range finders were used to supplement data collected by the radar. Calibrations in order to correct the readings provided by the GPS were necessary due to interference by the observation tower.

Track data for range finders and radar were also integrated with weather data including wind direction, wind speed, air pressure, clearness, humidity, total precipitation and air temperature. In addition, the relative flight direction of the bird in relation to wind direction was also calculated.

Generalised Additive Models (GAMs) with a Tweedie distribution were used to look at track densities derived by radar for all bird tracks and common scoter tracks in relation to distance to the radar and distance to the windfarm. Generalized Additive Mixed Models (GAMMs) with a correlation structure (to deal with spatial and temporal autocorrelation) were used to look at the flight altitude in relation to weather variables and distance to the nearest wind turbine. However, this information could not be used to quantify an avoidance rate.

Study period

Data collection carried out during spring and autumn from September 2010 to May 2012. No further details given.

Radar observations: 15 min per h during daylight.

Laser range finders: operated permanently with observation periods of a minimum of 15 min per h.

Species

All spring and autumn migrants (seabirds, water birds, ducks and passerines).

Conditions data collected under

Not specified.

Results

Tracks recorded by both horizontal radar and the laser range finders were mapped for a range of species/groups in order to visualise movement patterns. It was proposed that diver spp (small sample size), northern gannet and common scoter tended to migrate along corridors along the periphery of the windfarms, although looking at the maps provided it is clear that northern gannet[17] and common scoter[18] did occur within the windfarms, notably Horns Rev 2. This was thought to be a result of the bathymetry as common scoters seemed to associate with waters less than 10 m in depth.

At Horns Rev 2 both distance to radar and distance to the windfarm were significant predictors of the densities for all birds tracks combined [19] and common scoter tracks. Response curves[20] produced by the models were similar for both analyses, which was unsurprising given the relative proportion of all tracks that were from common scoter. A peak in the density of birds occurred at around 1,500-2,500 m from the windfarm and was argued to provide evidence for a barrier effect due to birds

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[17] Figure 5-14- Skov *et al*. 2012.

[18] Figure 5-15- Skov *et al*. 2012.

[19] GAM; Distance to radar F=321.5, $p < 0.01$ and distance to windfarm F=286.4 , $p < 0.01$. Overall deviance explained 18.6% - Skov *et al*. 2012.

[20] Figure 5-23 - Skov *et al*. 2012.

altering their flight path. Similarly at Horns Rev 1, both distance to radar and distance to the windfarm were significant predictors for all bird tracks and common scoter tracks. In terms of the response curves, distance to windfarm the peak for all birds was between 2,000-3,000 m, whereas for common scoter it was around 1,000-2,000 m[21].

Assessment of methodology

From the results provided it is not possible to quantify an overall macro-avoidance rate although this study did provide information on the distances to which barrier effects were observed.

A1.3 Nysted offshore Windfarm

Location / habitat

Marine, offshore 10 km.

Turbine /array specification

Turbine array consists of 72 2.3 MW Bonus turbines covering 24 km^2. Distance between turbines – north to south (480 m) and east to west (850 m). Turbine specifications given as: hub height 69 m; rotor blade length 41 m; total height 110 m. Clearance above water is 28 m.

Case study number 1

Petersen, I.K., Christensen, T.K., Kahlert, J., Desholm, M. & Fox, A.D. 2006. *Final results of bird studies at the offshore windfarms at Nysted and Horns Rev, Denmark*. Commissioned by DONG Energy and Vattenfall A/S. National Environmental Research Institute.

Desholm, M. & Kahlert, J. 2005. Avian collision risk at an offshore windfarm. *Biology Letters* 1: 296-298[22].

Methods

Peterson *et al.* (2006) focussed on barrier effects, displacement effects, physical changes to the habitat and collision risk. Work was carried out at Horns Rev and Nysted offshore windfarm but there were differences in methodology and timing of data collection. Study at Nysted covered the three phases of: baseline (1999-2002); during construction (2002-2003) and post-construction (2003-2005). Desholm and Kahlert (2005) reported the results from the barrier effects and collision risk work only.

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[21] Figure 5-26 -- Skov *et al*. 2012.

[22] Assumed to be derived from the same data as Peterson *et al.* 2006.

Radar observations: Recordings by radar (Furuno FR125) were carried out from an observation tower, 5 km north-east of the windfarm area. The range was approximately 11 km and covered a circular area of 388 km^2. Migration was mapped by tracing the course of flocks onto a transparency and subsequently digitised. Only tracks longer than 5 km were included in the analyses.

The lateral response to the windfarms was investigated by setting a number of transects: the eastern gate (located along the full length the most eastern edge of the windfarm); the northern gate (located along the full length the most northern edge of the windfarm) and the buoy transect (running from north to south from the observation tower to a buoy, 6.9 km in length). During autumn migration, tracks of flocks of birds travelling in a westerly direction which crossed the buoy transect were selected to see if they crossed the eastern gate (in order to derive the percentage of birds which did so). In contrast, during spring migration the flight behaviour of birds was studied after they passed the windfarm and so is not considered further here. The total numbers of flocks of birds crossing the eastern and northern gate were also counted. In addition, migration intensities were compared for an area within the windfarm with an adjacent area outwith the windfarm (both less than 11 km^2 in area). Each area was subdivided into squares of 0.1 km^2 and within each cell, the lengths of radar tracks (bird flocks) were expressed as the total sum of track meters (the track density). In order to derive the change due to the windfarm, proportional differences in the bird densities within and inside the windfarm from the baseline data (pre-construction) were used to correct the data collected post-construction to derive avoidance rates.

In order to determine the response distance (where avoidance occurs) to the windfarm, transect lines to the east of the windfarm were set up which ran parallel to the direction of the rows of turbines (from north to south). These were spaced at intervals of 100, 200, 300, 400, 500 m and then at intervals of 500 m to 4,000 m and after which there were a further two transects at 5,000 and 6,000 m. The mean ± s.d. migration course of tracks were calculated for each transect (based on the gap between the transect itself and the 100 m interval to the west).

***Visual observations**:* Abundance, phenology, diurnal pattern and flock sizes of species were recorded along the buoy transect. Count data was then converted into number of birds per 15 mins for all westerly bound birds in autumn and easterly bound birds in spring (although again the latter represents the number of birds after passing through the windfarm).

Study period

Radar observations: spring (easterly-orientated migration) and autumn (westerly-orientated migration) periods covered. Total number of hours or breakdown by season not reported.

***Visual observations**:* During the main survey periods of 14 March to 19 April and 30 August to 12 November from 1999 - 2005, observations were carried out two days per week covering day and night time periods. A total of 259 h and 579 h observations gathered for the spring and autumn periods.

Species

Staging and migrating birds but common eider and geese spp most commonly recorded.

Conditions data collected under

Not specifically described but very little data of conditions under poor visibility (<1 km).

Results

The probability of birds crossing the windfarm was analysed using a logistic regression model and included the following explanatory terms and first order interactions (phase of development; distance to the observation tower when crossing the buoy transect), time of day, direction of winds (all of which were found to have significant effects). It was shown through comparison of data from the baseline and operation phases that 0.78 of all birds[23], which consisted mostly of common eider, avoided entering the windfarm post-construction during autumn migration. This was based on 40% of flocks entering the eastern edge of the windfarm during the baseline period compared to 9% during operation[24]. This was suggested to equate to 8 out of 10 flocks crossing the eastern gate during the baseline study then avoiding the windfarm during the post-construction phase. It was also shown that during the post-construction phase, the numbers of flocks crossing the eastern gate were higher at night than during the day (Desholm and Kahlert 2005 cited values of 13.5 % and 4.5 % respectively).

More specifically there was notable inter-annual variation in macro-avoidance rates for autumn migrating birds, again mostly common eider, ranging from 0.63 and 0.83[25] in the use of the windfarm post-construction compared to the baseline. These rates were derived from figures of 0.08-0.09 of flocks passing the eastern side of the windfarm compared to 0.24-0.48 passing the eastern gate of the windfarm during the pre-construction period[26].

There was a difference in migration intensity during the baseline period as the track densities in the eastern windfarm were 60% of the reference area which suggested a problem with detection rate. Nevertheless a significant reduction in track densities was reported for the post-construction period but there was acknowledgement that a reduction could be partially explained by problems of what is termed a shadow effect to do with individual turbines.

The standard deviation of the orientation was used to determine the lateral deflection as means of quantifying response distance to the windfarm (citing Kahlert *et al.*

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[23] Figure 121. Calculated as 1-(0.09/0.40) - Peterson *et al.* 2006.

[24] Desholm and Kahlert (2005) reported the proportion of flocks entering the windfarm decreased from 40.4% during pre-construction to 8.9% during initial operation. Data collection methods were not extensively described - Peterson *et al.* 2006.

[25] Calculated as 1-0.08/0.48 and 1-0.09/0.24 - Peterson *et al.* 2006.

[26] Figure 122 - Peterson *et al.* 2006.

(2005) as justification for this approach). Analyses of data collected during the autumn migration, showed a significant interaction between the phase of development and distance to the windfarm (other terms were also significant but not discussed here due to lack of information presented which can be evaluated with respect to providing evidence for the response distance)[27]. Plots of the means of annual standard deviation values showed that there was little change in orientation for distances between 100 m and 5 km from the windfarm during the baseline period[28]. However, during the operation period, the orientation of tracks steadily changed over the distances 5 to 1 km away from the windfarm (orientation of birds at 3 km from the windfarm were significantly different to the baseline period) and the greatest deflection occurred between 500 m and 100 m (note that the way the transects were set up, there was a gap between 500 m and 1 km). A tendency was also reported for the first deflection to be recorded at greater distances during the day compared to the night time period (based on the multiple use of pair-wise t tests across each distance interval)[29].

Assessment of methodology

As there was a before and after comparison carried out at Nysted this was argued to provide greater confidence (compared to Horns Rev) that any changes were as a direct result of the windfarm presence.

The response distance was only possible for birds entering the windfarm during autumn (the area used during spring migration was beyond the edge of the radar range and hence the derived figures are based on autumn migration only. Moreover, tracks do not differentiate between individuals or flocks, therefore the reported macro-avoidance values do not respond to the level of individual birds.

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[27] Table 41- Peterson *et al.* (2006).
[28] Figure 119 - Peterson *et al.* (2006).
[29] Table 42 - Peterson *et al.* (2006).

Case study number 2

Blew, J., Hoffman, M., Nehls, G. & Hennig, V. 2008. *Investigations of the bird collision risk and the responses of harbour porpoises in the offshore windfarms Horns Rev, North Sea, and Nysted, Baltic Sea, in Denmark. Part 1: Birds*. Report from the University of Hamburg and BioConsult SH, 145pp.

Methods

Methods used were exactly the same as used for Horns Rev (Appendix 1, section A1.2)

Study period

March to May to coincide with spring migration (44 ship days in 2005 and 2006) and September to November to cover autumn migration (51.5 ship days in 2005 and 2006).

Radar appeared to have been run continuously.

Species

Wide range of non-pelagic waterbirds with high numbers of common eider as well as raptors and songbirds. Transect counts showed that in spring, the common eider was by far the most common bird recorded and in autumn it was the great cormorant.

Conditions data collected under

Horizontal radar observations were limited to calm sea state conditions (wind speed < 2 ms^{-1}) and generally dry weather. Weather and sea state conditions tended to be better than those experienced at Horns Rev where fewer observation days were possible.

Visual observations were stopped when visibility <1 km.

Results

Radar tracks were categorised according to their direction in relation to the first row of the windfarm: flying towards (± 45° either side of perpendicular to the windfarm; flying away; and flying parallel (more or less). Initially tracks were presented regardless of their location (and therefore distance) in relation to the windfarm (but included tracks within the boundary of the outer row of the windfarm). During the day the overall number of tracks flying parallel to the windfarm was higher (n = 2,274) compared to towards (n = 1,725) or away (n = 563) from the windfarm. This pattern was not evident at night when the numbers flying towards (n = 968) and parallel (n = 804) were more similar but still much higher than flying away (n = 216).

In terms of determining whether horizontal avoidance occurred, the mean (and standard deviations) of angles of the approaching tracks were presented for the four

500 m width distance bands, for all anchor points east and west of Nysted offshore windfarm. It was reported that the angles did not increase (as would be predicted if horizontal avoidance occurred) or differ with decreasing distance to the windfarm (no statistical analyses were carried out).

Although the visual observations were designed primarily to look at the differences in flight height distribution, they were able to provide supporting evidence for macro avoidance occurring. For all gull spp significantly less birds were present inside the windfarm. No results for northern gannet were provided.

Assessment of methodology

See Appendix 1, section A1.2 for a discussion regarding the work carried out on radar and visual observations at Horns Rev where the same approach was used. With respect to looking for evidence of horizontal avoidance this study was unable to show evidence for a change in flight orientation. It was unclear though whether this was due to relatively wide bands being used (500 m in width) as other studies have used smaller intervals of 100 m at distances less than 1,000 m from the windfarm.

APPENDIX 2 Evidence review macro-response – displacement and attraction studies

A2.1 Egmond aan Zee

Leopold, M.F., Dijkman, E.M. & Teal, L. 2011. *Local Birds in and around the Offshore Windfarm Egmond aan Zee (OWEZ) (T-0 & T-1, 2002-2010)*. Texel, The Netherlands: Wageningen IMARES.

Leopold M.F., Camphuysen C.J., van Lieshout S.M.J., ter Braak C.J.F. & Dijkman E.M. 2004. *Baseline studies North Sea windfarms: Lot 5 marine birds in and around the future site Nearshore Windfarm (NSW)*. Alterra-rapport 1047.

Lindeboom, H.J., Kouwenhoven, H.J., Bergman, M.J.N., Bouma, S., Brasseur, S., Daan, R., Fijn, R.C., de Haan, D., Dirksen, S., van Hal, R., Hille Ris Lambers, R., ter Hofstede, R., Krijgsveld, K.L., Leopold, M. & Scheidat, M. 2011. Short-term ecological effects of an offshore windfarm in the Dutch coastal zone; a compilation. *Environmental Research Letters* **6**. doi:10.1088/1748-9326/6/3/035101.

Location/habitat

Marine 10-18 km offshore.

Turbine /array specification

Hub height 70 m and a rotor diameter 90 m (rotor altitude min 25 m, max rotor altitude 115 above mean sea level). Turbine array consists of 36 Vestas V90 3 MW turbines covering an area 27 km^2. Distance within turbines is 650 m within rows and 1000 m between rows.

Methods

The focus of Leopold *et al.* (2004) and (2011) was to look at avoidance and attraction by birds to the windfarm at Egmond aan Zee for what were termed local birds (although the survey work did cover the Princess Amalia windfarm site, results specific to this windfarm site were not presented). Survey periods covered the pre-construction and post-construction phases of the development. Lindeboom *et al.* (2011) reported the impacts of the windfarm on a range of taxonomic groups but with respect to birds presented less detail than the above reports and therefore is not considered further here.

The study area was approximately 725 km^2 (22 x 33 km). It was selected on the basis that it would include an adjacent offshore windfarm, Princess Amalia, and an anchorage area, where ships wait before entering the nearby major port. Ten transect lines were selected running east to west at distances of 2.47 km apart (with eight additional transect lines added in 2008 running north east to south west). The aim was to cover each transect twice (this was possible until the additional transect lines were added) and the transect lines were sailed in the same order each survey period. Successfully completed surveys ranged between 4-8 days in duration.

Ship based strip census surveys based on the methods adopted in the baseline studies in 2002-2004 (described in Leopold *et al.* 2004) which were originally derived from Tasker *et al.* (1984); Komdeur *et al.* (1992) and Camphuysen and Garthe (2004). All swimming birds were assigned to distance bands: AB (0-100 m); C (100-200 m) and; D (200-300 m) and all observations were assigned to five minute intervals. Flying birds were recorded using the snap shot methodology at intervals of 1 min.

Although BACI design was originally set to look at bird responses to the windfarm, there was considerable annual variation in seabird presence which hampered the ability to look for any differences between pre-construction and post-construction. Therefore the results focussed on comparisons within surveys (e.g. species-specific monthly counts). Presence/absence data were used as the response in Generalised Additive Mixed Models, which took into account temporal auto-correlation, for all individual species/month combinations there were sufficient data for. Otherwise a more simple General Additive Model was used or, in some cases, statistical models could not be run (birds were counted less than 10 occasions). Therefore, the number of surveys that were available for further analyses varied according to species and were a reflection of the relative abundance of birds each month. Presence /absence data were argued to be more appropriate as they were less affected by the large numbers of zero counts or the few counts with very large numbers of birds recorded. These models took into account the distance to coast, the northing value and the presence of impact area as factors (Egmond aan Zee, Princess Amalia and the anchorage area were considered individually within these models). The model output was then used to predict and subsequently map the probability of birds occurring across the survey area.

Within surveys, there was the possibility of four outcomes: attraction (probability of finding birds inside the windfarm was significantly higher than expected on the basis of the general distribution pattern); avoidance (probability of finding birds inside the windfarm was significantly lower than expected); indifference (probability of finding birds within the perimeter was not impacted by the windfarm and insufficient data.

Study period

Baseline/pre-construction surveys: T-0 = September and October 2002; April, May, June, August and November 2003; February 2004 (described in Leopold *et al.* 2004).

Post-construction surveys: T-1a = April, June, August, September, November (incomplete) 2007 and January 2008 (May was not repeated); T-1b = April, June, August, September (incomplete), November 2008; January, 2010; T-1c = April, June, August, October (September not possible) November 2009 and; January and February 2010.

Species

Local seabirds as defined as those which reside for some time in the study area. Species accounts were presented for: diver spp, great crested grebe, northern fulmar, northern gannet, great cormorant, common scoter, little gull, black-headed gull, common gull, lesser black-backed gull, herring gull, great black-backed gull, black-legged kittiwake, Sandwich tern, common/arctic tern, common guillemot and razorbill).

Conditions data collected under

Generally aimed to survey in conditions with a Beaufort scale of less than 6 Bft but there were a number of transects that were carried out in higher winds of 6-7 Bft (when light conditions permitted).

Results

Northern gannet: Northern gannet tended to occur on all sides around Egmond aan Zee windfarm but rarely within the perimeter of the windfarm[30]. Observations recorded that those few birds that did enter only went one turbine deep. Where presence/absence analyses were possible for the post-construction period (n = 10 surveys), it was shown that the presence of the species was significantly negatively related to the Egmond aan Zee windfarm for only two surveys. Anecdotally it was reported that gannets never entered Princess Amalia Windfarm (which has a higher turbine density[31]). Also highlighted was the lack of searching feeding, resting in the windfarms during the surveys.

Lesser black-backed gull: It was evident that lesser black-backed gulls were often seen within perimeters of windfarm[32]. These birds tended to be either resting on the water or foundation structures or feeding at the tidal wakes around the monopiles. Presence/absence analyses for the post-construction period (n = 12 surveys), found that the presence of the species was negatively related to the Egmond aan Zee windfarm for only one survey (the rest were also negative but insignificant). This was counter to what would have been predicted as large fishing vessels only operated outside the windfarm which should have in effect reduced the numbers of birds inside the windfarm (resulting in an apparent avoidance). Most observations of lesser black-backed birds were anecdotally reported to be associated with, looking out for or resting in the wake of active fishing vessels.

Herring gull: Birds did occur in the windfarm area but overall fewer birds were recorded in the offshore environment compared to other gulls (notably in August where herring gulls remain mostly near shore). Like lesser black-backed gulls they were often associated with fishing vessels. Presence/absence analyses for the post-construction period (n = 14 surveys), found that the presence of the species was negatively related to Egmond aan Zee windfarm for eight surveys although this effect was only significant in three cases. Herring gull distribution patterns were thought to be likely to be attributable to overall latitudinal variation, as evidenced by the strong effect of distance to coast in the models (significant p values for six surveys).

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[30] Figure 31 - Leopold *et al.* 2011.

[31] 60 2 MW turbines which are evenly spaced (550 m apart) in area of 14 km^2 - Leopold *et al.* 2011.

[32] Figure 34 - Leopold *et al.* 2011.

Great black backed gull: Birds were reported as occurring in the windfarm area[33]. Presence/absence analyses for the post-construction period (n = 18 surveys), found that the presence of the species was positively related to the Egmond aan Zee windfarm in five cases, four significantly, although this effect was only apparent at low densities. There were also two surveys in which significant effects were reported. As reported for lesser black-backed gull, birds did tend to feed around fishing vessels but not in the same high numbers.

Black-legged kittiwake: birds were recorded within the windfarm and in general numbers declined with decreasing distance to shore (apart from in November and one January). Presence/absence analyses for the post-construction period (n = 5 surveys), found that the presence of the species was positively related to the Egmond aan Zee windfarm in three cases, one significantly.

Assessment of methodology

Overall, there was lack of consistent evidence for either displacement or attraction for any of the species. This could have been partly due to the importance of factors operating at the larger scale of study area. For the larger gull species, there was a strong association with fishing vessels in the study area. Since fishing was no longer permitted in the windfarm areas, this could have confounded any results reported to do with possible attraction or avoidance of windfarms. There was also evidence that distance to coast was an important factor in determining the overall distribution patterns of herring gulls.

There were potential issues relating to the choice of statistical approach. As comparisons of pre-construction and post-construction data was deemed not to be possible, multiple tests for individual surveys were carried out which may have led to the possibility of a Type 2 error (increased chances of reporting a false significant result). Also the numbers of observations were low for northern gannet and gull spp and consequently the modelling power was very low (Lindeboom *et al.* 2011). Moreover, the model outputs were in the form of p values and model co-efficients which could not be converted into avoidance rates without further details being presented (even if consistent effects had been observed). Therefore, from the results provided, it is not possible to derive displacement/attraction rates or thus macro-response rates for the study species.

A2.2 Robin Rigg

Natural Power. 2014. Analysis of Marine Ecology Monitoring Plan Data from the Robin Rigg Offshore Windfarm, Scotland (Post-construction Year 3). Draft Technical Report. E.ON Climate & Renewables.

Location/habitat

Marine, offshore < 11 km

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[33] Figure 38 - Leopold *et al.* 2011.

Turbine /array specification

Turbine array consists of 60 3.0 MW Vestas turbines which are positioned approximately 500 m apart. Turbine specifications are given as turbine towers 80 m high and a rotor blade length of 44 m.

Methods

The purpose of this report was to look at: displacement of key species; changes in patterns of abundance and distribution; compare observed patterns with predicted impacts/sensitivities from the EIA process.

Data collection was carried out during the pre-, during and post-construction periods.

Boat based surveys based on standard European Seabirds-At-Sea (ESAS) survey methods were carried our (e.g. prior to the publication of Camphuysen *et al.* 2004) as used in the baseline period. In order to ensure comparability between the different phases of the development, methods were kept the same throughout. Additional survey work has been carried out from year 3 of the post-construction period which corresponds to current best practice. The main difference between the two approaches is that for flying birds the former records flying birds using transect methodology whereas the latter uses the snap shot methodology currently regarded as best practice. A total of 10 parallel transects running in a south west to north east direction of 18 km in length and spaced 2 km apart.

For the purpose of analyses, each survey was divided into individual blocks of 600 m^2 (corresponding to the 300 m either side of the transect line as both sides of the boat are surveyed). In terms of the data, there was a cleaning process applied. Uneven sampling effort across the different phases of the development (some months were surveyed twice) was identified as an issue and therefore a single survey at random was selected. The study area was also cropped to remove an area in the northeast where shallow waters sometimes prevented access and two transects in the southeast were removed due to under surveying during the pre- and during construction phases. There was also a gap during the construction period where there was no building activity (January and July 2008) and these were also excluded from the analysis.

Birds on the water and birds in flight were analysed separately. Datasets that had fewer than 300 non-zero observations were not considered. Raw observations were mapped and summary statistics for the three development phases were calculated in order to provide an initial indication of any change. These included: mean number of sightings (groups of animals), mean number of individuals per segment and mean number of individuals per segment per month. These are not discussed here however and the results of models output are focussed upon.

Distance Sampling techniques were not used to correct the survey counts and a correction factor derived using the detection function was applied instead. Generalised Additive mixed effects mixture modelling carried out within a Bayesian framework were applied in order to deal with zero inflation (high number of zeros). Transect and survey were incorporated as random effects in order to deal with spatial and temporal autocorrelation. Covariates used in the models were latitude, longitude month (or season) and time of day.

Outputs of the models were used to produce density surface maps of the predicted distribution during the three different phases of the development. Abundance and density estimates for each species within the windfarm and the study area were produced for each phase. In order to look at avoidance, model outputs were used to predict the number of animals within the windfarm and for buffers 0.5, 1, 1.5 and 2 km of the three different windfarm phases. Model outputs were presented only for the comparisons of pre-construction to construction and pre-construction to post-construction (but it was not clear which of the spatial scales they related to).

Study period

Baseline surveys: monthly basis between May 2001 and April 2002. Further pre-construction surveys April and May 2003 and then on a monthly basis between January 2004 and September 2004 (excluding April and June) with further work in July 2007. Construction surveys: monthly basis between January 2008 and February 2010 (excluding November 2009). Post-construction: monthly surveys from March 2010 to February 2013 – scheduled to continue until 2015.

Species

Data were collected for a wide range of species (e.g. seabirds, seaducks, waders, passerines). Species accounts were only presented for the following key species: scaup, common scoter, red-throated diver, Manx shearwater, northern gannet, great cormorant, black-legged kittiwake, herring gull, great black-backed gull, common guillemot, and razorbill.

Conditions data collected under

Not specified but ESAS provide guidance regarding suitability of conditions.

Results

Northern gannet: Modelling of the numbers of northern gannet on the water was not possible as there were too few sightings. The predicted numbers of northern gannet in flight across the three different phases of the development were found not to be significantly different. There appeared to have also been relatively little change in the predicted densities for the windfarm site, windfarm plus buffers (at any of the scales) or even at the level of the study area[34]. Although northern gannet was recorded throughout the study area, densities of the gannets were reported as being generally low[35].

Black-legged kittiwake: The predicted numbers of black-legged kittiwake on the water across the three different phases of the development were found not to be

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[34] Figure 3.55 – Natural Power 2014.

[35] Figures 3.56-3.61- Natural Power 2014.

significantly different. There appeared to have also been relatively little change in the predicted densities for the windfarm site, windfarm plus buffers (at any of the scales) or even at the level of the study area[36]. A similar result was found for black-legged kittiwakes in flight[37].

Herring gull: Modelling of the numbers of herring gull on the water was not possible as there were too few sightings. The predicted number of herring gull in flight across the three different phases of the development were found to be significantly different with the numbers within the windfarm decreasing over the development (pre-construction to construction p = 0.0021, parameter estimate -0.750 and pre-construction to post-construction p = 0.0013, parameter estimate - 0.841).

Great black-backed gull: Modelling of the numbers of herring gull on the water was not possible as there were too few sightings. The predicted number of herring gull in flight were found to significantly differ from pre-construction to construction (p = 0.0166, parameter estimate -1.133) but not from pre-construction to post construction (p = 0.7854).

Assessment of methodology

There were insufficient data to allow modelling of the observations of birds on the water for northern gannet, herring gull, and great black-backed gull. For birds in flight, there was evidence for a significant decrease for herring gull both during the construction and post-construction periods whereas this decrease was only noted during construction for great black-backed gull. Northern gannet and black-legged kittiwake did not appear to respond to the presence of the windfarm. From the results provided, it was not possible to derive macro-response rates since it was not clear what models have been fitted and it was not apparent whether the changes were due to the presence of the windfarm or as result of changes at the scale of the overall study site. It is acknowledged though that despite this being year 3 of the post construction, it is not the final report and any reported results should be considered as preliminary findings.

A2.3 Blighbank

Vanermen, N., Stienen, E.W.M., Courtens, W., Onkelinx, T., Van de walle, M. & Verstraete, H. 2013. *Bird monitoring at offshore windfarms in the Belgian part of the North Sea - Assessing seabird displacement effects*. Rapporten van het Instituut voor Natuur- en Bosonderzoek 2013 (INBO.R.2013.755887). Instituut voor Natuur- en Bosonderzoek, Brussel.

Location/habitat

Marine, 42 km offshore

Turbine /array specification

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[36] Figure 3.82 - Natural Power 2014.
[37] Figure 3.83 - Natural Power 2014.

55 turbines. Additional information was not presented.

Methods

This report looked at Blighbank and Thorntonbank windfarms (but also referred to the more recent development of Lodewijckbak) in what is termed the windfarm concession zone located in the north eastern edge of the Belgian Part of the North Sea (BPNS). Surveys at both windfarms are still on going.

Data collection was carried out during the pre-construction, during and post-construction periods.

A BACI approach was adopted in order to monitor sea bird displacement. A control area of comparable size was selected on the basis of having similar attributes in terms of number of birds, environmental conditions and having sufficient historic data. A buffer zone of 3 km was applied to the boundary of the windfarm (and the control area), in order to reflect the distance to which the effects of the windfarm could be an issue for birds.

Boat transects were carried out on a monthly basis (citing Tasker *et al.* 1984) from 2008. The time interval used in this survey for recording was 10 minutes (a number of other windfarm surveys use 1 min). Although only transect routes used post 2012 were shown[38], despite some apparent minor shifts in the location the overall configuration was considered to be the same over the whole monitoring period (Nicolas Vanermen *pers. comm.*). An overview was provided of all the ESAS counts carried out by INBO during the period of 1992-2012 based on location of counts, this could not be used to look at survey effort which varied over the study period[39]. Count effort for Blighbank[40] (as shown by the number of surveys) indicated overall higher effort in the pre-construction period (but this included data possibly dating back to 1992). There was also marked monthly variation in effort in the preconstruction phase with peaks in February/August for the pre-construction period and in March/December for the post construction period.

Although distance sampling was used to correct count data to estimate the total numbers of birds within the BPNS (based on Buckland *et al*. 2001), it was not applied for modelling of the windfarm data (this was on the grounds that the correction factor used for both control and the windfarm area was likely to be the same Nicolas Vanermen *pers. comm.*). In order to analyse the count data, generalised linear models were used, with a negative binomial distribution assumed in order to cope with over dispersion. Modelling was carried out using area (the reference area or the impact area) and month (as a as a continuous variable in order to model seasonality) included as explanatory terms in what was termed the reference model (based on data collected prior to April 2008). The best model was then selected using a backward approach using a Wald test and looking at the resulting AIC values. The impact model was a simple extension of the count

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[38] Figure 27 - Vanermen *et al*. 2013.

[39] Figure 2 - Vanermen *et al.* 2013.

[40] Figure 29 - Vanermen *et al*. 2013.

component of the reference model with before and after being added as factor variables to the model. Although not carried out in this report, the natural exponent of the model coefficients can be used to derive the factorial change (and hence the overall percentage change in numbers from pre to post construction – see Table A6.1).

Species' preference for the windfarm area was calculated using Jacob's Selectivity Index (calculated using the proportion of birds that occur inside the entire windfarm concession zone compared to the total numbers within the BPNS and the proportion of the surface area of the concession zone to the total area of the BPNS) whereby values of -1 represent total avoidance and + 1 is total preference (attraction). However this data was only carried out for the baseline data and hence are not considered further here.

The impact of the windfarm was considered separately for the post-construction phase at the scale of the windfarm, the windfarm and buffer, and the buffer without the windfarm[41]. Displacement-related coefficients and their respective p values were reported.

Study period

The baseline period (reference period) referred to data pre-September 2009. The construction period ran from September 2009 to August 2010, and the post-construction period was from September 2010 onwards. Data collected during the initial construction period were not used in subsequent assessment due to access issues over this period. Results are presented for up until December 2012.

Species

Northern fulmar, northern gannet, great skua, little gull, common gull, lesser black-backed gull, herring gull, great black-backed gull, black-legged kittiwake, common guillemot, and razorbill.

Conditions data collected under

Not specified in the report. Conditions were, however, mostly favourable - boat surveys are cancelled when wave heights > 1.8 m, and in poor visibility (Nicolas Vanermen *pers. comm.*).

Results

Northern gannet: Model coefficients were significant for the scale of the windfarm and buffer and buffer without the windfarm (see Table A6.1). Therefore there were highly significant decreases in numbers of northern gannet in the windfarm and the buffer of 3 km at all three spatial scales considered.

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[41] Table 18 - Vanermen *et al.* 2013.

Lesser black-backed gull: Model coefficients were significant for the windfarm and buffer, and buffer without the windfarm, and were only just not significant for just the windfarm. Therefore there was a significant increase in numbers of lesser black-backed gull in the windfarm and the buffer of 3 km relative to the pre-construction period.

Herring gull: The model coefficient was only significant at the scale of the windfarm, indicating an increase in numbers in the windfarm area relative to the pre-construction period.

Great black-backed gull: The model coefficients were not significant, indicating no changes in numbers of the species relative to the pre-construction period.

Black-legged kittiwake: The model coefficients were not significant, indicating no changes in numbers of the species relative to the pre-construction period.

Table A2.1 Model outputs of Negative binomial modelling converted into factorial changes

Species	Scale	Model coefficient	P value	Factorial Change*	Overall change as a proportion
Northern gannet	Windfarm	-1.83	0.000	0.16	0.84
	Windfarm plus buffer	-1.52	0.000	0.22	0.78
	Buffer	-1.32	0.003	0.27	0.73
Lesser black-backed gull	Windfarm	1.57	0.059	4.81	-3.81
	Windfarm plus buffer	2.39	0.004	10.91	-9.91
	Buffer	2.37	0.006	10.70	-9.70
Herring gull	Windfarm	3.97	0.000	52.98	-51.98
	Windfarm plus buffer	1.26	0.111	-	-
	Buffer	0.83	0.269	-	-
Great black-backed gull	Windfarm	1.08	0.127	-	-
	Windfarm plus buffer	0.47	0.447	-	-
	Buffer	0.54	0.428	-	-
Black-legged kittiwake	Windfarm	0.25	0.605	-	-
	Windfarm plus buffer	0.50	0.264	-	-
	Buffer	0.77	0.092	-	-

*natural exponent of the model co-efficient.

Assessment of methodology

The results of this report should be considered as being preliminary since further data was collected for 2013. Nevertheless, northern gannet was shown to decrease in response to the presence of windfarm by a value of 0.84. This value could be taken as being indicative of macro-avoidance. Whereas both lesser black-backed gull and herring gull shown quite marked attraction to the windfarm. Great black-backed gull and black-legged kittiwake showed no overall response to the windfarm. From the results provided it was not possible to look at seasonal variation in displacement or attraction.

Sampling effort was biased towards the pre-construction phase and was characterised by variable effort on a monthly basis. Spatial coverage over the whole study period is likely to have been fairly consistent however. The data presented in this report is based on a BACI approach and potentially has limited value in looking at changes in the wider area but long term monitoring in the BPNS has continued throughout the study period and hence there is scope to include this at a later stage if required.

A2.4 Thorntonbank

Vanermen, N., Stienen, E.W.M., Courtens, W., Onkelinx, T., Van de walle, M. & Verstraete, H. 2013. *Bird monitoring at offshore windfarms in the Belgian part of the North Sea - Assessing seabird displacement effects*. Rapporten van het Instituut voor Natuur - en Bosonderzoek 2013 (INBO.R.2013.755887). Instituut voor Natuur- en Bosonderzoek, Brussel.

Location/habitat

Marine, 27 km offshore.

Turbine /array specification

Initially six turbines, final array to consist of 54 turbines.

Methods

See Appendix 2, section A2.3 for overall approach.

The impact of the windfarm was considered separately for the two different operation phases: phase 1 (turbine array consisting of six turbines) and; phase 2 (second construction period). Models were run at the scale of the windfarm and buffer only[42].

Power analyses were also carried out for the reference data collected in the Thorntonbank study area in order to determine the power required to detect change in numbers of birds (25, 50 and 75% decrease) and the length of the monitoring period required.

Study period

Monthly surveys were started in 2005 (although additional data were available from 1993 based on surveys that have been carried out of the whole region of the BPNS but coverage was uneven spatially and temporally). The baseline period (reference period) referred to data pre-April 2008. The construction period ran from April 2008 to May 2009, and the post-construction period (called here the impact period) was from June 2009 to April 2011. Thereafter there was another period of construction from May 2011 that was ongoing at the time of the report.

Species

Northern fulmar, northern gannet, great skua, little gull, common gull, lesser black-backed gull, herring gull, great black-backed gull, black-legged kittiwake, Sandwich tern, common tern, common guillemot, razorbill.

Conditions data collected under

Not specified but ESAS provide guidance regarding suitability of conditions.

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[42] Table 15 - Vanermen *et al.* 2013.

Results

Northern gannet: For both phase 1 and phase 2, the model coefficients were not significant, indicating no changes in numbers of the species relative to the pre-construction period.

Lesser black-backed gull: For phase 1, the model co-efficient was not significant. For phase 2, a significant model co-efficient of 2.13 was reported (p = 0.052) for the scale of the windfarm, indicating a decrease inside the windfarm (but this effect was not found for the other models at the scales of the windfarm plus buffer, and buffer without the windfarm).

Herring gull: For both phase 1 and phase 2, the model coefficients were not significant, indicating no changes in numbers of the species relative to the pre-construction period.

Great black-backed gull: For phase 1, the model co-efficient was reported as 1.5 and was found to be significant (p = 0.024) for the windfarm plus buffer indicating an attraction to the windfarm. Whereas for phase 2, the model coefficients were not significant, indicating no change in numbers of the species relative to the pre-construction period.

Black-legged kittiwake: For both phase 1 and phase 2, the model coefficients were not significant, indicating no changes in numbers of the species relative to the pre-construction period.

Assessment of methodology

The results of this study were derived from when the windfarm only consisted of 6 turbines (phase 1) or during the next phase of construction of a further 48 turbines (phase 2). Hence the years covered by this report do not include the post-construction phase of a fully post-construction windfarm. Hence the results are not considered further here as part of this review.

A2.5 Nysted

Petersen, I.K., Christensen, T.K., Kahlert, J., Desholm, M. & Fox, A.D. 2006. *Final results of bird studies at the offshore windfarms at Nysted and Horns Rev, Denmark*. Commissioned by DONG Energy and Vattenfall A/S. National Environmental Research Institute.

Location/habitat

See under section 5.4.1.3 under barrier effects.

Turbine /array specification

See under section 5.4.1.3 under barrier effects.

Methods

Aerial transect surveys were carried out using methodology described in Kahlert *et al.* 2004 (which prior to the publication of Camphuysen *et al.* 2004 was commonly cited by other studies as the standard methodology). A total of 26 parallel transects running north to south separated by distances of 2 km were carried out covering an area of 1,700 km^2. The area was extended by four additional transect lines in 2002 to increase the area to 1,846 km^2.

Jacob's selectivity indexes (D) were used in order to look at displacement and attraction. This approach essentially determines bird preferences for the windfarm area and a buffer zone (2 and 4 km) where birds could still be impacted, in relation to their preference to the whole study area. Values fell between -1 (displacement) and +1 (attraction). Bird encounters (for both individuals and groups here termed as clusters) rather than estimates of bird densities were used. Bird preferences were then compared by looking at the pre- and post-construction D values, based on a simple comparison of number rather by formal statistical analyses, in order to describe the change in bird utilisation of the windfarm.

Bird encounter rate (number of birds reported per km of survey route per observer) was used as a proxy of density in order to calculate mean densities in the windfarm area and in the buffer zone. Comparisons of the mean densities pre- and post-construction were carried out using Student's t-test with corrections for unequal variance. Sufficient data (with respect to the five priority species) was available for comparisons for herring gull at Nysted in January and Horns Rev in March.

Study period

Pre-construction period = August 1999 to August 2002 (n = 21 surveys); construction period = January 2003 to August 2003 (n = 3); post-construction period = January 2003 (sic) to November 2005 (n= 8). The timing of the actual surveys (e.g. by month were not reported). Only the pre-construction and post-construction surveys were used. There was a lack of autumn surveys for the post-construction phase and therefore only winter and spring surveys were available.

Species

Diver spp, great cormorant, long-tailed duck, common eider, common scoter, red-breasted merganser, herring gull and great black-backed gull.

Conditions data collected under

Not specified.

Results

Herring gull: Comparisons of pre- and post-construction selectivity indices for numbers clusters of birds showed no change[43]. Whereas selectivity indices for

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[43] Table 27 and 29 - Peterson *et al*. 2006.

numbers individuals showed a tendency towards decreased selectivity (e.g. less birds were using the area) for the windfarm as well as both buffer zones[44]. There was no significant difference between bird encounter rate between the pre- and post-construction phases in the windfarm area or the 4 km zone but a significant difference was found for the 2 km buffer. The report concluded there was no evidence for either attraction or avoidance.

Great black-backed gull: outputs of the models were all found to be insignificant apart for the selectivity indices for individual birds post-construction and hence are not reported further here as they have no meaningful comparison for pre-construction.

Assessment of methodology

Overall there was little evidence that herring gull showed any response to the presence of the windfarm.

There are a number of potential limitations of the approach used. There may be issues to do temporal coverage – from the information provided, it was difficult to be able to evaluate how sampling effort varied over the different phases of the development. Also whilst the Jacob's selectivity indices may provide an indication of the likely direction of response, these cannot be directly translated into displacement rates. Also the comparison of pre- and post-construction bird encounter rate had limited value since they provided no indication of changes in distribution that may have occurred at a wider scale (and therefore nothing to do with the presence of the windfarm).

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[44] Table 28 and 30 - Peterson *et al*. 2006.

A2.6 Horns Rev

Location/habitat

See under Appendix 1, section A1.2.

Turbine /array specification

See under section Appendix 1, section A1.2.

Methods

Aerial surveys: Aerial transect surveys were carried out using methodology described in Kahlert *et al.* (2004) which prior to the publication of Camphuysen *et al.* (2004) was commonly cited by other studies as the standard methodology. A total of 26 parallel transects separated by distances of 2 km were carried out covering an area of 1,350 km^2.

Study period

Pre-construction period = August 1999 to January 2002 (n = 16 surveys); construction period = March 2002 to August 2002 (n = 3); post-construction period January 2003 to November 2005 (n= 15). The timing of the actual surveys (e.g. by month were not reported). Only the pre-construction and post-construction surveys were used.

Species

Diver spp, northern gannet, common eider, common scoter, little gull, Arctic/common tern and guillemot.

Conditions data collected under

Not specified.

Results

Northern gannet: There were no observations of northern gannet inside the windfarm pre- or post-construction. Comparisons of pre- and post-construction selectivity indices for the buffer zones indicated increased avoidance at the 2 and 4 km zone. Insufficient numbers of birds were recorded in order to be able look at encounter rates and limited further interpretation of what the likely overall response of northern gannet to the windfarm.

Herring gull: Comparisons of pre- and post-construction selectivity indices for clusters and individuals of birds indicated a reduced avoidance of the windfarm area. The bird encounter rate revealed no significant difference between the pre- and post-construction period. It was concluded that despite an increased preference being found during construction (citing Christensen *et al.* 2003), attraction was not observed post-construction.

Black-legged kittiwake: Model outputs were not significant for numbers of clusters of birds post-construction and for both pre- and post-construction for numbers of individual birds. Hence the results are not reported here.

Assessment of methodology

See Appendix 2, section A2.5.

A2.7 Alpha ventus demonstration site

Bundesamt fur Seeschiffart und Hydrographie, BSH 2011. Okologische Begleitforshung bei alha ventus erste Ergebnisse (Environmental research at alpha ventus – first results). Contributions from the Event of 10 May 2010, Katholische Akademie Hamburg.

Mendel, B., Kotzerka, J., Sommerfeld, J., Schwemmer, H., Sonntag, N. & Garthe, S. 2014. Effects of the Alpha Ventus offshore test site on distribution patterns, behaviour and flight heights of seabirds. *In* Ecological Research at the Offshore Windfarm Alpha Ventus: Challenges, Results and Perspectives. Editors Federal Maritime and Hydrographic Agency, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Springer Spektrum.

All the post-consent monitoring reports from this OWF demonstration site are written in German (Stefan Garthe *pers. comm.*). The first reference reviewed is a report (BSH 2014) which has a full English translation. The second reference (Mendel *et al.* 2014) is a book chapter and is written in English. Neither reference can be considered to be fully comprehensive in the level of detail provided but given the importance of this OWF site this information should be included. The information which is cited below is largely taken from Mendel *et al.* (2014).

Location/habitat

45 km offshore

Turbine /array specification

Twelve turbines. Two designs (jacket foundation and tripod steel foundations) – no further information provided.

Methods

Two study areas were selected: the key study area, the size of which was in excess of 30 times the size of the windfarm itself and; a reference site which appeared to be nearly twice the size of the study area. Boat based surveys were carried out according to standard European Seabirds-At-Sea (ESAS) survey methods. Aerial-based methods were based on methods described in Pihl and Frikke (2002), Noer *et al.* (2000) and Diederichs *et al.* (2002) (full citations are given in Mendel *et al.* 2014). As well as data from the EIA studies, additional data from eight multiple-day ship-based surveys and 21 aerial surveys carried out in both study areas were available. No further information was provided, however (e.g. on the timing of the surveys in relation to season).

In order to carry out analyses of the changes in distribution patterns for pre-and post-construction data, data were collated into grid cells of 1 km^2 and only data from the key study area were used. A total of six species or species groups were looked at (divers, northern gannet, lesser-black backed gull, little gull, black-legged kittiwake and common guillemot) and only the most important period/s for each of these were focussed upon. Data were also collated over large time periods (usually seasons).

Changes in abundance were looked at using the pre- and post-construction data and only two species were considered (lesser-black backed gull and common guillemot). Generalised Linear Mixed Models of the abundances of birds at different distances in relation to the windfarm (0-2 km, 2-6 km and 6-10 km) were tested in three different models using a Poisson error distribution.

The percentage of birds recorded in each behavioural category was calculated for the key study areas and the reference area for lesser black-backed gull only.

Study period

Data from 2000-2008 were regarded as pre-construction (construction started in September 2008) and data from 2010-2012 represented the post-construction period.

Species

Northern gannet, northern fulmar, black scoter, skua spp, gull spp, and auks spp. Key species: Red-throated diver, black-throated diver, lesser black-backed gull, black-legged kittiwake, little gull, common guillemot and razorbill.

Conditions data collected under

Data collected according to ESAS methods (sea state < 5Bft).

Results

Changes in distribution

The statistical significance of the following results was not provided and interpretation of results was largely based on maps representing densities of birds for the 1 km^2 grid cell system of the key study area. Overall lower abundances were reported post-construction for six of the species/groups but only the relevant species are reported further here.

Northern gannet: the impact of the windfarm was hard to qualify due to the very low numbers recorded within the key study area. This species was reported to have occurred on seven occasions (nine individuals) within the windfarm area during the pre-construction period and none were observed post-construction. Data were taken from March to September and hence represented the breeding season.

Lesser-black-backed gull: a ‘clear decrease’ was reported to have occurred from the pre- to the post-construction period. Although low to medium densities were reported post construction within the windfarm area, the highest densities were found a few kilometres away from the windfarm site (previously some of the highest were found within the perimeter of the windfarm area during pre-construction). Data were taken from May to July and hence represented the breeding season.

Black-legged kittiwake: a ‘remarkable decline’ occurred post-construction not only within the perimeter of the windfarm but at the scale of the whole key study sites. Numbers recorded overall were very low however (e.g. highest number of birds recorded per km^2 was 5). Data were taken from November to April and hence represented the non-breeding season.

Changes in abundance

Lesser-black backed gull: Statistically significantly lower abundances were reported for the 0-2 km, 2-6 km and 6-10 km distance class and the models suggested that the disturbance effect was strongest within 2 km of the windfarm,

Assessment of methodology

Based on the information provided, it is not possible to carry out a proper assessment of the methodology used. The overall abundance of northern gannet was very low and therefore this study cannot be cited as evidence of the windfarm having an impact on their distribution. There is some evidence to suggest that displacement may be occurring for lesser black-backed gull and black-legged kittiwake based on the maps of the distribution of bird densities for pre- and post-construction, but there was a lack of statistical analyses. However a statistically significant reduction in the abundance of lesser black-backed gulls was reported for all the three distances classes from the windfarm.

APPENDIX 3 EVIDENCE REVIEW HORIZONTAL MESO-RESPONSE

A3.1 De Put, Nieuwkapelle

Everaert, J. 2008. *Effecten van windturbines op de fauna in Vlaanderen Onderzoeks resultaten, discussie en aanbevelingen*. INBO, Brussels

Methods

Baseline data describing bird movements within the area, prior to turbine construction, were collected on six days between December 2004 and February 2005 at periods of dawn and dusk. Following turbine construction, additional data were collected on six days between December 2005 and March 2006, again at dawn and dusk. Changes in the number of birds flying within 100 m and 300 m of each turbine pre- and post-construction were then modelled using a factorial ANOVA.

Seasons / time of day

Data were collected over the winter at dawn and dusk.

Species

Black-headed and common gulls.

Conditions data collected under

Not specified.

Location / habitat

Terrestrial site in Belgium.

Turbine / array specification

A two turbine array. Each turbine has a mast height of 75 m and a rotor diameter of 48 m.

Results

No significant differences were recorded in the number of black-headed or common gulls passing within 300 m or 100 m of the turbines between the pre- and post-construction periods.

Assessment of methodology

A key flaw in this study is the lack of a control site with which to compare differences in movement pre- and post-construction. A consequence of this is that it is not possible to determine whether the lack of significant changes reflects the local population remaining relatively stable or whether the overall proportion, but not numbers, of a variable local population passing the turbines has changed.

A3.2 Egmond aan Zee

Krijgsveld, K.L., Fijn, R.C., Japink, M., van Horssen, P.W., Heunks, C., Collier, M.P., Poot, M.J.M., Beuker, D. & Dirksen, S. 2011. *Effect studies Offshore Wind farm Egmond aan Zee: Final report on fluxes, flight altitudes and behaviour of flying birds*. Bureau Waardenburg

Methods

Radar Observations

Between July 2009 and March 2010, the flight paths of birds within the windfarm were recorded using a horizontal radar with range of 0.75 nautical miles. The study area included six turbines and it was possible to collect data on 235 out of the 239 days during the study period, although it was necessary to filter out data on an additional 59 days due to the incidence of 'clutter'. Data were then analysed using a t-test to assess whether birds were distributed evenly within the windfarm by comparing the number of birds passing within 50 m of a turbine to the number of birds elsewhere.

Seasons / time of day

Data were collected during daylight on eight occasions between July and December.

Species

Not stated

Conditions data collected under

All conditions.

Location / habitat

Marine 10 km offshore.

Turbine / array specification

Egmond aan Zee Offshore Windfarm covers an area of 27 km^2 and contains 36 turbines. Each turbine has a hub height of 70 m and rotor diameters of 90 m. Turbines are arranged in four rows, with 650 m between turbines in each row and 1 km between rows. The study of horizontal meso-responses covered six turbines at the edge of the windfarm.

Results

There was a statistically significant difference in the numbers of birds flying within 50 m of the turbines in comparison to the proportion of birds elsewhere in the study area. Over the course of the study period, this reflected a horizontal meso-response rate of 0.34 (i.e. the number of birds within 50 m of a turbine was 66% of that elsewhere within the windfarm).

Assessment of methodology

Data used in this study have been collected using radar, meaning near-continuous data collection was possible. In order to detect finer scale movements of birds in relation to the windfarm, the resolution of the radar was reduced to cover a distance of 0.75 nautical miles. As a consequence, it was possible to detect movements of birds that were as close as 1 m to turbines. However, a key limitation of the data is that it is not possible to relate echoes to individual species, or to determine whether a single echo reflects an individual birds, or a flock. An additional limitation is that birds at low altitudes may have been obscured by high waves, which they exploit in order to minimise energy expenditure.

A3.3 Horns Rev I and II

Skov, H., Leonhard, S.B., Heinanen, S., Zydelis, R., Jensen, N.E., Durinck, J., Johansen, T.W., Jensen, B.P., Hansen, B.L., Piper, W., Grøn, P.N. 2012. *Horns Rev 2 Monitoring 2010-2012. Migrating Birds.* Orbicon, DHI, Marine Observers and Biola. Report commissioned by DONG Energy

Methods

Radar Monitoring

Between September 2010 and May 2012 Bird movements were recorded using horizontal radar at stations within the Horns Rev I and Horns Rev II offshore windfarms. All movements within 6 km of the radar were recorded. Two observers were used during the data collection. The first observer followed the tracks and recorded information within a database. The second observer attempted to locate each of the tracked objects in the field using binoculars or a telescope and relayed information on the species identification, number and altitude to the first observer.

Seasons / time of day

Data were collected during the spring and autumn migration periods during the hours of daylight.

Species

Northern gannet (442 birds), common scoter (2,374 birds), large gulls (408 birds), terns (617 birds).

Conditions data collected under

Data were generally collected during relatively calm conditions (little wind or rain and good visibility).

Location / habitat

Horns Rev I is located 17.9 km from the Danish coast and Horns Rev II is located 31.7 km from the Danish coast.

Turbine / array specification

Horns Rev I is an array of 80 turbines, each with a hub height of 70 m and a rotor diameter of 80 m. Horns Rev II is an array of 91 turbines, each with a hub height of 68 m and a rotor diameter of 93 m.

Results

The study estimated the mean, minimum and maximum distances from turbines recorded by each species. On average, northern gannets were recorded passing within 1,119 m of turbines (range 0-2,840 m), common scoter were recorded passing within 921 m of turbines (range 0-4,302 m), large gulls were recorded passing within 783 m of turbines (range 50-2,252 m) and terns were recorded passing within 840 m of turbines (range 0-2,355 m). In practice, without knowing the shapes of these distributions, it is hard to use this information to estimate the magnitude or direction of horizontal meso-responses to the turbines. In practice, the mean distance to turbines is likely to be strongly influenced by the body size of the species concerned, or by their tendency towards flocking behaviour, both of which are likely to increase their detection at greater distances. However, of the 408 large gulls tracked, none passed within 50 m of the turbines, suggesting a strong, negative meso-response to the turbines occurring at a distance of at least 50 m.

Assessment of methodology

The way data are presented make it difficult to disentangle meso-responses to the turbines. In particular, biases may exist relating to the detectability of different species, which may make the estimates of mean distance to turbines unreliable. Of the information presented, the minimum distance to turbines for large gulls is of value in estimating a meso-response rate.

A3.4 Hungary

Janoska, F. 2012. Investigations of Bird Collisions in 2 Wind farms. *International Scientific Conference on Sustainable Development & Ecological Footprint*, Sopron, Hungary, March 26-27 2012

Methods

Between November 2010 and November 2011, two Hungarian windfarms were visited every two weeks. During visits, the altitude and flight direction of birds were noted.

Seasons / time of day

Data were collected throughout the year.

Species

Yellow-legged gull

Conditions data collected under

No Details given.

Location / habitat

Two terrestrial sites in Hungary.

Turbine / array specification

No details given.

Results

Of the yellow-legged gulls recorded, only 2.5% (23/917) were recorded flying within 75 m of turbines, reflecting a meso-response of 0.975, and only 0.6% (6/917) were recorded flying within 25 m of turbines, reflecting a meso-response of 0.994.

Assessment of methodology

Very little detail is given describing the methodology used. As a consequence, these data must be interpreted with extreme caution. In particular, it is unclear to what extent data reflect avoidance, and to what extent they more generally reflect the flight paths taken by birds passing through the area.

APPENDIX 4 EVIDENCE REVIEW VERTICAL MESO-RESPONSE

A4.1 Barrow Offshore Windfarm

Barrow Offshore Wind Limited. *Post Construction Ornithological Monitoring – Third Year Report and Overall Conclusions*.

Methods

Boat-based estimation of flight heights.

Following the construction of Barrow Offshore windfarm, boat-based surveys were carried out during the breeding season and autumn migration in 2006, 2008, 2009 and 2010. In total 12 surveys, each lasting a single day were carried out, of which 8 were during the breeding season (May to August) and 4 during autumn migration (September to November). Boat survey data were collected within the windfarm according to standard protocols (Camphuysen *et al.* 2004) and flying birds were assigned to height bands of <5 m, 5- 15 m, 15-100 m and >100 m. Birds at risk of collision were assumed to be all those flying >15 m. The proportion of birds observed flying at heights presenting a risk of collision were then summarised across all surveys. Pre-construction proportions at collision risk height within the windfarm were compared to post-construction proportions at collision risk height, although no detailed analyses were undertaken.

Seasons / time of day

Data were collected during the breeding season and autumn migration periods.

Species

Auk spp. (238 recorded in 2010), common guillemot (2,002 recorded in 2010), razorbill (691 recorded in 2010), great cormorant (5 recorded in 2010), red-throated diver (2 recorded in 2010), black-headed gull (6 recorded in 2010), common gull (5 recorded in 2010), great black-backed gull (23 recorded in 2010), herring gull (142 recorded in 2010), black-legged kittiwake (132 recorded in 2010), lesser black-backed gull (425 recorded in 2010), gull spp. (51 recorded in 2010), Arctic skua (2 recorded in 2010), northern gannet (53 recorded in 2010), Manx shearwater (12 recorded in 2010), Sandwich tern (30 recorded in 2010), common scoter (10 recorded in 2010),

Conditions data collected under

No details given.

Location / habitat

Marine 7 km Offshore

Turbine / array specification

An array of 30 turbines covering an area of 10 km^2 and arranged in four rows of seven or eight turbines each. The rows are separated by a distance of 750 m and within the rows, each turbine is separated by a distance of 500 m. Each turbine has a hub height of 75 m above sea-level and a rotor diameter of 90 m.

Results

Several species were not present in sufficient numbers to allow a reliable estimate of the changing proportion of birds flying at a height placing them at risk of collision. Of those that were, common guillemot, great black-backed gull, herring gull, lesser black-backed gull and Sandwich tern all showed a decline in the proportion of birds flying at risk height, with meso-responses of 1, 0.29, 0.65, 0.28 and 0.55 respectively. However, other species (or groups) showed an increase in the proportion of birds flying at risk height including black-legged kittiwake, unidentified gulls and northern gannet, with meso-responses of -0.41, -0.85 and -0.59 respectively, reflecting an apparent attraction to the rotor-swept area of the turbines.

Assessment of methodology

Boat-based data collection was robust, following standard methodologies (Camphuysen *et al.* 2004). However, in assessing the vertical response to turbines there is a key flaw in the available data. In order to compare flight height data to that collected pre-construction, the same flight height bands were used in both study periods, and it was assumed that all birds flying at a height of more than 15 m above sea-level were potentially at risk of collision. However, as the rotor-swept area covers an area from 30 m to 120 m above sea-level, this may lead to a significant over-estimate of the actual number of birds flying at collision risk height. As a result, the meso-response rates of birds within the windfarm may be underestimated. An additional, arguably less serious, flaw in the data collection is that estimates of the birds at collision risk height refer to flocks, rather than individuals. Flock size is likely to show significant variation, making it difficult to infer what the proportional changes mean in relation to actual numbers of birds.

A4.2 Blyth Offshore Windfarm

Rothery, P., Newton, I., Little B. (2009) Observations of seabirds at offshore wind turbines near Blyth in northeast England. *Bird Study* **56,** 1-14

Methods

Shore based observations were undertaken between 18 April 1998 and 30 August 2003 covering the pre-construction, construction and post-construction periods of Blyth Offshore Windfarm. Observations were carried out at pre-determined times, at least twice a month. All passing birds were recorded, and it was stated that all birds were visible at a range of 1 km, although the turbines are only likely to comprise a small part of the total observation area. All birds were assigned to one of four height categories – 0-9.1 m, 9.1-26.4 m, 26.4-92.4 m and >92.4 m. A total of 70.3 hours of monitoring were available for the pre-construction period and 351.6 hours for the post-construction period, although no analyses were undertaken to assess the significance of any changes in flight height.

Seasons / time of day

Data were collected throughout the year and during daylight hours.

Species

Northern gannet (432 birds post-construction), great cormorant (352 birds post-construction), common scoter (341 birds post-construction), common eider (1,034 birds post-construction), black-headed gull (978 birds post-construction), herring gull (1,408 birds post-construction), great black-backed gull (564 birds post-construction), black-legged kittiwake (1,350 birds post-construction), Sandwich tern (2,135 birds post-construction).

Conditions data collected under

Data collected under all conditions in which visibility was at least 1 km.

Location / habitat

A shallow spit, approximately 1 km from shore.

Turbine / array specification

Two turbines spaced 200 m apart with a hub height of 59.4 m above mean sea-level and a rotor diameter of 66 m.

Results

For each species, the change in the proportion of birds flying at altitudes greater than 9.1 m above mean sea-level pre and post-construction are available. For most species, a greater proportion of birds fly above 9.1 m post-construction than pre-construction. The increase in the proportion of gulls flying above 9.1 m varied from 114-238% during the summer and 267-2,900% in the winter. Similarly during the summer, the proportion of gannets flying above 9.1 m increased by 2,800%.

Assessment of methodology

Despite the authors’ assurances, it is unlikely that all birds were detected over the full range of the observation area. In particular, birds at lower altitudes may be obscured by waves, or be less visible against the sea surface. As a result, the proportion of birds at lower altitudes may have been under-estimated. In addition, the change in observation platform between pre- and post-construction periods is likely to have afforded an improved view of the observation area. These factors mean that pre- and post-construction comparisons of the estimates of birds at different altitudes may not be reliable. In addition, the presence of the turbines offering a fixed structure with which to assess birds' flight heights against, is likely to have improved the accuracy of estimates of flight heights made post-construction. Finally, by limiting the comparison to birds above 9.1 m, well below the rotor sweep of the turbines, the proportion of birds at risk is likely to be vastly over-estimated.

A4.3 Egmond aan Zee

Krijgsveld, K.L., Fijn, R.C., Japink, M., van Horssen, P.W., Heunks, C., Collier, M.P., Poot, M.J.M., Beuker, D., Dirksen, S. 2011. *Effect studies offshore wind farm Egmond aan Zee. Final report on fluxes, flight altitudes and behaviour of flying birds.* Bureau Waardenburg

Methods

Visual observations

Between spring 2007 and December 2009, 405 panorama scans were carried out from a met mast on the edge of the Egmond aan Zee Windfarm. Scans were undertaken once an hour during daylight covering a 360˚ angle around the windfarm with a pair of 10 x 42 binoculars fixed on a tripod. During each observation period, two scans were undertaken, the first to capture birds close to the sea surface and the second to capture birds at greater altitudes. The height of birds was estimated using trigonometry to combine the distance and angle between the bird and observer. Birds could be viewed to a distance of up to 3 km, although imperfect detection is likely to be an issue at these distances. The area covered by each panorama scan is approximately 50% within the windfarm and 50% outside, allowing for simple comparisons to be made of birds inside and outside of the windfarm, although differences were not assessed statistically.

Seasons / time of day

Data were collected during daylight, throughout the year. There was increased effort during the spring and autumn migration periods.

Species

Northern gannet, great cormorant, black-legged kittiwake, black-headed gull, common gull, lesser black-backed gull, herring gull, great black-backed gull, Sandwich tern, small gull spp., large gull spp., gull spp.

Conditions data collected under

Data collected under all conditions.

Location / habitat

Marine 10 km offshore.

Turbine / array specification

Egmond aan Zee Offshore Windfarm covers an area of 27 km^2 and contains 36 turbines. Each turbine has a hub height of 70 m and rotor diameters of 90 m. Turbines are arranged in four rows, with 650 m between turbines in each row and 1 km between rows.

Results

Species varied in their vertical responses to wind turbines. Of the 13 species or groups considered, the proportion flying at rotor height was lower inside the windfarm than outside for kittiwake, black-headed gull, northern gannet, great black-backed gull, Sandwich tern and unidentified gull species (no numbers were presented). Large gulls appeared to show little, or no vertical response to the turbines, with roughly the same proportion flying at rotor height inside as outside. In contrast, the proportions of great cormorants, common gulls, little gulls and other small gulls flying at rotor height showed a noticeable increase inside the windfarm.

Assessment of methodology

Data are presented as the proportions of birds at rotor height both within and outside the windfarm. Without any details on the number of birds involved, it is difficult to determine the strength of these data, and the subsequent findings. Of particular concern is the way in which data for unidentified gulls have been presented and the apparent inconsistency in the results for each category which show roughly the same proportion of unidentified large gulls at rotor height inside as outside the windfarm, more small gulls at rotor height inside than outside the windfarm, but unidentified gulls assigned to neither category significantly less likely to be at rotor height within the windfarm. Without more details of the species likely to be covered by each category, and their abundance within the study area, it is difficult to assign levels of confidence to the results presented.

A4.4 Gunfleet Sands I and II

RPS. 2008. *Gunfleet Sands Monitoring Report*, RPS, London

NIRAS. 2011. *Gunfleet Sands 2 Offshore Wind farms. Year 1 Post-construction Ornithological monitoring*. NIRAS, Cambridge

GoBe Consultants Ltd. 2012. *Gunfleet Sands Offshore Wind farm I & II – Post Construction Year 2 – Marine Licence Environmental Monitoring Report.* Prepared for DONG Energy.

Methods

Boat surveys

Pre- and post-construction monitoring data were collected as part of boat surveys following standardised methodologies (Camphuysen *et al.* 2004). Flying birds were assigned to one of the following flight height bands <5 m, 5- 15 m, 15 -150 m. Pre-construction surveys were carried out between October 2007 and March 2008. Post-construction surveys were carried out between October 2010 and March 2011 and between October 2011 and March 2012. However, differences were not assessed statistically.

Seasons / time of day

Data were collected over winter, during periods of daylight.

Species

Red-throated diver, black-headed gull, common gull, great black-backed gull, gull spp., herring gull, black-legged kittiwake, lesser black-backed gull

Conditions data collected under

No details given.

Location / habitat

Gunfleet Sands I & II offshore windfarms, approximately 7 km from the coast.

Turbine / array specification

Gunfleet Sands I and II contain 48 turbines between them, each with a hub height of 75 m and a rotor diameter of 107 m. The projects cover a total area of 16 km^2.

Results

The proportion of red-throated divers flying at collision risk height declined following the construction of the windfarm, by 39% in winter 2010/11 and by 96% in winter 2011/12. In contrast, the proportion of great black-backed gulls at rotor height showed an increase following construction, by 75% in winter 2010/11 and 53% in winter 2011/12. The proportion of herring gulls at rotor height showed little change between pre-construction years and either post-construction survey. Results for other species were less consistent. For example common gulls showed an increase in the proportion at rotor height in 2010/11 compared to pre-construction data, but a decrease in 2011/12.

Assessment of methodology

Data were collected following a relatively robust methodology and the height bands used were a reasonable match for the dimensions of the rotor swept area of each turbine meaning the proportions of birds at risk height are less likely to be significantly over-estimated. However, the limited duration of pre- and post-construction surveys, reflected in the quantity of data available, means that there may only be limited power to detect significant changes in species flight heights.

A4.5 Nysted/Horns Rev

Blew, J., Hoffman, M., Nehls, G., Hennig, V. 2009. *Investigations of the bird collision risk and the responses of harbour porpoises in the offshore windfarms Horns Rev, North Sea, and Nysted, Baltic Sea, in Denmark*.

Methods

X-Band Radar

The spring and autumn migration periods were monitored at Horns Rev and Nysted in 2005 and 2006 using x-band radar mounted on vessels anchored in each windfarm. In total, across both windfarms 71.5 days of monitoring were carried out during the spring and 93.5 days during the autumn. Data were captured up to a height of 1,500 m and movements were examined in two height bands <200 m and 200-500 m. All birds tracked for > 100 m and showing a change in movement of >20 m were considered to have changed altitude.

Seasons / time of day

Data were collected throughout spring and autumn in 2005 and 2006.

Species

Having used radar, it was not possible to determine the species captured by the radar.

Conditions data collected under

It was not possible to collect data during periods of strong wind or heavy rain. However, all other conditions were covered.

Location / habitat

Horns Rev 17.9 km from the Danish North Sea Coast.
Nysted 10.8 km from the Danish Baltic Sea Coast.

Turbine / array specification

Horns Rev is an array of 80 turbines covering an area of 21 km^2. Each turbine has a hub height of 70 m and a rotor diameter of 80 m.

Nysted is an array of 72 turbines covering an area of 26 km^2. Each turbine has a hub height of 69 m and a rotor diameter of 82 m.

Results

Across both windfarms, and within the 0-200 m observation band, 4.8% of birds flying towards the windfarm were shown descending by more than 20 m and 13.4% were shown ascending by more than 20 m during the day time. At night time, the values were 2.9% and 13.6% respectively. However, these proportions did not differ significantly from the observations within the 200-500 m band, suggesting that the change in flight heights did not differ from what may be expected to occur by chance and are therefore unlikely to reflect avoidance behaviour.

Assessment of methodology

The rotor-swept area of each turbine covers altitudes from 20-110 m. Consequently, as data were relatively coarse and restricted to all flights within a band of 0-200 m, it may not have been possible to detect responses to turbines. In addition, having used radar, any responses to turbines that had been recorded could not have been identified to species level.

A4.6 Robin Rigg

Natural Power Consultants. 2013. *Analysis of Marine Environmental Monitoring Plan Data from the Robin Rigg Offshore Wind farm, Scotland (Operational Year 3).* Natural Power, Castle Douglas.

Methods

Boat-based surveys

Pre- and post-construction boat surveys were carried out within the windfarm following standard methodologies (Camphuysen *et al.* 2004). Birds in flight were assigned to bands of 0-5 m, 6-25 m, 26-34 m, 35-125 m, 126-200 m and >200 m. Surveys were carried out on a bi-monthly basis during pre-construction monitoring (2001-2007), and on a monthly basis during post-construction monitoring (2010-2011). Where sufficient data were available, differences in the proportions of birds flying at rotor height were assessed using a chi-squared test.

Seasons / time of day

Surveys were carried out throughout the year, during daylight.

Species

Common scoter, red-throated diver, diver spp., Manx shearwater, northern gannet, great cormorant, black-legged kittiwake, herring gull, great black-backed gull, gull spp, common guillemot, razorbill, auk spp.

Conditions data collected under

No details given.

Location / habitat

Robin Rigg Offshore Windfarm, 11 km from shore.

Turbine / array specification

Robin Rigg is an array of 60 turbines, each with a hub height of 80 m and a rotor diameter of 88 m. The turbines are spaced at intervals of approximately 500 m.

Results

There were no significant differences in the proportions of birds flying at rotor height during pre- and post-construction surveys for common scoter and red-throated diver. However, the proportion of northern gannet, great cormorant, black-legged kittiwake and large gull species flying at rotor height within the windfarm all increased between pre- and post-construction. However, the low power of the data was noted raising concerns over the validity of the results.

Assessment of methodology

Flight height data were not collected following the standard ESAS methodology and concerns are raised that this is likely to lead to a double counting of individuals, meaning estimates of changes in the proportion of birds at collision risk height may not be reliable.

APPENDIX 5 EVIDENCE REVIEW MICRO-AVOIDANCE

A5.1 Egmond aan Zee

Krijgsveld, K.L., Fijn, R.C., Japink, M., van Horssen, P.W., Heunks, C., Collier, M.P., Poot, M.J.M., Beuker, D., Dirksen, S. 2011. *Effect studies offshore wind farm Egmond aan Zee. Final report on fluxes, flight altitudes and behaviour of flying birds.* Bureau Waardenburg

Methods

Between July and December 2009, the flight paths of birds around six turbines were observed visually. These flight paths were then related to short range radar tracks in order to estimate the altitude and distance to nearest turbine. As a result, a dataset containing high resolution observations of bird behaviour around turbines was created. Birds were assigned to 5 m horizontal distance bands beginning at the rotor hub. All birds flying between 20 and 120 m above sea-level (reflecting the rotor-swept area of each turbine) were considered to be at risk of collision and the number of birds within each 5 m band was compared to the number of birds that would have been expected if they had been distributed evenly. To assess the level of last-second avoidance action taken, the number of birds within the 45-50 m band (just outside the rotor-sweep) was compared to the number of birds recorded between 0 and 45 m from the rotor hub.

Seasons / time of day

Data were collected during daylight on eight occasions between July and December.

Species

Seabirds, waterbirds and other migrants.

Conditions data collected under

All conditions.

Location / habitat

Marine, 10 km offshore.

Turbine / array specification

Egmond aan Zee Offshore Windfarm covers an area of 27 km^2 and contains 36 turbines. Each turbine has a hub height of 70 m and rotor diameters of 90 m. Turbines are arranged in four rows, with 650 m between turbines in each row and 1 km between rows. The study of micro-avoidance covered six turbines at the edge of the windfarm.

Results

Whilst 1,610 birds in 409 groups were recorded over the course of the study, only 115 in 52 groups were recorded passing within 50 m of the turbines. Of these, only 36 birds were recorded between 20 and 120 m, at heights placing them at risk of collision. Of the 36 birds passing within 50 m of the turbine and at rotor height, it is reported that 0.926 did not fly within the rotor swept window of the turbine (i.e. 2-3 birds). This would reflect a micro-avoidance rate of 0.926.

Assessment of methodology

The described methodology of combining visual and radar observations to record the tracks of birds approaching turbines is robust. This makes it possible to relate tracks to individual species and to determine how close each individual, or flock, gets to a turbine. Focussing on the area 50 m either side of the rotor hub and comparing the proportion in the 45-50 m band to the proportion in the 0-45 m band data is likely to capture the type of last-minute action covered by micro-avoidance.

However, only limited weight can be given to the data presented here. Observations were recorded on only four days, during which only 36 birds were recorded passing within 50 m of the turbine, the distance presented to represent micro-avoidance. This figure may be substantially inflated as it includes a single observation of a flock of 28 skylark.

A5.2 Greater Gabbard

RPS. 2011. *Galloper Wind farm Project Environmental Statement – Technical Appendices 2: Appendix 4: Greater Gabbard post-construction vantage point surveys*, RPS, Glasgow

Methods

Visual Observations

Two surveyors collected data from 180˚ arcs to the port and starboard sides of a stationary vessel within Greater Gabbard Offshore Windfarm. Each arc had a radius of 2 km and all birds entering each arc were recorded during snapshot counts taken every 15 seconds. The location of the boat and the viewing area, which covered a total of 15.9 km^2, included seven operational turbines and a total of 36 hours of data were collected during the survey. The flight paths of each bird within the viewing area were noted, as was the proportion of time each bird spent at different heights.

Seasons / time of day

Data were collected between 1st June 2011 and 28th July 2011, with each survey lasting four hours.

Species

Northern gannet (0.14 birds/hr), Arctic skua (0.03 birds/hr), lesser black-backed gull (3.69 birds/hr), herring gull (0.11 birds/hr), black-legged kittiwake (1.28 birds/hr).

Conditions data collected under

Conditions were limited to sea-states one and two, to ensure the vessel remained as a stable observation platform.

Location / habitat

Greater Gabbard, UK (offshore).

Turbine / array specification

The survey monitored seven operational turbines, each with a hub height of 77.5 m and a rotor diameter of 107 m.

Results

Over the course of the study period, 190 flights through the area were recorded. Of these, the vast majority did not pass close to the turbines. Given the proportion of the total study area occupied by turbines, this is unsurprising. As a consequence, only a single evasive manoeuvre, involving a kittiwake, was recorded.

Assessment of methodology

The length of the observation periods carried out during this study were extremely limited, so it is difficult to make an accurate assessment of how widespread different avoidance actions are. In addition, records of avoidance action have been made in a subjective fashion, both in relation to assessing the number of birds on a collision course for the turbines, and in assessing the actions recorded. For these reasons, it is not possible to quantify the micro-avoidance behaviour reported in this study.

A5.3 Kessingland Windfarm

Wild Frontier Ecology. 2013. *Kessingland Windfarm Annual Post-construction Monitoring Report Year 2.* Wild Frontier Ecology, Norfolk

Methods

Bird activity was monitored within the windfarm through nine two-hour vantage point surveys at each turbine carried out between November 2012 and March 2013. In total 36 hours of survey effort was completed throughout the study period. The response of birds whose flight paths were likely to overlap with turbines was noted.

Seasons / time of day

Late morning – early afternoon during winter.

Species

Black-headed gull (97 birds/hr), common gull (31.4 birds/hr), lesser black-backed gull (11 birds/hr), herring gull (56.72 birds/hr), great black-backed gull (0.28 birds/hr).

Conditions data collected under

No details given.

Location / habitat

Kessingland, Suffolk, UK (terrestrial).

Turbine / array specification

Two turbines with hub heights of 80 m and rotor diameters of 92 m. Distance between turbines within each row is not described.

Results

All birds recorded as being on a collision course with the turbines were observed to take evasive action to avoid collision. Typically this action occurred at a distance of 0-50 m from the turbine. Over the course of the study period, five black-headed gulls, two lesser black-backed gulls and a herring gull were recorded taking evasive action. In three instances this involved a change in altitude to fly below the rotor blades, whilst in other instances it involved a change to flight direction. In the case of the two lesser black-backed gulls, both were observed to take last minute evasive action at just five metres from the blades.

Assessment of methodology

The length of the observation periods carried out during this study were extremely limited, so it is difficult to make an accurate assessment of how widespread different avoidance actions are. In addition, records of avoidance action have been made in a subjective fashion, both in relation to assessing the number of birds on a collision course for the turbines, and in assessing the actions recorded and the distances at which they occur. For these reasons, it is not possible to quantify the micro-avoidance behaviour reported in this study.

A5.4 Nysted

Desholm, M. 2005. *TADS investigations of avian collision risk at Nysted offshore wind farm, autumn 2004*. NERI, Denmark

Petersen, I.K., Christensen, T.K., Kahlert, Desholm, M., Fox, A.D. 2006 *Final results of bird studies at the offshore wind farms at Nysted and Horns Rev, Denmark*, NERI, Denmark

Methods

Using a Thermal Animal Detection System (TADS) all bird movements past a single turbine during spring and autumn 2004 and spring and autumn 2005 were recorded. Birds were detected at distances of up to 120 m.

Seasons / time of day

Data were collected throughout both day and night in the spring and autumn.

Species

Mostly migrant passerines and waterbirds.

Conditions data collected under

All conditions.

Location / habitat

Located approximately 11 km offshore in the Danish part of the Baltic Sea.

Turbine / array specification

An array of 72 turbines arranged in eight rows of nine turbines each. Turbines have a hub height of 69 m and a rotor diameter of 92 m.

Results

In over 123 days of continuous monitoring, cameras captured 5,507 video sequences of which only 14 were found to include birds. Of these, none revealed birds passing close to the turbine.

Assessment of methodology

The methodology is robust with sufficient capability to record all birds passing the turbine over the study period. However, the low frequency with which birds were recorded passing close to the turbine suggests that the data are unlikely to have sufficient power to detect avoidance activity.

APPENDIX 6 EVIDENCE REVIEW WITHIN-WINDFARM AVOIDANCE

A6.1 Avonmouth Docks

The Landmark Practice. 2013. *Birds and Wind Turbines At Avonmouth Docks. Year 5 Monitoring Report for Ecotricity.* The Landmark Practice, Bristol

Methods

Monitoring was undertaken at the Avonmouth Docks windfarm between October and March in the winters of 2007/08, 2008/09, 2009/10, 2011/12. Three vantage point surveys, each lasting three hours, were carried out in each month to record bird activity at the site. Flight altitude was estimated in five bands 0-20 m, 20-40 m, 40-80 m, 80-160 m and >160 m.

During the visits for each vantage point survey, a search with a radius of 60 m around each turbine was carried out for corpses. Additional surveys were carried out following periods of severe weather. In total 343 checks were carried out around the base of each turbine in the post-construction period.

Seasons / time of day

Vantage point surveys were carried out between October and March, and timed so that periods of rising, falling and high tide were covered each month.

Species

Black-headed gull (4.4 birds/hr 2007/08, 7.1 birds/hr 2008/09, 2.9 birds/hr 2009/10, 12.8 birds/hr 2011/12), herring gull (6.8 birds/hr 2007/08, 13 birds/hr 2008/09, 18.8 birds/hr 2009/10, 38.2 birds/hr 2011/12)

Conditions data collected under

Not stated.

Location / habitat

Avonmouth Docks, coastal.

Turbine / array specification

A line of 3, 2 MW Enercon E82 turbines, with a hub height of 79m and a rotor diameter of 83 m.

Results

A single black-headed gull was identified as a probable collision victim in the winter of 2007/08. An average of 4.4 black-headed gulls were recorded passing through the site over the study period, suggesting a total flux rate of 10,530 birds, of which 57 were predicted to collide based on option 1 of the Band model, 2 were predicted to collide based on option 2 of the Band model and 1 was predicted to collide based on option 3 of the Band model. This reflects avoidance rates of 0.9826 using option 1 of the Band model, 0.5152 using option 2 of the Band model and -0.0005 using option 3 of the Band model.

Assessment of methodology

The corpse search methodology is likely to provide an accurate estimate of collision numbers as previous studies have shown that the majority of corpses are recovered within 40 m of a turbine base (Orloff & Flannery 1992, Munster *et al.* 1996, Howell 1997). Furthermore, corpses were examined to confirm collision as cause of death. No corrections were carried out to account for searcher efficiency or predator activity. However, given the habitat surrounding the turbines and the frequency of searches through the study period, it is unlikely corpses would have been missed. Bird activity surveys were carried out throughout the study period and are therefore likely to give a realistic impression of bird activity in the area.

As the bird activity surveys were carried out concurrently with the corpse searches and covered the same area, these data were combined with data from other sites to estimate representative avoidance rates.

A6.2 Altamont Pass

Thelander, C.G., Smallwood, K.S. & Rugge, L. 2003. *Bird risk behaviours and fatalities at the Altamont Pass Wind Resource Area*. National Renewable Energy Laboratory, Colorado.

Methods

Visual observations and fatality searches.

Circular areas with a 50 m radius around the base of 685 wind turbines were searched for corpses every five to six weeks between 1998 and 2000. These searches were combined with 1,958 30 minute point counts carried out in 20 study plots on 303 different days between 1998 and 2000.

Seasons / time of day

Counts carried out throughout the year and between 0700 h and dusk.

Species

Gulls (0.48 birds/hour).

Conditions data collected under

All conditions unless wind or rain resulted in visibility dropping to <60 m.

Location / habitat

Altamont Pass, California, U.S.A. (terrestrial).

Turbine / array specification

685 turbines arranged in 109 rows across an area of 50 km^2. Turbine hub heights ranged from 14 m-30 m, with rotor diameters of 17-23 m. Distance between turbines within each row is not described.

Results

At this site, a total of five gulls, of unknown species, were recovered following collision with turbines. Across the study plots as a whole, the average rate at which gulls passed through the windfarm was 0.48 birds per hour, reflecting a total of 7,428 gull movements within the area over the two year study period. Site specific flight height data were not available, so it was not possible to calculate an avoidance rate based on option 1 of the Band model. Assuming no avoidance behaviour, and a bird with the characteristics of a herring gull, the total number of collisions expected would have been 296 per annum under option 2 of the Band model and 295 under option 3 of the Band model. The collision rate of five birds over the study therefore indicates a within-windfarm avoidance rate of 0.9831 using option 2 and 0.9831 using option 3. The similarity between these values reflects the relatively small size of the turbines installed at the site, in particular the rotor-swept area, diameters of 17-23 m are significantly smaller than many of the turbines installed at offshore sites.

Assessment of methodology

The corpse search methodology is likely to provide an accurate estimate of collision numbers as previous studies have shown that the majority of corpses are recovered within 40 m of a turbine base (Orloff & Flannery 1992, Munster *et al.* 1996, Howell 1997). Furthermore, corpses were examined to confirm collision as cause of death. Correction factors were applied to account for carcass removal by scavengers, but not to correct for searcher efficiency. However, the limited size of the search area and terrain made it unlikely that any corpses would have been undetected.

To minimise the effects of observer bias in point counts, paired observations were carried out during the early part of the study period so that different observers calibrated their perceptions of altitude, distance and behaviour with one another. However, no correction was applied for the detection distance of different species. This is a concern given that study plots were up to 4 km^2, meaning that the total number of birds present within the study areas may have been an underestimate and that, therefore, the final, derived avoidance rate would also have been an underestimate.

However, as it has been necessary to extrapolate bird activity data across the site, this has not been combined with data from other sites to identify representative avoidance rates.

A6.3 Blyth Harbour

Visual observations and fatality searches.

Lawrence, E.S., Painter, S. & Little, B. 2007. Responses of birds to the wind farm at Blyth Harbour, Northumberland, UK. In de Lucas, M., Janss, G.F.E., Ferrer, M. 2007. *Birds and Wind farms Risk Assessment and Mitigation*, Quercus, Madrid.

Newton, I. & Little, B. 2009. Assessment of wind farm and other bird casualties from carcasses found on a Northumbrian beach over an 11-year period. *Bird Study*, **56,** 158-167.

Methods

Once a week over an 11 year period, a 4.7 km stretch of beach near Blyth in Northumberland was searched for corpses. Depending on the condition of the birds, an attempt was made to assign a cause of death to each carcass, and those with symptoms thought to be typical of collision with a wind turbine – head or one or both wings missing, broken bones blood in body cavity and a ruptured liver – were identified. The total number of carcasses found was then corrected to account for those lost to scavengers, those not washed up on the beach and those not found during searches.

Between October 1996 and August 1998, 31 three hour-long periods of observation were made of flight activity perpendicular to the turbine row and in the vicinity of five of the nine turbines. Observations were made from a point on the shore opposite the turbines, at a distance of approximately 80 m. In total 93 hours of observational data were collected.

Seasons / time of day

Fatality data were collected throughout the year. Bird activity data were also collected throughout the year, between the hours of 0800 and 1500 h, with observation periods split equally between the morning and afternoon.

Species

Around 80% of the flight activity within the windfarm involved herring gull and great black-backed gull, and other gull species made up a significant proportion of the remaining species. However, as species-specific data were not available regarding the corpses collected and it was stated that the majority of those collected belonged to gulls, to calculate an avoidance rate, it was necessary to consider gulls collectively.

Conditions data collected under

No details given.

Location / habitat

Blyth Harbour breakwater, Northumberland, UK (coastal).

Turbine / array specification

Nine turbines arranged in a row along a harbour breakwater. The turbines are spaced at 200 m intervals and have a hub height of 25 m with a 25 m rotor diameter.

Results

Results were presented as average collision rates and passage rates over the study period as a whole. Based on the data presented an average of 417,954 birds, most of which were large gulls, would have been expected to pass through the windfarm over the study period. Of these, approximately 3,047, assuming birds with the characteristics of a herring gull, would have been expected to collide with turbines in the absence of avoidance behaviour using option 1 of the Band Model and 3,083 using option 2 and 3,007 using option 3. Having corrected for the imperfect detection of corpses, between 148.5 and 193.5 collisions with wind turbines were expected in an average year. This suggests a within-windfarm avoidance rate of 0.3966-0.5369 using option 1, 0.4037-0.5423 using option 2 and 0.3886-0.5308 using option 3.

Assessment of methodology

The fatality searches were intensive throughout the study period and followed a robust methodology to account for corpses that went undetected. In particular, the potential for corpses to wash up within the study area was tested experimentally.

The observational data were limited to a two year period in the middle of the study. The data may have underestimated gull movements within the surrounding area for two key reasons. Firstly, no corrections were applied to account for imperfect detection of birds. Secondly, by limiting observations to the period between 0800 and 1500 h, key movements of gulls to and from roost sites may have been missed during the summer and autumn. Underestimating bird activity within the area would lead to an underestimate of the number of collisions expected in the absence of avoidance behaviour, and consequently, the final derived avoidance rates would also be underestimated.

Activity data were only collected between 206 and 2008 and only between turbines 5 and 9. As the mean annual collision rates relate to the whole of the study period, and to all 9 turbines, it is necessary to extrapolate activity data both temporally and spatially to derive a flux rate. Therefore, these data have not been included when deriving representative avoidance rates.

A4.4 Blyth Offshore Windfarm

Rothery, P., Newton, I. & Little, B. 2009. Observations of seabirds at offshore wind turbines near Blyth in northeast England. *Bird Study*, 56, 1-14

Methods

Visual observations

Following the installation of the offshore turbines, observations of birds in the vicinity of the turbines were made on 177 occasions between 12 January and 30 August

2003, totalling almost 352 hours of observation. Observations were made from the shore and distances and heights of flying birds were calibrated against objects of known size and fixed locations.

Seasons / time of day

Observations were made between January and August. Data collection was focussed on the period between 1130 and 1600, consequently, during the summer movements to and from breeding colonies may have been missed.

Species

Northern gannet (1.23 birds/hr), great cormorant (1 bird/hr), common scoter (0.96 birds/hr), common eider (2.77 birds/hr), black-headed gull (2.78 birds/hr), herring gull (4 birds/hr), great black-backed gull (1.6 birds/hr), black-legged kittiwake (3.83 birds/hr), Sandwich tern (6.07 birds/hr).

Conditions data collected under

No details given.

Location / habitat

Blyth, Northumberland, UK (offshore).

Turbine / array specification

Two turbines separated by 200 metres. Each turbine had a hub height of 59.4 m above mean sea-level and a rotor diameter of 66 m.

Results

Throughout the study period, no collisions were recorded involving any of the species observed in the vicinity of the windfarm, reflecting a within-windfarm avoidance rate of 1.0000 for each species considered (Northern gannet, great cormorant, common scoter, common eider black-headed gull herring gull, great black-backed gull, black-legged kittiwake and Sandwich tern).

Assessment of methodology

No corrections were applied to account for the imperfect detection of birds during the survey. Consequently, the true level of bird activity within the study area was likely to have been underestimated. Additionally, it was not possible to search for carcasses, meaning that inferences about avoidance behaviour can only be drawn from the failure of observers to detect a collision from a total of 352 hours of monitoring. Given the low probability of a collision occurring, and the levels of flight activity recorded, this outcome is unsurprising. It is also important to note that the size of the OWF was very small (two turbines) and therefore caution must be applied when considering how applicable these avoidance rates are for much bigger arrays.

As insufficient observational data have been collected to record a collision, these data have not been included in those used to derive representative avoidance rates.

A6.5 Boudwijnkanaal

Everaert, J. 2008. *Effecten van windturbines op de fauna in Vlaanderen: Onderzoeksresultaten, discussie en aanbevelingen*. INBO, Brussels

Everaert, J. & Kuikjen, E. 2007. *Wind turbines and birds in Flanders (Belgium): Preliminary summary of the mortality research results.* INBO, Brussels

Everaert, J., Devos, K. & Kuijken, E. 2002. *Windturbines en vogels in Vlaanderen: Voorlopige onderzoeksresultaten en buitenlandse bevinigen*. INBO, Brussels

Methods

Visual observations and fatality searches.

Systematic fatality searches were carried out once every 14 days between 2001 and 2006. Searches were carried out within a circular area, with a radius of 100 m, centred on each turbine. Corrections were applied to the data to account for imperfect detection and searcher efficiency.

Observational data describing the number of birds passing the turbine hub were collected between September and December 2005 between turbines 8 and 14. The resultant data were used to extrapolate the total number of birds likely to have passed the turbines over this period. Observational data are presented as a mean daily total collected during the period from two hours before dawn to four hours after dusk in October, reflecting a total of 17 hours of observations.

Seasons / time of day

Fatality data were collected throughout the year, behavioural data were collected between September and December.

Species

Gulls (1,075 birds/day).

Conditions data collected under

No details given.

Location / habitat

Boudwijnkanaal, Brugge, Belgium (terrestrial).

Turbine / array specification

A row of 14 turbines, each with a hub height of 55 m and a rotor diameter of 48 m. Distance between turbines within each row is not described.

Results

Collisions involving gulls were recorded in each year of the study, with a minimum of 21.2 collisions occurring in 2001 when only five of the 14 turbines were operational and a maximum of 264.6 collisions occurring in 2003, when all 13 turbines were operational. Behavioural data were only collected between September and December 2005 from between turbines 8 and 14. Extrapolating from these data to estimate the total number of collisions expected in each year in the absence of any avoidance action gives predictions of 550 collisions in 2001 using option 1 of the Band model, 252 using option 2 and 227 using option 3, and 3,262 collisions in each year between 2002 and 2006 using option 1, 1,497 using option 2 and 1,348 using option 3. Based on these analyses, within-windfarm avoidance rates would have been 0.9615 in 2001, 0.9299 in 2002, 0.9189 in 2003, 0.9284 in 2004, 0.9287 in 2005 and 0.9338 in 2006 using option 1. Using option 2, meso-micro avoidance rates would have been 0.9160, 0.8472, 0.8232, 0.8440, 0.8446 and 0.6990. Using option 3, meso-micro-avoidance rates would have been 0.9067, 0.8302, 0.8037, 0.8268, 0.8273 and 0.6656 respectively.

However, bird activity was only recorded around turbines 8 and 14 in October 2001 and October 2005. If we consider collisions recorded around these turbines in each of these time periods, the predicted number of collisions is 103 herring gulls in October 2001 and 145 black-headed gulls, 90 herring gulls and 260 birds in total during October 2005. The actual number of collisions recorded was 1, 6, 4 and 11 respectively, reflecting avoidance rates of 0.9903, 0.9586, 0.9556 and 0.9577 using option 1 of the Band model, 0.9789, 0.3658, 0.7865 and 0.8077 using option 2 of the Band model and 0.9765, 0.1886, 0.7629 and 0.7865 using option 3 of the Band model.

Assessment of methodology

Fatality data have been collected on a regular basis and following a robust methodology. Corrections have been applied to these data to account for the imperfect detection of corpses due to scavenger behaviour and searcher efficiency.

The observational data that have been collected are extremely limited. Data collection has been restricted to the September to December period in a single year. It is unclear how accurately this reflects bird movements within the windfarm over the rest of the study period. This may have a significant, but unquantifiable impact on the final, derived within-windfarm avoidance rates. In addition, it is unclear whether corrections have been applied to the observational data to account for the imperfect detection of birds.

Using the overall data, it is necessary to make both spatial and temporal extrapolations to estimate the avoidance rates. For this reason, we only use the data collected around turbines 8-14 in October 2001 and 2005 to derive representative avoidance rates.

A6.6 Bouin

Dulac, P. 2008. *Evaluation de l'impact du parc eolian de Bouin (Vendee) sur l'avifaune et les chauves-souris. Bilan de 5 anness de suivi*. Ligue pour la Protection des Oiseaux, Nantes.

Methods

Visual observations and fatality searches.

Weekly searches were carried out for corpses at the foot of turbines between 2002 and 2006. Searches were restricted to a 100 m^2 box centred on each turbine. To aid searching, each box was divided into a grid with squares of 25 m^2.

Observational data were collected from four points, covering 1 km each. Each month a two hour count was made from each point, with a total of 474 hours of observational data collected from the site as a whole between 2002 and 2006.

Seasons / time of day

Data were collected throughout the year and protocols were designed so that full day was covered.

Species

Black-headed gull (16.23 birds/hr), herring gull (2.26 birds/hr), other gulls (2.09 birds/hr).

Conditions data collected under

The observational protocol was designed to collect data throughout the tidal cycle and in all weather conditions.

Location / habitat

Bouin, Baie de Bourgneuf, France (Coastal)

Turbine / array specification

A single row of eight turbines, each with a hub height of 60 m and a diameter of 80 m. Distance between turbines within each row is not described.

Results

At this site, 30 gulls were recovered from turbine bases over the course of a four year study period. Of these, 28 were black-headed gulls, one was a yellow-legged gull and one was a Mediterranean gull. Using option 1 of the Band model, 584 black-headed gulls and 206 'other' gulls were predicted to collide with the turbines, reflecting avoidance rates of 0.9520 and 0.9903 respectively. For option 2, 483 and 354 birds were predicted to collide respectively, reflecting avoidance rates of 0.9421 and 0.9943. For option 3, the corresponding figures were 237 and 251 birds predicted to collide reflecting avoidance rates of 0.8820 and 0.9920. No collisions were recorded for herring gulls, despite a predicted collision rate of 216 per annum, reflecting a within-windfarm avoidance rate of 1 for options 1, 2 and 3 of the Band model.

Assessment of methodology

Fatality data were collected following a robust protocol, with corrections applied to account for birds lost to scavengers and search efficiency. The intensive nature of these searches, weekly over a four year period, is likely to mean that fatality rates were estimated with a high degree of accuracy.

Observational data were collected over a four year period. However, no corrections were applied to account for imperfect detection. Consequently, bird activity in the area and the derived within-windfarm avoidance rates were likely to have been underestimated.

As activity data were a spatial and temporal match for the period over which collision data were collected, these data were included when estimating representative avoidance rates.

A6.7 Buffalo Ridge

Johnson, G.D., Erickson, W.P., Strickland, M.D., Shepherd, M.F., Shepherd, D.A. 2000. *Avian Monitoring Studies at The Buffalo Ridge, Minnesota Wind Resource Area: Results of a 4-year study.* Western EcoSystems Technology Inc., Wyoming.

Methods

Visual observations and fatality searches.

Fatality searches were carried out within 126 m x 126 m plots, centred on 61 turbines. Searches were carried out every two weeks and observers covered the area by walking parallel transects separated by a distance of 6 m. This was combined with a series of large bird counts carried out every two weeks for a 0.8 km radius surrounding each of six observation stations. During each survey, two 30 minute observations were made, one in the morning and one in the afternoon. In total 70 hours of survey data were collected over the course of the study period.

Seasons / time of day

Fatality searches were carried out throughout the year. Large bird counts were carried out between 0800 and 1600 h and restricted to the period from 15 March to 15 November.

Species

Herring gull (0.1 birds/hour).

Conditions data collected under

No details given.

Location / habitat

Buffalo Ridge, Minnesota, U.S.A. (terrestrial).

Turbine / array specification

143 turbines arranged in 26 rows with between 100 m and 200 m between each turbine. Each 750 kW turbine had a hub height of 50 m and a diameter of 48 m.

Results

At this site, one herring gull was recovered following collision with turbine. Across the study plots as a whole, the average rate at which herring gulls passed through the windfarm was 0.03 birds per hour, reflecting a total of 625 gull movements within the area over the two year study period. Assuming no avoidance behaviour, the total number of collisions expected would have been 3 using option 1 of the Band model, 5 under option 2 of the Band model and 5 under option 3 of the Band model. The collision rate of 1 bird over the study therefore indicates a within-windfarm avoidance rate of 0.6503 using option 1, 0.8149 using option 2 and 0.7923 using option 3.

Assessment of methodology

The methodology was generally sound with a well-structured search likely to detect all corpses within the study area. Corrections were made for both corpses removed by scavengers and also searcher efficiency. The large bird survey also followed a sound methodology, with corrections applied to account for imperfect detection. However, as observations were limited to 0800 to 1600 h and November to March, it is possible that they failed to detect daily or seasonally important gull movements. This may reflect the fact that raptors were the primary concern at this site.

As it was necessary to extrapolate bird activity data spatially to estimate an avoidance rate, these data have not be included when deriving representative avoidance rates.

A6.8 De Put

Everaert, J. 2008. *Effecten van windturbines op de fauna in Vlaanderen: Onderzoeksresultaten, discussie en aanbevelingen*. INBO, Brussels

Everaert, J. & Kuikjen, E. 2007. *Wind turbines and birds in Flanders (Belgium): Preliminary summary of the mortality research results.*

Methods

Visual observations and fatality searches.

Systematic fatality searches were carried out once every 14 days between April 2005 and March 2006. Searches were carried within a circular area, with a radius of 100 m, centred on each turbine. No correction factors were used to account for scavengers or imperfect searcher efficiency.

Observational data describing the number of birds passing within 100 m of the turbine hub were collected between January and February 2006, the period in which the corpses were recovered. The resultant data were used to estimate the total number of birds likely to have passed the turbines over this period. In total 18 hours of survey data were collected.

Seasons / time of day

Observational data were collected throughout the day during January and February 2006.

Species

Black-headed gull and common gull (3,186 during the study period).

Conditions data collected under

No details given.

Location / habitat

De Put, Nieuwkapelle, Belgium (terrestrial).

Turbine / array specification

A row of two turbines, each with a hub height of 75 m and a rotor diameter of 100 m.

Results

In January and February 2006, the corpses of two gulls, one common gull and one black-headed gull, were recovered. Based on the number of birds estimated to have passed through the windfarm during the study period, the combined number of collisions predicted in these two species would be 19 using option 1 and none using options 2 and 3. The two recorded collisions therefore reflect a micro-meso avoidance rate of 0.8928 for common and black-headed gulls using option 1, -9.1051 using option 2 and -11.8383 using option 3.

Assessment of methodology

Whilst fatality searches appear to have been relatively robust and intensive throughout the study period, no corrections were applied to account for the imperfect detection of corpses, either through searcher inefficiency or through loss to scavengers. This may have led to an underestimate of the total number of collision victims.

Details of the methodology used to collect observational data of bird behaviour within the windfarm were sparse. In particular, no details were given of the length of observations used to collect data during the study. There also appears to have been no attempt to account for the imperfect detection of birds, meaning the total number passing through the study area may have been an underestimate. This, in turn would also mean that the final within-windfarm avoidance rate had been underestimated.

As bird activity and collision data have been collected concurrently, these data have been included when deriving representative avoidance rates.

A6.9 Gneizdzewo

Zielinski, P., Bela, G. & Marchlewski, A. 2008. *Report on monitoring of the wind farm impact on birds in the vicinity of Gniezdzewo (gmina Puck, pomorskie voivodeship)*

Zielinski, P., Bela, G. & Marchlewski, A. 2010. *Report on monitoring of the wind farm impact on birds in the vicinity of Gniezdzewo (gmina Puck, pomorskie voivodeship)*

Zielinski, P., Bela, G. & Marchlewski, A. 2011. *Report on monitoring of the wind farm near Gniezdzewo impact on birds (gmina Puck, pomorskie voivodeship)*

Zielinski, P., Bela, G. & Marchlewski, A. 2012. *Report on monitoring of the wind farm near Gniezdzewo impact on birds (gmina Puck, pomorskie voivodeship)*

Methods

Visual observations and fatality searches.

Collision surveys were carried out in the autumns of 2008, 2010, 2011 and 2012 (September-November). Corpse searches were carried out within 70 m radius of each turbine, on average every 2-3 days.

Over the same periods each year (mid-September – mid-November), activity surveys were carried out within the windfarm. Between 60 and 70 hours of observational data were collected each year, with observation sessions lasting up to 6 hours.

Seasons / time of day

Data were collected throughout the day during the autumn migration period in each year.

Species

Great cormorant (0.17-1.44 birds/hr), gulls (3.88-44.14 birds/hr), little gull (0.23 birds/hr), common gull (0.57 -1.73 birds/hr), black-headed gull (0.51-4.94 birds/hr), herring gull (1.06-5.39 birds/hr).

Conditions data collected under

All conditions

Location / habitat

Gniezdzewo, Poland (terrestrial).

Turbine / array specification

An array of 19 turbines arranged in four rows. Each turbine had a rotor diameter of 80 m and a hub height of 80 m.

Results

In the four autumns over which data have been collected, only a single collision involving a gull was recorded, a black-headed gull during the 2010 field season. No site specific flight height data were available, so it was necessary to use the distributions presented in Johnston *et al.* (2014a) and option 2 of the Band Model to estimate avoidance rates. In the 2010 field season, 460 black-headed gulls were predicted to have passed through the windfarm, with a predicted collision rate of 0.2 birds. The avoidance rate for black-headed gulls during autumn 2010 would, therefore, have been –3.9524, suggesting that a significant number of birds were attracted to the rotor swept area of the turbine. Using option 3 of the Band model, the collision rate was predicted to be 0.1 birds, reflecting a within-windfarm avoidance rate of -8.9238. However, it should be noted that this collision rate is based on a relatively low number of birds passing through the windfarm and as a result may be unreliable. The unusual nature of this result is confirmed as in three additional years of monitoring, no black-headed gull collisions were recorded, despite often higher levels of flight activity. The avoidance rate for cormorants and all other gull species in all years would have been 100%.

Assessment of methodology

The search for collision victims has been robust, with specially trained dogs used to increase detection. However, no corrections have been applied to account for birds lost to scavengers, potentially meaning the collision rates have been under-estimated.

No correction has been applied to the activity surveys to account for the imperfect detection of birds. As a consequence, the total number of birds passing through the area, and therefore potentially the final avoidance rates, may be under-estimated.

As collision and activity data were collected concurrently, from the windfarm as a whole, throughout the study period, they have been included when deriving representative avoidance rates.

A6.10 Greater Gabbard

RPS. 2011. *Galloper Wind farm Project Environmental Statement – Technical Appendices 2: Appendix 4: Greater Gabbard post-construction vantage point surveys*, RPS, Glasgow

Methods

Visual observations

Two surveyors collected data from 180˚ arcs to the port and starboard sides of a stationary vessel within Greater Gabbard Offshore Windfarm. Each arc had a radius of 2 km and all birds entering each arc were recorded during snapshot counts taken every 15 seconds. The location of the boat and the viewing area, which covered a total of 15.9 km^2, included seven operational turbines and a total of 36 hours of data were collected during the survey. The flight paths of each bird within the viewing area were noted, as was the proportion of time each bird spent at different heights.

Seasons / time of day

Data were collected between 1st June 2011 and 28th July 2011, with each survey lasting four hours.

Species

Northern gannet (0.14 birds/hr), Arctic skua (0.03 birds/hr), lesser black-backed gull (3.69 birds/hr), herring gull (0.11 birds/hr), black-legged kittiwake (1.28 birds/hr).

Conditions data collected under

Conditions were limited to sea-states one and two, to ensure the vessel remained as a stable observation platform.

Location / habitat

Greater Gabbard, UK (offshore).

Turbine / array specification

The survey monitored seven operational turbines, each with a hub height of 77.5 m and a rotor diameter of 107 m.

Results

The predicted number of collisions, in the absence of avoidance behaviour, within the 36 hour study period would have been less than 1 bird from each species. However, no collisions were recorded reflecting an avoidance rate of 1.000 for all species over the course of the study period.

Assessment of methodology

No corrections were applied to account for the imperfect detection of birds during the survey. Consequently, the true level of bird activity within the study area is likely to have been underestimated. Additionally, it was not possible to search for carcasses, meaning inferences about avoidance behaviour can only be drawn from the failure of observers to detect a collision with 36 hours of monitoring. Given the low probability of a collision occurring, and the levels of flight activity recorded, this outcome is unsurprising.

Given the limited data collection during the study period, these data have not been included when deriving representative avoidance rates.

A6.11 Groettocht

Krijgsveld, K.L., Akershoek, K., Schenk, F., Dijk, F. & Dirksen, S. 2009. Collision risk of birds with modern large wind turbines. *Ardea* **97:** 357-366.

Methods

Radar observations and fatality searches.

Fatality searches were carried out within a 100 m radius around each turbine every 2-3 days. Searches were carried out by walking parallel transects, each separated by 4-6 m. Searches were carried out between October and December 2004.

Flight movements were quantified using a 12 kW x-band marine surveillance radar overnight between 1800 and 0700 h on 20 October 2004, 22 November 2004 and 22 December 2004, and the number of radar echoes up to 140 m (the maximum turbine height) were estimated as a measure of flux through the windfarm area.

Seasons / time of day

Resultant data reflect overnight collision rates of birds between October and December 2004.

Species

Key movements recorded included gulls travelling between Lake Ijsselmeer and a nearby roost site around dusk and dawn. However, amongst the five corpses encountered, there were only two gull carcasses, a common gull and a herring gull.

Conditions data collected under

Not specified.

Location / habitat

Agricultural area in the Netherlands.

Turbine / array specification

The array consists of a single line of seven turbines, each separated by 285 m. Turbines have a hub height of 78 m and a rotor diameter of 66 m. However, only the areas under five turbines were searched for carcasses.

Results

The average flux of birds through the area was 370 birds/km/hr, reflecting a movement of 873,534 birds through the study period as a whole. Site specific flight height data were not available for the site, so it was necessary to use the distributions presented in Johnston *et al.* (2014a) to estimate the proportion of birds at collision risk height, and option 2 of the Band model to estimate predicted collision numbers. In total, the remains of five birds (one herring gull, one common gull, one redwing, two unidentified species) were retrieved. Given that it is not possible to relate the radar tracks to individual species, we calculated the probability of collision based on a bird with the characteristics of first a herring gull, giving a predicted collision rate of 2131 birds over the study period, and an overall avoidance rate of 0.9991 based on option 2 and a collision rate of 1648 birds over the course of the study, with an avoidance rate of 0.9988 using option 3.

Assessment of methodology

The total collision rate may be an underestimate as the initial searching rate of once every three days was lowered to once every two days following the outcome of depredation tests. However, all corpses present were likely to be discovered as only turbines where the surrounding vegetation was low were searched for remains. With the exception of concerns over the depredation rate, the fatality searches were robust.

Flux rates were estimated using x-band radar, with the considerable disadvantage that it cannot be used to estimate the flux rates of different species. As a consequence, using individual species collision rates to estimate an avoidance rate may have led to an inaccurate estimate of the true value. In addition, as a single radar echo may represent multiple birds, there was a considerable risk that the true movement of birds through the area was underestimated and that, therefore, the overall avoidance rate was also underestimated.

As it was necessary to extrapolate activity data both spatially and temporally to estimate the avoidance rates, these data have not been used to derive representative avoidance rates.

A6.12 Haverigg

RPS. 2011. *Galloper Wind farm Project Environmental Statement – Technical Appendices 2: Appendix 3: Information on gull flight behaviour at operational wind farms and the estimation of avoidance rates for use in the Band Collision Risk Model*, RPS, Glasgow.

Methods

Visual observations

In July and August 42 hours of vantage point surveys were carried out at Haverigg Windfarm following the standard SNH vantage point methodology (SNH 2010).

Seasons / time of day

Surveys were carried out in July and August.

Species

Gulls (19.90 birds/hr).

Conditions data collected under

Not stated.

Location / habitat

Haverigg Windfarm, Cumbria, UK (terrestrial).

Turbine / array specification

Haverigg Windfarm consists of two groups of four turbines. The first four turbines have a hub height of 45 m and a rotor diameter of 42 m, whilst the remaining four, larger, turbines have a rotor diameter of 52 m.

Results

During 42 hours of vantage point observations, a total of 836 gulls, mostly herring and lesser black-backed gulls were recorded entering the windfarm at a rate of 19.90 birds/hr. However, during the observation periods, no collisions were recorded, reflecting an avoidance rate of 1 over the course of the study period under options 1,2 and 3 of the Band model.

Assessment of methodology

The evidence provided by the survey is limited as no corpse searches were carried out in the area surrounding the windfarm. Whilst 42 hours of survey effort were carried out, no collisions were recorded. However, given the likely rarity of collisions occurring, this is unsurprising. Furthermore, the levels of flight activity within the windfarm are likely to have been underestimated as no correction was made for the imperfect detection of birds.

As insufficient monitoring data have been collected to observe collisions, these data have not been included when deriving representative avoidance rates.

A6.13 Hellrigg

Percival, S. 2012. *Hellrigg Wind farm: Goose Refuge Monitoring Report Winter 2011-12*, Ecology Consulting, Durham

Percival, S. 2013. *Hellrigg Wind farm: Goose Refuge Monitoring Report Winter 2012-13*, Ecology Consulting, Durham

Methods

An area covered by a 100 m radius around the base of each turbine was searched between December and March in the winters of 2011/12 and 2012/13 on a weekly basis. Searches were carried out slowly and carefully, with particular care taken over areas containing large clumps of vegetation. The locations of each corpse were carefully noted, and each was left in place to provide information about decay rates and detectability.

Bird activity data were collected through vantage point surveys from a single point following standard SNH guidance. The flight lines of each species were noted and flight altitudes estimated. In total 38 hours of flight observations were collected in this way each winter.

Seasons / time of day

Data were collected between December and March each year, with effort made to cover dawn and dusk movements of birds as well as general daytime movements of birds.

Species

Common gull (8.47 birds/hr in 2011/12 and 507.17 birds/hr in 2012/13), lesser black-backed gull (0.3 birds/hr in 2011/12 and 0.41 birds/hr in 2012/13), herring gull (3.71 birds/hr in 2011/12 and 72.49 birds/hr in 2012/13), great black-backed gull (0.05 birds/hr in 2011/12 and 0.49 birds/hr in 2012/13), black-headed gull (4.79 birds/hr in 2011/12 and 131.48 birds/hr in 2012/13)

Conditions data collected under

Not stated.

Location / habitat

Hellrigg windfarm, onshore.

Turbine / array specification

An array of four turbines with a hub height of 80 m and a rotor diameter of 82 m.

Results

A single collision involving a herring gull was recorded in 2011/12. Based on the passage rate of 3.71 birds/hr, 13 collisions would have been expected in the absence of avoidance behaviour based on option 1 of the Band model, 3 collisions based on option 2 of the Band model and 2 collisions based on option 3 of the Band model. This reflects avoidance rates of 0.9209, 0.6635 and 0.5133 respectively.

Assessment of methodology

Analysis of the length of time corpses remained at the site, suggested that the mean time to disappearance was 22 days, well in excess of the 7 day search intervals. In combination with the systematic and methodical searches carried out at the site, this suggests it is unlikely any corpses went undetected.

Bird activity data were collected following standard SNH vantage point methodology. However, as no correction was made for imperfect detection, the levels of flight activity at the site and, therefore, the overall avoidance rates, may have been underestimated.

As mortality and activity data were collected concurrently at the site, following robust methodologies, these data were used when deriving representative avoidance rates.

A6.14 Keewaunee County

Howe, R.W., Evans, W. & Wolf, A.T. 2002. *Effects of Wind Turbines on Birds and Bats in Northeastern Wisconsin*. Report to Wisconsin Public Service Corporation and Madison Gas and Electric Company.

Methods

Visual observations and fatality searches.

Intensive searches were carried out between July 1999 and July 2001. Searches were carried out at least once a week. Surveyors visited a 60 m x 60 m area centred on each of the turbines and covered a series of nine 60 m transects in each. These searches were complemented by a series of 3,214 3 minute short counts carried out on 160 dates between 1998 and 2001, to estimate the number of birds within the area.

Seasons / time of day

Surveys were carried out between June and November, with a bias towards data collection during the morning.

Species

Herring gull (0.012 birds/hour), Franklin’s gull (0.019 birds/hour), ring-billed gull (1.589 birds/hour).

Conditions data collected under

No details given.

Location / habitat

Keewaunee County, Wisconsin, U.S.A. (terrestrial).

Turbine / array specification

31 turbines with a hub height of 65 m and a rotor diameter of 47 m, within three clusters of 8, 9 and 14 turbines. Distance between turbines within each row is not described.

Results

At this site, one herring gull was recovered following collision with turbine. Across the study region as a whole, the average rate at which herring gulls passed through the area was 0.012 birds per hour, reflecting a total of 131 gull movements within the area over the two year study period. No site specific flight height data were available, meaning it was necessary to use the flight height distributions presented in Johnston *et al.* (2014a) and option 2 of the Band model. Assuming no avoidance behaviour, no collisions would have been expected under options 2 or 3 of the Band model. The collision rate of 1 bird over the study therefore indicates a within-windfarm avoidance rate of -12.0935 using option 2 and -13.5238 using option 3.

Assessment of methodology

The methodology was generally sound with a well-structured search likely to detect all corpses within the study area. Corrections were made for both corpses removed by scavengers and also searcher efficiency. However, no corrections were made to account for imperfect detectability during the bird surveys.

As it was necessary to extrapolate bird activity data spatially to estimate avoidance rates, these data have not been used to derive representative avoidance rates.

A6.15 Kessingland Windfarm

Wild Frontier Ecology. 2013. *Kessingland Wind farm Annual Post-construction Monitoring Report Year 2.* Wild Frontier Ecology, Norfolk.

Methods

Visual observations and fatality searches.

Fatality searches were undertaken around the bases of each turbine on nine occasions between November 2012 and March 2013. Surveyors walked a series of transects, separated by 10 m, within 65 m of the turbine base to search for corpses. A corpse correction factor of 1.79 was applied to account for corpses removed by scavengers.

Bird activity was monitored within the windfarm through nine two-hour vantage point surveys at each turbine carried out between November 2012 and March 2013. In total 36 hours of survey effort was completed throughout the study period.

Seasons / time of day

Data collection was carried out over winter 2012/13, between November and March. Surveys were carried out for two hour periods between 0800 and 1500 h.

Species

Black-headed gull (48.5 birds/hr), common gull (15.69 birds/hr), lesser black-backed gull (5.5 birds/hr), herring gull (28.36 birds/hr), great black-backed gull (0.14 birds/hr).

Conditions data collected under

No details given.

Location / habitat

Kessingland, Suffolk, UK (terrestrial).

Turbine / array specification

Two turbines with hub heights of 80 m and rotor diameters of 92 m. Distance between turbines within each row is not described.

Results

Black-headed, common, lesser black-backed, herring and great back-backed gulls were recorded within the study area at varying frequencies. Three gulls were found to have collided with the turbines – one black-headed gull, one common gull and one herring gull. After applying corpse correction factors, these estimates were revised to 1.79 birds of each species. No site specific flight height data were available, so it was necessary to use the modelled flight height distributions presented in Johnston *et al.* (2014a) and option 2 of the Band model. Given the number of birds likely to have passed through the windfarm during the study period, the predicted collision numbers would have been 28, 21 and 76 respectively. Using option 2, the avoidance rate for black-headed gull would therefore be 0.9367, for common gull it would be 0.9147 and for herring gull it would be 0.9764. Using option 3, the expected collision rates were 13, 12 and 51 respectively, reflecting avoidance rates of 0.8664, 0.8505 and 0.9647. No collisions were recorded involving lesser or great black-backed gulls, reflecting avoidance rates of 1.000 for these species.

Assessment of methodology

The fatality searches appear to have been robust, with corpse correction factors applied to account for loss of corpses to scavengers. However, during vantage point surveys, no corrections were applied to account for imperfect detection. As a result, bird activity within the area was likely to be underestimated, and therefore, the final, derived avoidance rates were also likely to be underestimated.

As collision and bird activity data were collected concurrently over the same area, these data were included when deriving representative avoidance rates.

A6.16 Kleine Pathoweg

Everaert, J. 2008. *Effecten van windturbines op de fauna in Vlaanderen: Onderzoeksresultaten, discussie en aanbevelingen*. INBO, Brussels

Everaert, J. & Kuikjen, E. 2007. *Wind turbines and birds in Flanders (Belgium): Preliminary summary of the mortality research results.*

Methods

Throughout 2005 and 2006, an area covered by a 100 m radius around the base of each turbine was searched for collision victims once every 2 weeks. Correction factors were applied to the resultant data to account for searcher efficiency and the removal of corpses by scavengers.

Between September and December 2005, bird activity data were collected between turbines 3 and 7. Data were collected from 2 hours before sunrise to 4 hours after sunset and presented as an average number of birds/day – reflecting an average of 16 hours of survey effort over this period.

Seasons / time of day

Bird activity data were collected between September and December, from 2 hours before sunrise to 4 hours after sunset.

Species

Black-headed gulls (345 birds/day), ‘large’ gulls (327 birds/day).

Conditions data collected under

Not stated.

Location / habitat

Kleine Pathoweg (Belgium), terrestrial.

Turbine / array specification

A line of 7 turbines, each separated by 280 m. Turbines had a hub height of 85 m and a rotor diameter of 70 m.

Results

In 2005, 240.9 gulls were believed to have collided with turbines once corrections had accounted for imperfect corpse detection. In 2006, this figure was 220.3. Based on a passage rate of 42 birds per hour, in 2005 these figures reflect an avoidance rate of 0.8795 using option 1 of the Band model, -0.2529 using option 2 of the Band model and -0.6887 using option 3 of the Band model. In 2006, these figures reflect an avoidance rate of 0.8898 using option 1 of the Band model, -0.1458 using option 2 of the Band model and -0.5443 using option 3 of the Band model.

Assessment of methodology

Fatality data have been collected on a regular basis and following a robust methodology. Corrections have been applied to these data to account for the imperfect detection of corpses due to scavenger behaviour and searcher efficiency.

The observational data that have been collected are extremely limited. Data collection has been restricted to the September to December period in a single year. It is unclear how accurately this reflects bird movements within the windfarm over the rest of the study period. This may have a significant, but unquantifiable impact on the final, derived within-windfarm avoidance rates. In addition, it is unclear whether corrections have been applied to the observational data to account for the imperfect detection of birds.

As it has been necessary to make spatial and temporal extrapolations to estimate avoidance rates, these data have not been used when deriving representative avoidance rates.

A6.17 Oosterbium

Methods

Visual observations and fatality searches.

Searches were carried out within a 50 m radius of the base of each turbine in autumn 1990 and spring 1991. Searches were carried out on 25 days in the spring and 40 days during autumn. All corpses were assessed in order to determine the cause of death and identify those killed by turbines. Corrections were applied to the data to account for searcher efficiency and scavenger activity.

Bird activity within the windfarm and a surrounding 500 m buffer was assessed during spring 1991 and autumn 1990. These activity levels were used to extrapolate the number of bird-days spent within the windfarm for each species or group of species.

Seasons / time of day

Data covered both the nocturnal and diurnal movements of birds in the spring and autumn.

Species

Gulls (158,600 bird days, autumn 1990; 43,800 bird days, spring 1991).

Conditions data collected under

No details given.

Location / habitat

Oosterbierum, Netherlands (terrestrial)

Turbine / array specification

A cluster of 18 turbines with hub heights of 35 m and a rotor diameter of 30 m, situated within 55 hectares of farmland. Distance between turbines within each row is not described.

Results

Gulls were recorded within the area more commonly during the autumn than the spring. However, the number of collisions was greatest during the spring, when 37 corpses were recovered in comparison to 12 in the autumn. No site specific flight height data were available so it was necessary to use the modelled distributions presented in Johnston *et al.* (2014a) and option 2 of the Band model. During the autumn, the predicted number of collisions in the absence of avoidance was 883 birds. Therefore, the 12 collisions recorded during the autumn reflects a meso-micro avoidance rate of 0.9864. Using option 3, the predicted number of collisions was 846, reflecting a meso-micro avoidance rate of 0.9858. During the spring, the predicted number of collisions in the absence of avoidance was 244 using option 2 and 234 using option 3. Therefore, the 37 collisions recorded during the spring reflects a meso-micro avoidance rates of 0.8483 and 0.8417 respectively.

Assessment of methodology

Fatality searches were carried out intensively throughout the spring and autumn seasons. They followed a robust methodology with corrections made for both searcher efficiency and scavenger activity.

Activity data were collected throughout the period covered by the fatality searches. However, it appears no corrections were made to the data to account for imperfect detection, meaning activity levels in the area may have been underestimated. As a consequence, the number of collisions predicted in the absence of avoidance, and therefore the derived avoidance rate would also have been underestimated.

As activity and mortality data were collected concurrently and no spatial extrapolation was necessary, these data were used when deriving representative avoidance rates.

A6.18 Waterkapptocht

Krijgsveld, K.L., Akershoek, K., Schenk, F., Dijk, F. & Dirksen, S. 2009. Collision risk of birds with modern large wind turbines. *Ardea* **97,** 357-366.

Methods

Radar observations and fatality searches.

Fatality searches were carried out within a 100 m radius around each turbine every 2-3 days. Searches were carried out by walking parallel transects, each separated by 4-6 m. Searches were carried out between October and December 2004.

Flight movements were quantified using a 12 kW x-band marine surveillance radar overnight between 1800 and 0700 h on 18 October 2004, 17 November 2004 and 20 December 2004, and the number of radar echoes up to 140 m (the maximum turbine height) were estimated as a measure of flux through the windfarm area.

Seasons / time of day

Resultant data reflect overnight collision rates of birds between October and December 2004.

Species

Key movements recorded included gulls travelling between Lake Ijsselmeer and a nearby roost site around dusk and dawn. However, amongst the seven corpses encountered, there was only a single gull carcass, that of a black-headed gull.

Conditions data collected under

Not specified.

Location / habitat

Agricultural area in the Netherlands.

Turbine / array specification

The array consists of a single line of eight turbines, each separated by 300 m, with a larger 1 km gap between turbines 4 and 5. Turbines have a hub height of 78 m and a rotor diameter of 66 m. However, only the areas under five turbines were searched for carcasses.

Results

The average flux of birds through the area was 251 birds/km/hr, reflecting a movement of 1,195,011 birds through the study period as a whole. In total, the remains of seven birds (one common pheasant, one oystercatcher, one black-headed gull, one skylark and two goldcrests) were retrieved. No site specific flight height data were available, so it was necessary to use the modelled distributions presented in Johnston *et al.* (2014a) and option 2 of the Band model. Given that it was not possible to relate the radar tracks to individual species, we calculated the probability of collision based on a bird with the characteristics of a black-headed gull, giving a predicted collision rate of 1,446 birds over the study period, and an overall avoidance rate of 0.9952. Using option 3, the predicted number of collisions was 1,118 birds, reflecting an overall avoidance rate of 0.9937.

Assessment of methodology

The total collision rate may have been an underestimate as the initial searching rate of once every three days was lowered to once every two days following the outcome of depredation tests. However, all corpses present were likely to be discovered as only turbines where the surrounding vegetation was low were searched for remains. With the exception of concerns over the depredation rate, the fatality searches were robust.

Flux rates were estimated using x-band radar, with the considerable disadvantage that it cannot be used to estimate the flux rates of different species. As a consequence, using individual species collision rates to estimate an avoidance rate may lead to an inaccurate estimate of the true value. In addition, as a single radar echo may represent multiple birds, there was a considerable risk that the true movement of birds through the area was underestimated and that therefore the overall avoidance rate has also been underestimated.

As it was necessary to make temporal and spatial extrapolations with these data, they were not used to derive representative avoidance rates.

A6.19 Yttre Stengrund/Utgrunden Offshore Windfarm

Petterson, J. 2005. *The impact of Offshore Wind farms on Bird Life in Southern Kalmar Sound, Sweden: A final report based on studies 1999-2003*. Lund University.

Methods

Visual observations

Field data were collected from three observation points located within the Southern Kalmar Sound – Eckelsudde in Oland in the east of the observation area, Olsang in the west of the observation area and Utgrunden Lighthouse in the centre of the Sound of Kalmar. The observation points made it possible to cover the whole of the Sound of Kalmar, including both windfarm sites. The sound was divided into four 5 km zones, each of which was further subdivided into 1-2 km wide zones. The observation point at Olsang covered the first of these 5 km zones, the Utgrunden Lighthouse covered the second and third 5 km zones and the Eckelsudde observation point, the fourth. Observers recorded to the exact minute the location of all flocks of migrating waterbirds they encountered, so that data could be combined into a single dataset at a later date.

Seasons / time of day

Data were collected throughout the spring (22 March to 8 April) and autumn (6 to 28 October) migration periods between 2001 and 2003.

Species

Conditions data collected under

All conditions.

Location / habitat

Southern Kalmar Sound, Sweden (offshore).

Turbine / array specification

Five 2 MW turbines with a hub height of 60 m and a rotor diameter of 72 m at Yttre Stengrund.

Seven 1.5 MW turbines with a hub height of 65 m and a rotor diameter of 70 m at Utgrunden. Distance between turbines within each row is not described.

Results

No collisions were recorded amongst any species during the spring migration periods, reflecting an avoidance rate of 1. No site specific flight height data were available at this site, so it was necessary to use the modelled distributions presented in Johnston *et al.* (2004). A single collision event was recorded involving four common eider during autumn 2003, reflecting an avoidance rate of 0.1861 using option 2 of the Band model and -0.1098 using option 3. No other collisions were recorded amongst other species, again indicating an avoidance rate of 1.

Assessment of methodology

Methodology is sound with careful calibration of estimates of distance between observers and co-ordination of counts to minimise double-counting. However, there was no correction applied to account for imperfect detection, meaning the total number of birds may have been under-estimated.

As insufficient data have been collected to detect a collision amongst any of the priority species, these data have not been used to derive representative avoidance rates.

A6.20 Zeebrugge

Everaert, J. 2008. *Effecten van windturbines op de fauna in Vlaanderen: Onderzoeksresultaten, discussie en aanbevelingen*. INBO, Brussels

Everaert, J. & Kuikjen, E. 2007. *Wind turbines and birds in Flanders (Belgium): Preliminary summary of the mortality research results.* INBO, Brussels

Everaert, J. & Stienen, E.W.M. 2007. Impact of wind turbines on birds in Zeebrugge (Belgium) Significant effect on breeding tern colony due to collisions. *Biodiversity and Conservation*, 16, 3345-3359

Everaert, J., Devos, K. & Kuijken, E. 2002. *Windturbines en vogels in Vlaanderen: Voorlopige onderzoeksresultaten en buitenlandse bevinigen*. INBO, Brussels

Methods

Visual observations and fatality searches.

Between 2001 and 2007 systematic fatality searches were carried out within a 50 m radius around the base of turbines on a fortnightly basis, increasing to 3-4 times a week during the breeding season. Every turbine was searched, and corrections were made to account for searcher efficiency and scavenger activity.

An initial set of bird activity surveys were carried out at the site in 2000 and 2001. Bird activity within a 400 m section of the breakwater was monitored on four days between June and July in 2000 and 2001, with eight days data collected in total. An additional four days of monitoring were carried out on four days and two nights between September and October 2001.

In June 2004 and 2005, a second set of bird activity were carried out. In each year, two full days of monitoring data were collected covering the period from dawn to dusk. During this period, data were collected between turbines 7 and 12, covering a 720 m section of the breakwater.

Seasons / time of day

Fatality searches were carried out throughout the year. Activity surveys were limited to the breeding season and autumn. Data were collected throughout the day between dawn and dusk, with additional nocturnal surveys carried out during the autumn.

Species

Gulls (234 birds/day), little tern (375-1,860 birds/day), common tern (4,228-10,263 birds/day), Sandwich tern (11-12,334 birds/day).

Conditions data collected under

No details given.

Location / habitat

Zeebrugge, Belgium (Coastal)

Turbine / array specification

25 turbines arranged along Zeebrugge Harbour breakwater. Turbines vary in size from hub heights of 23-55 m and rotor diameters of 22-48 m. Details of collisions at individual turbines are not given, so avoidance rates are estimated assuming turbines with a hub height of 34 m and rotor diameter of 34 m, the most common turbine within the windfarm. Distance between turbines within each row is not described.

Results

Collisions were recorded in every year. For Sandwich terns, collisions varied from seven to 54 birds per year. Using option 1 of the Band model, the estimated number of collisions per year, in the absence of avoidance behaviour, varied from 6,383 birds to 10,299, 8,024 to 10,326 using option 2 and 5,984 to 8,035 using option 3. The meso-micro avoidance rates derived from the values are 1 between 2001 and 2003, 0.9915 in 2004, 0.9972 in 2005, 0.9992 in 2006 and 0.9993 in 2007 using option 1, and 1 between 2001 and 2003, 0.9948 in 2004, 0.9963 in 2005, 0.9989 in 2006 and 0.9991 in 2007 using option 2. Using option 3, the avoidance rates are 1 between 2001 and 2003, 0.9933 in 2004, 0.9952 in 2005, 0.9986 in 2006 and 0.9989 in 2007. Collision data were also obtained relating to June 2004 and June 2005, the periods in which bird activity data were collected and relating to only the turbines around which activity was monitored. In both years, 3 Sandwich terns were observed to have collided between turbines 7-12 in June. Given passage rates of 896 birds/hr in June 2004 and 725 birds/hr in June 2005, this reflects an avoidance rate in 2004 of 0.9895 using option 1 of the Band model, 0.9935 using option 2 of the Band model and 0.9917 using option 3 of the Band model. In 2005, the corresponding values are 0.9940, 0.9920 and 0.9897.

For little terns, collisions varied from two to 12 birds per year. Using option 1 of the Band model, the estimated number of collisions per year, in the absence of avoidance behaviour, varied from 990 birds to 1,087, 165 to 838 using option 2 and 128 to 650 using option 3. The meso-micro avoidance rates derived from the values are 0.9923 in 2001, 0.9914 in 2002, 0.9904 in 2003, 0.9950 in 2004, 0.9982 in 2005, 0.9963 in 2006 and 0.9890 in 2007 using option 1, and 0.9516 in 2001, 0.9455 in 2002, 0.9395 in 2003, 0.9940 in 2004, 0.9884 in 2005, 0.9768 in 2006 and 0.9304 in 2007 using option 2. Using option 3, the avoidance rates were 0.9516 in 2001, 0.9455 in 2002, 0.9395 in 2003, 0.9940 in 2004, 0.9884 in 2005, 0.9768 in 2006 and 0.9304 in 2007. No little tern collisions were recorded in the June 2004 and 2005 data relating to turbines 7-12.

For common terns, collisions varied from 12 to 164 birds per year. Using option 1 of the Band model, the estimated number of collisions per year, in the absence of avoidance behaviour, varied from 4,503 birds to 6,869, 2,475 to 6,530 using option 2 and 1,931 to 5,094 using option 3. The meso-micro avoidance rates derived from the values are 0.9970 in 2001, 0.9977 in 2002, 0.9951 in 2003, 0.9758 in 2004, 0.9812 in 2005, 0.9761 in 2006 and 0.9834 in 2007 using option 1, and 0.9919 in 2001, 0.9939 in 2002, 0.9871 in 2003, 0.9833 in 2004, 0.9501 in 2005, 0.9365 in 2006 and 0.9559 in 2007 using option 2. Using option 3, meso-micro avoidance rates were 0.9896 in 2001, 0.9922 in 2002, 0.9834 in 2003, 0.9786 in 2004, 0.9360 in 2005, 0.9186 in 2006 and 0.9434 in 2007. Collision data were also obtained relating to June 2004 and June 2005, the periods in which bird activity data were collected and relating to only the turbines around which activity was monitored. In 2004 6 common terns were observed to have collided between turbines 7-12 in June, in 2005, this figure was 9. Given passage rates of 603 birds/hr in June 2004 and 248 birds/hr in June 2005, this reflects an avoidance rate in 2004 of 0. 9703 using option 1 of the Band model, 0.9796 using option 2 of the Band model and 0.9738 using option 3 of the Band model. In 2005, the corresponding values are 0.9720, 0.9255 and 0.9045.

For gulls, collisions varied from 110 to 354 birds per year. Using option 1 of the Band model, the estimated number of collisions per year, in the absence of avoidance behaviour, varied from 2,334 birds to 2,537, 2,856 to 3,104 using option 2 and 2,698 to 2,932 using option 3. The meso-micro avoidance rates derived from the values are 0.8979 in 2001, 0.8481 in 2002, 0.8817 in 2003, 0.9105 in 2004, 0.9173 in 2005, 0.9547 in 2006 and 0.9092 in 2007 using option 1, and 0.9166 in 2001, 0.8758 in 2002, 0.9033 in 2003, 0.9268 in 2004, 0.9324 in 2005, 0.9630 in 2006 and 0.9258 in 2007 using option 2. Using option 3 meso-micro avoidance rates were 0.9117 in 2001, 0.8686 in 2002, 0.8976 in 2003, 0.9226 in 2004, 0.9285 in 2005, 0.9608 in 2006 and 0.9214 in 2007.

Data were also obtained relating to black-headed, lesser black-backed and herring gull collisions in June-July 2000, June-July 2001 and September-October 2001, periods corresponding to the times during which gull activity data were collected and restricted to the turbines around which gull data were collected. No collisions were reported involving black-headed gulls. In June-July 2000, a single collision was reported involving a herring gull, reflecting an avoidance rate of 0.9861 using option 1, 0.9829 using option 2 and 0.9819 using option 3. In June-July 2001 and September-October 2001, two collisions were reported involving herring gulls, reflecting avoidance rates of 0.9722 and 0.9976 respectively using option 1, 0.9659 and 0.9959 using option 2 and 0.9639 and 0.9957 using option 3. Single collisions were reported involving lesser black-backed gulls in each of June-July 2001 and September to October 2001, reflecting avoidance rates of 0.9706 and 0.9990 respectively using option 1, 0.9680 and 0.9977 using option 2 and 0.9656 and 0.9975 using option 3.

Assessment of methodology

The study at Zeebrugge offers one of the most comprehensive datasets for collisions involving marine birds. Fatality data have been collected over a seven year period following a robust methodology with corrections made to account for searcher efficiency and scavenger activity. However, a key limiting factor in the dataset is the accompanying bird activity data. In the case of terns, activity data is limited to the period of peak tern activity in June. As a consequence, extrapolating from this to cover the full period when terns are present is likely to vastly over-estimate activity in the area, and therefore the predicted collision numbers. This means that the avoidance rates derived for each year are likely to be significantly over-estimated. This reflects the limitations in the way data are presented within the reports. Ideally, collisions would be broken down on a month by month and turbine by turbine basis, so that avoidance rates could be calculated for the areas in which activity data were collected, rather than extrapolating across the windfarm as a whole.

We used only the collision data collected from gulls during the period in which activity data were collected, and from only those turbines around which activity data were collected, in deriving representative avoidance rates.

ANNEX 1

USING A COLLISION RISK MODEL TO ASSESS BIRD COLLISION RISKS FOR OFFSHORE WINDFARMS
(SOSS Guidance: March 2012)

SUPPLEMENT – AVOIDANCE RATES USING THE BASIC AND EXTENDED MODELS
March 2014 – Bill Band

This is a supplement to guidance prepared for the Crown Estate as part of the Strategic Ornithological Support Services programme, project SOSS-02[45]. That provides guidance for offshore wind developers, and their ecological consultants, on using a collision risk model to assess the bird collision risks presented by offshore windfarms. The March 2012 version of the guidance enabled use to be made of flight height distribution data.

This supplement is an addition to Stage E – Avoidance and Attraction. That section describes how, having used the collision model to calculate the potential collision rate if birds take no avoiding action, one should then apply an avoidance rate A to allow for the fact that many species of birds do in fact take avoiding action, either at long range (macro) or at close range (micro).

Paragraph 80 notes that

‘if the extended model taking account of flight height distribution is used, it is important that the calculations on which avoidance rates are based also start with a no-avoidance collision rate derived using the extended model’.

Most of the published literature on avoidance rates is currently based on using the basic model. **This supplement shows how such avoidance rates may be modified to enable their application to the extended model.**

Avoidance in the basic and extended models

The two models – basic and extended – yield different predictions of the rate of collisions before avoidance is taken into account. The extended model is a more refined model which takes into account the effect of flight height distribution. It takes into account the fact that, for a given number of flights at risk height, a flight height distribution skewed towards low altitude leads to a smaller proportion of birds passing through the rotor, and bird passages through parts of the rotor with less risk, than if the distribution were uniform.

The outputs of the two models may be formally compared if the data input to the basic model on the proportion of flights at risk height (Q'_{2R}) is derived from the same

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[45] Project SOSS -02: see http://www.bto.org/science/wetland-and-marine/soss/projects

flight height distribution used in the extended model, as in Option 2 of the spreadsheet accompanying the SOSS guidance. That is, the comparison should be made between the collision rate using the basic model (Option 2) in the spreadsheet, and the extended model (Option 3).

The collision rates (before avoidance) projected by the two models are:

Basic model (Option 2):

$C_{basic} = v(D_A/2R)(T\pi R^2)t \times Q_{2R}' \times p_{average} \times Q_{op}$ (guidance eq.5[46])

i.e. flux factor $\times\ Q_{2R}' \times p_{average} \times Q_{op}$

Extended model (Option 3):

$C_{extended} = v(D_A/2R)(T\pi R^2)t \times (2/\pi) \iint d(y)\, p(x,y)\, dxdy \times Q_{op}$ (guidance eq. 9)

i.e. flux factor x collision integral x Q_{op}

Where the bird flight height distribution is skewed towards low altitude, the extended model prediction $C_{extended}$ is usually less than C_{basic}, because this equation takes full account of the reduction in risk at lower parts of the rotor. Let g be the ratio $C_{extended} / C_{basic}$, g is thus usually less than 1. The value of g may be obtained by dividing the second of the above equations by the first:

$$\mathbf{g = C_{extended} / C_{basic} = collision\ integral\ /\ (Q'_{2R} \times p_{average})} \quad \text{…. eq. S1}$$

and this is readily calculated from the 'Overall collision risk' spreadsheet

g = cell D35 / (cell D33 x cell D27)

The expected collision rate must then take into account the proportion A of birds avoiding the turbines (e.g. by displacement, or by evasive action), by multiplying the above no-avoidance collision rates by the proportion (1-A) which do not avoid. Values of A are typically in the range 90-100%. It is more helpful to think in terms of the non-avoidance rate A' = 1 – A , such that A' is the small proportion of birds which do not avoid the turbines. The expected collision rate is then

$A'_{basic}\, C_{basic}$ in the basic model, or .. eq. S2a

$A'_{extended}\, C_{extended}$ in the extended model. .. eq. S2b

The two models require the use of different non-avoidance rates. The calculation of $C_{extended}$ takes account of the effect of a skewed flight distribution, such that the

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[46] Strictly, equation (5) of the guidance refers to Q_{2R} derived from site survey, as used in the basic model (Option 1), rather than Q'_{2R}, derived from the assumed flight height distribution, as required here.

factor $A_{extended}$ (= 1 – $A'_{extended}$) refers only to genuine behavioural avoidance. The calculation of C_{basic} in the basic model does not, such that any such effect, in the basic model, must be covered by the avoidance factor A_{basic}.

Establishing avoidance rates from reference windfarms

Values of A'_{basic} and $A'_{extended}$ for use in the two models are obtained by monitoring collisions at one or more reference windfarms, and working back from the two models. For either model we have

Non-avoidance rate A' = Actual no of collisions / Predicted number of collisions C.

		using basic model	*using extended model*
Actual no of collisions	=	$A'_{basic} \times C_{basic}(ref)$	$= A'_{extended} \times C_{extended}(ref)$

thus $A'_{extended} = A'_{basic} \times C_{basic}(ref) \; / \; C_{extended}(ref)$

but $g(ref) = C_{extended}(ref) / C_{basic}(ref)$

so $\mathbf{A'_{extended} = A'_{basic} / g\,(ref)}$ … eq. S3

$A'_{extended}$ is the non-avoidance rate from the reference windfarm, for use with the extended model. Equation (S3) describes how it is related to the value of A'_{basic} derived using the basic model, using the g factor for this reference windfarm.

Where data from several reference windfarms are used to yield an average A'_{basic} , then the value for $A'_{extended}$ should be the average of A'_{basic} / g(ref) as calculated for each of the reference windfarms.

Applying reference avoidance rates to new or projected windfarms

Avoidance rates, derived from collision studies at one or more reference windfarms, may be used to inform the calculation of collision rate at a new or projected windfarm. The assumption in applying such avoidance rates is that the birds' behavioural response to the new windfarm will be similar to their response to the reference windfarm, and hence the proportion of birds avoiding the turbines of the new windfarm, further to the calculation of a no-avoidance collision rate, is likely to be the same as for the turbines of the reference windfarm.

Thus, having established values A'_{basic} and $A'_{extended}$ for non-avoidance, as derived from the reference windfarm, these same values may be assumed to apply to new or projected windfarms for the same bird species. If C_{basic}(new) and $C_{extended}$ (new) are the no-avoidance collision rates calculated for the new windfarm, the predicted collisions after avoidance for the new windfarm are:

basic model: $\mathbf{A'_{basic}\; C_{basic}\,(new)}$ .. eq. S4a

extended model: $A'_{extended}$ $C_{extended}$ (new) .. eq. S4b

A'_{basic} is the avoidance rate established from the reference windfarm(s) using the basic model, and $A'_{extended}$ that using the extended model; they are related as in equation (S3).

Dealing with lack of information on g(ref)

Published information on avoidance rates for reference windfarms has not so far included information on avoidance using the extended model, or on g(ref), the ratio between the outputs (before avoidance) of the extended and basic models. Calculation of g(ref) requires information on bird size and speed, turbine parameters, and the flight height distribution at the reference site; however it does not need information on bird density, levels of flight activity, or number of transits. If this limited subset of data is available, then it should be possible to calculate g(ref) for the reference windfarm, for the bird species under assessment.

Example:

Monitoring studies have established that for a certain bird species, an overall avoidance rate of 98% may be assumed. This has been derived using theoretical collision rates derived using the basic model, and comparing these with the actual collision mortality observed on an existing windfarm – the 'reference' windfarm.

$\mathbf{A_{basic} = 98\%}$ so the non-avoidance rate $A'_{basic} = 2\%$.

Using the extended model, the calculated g factor for this reference windfarm is 0.46. Thus the non-avoidance rate appropriate for use with the extended model is

$A'_{extended} = 2\%/0.46 = \mathbf{4.38\%}$

The corresponding avoidance rate for use with the extended model is

$\mathbf{1 - A' = 95.62\%}$

A developer now undertakes collision risk assessment for a proposed offshore windfarm. The CRM extended model which takes account of flight height distributions may be used, provided that it makes use of the avoidance rate appropriate for the extended model.

For the proposed windfarm, the projected collision rates are 23 (basic model) and 8 (extended model) per year. Applying the above non-avoidance rates of 2% and 4.38% respectively yields

expected collisions(basic) = 2% x 23 = 0.46 birds/annum

expected collisions (extended) = 4.38% x 8 =0.35 birds/annum

The two models yield different results because the second model takes flight height distribution into account, a factor ignored in the basic model.

It is recommended that any future publication of reference avoidance rates, derived from collision monitoring studies, should state both that for use in the basic model and that for use in the extended model. This will require application of both models to the reference windfarm.

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St Andrew's House
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EH1 3DG

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Appendix 11 to Deadline 7 submission – Furness et al., 2013

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Assessing vulnerability of marine bird populations to offshore wind farms

Robert W. Furness [a,b,*], Helen M. Wade [c], Elizabeth A. Masden [c]

[a] MacArthur Green Ltd, 95 South Woodside Road, Glasgow G20 6NT, UK
[b] College of Medical, Veterinary and Life Sciences, University of Glasgow, Glasgow G12 8QQ, UK
[c] Environmental Research Institute, Centre for Energy and the Environment, North Highland College, University of the Highlands and Islands, Ormlie Road, Thurso, Caithness KW14 7EE, UK

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ABSTRACT

Offshore wind farms may affect bird populations through collision mortality and displacement. Given the pressures to develop offshore wind farms, there is an urgent need to assess population-level impacts on protected marine birds. Here we refine an approach to assess aspects of their ecology that influence population vulnerability to wind farm impacts, also taking into account the conservation importance of each species. Flight height appears to be a key factor influencing collision mortality risk but improved data on flight heights of marine birds are needed. Collision index calculations identify populations of gulls, white-tailed eagles, northern gannets and skuas as of particularly high concern in Scottish waters. Displacement index calculations identify populations of divers and common scoters as most vulnerable to population-level impacts of displacement, but these are likely to be less evident than impacts of collision mortality. The collision and displacement indices developed here for Scottish marine bird populations could be applied to populations elsewhere, and this approach will help in identifying likely impacts of future offshore wind farms on marine birds and prioritising monitoring programmes, at least until data on macro-avoidance rates become available.

1. Introduction

To meet targets for a reduction in greenhouse gas emissions, many Governments, especially within the European Union but also in North America, are encouraging the development of renewable energy generation such as offshore wind farms. There is the potential however for such developments to have adverse effects on the environment and particularly on marine birds through collision mortality, disturbance, or foraging habitat loss. Collision is more likely to occur if seabirds fail to avoid wind farms, whereas displacement from foraging habitat is more likely to occur if seabirds do avoid wind farms. Thus displacement may be a consequence of avoidance behaviour. Disturbance, caused by structures or by human activity associated with wind farms, may also cause displacement if birds move away from wind farms due to associated disturbance. Here we define displacement as a reduced number of birds occurring within or immediately adjacent to offshore wind farms, and we define disturbance as birds spending extra time and/or energy to avoid structures or human activity associated with offshore wind farms. Birds may show two kinds of avoidance behaviour at offshore wind farms, often termed ‘macro-avoidance’ and ‘micro-avoidance’. Macro-avoidance occurs when birds alter their flight path to keep clear of the whole wind farm (Desholm and Kahlert, 2005), whereas micro-avoidance occurs when birds enter the wind farm but take evasive action to avoid individual turbines (Band, 2011; Cook et al., 2012). If species-specific rates of macro-avoidance and micro-avoidance were known, it would be easy to assess vulnerability of different species’ populations. However, data on macro-avoidance rates are very limited and inconsistent, while data on micro-avoidance by marine birds at offshore wind farms are extremely scarce (Cook et al., 2012). For example, it has been stated that northern gannets *Morus bassanus* show higher macro-avoidance (64% Krijgsveld et al., 2011) than shown by gulls. However, while Krijgsveld et al. (2011) report an 18% macro-avoidance rate by gulls, Petersen et al. (2006) report a 76% macro-avoidance rate by gulls, higher than that reported for gannets. Until avoidance rates are better quantified we have assumed that avoidance rates are not significantly different among taxa, since existing data fail to contradict that simplification.

The increase in electricity generation from offshore wind creates an urgent need to assess effects on marine birds, and potential impacts on their populations. The most detailed studies of the effects of wind farms on marine birds have been at the Nysted and Horns Rev offshore wind farms in Danish waters, where

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* Corresponding author. MacArthur Green Ltd, 95 South Woodside Road, Glasgow G20 6NT, UK. Tel.: +44 141 342 5404; fax: +44 141 330 5971.
E-mail address: bob.furness@macarthurgreen.com (R.W. Furness).

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research has demonstrated a low risk of collision, though for a limited set of species, notably common eiders *Somateria mollissima* (Desholm and Kahlert, 2005). Fox et al. (2006a,b) however emphasised the high variability in behavioural responses and thus vulnerability amongst marine bird species to offshore wind farms. Due to this variability in behavioural responses, it is vital to identify species' populations most likely to be at risk. In Europe, many marine birds breed within Special Protection Areas (SPAs) and so are protected by European law, in particular the Birds Directive (2009/147/EC). This legal protection has the potential to constrain development of offshore wind farms so there is a strong incentive to improve understanding of the risks and to develop better directed monitoring. Offshore wind in the United States similarly needs to consider possible impacts on marine bird populations in the context of protection afforded by legislation such as the Endangered Species Act.

A traditional method in conservation for setting priorities is to develop lists of at-risk species (Gardali et al., 2012) but a means by which to identify which species are most vulnerable is therefore necessary. A well-established approach has been to use indices of sensitivity or population vulnerability to particular hazards (Furness and Tasker, 2000; Gardali et al., 2012; Garthe and Hüppop, 2004; Sonntag et al., 2012). Garthe and Hüppop (2004) developed an index of marine bird population vulnerability to offshore wind farms, based on scores of conservation importance of different species' populations and perceived behaviour-related risks of collision and displacement, combined into a single index. They applied this index to marine birds in the southern North Sea. Here we develop and refine the approach advocated by Garthe and Hüppop (2004), extending the species list and incorporating new data from recent research on the flight behaviour of marine birds. An important innovation in our approach is the separation of assessments of risk due to collision and risk due to avoidance/displacement. This separation is particularly useful where the species most at risk of collision differ from those most at risk of displacement, as is the case here. Our assessment focuses on the example of marine birds in Scotland, but the approach could equally be applied elsewhere.

2. Methods

We followed the approach of Garthe and Hüppop (2004) scoring broadly similar factors in the assessment of vulnerability of marine bird populations to offshore wind farms. Where we used the same factors as Garthe and Hüppop (2004), scores allocated by them were reviewed individually. In many cases those scores appeared appropriate but where more recent data were available, scores were modified. As far as possible, the scoring criteria for each factor and the respective provisional scores for each marine bird species were evidence-based, with data taken from the reviewed literature. Scoring criteria and provisional scores were subsequently circulated to a group of appropriate experts for review, in order to ensure consensus support for the final criteria and scorings from a range of stakeholders; including seabird ecologists and conservationists (see details in Acknowledgements). The list of marine bird species assessed includes true seabirds, wintering sea ducks and grebes, and white-tailed eagle *Haliaeetus albicilla*. This last species was included because it feeds extensively over the sea, and there are detailed studies of its collisions at coastal terrestrial wind farms. Both breeding and nonbreeding (wintering or passage) marine birds were scored. A few marine bird species of conservation importance that occur in Scotland were omitted, on the basis that they occur very infrequently, if ever, in Scottish marine areas identified as suitable for offshore wind farms (Marine Scotland, 2011). These included red-breasted merganser *Mergus serrator* and little gull *Hydrocoloeus minutus*.

The method considers factors representing conservation importance and factors representing aspects of sensitivity to wind farm impacts. In some regions, a single factor may be adequate to rank and assign scores for conservation importance, but often there are multiple rankings available, based on slightly different criteria. In such cases an average of several rankings may provide a better scoring system than relying on any one individual factor. In our case study, four factors represent the conservation importance of the species in a Scottish context; status in relation to the Birds Directive, percentage of the biogeographic population that occurs in Scotland, adult survival rate, and UK threat status. Status in relation to the Birds Directive gives emphasis to species considered by the European Commission to be in particular need of conservation protection through European legislation. However, some of these species show increasing populations. UK threat status emphasises species showing population decline, but may give a low score to populations of high endemism if these are not in decline. Percentage of biogeographic population in the focal area emphasises endemism but does not take account of population trend. Considering adult survival rate recognises that added mortality of adult birds with high natural survival rates (and corresponding low productivity) has a greater impact on population dynamics than added mortality to populations with low survival rates. Combining these factors appears to provide a better ranking of conservation importance than achieved by any component factor (for details of these factors and scores see Furness et al., 2012).

Six factors represent aspects of species' behaviour that contribute to their potential vulnerability to wind farms (flight altitude, flight manoeuvrability, percentage of time flying, nocturnal flight activity, disturbance by wind farm structures, ship and helicopter traffic, and habitat specialisation). Scores were assigned on a scale of 1–5 for almost all factors, where 5 is a strong anticipated negative impact. It was felt more appropriate to score the factor assessing flight altitude as a percentage value of a species' flight altitude spent at turbine blade height, rather than on a five point scale. Individual factor scores were combined to give a total for each species that ranked species according to their vulnerability to offshore wind farm developments separately in terms of collision risk and habitat loss through avoidance. The factors assessed and calculations used to combine factor scores are outlined below.

2.1. Flight altitude

This factor is widely considered to be of overwhelming importance in determining the risk of collision of marine birds with offshore wind turbines (Band, 2011; Cook et al., 2012). Birds that only fly very low over the water will be below the area swept by turbine blades, whereas marine birds that habitually fly at greater heights may experience a greater risk of collision with blades if flight heights coincide with rotor swept areas of a wind farm. Flight altitude scores were initially taken from Garthe and Hüppop (2004), and Cook et al. (2012) but we present flight altitude as percentages of birds flying at blade height (Table 1), as opposed to collapsing such data into a 5 point scale (Garthe and Hüppop, 2004). When there was a lack of consensus between Garthe and Hüppop (2004) and Cook et al. (2012), we estimated a flight altitude that was consistent with these two reviews and was consistent with data from closely related species, or with other published data such as Rothery et al. (2009), and Krijgsveld et al. (2011), trying to account for very different sample sizes in different studies, different methods of measurement, and trying to retain consistency across related species. Flight altitude includes birds in all activities (such as foraging, commuting, migrating). It may vary seasonally, but there are too few data available at present to test this possibility.

Table 1
Estimated percent of flight at turbine blade height (ca. 20–150 m asl).

Species	Reference	Estimated % at blade height
Greater scaup	Dirksen et al., 1998 (10%, no sample size quoted, radar at night). Assumed similar to other ducks.	3
Common eider	Krüger and Garthe, 2001 (2%, n = 14,405, land-based obs) Day et al., 2003 (0%, n = 17, land-based obs) Garthe and Hüppop, 2004 (score of 1, median height <5 m). Leopold et al., 2004 (1.3%, n = 235, ship-based obs) Petterson, 2005 (Utgrunden, 0%, n = 57, radar) Petterson, 2005 (Yttre Stengrund, 20%, n = 2044, radar) Sadoti et al., 2005a (0%, n = 84, boat-based obs) Petersen et al., 2006 (16%, n = 193 flocks mostly eiders, radar) Larsen and Guillemette, 2007 (2%, n = 1277 platform-based obs) Rothery et al., 2009 (0%, n = 1282, land-based obs) Paton et al., 2010 (0.2%, n = 24,195 land-based obs) Paton et al., 2010 (0%, n = 294 ship-based obs)	3
Long-tailed duck	Day et al., 2003 (0%, n = 108, land-based obs) Paton et al., 2010 (0%, n = 280 land- or ship-based obs) Cook et al., 2012 (0%, n = 114 ship-based obs) Our estimate assumes this species is similar to other ducks.	3
Common scoter	Krüger and Garthe, 2001 (3%, n = 6754, land-based obs) Garthe and Hüppop, 2004 (score of 1, median height <5 m) Leopold et al., 2004 (0.8%, n = 2258, ship-based obs) Sadoti et al., 2005a (43%, n = 96, boat-based obs) Npower renewables, 2006 (0.2%, n = 1274, boat-based obs) Rothery et al., 2009 (0%, n = 341, land-based obs) Paton et al., 2010 (0.2%, n = 4756 land-based obs) Paton et al., 2010 (0%, n = 277 ship-based obs) Cook et al., 2012 (1%, 95% ci <0.1–17%, n = 30,847 ship-based obs) Garthe et al., 2012b (24%, no sample size, boat-based obs)	3
Velvet scoter	Day et al., 2003 (0%, n = 5, land-based obs) Garthe and Hüppop, 2004 (score of 1, median height <5 m); Sadoti et al., 2005a (3%, n = 88, boat-based obs) Paton et al., 2010 (7.0%, n = 2973 land-based obs) Paton et al., 2010 (0%, n = 161 ship-based obs) Cook et al., 2012 (0%, n = 20 ship-based obs)	3
Common goldeneye	Dirksen et al., 1998 (5%, no sample size quoted, radar at night) Paton et al., 2010 (11.3%, n = 336 land-based obs) Assumed similar to other ducks	3
Red-throated diver	Krüger and Garthe, 2001 (0%, n = 247, land-based obs) Garthe and Hüppop, 2004 (score of 2, median height 5–10 m) Leopold et al., 2004 (8.5%, n = 284, ship-based obs, may include a few black-throated divers) Krijgsveld et al., 2005 (24%, n = 103, radar, may include a few black-throated divers) Sadoti et al., 2005a (3%, n = 28, boat-based obs) Npower renewables, 2006 (0%, n = 13, boat-based obs) Paton et al., 2010 (7.1%, n = 1226 land-based obs) Paton et al., 2010 (28.3%, n = 106 ship-based obs) Krijgsveld et al., 2011 (5%, no sample size, radar) Cook et al., 2012 (2%; 95% ci <0.1–22%, n = 9715 ship-based obs)	5
Black-throated diver	Garthe and Hüppop, 2004 (score of 2, median height 5–10 m); Cook et al., 2012 (0.1%; 95% ci <0.1–30%, n = 126 ship-based obs) Score is a compromise between conflicting data in these two studies and a view from reviewers that all divers should be same.	5
Great northern diver	Sadoti et al., 2005a (4%, n = 27, boat-based obs) Paton et al., 2010 (22.8%, n = 2762 landb-ased obs) Paton et al., 2010 (5.8%, n = 292 ship-based obs) Cook et al., 2012 (0%, n = 14 ship-based obs); Kerlinger, 1982 (migration can occur at 1000 to 3000 m heights)	5
Great-crested grebe	Garthe and Hüppop, 2004 (score of 2, median height 5–10 m); Leopold et al., 2004 (0%, n = 32, ship-based obs) Cook et al., 2012 (0%, n = 82 ship-based obs)	4
Slavonian grebe	Paton et al., 2010 (23.5%, n = 85 land-based obs) Assumed similar to great-crested grebe	4
Northern fulmar	Garthe and Hüppop, 2004 (score of 1, median height <5 m); Leopold et al., 2004 (0%, n = 178, ship-based obs) Krijgsveld et al., 2005 (0%, n = 10, radar) Cook et al., 2012 (0.2%; 95% ci <0.1–22%, n = 29,168 ship-based obs).	1
Sooty shearwater	Paton et al., 2010 (0%, n = 5 land-based obs) Paton et al., 2010 (0%, n = 16 ship-based obs) Cook et al., 2012 (0%, n = 2 ship-based obs) Assumed similar to Manx shearwater	0
Manx shearwater	Cook et al., 2012 (0.04%; 95% ci <0.01–10%, n = 6957 ship-based obs)	0
European storm-petrel	Cook et al., 2012 (2% (range 0–2.5%), n = 52 ship-based obs)	2
Leach's storm-petrel	Assumed similar to European storm-petrel	2

Table 1 (*continued*)

Species	Reference	Estimated % at blade height
Northern gannet	Garthe and Hüppop, 2004 (score of 3, median height 10–20 m but few above 50 m); Leopold et al., 2004 (13%, $n = 803$, ship-based obs) Krijgsveld et al., 2005 (44%, $n = 143$, radar, excludes birds following fishing boats) Sadoti et al., 2005a (20%, $n = 85$, boat-based obs) Npower renewables, 2006 (16%, $n = 50$, boat-based obs) Rothery et al., 2009 (13%, $n = 414$, land-based obs) Paton et al., 2010 (10%, $n = 8560$ land-based obs) Paton et al., 2010 (6.9%, $n = 1278$ ship-based obs) Krijgsveld et al., 2011 (30%, no sample size, radar) Cook et al., 2012 (estimated 9.6%; 95% ci <0.1–20%, $n = 44{,}851$); Garthe et al., 2012b (9%, no sample size, boat-based obs)	16
Great cormorant	Garthe and Hüppop, 2004 (score of 1, median height <5 m). Leopold et al., 2004 (7.5%, $n = 929$, ship-based obs) Rothery et al., 2009 (13%, $n = 352$, land-based obs) Npower renewables, 2006 (7%, $n = 113$, boat-based obs) Paton et al., 2010 (7.3%, $n = 2014$ land-based obs) Paton et al., 2010 (0%, $n = 15$ ship-based obs) Krijgsveld et al., 2011 (28%, no sample size, radar)	4
Shag	Npower renewables, 2006 (0%, $n = 5$, boat-based obs) Cook et al., 2012 (12.4% with model fit relatively poor; 95% ci 1.9–60%, $n = 233$ ship-based obs).	5
White-tailed eagle	Nygård et al., 2010 (24% of flights in study wind farm were at blade height (hub height = 70 m, blade radius = 38–41 m)	24
Arctic skua	Garthe and Hüppop, 2004 (score of 3, median height 10–20 m but few above 50 m); Npower renewables, 2006 (0%, $n = 2$, boat-based obs) Paton et al., 2010 (21.1%, $n = 19$ land-based obs) Paton et al., 2010 (0%, $n = 1$ ship-based obs) Cook et al., 2012 (3.8%; 95% ci <0.1–16%, $n = 331$ ship-based obs) Observations of Arctic skuas from seawatching and from birds foraging at sea in breeding areas suggest higher flying than Cook et al., 2012 model, as does G&H 2004 score. Our estimate follows Garthe and Hüppop, 2004 and suggestions from reviewers more closely than the data in Cook et al. (2012).	10
Great skua	Garthe and Hüppop, 2004 (score of 3, median height 10–20 m but few above 50 m); Cook et al., 2012 (4.3%; 95% ci 1.2–28%, $n = 1202$ ship-based obs) Observations of great skuas from seawatching, from birds foraging at sea in breeding areas, and from deployment of GPS data loggers by H. Wade, C. Thaxter and colleagues) suggest higher flying than Cook et al., 2012 model, as does G&H 2004 score. Our estimate follows Garthe and Hüppop, 2004, unpublished GPS logger data, and suggestions from reviewers more closely than data in Cook et al. (2012).	10
Black-headed gull	Bergh et al., 2002 (4%, $n = 82$, land-based obs at Slufterdam) Bergh et al., 2002 (78%, $n = 41$, land-based obs at Slag Dobbelsteen) Scored 5 by Garthe and Hüppop (2004) (median height 10–20 m with 10% above 100 m). Krijgsveld et al., 2005 (25%, $n = 334$, radar, excludes birds following fishing boats) Rothery et al., 2009 (4%, $n = 978$, land-based obs) Krijgsveld et al., 2011 (30%, no sample size, radar) Cook et al., 2012 (7.9%; 95% ci 0.4–50%, $n = 4490$ ship-based obs). Estimate also considers values for related gull species, and radar studies reporting a higher flight height than obtained from boat-based windfarm surveys (Cook et al., 2012)	18
Common gull	Bergh et al., 2002 (58%, $n = 120$, land-based obs at Slag Dobbelsteen) Garthe and Hüppop, 2004 (score of 3, median height 10–20 m but few above 50 m); Krijgsveld et al., 2005 (48%, $n = 1517$, radar, excludes birds following fishing boats) Npower renewables, 2006 (18%, $n = 102$, boat-based obs) Cook et al., 2012 (22.9%; 95% ci 8.5–47%, $n = 10{,}190$ ship-based obs); Garthe et al., 2012b (11%, no sample size, boat-based obs)	23
Lesser black-backed gull	Bergh et al., 2002 (34%, $n = 92$, land-based obs at Slufterdam) Bergh et al., 2002 (90%, $n = 1828$, land-based obs at Slag Dobbelsteen) Garthe and Hüppop, 2004 (score of 4, median height 10–20 m with 10% above 50 m); Krijgsveld et al., 2005 (55%, $n = 2470$, radar, excludes birds following fishing boats) Npower renewables, 2006 (35%, $n = 66$, boat-based obs) Krijgsveld et al., 2011 (60%, no sample size, radar) Cook et al., 2012 (estimated 25.2%; 95% ci 7.8–52%, $n = 35{,}142$ ship-based obs); Garthe et al., 2012b (29%, no sample size, boat-based obs)	30
Herring gull	Bergh et al., 2002 (33%, $n = 71$, land-based obs at Slufterdam) Bergh et al., 2002 (84%, $n = 7327$, land-based obs at Slag Dobbelsteen) Garthe and Hüppop, 2004 (score of 4, median height 10–20 m with 10% above 50 m); Krijgsveld et al., 2005 (50%, $n = 2223$, radar, excludes birds following fishing boats) Sadoti et al., 2005a (22%, $n = 63$, boat-based obs) Sadoti et al., 2005b (5%, $n = 63$, boat-based obs) Npower renewables, 2006 (37%, $n = 142$, boat-based obs) Rothery et al., 2009 (33%, $n = 1408$, land-based obs) Paton et al., 2010 (15.0%, $n = 51{,}036$ land-based obs) Paton et al., 2010 (13.8%, $n = 1652$ ship-based obs) Krijgsveld et al., 2011 (55%, no sample size, radar) Cook et al., 2012 (estimated 28.4%; 95% ci 16–48%, $n = 25{,}252$ ship-based obs); Garthe et al., 2012b (40%, no sample size, boat-based obs)	35

(*continued on next page*)

Table 1 (*continued*)

Species	Reference	Estimated % at blade height
Great black-backed gull	Garthe and Hüppop, 2004 (Score 3, median height 10–20 m but few above 50 m) Krijgsveld et al., 2005 (57%, $n = 143$, radar, excludes birds following fishing boats) Sadoti et al., 2005a (28%, $n = 163$, boat-based obs) Sadoti et al., 2005b (6%, $n = 35$, boat-based obs) Npower renewables, 2006 (23%, $n = 22$, boat-based obs) Rothery et al., 2009 (44%, $n = 564$, land-based obs) Paton et al., 2010 (8.5%, $n = 8610$ land-based obs) Paton et al., 2010 (8.8%, $n = 1001$ ship-based obs) Krijgsveld et al., 2011 (60%, no sample size, radar) Cook et al., 2012 (33.1%; 95% ci 18–57%, $n = 8911$ ship-based obs) Garthe et al., 2012b (56%, no sample size, boat-based obs)	35
Black-legged kittiwake	Day et al., 2003 (10%, $n = 36$, land-based obs) Garthe and Hüppop, 2004 (Score 2, median 5–10 m) Leopold et al., 2004 (9%, $n = 637$, ship-based obs) Chamberlain et al., 2005 (4%, $n = 2036$, ship-based obs) Krijgsveld et al., 2005 (38%, $n = 2459$, radar, excludes birds following fishing boats) Npower renewables, 2006 (8%, $n = 79$, boat-based obs) Rothery et al., 2009 (11%, 1350, land-based obs) Paton et al., 2010 (0%, $n = 56$ land-based obs) Paton et al., 2010 (10.9%, $n = 55$ ship-based obs) Krijgsveld et al., 2011 (45%, no sample size, radar) Cook et al., 2012 (15.7%; 95% ci 8–24%, $n = 62{,}975$ ship-based obs); Garthe et al., 2012b (18%, no sample size, boat-based obs)	16
Little tern	Everaert and Stienen, 2007 (23%, $n = 2124$, land-based obs at a coastal wind farm) Assumed similar to other terns	7
Sandwich tern	Krüger and Garthe, 2001 (0%, $n = 959$, land-based obs) Garthe and Hüppop, 2004 (Score 3, median height 10–20 m but few above 50 m) Leopold et al., 2004 (4.5%, $n = 419$, ship-based obs) Krijgsveld et al., 2005 (56%, $n = 236$, radar, may include some other tern species) Npower renewables, 2006 (5%, $n = 20$, boat-based obs) Everaert and Stienen, 2007 (10%, $n = 27{,}571$, land-based obs at a coastal wind farm) Rothery et al., 2009 (3%, $n = 2137$, land-based obs) Perrow et al., 2011a (48%, no sample size, boat-based obs) Krijgsveld et al., 2011 (50%, no sample size, radar) Cook et al., 2012 (3.6%; 95% ci 0.7–35%, $n = 33{,}392$ ship-based obs); Garthe et al., 2012b (8%, no sample size, boat-based obs)	7
Common tern	Bergh et al., 2002 (8%, $n = 113$, land-based obs at Slufterdam) Krüger and Garthe, 2001 (0%, $n = 271$, land-based obs) Garthe and Hüppop, 2004 (score of 2, median 5–10 m) Leopold et al., 2004 (0.6%, $n = 1011$, ship-based obs, includes some Arctic terns) Sadoti et al., 2005a (6.2%, $n = 130$, boat-based obs 2003; 5.7%, $n = 163$, boat-based obs 2004, may include some roseate terns) Sadoti et al., 2005b (4%, $n = 29$, boat-based obs) Npower renewables, 2006 (41%, $n = 79$, boat-based obs) Everaert and Stienen, 2007 (13%, $n = 14{,}491$, land-based obs at a coastal wind farm) Hatch and Brault, 2007 (6.2%, $n = 3154$ (including some roseate terns) Paton et al., 2010 (3.8%, $n = 3644$ land-based obs) Paton et al., 2010 (11.5%, $n = 61$ ship-based obs) Cook et al., 2012 (12.7%; 95% ci 6–19%, $n = 19{,}332$ ship-based obs); Garthe et al., 2012b (0%, no sample size, may include a few Arctic terns)	7
Roseate tern	Paton et al., 2010 (0%, $n = 125$ land-based obs) Paton et al., 2010 (12.5%, $n = 8$ ship-based obs) Assumed similar to other terns	5
Arctic tern	Alerstam and Gudmundsson, 1999 (migrate mainly above collision risk height from 200 to 2000 m, radar) Gudmundsson et al., 2002 (migration mainly nocturnal, mean height 800 m, radar) Garthe and Hüppop, 2004 (score of 1, median <5 m); Cook et al., 2012 (2.8%; 95% ci <0.1–23%, $n = 2571$ ship-based obs)	5
Common guillemot	Day et al., 2003 (0%, $n = 172$, land-based obs, may include a few Brunnich's guillemots) Garthe and Hüppop, 2004 (score of 1, median <5 m); Leopold et al., 2004 (0.6%, $n = 316$, ship-based obs) Krijgsveld et al., 2005 (3%, $n = 440$, radar, may include some razorbills and puffins) Npower renewables, 2006 (5%, $n = 56$, boat-based obs) Paton et al., 2010 (0%, $n = 131$ ship-based obs) Cook et al., 2012 (0.01%; 95% ci <0.01–3.9%, $n = 36{,}260$ ship-based obs) In breeding areas, often commutes to/from colony at heights relating to altitude of nest sites which can be up to 200 m above sea level	1

Table 1 (*continued*)

Species	Reference	Estimated % at blade height
Razorbill	Garthe and Hüppop, 2004 (score of 1, median <5 m); Leopold et al., 2004 (0%, $n = 33$, ship-based obs) Sadoti et al., 2005a (0%, $n = 3$, boat-based obs) Npower renewables, 2006 (0%, $n = 17$, boat-based obs) Paton et al., 2010 (0%, $n = 135$ land-based obs) Paton et al., 2010 (0%, $n = 93$ ship-based obs) Cook et al., 2012 (0.4%; 95% ci <0.1–25%, $n = 13{,}171$ ship-based obs) In breeding areas, often commutes to/from colony at heights relating to altitude of nest sites which can be up to 200 m above sea level	1
Black guillemot	Paton et al., 2010 (0%, $n = 1$ land-based obs) Assume similar to closely related species	1
Little auk	Paton et al., 2010 (0%, $n = 125$ ship-based obs) Cook et al., 2012 (0.03%; 95% ci <0.01–15%, $n = 1287$ ship-based obs)	1
Atlantic puffin	Garthe and Hüppop, 2004 (score of 1, median <5 m); Paton et al., 2010 (0%, $n = 5$ ship-based obs) Cook et al., 2012 (0.1%; 95% ci <0.1–8%, $n = 5981$ ship-based obs)	1

2.2. Flight manoeuvrability

This factor takes into account the aerial agility of species and hence their potential to avoid collision with wind turbines at sea. Following Garthe and Hüppop (2004), we assume that, all other factors being equal, birds with low flight manoeuvrability are more likely to collide with wind turbines at offshore wind farms than birds with high flight manoeuvrability. Scores were taken from Garthe and Hüppop (2004), but adjusted where more recent data suggest appropriate. For additional species, scores were based on peer-reviewed literature and subjective judgement moderated by expert opinion. Species were classified from 'very high flight manoeuvrability' (score 1) to 'very low manoeuvrability' (score 5) (electronic Appendix 1). The value is considered to be a consequence of morphology rather than behaviour. It may vary seasonally (for example in relation to moult) but such detail is beyond the scope of this assessment.

2.3. Percentage of time flying

This factor was assumed to indicate risk of collision because marine birds that spend more time flying while at sea (whether while breeding, migrating, wintering, or as prebreeders) are more likely to be at risk of collision. Where available, scores were taken from Garthe and Hüppop (2004) and adjusted where more recent data suggest appropriate. For other species, scores were calculated from data on activity budgets following the procedure outlined by Garthe and Hüppop (2004). Species were scored 1 if 0–20% of time at sea was spent in flight, 2 if 21–40% was spent flying, 3 if 41–60% was spent flying, 4 if 61–80% was spent flying, and 5 if 81–100% was spent flying (electronic Appendix 2). This factor will probably vary seasonally, with the literature indicating more flight activity while rearing chicks than during the incubation period, and more flight while breeding than during winter. Peaks of flight activity occur in migrant species during the migration, while flight activity may be reduced during post-breeding moult. However, these refinements are not yet well enough documented to assess scores separately for different seasons, although that could be a useful development of the method.

2.4. Nocturnal flight activity

Although various observations exist, detailed data on nocturnal flight activity are not available for many species. Geolocation and GPS logger data are starting to change this situation, predominantly for large Southern Ocean seabirds (Mackley et al., 2010, 2011; Phalan et al., 2007), but with data now available for northern gannet (Garthe et al., 2012a) and black-legged kittiwake *Rissa tridactyla* (Kotzerka et al., 2010). Similar data should soon be available for some other North Atlantic seabirds including great skuas *Stercorarius skua* for which logger deployments have already provided data on migrations and wintering areas (Magnusdottir et al., 2012). We used scores published in Garthe and Hüppop (2004) for the species where these were available: Score 1 (limited flight activity at night) to score 5 (much flight activity at night) (electronic Appendix 3). We used published data where possible, and information (often qualitative rather than quantitative) from individual species studies or from handbooks (Cramp and Simmons, 1977, 1980; del Hoyo et al., 1992, 1996; Glutz von Blotzheim and Bauer, 1982). Classifications were also moderated by experts.

2.5. Disturbance by wind farm structures, ship and helicopter traffic

Marine bird species vary in their reactions to offshore wind farms and the ship and helicopter traffic that occurs during maintenance of the turbines. Where available, scores were taken from Garthe and Hüppop (2004) and adjusted where more recent data were available (e.g. Schwemmer et al., 2011). For additional species, information on disturbance sensitivity was taken from the peer-reviewed literature, and scores were moderated by experts. Scoring categories were: 1 (limited escape behaviour and a very short flight distance when approached), to 5 (strong escape behaviour, at a large response distance) (electronic Appendix 4).

2.6. Habitat specialisation

Marine birds vary in the range of habitats they use, for example relating to water masses and frontal systems and whether they use these as specialists or generalists. This score classifies species into categories from 1 (tend to forage over large marine areas with little known association with particular marine features) to 5 (tend to feed on very specific habitat features, such as shallow banks with bivalve communities, or kelp beds) (electronic Appendix 5). Where available, scores presented by Garthe and Hüppop (2004) were used. Scores for other species were based on foraging ecology described in single species studies in the literature, or from standard handbook descriptions.

2.7. Calculating species vulnerability scores for collision risk and displacement concern

Garthe and Hüppop (2004) calculated species vulnerability scores according to Equation (1), where *e*, *f*, *g*, *h*, *i* and *j* represent flight altitude, flight manoeuvrability, percentage of time flying, nocturnal flight activity, disturbance by wind farm structures, ship and helicopter traffic, and habitat specialisation respectively.

$$\text{Species vulnerability score} = (e+f+g+h)/4 \times (i+j)/2 \times \text{conservation score} \tag{1}$$

This recognised that the first four factors all relate to flight ability and flight behaviour, while the last two factors relate to habitat use and susceptibility to disturbance. Thus their index combined both collision risk and disturbance/habitat loss considerations into a single score.

We use an alternative approach and score separately for collision concern and for disturbance/habitat displacement concern. For collision risk, we give a high weighting to flight altitude (*e*), and lower weighting to manoeuvrability (*f*), percentage of time flying (*g*), and nocturnal flight activity (*h*) (Equation (2)).

$$\text{Collision risk score} = e \times (f+g+h)/3 \times \text{conservation importance score} \tag{2}$$

For disturbance/habitat displacement we calculated a vulnerability index according to Equation (3) where *i* and *j* represent disturbance by wind farm structures, ship and helicopter traffic, and habitat specialisation respectively. We divided the total by 10 (an arbitrary value) to recognise that the disturbance/displacement impact on populations is likely to be considerably less than a direct mortality impact such as from collisions and therefore the two scales should not be compared in a quantitative way but only in terms of the species ranking within one scale.

$$\text{Disturbance/displacement score} = ((\mathrm{i} \times \mathrm{j}) \times \text{conservation importance score})/10 \tag{3}$$

3. Results

Factors and species-scores were sent to a panel of seabird experts for comment. Most reviewers suggested no change to the factors used, and no change to most scores. Most reviewers felt that one or two out of the 228 scores should be adjusted, so agreed with more than 99% of the scores. The few scores that were consistently questioned by reviewers were altered to bring them in line with this consensus opinion.

The ranked species' vulnerability scores in the context of collision risk (and considering the conservation importance of the species) are summarised in Table 2. The percentage of a species' flight altitude at turbine blade height ranged from values of 0–35. The mean of the other factors ranged from 1.3 to 3.7 (within a theoretically possible range of 1–5). Details of the derivation of the component scores are given in Table 2 and the electronic Appendix. The highest scores indicate that the larger gull species (great black-backed gull *Larus marinus*, herring gull *Larus argentatus*, and lesser black-backed gull *Larus fuscus*), northern gannet and white-tailed eagle are the species likely to be most at risk of collision with offshore wind turbines.

The ranked species vulnerability scores in the context of disturbance or habitat displacement (and considering the conservation importance of the species) are summarised in Table 3. The highest scores indicate that all diver species and common scoter are most likely to be at risk of disturbance or displaced from habitats as a result of offshore wind turbines. Details of the derivation of the component scores are given in the electronic Appendix tables.

4. Discussion

The key results from our assessment are ranked species lists referring to species' vulnerability to offshore wind farms in the context of collision risk (Table 2) and vulnerability in the context of disturbance or habitat displacement (Table 3). For collision risk, the five top ranking species had scores that were greater than half of the maximum score achieved overall (by herring gull, with a collision risk score of 1306). These species were herring gull, great black-backed gull, lesser black-backed gull, white-tailed eagle and northern gannet. In the rankings for disturbance or habitat displacement concern, only three species had scores that were over half of the maximum score possible (maximum score possible was 50). In contrast to species indicated as having a high collision risk, the species identified as most vulnerable to disturbance or displacement were diver species and common scoter. Garthe and Hüppop (2004) identified divers and common scoter as the species with the highest sensitivity index scores in the southern North Sea, suggesting that their index weighted disturbance/displacement impacts more strongly than collision mortality risk. The differing results for the two potential risks shown by our assessment are a result of species-specific variability in behaviour. The species identified as of highest concern in the table rankings should be the focus for monitoring and for further research investigating the effects of offshore wind farms on marine birds in Scottish waters, and we suggest that this approach should be extended to consider marine bird communities in other countries.

4.1. Development/evolution of our approach

Following discussions and comments from reviewers, we developed the approach taken by Garthe and Hüppop (2004) to recognise that there is broad support for the view that collision concern should be considered separately from displacement concern, as the rankings of species in each context are very different. We also differ in our approach to Garthe and Hüppop (2004) by not ranking all scores for factors measuring the vulnerability of species to offshore wind turbines on a scale of 1–5. Instead, the factor assessing flight altitude was considered in greater detail by presenting the percentage of a species flight altitude spent at wind turbine blade height. In combination with an increased weighting given to this factor when calculating collision risk scores, our method incorporates the broad consensus of opinion among reviewers that flight height is considerably more important than the other factors considered here in assessing collision risk of marine birds with wind turbines. There were mixed views regarding the relative importance of the other three factors of manoeuvrability, percentage of time flying and the amount of nocturnal flight in affecting collision risk, and the down-weighting of these three factors recognised this. This change in approach is more appropriate now than it was when Garthe and Hüppop (2004) prepared their paper, because there are now considerably more detailed data on marine bird flight height from the work of Paton et al. (2010), Krijgsveld et al. (2011), Cook et al. (2012), Garthe et al. (2012b) and others.

4.2. Limitations of indices of sensitivity

The method of calculating indices and ranking species has been criticised for the uncertainty in how to incorporate a variety of different factors, often scored on different scales and sometimes with

Table 2
Ranked species concern in the context of collision impacts: percent flying at blade height × 1/3(manoeuverability score + % time flying score + nocturnal flight score) × conservation importance score (ranked by index value).

Species	Flight % at blade height	Flight agility	% of time flying	Night flight	Conservation importance score	Total risk score
Herring gull	35	2	2	3	16	1306
Great black-backed gull	35	2	2	3	15	1225
Lesser black-backed gull	30	1	2	3	16	960
White-tailed eagle	24	3	5	1	12	864
Northern gannet	16	3	3	2	17	725
Common gull	23	1	2	3	13	598
Black-legged kittiwake	16	1	3	3	14	523
Arctic skua	10	1	5	1	14	327
Great skua	10	1	4	1	16	320
Black-headed gull	18	1	1	2	12	288
Sandwich tern	7	1	5	1	15	245
Black-throated diver	5	5	3	1	16	240
Great northern diver	5	5	2	1	18	240
Common tern	7	1	5	1	14	229
Red-throated diver	5	5	2	1	16	213
Little tern	7	1	5	1	13	212
Arctic tern	5	1	5	1	17	198
Roseate tern	5	1	5	1	15	175
Shag	5	3	2	1	15	150
Slavonian grebe	4	4	2	2	13	139
Greater scaup	3	4	2	5	11	121
Common eider	3	4	2	3	13	117
Great cormorant	4	4	2	1	11	103
Common goldeneye	3	3	2	3	12	96
Common scoter	3	3	2	3	12	96
European storm-petrel	2	1	3	4	17	91
Velvet scoter	3	3	2	3	11	88
Leach's storm-petrel	2	1	3	4	16	85
Great-crested grebe	4	4	3	2	7	84
Long-tailed duck	3	3	2	3	8	64
Northern fulmar	1	3	2	4	16	48
Common guillemot	1	4	1	2	16	37
Razorbill	1	4	1	1	16	32
Black guillemot	1	4	1	1	13	30
Atlantic puffin	1	3	1	1	16	27
Little auk	1	3	1	1	9	15
Manx shearwater	0	3	3	3	17	0
Sooty shearwater	0	3	3	3	12	0

correlations among the factors being used (Desholm, 2009). Considering birds of all species and not just marine birds, Desholm (2009) argued that in order to prioritise bird species for assessment of the impact of collision mortality at offshore wind farms, it is possible to consider just two criteria; proportion of the biogeographic population at risk at a wind farm site, and population 'elasticity', which is mainly determined by adult survival rate. Birds with high adult survival rates (such as most marine birds) will be more severely impacted by wind farm mortality than birds with low natural survival rates (such as most terrestrial migrant passerines). That approach has the benefit of great simplicity, and works well when ranking bird species ranging from small passerines with very short life expectancy and high reproductive output through to marine birds with long life spans and low fecundity (Desholm, 2009). However, that method does not discriminate well between species with similar demographic parameters (most marine birds have similarly high adult survival rates), and it does not take into account the fact that some kinds of marine birds are more, or less, likely to collide with wind turbines as a consequence of their species-specific ecology or behaviour. For example, among marine birds with comparable demography, species that regularly fly at turbine blade height are apparently more at risk from collision mortality than species that only fly low over the water. Nor does that method take account of the possible effects of offshore wind farms on marine birds through effects such as deflection of flight paths (Masden et al., 2009; Speakman et al., 2009) or loss of foraging habitat (Fox et al., 2006a,b). In our analysis we are dealing mainly with species at the long-lived end of this spectrum of life histories and so the simple model focusing only on adult survival rate, but not on differences in ecology and behaviour, becomes less useful as there is relatively little variation in this among most marine bird species.

4.3. *Limitations of data sources, implications for results, and future improvements*

There are limitations inherent in the index resulting from data sources, which should be considered when interpreting our results. Flight altitude was considered to be the most important factor in calculating collision risk for marine bird species at offshore wind farms. In calculating the collision risk for species, Cook et al. (2012) provide the most detailed review of available data on flight altitude, however there are inherent limitations in these data, which should be considered. These include the fact that most data are from boat-based observations and as such, observations potentially include significant numbers of marine birds scared into flight by the boat (Camphuysen et al., 2004). Such birds tend to fly low over the water so will bias the distribution of flight heights. Birds of some species may also be attracted to boats. Additionally, most estimates of the height of flying marine birds used by Cook et al. (2012) are very crude, mostly being based on estimates by observers and not on measurements. It is worth noting that the data reported by Cook et al. (2012) can differ quite considerably to flight heights of

Table 3
Ranked species concern in the context of disturbance and/or displacement from habitat (Disturbance score × Habitat flexibility score × Conservation Importance score)/10.

Species	Disturbance by ship and helicopter traffic	Habitat use flexibility	Conservation importance score	Species concern index value
Black-throated diver	5	4	16	32
Red-throated diver	5	4	16	32
Great northern diver	5	3	18	27
Common scoter	5	4	12	24
Common goldeneye	4	4	12	19
Greater scaup	4	4	11	18
Velvet scoter	5	3	11	16
Common eider	3	4	13	16
Black guillemot	3	4	13	16
Slavonian grebe	3	4	13	16
Common guillemot	3	3	16	14
Razorbill	3	3	16	14
Shag	3	3	15	14
Great cormorant	4	3	11	13
Little tern	2	4	13	10
Arctic tern	2	3	17	10
Atlantic puffin	2	3	16	10
Long-tailed duck	3	4	8	10
Roseate tern	2	3	15	9
Sandwich tern	2	3	15	9
Common tern	2	3	14	8
Great-crested grebe	3	4	7	8
Great black-backed gull	2	2	15	6
Black-legged kittiwake	2	2	14	6
Common gull	2	2	13	5
Black-headed gull	2	2	12	5
Little auk	2	2	9	4
Northern gannet	2	1	17	3
Herring gull	2	1	16	3
Great skua	1	2	16	3
Lesser black-backed gull	2	1	16	3
Arctic skua	1	2	14	3
White-tailed eagle	1	2	12	2
Manx shearwater	1	1	17	2
European storm-petrel	1	1	17	2
Leach's storm-petrel	1	1	16	2
Northern fulmar	1	1	16	2
Sooty shearwater	1	1	12	1

marine birds that have been measured by radar (Krijgsveld et al., 2011; Cook et al., 2012). This discrepancy is unexplained, but it seems likely that the radar measurements of flight height are more reliable where confident of species attribution. Our index indicates that many marine bird species rarely fly at turbine blade height, and so appear to have negligible risk of population-level impacts from collision mortality. These include sea ducks, alcids, storm-petrels and shearwaters (though the possibility that such birds may occasionally fly higher than normal as a result of disturbance needs to be borne in mind). The low risk for these species is consistent with empirical data from long-established offshore wind farms (ICES, 2011). However, it would be desirable to have more data on flight heights to allow this inference to be converted into a confident conclusion that might permit species to be scoped out of assessments. In light of new, more detailed data it will be possible to revise the scorings presented here and establish with more confidence those species at risk. We do suggest however, that species presented here with high scores should be of particular concern in relation to offshore wind developments. Gulls, white-tailed eagles, northern gannets, skuas and divers are identified as being the groups whose populations are most at risk in a Scottish context.

The recent increase in the use of data loggers on seabirds is starting to provide more detailed information on the at-sea activity of seabirds. This should help achieve an increase in the amount of data available and improve the quality of flight altitude data and information required for some of the other factors considered in calculating collision risk (e.g. percentage of time spent in flight and nocturnal flight activity). It is also possible that, in the near future, collection of quantitative data on time spent in flight from geolocation data loggers (for example, based on salt-water switch recording time spent with the logger immersed in seawater) will allow scorings to be converted into a quantitative scale rather than the present qualitative one.

Previous studies indicate that some species of marine bird avoid wind farms and as such, collision levels are low (Fox et al., 2006b; ICES, 2011; Petterson, 2005; Lindeboom et al., 2011). Our collision risk index is likely to require modification in future as more data become available, and at present should be considered precautionary in that the relative avoidance responses of different species are not yet well known. In assessing the potential importance of displacement for different marine bird species, although there was strong consensus among reviewers for the scores used, this consensus may be more a result of uncertainty than confident agreement, and so the ranking of species needs to be treated with caution. However, we suggest that species with scores over 15 (divers, scoters, goldeneye *Bucephala clangula*, scaup *Aythya marila*, common eider, black guillemot *Cepphus grylle*, Slavonian grebe *Podiceps auritus*) should be considered as focal species for concern with regards to potential displacement effects. Species with scores below 8 (northern fulmar *Fulmarus glacialis*, storm-petrels, shearwaters, gulls, skuas, northern gannet, little auk *Alle alle*, and white-tailed eagle) seem very unlikely to be affected by displacement. It is worth noting that whilst it is clear that some marine birds do strongly avoid wind turbines at sea, recent work modelling the cumulative impact of disturbance by wind turbines suggests that the impact of these through increased travel distances and habitat loss is trivial, even for species that show especially strong avoidance behaviour and have a high displacement ranking, such as red-throated divers *Gavia stellata* (Topping and Petersen, 2011).

We are aware that our vulnerability index deals with a limited set of factors and that there are other potential impacts that are not necessarily covered. For example, Perrow et al. (2011b) presented evidence suggesting that little tern *Sternula albifrons* breeding success in a colony in Norfolk may have been reduced by a shortage of young herring *Clupea harengus* around Scroby Sands offshore wind farm caused by monopile installation affecting fish reproduction locally. To an extent, the high sensitivity of little tern would be indicated by our six factors because they are seabirds with a very short foraging range that utilise a very particular and restricted foraging habitat, so score as sensitive on the habitat flexibility factor. However, complex and indirect ecosystem effects such as alteration of fish and benthic invertebrate abundance by wind farms is something that is extremely difficult to predict, so caution is needed in interpretations and collecting post-construction monitoring data will be important. Once operational, offshore wind farms may possibly enhance food supplies for marine birds by acting as marine protected areas (e.g. closed to trawl fishing; Defew et al., 2012). Siting of wind farms can also be influential at specific sites. For example, turbines placed between a common tern *Sterna hirundo* colony and their feeding habitat have had a high impact on a particular colony (Everaert and Stienen, 2007; Stienen et al., 2008), which might not be the case where a wind farm is placed away from the obligatory flight line of birds from a specific breeding site. In addition, the perception of risk, which seems to vary among species, and possibly may be as important a factor as anatomical constraints, may also be relevant, but cannot readily be scored on a scale, though avoidance may possibly be a proxy for perception of risk. We considered these indirect and uncertain effects to be beyond the scope of this review, but emphasise that they should not be assumed to be negligible.

An additional factor that we could not easily consider here but should not be ignored is the possibility that weather conditions may affect collision risk for marine birds. For example, weather conditions such as fog or heavy rain, may obscure turbines. Such effects might over-ride any species-specific differences in vulnerability. In reviewing the results of studies at demonstration offshore wind farms in Denmark, Fox et al. (2006b) stated "observations at Nysted that waterbirds tend not to fly in the area of the turbines at night, or under adverse weather conditions (as found elsewhere; Petterson, 2005) suggest that collision risk is not likely to be high even under conditions when the turbines are less visible". These observations suggest that catastrophic mortality incidents caused by adverse weather conditions are less likely at offshore wind farms than has been suggested by some, although breeding birds may not have the flexibility to respond in this way. In addition, presence of lights on wind farms may affect collision risk for marine birds, but the susceptibility of different species to attraction to lights at sea is not well known (Merkel and Johansen, 2011).

4.4. Applications and future testing

In scoping potential areas for offshore wind farm development in Scottish waters, Davies and Watret (2011) considered constraints implied by seabird SPAs, and the distribution at sea of seabirds as indicated by the European Seabirds at Sea database. These data were combined with the flight height data presented by Cook et al. (2012) to assess numbers of marine birds flying at collision height risk in different parts of the Scottish marine area. The development of sensitivity scoring and conservation importance scoring for individual species of marine birds may help to refine such assessment of environmental constraints by allowing a focus on the marine bird species of greatest concern. This would most usefully be combined with mapping (e.g. Garthe and Hüppop, 2004) of the distribution of seabird SPAs and the numbers of each species protected at these sites.

The scores presented in this paper, and similar scoring for other species, will help developers preparing Environmental Statements for new sites, by providing a clearer focus on the key species likely to be of concern in relation to collision risk and in relation to displacement impacts. Nevertheless, these scores should be seen as iterative, requiring to be updated as more data become available, and possibly to be made obsolete when macro- and micro-avoidance rates are measured for a range of species at a range of offshore wind farms. The ranking of marine bird species in our collision risk index accords well with the concerns of offshore wind farm developers in Scottish waters, gulls and gannets being a particular concern at many offshore wind farms as expressed in Environmental Statements and Environmental Impact Assessments. However, there is a need for post-construction monitoring data from offshore wind farms to assess more fully the accuracy of these predictive indices, and there is an urgent need to study both macro-avoidance and micro-avoidance behaviour of different seabird species.

5. Conclusions

This paper advances previous work on likely impacts of offshore wind farms on marine bird populations by separating risks of collision mortality from risks of disturbance/displacement. These two aspects affect different marine bird species. An offshore wind farm collision risk index identifies populations of gulls, white-tailed eagles, northern gannets and skuas as the marine birds in Scottish waters most vulnerable to collision mortality impacts. In contrast, populations of divers and common scoters appear most vulnerable to displacement impacts. The collision risk index is particularly affected by the proportion of birds flying at collision risk height, and there is a need to collect more data on marine bird flight heights. Populations identified as most vulnerable should be the focus of future monitoring studies, but there is a need to develop research into macro- and micro-avoidance rates and how these vary among species.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2013.01.025.

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Full title: Light pollution causes object collisions during local nocturnal manoeuvring flight by adult Manx shearwaters (*Puffinus puffinus*)

Running head: Lights out for Manx shearwaters

Tim Guilford[1], Oliver Padget[1], Sarah Bond[1] and Martyna M. Syposz[1]

[1] Department of Zoology, University of Oxford, Oxford, Oxfordshire, England

* *Correspondence author: E-mail: tim.guilford@zoo.ox.ac.uk*

Abstract

Understanding the detrimental effects of anthropogenic light on nocturnally mobile animals is a long-standing problem in conservation biology. Seabirds such as shearwaters and petrels can be especially affected, perhaps because of their propensity to fly close to the surface, making them vulnerable to encountering anthropogenic light sources.

We investigated the influence of light pollution on adult Manx shearwaters at close range in foggy conditions. We recorded collisions with a building at a breeding colony for six consecutive pairs of intervals in which the house lights were left on as normal for 135 seconds, then turned off for 135 seconds. The relationship between lighting condition and collision frequency was highly significant, with a collision rate in the presence of lighting around 25 times that in its absence. Our results show that birds were clearly affected by the lights, by being either directly attracted, or disorientated during flight close to the structure. This could have been due to the light source itself, or an indirect effect of the all-round reflective glow in the fog perhaps interfering with visual or magnetic control inputs on both sides of the bird simultaneously. Our results suggest a mechanism by which the screening of artificial lights close to shearwater breeding areas, at least during foggy nights, could lead to improved welfare and

survival at breeding colonies.

Introduction

Understanding the detrimental effects of anthropogenic light on nocturnally mobile animals is a long-standing problem in conservation biology (Montevecchi 2006; Gaston *et al.* 2013; Gaston *et al.* 2014). Artificial light at night can draw individuals from long distances, whilst repelling others, affecting many activities including foraging (e.g. Garber 1978; Frank 2009; Pereszlényi *et al.* 2017), reproductive behaviour (e.g. Miller 2006; Kempenaers 2010; de Jong *et al.* 2015; Russ *et al.* 2017), and daily, monthly or annual movements (e.g. Salmon 2003; Mathews *et al.* 2015; Rodríguez *et al.* 2017).

Amongst the most endangered groups of birds (Croxall et al. 2012), shearwaters and petrels (Procellariiforms) are especially badly affected by anthropogenic light sources and the grounding of their fledglings in particular has been studied in many parts of the world (Rodríguez *et al.* 2017). Manx Shearwaters (*Puffinus puffinus*), which breed at island colonies predominantly around the UK and Ireland, are classified as of Least Concern by the IUCN, but still they are often reported grounding in artificially lit urban areas or at other light sources particularly during the fledging period (Brooke, M. 1990; Le Corre *et al.* 2002; Rodríguez et al. 2008; Miles *et al.* 2010; Archer *et al.* 2015). There are fewer studies on the grounding of adults on land, in this or other species, since adults usually constitute a small percentage of the individuals affected in any fallout (Le Corre *et al.* 2002; Rodríguez & Rodríguez 2009; Telfer *et al.* 1987). Here we report a short experiment designed to test the instantaneous effect of anthropogenic house light on collisions with a man-made object, and outside of the fledging period when only adults are present at breeding colonies.

Electric lighting is used to provide night service to the seasonal residents (a nightly summer maximum of 42 staff and tourists, of which up to 10 might stay in the Island Office) of the several buildings on Skomer Island National Nature Reserve, which is an internationally important Manx shearwater breeding colony. Shearwaters returning to the colony sometimes collide with the buildings and higher numbers of crashing seabirds are expected on cloudy and rainy nights (Telfer *et al.* 1987; Jones 1980). It may be that more birds visit breeding colonies in such conditions anyway, when there is less ambient light from the moon (Riou & Hamer 2008), but it is also possible that visual guidance in local manoeuvring flight is less effective and this contributes to collision risk. To determine whether there is a local effect of artificial light on collisions with the structure from which it is emanating, we conducted a very short experiment.

Study area

Skomer Island (51° 44´ N; 5° 19´ W) hosts the biggest colony of Manx shearwaters in the world, an estimated 316 000 breeding pairs, making up around 36% of the global breeding population when combined with the neighbouring islands of Skokholm and Middleholm (Perrins *et al.* 2012), The other species active at night on the island include European storm petrels (*Hydrobates pelagicus*), rarely seen close to the Island Office and not on the night of our experiment, and extremely unusually, vagrant shearwater species. There are no migratory passerines at this time of year. By contrast, thousands of Manx shearwaters fly low over the colony each night at this time of year as they return to their burrow nests (if breeding), or in display flights whilst calling to prospective partners. Typically, when a shearwater collides with the building it will make a loud thud (too loud for a smaller bird), and will fall to the ground where it will remain for a few seconds or minutes, appearing stunned, before walking into the undergrowth. It is therefore overwhelmingly likely that every single impact we heard was of a different individual Manx shearwater. We do not know the fate of crashed birds in general, but very occasionally we find a bird killed by the impact or bleeding from the head (TG personal observations), suggesting that whilst the vast majority escape to cover in the minutes following collision, there is the potential for serious injury which might affect future survival. We did not attempt to recover or assess birds for the effects impact during this experiment.

Methods

On 27th May 2015, whilst undertaking fieldwork, we noticed that for several hours there were many shearwater collisions with the building. We therefore opportunistically conducted an experiment, exploiting the occasion of an unusually foggy night. The number of significant shearwater collisions with a prominent man-made structure, the Island Office (Fig. 1), on Skomer Island NNR, was recorded by tallying in a notebook each audible crash with roof, walls or windows that could be heard from inside the researchers' quarters located centrally on the seaward (north) side of the structure. The predominantly wooden building is of a two-part design with a lower one-storey section measuring 17.5m x 7.7m x 5.5m

high at the top of the pitched roof leading to a taller two-storey section measuring 7.6m x 12.0m x 8.5m at the highest point. The design of the study was decided as soon as we started observing the phenomenon and data on collision incidents were then recorded for six consecutive pairs of intervals in which (A) the house lights were left on as normal for 135 seconds, then (B) the lights were turned off. This interval (2.25 minutes) was decided arbitrarily but to provide a short period (half an hour) that would allow six replicates during the middle of the night whilst the weather conditions persisted and before the colony became empty as the nights in May are short at this latitude. No other artificial lighting, except the very dim emergency exit panels and LEDs from electronic equipment indoors, was visible in the building. Luminance from two white fluorescent twin

tube compact lights (Pro-light 11W 2700k) was visible externally via two rectangular glass windows (each 0.8m x 1.0m tall), and one small (0.37m diameter) round window in the external door, and it is these sources that were extinguished during the lights-off treatment. The experiment started at 2330 GMT and lasted 27 minutes.Results

The relationship between lighting condition and collision frequency was highly significant (Wilcoxon Test W=0, N=6, P=0.0044; Table 1), with a collision rate in the presence of lighting (5.9 collisions per minute) around 25 times that in its absence (0.2 collisions per minute).

Table 1. Results from study shows the collision count data (rates per minute in brackets) across the six sequential treatment interval pairs.

Interval	**I**	**II**	**III**	**IV**	**V**	**VI**	**Mean**	**Median**
Lights on	13 (5.8)	14 (6.2)	10 (4.4)	11 (4.9)	18 (8.0)	14 (6.2)	13.3 (5.9)	13.5 (6.0)
Lights off	1 (0.4)	0 (0)	0 (0)	1 (0.4)	0 (0)	1 (0.4)	0.5 (0.2)	0.5 (0.2)

Discussion

The extinguishing of artificial building lights caused a dramatic (25-fold) and almost instantaneous reduction in shearwater collisions with the man-made structure from which the light was emanating. It is possible that the sound of one bird may be masked by another, so our numbers may even be, to some extent, underestimates. In addition, the recorders informally observed that collisions during the lights-off treatment always occurred shortly after the switch in treatment, suggesting that collisions during the lights-off period were mainly influenced by the effect of the light that had just been turned off. Because the treatment intervals were short (135 seconds) our experiment suggests a predominantly local effect of lighting, with collisions by birds already at the colony and in the vicinity of the buildings. In an earlier GPS tracking study we estimated the mean speed of Manx shearwaters in flight to be around $11 m.s^{-1}$ (Guilford et al. 2008), allowing for the maximum attraction distance during an illuminated period to be about 1.5km on this relatively calm night. Of course it is possible that birds may have been attracted in to the area by illumination prior to the experiment, or during a previous lights-on interval during the experiment itself, but restricted penetration of light in foggy conditions is likely to mean that in fact our building lights were only visible from much shorter distances. Furthermore, the often immediate effect of turning on the lights and the striking disparity in collision rates between the on and off treatments, strongly suggests that a local effect of the light is responsible for inducing collision. A different design would be required to determine whether, as has been suggested for urban groundings (e.g Miles *et al.* 2010; Reed *et al*. 1985), artificial lights can also attract birds from longer distances under some conditions. A study using GPS on Cory's shearwaters Rodríguez *et al.* (2015) showed that locations where birds were rescued had greater light pollution levels than at colonies, and found that areas with high intensity light attracted birds from further away than areas with low intensity light. In our study, birds already at or close to the colony are either being attracted by the light source locally, or are being disoriented during visually guided flight close to the structure either directly by the light source or indirectly by the reflected glow in the fog.   These two effects could operate in combination: Day *et al.* 2003). Although it might have been interesting to replicate this experiment under different conditions this has not been possible because curtains have been fitted to the building windows (in response to our observations) so that very restricted light now emanates from the structure under normal operation. Paradoxically, manipulation of light levels would now involve knowingly inducing potentially fatal collisions with the structure, whereas in the current experiment it opportunistically involved reducing them, thereby changing the ethical and legal basis of the research under UK law.

The mechanism by which light interferes with normal behaviour in flying birds is unknown. Hypotheses range from direct interference with stellar, lunar, or magnetic compass orientation mechanisms, to a normal attraction to light sources having its origin in mechanisms for hunting bioluminescent prey (for reviews see Montevecci 2006; Gaston *et al.* 2013). In our experiment birds would have been engaging in control flights above the colony rather than directional flights of any distance. This makes it unlikely that the mechanism interfered with was part of either long-distance guidance (the role normally assumed for compass orientation in migratory birds for example), or hunting. Direct attraction to the light is a possibility (Reed, 1986), but it is interesting that most of the collisions witnessed in our experiment were not with the windows themselves, from which the light emanated, but with the surrounding structure. Furthermore, in fog as here light is scattered to produce a locally bright glow but with little distance penetration, so birds should if anything be attracted from less far than on clear nights. Although we did not explicitly compare fog with clear conditions in this experiment, it is certainly the informal experience of researchers (see also Black, 2005) that collisions are much rarer on clear nights which is the opposite of what would be expected if direct attraction was responsible. In the absence of the light, birds are apparently normally able to avoid collision with this structure despite the poor visibility. One hypothesis, therefore, is that sudden proximity to relatively bright light may disrupt the ability of birds to use their normal dark-adapted visual guidance effectively. This could be more pronounced on dark nights when birds are more dependent on dark-adaptation. Perhaps the scattering of light in fog also contributes by interfering with dark-adaptation in multiple directions, simultaneously disabling low-light visual guidance input from both eyes. A second hypothesis, however, is that birds manoeuvring in low light conditions might make use of a magnetic compass as a "heading indicator" (Guilford & Taylor 2014) to monitor and control local changes in orientation relative to the ground. The suggestion that birds moving in a fluid medium might use compasses as heading indicators in flight control has been made before for a sun-compass during diurnal flight (Guilford & Taylor 2014), and we now know that Manx shearwaters have a time-compensated sun compass (Padget *et al.* 2018), but in nocturnal flight when solar cues are unavailable a magnetic compass might operate in a similar way. It is possible, therefore, that a light-dependent magneto-receptor (Hore & Mauritsen 2016) becomes temporarily disrupted by saturation in the presence of bright light, and that this disrupts the bird's ability to guage its heading changes during local flight manoeuvers, causing collision. Again it is possible that in fog input from both eyes (eyes are thought to be the organs responsible for sensing magnetic direction) become affected simultaneously because of local light scattering.

Whether the effect of light witnessed in our experiment is an effect on visual or magnetic guidance in flight control remains to be determined. However, our results do suggest that light pollution may cause interference effects at several scales, with disruption of local flight control in addition to one or more attraction or compass disorientation effects operating at longer distances.

Measurements made during a rescue programme for Manx shearwaters suggested that around 7% of fledglings die as a result of grounding (Syposz *et al*. 2018), but such estimates are biased and the likely death rate may generally be much higher (about 40% in a study of short-tailed shearwaters) where humans do not intervene (Le Corre *et al.* 2002; Rodríguez & Rodríguez 2009; Fontaine *et al.* 2011; Rodríguez *et al.*, 2017). In particular the seriousness of the effect on flying shearwaters of collision with a man-made structure is not well understood. Shearwaters rarely alight on a terrestrial surface with great control unless the wind strength and direction is very favourable (personal observation), so it is common to see or hear them crash into the undergrowth during normal attempts to land and they may be at least partially adapted to rough landings. However, after collision with buildings birds can usually be found sitting still for some time before making their way to cover, but on occasion may be found bleeding from the beak or killed by the impact. The longer-term effect of collisions on birds that survive immediate impact is not known, however. Birds that perish on the surface during the night, or fail to reach their nests, are likely to be removed and eaten by aerial predators and scavengers (mainly great black-backed gulls *Laurus marinus* on Skomer, where there are no mammalian predators) (Raymond *et al.* 1993).

Our results suggest that the normal controlled flight behaviour of adult shearwaters can be severely negatively affected by proximity to artificial lights on structures under some nocturnal conditions. They suggest a mechanism by which the screening of artificial lights close to shearwater breeding areas, at least during foggy nights, could lead to improved welfare and survival at breeding colonies. Off-shore, artificial light sources on structures or vessels are known to cause collisions in open water, particularly during foggy conditions, which can be reduced by light-screening or reduction (Black, 2005; Glass & Ryan, 2013). So in addition it is possible that lights on vessels close to colonies, or close to the flight paths of returning birds, might interfere with collision avoidance behaviour in adult shearwaters, even if they do not attract birds from a distance. Large, highly lit tankers commonly anchor in the waters close to Skomer, but their effect on the Manx shearwaters remains unknown.

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Figure 1. Photograph of the Island Office showing its position on the shearwater nesting slopes at north haven on Skomer island. The windows through which light emanated during the lights-on treatment are the two furthest right of the line of five in the lower section of the building, and a small circular window in the door immediately right of these.

Table 1. Results from study shows the collision count data (rates per minute in

brackets) across the six sequential treatment interval pairs.

Interval	**I**	**II**	**III**	**IV**	**V**	**VI**	**Mean**	**Median**
Lights on	13 (5.8)	14 (6.2)	10 (4.4)	11 (4.9)	18 (8.0)	14 (6.2)	13.3 (5.9)	13.5 (6.0)
Lights off	1 (0.4)	0 (0)	0 (0)	1 (0.4)	0 (0)	1 (0.4)	0.5 (0.2)	0.5 (0.2)

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NATURAL ENGLAND

JNCC
Joint Nature Conservation Committee

Scottish Natural Heritage
All of nature for all of Scotland

Joint Response from the Statutory Nature Conservation Bodies to the Marine Scotland Science Avoidance Rate Review

25th November 2014

1. Summary of recommendations

This joint response from the Statutory Nature Conservation Bodies (SNCBs)[1] is intended to provide recommendations on how the Offshore Wind Farm (OWF) industry could appropriately apply findings from the Marine Scotland Science Avoidance Rate Review[2] (hereafter 'the report') to the impact assessment process. This section provides a summary of our recommendations on best practise impact assessment using Collision Risk Modelling (CRM) in light of the report. The rationale for these recommendations is outlined within the main body of the paper.

Basic Band model (Options 1 and 2) recommendations

Whenever the Basic Band model (Options 1 or 2) are used for collision mortality estimation:

- Collision mortality estimates should be presented using the mean total avoidance rate (as detailed in Table 1 below) as well as a range of avoidance rates that reflects the variability and uncertainty linked to it (i.e. ±2SD).

Basic Band model (Option 2) recommendations

Whenever the Basic Band model (Option 2) is used for collision mortality estimation:

- Collision mortality estimates should be presented using the mean total avoidance rate (as detailed in Table 1 below) as well as a range of avoidance rates that reflects the variability and uncertainty linked to it (i.e. ±2SD).

Furthermore, the following information should also be provided:

- Presentation and comparison of both site-specific and generic flight height data (including median and confidence limits).
- A range of collision mortality estimates using the lower and upper confidence limits of the generic modelled flight distribution.

Extended Band model (Option 3) recommendations

It is **not appropriate** to use the **Extended Band model** in predicting collisions for **northern gannet** or **black-legged kittiwake**, at the current time.

Whenever the Extended Band model (Option 3) is used for **large gull** collision mortality estimation:

- Collision mortality estimates should be presented using the mean total avoidance rate (as detailed in Table 2 below) as well as a range of avoidance rates that reflects the variability and uncertainty linked to it (i.e. ±2SD).

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[1] To be read as comprising the Joint Nature Conservation Committee (JNCC), Natural England (NE), Natural Resource Wales (NRW), Northern Ireland Environment Agency (NIEA), Scottish Natural Heritage (SNH).

[2] Cook, A.S.C.P., Humphries, E.M., Masden, E.A., and Burton, N.H.K. 2014. The avoidance rates of collision between birds and offshore turbines. BTO research Report No 656 to Marine Scotland Science.

Furthermore, the following information should also be provided:

- Presentation and comparison of both site-specific and generic flight height data (including median and upper and lower confidence limits).
- Presentation of both Basic Band model outputs (Options 1 and 2) with the measures of confidence outlined in **Section 3.4**, in addition to Extended Band model outputs.
- A range of Extended Band model collision mortality estimates using lower and upper confidence limits of the generic flight distribution.

2. Introduction

The SNCBs welcome this important piece of work and congratulate Marine Scotland Science (MSS) for taking the initiative to commission this report and the British Trust for Ornithology (BTO) for conducting such a thorough review.

We note that a key finding of the report is the absence of studies of collision mortality and avoidance rates at offshore wind farms. The report concludes that the bulk of avoidance rate studies are from onshore or coastal wind farms. Having reviewed this body of work the report concludes that for many species (or groups of species) there are insufficient empirical data to derive meaningful avoidance rates at micro-, meso- or macro-scales. To a large degree, this inability to quantify these separate components of overall avoidance rates was due to lack of spatial resolution in empirical data and/or technical capacity to separate these components of overall avoidance.

The lack of empirical data from offshore wind farms contributing to the report's conclusions must be considered in the future applicability of recommended avoidance rates in an offshore context. Nevertheless, with many offshore projects at critical junctures in the decision-making process, we support some of the report's findings for use in offshore wind farm collision risk modelling, until such time as more empirical data are available.

This joint SNCB position represents a considerable shift in advice on avoidance rates for use with collision risk modelling in light of the report. This reflects the obligation on SNCBs to amend their advice as the best available evidence continues to evolve. However, it must be recognised that further empirical data on bird avoidance, flight heights and activity at offshore wind farms will continue to accrue and may alter our understanding of the likelihood of seabird collisions in the future. Therefore, the SNCBs position on avoidance rates may, as the current response bears testimony, be subject to change as more empirical data become available, e.g. ORJIP study (refer to section 6).

The following advice is applicable only to collision risk modelling for the five priority species and other gull species covered by the report. For other seabirds (e.g. skuas) and waterbirds (e.g. divers, seaducks, etc.) the report does not conduct an analysis or provide recommended avoidance rates for any version of the Band model. In light of this, the SNCBs continue to recommend the basic Band model, in conjunction with a default 98% avoidance rate, for predicting collisions of species other than those detailed here, until such time as further species-specific work has been undertaken.

3. General Statements of Agreement

3.1 Avoidance rates for use with the Basic Band model

The SNCBs support the recommended avoidance rates (AR) presented in the report in relation to four of the five priority species (the exception being black-legged kittiwake) as we consider these rates to be the best available evidence regarding the average avoidance rates for use with these species (Table 1 below). However, it should be noted that in several instances these are not derived from species-specific information and as such represent avoidance rates for species groupings (e.g. 'large gulls') rather than for an individual species.

The SNCBs also recommend that the estimated variance in empirically derived estimates of within windfarm avoidance rates, as presented within the report, be acknowledged and explored in any application of these total avoidance rates in future collision risk modelling.

Collision mortality estimates should be presented using the mean total avoidance rate as well as a range of avoidance rates that reflects the variability and uncertainty linked to it (i.e. ±2SD).

Table 1. Basic Band avoidance rates derived from MSS avoidance rate report Table 7.2. This table represents new avoidance rates (± 2SD) supported by the SNCBs for use in impact assessment collision risk modelling.

Species (rate used)	**Basic Band model avoidance rate (2SD)**
Northern gannet (all gull avoidance rate)	**0.989** (± 0.002)
Black-legged kittiwake (~~small~~ all gull avoidance rate)	~~0.992~~ **0.989** (± 0.002)*
Lesser black-backed gull (large gull avoidance rate)	**0.995** (± 0.001)
Herring gull (species-specific avoidance rate)	**0.995** (± 0.001)
Great black-backed gull (large gull avoidance rate)	**0.995** (± 0.001)

** Note: 'strike-through' data as presented in Table 7.2 of the report; data in 'bold' as recommended by SNCBs (see section 4.1 below for further explanation).*

3.2 Northern Gannet avoidance rates for Basic Band model

We note that the northern gannet avoidance rate represents, in reality, an 'all gull' avoidance rate, due to the absence of species-specific within windfarm avoidance data. We agree it is inappropriate to combine a within wind farm avoidance rate for this species based on the rates established for gulls with the gannet-specific macro-avoidance rate of 0.64, as this would result in a non-evidence based total avoidance rate higher than for any of the other groups considered. However, we agree that, without a within windfarm avoidance component for gannets, and acknowledging their more marked tendency to exhibit macro-avoidance behaviour; it is reasonable to ascribe to gannets the lowest of the total avoidance rates determined for any of the other groups (i.e. the 'all gull' category). In the absence of gannet-specific data for all elements of avoidance, this is also appropriately precautionary.

3.3 Use of avoidance rates to 3 decimal places

The SNCBs advise that, following recommendations in the report, practitioners of collision risk modelling now use avoidance rates to three decimal places as outlined above rather than rounding figures to two as typically done previously (e.g. 0.98). The report presents within windfarm avoidance rates to 4 decimal places (Table 7.1) but given the inherent uncertainty in the data the final recommended total avoidance rates are presented to only 3 decimal places (Table 7.2). The SNCBs agree with the recommendation in the report to use avoidance rates to three decimal places, until such time as improvements are made to the characterisation of uncertainty within the models, avoidance rates and flight height distributions used.

3.4 Recommended avoidance rates for use with Band model Option 2

We acknowledge that Options 1 and 2 of the Band model are mathematically identical (the Basic Band model) and consequently that it is appropriate to use the same predictive avoidance rate for both options. But the estimates of avoidance rates within section 5.4 of the report derived using Option 2 were in every case lower than using Option 1.

The SNCBs accept that this reflects the mismatch between the observed site-specific values of the proportion of birds recorded flying at predicted collision risk height (PCH) and the equivalent values derived using generic modelled flight height distribution data, and hence that the lower avoidance rates derived under Option 2 are anomalous.

We accept the recommendation that the higher avoidance rates derived using Option 1 should be used with the Basic Band model. For any future application of these recommended Basic Band model avoidance rates in combination with generic modelled flight height distribution data (i.e. use of Option 2), we advise the following is included:

- Presentation and comparison of both site-specific and generic flight height data (including median and confidence limits).
- A range of collision mortality estimates using the lower and upper confidence limits of the generic modelled flight distribution.
- A range of collision mortality estimates reflecting the empirically derived range of uncertainty around the mean avoidance rate (as detailed in Table 1 above).

This is to ensure due consideration is given to the uncertainty surrounding the generic flight height distribution and its applicability to the wind farm in question and the uncertainty around the avoidance rate itself.

4. Areas of Disagreement or Uncertainty

4.1 Kittiwake avoidance rates for Basic Band model

The SNCBs consider that the principles applied to northern gannet avoidance rate recommendations in the face of lack of species-specific data (i.e. application of the lowest “all gull” alternative rate derived by the review) should also be applied to black-legged kittiwake avoidance rates. The report includes kittiwake within the ‘small gull’ category, the data for which are predominantly derived from common gulls and black-headed gulls. Indeed, no species-specific data for kittiwakes are represented within the ‘small gull’ category at all.

While the report provides a theoretical argument towards the inclusion of kittiwakes within the ‘small gull’ category, there are equally arguments that could be put forward in support of their treatment as part of the ‘large gull’ category (i.e. typical flight speeds and generally more marine behaviour). Consequently, we feel these somewhat subjective arguments should be discounted in favour of a more consistent and precautionary approach with regards the treatment of other species lacking species-specific within windfarm avoidance rate data (namely gannets).

Therefore, we recommend that, until such time as it is possible to calculate a species-specific avoidance rate for kittiwakes, they are classed under the more generic (and precautionary) ‘all gull’ category.

4.2 Applicability of Extended Band model avoidance rates

The SNCBs highlight that the report makes no recommendation regarding avoidances rates for use with the Extended Band model for northern gannets and black-legged kittiwakes due to a lack of species-specific data.

This means it is not appropriate to use the Extended Band model in predicting collision figures for these species at the current time.

For the other three priority species covered by the report (see Table 2 below), we note that while we accept the work undertaken to derive avoidance rates for use with Option 3; we remain concerned over the use of the Extended Band model. In particular, we have concerns regarding its sensitivity to flight height distribution data, and the uncertainty this component introduces to variation in estimates of collision.

Table 2. Extended Band avoidance rates taken from MSS avoidance rate report Table 7.2.

Species (rate used)	**Extended Band model avoidance rate (2SD)**
Northern gannet	Not available
Black-legged kittiwake	Not available
Lesser black-backed gull (large gull avoidance rate)	**0.989** (± 0.002)
Herring gull (species-specific avoidance rate)	**0.990** (± 0.002)
Great black-backed gull (large gull avoidance rate)	**0.989** (± 0.002)

We advise those wishing to present Extended Band model predictions for those species/groupings where sufficient data on appropriate avoidance rates has been compiled within the report (i.e. those noted in Table 2 above), that the following information must also be provided:

- Presentation and comparison of both site-specific and generic flight height data (including median and upper and lower confidence limits).
- Presentation of both Basic Band model outputs (Options 1 and 2) with the measures of confidence outlined in **Section 3.4**, in addition to Extended Band model outputs.
- A range of collision mortality estimates reflecting the empirically derived range of uncertainty around the mean avoidance rate applicable to the output of the extended Band model (as detailed in Table 2 above).
- A range of Extended Band model collision mortality estimates using lower and upper confidence limits of the generic flight distribution.

Presentation of uncertainty around both flight heights and avoidance rates and incorporation into the analysis in this way, will provide clarity over the range of possible collision mortality outcomes and which collision risk model outputs are most appropriate for the assessment of the wind farm(s) in question.

5. Further Detailed Explanation of SNCB Positioning

5.1 Constraints on the wider applicability of Extended Band model avoidance rates

The report highlights, in many instances, significant differences between the observed proportion of birds at PCH (within the studies used to derive the avoidance rate estimates) and the proportion predicted to be at collision risk height derived from generic modelled distributions of flight heights. The latter estimates are almost invariably lower than the former.

In the case of 'small gulls' this discrepancy is so great that the report concludes it would be inappropriate to use avoidance rates derived for the Extended Band model for this group. Similar discrepancies, although less marked, also occur in the case of 'all gulls', 'large gulls' and 'herring gull'. Therefore, while accepting that the greater discrepancy in the case of 'small gulls' is such that the resultant extended model avoidance rate for that group (0.9027) and for 'all gulls' (which includes small gulls) (0.9672) are so unreliable as to be of no practical use, we can accept the use of the Extended Band model ARs derived for herring gulls and the other two larger species of gulls (Table 2 above), provided this is accompanied by acknowledgement of uncertainty around the underlying flight height data, and provided that equivalent Basic Band model AR outputs are presented for consideration alongside those from the extended Band model.

5.2 Need for on-going exploration of other aspects of uncertainty within the collision risk modelling framework

The SNCBs acknowledge that the Extended Band model is a more refined mathematical model than the Basic Band model in that it allows consideration of the fine-scale variation in the distribution of flight heights of birds flying within the rotor swept height band, and the variation as a function of height within that risk band in the probability of: i) passing within the perimeter of the rotating disc and ii) being hit during that passage. This Extended Band model is therefore a more advanced tool with which to derive estimates of the non-avoidance collision mortality.

However, the use of Option 3 in collision risk modelling is dependent upon; i) the availability of appropriate non-avoidance rates to apply to its non-avoidance estimate of collision mortality and ii) the degree of uncertainty around and confidence in the general applicability of the modelled flight height distribution on which it is based.

The report presents two pieces of evidence that highlight the significance of having robust estimates of the proportion of birds at PCH. These are:

- Deriving an Extended Band model AR for 'small gulls' was thwarted by the consistent mismatch between generic modelled flight height distributions and the observed proportion of birds flying at PCH in the empirical studies from which ARs were being derived. This may be because the empirical studies used within the report to derive ARs were all onshore, while the suite of studies used to model generic flight height distributions included more offshore data. In any event, this mismatch indicates extreme caution is needed when applying the generic flight height distribution required of the Extended Band model.

- The exploration of the sensitivity of the non-avoidance rate to variation in several key parameters indicates that the non-avoidance rate predicted by the Extended Band model can be highly sensitive to variation in the simulated flight height distribution. Although this appears not to be a consistent issue, it occurs sufficiently often to support the assertion above that extreme caution is needed in application of the generic flight height distributions to different sites.

Finally, there remains the issue of whether the derivation of collision mortality estimates using the Extended Band model is or is not more sensitive to errors in the attribution of birds to differing flight height bands in the field. Irrespective of the relative sensitivity of the Basic Band model and the Extended Band model in this respect, it is clear that errors in height estimation is another factor which needs to be considered in applying any estimate of flight height in collision risk modelling.

5.3 Issues limiting applicability of the correction factor g

The SNCBs note that the report shows in Annex 1 how the avoidance rates for use with the Basic and Extended Band models are related. The Basic model gives an estimate of no avoidance collision mortality, if information is available on turbine and bird parameters and the number of bird flights at risk height. The Extended model refines this estimate to take account of the distribution of flight heights, if detailed information on the latter is also available. The ratio between the Extended Band model estimate of collision rate and that from the Basic Band model, **if the same height distribution data are used in the latter to calculate the proportion of flights at collision risk height**, is termed the *g* factor.

Annex 1 of the report shows that if both models are applied to a reference windfarm, working back from an observed collision rate such as to derive the avoidance rate appropriate for each model, the non-avoidance rate for use with the Extended model **must be** *1/g* times the non-avoidance rate for the Basic model. This non-avoidance rate may then be used in estimating collision mortality at any new windfarm, using the Extended model, **if the flight height distribution at the new windfarm site is known**. **Thus to make use of the Extended model requires knowledge of the flight height distribution at both the reference site and at the new windfarm site**.

g factors have been estimated in Appendix 7 of the report, by comparison of the non-avoidance collision mortality estimates from the Basic and Extended Band models, both being based on assumed generic flight height distributions. It is clear, though, that there is a substantial mismatch between the observed values of the proportion of birds at collision risk height (PCH) and the proportion at risk height calculated from the generic modelled flight height distributions. The SNCBs consider it likely that estimates based on the latter are in many cases unreliable. The current review indicates that there is very little site-based information on the flight height distribution at the 'reference' windfarms reviewed, such as to enable *g* factors to be derived at each of these reference sites on the basis of site-specific data.

Until detailed flight height distributions are derived on a site-specific basis for a reference windfarm (or the applicability of a generic flight height distribution confirmed), the **SNCBs advise that the *g* factors presented in Appendix 7 should not be used to derive a windfarm avoidance rate for use with the Extended model at any new offshore windfarm**. In particular it would be wholly wrong to use avoidance rates appropriate for the Basic Band model, but based on observed values of the proportion of flights at risk, in conjunction with the *g* factors in Appendix 7 of the report which are calculated based on the generic flight distributions.

Where the report recommends use of avoidance rates for use with the Extended Band model, these are based on the assumed generic flight height distributions and hence may also be inaccurate. However, for these reference windfarms, the generic flight height distributions almost always predict a substantially smaller proportion of bird flights at risk height than have been observed in the site data. A correspondingly greater proportion of birds must be deemed not to take avoiding action in order to match the observed rate of collision at each reference windfarm. Hence the avoidance rates so calculated are precautionary, that is to say the true avoidance rates are most likely to be greater. **For those species for which they are quoted, the SNCBs accept the use of these avoidance rates with the Extended Band model (Table 2 above), subject to the qualifications set out in the report and presentation of the additional information as set out in section 4.2 above.**

The SNCBs acknowledge that as more detailed flight height information is acquired, it may prove possible to derive more reliable estimates of the non-avoidance rates for use with the Extended Band model, and the associated *g* factors. Nonetheless we advise that even then, any future application of the Extended Band model in collision risk mortality estimation should take account of the degree of uncertainty in all aspects of the underlying flight height data used, and present a range of possible outputs which reflect the degree of uncertainty around the assumed flight height distribution.

6. Next Steps

As outlined, this joint SNCB position reflects the obligation on SNCBs to amend their advice as the best available evidence continues to evolve. Consequently, this SNCB position statement will be subject to review as more empirical data become available (e.g. ORJIP study). Further to this, we advise that:

1. A review of this position statement will be undertaken by the SNCBs once ongoing work to quantify error and uncertainty in flight height distributions and collision risk modelling reports are completed. A NERC funded project, undertaken by Dr Liz Masden[3] , is expected to address some of these outstanding questions by spring 2015.

2. A strategic data collection programme should be drawn-up and agreed between all interested parties to supplement data collected under ORJIP. This should be aimed at gathering additional species-specific avoidance behaviour data (particularly for gannets and kittiwakes) to allow derivation of more refined avoidance rates than those recommended in the MSS report. Implementation of the programme should be overseen by regulatory bodies in recognition of their key role in the consenting process and formulation of licence conditions.

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[3] Environmental Research Institute, University of Highlands and Islands, Thurso.

Spatio-temporal patterns of foraging behaviour in a wide-ranging seabird reveal the role of primary productivity in locating prey

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Adam Kane
University College Cork

Enrico Pirotta
University of St Andrews

Saskia Wischnewski
RSPB

Mark Jessopp
University College Cork

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Spatio-temporal patterns of foraging behaviour in a wide-ranging seabird reveal the role of primary productivity in locating prey

Adam Kane[1,2,*,#], Enrico Pirotta[2,3,#], Saskia Wischnewski[2,5], Emma Jane Critchley[2,6], Ashley Bennison[2,7], Mark Jessopp[2,7], John L. Quinn[2,4]

[1]School of Biology and Environmental Science and Earth Institute, University College Dublin, D04 N2E5, Ireland
[2]School of Biological, Earth and Environmental Sciences, University College Cork, Cork, T23 TK30, Ireland
[3]Department of Mathematics and Statistics, Washington State University, Vancouver, Washington 98686, USA
[4]Environmental Research Institute, University College Cork, Lee Road, Cork, T23 XE10, Ireland

[5]*Present address:* RSPB Centre for Conservation Science, RSPB, The Lodge, Sandy, SG19 2DL, UK
[6]*Present address:* Marine Science Institute, University of California, Santa Barbara, California 93106, USA
[7]*Present address:* MaREI Centre, Environmental Research Institute, University College Cork, P43 C573, Ireland

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ABSTRACT: Predicting the distribution and behaviour of animals is a fundamental objective in ecology and a cornerstone of conservation biology. Modelling the distribution of ocean-faring species like seabirds remains a significant challenge due to ocean dynamics, colony-specific effects and the vast ranges seabirds can cover. We used a spatial and behavioural approach to model the distribution of the Manx shearwater *Puffinus puffinus*, a pelagic, central-place forager that can cover great distances while foraging. GPS data from birds tagged in 2 colonies over 3 yr were modelled with a range of environmental predictors of marine productivity. For both colonies, transitions to foraging behaviour correlated with chlorophyll *a*, and the distribution of foraging behaviour was also associated with areas of high chlorophyll *a* concentration in coastal but not offshore areas for one colony. Furthermore, there was evidence for colony differences in habitat use, prevalence of nocturnal foraging, and for some competitive exclusion on foraging grounds, even though the colonies were 170 km apart. Despite the extensive dataset, our models had modest predictive power, which we suggest can probably only be improved by including biotic interactions, including more direct measures of food resource distribution. Our results highlight the importance of including spatial complexity and data from multiple sites when predicting the distribution of wide-ranging predators, because patterns of distribution and habitat use likely differ across the range of a population.

KEY WORDS: Distribution · Foraging · Hidden Markov model · Manx shearwater · *Puffinus puffinus* · Productivity

1. INTRODUCTION

Understanding where and when species are distributed is a fundamental objective in ecology and critical for effective conservation (Hays et al. 2016, Critchley et al. 2018). Capturing the underlying biotic and abiotic factors that influence an individual's use of space is central to this process (Guisan et al. 2017). Food is perhaps the main proximate driver of a species' distribution, as mobile animals spend most of their time and energy budget navigating through their environment searching for resources (Sequeira et al. 2018). Finding food for many species is a major challenge, especially when food cues are cryptic, and

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*Corresponding author: adam.kane@ucd.ie

[#] These authors contributed equally to this work.

in these cases, it is even more challenging for ecologists to predict where these animals are likely to occur on the basis of their foraging needs. The dynamic nature of the oceans greatly reduces the predictability of prey patch location. Nevertheless, some oceanographic features, such as frontal zones and bathymetric topography, can still correlate with highly productive areas by concentrating nutrient-rich waters (Cox et al. 2018). These areas are hotspots of primary productivity which support a diverse marine community including potential prey for marine predators (Cox et al. 2018). Marine predators can avail of these prey patches — if they can sense them.

One group of higher trophic level marine predators, seabirds, consists of both visual and olfactory foragers. For instance, diurnal northern gannets *Morus bassanus* rely on visual cues, including the presence of conspecifics as well as other species (Davoren et al. 2010, Wakefield et al. 2013). Other species use their olfactory sense (Nevitt et al. 1995, Nevitt & Bonadonna 2005, Dell'Ariccia et al. 2014, Abolaffio et al. 2018). In particular, tubenoses (Procellariiformes) such as shearwaters and petrels respond to volatile, biogenic compounds, including dimethyl sulphide (DMS), produced by algae in response to zooplankton grazing (Dacey & Wakeham 1986). These 'infochemicals' have been proposed as important indicators of food patches to a variety of marine predators, including whale sharks, seals and seabirds (Savoca & Nevitt 2014 and references therein).

Patch predictability also has a temporal component in that diel movements of prey (a predator avoidance strategy) (Fortier et al. 2001) can influence their availability to predators (Hays et al. 2016). Seabirds adjust their foraging tactics in response. Common murre *Uria aalge* dive-depths correlate with the vertical distribution of their capelin prey, while Cory's shearwater *Calonectris borealis* vary between diurnal and nocturnal foraging depending on the behaviour of prey in different habitats (Regular et al. 2010, Dias et al. 2012). The coupling in space and time of food and forager means that habitat models can help us understand the distribution of marine predators (Redfern et al. 2017, Warwick-Evans et al. 2018). Such models often use chlorophyll *a* (chl *a*) concentration and sea-surface temperature, 2 remotely sensed proxies of primary productivity that have been shown to correlate with hotspots of seabird diversity (O'Hara et al. 2006, Bennison & Jessopp 2015, Grecian et al. 2016).

Yet, the relationship between seabird locations and these proxies, notably chlorophyll levels, varies considerably by species and by location. Cape gannets *Morus capensis* switched from transiting to foraging behaviour in response to chl *a* concentration (Sabarros et al. 2014), but northern gannet foraging locations and chl *a* fronts were unrelated (Scales et al. 2014). Suryan et al. (2012) only found a relationship with the distribution of a seabird community by developing a complex chl *a* index. Thus, the universality of chl *a* as a simple and effective predictor of seabird distribution is far from clear.

This is perhaps unsurprising, given the trophic mismatch between the presence of chlorophyll and seabird species feeding at higher trophic levels (Grémillet et al. 2008), as well as the fact that many seabird species do not have as sensitive a sense of smell as the tubenoses. Indeed, McPherson & Jetz (2007) warned that distribution models applied to species at higher trophic levels will be a poorer fit, because such species will respond more to biotic interactions, which are difficult to incorporate. Moreover, the flexibility of seabird foraging strategies (Dias et al. 2012, Shoji et al. 2015), the discovery of significant colony differences in seabird space (Wakefield et al. 2013) and the variation in ocean habitat (Weimerskirch 2007), all add layers of complexity to distribution modelling.

Here we developed a model that integrates potential spatial, temporal and colony-specific influences on the distribution of a wide-ranging, pelagic seabird species — the Manx shearwater *Puffinus puffinus*. We used the framework of species distribution models (SDMs), but explicitly took account of the influence of foraging behaviour in determining a species' distribution (Tremblay et al. 2009). This recent advance is significant because species–environment relationships are behaviour-specific: for example, an individual will have different environmental requirements when foraging, compared to when it is resting (Trathan et al. 2008, Lundy et al. 2012, Sabarros et al. 2014, Scales et al. 2016). Such a distinction is made possible by high-resolution tracking technology that can help discriminate between different movement patterns, potentially corresponding to different behavioural states (Dean et al. 2013, Gibb et al. 2017). For instance, a foraging seabird typically engages in an area-restricted search (ARS) where a high probability of encountering prey is expected (Fauchald & Tveraa 2003).

Within this framework, we used GPS tracking data to explore the spatio-temporal patterns of Manx shearwater foraging activity across 2 colonies and over 3 yr in the Northeast Atlantic. The likely sensitivity of Manx shearwaters to DMS (Nevitt et al. 1995) led us to hypothesize that patches of high primary productivity could act as an environmental signal for these birds to engage in ARS. Diel movements of prey, colony-specific foraging spots reported in other seabirds and dual foraging strategies in Manx shearwaters motivated us to also investigate how these features would shape the distribution of the foraging habitat of this species.

2. MATERIALS AND METHODS

2.1. Study sites

Birds were tracked from 2 study colonies off the west coast of Ireland: Great Blasket (Co. Kerry; 52.10315° N, 10.5223° W) and High Island (Co. Galway; 53.54663° N, 0.2573° W), which host populations of 29 000 and 900 breeding pairs of Manx shearwaters, respectively (Mitchell et al. 2004, Arneill 2018). Field work took place during July–August in 2014 and 2015 in both colonies, but additionally in 2016 on High Island. The specific areas within islands used for trapping birds were similar across years.

2.2. Tagging procedures and ethics statement

This work was approved by University College Cork animal ethics committee and licensed by the National Parks and Wildlife Service (Ireland) and the British Trust of Ornithology (UK). Chick-rearing birds were caught at night using purse nets at burrow entrances in 2014 and 2015 on Great Blasket. On High Island, we used purse nets in 2014 (chick-rearing), but set up access tunnels in 2015 (incubation and chick rearing) and 2016 (chick-rearing) to monitor adults and chicks (Wischnewski et al. 2019), to determine potential tagging effects. Both parents in a pair were never tagged at the same time as a precaution against potential effects on chicks. GPS tags (i-gotU GT-120, Mobile Action Technology) were set up to record at 4 min, 8 min (both chick-rearing) and 12 min (incubation) intervals. The start time was set to either 02:00 or 03:00 h after the planned deployment to ensure the tags were recording after the adults had left the burrow. GPS tags were waterproofed using heat shrink (Finitube CLR-25, FinishAdapt) and attached to the bird's dorsal body feathers using strips of Tesa tape (4651). Tagged adults were weighed before deployment to ensure tags never exceeded 4% of the adult's body mass to minimise potential tag effects. Tag effects were investigated during a previous study using much of the same data; for further details on the field procedure, refer to Wischnewski et al. (2019).

2.3. Data processing

All data processing and analyses were carried out in R version 3.5.1 (R Development Core Team 2011). We analysed data for 84 deployments: 65 from the High Island Colony (6 from 2014, 51 from 2015, 8 from 2016) and 19 from the Great Blasket Island colony (8 from 2014, 11 from 2015) after data preparation. In the High Island colony, 14 deployments were carried out during the incubation period. We removed tracks that had fewer than 10 relocations, and points that occurred within 5 km of the colonies to avoid including colony-associated behaviours like preening or rafting, which we were not interested in (McSorley et al. 2008). Tag malfunctions caused occasional gaps in the data, so we split tracks into multiple segments if the gap between consecutive locations was more than twice the average tag resolution (e.g. for 4 min interval tags, if the gap was greater than 8 min) to reduce extrapolation over long unobserved periods. Over 80% of the relocations had a time interval of less than 5 min, so we regularised our dataset to 5 min intervals using the 'adehabitatLT' package (Calenge 2006); regular intervals were a requirement for our subsequent analysis (McClintock & Michelot 2018). We assessed how this regularisation affected our results for High Island (which included some tracks at a 12 min resolution), as detailed in the Supplement at www.int-res.com/articles/suppl/m646p175_supp.pdf. Chl *a* data were sourced from MODIS sensor on NASA's Aqua satellite, at a spatial resolution of 4 km and monthly temporal resolution (https://oceancolor.gsfc.nasa.gov/). Each relocation had a chl *a* value appended to it using Movebank's inverse-distance weighted algorithm (Dodge et al. 2013). Where Movebank failed to append chlorophyll values for some of the relocations, these were removed along with the points that occurred after. This was again essential in order to preserve the regularised track.

2.4. Behavioural transitions and productivity

We applied a 3-state hidden Markov model (HMM) to the tracking data (projected to 29N UTM) for each colony separately to identify different movement modes based on the features of an animal's track, using the 'momentuHMM' package (McClintock & Michelot 2018). While the statistical distributions of the response variables used in the models (here, step length and turning angle) drive the characterisation of such movement modes, previous work with state-space models and HMMs has demonstrated that these statistical states can be associated with the underlying behavioural state of tracked individuals (Patterson et al. 2008). In particular, inferred foraging states of HMMs have been shown to perform well in overlapping with actual prey capture events in seabirds (Bennison et al. 2018). Previous research on Manx shearwaters identified 3 movement modes along a bird's track, which can be interpreted as 3 biologically meaningful behavioural states: resting, ARS and transiting (Dean et al. 2013). Transiting is characterised by large step lengths with small turning angles; ARS has intermediate step lengths and large turning angles, and resting is characterised by short step lengths and intermediate turning angles. The ARS state is widely accepted to reflect putative foraging (Fauchald & Tveraa 2003). To investigate whether surface chl *a* could act as a cue for shearwaters to initiate foraging activity, we ran models that included and excluded the effect of monthly chl *a* concentration on the transition probabilities among states (Grecian et al. 2018) and compared them using AIC. We selected a gamma distribution for the step length distribution (units in metres) and a von Mises distribution for the turning angle distribution (units in radians).

2.5. Spatio-temporal distribution of foraging behaviour

Typically, telemetry data are analysed in a use–availability framework (Aarts et al. 2008, Warton & Aarts 2013), where a movement rule (e.g. the maximum distance covered) is assumed to define the boundaries of available habitat, and where logistic regression is fitted to locations and random pseudo-absences to quantify overall distribution and habitat use. In contrast, we were interested in describing the habitat where shearwaters engaged in putative foraging (i.e. ARS behaviour, representing model presences) as opposed to the habitat that was merely travelled through. The absences in our model were therefore represented by locations where the birds were classified to be in transit mode. To avoid extrapolation beyond the range of available covariates, any inference was restricted to regions covered by the trips of tracked shearwaters. The Viterbi algorithm was used to extract the most likely sequence of states resulting from the HMM (Viterbi 1967). Locations classified as resting were excluded from further analysis, because birds could initiate this behaviour immediately after foraging but progressively drift away from foraging areas (Yoda et al. 2014), thus potentially confounding the results of the analysis.

Binary behavioural mode at each location (ARS or transit) was then modelled as a function of a set of environmental covariates recognised as potential oceanographic drivers of habitat use (Cox et al. 2018). Depth in metres at a 30 arc-second resolution was obtained from the GEBCO dataset (www.gebco.net). Slope gradient (rise over run; hereafter 'slope') was computed from depth using the package 'SDMTools' in R (VanDerWal et al. 2014). Seafloor rugosity (hereafter 'rugosity') was calculated as the standard deviation of depth over 5 grid cells using the package 'raster' (Hijmans & Van Etten 2016). Sea surface temperature (SST) and surface chl *a* concentration were again extracted from the data collected by the MODIS sensor on NASA's Aqua satellite, monthly composites at a resolution of 4 km. The standard deviation of SST over 5 grid cells (VSST) was used to characterise potential frontal systems or upwelling areas. The models also included latitude, longitude and 2 temporal covariates (hour and day of year). We assessed multicollinearity among explanatory variables using the variance inflation factor (VIF) and a plot of paired correlations. If 2 variables were collinear, Akaike's information criterion (AIC) was used to select the one to retain in subsequent analyses.

Models were fitted in a binomial generalized additive mixed modelling (GAMM) framework using the package 'mgcv' for R (Wood 2017), where segment ID was used as a random effect. Because preliminary analysis suggested large serial autocorrelation in model residuals, a first-order autoregressive correlation structure was fitted within each level of the random effect (that is, each segment). We used penalised thin-plate regression splines with shrinkage to model the relationship between the response variable and each of the explanatory variables, with the exception of hour, which was fitted using a cyclic spline to capture daily patterns. We used a bi-dimensional thin-plate regression spline for the geographical covariates (longitude and latitude). Shrinkage modifies the smoothing penalty so that a smooth can be identically zero and removed from the model (Marra & Wood 2011). Moreover, variables that had approximate p-values >0.05 were also excluded from the model, and the model was refitted to remaining variables (Redfern et al. 2017). We fitted separate models to tracks from Great Blasket Island and High Island, because we hypothesized that different processes could characterise the distribution of birds from the 2 colonies (Grémillet et al. 2004, Wakefield et al. 2013). We also refitted the final GAMM for High Island excluding the 14 deployments during the incubation period, to assess whether the different reproductive status affected the spatio-temporal distribution of foraging behaviour.

Previous work on the birds at these colonies revealed distinct offshore and coastal foraging trips (Wischnewski et al. 2019). In order to reflect the potential differences in spatial distribution processes between the 2 habitats, a threshold distance from shore of 80 km was chosen to define the habitat of each fix (coastal or offshore), based on preliminary exploration of the data. The categorical factor for habitat was then used to replicate the smooths for all environmental variables (with the exception of the bi-dimensional spline for longitude and latitude) via the 'by' argument provided by the 'mgcv' package.

We assessed the performance of the final model for each of the 2 colonies using a confusion matrix, which compared the occurrence of foraging predicted by the GAMMs with the behavioural mode estimated by the HMM. As a measure of the goodness-of-fit of the models, we also calculated the area under the receiver operating characteristic curve (AUC) using the package 'ROCR' for R (Sing et al. 2005). The contribution of each explanatory variable was visualised using partial residual plots generated using 'mgcv'. Model predictions were plotted for a regular grid of 0.1° × 0.1° cells, cropped to the geographical area covered by tracked shearwaters. Values of retained explanatory variables were extracted at the centroid of each cell. For dynamic variables, the median over the study period was used for predictions. Uncertainty in model predictions was visualised by plotting the upper and lower 95% confidence intervals of the predictions in each grid cell.

Additional uncertainty could derive from the behavioural mode classifications resulting from the HMM, which determined the value of the response variable used in the GAMM. To our knowledge, there is no coherent way to propagate this uncertainty through the GAMM analysis in a frequentist framework, because the most likely state sequence is obtained from the Viterbi algorithm. As an alternative, we used the estimated probabilities associated with each behavioural mode (obtained from the HMM) in a multinomial draw at each location. This returned a new sequence of behavioural mode estimates, which was then used in the GAMM analysis. This procedure was repeated 100 times and, at each iteration, the AUC, confusion matrix and spatial predictions were recalculated. Summaries of these metrics across iterations provided an indication of the effects of state classification uncertainty on the final results.

The extent of the overlap in the distribution of foraging locations between colonies was quantified using Bhattacharyya's affinity (BA) (Bhattacharyya 1943), following the procedure described by Cleasby et al. (2015) and Grecian et al. (2018). Specifically, the bivariate kernel utilisation distribution of foraging locations of birds belonging to each colony was calculated using the package 'adehabitatHR' (Calenge 2006, 2011), with a smoothing parameter of 10 km and a grid size of 1 km. BA was computed for the 2 observed 95% utilisation distributions and compared to a null distribution of BA values, obtained by randomly reassigning individuals to the 2 colonies and recalculating the utilisation distributions 1000 times. Finally, the approach described by Jones et al. (2016) was used to compare the predicted distribution of Manx shearwater foraging activity from the 2 sampled colonies. A spatially local measure of similarity in the means of the 2 distributions over a 3 × 3 cell window was plotted to visualise any difference between colonies. This comparison was restricted to the region that was covered by tracks from both colonies.

3. RESULTS

3.1. Behavioural states

The HMM clearly differentiated 3 behavioural states for both the High Island and Great Blasket populations: one with large step lengths and small turning angles, one with short step lengths and small turning angles and one with intermediate step lengths and large turning angles (Fig. 1). These characteristics match to a transiting, a resting and a foraging/ARS state, respectively, and were similar in both colonies (Tables S1 & S2). According to the AIC scores, for both colonies the 3-state HMM that included the effect of monthly chl *a* concentration on transition probabilities was preferred over the model without this covariate (Table 1, Fig. 2). The pattern shows that the probability of switching from transiting to ARS increased for increasing chlorophyll concentrations (Fig. S1 & S2). State classifications in High Island were partly affected by the temporal resolution used for regularising locations (resulting in an 83% match between classifications using a 12 min or a 5 min regularisation), but this did not change the effect of chlorophyll on the transition probabilities (Tables S3 & S4, Figs. S3–S6).

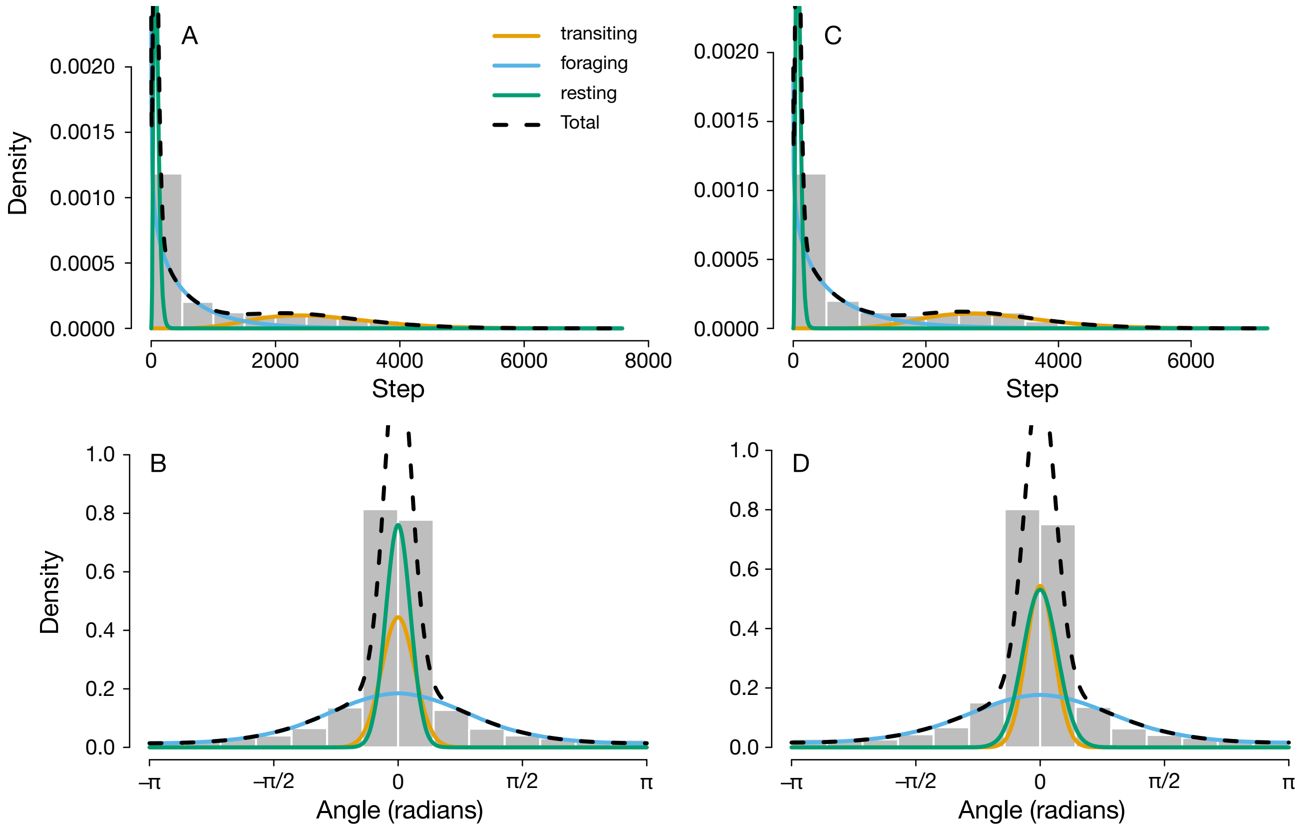

Fig. 1. Plots from the hidden Markov models showing the state-dependent distributions of step lengths and turning angles for all birds from each of the 2 colonies which were interpolated to 5 min. (A,B) High Island birds and (C,D) Great Blasket birds are shown

Table 1. Comparison of Akaike's information criterion (AIC) values for the 3-state hidden Markov models within colonies. The models display those with and without the covariate, monthly chlorophyll concentration

Model	AIC	ΔAIC
Great Blasket with covariate	293 498	0.0
Great Blasket without covariate	293 508	10.0
High Island with covariate	1 242 879	0.0
High Island without covariate	1 242 985	106

The final foraging location dataset used for the GAMM analysis included 56 630 locations for High Island, and 13 358 locations for Great Blasket. After excluding resting locations, HMM results indicated that 33% of locations corresponded to transit behaviour and 67% to ARS behaviour for High Island. For Great Blasket, the proportions were 34% and 66%, respectively. In both island datasets, the assessment of multicollinearity highlighted that longitude and latitude were collinear with depth and SST, and slope with rugosity. The AIC suggested that latitude, longitude, slope (for High Island) and rugosity (for Great Blasket) were better predictors of ARS activity than their collinear counterparts, so these variables were retained in further analyses.

3.2. High Island SDM

After shrinkage reduced the relationship with irrelevant predictors to 0 and non-significant variables were removed, the final model for High Island included chl *a*, VSST, slope, hour and day of year, all interacting with the categorical factor for habitat, as well as the bi-dimensional smooth for longitude and latitude. VSST had a significant positive linear relationship with the occurrence of ARS in both habitats ($p < 0.05$; Fig. 3C,D), chl *a* had a positive relationship but only near the coast ($p < 0.01$; Fig. 3A,B), whereas slope and day of year had a significant positive relationship with ARS only in offshore areas ($p < 0.05$; Fig. 3E,F,I,J). However, for all of these variables, the associated confidence intervals were wide, suggesting that these effects should

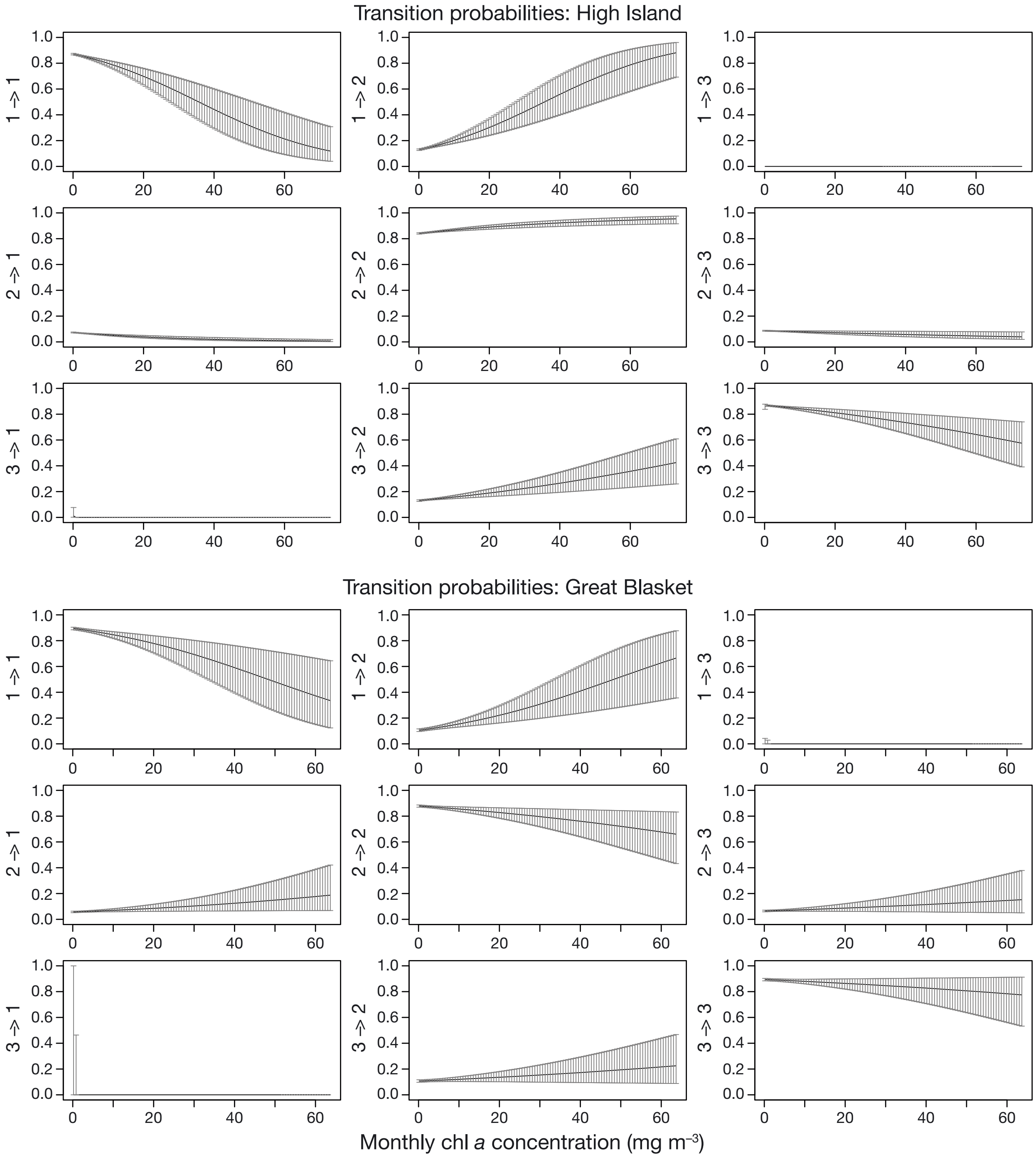

Fig. 2. Plots of the transition probabilities between behavioural states as a function of monthly chl *a* (mg m^{-3}) for the 2 colonies (top: High Island; bottom: Great Blasket). State 1 = transiting, state 2 = area-restricted search, state 3 = resting. The plots show the average trend with a 95% confidence interval

be interpreted with caution. Finally, the cyclic smooth for hour suggested a higher chance of birds engaging in ARS behaviour at night with a smaller peak in the central hours of the day offshore ($p < 0.001$; Fig. 3G), while near the coast this peak became more prominent ($p < 0.001$; Fig. 3H). When the final model was refitted excluding deployments during the incubation period, the estimated relationships with hour of the day, chl *a* and slope did not change; however, the relationship with VSST near the coast was not significant, and the relationship with day of year was non-linear.

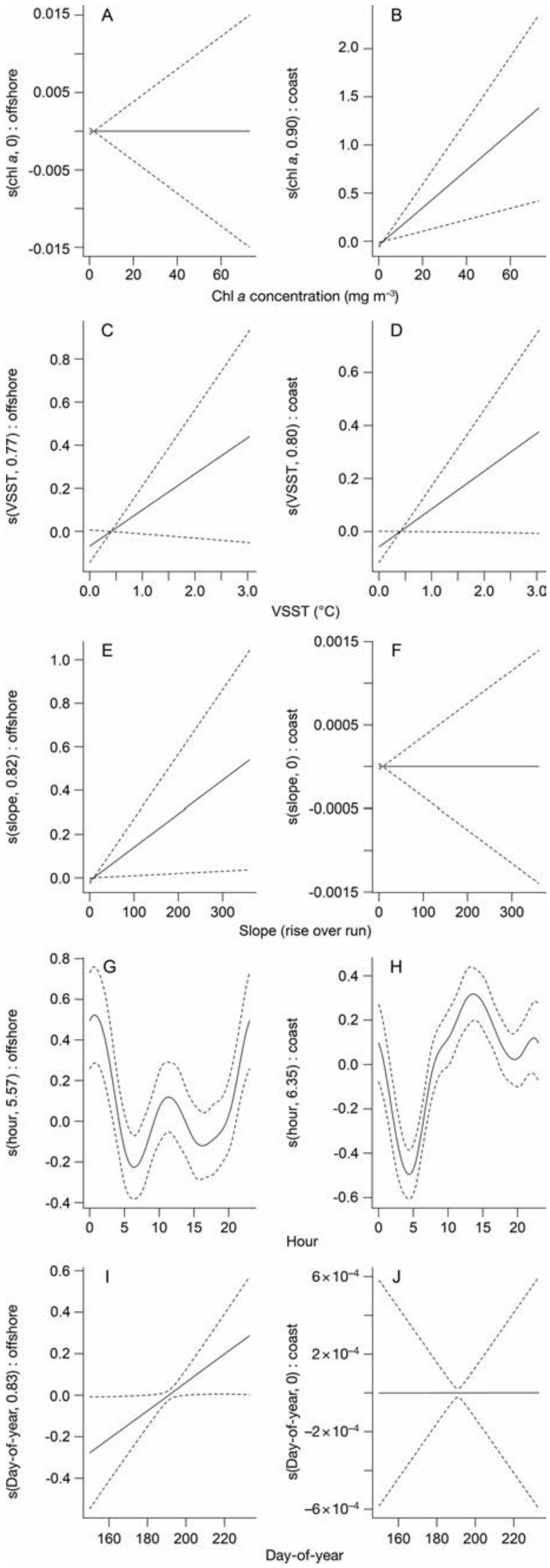

Fig. 3. Partial residual plots for the final model fitted to tracks from High Island. Estimated relationships between the occurrence of area-restricted search behaviour and (A,B) chl *a* concentration, (C,D) standard deviation of sea surface temperature (VSST), (E,F) slope, (G,H) hour, and (I,J) day of year (A,C,E,G,I) offshore and (B,D,F,H,J) near the coast. Relationships are on the logit link scale, and the estimated degrees of freedom for the corresponding model term are reported in brackets in the *y*-axis label. Dashed lines represent the 95% confidence intervals

3.3. Great Blasket SDM

The final model for Great Blasket included hour and day of year, as well as longitude and latitude as a bi-dimensional smooth. Most ARS activity occurred in the central hours of the day near the coast ($p < 0.001$; Fig. 4B), while this relationship was not significant in the offshore habitat (Fig. 4A). Finally, the occurrence of ARS declined linearly during the study period (July–August) offshore ($p < 0.001$; Fig. 4C), while it did not change closer to shore (Fig. 4D). For both colonies, the bi-dimensional smooth for latitude

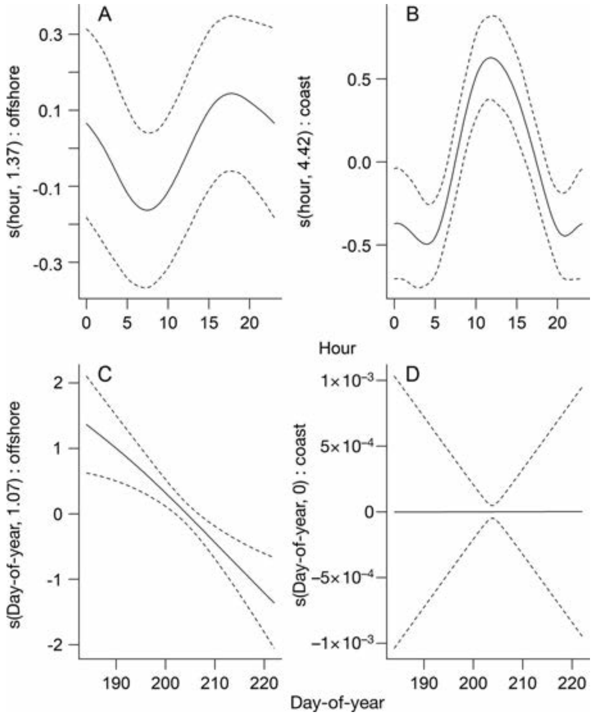

Fig. 4. Partial residual plots for the final model fitted to tracks from Great Blasket. Estimated relationships between the occurrence of area-restricted search behaviour and (A,B) hour and (C,D) day of year (A,C) offshore and (B,D) near the coast. Relationships are on the logit link scale, and the estimated degrees of freedom for the corresponding model term are reported in brackets in the *y*-axis label. Dashed lines represent the 95% confidence intervals

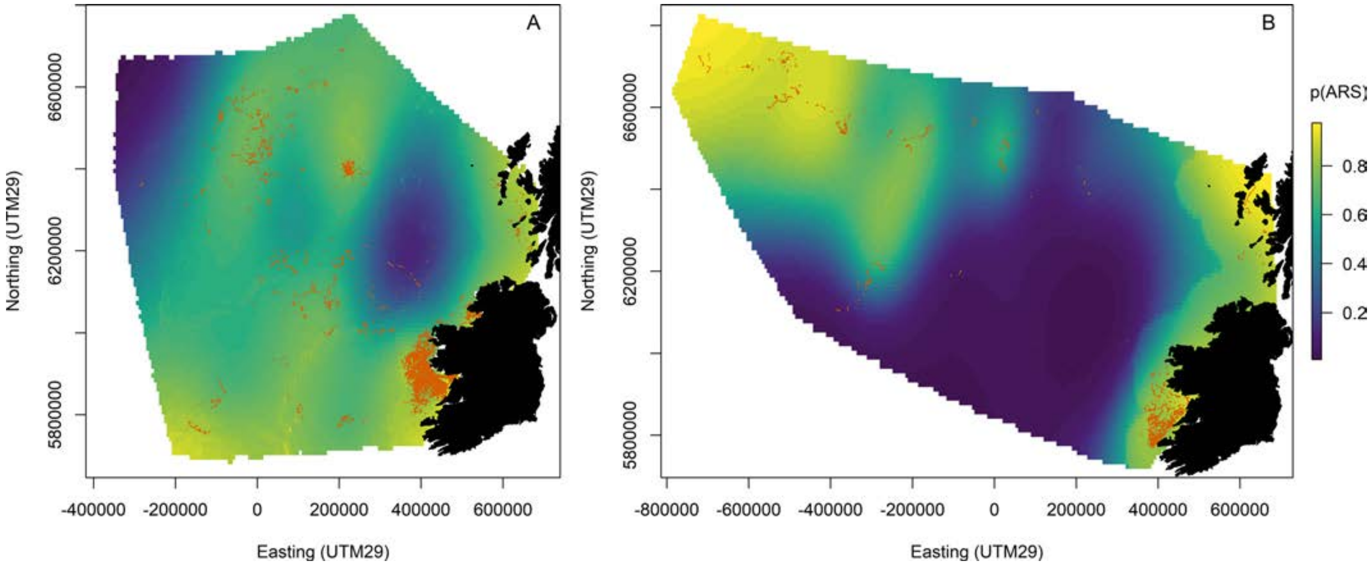

Fig. 5. Predicted probability of occurrence of area-restricted search (ARS) behaviour based on the final models for (A) High Island and (B) Great Blasket. The locations where birds were estimated to engage in ARS are plotted as orange dots

and longitude captured most of the spatial distribution of ARS behaviour, as suggested by the prediction maps (Fig. 5).

3.4. Model fits

The confusion matrices suggested that the model for Great Blasket better fit the data, with an average 69% correct classifications of ARS and transit behaviour compared to 62% for High Island. This was confirmed by the AUC (0.76 vs. 0.67). The better performance of the model for Great Blasket was also apparent from the prediction maps (Fig. 5). Model predictions suggested that birds from High Island were foraging over a diffuse region, whereas birds from Great Blasket concentrated in more defined areas. However, there was a substantial difference in the number of deployments from each colony (65 for High Island vs. 19 for Great Blasket), which could explain this difference.

Uncertainty from the GAMM analysis intensified or weakened predicted distributions but did not change the overall spatial patterns (Figs. S7 & S8). Uncertainty resulting from the assignment of behavioural modes by the HMM also did not have a strong influence on final predictions (Figs. S9 & S10). In addition, resampling of the HMM states did not affect the AUC or the percentage of correct classifications from the confusion matrix: for High Island, the mean AUC across resamples was 0.675 (0.670–0.679), and the mean percentage of correct classifications was 62.6% (62.1–63.0%); for Great Blasket, the mean AUC across resamples was 0.757 (0.751–0.761), while the mean percentage of correct classifications was 69.5% (68.5–70.2%).

3.5. Distribution overlap

BA for the 2 colonies was 0.54, suggesting a moderate level of overlap in the distributions. When compared to the distribution of BA values obtained from randomly reassigning individuals to the colonies, the observed BA was significantly lower than the null expectation (Fig. 6; all randomised BA values were greater than the observed one), supporting the existence of segregation in foraging areas between the 2 colonies. The structural similarity analysis showed that, in the region covered by tracks from both colonies, most of the overlap between predicted distributions occurred near the coast and in the far-offshore regions, while the areas in between were mainly used by High Island birds (Fig. 7). In addition, Great Blasket birds foraged further offshore, and there was an area of similarly low mean predicted probability of ARS occurrence in the north-eastern section of the study area (Fig. 7).

4. DISCUSSION

We paired movement patterns recorded via high-resolution GPS tracking with environmental covari-

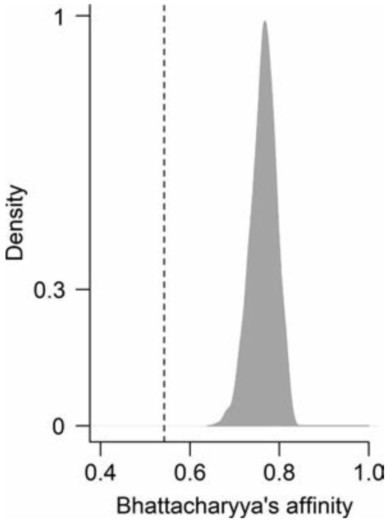

Fig. 6. Observed value of Bhattacharyya's affinity (dashed line) for the 95% utilisation distributions of area-restricted search locations of Manx shearwaters from High Island and Great Blasket, and the null distribution of Bhattacharyya's affinity values obtained from randomly reassigning individuals to the 2 colonies for 1000 times

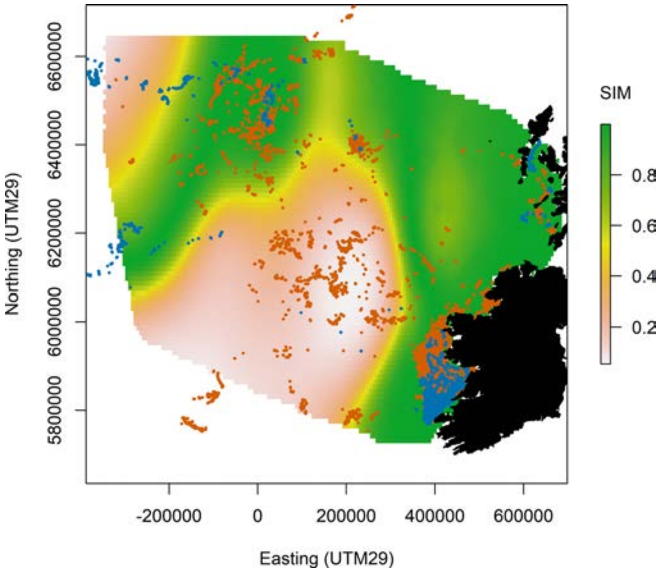

Fig. 7. Similarity in means (SIM) between the predicted distributions of area-restricted search (ARS) behaviour for birds from High Island (HI) and Great Blasket (GB), resulting from the structural similarity analysis. ARS locations are indicated by red dots for HI birds, and blue dots for GB birds

ates to describe the behaviour and foraging distribution of Manx shearwaters from 2 colonies. Differences between colonies, and spatio-temporal variation in foraging behaviour in general, were pronounced. We found 2 distinct patterns that were associated with proxies of productivity. First, transitions from non-foraging to putative foraging (ARS) were associated with increased chlorophyll concentration, and second, the distribution of foraging birds specifically was also explained by proxies of food availability, but only in High Island birds. Nocturnal foraging occurred in one of the 2 colonies (High Island). Birds from both colonies overlapped in where they foraged, but there was also clear evidence for some segregation. Our analyses highlight the importance of incorporating spatio-temporal variation into models of foraging behaviour.

ARS is a recurrent pattern in the tracks of foraging animals in general, highlighting the potential advantage of this behaviour in locating prey, and its utility in modelling the distribution of foragers (Weimerskirch 2007). Although prey capture attempts may occur during transiting, ARS is more closely associated with searching intensively in areas where prey is more likely to be present (Weimerskirch 2007). Consistent with our hypothesis, chl *a* concentration correlated with transitions from transiting to ARS behaviour, suggesting that the birds can identify high productivity patches of water, which they use as a signal to engage in putative foraging behaviour. Both Sabarros et al. (2014) and Grecian et al. (2018) recorded similar switching patterns among gannet foraging that were linked to chl *a* and frontal intensity, respectively. Furthermore, the positive link we demonstrated with GAMMs between chlorophyll, VSST (indicator of potential fronts; Ping et al. 2016), slope and where High Island birds foraged also supports the hypothesis that shearwaters locate and concentrate their foraging activity in areas of high productivity, although these relationships presented large uncertainty. Together, the combined HMM and GAMM analyses in our study support the idea that proxies of food availability can be used to model the distribution of animals that forage over large spatial scales on cryptic prey. Our focus on ARS alone helped reveal this association in contrast to much previous work, which has tended not to incorporate behaviour-specific environmental associations (Tremblay et al. 2009).

Despite this support, the use of proxies in SDMs has also come under scrutiny. One of the main reasons for this is the potential for spatial and temporal mismatches between primary producers and foragers at higher trophic levels (McPherson & Jetz 2007, Grémillet et al. 2008). Manx shearwaters are generalist foragers that feed on both high and low trophic level prey, including zooplankton, and this may explain why the association appears in our system and not in others (Petry et al. 2008, Brooke 2013), albeit with large uncertainty in the GAMMs. This also tallies with recent research using a variety of approaches that provide indirect support for links between infochemicals produced by plankton and behaviour of marine predators, including closely related *Calonectris* shearwaters (Dell'Ariccia et al. 2014, Abolaffio et al. 2018).

Nevertheless, the relationship with chlorophyll from the GAMMs was only seen among near-coast foragers for High Island, coincident with the higher and more variable chl *a* concentrations there (Fig. S11). The lack of an association offshore could indeed be explained by a mismatch between plankton and what individuals are foraging on in this habitat. Manx shearwaters may take offshore trips for self-maintenance (Shoji et al. 2015, Wischnewski et al. 2019), with birds likely looking for more energy-rich prey at higher trophic levels, where chl *a* would not necessarily be a useful cue. The Great Blasket birds also showed no association despite the correlation of switches in behaviour seen in the HMM. Indeed, many of the ARS locations of the Great Blasket birds were located beyond the farthest distances foraged by the High Island birds. Previous work on the species identified colony-specific dietary preferences, with Skomer Island birds favouring fish compared to Isle of Rum birds, which consumed significant proportions of squid (Dean 2012, Brooke 2013). Our High Island birds were also associated with slope gradients when foraging offshore, another indicator of productive waters for higher trophic prey (Warwick-Evans et al. 2018). The lack of a relationship with chlorophyll in offshore areas is surprising here, since high slope areas are linked to upwelling zones. Manx shearwaters are also known to group with other seabirds as well as cetaceans, a behaviour that facilitates finding food patches (Skov et al. 1995). The absence of these commensal associations and other biotic factors in our models could explain not only why food proxies do not predict foraging behaviour but also why our goodness-of-fit is low (McPherson & Jetz 2007). We also did not distinguish between phases of the trip, where the different level of satiation of an individual could affect its propensity to forage. Time–depth recorders or stomach temperature loggers could help quantify prey capture attempts and thus facilitate the exploration of an individual's satiation.

Whatever the reason for the patterns observed, our results emphasise the need to consider that environmental correlates may only be detected across part of the foraging range of animals originating from the same colony, and that this should be expected in predators that feed on prey from different levels of trophic food webs. Our ability to detect an association of foraging behaviour with VSST near the coast for High Island birds was also dependent on the inclusion of birds tracked during incubation. This could simply result from the reduced number of tracks used to fit the model and the large uncertainty around the estimated relationships, but further data collection is required to elucidate the role of reproductive status on foraging behaviour and habitat use in this species (Wischnewski et al. 2019).

Our data also revealed a temporal source of variation, whereby High Island birds engaged in ARS at night offshore. Nocturnal foraging is known to occur in seabirds, such as the habitat-dependent foraging schedules described by Dias et al. (2012) in Cory's shearwaters *Calonectris diomedea*. Here, the birds foraged at night in areas of relatively cold and deep water, the Northwest Atlantic. The authors proposed that the birds were targeting mesopelagic prey undergoing nocturnal diel vertical migrations, which may be the case for the High Island colony foraging offshore. By contrast, Dean (2012) showed how Manx shearwaters from Skomer Island constrain their dives to daylight hours, which corresponds to the diurnal diel movements of their primary prey at that colony, clupeid fish. The Great Blasket birds seemed to match this diurnal foraging pattern. At a much larger timescale, we recorded a decline in offshore ARS with day of year among the Great Blasket colony but the opposite pattern with the High Island colony. A dietary analysis may explain many of these patterns, but we also recognise that they may be a consequence of sampling effort, as we have less tracking data from later in the season.

Despite being 170 km apart, Manx shearwaters from both colonies foraged in similar areas both along the coast, especially in Galway Bay, and offshore in the Atlantic and around the Scottish Islands. This is unsurprising given the huge distances this species can traverse (Wischnewski et al. 2019). However, there was also some indication of distinct segregation (Figs. 6 & 7). First, Great Blasket birds were less likely to forage in the northern waters of Galway bay, while High Island birds were less likely to do so in the southern waters. This recalls similar patterns observed in gannets, which are driven by density-dependent competition enhanced by cultural information transfer at the colony (Wakefield et al. 2013). Although the separation between our colony foraging ranges was less marked (Fig. 7) than in the gannet study, competitive exclusion through interference competition is likely to play a role. Second, the Great Blasket birds did not appear to engage in foraging behaviour at intermediate distances from the colony, in areas where the High Island birds regularly foraged (Fig. 7). Segregation offshore is more likely to occur by chance, owing to the enormous habitat available. However, this may also be a sample size issue, as our Great Blasket dataset was considerably smaller than that of High Island.

5. CONCLUSION

Marine predators live in a dynamic environment and must rely on a suite of signals to detect their prey. Our analysis revealed colony-specific, spatial, environmental and temporal patterns in the distribution of foraging behaviour in the Atlantic habitat of the Manx shearwater. We suggest that the birds respond to olfactory cues at patches with high primary productivity in order to find food but may use other signals of prey availability far out to sea, including during nocturnal foraging. Indeed, our study emphasises that foraging patterns in a single population cannot be generalised based on data from a single colony alone even in a wide-ranging species that encounters extensive environmental variation.

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Vulnerability of northern gannets to offshore wind farms; seasonal and sex-specific collision risk and demographic consequences

Jude V. Lane [a,*], Ruth Jeavons [a], Zoe Deakin [b], Richard B. Sherley [c], Christopher J. Pollock [a], Rebecca J. Wanless [a], Keith C. Hamer [a]

[a] *School of Biology, University of Leeds, Leeds, UK*
[b] *School of Biosciences, Cardiff University, Cardiff, UK*
[c] *Centre for Ecology and Conservation, University of Exeter, Penryn, UK*

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ABSTRACT

There is a pressing need to quantify the risks of renewable energy developments such as offshore wind farms for protected populations. However, assessments are often based on incomplete data, or fail to consider variation in risk between sexes and at different times of year. We tracked northern gannets foraging from the world's largest colony (Bass Rock, Scotland) across five consecutive breeding seasons. We examine how seasonal and sex differences in behaviour affect the collision risk from planned and operational wind farms within their foraging range and assess the likely consequences for long-term population viability. Both sexes made shorter trips during chick-rearing than prior to chick-hatching, spent a greater proportion of time within wind farm sites and had an eight times greater potential collision risk during chick-rearing. Females made longer trips than males at both these times of year, flew higher and spent more time within wind farm sites, leading to three times greater collision risk for females. After accounting for the potential additional mortality from collisions, and assuming that the death of a parent also led to the loss of its offspring, the breeding population was projected to increase by 3.57% (95% CI: 2.16–5.15%) per year, compared with 6.56% (95% CI: 4.59–8.73%) in the absence of turbines, suggesting a negligible effect on population viability. However, additional mortality could result in greater immigration from neighbouring colonies, potentially affecting their viability and highlighting a need for research within a metapopulation framework to assess the impacts of offshore wind developments on vulnerable species across multiple connected sites.

1. Introduction

Marine environments are facing increasing pressure from human activities including fisheries, shipping and offshore developments such as oil and gas installations and wind farms (Halpern et al., 2019; O'Leary et al., 2020). For instance, commitments to reduce reliance on fossil fuel energy are driving order-of-magnitude increases in offshore wind capacity in Europe, China and the US (GWEC 2019), making predicting the likely ecological impacts of these developments a conservation priority (May et al., 2017). Seabirds are key components of marine ecosystems and may be affected by offshore wind farms through direct mortality from collisions with turbines, as well as indirect effects such as forcing birds to travel further to forage (Furness et al., 2013; Masden et al., 2015), although some species may also be attracted to wind farms (Vanermen et al., 2015). Predicting the likely sizes of these effects on the populations of seabirds breeding at different colonies requires colony-specific information on the movements and behaviour of birds at sea, particularly when there may be cumulative impacts on a breeding colony from several different wind farms (Green et al., 2016). Such data can be obtained using bird-borne data loggers (Wade et al., 2014; Thaxter et al., 2015) but the use of such technology is often restricted to periods when devices can be deployed and retrieved from birds, which may not be representative of the entire breeding season. Changes in the distribution and abundance of prey may alter the movements and behaviour of birds over the course of a breeding season, as may changes in the constraints limiting individuals' foraging trip durations and hence the maximum ranges of trips (Kappes et al., 2015; Votier et al., 2017). In particular, nesting birds may face greater constraints when they need to return frequently to the nest to feed dependent offspring than at earlier stages of the breeding season (Ito et al., 2010; Widmann et al., 2015).

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[*] Corresponding author. School of Biology, Faculty of Biological Sciences, University of Leeds, Irene Manton Building, Leeds, LS2 9JT, UK.
E-mail address: J.Lane@leeds.ac.uk (J.V. Lane).

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Behaviour may also differ between sexes, as a result of differing parental roles, competitive exclusion, niche partitioning or different nutritional requirements (Lewis et al., 2002). Hence assessments of interactions between seabirds and wind farms need to take account of variation in foraging movements and behaviour in relation to both stage of the breeding season and sex to properly evaluate the risks posed to populations at different sites.

Another key area of uncertainty concerns the population-level impacts of additional mortality caused by interactions with wind farms. Previous approaches to this question have often focused on determining the maximum number of additional mortalities a population could theoretically sustain through compensatory reductions in natural mortality, for instance using Potential Biological Removal (PBR) algorithms (Dillingham and Fletcher 2008). However these approaches are often prone to overestimating sustainable levels of offtake (Milner-Gulland and Akçakaya 2001) and several authors have strongly recommended that potential impacts should instead be assessed using matrix-based population projection models (Green et al., 2016; O'Brien et al., 2017). These models, however, require detailed information on age- or stage-specific vital rates, particularly adult survivorship, which has the greatest elasticity (i.e. the largest proportional effect on population growth) in species with high annual adult survival, delayed sexual maturity and low annual reproductive output, such as seabirds (Miller et al., 2019).

Northern gannets *Morus bassanaus* (hereafter gannets) are potentially at high risk of mortality from collisions with offshore wind turbines during the breeding season (Furness et al., 2013; Bradbury et al., 2014) due to their long foraging ranges (Hamer et al., 2007; Wakefield et al., 2013), their flight heights (particularly during periods of active foraging for prey; Cleasby et al., 2015a; Lane et al., 2019) and the proximity of several consented offshore wind developments to large gannet colonies of international importance (Warwick-Evans et al., 2018). However, tracking data for adult gannets have so far been confined to birds raising chicks, and they may not be representative of behaviour during earlier phases of breeding (Besel et al., 2018; Botha and Pistorius 2018). Similarly, while males and females are known to differ in their foraging distributions and diving behaviour during chick-rearing (Lewis et al., 2002; Cleasby et al., 2015b), differences earlier in the breeding season have not been examined, and the consequences of sex-specific foraging behaviour for potential collision risk have not been assessed.

Here we examine the foraging tracks of gannets at the world's largest colony, Bass Rock, UK (56° 6′ N, 2° 36′ W), to assess the incidence of seasonal and sex-specific differences in the movements and behaviour of birds at sea and the implications for collision risk. We examine how representative data for birds rearing chicks are of foraging trips earlier in the season, and we compare tracks of males and females at these different times of year. By combining this information with spatially-explicit data on the flight heights of males and females during periods of commuting and active foraging, we next calculate the potential collision risk across all proposed, consented or operational wind farms within the overall foraging ranges of birds. We then use capture-mark-recapture methods to estimate adult survival rates for males and females and construct population projection matrices to gauge the implications of potential additional mortality caused by wind turbines for the viability of this population.

2. Materials and methods

2.1. Study site and data collection

Fieldwork at Bass Rock took place between mid-April and mid-August over five consecutive years (2015–2019). Using a 6-m telescopic pole fitted with a metal noose or hook, adult gannets were caught at the nest site during April (prior to egg-laying) in 2017–2019 ($n = 48$ birds) or during June–August (while attending chicks) in 2015–2019 ($n = 140$ birds). To reduce disturbance, no attempt was made to capture birds during incubation, when eggs are very vulnerable to predation by gulls (Nelson 2002). All birds caught prior to egg-laying had bred in the previous year and were holding a territory. Birds were sexed from observations of sex-specific behaviour (Redman et al., 2002) or in some cases from DNA (Cleasby et al., 2015b).

Unless already ringed, birds were fitted with a numbered metal British Trust for Ornithology (BTO) ring and a coloured engraved plastic ring with a unique alphanumeric code for easy identification at the nest site. We then equipped each bird with a GPS logger (igotU-GT600, Mobile Action Technology, Taipei, Taiwan) attached to the upper side of the central tail feathers and, during chick-rearing in 2015–2017, a subset of birds ($n = 63$) also had a pressure logger (MSR-145W, MSR Electronics, Seuzach, Switzerland) attached to the underside of the central tail feathers (Cleasby et al., 2015a; Lane et al., 2019). GPS loggers weighed 30–33 g and were programmed to record locations at 1- or 2-min intervals, with those deployed in April 2018 programmed to commence recording on 8 May (after most eggs were laid and well before the earliest chicks hatched at the colony; Nelson 2002). Pressure loggers weighed 18 g and recorded pressure and temperature at 1 Hz. Both loggers were attached using Tesa® tape (Beiersdorf AG, Hamburg, Germany).

Birds equipped with loggers in April each year were recaptured mainly in June, during the chick-rearing period at the colony, with trips recorded between 23 April and 3 June. Birds equipped with loggers during chick-rearing were recaptured after 7–14 days. Handling time of all birds at both deployment and retrieval of loggers was no longer than 15 min and, on both occasions, birds returned to their nest site and resumed normal behaviour almost immediately. The combined weight of loggers was <2% of body mass (~3 kg; Nelson 2002), which was well within recommended guidelines (Phillips et al., 2003), and previous studies at this colony confirmed that such deployments had no discernible impact on trip duration or body mass (Hamer et al. 2007, 2009; Cleasby et al., 2015a).

2.2. Trip metrics and spatial distribution

To account for any irregularities in the GPS data, all locations were interpolated to 2-min intervals using the R package adehabitatLT (Calenge 2006). For every foraging trip, we calculated the duration (h), total distance travelled (km) and maximum distance (km) on a direct bearing from the colony (Wakefield et al., 2013). In addition, we used speeds and turning angles derived from the GPS data to classify the behaviour of birds at sea as one of three categories: commuting, characterised by long step-lengths and small turning angles; active foraging, characterised by short step-lengths and large turning angles; resting on the water, characterised by short step-lengths and small turning angles (see Wakefield et al., 2013 for validation of these discrimination criteria; Grecian et al., 2018).

All trips recorded from birds tagged in April each year were undertaken well before the main chick-rearing period at the colony (median hatch date ~12 June; Nelson 2002). However, we could not be certain of a bird's reproductive status during individual trips, and so they were pooled into a single category termed 'pre-hatching period', including pre-laying and incubating pairs and potentially some failed breeders (not all of these birds had a chick when they were recaptured to retrieve the logger), for comparison with trips by birds that were confirmed as provisioning a chick (all birds tagged during chick-rearing were still attending a live chick when the logger was retrieved). Trip metrics (duration, distance travelled, maximum displacement from the colony and the proportion of each trip spent commuting, foraging and on the water) were then compared with respect to stage of season (pre-hatching or chick-rearing period) by fitting linear mixed models (LMM) using restricted maximum-likelihood (REML) in the R package 'nlme' (Pinheiro et al., 2018). Sex and year were included as fixed effects and bird identity nested within year was included as a random effect to account for repeated trips per individual and individuals repeated across years.

All trip metrics were right skewed and were therefore square-root transformed prior to analysis. Model selection was based on Akaike's Information Criterion (AICc), with the top model refitted to obtain χ^2 and p values. Where there was no clear top model (ΔAICc < 2; Burnham and Anderson 2002) model averaged parameters and their relative importance were extracted from all models with ΔAICc < 2 using the R package 'MuMIn' (Bartoń 2015).

Previous data have indicated that adult gannets are much more likely to fly at collision risk height (i.e. within the range of heights swept by turbine blades) when actively foraging than when commuting to or from the colony (Cleasby et al., 2015a). Hence in addition to examining the full tracks of birds at sea, we also assessed the spatial distribution of actively-foraging birds. Using only those GPS locations classified as active foraging, we estimated 50% and 95% utilization distributions (UDs; Fieberg and Kochanny 2005) for each sex and stage of the season (data sets pooled across years), using kernel analysis conducted with the R package 'adehabitatHR' (Calenge 2006) with a 1 km^2 grid and a smoothing parameter of 10 km (Cleasby et al., 2015b). We also calculated the 95% UDs for all GPS locations at sea, to determine the proportion of the overall foraging area encompassing wind farm sites for males and females during each stage of the season.

2.3. Flight height estimation

To compare the flight height of males and females during chick-rearing and enable us to include flight heights for individual wind farm sites in collision risk assessments, we used the barometric formula (Berberan-Santos et al., 1997; Wallace and Hobbs 2006) to estimate height h (meters) above sea level from pressure logger data:

$$h = -\frac{KT}{Mg}\ln\left(\frac{P}{P_o}\right) \tag{1}$$

where P_0 and P are the atmospheric pressures (Pascals) at sea level and at height h (meters) respectively; K is the universal gas constant for air (8.31432 N m mol^{-1} K^{-1}); M is the molar mass of air (0.0289644 kg mol^{-1}); g is the acceleration due to gravity (9.80665 ms^{-2}); and T is the temperature (K) of the atmosphere between h_0 and h. We obtained calibration pressures (P_0) when birds spent time on the water (Cleasby et al., 2015a) and we accounted for spatial and temporal changes in atmospheric pressure during long periods of sustained flight by adjusting calibration pressures throughout the duration of each flight bout using the ERA-Interim reanalysis sea surface pressure dataset (6-hourly data at $0.125 \times 0.125°$ or approximately 8×8 km resolution; Dee et al., 2011) following Lane et al. (2019).

Flight heights were modelled using LMM with sex, behaviour (commuting or active foraging) and year as fixed effects. Models also included individual foraging trip identity nested within bird identity as a random effect, to account for repeated measures within each foraging trip and multiple trips per bird. A temporal autocorrelation structure was also included to control for non-independence of successive data within each trip (Lane et al., 2019).

2.4. Modelling collision risk

Birds are at risk of striking turbines only when in flight, and they tend to rest on the sea surface overnight (Hamer et al., 2009; this study). Hence following previous authors (Wakefield et al., 2013; Cleasby et al., 2015a) we first estimated the density, d, of males and females in flight during daylight hours (including twilight), within each 1 km^2 grid-square during pre-hatching and chick-rearing stages of the season as:

$$d = \widehat{u}_{i,x}NZ \tag{2}$$

where $\widehat{u}_{i,x}$ is the empirical probability density of use of cell x by bird i during daylight hours, N is the number of birds of each sex predicted to be at sea, estimated by multiplying the number of breeding pairs (75,000 in 2014; Murray et al., 2015) by the observed proportion of time birds of each sex spent at sea, and Z is the proportion of time at sea that was spent in flight during daylight hours (defined separately for every trip to account for seasonal and latitudinal variation in day-length, and including civil twilight; Furness et al., 2018). For each sex and stage of the season, to estimate the mean density of birds in flight within each proposed wind farm site within the 95% UDs of birds, we then summed the number of birds expected in each 1 km^2 grid square within the boundaries of each site (from eqn. (2) above) and divided each sum by the total area of the site (km^2); boundaries and areas of sites were determined using shape files downloaded from The Crown Estate (2020) and The Crown Estate Scotland (2020).

For each wind farm site, we next calculated the proportion of time males and females spent in flight commuting and actively foraging during each stage of the season (see 2.2 above). For trips during chick-rearing, we then combined this information with spatially-explicit flight height data and specifications of turbines at each site (Table S1 in Supporting information) to calculate the proportion of time spent at collision risk height (i.e. within the height envelope swept by the turbine blades) during commuting and active foraging in each case. Flight height data were not obtained for birds tagged during the pre-hatching period so the proportions of flight at risk height during active foraging and commuting were presumed to be the same as those estimated at each site during chick-rearing. The total proportion of flight at collision risk height (P_H) was next calculated for each sex at each site during each stage of the season as:

$$P_H = P_F R_F + P_C R_C \tag{3}$$

where $P =$ proportion of time spent foraging (P_F) or commuting (P_C) and $R =$ proportion of flight at collision risk height during each activity.

We next applied these data to a mechanistic collision risk model (Band 2012) to assess the overall number of potential collisions across wind farm sites within the 95% foraging distributions of male and female gannets from Bass Rock at each stage of the season, assuming an overall turbine avoidance rate (combined macro-avoidance of wind farm areas and micro-avoidance of individual turbines when within a wind farm area; Garthe et al., 2017) of 0.989 (considered the most appropriate for gannets by Cook et al., 2018 based on a synthesis of available data; details of collision risk models in Appendix S1 in the Supporting Information).

2.5. Survival analysis

Between 2010 and 2016, 198 adult gannets breeding at Bass Rock (115 male, 83 female; see Table S3 in Supporting Information) were caught and fitted with an individually numbered colour-ring. During multiple return visits to the site in subsequent years, visual searches were undertaken for all marked birds and a record of re-sightings made to build up an encounter history of each marked individual. To estimate annual survival (ϕ) and resighting (p) probabilities of males and females, capture-mark-recapture (CMR) models were specified in MARK (Version 8.2, White and Burnham 1999). Following Deakin et al. (2019), a fully sex- and time-dependent Cormack-Jolly-Seber (CJS) model was evaluated for goodness-of-fit (GOF) and tested for evidence of transience (presence of individuals that permanently left the population after being caught and released) and trap-dependence (probability that recapture was not independent between years) using U-CARE (Choquet et al., 2009). The CJS model fitted the data well (GOF: ${\chi^2}_{25} = 14.84$, $P = 0.94$) with no evidence of transience ($z = -0.84$, two-sided test, $P = 0.4$) but there was evidence of trap dependence ($z = -2.22$, two-sided test, $P = 0.026$). The signed statistic for trap dependence (TEST2. CT) suggested trap happiness in females ($z = -2.67$, $P = 0.007$) but not males ($z = -0.46$, $P = 0.65$). The data were therefore split for time-dependence in U-CARE and a two-stage time-since-marking (TSM) structure was applied to model resightings of females (Pradel 1993), with the first stage set as a constant. After accounting for trap-dependence a variance inflation factor (ĉ) of 0.457 was estimated by U-CARE, suggesting underdispersion in the data. We therefore set $\hat{c} = 1$, as recommended for cases where $\hat{c} < 1$ (White et al., 2001). The candidate model set was built adjusting the survival and resighting probability parameters so that they could vary by sex (*s*), with year (*t*) or remain constant over time (*c*). Estimates of survival and resighting probabilities (weighted means ± 95% confidence intervals, CI) were calculated using model averaging across the full model set (White et al., 2001).

2.6. Population projection models

To predict the potential population-level consequences of mortality from collision with turbines we constructed age-structured (Lefkovitch) matrix population models, in keeping with recommendations of previous authors (Green et al., 2016; O'Brien et al., 2017) (see Fig. S1 in Supporting Information for details). Survival rates of juveniles (birds in their first year) and immature birds (second to fifth year) were taken from previous estimates based on BTO ring recoveries of birds from Bass Rock (Wanless et al., 2006). Annual adult survival rate was modelled as stochastic to account for uncertainty in our estimates of this parameter (Deakin et al., 2019). We first projected our population model over a period of 21 years from 1994 - 2014 to compare our model with observed nest counts (Apparently Occupied Sites, AOSs; Murray et al., 2015). Three different survival scenarios were then modelled, the first using random samples from the model-averaged survival estimates (ϕ_a) in the absence of operational offshore wind turbines, the second using the predicted mortality from collision with wind turbines to adjust the survival of adults assuming that wind farm mortality was entirely additive, and the third adjusting both adult survival and the probability of chicks fledging (ϕ_c) in this way, assuming that the death of a parent during the breeding season also resulted in the loss of its egg or chick. In each case, parameter uncertainty on the adult survival rates was incorporated by drawing 100,000 samples from a beta distribution (Deakin et al., 2019).

For each scenario, we modelled changes in breeding population size over a period of 25 years, corresponding with the proposed period of

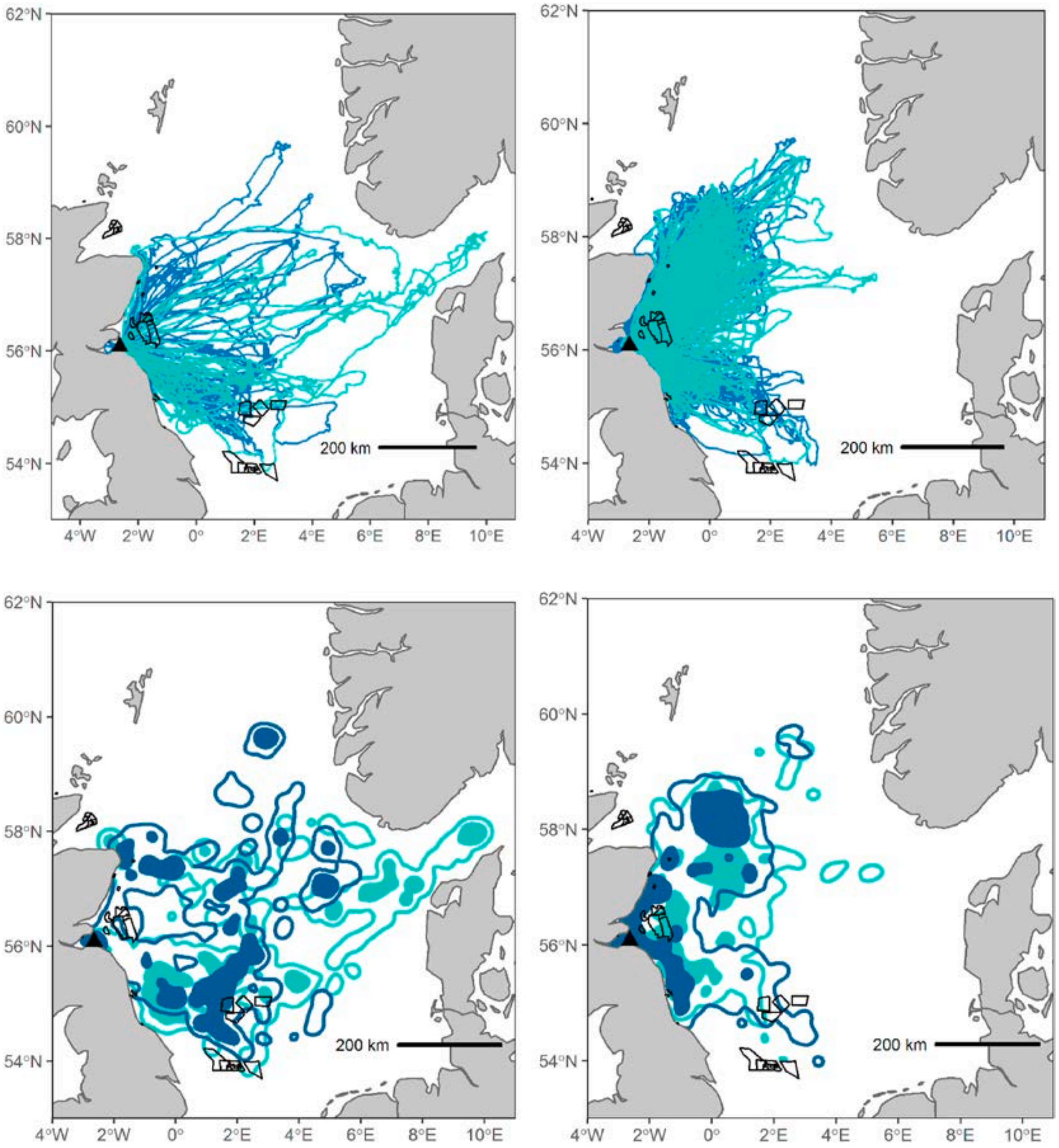

Fig. 1. (**Top**) foraging tracks and (**bottom**) utilization distributions (UDs) of female (green) and male (blue) gannets tracked from Bass Rock (black triangle) (**left**) prior to chick hatching (pooled data for 2017–2019) and (**right**) during chick-rearing (pooled data for 2015–2019). UDs are based on active foraging locations and shading denotes UD contours (filled, 50%; unfilled, 95%). Wind farm sites are outlined in black. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

operation of turbines (Bouty et al., 2017). In addition, to estimate the level of additional mortality that would be required to halt net population growth, the survival rate for females was adjusted until the simulated value for population growth (λ) became equal to 1, assuming that only adult birds experienced this additional mortality.

3. Results

We acquired high-resolution GPS data for 508 trips by 154 birds (288 trips by 84 males; 220 trips by 70 females; all recorded trips were included in the analysis but loggers were lost or malfunctioned on 34 of 188 deployments). Most trips by birds of both sexes travelled northeast or southeast of the colony, particularly during chick-rearing, with a higher proportion of trips travelling due east of the colony prior to chick-hatching (Fig. 1). Overall foraging areas of birds (95% UDs for all GPS locations at sea) covered a large area of ocean (~100,000 km^2 for each sex and stage of the season), of which ~2% encompassed wind farm sites (Table 1). Each adult on average spent 48% of time at sea during the pre-hatching period (males, 44%; females, 54%) and 50% of time at sea during chick-rearing (males, 49%; females, 51%).

3.1. Foraging trip durations, destinations and time-activity budgets at sea

Birds made significantly longer trips during the pre-hatching period than during chick-rearing in terms of duration (1.9–2.5 times longer on average; LMM; $\chi^2 = 63.3$, $p < 0.001$), distance travelled (1.5 times longer on average; $\chi^2 = 17.6$, $p < 0.001$) and maximum displacement (1.4 times longer on average; $\chi^2 = 9.9$, $p = 0.002$; Table 2), with core foraging areas (50% UDs of active foraging sites) in particular covering a much broader range of latitudes and longitudes during the pre-hatching period than during chick-rearing (Fig. 1). Females also made significantly longer trips than males in all three respects (duration, 1.1–1.4 times longer on average; $\chi^2 = 9.8$, $p = 0.002$; distance travelled, 1.1–1.2 times longer on average; $\chi^2 = 9.5$, $p = 0.002$; maximum displacement, 1.1 times longer on average; $\chi^2 = 8.7$, $p = 0.003$; Table 2), with only females during the pre-hatching period making trips that extended beyond 6°E, reaching as far as the Jutland coast, Skagerrak and the Norwegian trench (Fig. 1). Using an information theoretical approach, the best-supported models for trip duration, distance travelled and maximum displacement from the colony all included stage of season, sex and year (ΔAICc > 5 in each case; Tables S4 and S5 in Supporting Information).

Time-activity budgets of birds during foraging trips differed significantly between the two stages of the season, with a significantly smaller proportion of time at sea spent commuting and a significantly greater proportion of time spent resting on the sea surface during the pre-hatching period than during chick-rearing (LMM; $\chi^2_1 = 4.99$, $p = 0.025$ and $\chi^2_1 = 4.93$, $p = 0.023$, respectively; Fig. 2). There was no significant difference, however, in the proportion of time spent actively foraging ($\chi^2 = 0.63$, $p = 0.43$; Fig. 2). Using an information theoretical approach, there was support for a difference between stages of the season in the proportions of time spent commuting and resting on the sea surface, together with a marginally significant difference between sexes in the proportion of time spent commuting ($\chi^2_1 = 3.52$, $p = 0.06$; Fig. 2), and for a difference among years in all three measures (Tables S6–S8 in Supporting Information).

Table 1
Total foraging area (95% UD for all GPS locations at sea) of male and female gannets from Bass Rock and the proportion of this area encompassing wind farm sites during pre-hatching and chick-rearing stages of the breeding season. Data pooled across years.

Season	Sex	Foraging area (km^2)	Proportion of foraging area containing wind farm sites (%)
Prior to chick hatching	Males	127,310	1.53
	Females	140,211	1.69
Chick-rearing	Males	97,739	2.12
	Females	100,508	2.20

Table 2
Characteristics of foraging trips by male and female gannets during pre-hatching and chick-rearing stages of the breeding season (n = 43 trips by 15 males, 24 trips by 9 females pre-hatching; 245 trips by 69 males, 196 trips by 61 females during chick-rearing).

	Sex	Pre-hatching		Chick-rearing	
		Median	IQR	Median	IQR
Duration (h)	Male	44.1	35.2–63.2	22.8	17.4–29.7
	Female	63.6	47.8–69.5	24.9	19.1–31.6
Distance (km)	Male	743.5	593.7–925.5	481.5	261.6–721.8
	Female	846.3	726.1–1121.9	554.3	374.5–716.4
Maximum displacement (km)	Male	292.6	215.7–333.7	205.1	107.6–300.5
	Female	308.2	254.3–419.3	224.4	149.3–293.5
Commuting flight height (m)	Male	–	–	15.3	5.9–32.7
	Female	–	–	19.7	7.5–42.9
Foraging flight height (m)	Male	–	–	25.0	9.8–42.4
	Female	–	–	34.6	13.9–54.6

3.2. Flight heights

Birds of both sexes flew higher when actively foraging than when commuting ($\chi^2_1 = 85.5$, $p < 0.001$) and females flew higher than males during both these activities ($\chi^2_1 = 6.32$, $p = 0.012$; Table 2). Using an information theoretical approach, there was strong support for differences in flight height between sexes, activities and years (Tables S9 and S10 in Supporting Information).

3.3. Collision risk

Irrespective of sex, the distribution of birds in flight at sea was much more diffuse during the pre-hatching period than during chick-rearing, resulting in much higher peak densities of birds km^{-2} during chick-rearing than pre-hatching (Fig. 3). In addition to high densities of birds in flight around the Bass Rock, densities were highest along the coast to the south-east of the colony during the pre-hatching period and to the north-east of the colony during chick-rearing, resulting in higher densities within the proposed wind farm sites in the outer Firth of Forth during chick-rearing than pre-hatching, particularly for females. Densities of both sexes were relatively low at other wind farm sites within birds' overall foraging ranges at both stages of the season (Fig. 3).

Both sexes spent a high proportion of their flight time within wind farm sites commuting at relatively low height rather than actively foraging (mean ± SD; pre-hatching = 83.5 ± 14.0% for males, 94.6 ± 12.4% for females; during chick-rearing = 74.8 ± 14.2% for males, 64.7 ± 28.5% for females). The predicted number of collisions across all wind farm sites within the ranges of birds from Bass Rock was 59 per month during the pre-hatching period and 452 per month during chick-rearing, with ~75% of predicted collisions being by females in each case (Table 3). Combining the monthly totals for males and females from April to August, an estimated 1474 collisions would be predicted to occur each breeding season, with three times the number of collisions for females than for males (Table 3).

3.4. Survival analysis

Of the 198 birds colour ringed on Bass Rock between 2010 and 2016, 192 (115 males, 83 females) were resighted at least once. The top model included constant survival but the model set included support for effects of both sex and time on survival, and there was also support for sex- and time-dependent resighting probability in the top models (Table 4). Model averaging therefore resulted in separate survival and resighting probabilities for males and females each year. Annual survival estimates

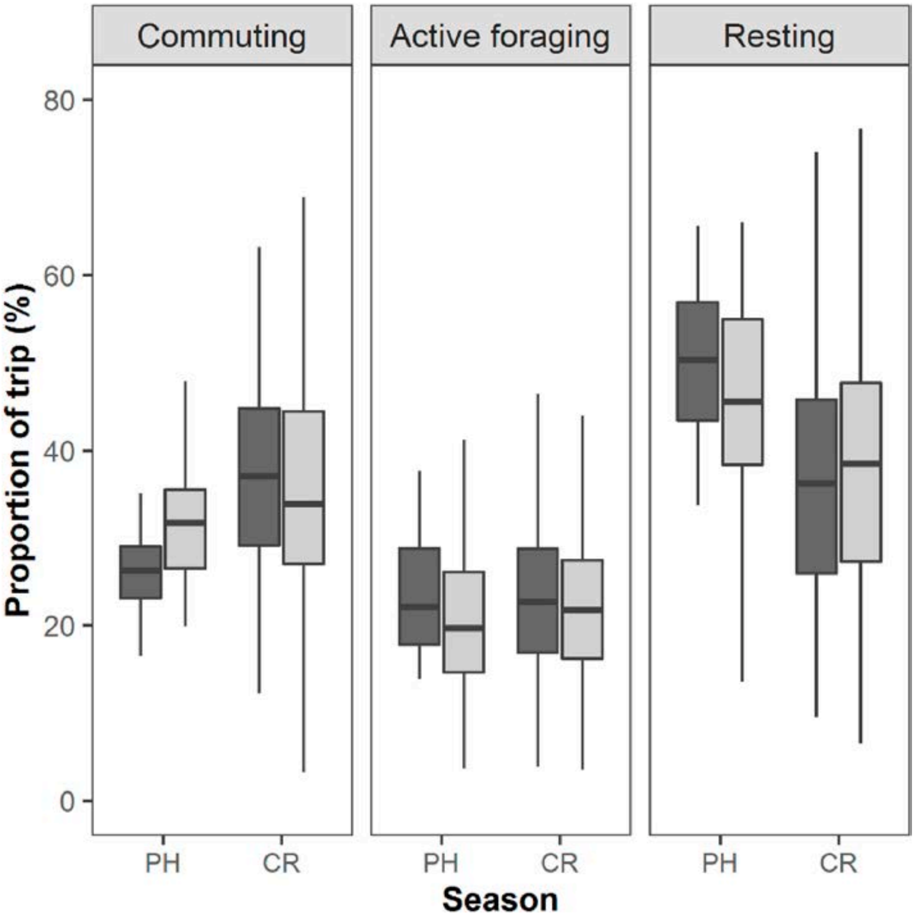

Fig. 2. At-sea time-activity budgets of gannets at Bass Rock. Data show the proportion of total daylight hours (medians, IQRs and ranges) spent in commuting, active foraging and resting on the water for females (dark grey) and males (light grey) prior to hatching and during chick-rearing stages of the breeding season (PH and CR, respectively). Data pooled across years.

ranged from 0.949 (95% CI: 0.830–0.986) to 0.965 (0.911–0.987) for males and from 0.944 (0.836–0.983) to 0.961 (0.898–0.985) for females, with mean (SD) survival for males and females of 0.959 (0.005) and 0.955 (0.005), respectively. Resighting probability of males varied between years, from 0.936 (0.869–0.970) to 0.941 (0.890–0.970), while resighting probability of females was 0.936 (95% CI: 0.834–0.976) in the first year after marking and varied between years thereafter, from 0.811 (0.683–0.896) to 0.831 (0.731–0.899).

3.5. Potential population impacts

The annual survival estimates for gannets from Bass Rock were predicted to decrease to a greater extent among females than males as a result of collisions with wind turbines; from 0.955 to 0.940 among females, from 0.959 to 0.954 among males. Hence our population projection model (PPM) focused on the impact of changes in female survivorship on population growth. The current survival estimate for females (0.955) gave a mean population growth rate (λ) of 1.040 (95% CI: 1.031–1.047) that closely matched the observed increase in breeding pairs between 1994 and 2014 (see Fig. S2 in Supporting Information), resulting in a projected population of 77,771 (65,314 - 91,013) pairs in 2014 (observed count = 75,259 AOSs.) The predicted mean population growth rate decreased to 1.027 (95% CI: 1.019–1.035) when the adult survival estimate was decreased to 0.940 to include the predicted additional mortality from collision with turbine blades and to 1.026 (1.017–1.034) when fledging success was additionally decreased to 0.705, assuming that the death of a parent during the breeding season also resulted in the loss of its egg or chick. However, the number of breeding pairs was still predicted to increase by 3.57%–3.81% per annum in the presence of wind turbines, reaching between 142,364 and 146,861 in 25 years' time (Fig. 4). Assuming the death of a parent also led to the loss of its offspring, for population growth rate to be halted ($\lambda = 1$) annual survival of females would need to decline by 0.045–0.910, an additional 3375 deaths during the breeding season each year above the current (pre-construction) level.

4. Discussion

Gannets rearing chicks made much shorter trips than those recorded earlier in the breeding season in terms of both durations and distances travelled, with a smaller proportion of each trip spent resting on the sea surface during chick-rearing, presumably reflecting a benefit in returning quickly to the colony at this stage of the season to feed dependent offspring (Hamer et al., 2007; Lane et al., 2019). Trips recorded during the pre-hatching period probably included some that were from pre-laying or failed breeders in addition to birds whose partners were incubating, but they were nonetheless consistently longer than trips by birds rearing chicks, with no overlap between these two stages of the season in interquartile ranges (IQRs) for trip durations by either sex and little overlap in IQRs for distances travelled (Table 2). This consistency in trips recorded pre-hatching probably arose because all these birds were acting as central-place foragers (birds occupy and vigorously defend nest sites throughout the breeding season regardless of whether or not they have an egg or chick; Nelson 2002) but with fewer constraints on trip duration during this period than post-hatching. Hence while there may have been some differences in foraging behaviour

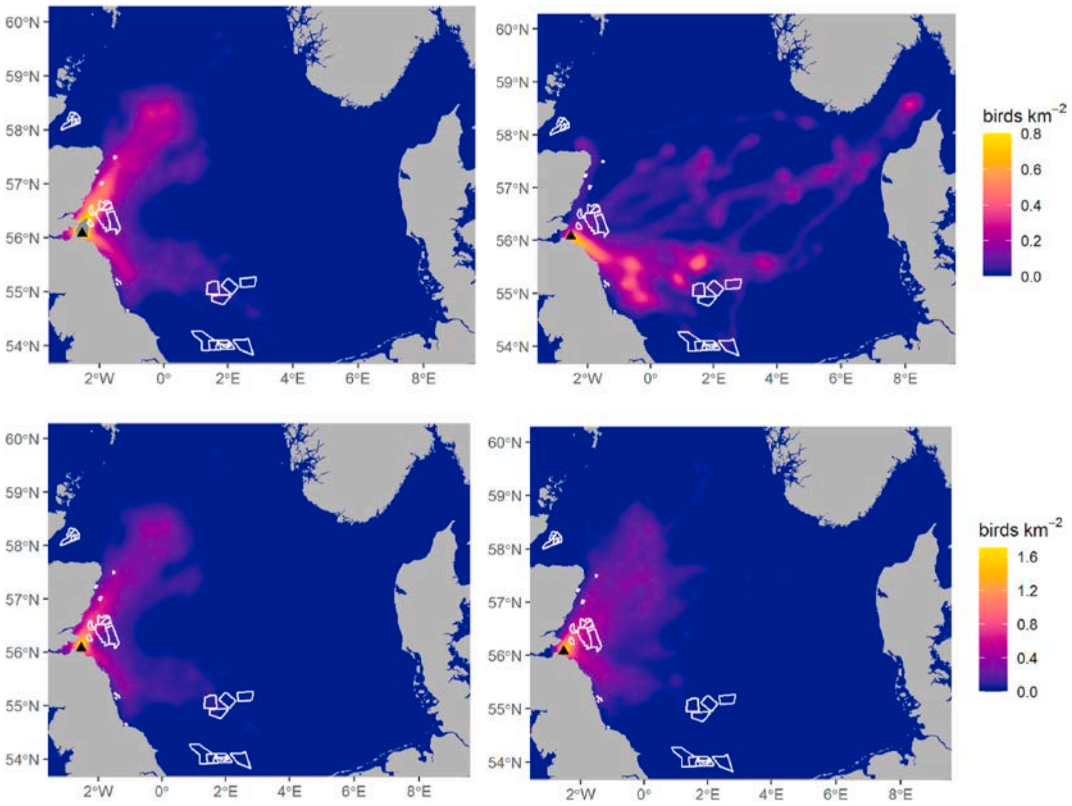

Fig. 3. Estimated density of **(left)** male and **(right)** female northern gannets in flight (birds km^{-2}) tracked from the Bass Rock (black triangle) during **(top)** pre-hatching and **(bottom)** chick rearing stages of the breeding season. Wind farm sites are outlined in white. Note different scales for densities pre- and post-hatching.

Table 3

Predicted number of potential collisions per month during the pre-hatching period (April–May) and chick-rearing period (June–August) for male and female gannets from Bass Rock, summed across wind farm sites within foraging areas of birds, plus total predicted numbers of collisions for each sex across the core breeding season (April–August) each year.

	Pre-hatching	Chick-rearing	TOTAL
Male	24	103	**357**
Female	35	349	**1117**

before and after egg-laying or between failed and successful breeders during incubation, as have been found in some other species (Fijn et al., 2014; Ponchon et al., 2017), any such differences were small compared to those between trips recorded during the pre-hatching period and those made by birds rearing a chick. Ponchon et al. (2019) similarly recorded no difference in the foraging behaviour of failed and successful black-browed albatrosses *Thalassarche malanophris* except during chick-rearing, when successful birds foraged more intensively to meet the food requirements of their chick as well as themselves.

Variation in the foraging movements and behaviour of birds across the breeding season could have resulted from seasonal changes in habitat usage (Thaxter et al., 2015) or in the distribution and abundance of prey in addition to differences in time-constraints acting upon birds. For instance, gannets focus their foraging activity around meso- and sub-mesoscale features such as oceanographic fronts (Hamer et al., 2009; Grecian et al., 2018) and there may have been seasonal differences in the position, size, intensity and/or duration of such features, requiring birds to travel further from the colony to locate prey earlier in the season. However, we recorded no significant difference in the proportion of each trip spent in active foraging during pre-hatching and chick-rearing periods, which suggests that any seasonal differences in overall prey availability were not large. There was nonetheless some annual variation in the movements and behaviour of birds at each stage of the season, presumably reflecting year-to-year variation in prey distribution and abundance (Hamer et al., 2007), and we accounted for this variation by using data pooled across years to calculate collision risks during pre-hatching and chick-rearing periods.

Table 4

Top six models (ranked by QAIC$_c$) of survival and resighting probabilities of adult female and male northern gannets breeding on Bass Rock, Scotland (2010–2017). Inflation factor ($\widehat{c}$) = 1.000. Model subscripts relate to effects fitted to survival (ϕ) and resighting (p) probabilities (s: sex; c: time constant; t: time dependent; m: male; f: female). QAIC$_c$: quasi-likelihood adjusted Akaike's information criterion (AIC); ΔQAIC$_c$: difference in QAIC$_c$ between the best model and the model in question; Num. Par.: number of parameters estimated in the model; QDeviance: quasi-likelihood adjusted deviance.

Model	QAICc	ΔQAICc	AICc Weights	Model Likelihood	Num. Par.	QDeviance
ϕ *(c) p (m:c, f:c/c)*	519.93	0	0.481	1	4	130.78
ϕ *(s) p (m:c, f:c/c)*	521.31	1.38	0.241	0.502	5	130.13
ϕ *(t) p (m:c, f:c/c)*	522.45	2.52	0.136	0.284	10	120.97
ϕ *(c) p (m:c, f:c/t)*	523.95	4.01	0.065	0.135	9	124.53
ϕ *(c) p (m:t, f:c/c)*	524.83	4.90	0.042	0.086	10	123.35
ϕ *(s) p (m:c, f:c/t)*	525.14	5.20	0.036	0.074	10	123.65

In addition to variation across the breeding season, our data also revealed consistent sex differences in colony attendance and foraging behaviour. Females spent a greater proportion of time at sea than males, particularly prior to chick-hatching, probably due to males having a greater role than females in defending nest sites and an exclusive role in providing and augmenting nest material, particularly prior to chick-hatching (Nelson 2002; Redman et al., 2002). Females also made consistently longer foraging trips than males in terms of both durations and distances travelled, indicating that sex differences during chick-rearing (Lewis et al., 2002; Malvat et al., 2020) also occur earlier

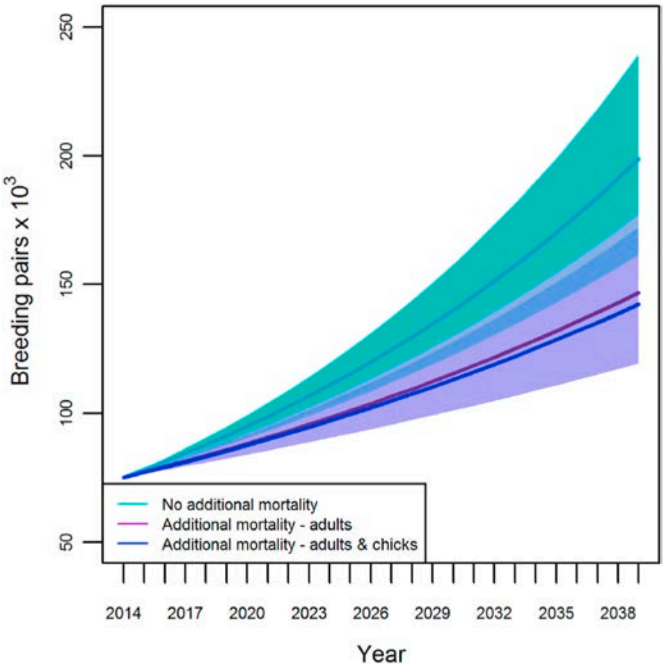

Fig. 4. Predicted mean population trajectory (number of breeding pairs) for the Bass Rock gannet colony under three scenarios: (1) without additional mortality from wind turbines (green line); (2) including additional adult mortality from wind turbines (purple line) and; (3) including additional adult mortality from wind turbines and associated decrease in breeding success (blue line). All models are based on a starting population of 75,259 breeding pairs in 2014 with a stable age distribution. Model predictions assume a closed population and are applied over 25 years, the expected operational lifetime of an offshore wind farm. Coloured polygons show the bootstrapped 95% CI (2.5th and 97.5th percentiles) from 100,000 model runs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in the breeding season. At Bass Rock, sexual segregation is driven largely by differences in habitat usage, with males foraging more in mixed waters along the coast and over offshore banks, and females foraging more in stratified waters (Cleasby et al., 2015b, Fig. 1). This habitat segregation in turn results in sex-specific foraging behaviour, with females diving to greater depths than males, particularly during V-shaped dives when birds rely on momentum to attain depth (Lewis et al., 2002; Cleasby et al., 2015b). We found that females also flew at greater heights than males, particularly during periods of active foraging, presumably to provide additional dive momentum allowing them to penetrate further beneath the water surface (Garthe et al., 2014).

We did not record flight heights prior to chick-hatching, but our data were similar to heights recorded elsewhere in studies lasting throughout the year. For instance, birds moving through an offshore wind farm in the English Channel flew at a median height of 17m (recorded using video and radar; Figure 5.11 in Skov et al., 2018), while birds in the North Sea and Baltic Sea, recorded using laser rangefinders, flew at a median height of 14m during periods of commuting (i.e. no rapid changes in height; Table 1 in Borkenhagen et al., 2018), compared to median heights of 15m for males and 19m for females during commuting flight in this study. Similarly, data obtained mainly during the incubation period at a colony in Canada recorded that birds initiated plunge dives from a mean height of 37m (Garthe et al., 2014) compared to median foraging flight heights of 25m for males and 35m for females in this study. Accordingly, we used data from birds rearing chicks to characterise flight heights throughout the breeding season. Average flight heights vary spatially due to variation in the likelihood of foraging versus commuting and differences in foraging flight heights over mixed and stratified waters (Cleasby et al., 2015a), and we accounted for this variation by using spatially explicit data on heights during each of these activities to calculate collision risks at wind farm sites. Flight heights also vary between years (Cleasby et al., 2015a; this study) and we accounted for this variation by using data pooled across years. Over shorter time scales, birds fly lower into head winds than with tail winds when commuting (Skov et al., 2018; Lane et al., 2019) but most flight at collision risk height is during periods of active foraging, when heights are not affected by wind speed or direction (Lane et al., 2019).

In keeping with spatial density estimates from survey data (Waggitt et al., 2020) and previous tracking data from Bass Rock (Hamer et al., 2007; Cleasby et al., 2015a), areas with the highest densities of gannets at sea were close to the colony and overlapped with wind farm sites in the outer Firth of Forth. Many of these birds were commuting to or from foraging areas further from the colony, at heights typically below collision-risk height. However, gannets also forage during the outward portions of trips (Hamer et al., 2009), increasing their potential collision risk. Combined with the high density of birds close to the colony, this resulted in >99% of predicted collisions occurring within these sites, with fewer than 1% predicted to occur across remaining sites within birds' overall foraging ranges. There was also a much higher density of birds within wind farm sites close to the colony during chick-rearing than pre-hatching, corresponding with longer trips pre-hatching and resulting in the total predicted monthly collisions prior to chick-hatching being only ~10% of those during chick-rearing (calculated from data in Table 3). In addition, despite females making longer trips than males there were a higher density of females than males within wind farm sites in the outer Firth of Forth, associated with males foraging more than females in mixed waters closer inshore (Cleasby et al., 2015b, Fig. 1). This higher density of females combined with a higher proportion of flight at collision risk height by females resulted in the total number of predicted collisions by females being three times that of males. These data highlight the importance of accounting for seasonal and sex-specific variation in collision risks when assessing impacts on potentially vulnerable populations.

Our overall prediction of 1474 collisions across the core breeding season (April to August) each year (hence excluding migration periods; MacArthur Green 2018; Deakin et al., 2019) was slightly higher than that obtained from aerial survey data at sites in the outer Firth of Forth during the same period of year and with same assumed turbine avoidance rate (98.9%) as in our study (1281 predicted collisions per breeding season; Table 13.75 in MacArthur Green, 2018). Survey data are not able to determine the origins of birds observed at sea but gannets have mutually exclusive colony-specific home ranges during the breeding season (Wakefield et al., 2013) and hence all those recorded in the outer Firth of Forth during these months were probably from Bass Rock. Our estimate assumed that data obtained from birds rearing chicks were representative of the entire breeding population at this time of year, whereas 18% of breeding attempts by gannets typically fail prior to hatching (Nelson 2002). Failed breeders are not constrained to return to the colony frequently to feed chicks and so, unlike successful breeders, their trip durations and foraging ranges may be no shorter during the chick-rearing period than earlier in the year. Assuming that their collision risk is unaltered accordingly, the predicted number of collisions per month during the chick-rearing period would be reduced from 452 to 382 ([452 × 0.82] + [59 + 0.18]; calculated from data in Table 3) resulting in an overall prediction of 1264 collisions each core breeding season, which is very similar to that based on aerial survey data.

Our PPM predicted that additional mortality from wind farms would reduce the growth rate of the gannet population at Bass Rock but would be insufficient to drive the population into decline. We did not consider potential displacement and barrier effects (Masden et al., 2015) but these are unlikely to be large because currently planned and operational wind farm sites comprised <2.5% of the area encompassed by the foraging ranges of birds. We assessed only the core breeding season and did not consider mortality during spring and autumn migration periods. Nor did we consider impacts of wind farms on immature birds, which also act as central-place foragers during the breeding season (Votier et al., 2017; Grecian et al., 2018). However, we estimate that an additional mortality of ~3300 breeding females per year would be needed to halt population growth, which is around three times our predicted number of collisions by females each breeding season (~950–1120, depending on the foraging trip characteristics of failed breeders during the chick-rearing period at the colony). Moreover, as recommended (Green et al., 2016), our model assumes that mortality from wind farms is entirely additive and takes no account of density-dependence (Lewis et al., 2001; Davies et al., 2013), which might off-set losses from collisions. This was a precautionary approach, in keeping with conclusions from recent analyses that any compensatory responses are unlikely to offset losses from breeding populations due to additional mortality associated with wind farms, and that depensatory responses (i.e. positive density-dependence) are unlikely to occur except in small populations of species that are more vulnerable than gannets to predation (Horswill et al., 2017; Miller et al., 2019). Population extinction risk can also be increased by stochastic variation in environmental conditions (Lande et al., 2003), although gannets are comparatively robust in this respect due to their life history and breeding ecology (Hamer et al., 2007; Montevecchi et al., 2009) making impacts of environmental stochasticity on population dynamics much less of an issue for gannets than for many other species (Miller et al., 2019).

Our results suggest that despite additional mortality from collisions with turbines, currently planned and operational wind farms would be unlikely to materially affect the viability of the gannet population at Bass Rock. Nonetheless, our PPM predicted that over a period of 25 years, uncompensated additional mortality of adults due to wind turbines would result in a breeding population only 71% of the predicted size in the absence of wind farms (data in Fig. 4, assuming death of one parent also resulted in loss of offspring). In practice, such sustained population growth is unlikely to occur under either scenario because the population at Bass Rock is probably approaching carrying capacity due to limited space for additional nesting sites (Murray et al., 2015). However, additional mortality at Bass Rock could result in changes to dispersal and recruitment (Seward et al., 2018; Bosch et al., 2019) with enhanced net immigration into this site potentially having adverse effects on population sizes at other colonies (Sanz-Aguilar et al., 2016; Miller et al., 2019). Hence our findings highlight a need for empirical data and theoretical research within a metapopulation framework (Votier et al., 2011) to assess impacts of offshore wind developments across multiple connected sites.

CRediT authorship contribution statement

Jude V. Lane: Methodology, Investigation, Formal analysis, Writing - original draft, Project administration. **Ruth Jeavons:** Data collection, Writing - review & editing. **Zoe Deakin:** Formal analysis, Writing - review & editing. **Richard B. Sherley:** Formal analysis, Writing - review & editing. **Christopher J. Pollock:** Data collection, Writing - review & editing. **Rebecca J. Wanless:** Data collection, Formal analysis. **Keith C. Hamer:** Conceptualization, Methodology, Data collection, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2020.105196.

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Effects of windscape on three-dimensional foraging behaviour in a wide-ranging marine predator, the northern gannet

Jude V. Lane[1,*], **Dominick V. Spracklen**[2], **Keith C. Hamer**[1]

[1]School of Biology, University of Leeds, Leeds LS2 9JT, UK
[2]School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

ABSTRACT: Marine birds are strongly exposed to weather conditions at sea but to date, few studies have investigated the influences of wind or rainfall on their time–activity budgets or foraging routines. Here, we used data from GPS and pressure loggers to investigate the effects of wind speed and direction and rainfall on the 3-dimensional foraging behaviour of gannets *Morus bassanus* breeding at Bass Rock, Scotland. We found that birds spent more time actively foraging during stronger winds, but there was no subsequent increase in overall trip duration because individuals compensated by decreasing the time they spent on the water during stronger winds. Birds returned more quickly from distant foraging grounds, and those encountering head winds spent less time on the water and so were able to compensate to some extent for an adverse effect of head winds on speed of travel over the return leg. These data strongly suggest that by reducing time spent on the water, birds were able to buffer trip durations against adverse effects of strong winds encountered during both commuting and active foraging. Birds also commuted at greater heights with increasing tail wind speed and at lower heights with increasing head wind speed, potentially providing an additional behavioural buffer against the adverse effects of strong head winds during foraging trips. There was no discernible effect of rain on foraging, but the behavioural flexibility recorded here is likely to be critical to maintaining nest attendance patterns and food provisioning rates of chicks across variable environmental conditions encountered at sea.

KEY WORDS: Foraging behaviour · GPS tracking · Northern gannet · *Morus bassanus* · Wind speed · Rainfall · Flight height

1. INTRODUCTION

Foraging behaviour is a large part of the daily routines of many species and an essential link between prey availability and predator reproductive success. For central-place foraging species, including many birds, a key issue in this context is the extent of behavioural flexibility in response to changing environmental conditions encountered during trips, especially when parents need to travel long distances to obtain prey (Tarroux et al. 2016, Kokubun et al. 2018). Wind is a major component of the environmental conditions experienced by birds (Hernández-Pliego et al. 2017, La Sorte & Fink 2017), and increases in mean wind speeds and storm frequencies are predicted to occur as a result of anthropogenic climate change, particularly in mid-latitudes (McInnes et al. 2011, Young et al. 2011), along with increases in the frequency and intensity of extreme weather events (Coumou et al. 2015). Yet while research on the biological impacts of global climate change has focused extensively on the effects of changes in temperature and rainfall (Terraube et al. 2017, Zuckerberg et al. 2018), impacts of changing wind conditions have received much less attention (Elliott et al. 2014).

Marine birds are particularly exposed to wind conditions while foraging at sea and during commutes between terrestrial breeding sites and marine foraging grounds. Wind also influences wave patterns and turbulence (Salisbury et al. 2013, Albert et al. 2016),

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*Corresponding author: j.lane@leeds.ac.uk

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which can alter the vertical distribution of forage fish in the water column and make them more difficult for surface-feeding and shallow-diving birds to locate and pursue (Konarzewski & Taylor 1989, Finney et al. 1999, Baptist & Leopold 2010, Parker-Stetter et al. 2016), while adverse winds may also reduce the speed with which parents can return to feed their offspring and relieve their partner at the nest. Many seabirds forage over large areas of ocean, so how they are affected by wind conditions encountered at sea may thus have important consequences for trip durations, nest attendance patterns and chick provisioning rates. Yet while a number of recent studies have examined changes in flight behaviour and energy expenditure in relation to wind conditions (Kogure et al. 2016, Gibb et al. 2017, Goto et al. 2017, Shepard et al. 2019), impacts on time–activity budgets and overall foraging routines have rarely been examined (Lewis et al. 2015).

Wind conditions also influence flight heights of birds (Krüger & Garthe 2001, Villegas-Patraca & Herrera-Alsina 2015, Tarroux et al. 2016). Over both land and open water, flying lower into head winds allows birds to take advantage of wind shear, where wind speed may be reduced by ~15–20 % at heights below 4 m, while flying less than 1.5× wingspan above the surface also allows birds to utilise ground effect, where lift is increased and aerodynamic drag is decreased as a result of the ground interrupting wingtip vortices and downwash behind the wing (Rayner 1991, Finn et al. 2012). Hence flying close to the surface reduces flight costs when flying into head winds while flying higher with tail winds enables faster and more efficient flight (Liechti et al. 2000, Krüger & Garthe 2001, Green 2004). Adjustments in flight height may thus be an important component of seabirds' responses to changing wind conditions at sea, but there are few previous data to address this question. For seabirds that exploit prey close to the water surface, foraging efficiency may also be influenced by rainfall, but the effects of rain on foraging behaviour are poorly understood (Pistorius et al. 2015).

Northern gannets *Morus bassanus* (hereafter gannets) are plunge-diving predators that obtain most of their prey within 10 m of the water surface (Lewis et al. 2002, Cleasby et al. 2015a). During chick-rearing, adults make foraging trips lasting up to 1 d or longer and covering 10s to 100s of km (Hamer et al. 2000, Wakefield et al. 2013). Flight comprises ~50 % of total trip time, and the dive rate of birds per daylight hour is apparently unrelated to trip duration (Lewis et al. 2004). Birds can reduce time away from the nest by returning to the colony at greater speeds from more distant foraging locations, but speeds decrease for the furthest destinations, probably due to constraints on energy expenditure during sustained flight (Hamer et al. 2007). Energy expenditure in flight is also strongly affected by wind speed and direction (Amélineau et al. 2014), but it is not clear how wind conditions affect birds' average speed of travel at sea or to what extent they can adjust their behaviour to reduce potential impacts of adverse wind conditions on time away from the nest. In addition, birds fly higher when actively foraging than when commuting between the nest site and foraging sites (Cleasby et al. 2015b), but it is not known how wind conditions or rainfall affect flight heights during commuting or foraging. Here, we investigated variation in the 3-dimensional foraging behaviour of gannets in response to weather conditions in the North Sea. We first examined how wind speed and direction and rainfall affect birds' foraging trip durations and time–activity budgets at sea. We then assessed how wind conditions affect birds' speed of travel and to what extent birds adjust their time–activity budgets to reduce the impact of adverse wind conditions on their rate of return to the nest from distant foraging sites. We next examined the influence of wind and rainfall on the flight heights of birds during commuting and active foraging.

2. MATERIALS AND METHODS

2.1. Study site and data collection

Fieldwork took place at Bass Rock, UK (56° 6′ N, 2° 36′ W) between mid-June and mid-August of 2015–2017. In total, 63 adult gannets with chicks were caught at the nest using a 6 m telescopic pole fitted with a metal noose or hook. Each bird was fitted with a metal British Trust for Ornithology ring and a coloured plastic ring with a unique alphanumeric code for easy identification at the nest site. We then recorded body mass to the nearest 10 g using an electronic scale. Each bird had a GPS logger (igotU-GT600, Mobile Action Technology) attached to the upper side of the central tail feathers and a logger recording atmospheric pressure and temperature (MSR-145W, MSR Electronics) attached to the central tail feather, on the underside to reduce Bernoulli effects during take-off from the water. GPS loggers weighed 30 g and recorded location at 2 min intervals; pressure loggers weighed 18 g and recorded at 1 Hz; both were attached using Tesa© tape. All sampled birds were recaptured after 7–14 d to retrieve loggers. Handling time of birds at both deployment and recapture was no longer than 15 min, and on both occasions birds returned to their chick almost immediately and resumed normal behaviour. The combined weight of loggers was <2% of body mass, which was well within recommended guidelines (Phillips et al. 2003); previous studies at this colony recorded that such deployments had no discernible impact on trip duration or body mass (Hamer et al. 2007, 2009, Cleasby et al. 2015a).

2.2. Trip analysis

For each foraging trip we determined the duration (h), total distance travelled (km), maximum distance (km) on a direct bearing from the colony and departure angle (degrees) from the colony (an average of the first 5 bearings >10 km from the colony; Patrick et al. 2014). We used the furthest location from the colony to distinguish between outbound and inbound stages of each trip; inbound distance was the total distance travelled from the furthest location back to the colony. We also calculated the direction of travel throughout each trip as the bearing between successive locations. In addition, speeds and turning angles derived from GPS data were used to classify the behaviour of birds at sea into 3 categories: commuting, characterised by long step lengths and small turning angles; active foraging, characterised by short step lengths and large turning angles; and time spent on the water, characterised by short step lengths and small turning angles (Wakefield et al. 2013, Amélineau et al. 2014, Grecian et al. 2018). Validation of these discrimination criteria against a separate sample of birds equipped with GPS loggers and time–depth recorders (TDRs) showed that, within individuals, 99% of GPS locations occurring within 10 min of dives detected using TDRs were classified as foraging (Wakefield et al. 2013).

2.3. Weather conditions

We obtained data on wind speed and direction and rainfall during foraging trips from the ERA-Interim reanalysis data set produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (6-hourly data at 0.125 × 0.125° or approximately 8 × 8 km resolution) (Dee et al. 2011). For every bird location at sea, we extracted the nearest data in time and space for rainfall (mm h^{-1}) and 10 m zonal (west–east) and meridional (south–north) wind components at 10 m a.s.l. (max. distance: 4 km; max. time difference: 3 h). We then calculated wind speed (m s^{-1}) and direction (°) using Eqs. 1 and 2, respectively:

$$Ws = \sqrt{Uw^2 + Vw^2} \quad (1)$$

$$Wv = \frac{180}{\pi}\left(\text{atan}(Vw, Uw)\right) \quad (2)$$

where Ws = wind speed, Uw = zonal wind component, Vw = meridional wind component and Wv = meteorological wind direction.

Following Amélineau et al. (2014), we used bird–wind angle (BWA) to characterise the relationship between wind direction and the bird's direction of travel. Absolute values of 0–45° (i.e. up to 45° to left or right of bird's heading) were categorised as head winds, 45–135° as cross winds and 135–180° as tail winds.

2.4. Flight height estimation

Following Cleasby et al. (2015b), we used the barometric equation to estimate the height of the bird (h) above sea level:

$$h = \frac{KT}{mg}\ln\left(\frac{P}{P_0}\right) \quad (3)$$

where P_0 and P are the atmospheric pressures (Pa) at sea level and at height h (m) respectively; K is the universal gas constant for air (8.31432 N m mol^{-1} K^{-1}); m is the molar mass of air (0.0289644 kg mol^{-1}); g is the acceleration due to gravity (9.80665 m s^{-2}); and T is the temperature (K) of the atmosphere between h_0 and h (see Supplement 1 at www.int-res.com/articles/suppl/m628p183_supp.pdf). We obtained calibration pressures (P_0) when birds spent time on the water (Cleasby et al. 2015b) and we accounted for spatial and temporal changes in atmospheric pressure during long periods of sustained flight by adjusting calibration pressures throughout the duration of each flight bout using the ERA-Interim reanalysis sea surface pressure data set (6-hourly data at 0.125 × 0.125° or approximately 8 × 8 km resolution) (Dee et al. 2011).

2.5. Statistical analysis

All analyses were conducted using R v.3.2.2 (R Core Team 2016). We used linear mixed-effects models (LMMs) fitted using the R package 'nlme' (Pinheiro et al. 2018) to examine how wind speed, direction and rainfall affected trip durations and the proportion of each trip spent actively foraging, commuting and on the water. Our rationale here was that birds show pronounced individual foraging site fidelity during chick-rearing (Hamer et al. 2001, Wakefield et al. 2015), so the distance travelled on each trip was modelled as a predictor variable that, together with different weather variables, could potentially affect both total trip duration and the proportion of time spent in different activities per trip. We included a mean value for wind speed, wind direction and rainfall per hour for each trip and we included year as a fixed effect to account for differences in trip parameters between years. We also included bird identity as a random effect to control for repeated measures due to multiple trips per bird. Continuous predictor variables were normalised to increase the interpretability of parameter estimates (Schielzeth 2010), and we tested for collinearity between predictor variables to ensure this would not cause difficulties for determining true relationships (Freckleton 2011).

In view of the large number of predictor variables and potential interactions, model simplification and selection were performed using a multi-model inference approach based on the methods and recommendations of Grueber et al. (2011), using the 'MuMIn' package (Bartoń 2015). A set of candidate models was first identified for each response variable, with all possible subsets of predictor variables and interactions considered. Support for different candidate models was then assessed using Akaike's information criterion adjusted for small sample size (AIC_c) and Akaike weights. Models with the greatest raw AIC_c weight and a $\Delta AIC_c > 2$ from the next ranked model were considered to have the best model fit (Burnham & Anderson 2002), but where there was uncertainty over the top model, parameter estimates and the relative importance of each parameter were averaged across selected models, with test statistics and p-values extracted using MuMln.

To assess how wind conditions influenced flight speed and whether or not gannets adjusted their behaviour to compensate, we first used a LMM to examine how mean wind speed and direction affected mean ground speed during periods of commuting flight. This analysis included foraging trip identity nested within bird identity as a random effect, to account for repeated measures within each foraging trip and multiple trips per bird. A temporal autocorrelation structure was also included to control for non-independence of successive data within each trip. We then used LMMs to examine how median wind speed and direction affected the average speed of travel during daylight hours and the proportion of day time spent on the water during the return leg of each trip. Travel speeds were right-skewed and were therefore square-root transformed prior to analysis. Each model also included bird identity as a random effect to control for multiple trips per bird. We ran 3 models for both travel speed and proportion of time on the water, to include all combinations of distance and distance^2 to account for potential non-linear relationships (Hamer et al. 2007), and we then selected the best model using AIC_c values.

To examine how wind and rainfall affected flight heights, we first used a LMM to compare the median heights of birds during each period of commuting and active foraging. Rainfall was the mean value during each period of flight. Wind direction was characterised from BWA and cross winds were excluded from the analysis. Foraging trip identity nested within bird identity was included as a random effect to account for repeated measures within each foraging trip and multiple trips per bird, and a temporal autocorrelation structure was included to control for non-independence of successive data within each trip. We then used a linear model (LM) to examine the influence of wind speed on flight heights. For this analysis, wind speeds were binned at 1 m s^{-1} intervals, with head winds having negative speeds and tail winds positive speeds, and a mean height was used for each wind speed interval. Heights were right-skewed and were therefore square-root transformed prior to calculating means. Some estimated flight heights were below 0 m and, following Cleasby et al. (2015b), these were retained in the analysis by adding the minimum estimated height (absolute value) to all cases to permit square root-transformation.

3. RESULTS

We acquired combined GPS and altitude data for 188 trips by 46 individuals (106 trips by 29 birds in 2015; 47 trips by 16 birds in 2016; 35 trips by 13 birds in 2017; data from 17 birds were incomplete). Most trips travelled northeast or southeast of the colony, with fewer travelling due east (Fig. 1). The prevailing wind direction was from the southwest (Fig. S1 in Supplement 2) and accordingly, birds spent most of their time in flight with cross winds and tail winds when commuting away from the colony, and with head winds and cross winds when returning to the colony (Fig. 2a,c). When actively foraging, however, birds spent significantly more time flying into the wind (mean ± SD: 33 ± 14 %) and less with the wind behind them (18 ± 10 %) than expected by chance (Fig. 2b; $\chi^2_2 = 511.0$, $p < 0.0001$; birds frequently

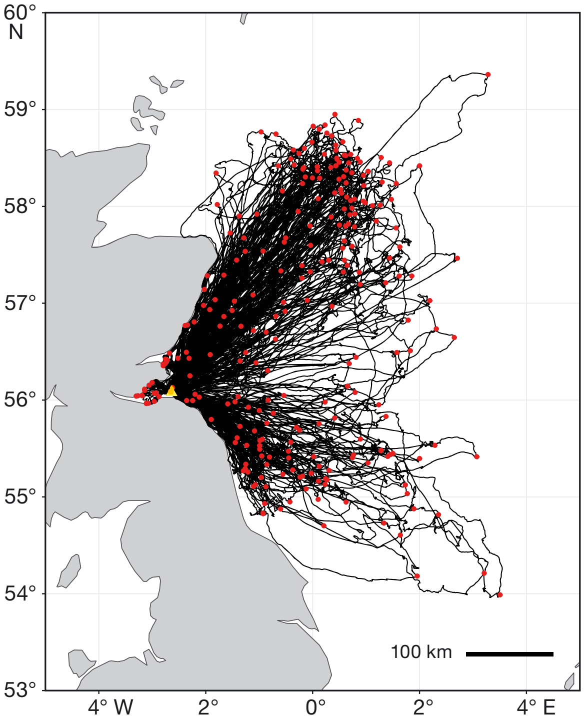

Fig. 1. Tracks of foraging trips (n = 263) by adult northern gannets rearing chicks at Bass Rock between mid-June and mid-August of 2015–2017. Red dots: maximum distance from the colony on each trip; yellow triangle: colony location

changed direction while actively foraging so would have been expected by chance to spend 25 % of their time with head winds, 50 % with cross winds and 25 % with tail winds).

3.1. Trip durations and time–activity budgets at sea

The mean duration of foraging trips was 24.3 ± 10.7 h (range: 1.5–70.3 h). Both trip duration and the proportion of each trip spent commuting were significantly positively related to total distance travelled (Fig. 3; LMM; $\chi^2_1 = 378.5$, $p < 0.001$ and $\chi^2_1 = 57.1$, $p < 0.001$, respectively) but no weather variables improved either model ($\Delta AIC_c > 5$ for trip duration, >2 for proportion of trip commuting; AIC_c weight dropped from >0.8 to <0.1 and from >0.5 to <0.2, respectively; Table 1). The proportion of time spent actively foraging per trip increased significantly with increasing wind speed (Fig. 3c; $\chi^2_1 = 14.6$, $p < 0.001$) but the model was not improved by including any other variable ($\Delta AIC_c > 5$ in each case; Table 1). There was no clear top model for the proportion of daylight hours spent on the water, but model averaging of the top 3 models (i.e. those with $\Delta AIC_c < 2$; Table 1) found distance travelled per trip and wind speed to be the most significant factors (Table 2), indicating that the proportion of time on the water decreased as distance travelled increased and with increasing wind speed (Figs. 3d & 4).

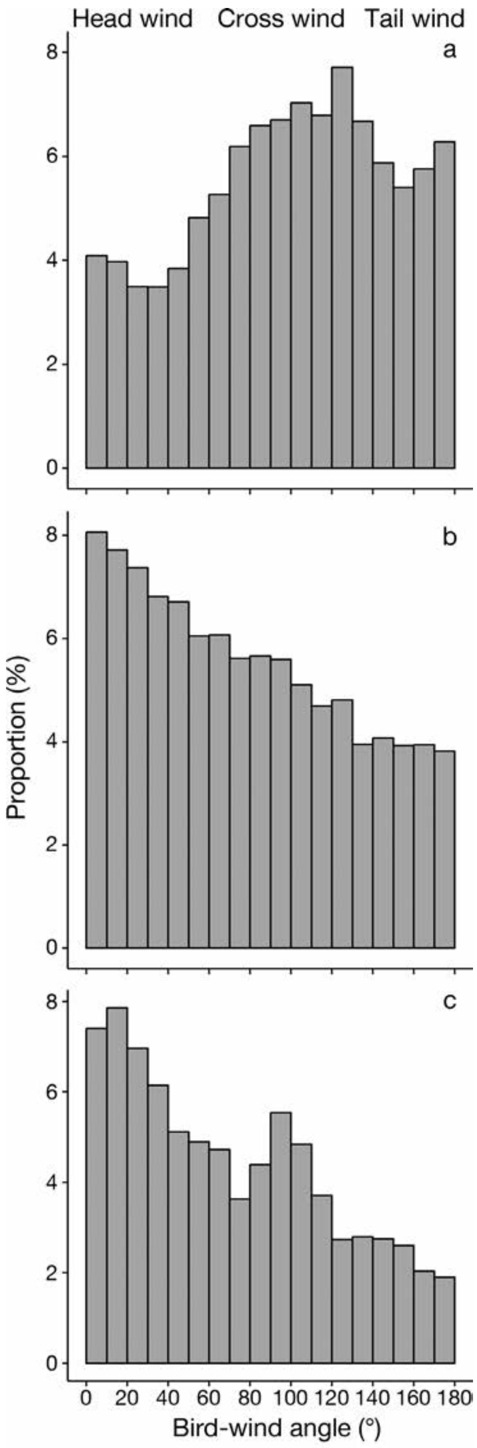

Fig. 2. Frequency distribution of bird–wind angles for GPS locations of northern gannets during (a) outbound commuting (n = 19 238 locations), (b) active foraging (n = 20 446) and (c) inbound commuting (n = 21 233)

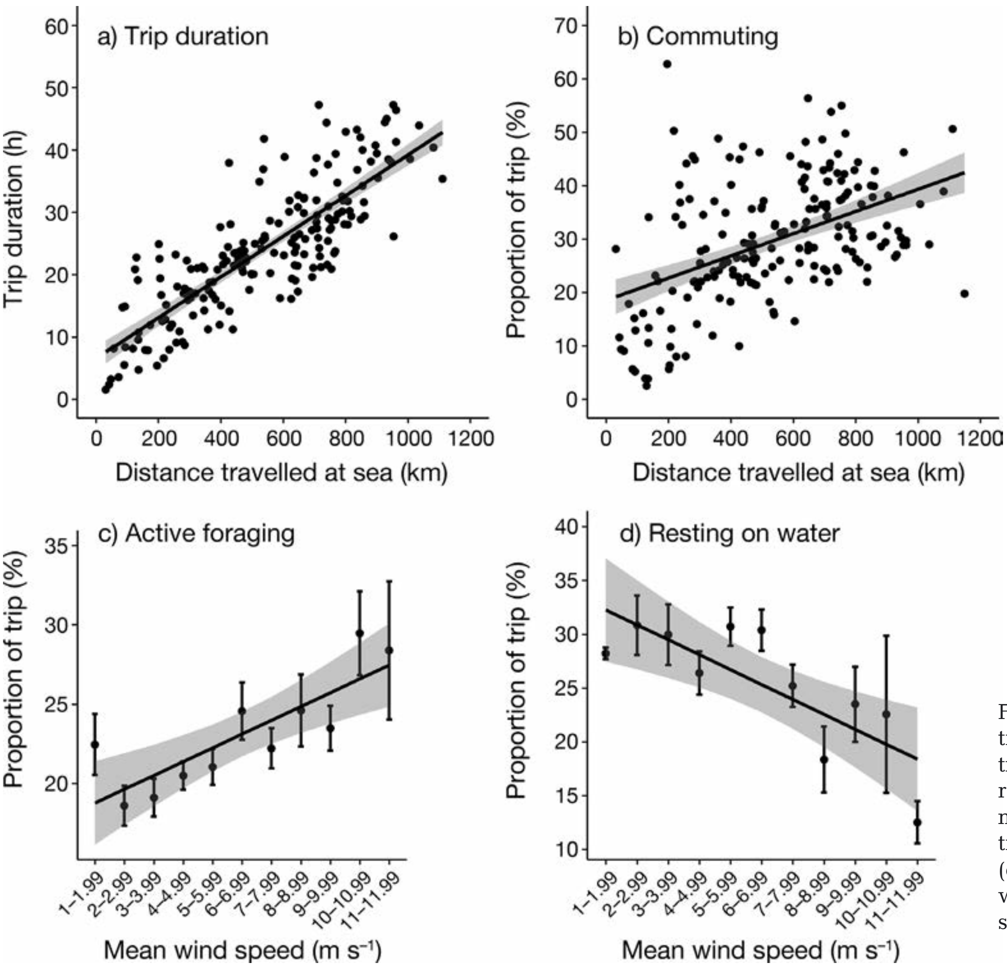

Fig. 3. Northern gannet (a) trip duration and (b) proportion of the trip commuting in relation to total trip distance; mean ± SE proportion of the trip (c) actively foraging and (d) resting in relation to mean wind speed encountered at sea. Line (shading): model prediction (95 %CI)

3.2. Flight speeds and rates of return to the nest

During periods of commuting, whether outbound or inbound, ground speeds were faster with a tail wind component than with a head wind component (LMM; $\chi^2_2 = 301.5$, $p < 0.001$; mean ± SD: 17.5 ± 3.4 and 12.6 ± 2.0 m s^{-1}, respectively). As expected, ground speeds increased as the tail wind component increased and the head wind component decreased (Fig. 5a; $\chi^2_1 = 278.67$, $p < 0.001$). The average speed of travel over the return leg of a trip was significantly related to both distance from the colony and distance^2 (LMM; $\chi^2_1 = 14.0$, $p < 0.001$ and $\chi^2_1 = 5.9$, $p < 0.05$, respectively) indicating a non-linear relationship with distance, while the best-performing model according to AIC$_c$ also included wind speed and direction (Table 3): average travel speed increased with increasing distance from the colony up to 100–200 km (fastest for birds returning with a tail wind, slowest for those returning into a head wind), beyond which the relationship levelled off (Fig. 5b). Time spent on the water during the return leg of a trip was also significantly related to inbound distance travelled ($\chi^2_1 = 5.9$, $p < 0.05$) with the best-supported model also including distance^2 and wind speed and direction (Table 3). For return legs up to 100–200 km, time on the water decreased with increasing distance and was greatest for birds returning with a tail wind and least for those returning into a head wind (Fig. 5c).

3.3. Flight heights

Median flight height was significantly lower during periods of commuting than active foraging (LMM; $\chi^2_1 = 4.75$, $p < 0.05$; Table 4) but was unaffected by rainfall. Birds also flew lower into head winds than with tail winds when commuting ($\chi^2_1 = 37.6$, $p < 0.001$) but not while actively foraging, when median height was ~28 m irrespective of wind direction (Table 4). In addition, commuting flight heights increased with increasing tail wind speed and decreased as head wind speed increased (LM; $F_{1,18}$ =

Table 1. Top model sets for estimating effects of weather parameters on different components of northern gannet behaviour during foraging trips. LogLik: log-likelihood; AIC_c: Akaike's information criterion corrected for small sample size

Rank	Model	df	LogLik	AIC_c	ΔAIC_c	AIC_c weight
Trip duration						
1	Trip distance	5	−185.87	382.1	0.00	0.827
2	Trip distance + rainfall	6	−187.55	387.6	5.48	0.053
3	Trip distance + wind speed	6	−187.91	388.3	6.21	0.037
4	Trip distance + wind direction	6	−187.98	388.4	6.34	0.035
5	Trip distance + year	7	−186.93	388.5	6.41	0.034
6	Trip distance + rainfall + year	8	−188.49	393.8	11.71	0.002
	Null model	4	−293.45	595.1	213.04	0.000
Proportion of trip commuting						
1	Trip distance	5	−265.13	540.6	0.00	0.518
2	Trip distance + rainfall	6	−265.11	542.7	2.10	0.181
3	Trip distance + year	7	−264.57	543.8	3.19	0.105
4	Trip distance + wind direction	6	−266.51	545.5	4.90	0.045
5	Trip distance + rainfall + year	8	−264.40	545.6	5.04	0.042
6	Trip distance + wind speed	6	−266.76	546.0	5.40	0.035
	Null model	4	−288.37	585.0	44.36	0.000
Proportion of trip actively foraging						
1	Wind speed	5	−187.43	385.2	0.00	0.825
2	Wind speed + wind direction	6	−189.34	391.2	5.97	0.042
3	Wind speed + rainfall	6	−189.42	391.3	6.13	0.039
4	Wind speed + trip distance	6	−189.48	391.4	6.23	0.037
5	Wind speed + year	7	−188.86	392.4	7.16	0.023
6	Null model	4	−192.40	393.0	7.82	0.017
Proportion of trip on the water						
1	Trip distance + wind speed + year	8	−247.53	511.9	0.00	0.418
2	Trip distance + wind speed + rainfall + year	9	−247.37	513.8	1.89	0.162
3	Trip distance + wind speed	6	−250.70	513.9	1.99	0.154
4	Trip distance + wind speed + wind direction + year	9	−247.97	515.0	3.09	0.089
5	Trip distance + wind speed + wind direction + year + wind speed × wind direction	10	−247.76	516.8	4.91	0.036
6	Trip distance + wind speed + rainfall	7	−251.13	516.9	5.02	0.034
	Null model	4	−270.90	550.0	38.15	0.000

Table 2. Model-averaged estimates for factors affecting the proportion of each trip spent resting on the water by northern gannets during daylight hours; n = 3 models

Parameter	Estimate	Confidence interval	p	Relative importance
Trip distance	5.13	−0.56 to −0.27	<0.001	1.0
Wind speed	−0.42	−0.42 to −0.43	<0.001	1.0
Rainfall	0.13	−0.01 to 0.27	0.06	0.22
Year (2016)	0.06	−0.26 to 0.40	0.69	0.79
Year (2017)	0.56	0.19 to 0.92	0.002	0.79

17.9, $p < 0.001$; Fig. 6; slope [±SE] = 1.06 ± 0.25, $R^2 = 0.47$) whereas there was no discernible effect of wind speed on heights during active foraging (slope = −0.17 ± 0.25, $R^2 = 0.02$).

4. DISCUSSION

Wind conditions encountered at sea have complex effects on birds' time–activity and energy budgets, with potentially contrasting effects on the time and energy spent commuting between the colony and distant foraging sites and during periods of active foraging. For black-legged kittiwakes *Rissa tridactyla* and little auks *Alle alle*, which are purely flapping species, energy expenditure increased and food-provisioning rates of chicks decreased during strong winds (Gabrielsen et al. 1987, 1991, Konarzewski & Taylor 1989, Christensen-Dalsgaard et al. 2018). In contrast, however, northern fulmars *Fulmarus glacialis*, which are flap-gliders, had lower energy expenditure due to a lower wing beat frequency during stronger winds (Furness & Bryant 1996), while higher average wind speeds led to enhanced foraging efficiency and breeding success in wandering albatrosses *Diomedea exulans* (Weimerskirch et al. 2012). For northern gannets, we found that while wind speed and direction had strong effects on the speed of travel between the colony and distant foraging sites, there was no effect on the proportion of each trip spent commuting, probably because with a constant wind direction, birds would encounter both head and tail winds over the outward and return portions of a trip. Birds spent more time flying into head winds during active foraging than when commuting, probably to provide additional lift and reduce ground speed to aid detection of prey (Machovsky-Capuska et al. 2012, Amélineau et al. 2014). However, birds also spent more time actively foraging during stronger winds, probably because strong winds disrupted the water surface (Sundarabalan et al. 2016), reducing prey visibility and hence potentially leading to both more time spent locating prey and a greater number of dives to capture prey as a result of lower success rates per dive (Finney et al. 1999, Elliott et al. 2014, Pistorius et al. 2015). Frequent dives and associated take-offs from the water surface are

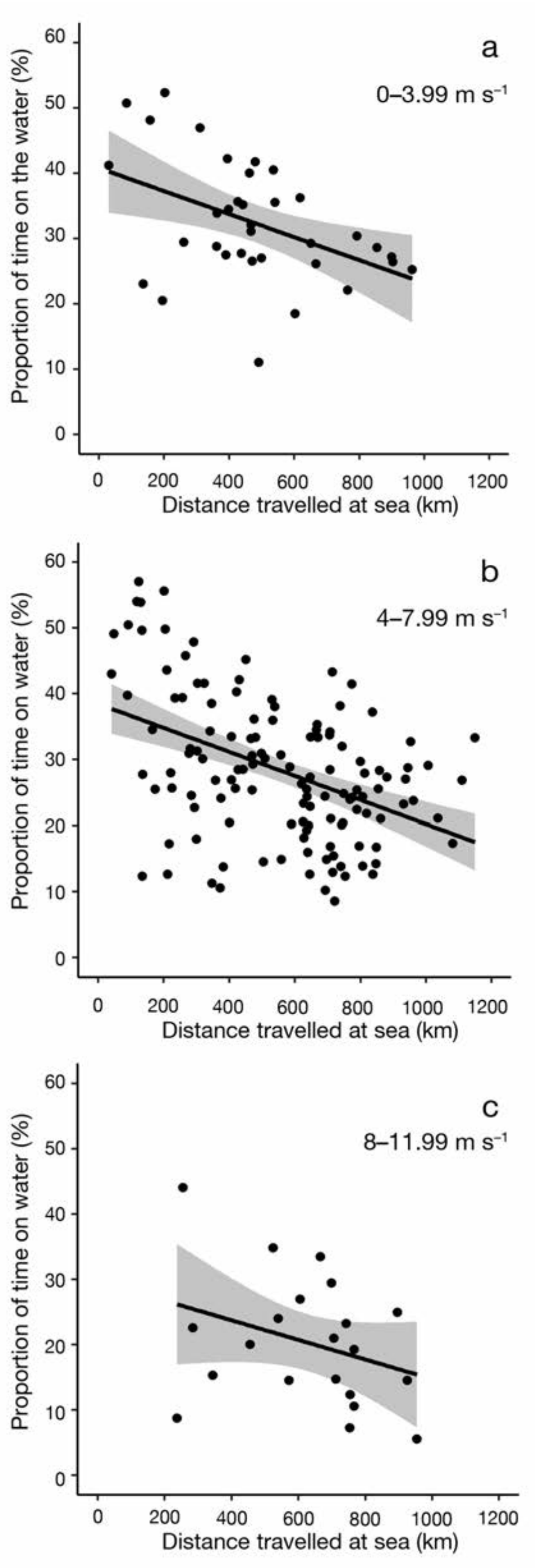

Fig. 4. Proportion of daylight hours spent on the water by northern gannets in relation to distance travelled per trip and mean wind speed encountered during the trip. Lines (with 95% CI) plotted using model-averaged estimates for each predictor variable (see Table 2)

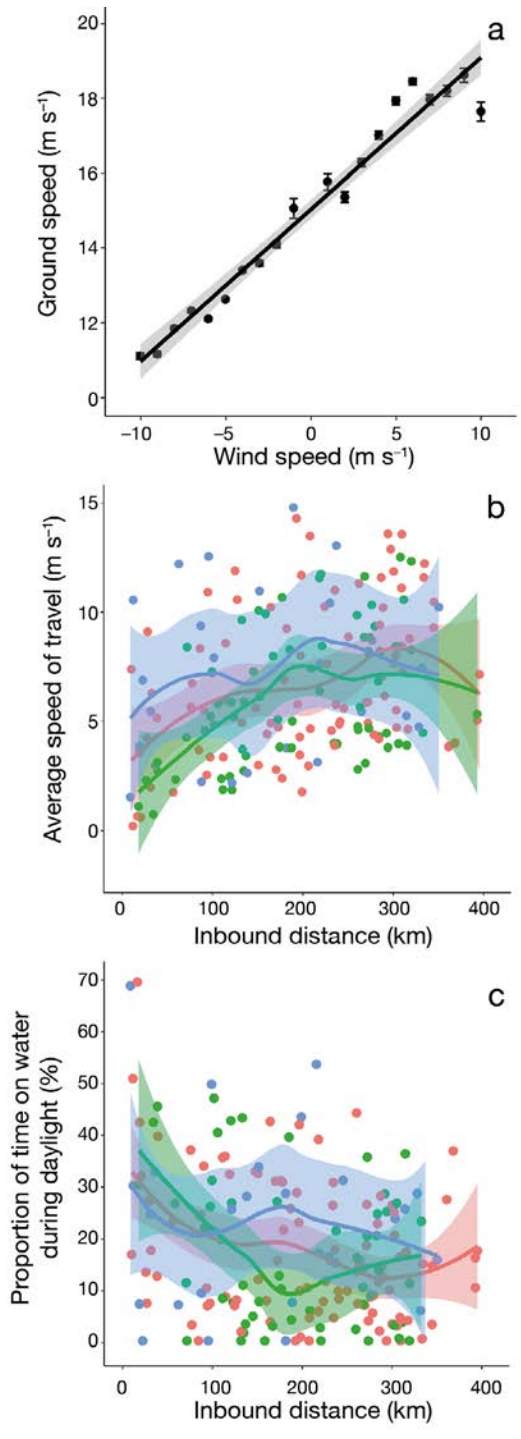

Fig. 5. (a) Mean (±SE) ground speeds of commuting northern gannets in relation to the mean wind speed at 10 m a.s.l. over a trip for tail winds (speed > 0) and head winds (speed < 0). (b) Average speed of travel and (c) proportion of daylight hours on the water during the return leg of foraging trips in relation to distance (km) for different bird–wind angles. Lines: linear model predictions in (a) and predictions estimated with loess function in R (blue: tail winds; red: cross winds; green: head winds) in (b,c). Shaded areas: 95%CI. Based on 188 foraging trips

Table 3. Top model sets for estimating effects of different variables on average speed of travel and proportion of time resting on the water during the return leg of each trip by northern gannets. LogLik: log-likelihood; AIC_c: Akaike's information criterion corrected for small sample size

Model	df	LogLik	AIC_c	ΔAIC_c
Speed				
Distance + distance^2 + wind speed + wind direction	7	−182.16	379.0	0
Distance + wind speed + wind direction	6	−184.28	381.0	2.0
Distance^2 + wind speed + wind direction	6	−187.94	388.3	9.3
Resting				
Distance + distance^2 + wind speed + wind direction	7	−376.47	767.6	0
Distance + wind speed + wind direction	6	−378.48	769.4	1.8
Distance^2 + wind speed + wind direction	6	−379.72	771.9	4.3

Table 4. Flight heights of northern gannets during commuting and active foraging with head and tail winds. IQR: interquartile range

	Head wind			Tail wind		
	n	Flight height (m)		n	Flight height (m)	
		Median	IQR		Median	IQR
Commuting	8600	12.6	3.8–29.2	6246	25.6	9.6–46.1
Active foraging	7072	27.8	9.4–47.3	4463	28.3	7.7–48.7

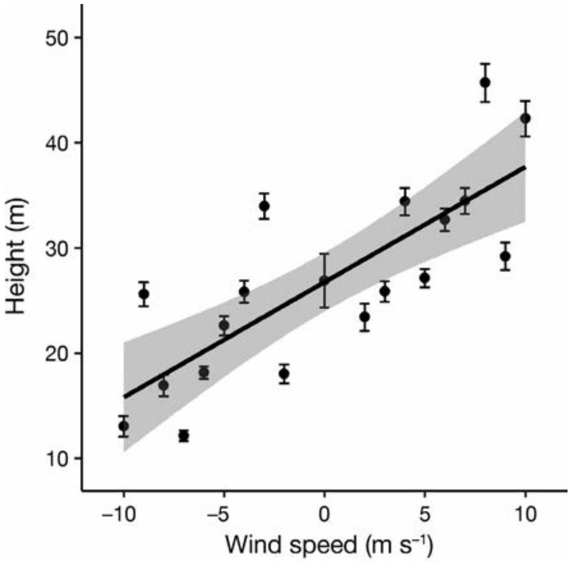

Fig. 6. Mean (±SE) flight heights of commuting northern gannets in relation to the mean wind speed at 10 m a.s.l. over a trip for tail winds (speed > 0) and head winds (speed < 0). Line (shading): linear model prediction (95%CI)

energetically expensive (Sakamoto et al. 2013), so a greater time spent actively foraging in stronger winds may explain why, while energy spent in commuting flight decreased with increasing wind speed in northern gannets (Amélineau et al. 2014), overall energy expenditure during trips increased with increasing wind speed in closely related Cape gannets *M. capensis* (Mullers et al. 2009).

We found that the increase in time spent foraging as wind speed increased did not result in any increase in overall trip duration, because birds compensated by decreasing the time they spent on the water during stronger winds, presumably reflecting a benefit in returning quickly to feed dependent offspring and relieve the partner at the nest. We also found that adults returned to Bass Rock at higher speeds from more distant foraging locations up to ~200 km from the colony, a similar pattern to that recorded by Hamer et al. (2007), who also found that speeds decreased for the furthest destinations, probably due to constraints on energy expenditure during sustained flapping flight. In keeping with this notion, we found that the increase in average speed of travel for distances up to ~200 km was accompanied by a decrease in the proportion of time on the water, particularly for birds flying into head winds, with an asymptote in speed of travel corresponding with a levelling off in time on the water beyond this distance. These data strongly suggest that by reducing time spent on the water, birds were able to buffer trip durations against adverse effects of strong winds encountered both while commuting and during active foraging.

In addition to altering time spent on the water during trips, birds also adjusted their flight heights in relation to wind speed and direction. The higher proportion of commuting flight at low elevations into head winds compared with tail winds was similar to that recorded in a wide range of species during migration (Krüger & Garthe 2001) and supports the notion that individuals can make use of both wind shear and ground effect to ameliorate the impacts of strong head winds on ground speed and energy expenditure (Finn et al. 2012, Tarroux et al. 2016). During the breeding season, this flexibility in commuting flight height may provide an additional behavioural buffer against the adverse effects of strong head winds during foraging trips.

Oceanic winds affect the prey fields of marine predators by altering their ability to access, detect and capture prey, acting as an additional dimension in their *N*-dimensional niche space (Raymond et al. 2010, Wilson et al. 2011, Weimerskirch et al. 2012). While gannets were able to buffer adverse effects of strong winds by reducing time spent drifting on water during trips and also by altering their flight heights in relation to wind conditions, other species may have different behavioural responses. For instance, Brünnich's guillemots *Uria lomvia* and black-legged kittiwakes buffered the adverse effect of high winds on food-provisioning rates of chicks by switching to other food sources during windy days or increasing food delivery rates when weather improved (Elliott et al. 2014). Such behavioural flexibility is likely to be critical to maintaining fitness across variable environmental conditions encountered at sea, and parallels that recorded at an annual time-scale in a number of species in response to climate-related variation in prey abundance and availability (Grémillet et al. 2012, Kokubun et al. 2018).

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This report presents the results of marine and freshwater scientific work carried out for Marine Scotland under external commission.

Developing an avian collision risk model to incorporate variability and uncertainty

Elizabeth Masden
Environmental Research Institute
North Highland College – UHI
University of the Highlands and Islands
Thurso, KW14 7EE

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Part 1: Model Description

Background

As wind energy developments increase globally the potential associated environmental impacts are receiving considerable attention, particularly avian impacts. These potential impacts on bird populations can be grouped into three main types: direct mortality due to collision with turbines/infrastructure; physical habitat modification and/or loss; and behavioural responses of birds to turbines (Fox *et al.* 2006; Langston 2013). Focussing on avian collision, a variety of methods have been developed to aid the assessment of the risk of collision, including collision risk models.

After extensively reviewing both the peer-reviewed scientific literature and grey literature, 10 distinct collision risk models referring to birds and wind turbines were identified, the earliest dating back to 1996 (Tucker 1996). At their core, most avian collision risk models include a calculation of the probability of a collision occurring (assuming no evasive action or avoidance behaviour) and often also a measure of the number of birds at risk, if an estimate of likely collision events is to be calculated. The probability of collision is generally based on the probability of a turbine blade occupying the same space as the bird during the time that the bird takes to pass through the rotor swept area. This therefore relies upon information on both bird and wind turbine characteristics such as bird morphometrics and flight speed, turbine rotor speed and size, etc.

In the UK, the most frequently used avian collision risk model is commonly known as 'the Band model' (Band, Madders & Whitfield 2007) and was originally conceived in 1995. Since then it has undergone several iterations with the most recent associated with the Strategic Ornithological Support Services (SOSS) (Band 2012a; b). The Band model (Band 2012b) provides four different options for calculating collision risk.

- Option 1 - Basic model, i.e. assuming that a uniform distribution of flight heights between the lowest and the highest levels of the rotors and using the proportion of birds at risk height as derived from site survey.
- Option 2 - Basic model, but using the proportion of birds at risk height as derived from a generic flight height distribution provided.
- Option 3 - Extended model and using a generic flight height distribution.
- Option 4 - Extended model and using a flight height distribution generated from site survey.

The most recent update of the Band model guidance also provides an approach under which uncertainty can be expressed. However, this approach is relatively simplistic and can only be applied when the sources of variability are independent of one another. Furthermore, although provided, it is not routinely followed and so could be improved upon. From undertaking interviews with stakeholders (for summary see Appendix 1), it was established that a new collision risk model that was fundamentally different was not required by the industry and the Band model was considered generally fit for purpose. However, although the majority of the stakeholders questioned did not consider major changes necessary, the general opinion was that if it were possible to incorporate uncertainty into the modelling process, it would be beneficial. The main reasoning for this was that expressing collisions as a single number does not sufficiently represent the complexity of the situation. In addition, it is known that the Band model is sensitive to the choice of input parameters (Chamberlain *et al.* 2006). Variability in input parameters such as bird density, flight speed and turbine rotor speed are likely to contribute uncertainty to the final collision estimates. Sensitivity analyses of both the basic and extended options of the Band model are provided in Appendix 2.

General purpose of model update

The general purpose of this collision risk model update is to further develop the application of the Band model using a simulation approach to incorporate variability and uncertainty. In this report we refer to variability as the inherent heterogeneity of the environment and uncertainty as a lack of data or incomplete knowledge. The simulation model randomly samples from distributions for each of the model parameters and the simulations can then be used to derive average collision estimates, with associated confidence intervals. The model update will therefore allow for a better understanding of the uncertainty associated with the predicted collision impact of a wind farm development and provide confidence limits, something which has previously been absent. In addition, the incorporation of uncertainty would reduce the possibility that a collision estimate was driven by the choice of a single input parameter value. Ultimately, the update should aid streamlining of the planning/consenting stages of a development by providing information not only on the magnitude of collisions i.e. the number of collision events, but also the likelihood of that number of collisions occurring.

In this model update, variability and uncertainty are considered together in combination, rather than separately. Some model input parameters will have associated variability, for example bird body length, others may be expected to be point estimates with associated uncertainty, such as turbine rotor radius, and some parameters may have both variability and uncertainty. Ideally it would be possible to differentiate between variability and uncertainty but at present this is not possible due to a lack of data. However, including variability and uncertainty in combination in the model still provides a significant step forward.

The report describes the data required, and the methods used, to estimate collision risk. It is accompanied by a worked example and R code (available at http://dx.doi.org/10.7489/1657-1), which enables the collision risk calculations to be performed in a standardised and reproducible way.

Model format

Whereas previous iterations of the Band model have used Microsoft Excel, the collision risk model updated presented uses R http://www.r-project.org. Opinions given during stakeholder interviews (for summary see Appendix 1) were that the Excel spreadsheet was difficult to use at times and there was the potential for errors to be easily introduced into calculations, particularly if the spreadsheet did not update correctly when new input parameters were entered. In addition, the Excel spreadsheet does not allow results to be reproduced easily making auditing onerous, as values have to be entered manually for each occasion or scenario. Using R enables reproducible methods and results as code and data are provided along with the computational environment used. This improves understanding and allows verification of results, therefore increasing transparency.

Relationship to previous guidance on collision risk modelling

The model described and presented in this document is an update to the Band collision risk model (Band 2012b) which was most recently updated as part of SOSS. The mechanistic details of the Band model have not been altered and form the core of the model update described below.

The guidance (Band 2012b) states clearly that the collision estimate should be a best-estimate rather than a worst-case scenario.

"This guidance does not recommend use of 'worst case' assumptions at every stage. These can lead to an overly pessimistic result, and one in which the source of the difficulty is often concealed. Rather, it is recommended that 'best estimates' are deployed, and with them an analysis of the uncertainty or variability surrounding each estimate and the range within which the collision risk can be assessed with confidence. In stating such a range, the aspiration should be to pitch that at a 95% confidence level, that is, so that there is 95% likelihood that the collision risk falls within the specified range. However, given the uncertainties and variability in source data, and the limited firm information on bird avoidance behaviour, it seems likely that for many aspects the range of uncertainty may have to be the product of expert judgement, rather than derived from statistical analysis."

The model update presented in this document follows this principle by using ranges of values rather than a single, 'worst-case' scenario.

The previous guidance (Band 2012b) presented a method to express overall uncertainty in collision estimates (stage F), as there are a large number of sources of variability or uncertainty. Cook *et al.* (2012) and Johnston *et al.* (2014) are key resources to include in this process as they provide data with confidence limits. However, the uptake of stage F in the collision estimation process appears to have been minimal. There have also been cases of its misapplication with estimates presented with implausible confidence limits such as 40±100 collisions, suggesting that negative numbers of collisions are possible. In addition, the method for expressing uncertainty suggested in stage F does so *post hoc*, rather than being integrated in to the model itself. Also, combining sources of uncertainty as suggested is only applicable when parameters are independent. The model update described in this document further develops the concepts presented in stage F of the previous guidance.

Before the most recent iteration of the Band model (Band 2012b) was conceived, McAdam (2005) produced a model which incorporated species specific flight height distributions. Variation in flight height has now been incorporated in to the most recent update (Band 2012b), however, the model produced by McAdam (2005) used Monte Carlo simulation to obtain 500 samples. Using Monte Carlo methods allowed for the production of summary statistics rather than single collision estimates, as well as probability distributions of events (numbers of collisions) occurring. It was also executed using R rather than Excel. In the model update presented below, the method of Monte Carlo simulation used by McAdam (2005) has been applied to the most recent version of the Band model to allow the incorporation of uncertain parameter values.

General data requirements

The model update is based on the Band model (Band 2012b) therefore the types of data required are the same:

- Bird survey – data on the number of birds flying through or around the site, and their flight height
- Bird specification – details on bird morphology and flight speed
- Turbine specification – details on the number, size and rotation speed of turbine blades
- Bird behaviour – prediction of likely change due to wind farm, e.g. avoidance

The crucial difference from previous iterations of the Band model is that rather than using a single value for a given input parameter, for example bird flight speed, this update of the model randomly samples from a distribution of values. Using the randomly sampled parameter values, a collision risk estimate is calculated. This process is then repeated numerous times to produce a distribution of collision estimate for which summary statistics i.e. average and spread, can be calculated. Whereas the previous guidance and methods provided a measure of uncertainty post hoc, uncertainty is now incorporated in the modelling procedure itself with this update. Therefore, information regarding uncertainty in the data is required to be entered into the model.

Where possible, and when suitable, a mean and standard deviation should be provided for input parameters. These should capture the uncertainty within the data. For example, if the maximum turbine blade width has not been decided upon but is likely to be 5 metres then a mean = 5 should be provided with a standard deviation which describes the uncertainty and possible values. For this example, a mean of 5 and standard deviation of 0.3 would give a minimum of approximately 4 metres, and a maximum of approximately 6 metres. If there is no uncertainty and it is definite that the maximum blade width is to be 5 metres then a value of 5 should be entered as the mean and either 0 entered as the standard deviation or it left blank.

To incorporate uncertainty into the collision risk estimate, a mean and standard deviation will be required for the following parameters. Attention should be paid to the units of measure.

Table 1: Bird-related parameters

Parameter	**Units**	**Description/Notes**
Length	m (metres)	
Wingspan	m (metres)	
Flight speed	m/sec	Available from telemetry data or wind tunnel experiments
Flight type		Flapping or gliding
Nocturnal activity	Proportion e.g. 0.5 for 50%	Available from telemetry data or visual observations
Proportion at collision risk height	Proportion e.g. 0.5 for 50%	
Flight height distribution	Proportion e.g. 0.5 for 50%	Distribution curves from which the proportion of birds flying within 1 metre height bands are calculated. Data provided by BTO (Johnston *et al.* 2014). (See below)
Avoidance rate	Proportion e.g. 0.5 for 50%	Suggested values available from MSS avoidance report
Bird density	Birds/km^2	Birds in flight in daytime, taken from survey data

Table 2: Turbine-related parameters

Parameter	Units	Description/Notes
Rotor radius	m (metres)	Measured from the axis of rotation to blade tip.
Hub height	m (metres)	Sum of rotor radius and minimum blade clearance above HAT. (See below)
Max. blade chord width	m (metres)	
Rotation speed	rpm	See below
Blade pitch	Degrees relative to rotor plane	See below
Turbine operation time	Proportion e.g. 0.5 for 50%	Requires both information on wind availability and maintenance down time.

This model requires information on flight height distributions, if options 2, 3 or 4 are to be used. A generic flight height distribution is presented with the SOSS guidance (Band 2012a; b; Cook *et al.* 2012), however this does not provide information on the uncertainty associated with the distribution. Johnston *et al.* (2014) used a bootstrapping technique to provide confidence limits associated with the generic flight distribution and these bootstraps can be used within this model update to provide uncertainty associated with the flight height distribution curve. For each iteration of the model, a curve produced from a bootstrap sample is re-sampled and used. It is possible to use this update to calculate a collision risk estimate using option 4, should site-specific data on flight height distributions be available.

The model also requires information on wind speed ($m.s^{-1}$) at the proposed site as well as the relationship between rotor speed and wind speed and turbine pitch and wind speed. This allows rotor speed and pitch to be linked both to the wind speed and also to each other. This is achieved through the provision of data similar to that in table 3 (below), describing the relationship between wind speed and rotor speed and pitch, as well as information on wind speed at the site.

Table 3: Example data describing relationship between wind speed, rotor speed and blade pitch.

Wind speed (m/s)	Rotor Speed (rpm)	Pitch (degrees)
0	0	90
1	0	90
2	0	90
3	6	0
4	6	0
5	6	2
6	8	4
…	…	…

The turbine operation time is wind availability minus maintenance down time. Wind availability should be provided as a constant i.e. proportion of time the wind conditions allow for turbine operation and should be available from meteorological data. Maintenance time should be provided as a monthly mean and standard variation as it is expected that there will be uncertainty and variability surrounding maintenance.

Hub height is the distance from highest astronomical tide (HAT) to the axis of rotation of the turbine. This distance comprises the rotor radius and the distance between the minimum rotor tip height and HAT. Therefore, as rotor radius is already entered into the model, it is importantly only the distance component from HAT to the minimum rotor height that is required here and not the total hub height.

Calculating collision risk

As stated previously, this model is an update of the Band model. For more information on the Band model refer to (Band 2012a; b) and associated information on the SOSS website http://www.bto.org/science/wetland-and-marine/soss/projects.

Monte Carlo simulation

The model update presented herein uses Monte Carlo simulation. Monte Carlo simulation is a computational technique that uses random sampling to produce numerical results, and in this model update, is used to obtain values for uncertain input parameters, for example flight speed or bird length. These values are then used in the Band model. For each set of random samples, a collision estimate is calculated. Therefore if the simulation is run for 100 iterations, 100 sets of random input parameters will be sampled and 100 collision risk estimates calculated, instead of a single value. Monte Carlo simulation therefore allows for the presentation of a range of possible outcomes, when there is uncertainty surrounding the input data, and produces distributions of possible collision estimates. The distribution data can then be further re-sampled and used in stochastic population models, should this be required.

Sampling distributions

With the exception of rotor speed, pitch and flight height distributions, input values for the Band model are sampled from probability distributions. These distributions are parameterised using data provided by the user and have been constrained to the Normal distribution, or in cases where negative values are not plausible, the truncated Normal distribution. The user defines the mean or expected value and a standard deviation to describe the variation about the mean. Values in the middle near the mean are most likely to occur. The decision to use the Normal distribution was made on the basis of ease of parameterisation for the user as well as suitability. The Normal distribution was considered more suitable that a uniform distribution because in most cases it is expected that there will be a more likely value, and the uniform distribution, where all values are equally likely, would therefore enter more uncertainty than realistic into the model. It is however accepted that in all cases, the Normal distribution may not be the most suitable distribution, but there is a balance to be achieved between suitability and ease of use.

Collision risk options

The Band model provides four different options for calculating collision risk (Band 2012b). Options 1, 2 and 3 are the most frequently used. The model update calculates estimates for both the basic (options 1 and 2) and extended (option 3) versions of the Band model. It is possible to use this update to calculate a collision risk estimate using option 4, should site-specific data on flight height distributions be available. However, this would require a large amount of data collection, to provide information on variation in flight height distribution therefore the default option does not include option 4.

Running the model

As well as being designed to run numerous simulations of the Band model, this update is designed to loop through multiple species and multiple turbine designs automatically. Therefore once the initial user information is entered and the model begins, the user is not required to enter any further information and the results will be saved automatically to the location specified by the user. The number of results obtained will depend on the number of different turbine designs and species entered.

Model Output

The model outputs information on the expected numbers of collisions. The information is provided both as tables and figures. Descriptions of the outputs are listed below and illustrated examples are provided in the worked example.

TABLES

1. Overall summary table of collisions by species, turbine and model option. Results are presented as mean, standard deviation (SD) and coefficient of variation (CV), and median and inter quartile range (IQR).
2. Monthly summaries of collisions. Separate tables are produced according to species, turbine and model option for example 6_Black_legged_Kittiwake_monthlySummaryOpt3.csv. Results are presented as mean, standard deviation (SD) and coefficient of variation (CV), and median and inter quartile range (IQR).
3. Summary of sampled bird parameters by species, turbine and model option presented as mean and standard deviation (SD), and median and inter quartile range (IQR).
4. Summary of sampled turbine parameters by species, turbine and model option presented as mean and standard deviation (SD), and median and inter quartile range (IQR).

FIGURES

1. 3-panel boxplots of monthly collisions for model options 1, 2 and 3 by species, and turbine type.
2. Density plots of numbers of collisions by species, and turbine type. A density curve is plotted for each of the 3 model options.
3. If 2 or more turbine models are included, then a 3-panel figure will be produced for each species, with the panels representing model options 1, 2 and 3 and each panel containing density plots for the different turbines included.

In addition to the collision estimates, the model also saves a copy of the input files which were entered into the model, as well as a summary of the randomly sampled input parameter values. This would therefore allow for the model to be re-run and results verified (if required). It also outputs a text file stating the time elapsed between the start and the end of the model, the number of iterations, the species for which the model was run and also the different turbines i.e. 6MW, 8MW, etc. if more than one turbine type was specified.

Future work

During this project, an update to the Band collision risk model (Band 2012b) has been developed, however it is accepted that there are still aspects which could be improved further in the future with additional updates, particularly with improved data collection methods and understanding of the interactions between birds and wind farms. These are listed below.

1. Wind speed data: This model update has taken a step forward from previous iterations of the Band model by including the relationship between wind speed data and both rotor speed and rotor pitch, however there are still improvements which could be made. Due to a lack of clarity in the availability and format of site-specific wind speed data which is available to developers it was decided that in this model update, wind speed would be sampled from a truncated Normal distribution, parameterised by a mean and standard deviation set by the user. In the future, if consensus could be reached on wind data availability and format, a summary of the raw wind speed data could be used, rather than using it to parameterise a sampling distribution. If this were the case, then it would also be possible to programme the model to automatically calculate wind availability from the wind speed data, rather than this being entered manually.

2. Monthly vs. annual input parameters: The current model uses annual estimates for the majority of input parameters such as bird flight speed and percentage of nocturnal activity. It is possible that these may differ between the breeding and non-breeding season, and vary monthly, and in response to wind speed. However, at present it was considered that data of sufficient quality were not available for enough parameters on a monthly basis to warrant including this in the model for all. Should this be the case, including monthly values for all parameters could introduce unrealistic precision into the model; therefore only monthly values were included for bird density and turbine operation time. In the future it might be more appropriate to consider all input parameters on a monthly basis.

3. Linking wind speed and flight speed: Within this model update bird flight speed was not linked to wind speed. This alteration could improve the model, however little data is available regarding bird flight speeds, especially in relation to wind speed, though more flight speed data are becoming available as the number of projects using telemetry e.g. GPS tags, increases . The link between flight speed and wind speed was however included in the model produced by McAdam (2005), therefore it would be possible to include this relationship in future updates, should sufficient data become available.

4. Validate the model: Due to the difficulties associated with collecting collision data offshore, as yet, it has not been possible to validate this model update. This is the case for previous versions of the Band model and also collision risk models in general. In the guidance supplied alongside the 2012 update to the Band model, Band (2012b) highlights that there is likely to be uncertainty as a result of simplifications in the model itself. As an estimate, it is suggested that this may be in the region of 20%. By using the results of projects, such as the bird collision avoidance component of the Offshore Renewables Joint Industry Programme

(ORJIP) in the UK, to validate the model, it may be possible to quantify this uncertainty more accurately and reduce it through further refinements to the model.

5. Sensitivity analysis: Whilst it is possible to perform a manual sensitivity analysis on the model update (results available in Appendix 2), it would be useful in the future to have the utility to perform a sensitivity analysis as a matter of course during the assessment of collision risk. This would offer users the ability to highlight which parameters had the strongest influence on the final collision estimates and consider how best to target data collection in order to reduce uncertainty. It may also enable developers to plan mitigation strategies, for example by demonstrating how using fewer, larger turbines may reduce collision risk.

Part 2: Worked Example

Downloading R

Whereas previous iterations of the Band model have used Microsoft Excel, the collision risk model update presented uses R. To get the most recent version of R, go to the R website [redacted] and click the 'CRAN' link on the left hand side. Select a mirror site near you from the list provided, click the 'Windows' link on the next page, then the 'base' link on the following page, and then download the R installer from the link 'Download R 3.1.2 for Windows' (note that the version number you see may be different than this example).

The collision risk model (available at [redacted] requires the installation of an R package “msm” to allow sampling from a truncated normal distribution. This should be installed before the model is run.

To install the required package type the following

```
install.packages(“msm”)
```

into the R console and press return.

Once installed, this step should not be required again and the package will be loaded from within the model script.

Imagined scenario

This example is fictitious. The results are not characteristic of collision risks at any particular site.

A wind farm is planned for the North Sea. The imagined area has a width of 10 km and it is intended that the planned wind farm will generate 600MW. The location of the development area is at 55.8 degrees latitude and has a tidal offset of 2.5 metres. One of the seabirds present at the site and considered sensitive to collision risk is the black-legged kittiwake (*Rissa tridactyla*). This worked example estimates a collision risk estimate for kittiwake.

The wind farm is still in the design phase and there is some uncertainty surrounding the turbine design.

The collision risk model

The collision risk model update is provided as R code. The majority of the model is written as functions which are provided in individual files in a folder named ‘scripts’. These files do not need to be altered. In terms of code, the ONLY file that needs to be altered in order to run the collision risk model is "BandModel.R". All other files are called from R within this script.

In addition to a folder called ‘scripts’ and the code BandModel.R, there should also be a folder named ‘data’ that contains the data files required to run the model. The folder should contain the following:

*BirdData.csv - contains the biometric & flight speed data for species of interest. At present data for 12 species are included (Fulmar, Gannet, Lesser Black-backed Gull, Herring Gull, Great Black-backed Gull, Black-legged Kittiwake, Guillemot, Razorbill, Little Auk, and Puffin)

Species can be added as required, however, it is not necessary to remove data for species which are not being considered. It is important that the species names used are taken from the file BirdData.csv and are used throughout, otherwise the model will not recognise the species. The species names used in the code are as follows:

Species (scientific name)	**Code name used in model**
Fulmar (*Fulmarus glacialis*)	Northern_Fulmar
Gannet (*Morus bassanus*)	Northern_Gannet
Lesser Black-backed Gull (*Larus fuscus*)	Lesser_Black_Backed_Gull
Herring Gull (*Larus argentatus*)	Herring_Gull
Great Black-backed Gull (*Larus marinus*)	Great_Black_backed_Gull
Black-legged Kittiwake (*Rissa tridactyla*)	Black_legged_Kittiwake
Guillemot (*Uria aalge*)	Common_Guillemot
Razorbill (*Alca torda*)	Razorbill
Little Auk (*Alle alle*)	Little_Auk
Puffin (*Fratercula arctica*)	Atlantic_Puffin
Arctic skua (*Stercorarius parasiticus*)	Arctic_Skua
Great skua (*Stercorarius skua*)	Great_Skua

*CountData.csv - count data for the species of interest, should be entered as densities (Birds/km^2). Make sure that biometric data for each species included here is available in BirdData.csv

*FlightHeight.csv - modelled flight height distributions for 21 species of seabird/seaduck etc. taken from Johnston *et al.* (2014)

*TurbineData.csv - should contain information on the size etc. of the turbines being considered. Each row represents a different turbine model to be considered. The name should be the MW rating of the turbine.

* [insert species name]_ht.csv – should contain bootstrapped flight height distribution data from Johnston *et al*. (2014) for the species required. A separate file is required for each species.

* windpower_[insert turbine model name].csv – should contain the relationship between wind speed, rotor speed and pitch. A separate file is required for each turbine model/type.

Data requirements

BIRD DATA: these data are entered in to BirdData.csv

Bird length (Body_Length, Body_LengthSD): the bird body length data were taken from the Concise Birds of the Western Palearctic (OUP, 1994), BTO bird facts and other sources. A mean and standard deviation were estimated from these sources. Mean = 0.39 metres, standard deviation = 0.005.

Wing span (Wingspan, WingspanSD): the wing span data were taken from the Concise Birds of the Western Palearctic (OUP, 1994), BTO bird facts and other sources. A mean and standard deviation were estimated from these sources. Mean = 1.08 metres, standard deviation = 0.04.

Flight speed data (Flight_Speed, Flight_SpeedSD): the flight speed data used in this worked example were taken from the RSPB FAME project and were collected using GPS tags. The data were used to parameterise a normal distribution. A mean flight speed for each tagged bird was estimated (to remove variation within individual) and then an overall mean of these values was calculated. Mean = 7.26 $m.s^{-1}$, standard deviation = 1.5.

Nocturnal activity (Nocturnal_Activity, Nocturnal_ActivitySD): the data used in this worked example to estimate the proportion of nocturnal activity were taken from the RSPB FAME project and were collected using GPS tags. All records away from the nest and travelling at speeds considered to be flying were used. The data were used to parameterise a normal distribution. Mean = 0.033, standard deviation = 0.0045.

Proportion at collision risk height (Prop_CRH_Obs, Prop_CRH_ObsSD): these data are required for the basic model (option 1). A mean and standard deviation were calculated using the data within Black_legged_Kittiwake_ht.csv. For each bootstrapped distribution curve, the proportion of birds between the average minimum and average maximum rotor tip height was summed. From these values, a mean and standard deviation was calculated. Mean = 0.06, standard deviation = 0.009.

Avoidance (AvoidanceBasic, AvoidanceBasicSD, AvoidanceExtended, AvoidanceExtendedSD): This is the probability that a bird on a collision course with a turbine will take evading action to avoid collision. The data were taken from Cook *et al.* (2014) and for kittiwake, we used the 'all gulls' avoidance rate. The avoidance rate differs between the basic and extended models and a mean and standard deviation are required for both. Mean (basic) = 0.9893 and standard deviation (basic) = 0.0007; mean (extended) = 0.9672 and standard deviation (extended) = 0.0018.

COUNT DATA: these data are entered in to CountData.csv and are the number of birds in flight in the daytime presented as birds/km^2. A mean and standard deviation are required. For this worked example, data were taken from the Creyke Beck A Environmental Statement.

Month	**Mean**	**SD**
Jan	0.97	0.67
Feb	1.04	0.75
Mar	1.15	0.78
Apr	0.48	0.36
May	0.56	0.58
Jun	0.63	0.45
Jul	0.68	0.47
Aug	0.64	0.47
Sep	0.53	0.39
Oct	1.20	0.78
Nov	1.02	0.61
Dec	0.99	0.7

FLIGHT HEIGHT DISTRIBUTION DATA: these data are contained within FlightHeight.csv and the individual species files such as Black_legged_Kittiwake_ht.csv and are required for options 2 and 3. The data within FlightHeight.csv are provided by the British Trust for Ornithology (Johnston *et al*, 2014) and are generic flight height distributions. The file provides data on the proportion of birds within 1m height bands for 21 species. For example,

Height (m)	Black_legged_Kittiwake
1	0.089904
2	0.081107
3	0.072538
4	0.067068
5	0.061008
6	0.055579
7	0.050707
…	…

Confidence intervals were calculated around these best fit/generic flight height distributions using a bootstrapping approach, randomly sampling from the original dataset each time. These bootstraps are provided for each species in separate files, for example Black_legged_Kittiwake_ht.csv and are used to include uncertainty surrounding the flight height distribution.

TURBINE DATA: these data are entered into TurbineData.csv and are also contained within the turbine-specific files such as windpower_6. Names in parentheses are the names in the data files and scripts.

Rotor radius (RotorRadius, RotorRadiusSD): this is measured from the axis of rotation to blade tip and was taken from expert opinion. Mean = 80 and Standard deviation = 5

Hub height (HubHeightAdd, HubHeightAddSD): This is the measure that in addition to rotor radius sums to give the distance from HAT to the axis of rotation and was taken from expert opinion. Mean = 26.5 and Standard deviation = 2.

Maximum blade chord width (BladeWidth, BladeWidthSD): This is the maximum width of the rotor blade and was taken from expert opinion. Mean = 5.5 and Standard deviation = 0.3.

Turbine operation time (example for January is JanOp, JanOpMean, JanOpSD): This included both information on wind availability (JanOp) which is considered a constant and maintenance down time (JanOpMean, JanOpSD) which included uncertainty. Data were taken from the Inch Cape Environmental Statement.

Month	**Wind availability**	**Mean maintenance**	**SD maintenance**
Jan	96.28	6.3	2
Feb	96.53	6.3	2
Mar	95.83	6.3	2
Apr	92.78	6.3	2
May	90.86	6.3	2
Jun	92.22	6.3	2
Jul	89.11	6.3	2
Aug	89.92	6.3	2
Sep	93.71	6.3	2
Oct	96.14	6.3	2
Nov	97.14	6.3	2
Dec	96.41	6.3	2

Rotation speed (RotationSpeed, RotationSpeedSD): It is possible to specify a mean rotor speed and standard deviation, however the default model uses the relationship between wind speed and rotor speed provided to calculate the specific rotor speeds, therefore RotationSpeed and RotationSpeedSD in TurbineData.csv should be left blank. The relationship should be provided in a csv file named windpower_[insert model name here] for example windpower_6.csv

The table below shows an example relationship between wind speed, rotor speed and pitch. It was constructed using expert opinion as an example table and used within this worked example. It does not relate to a specific turbine specification currently available.

Wind speed (m/s)	**Rotor Speed**	**Pitch**
0	0	90
1	0	90
2	0	90
3	6	0
4	6	0
5	6	2
6	8	4
…	…	…

Blade pitch (Pitch, PitchSD): As for rotor speed, it is possible to specify a mean pitch and standard deviation, however the default model uses the relationship between wind speed and pitch provided to calculate the specific rotor pitch, therefore Pitch and PitchSD in TurbineData.csv should be left blank. The relationship should be provided in a csv file named windpower_[insert model name here] for example windpower_6.csv (as above).

Model set up

Before the model can be run it requires information to be entered into the file "BandModel.txt".

1. Set working directory

First, set the working directory. This is the location where the folders 'scripts' and 'data' have been saved as well as 'BandModel.R'. For example,

```
setwd("F:\\BAND CRM For R")
```

This step directs R to all the files and data that are required to run the model therefore all the files required much be within this directory.

2. Set results folder

The model will save output to a folder. Set the name of the results folder, for example, the name of the development. For example,

```
results_folder <- "windfarm1"
```

If no name is specified the model will default to the date. WARNING: If the model is run several times on the same day and no folder name is specified, it will over-write files in the folder.

3. Set model components

Next set the model components. These include:

The number of iterations the model simulation will execute, for example 1000

```
iter<- 1000
```

The species to include, for example kittiwake

```
CRSpecies = "Black_legged_Kittiwake"
```

If more species were to be included this would look like

```
CRSpecies = c("Black_legged_Kittiwake", "Northern_Gannet", "Arctic_Skua")
```

The target power (in MW) to be generated within wind farm, for example 600MW. This is used in conjunction with the turbine name i.e. 6 if a 6MW turbine, to calculate the number of turbines in the array.

```
TPower = 600
```

Large array correction (Yes/No), for example

```
LargeArrayCorrection = "yes"
```

The wind farm width (km), for example 10km

```
WFWidth = 10
```

The proportion of bird flights up/downwind, for example 50%

```
Prop_Upwind = 0.5
```

The latitude of the wind farm in decimal degrees, for example 55.8 degrees. This is used to calculate day length at the site location throughout the year.

```
Latitude = 55.8
```

The tidal offset in metres (to correct for flight heights being calculated in relation to mean sea-level and turbine dimensions being calculated in relation to Highest Astronomical Tide), for example 2.5 metres

```
TideOff = 2.5
```

4. Parameterise wind speed sampling distribution

The model uses wind speed data to calculate rotor speed and pitch. Wind speed data are therefore required. At the time of production it was unclear what format wind speed data would be available to wind farm developers. To avoid inconsistencies, the model samples wind speed from a truncated normal distribution parameterised by the user. The mean wind speed ($m.s^{-1}$) and standard deviation are required to be set, for example

```
windSpeedMean<- 7.74
windSpeedSD<- 3.2
```

It is expected that these will be obtained from met mast data or other sources of wind speed data such as NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA).

5. Running the model…

Once you have set the working directory and entered all of the necessary information, all that is needed to run the model is to copy and paste all of BandModel.R into the R console, or alternatively type

```
source("*****EnterMyDirectoryHere****\\BandModel.R")
```

in the R console, and press return.

The code is designed to loop through multiple species and multiple turbine designs in a single step. The number of results obtained will depend on the number of different turbine designs entered in TurbineData.csv and the number of different species for which data are entered and listed.

A progress bar will provide an indication of progress and at the end of the model, the time elapsed since the model was started will be displayed.

Model Output

The model outputs information on the expected numbers of collisions. The information is provided both as tables and figures, and according to the species and turbine designs entered into the model. Results are provided for the basic (options 1 and 2) and extended (option 3) versions of the model.

- Option 1 - using the basic model, i.e. assuming that a uniform distribution of flight heights between the lowest and the highest levels of the rotors and using the proportion of birds at risk height as derived from site survey.
- Option 2 - again using the basic model, but using the proportion of birds at risk height as derived from the generic flight height distribution provided.
- Option 3 - using the extended model and using the generic flight height distribution.

Tables

The file names of the tables indicate the type of information contained.

1. CollisionEstimates.csv: Overall summary table of collisions by species, turbine and model option. Results are presented as mean, standard deviation (SD) and coefficient of variation (CV), and median and inter quartile range (IQR).

Species	Turbine	Option	Mean	SD	CV	Median	IQR
Black_legged_Kittiwake	6	1	45.6455	12.5448	27.4831	45.1206	16.5493
Black_legged_Kittiwake	6	2	42.4292	14.5621	34.3210	40.3032	18.671
Black_legged_Kittiwake	6	3	35.4131	13.1271	37.0685	33.0278	16.466

2. 6_Black_legged_Kittiwake_monthlySummaryOpt1.csv : monthly summaries of collisions. Separate tables are produced according to species, turbine and model option. Results are presented as mean, standard deviation (SD) and coefficient of variation (CV), and median and inter quartile range (IQR).

Month	Mean	SD	CV	Median	IQR
Jan	3.080382	1.753642	56.92937	2.970413	2.441757
Feb	3.590156	2.012736	56.06263	3.439408	3.043374
Mar	4.884338	2.76244	56.55711	4.716011	4.134139
Apr	2.890070	1.763726	61.02710	2.648057	2.297968
May	4.255352	2.845274	66.86343	3.771635	3.664073
Jun	4.458946	2.63927	59.19044	4.172458	3.708436
Jul	4.529034	2.769847	61.15756	4.132559	3.751684
Aug	4.034511	2.423247	60.06296	3.738152	3.239942
Sep	2.720596	1.625044	59.73115	2.546583	2.131306
Oct	4.650331	2.451314	52.71267	4.471203	3.288374
Nov	3.484131	1.787375	51.30045	3.386141	2.557487
Dec	3.067742	1.625422	52.98432	2.964345	2.258359

3. 6_Black_legged_Kittiwake_sampledBirdParameters.csv: Summary of sampled bird parameters by species, turbine & model option presented as mean & standard deviation (SD), and median & interquartile range (IQR).

Parameter	Mean	SD	Median	IQR
AvoidanceBasic	0.989328	0.000696	0.989341	0.000986
AvoidanceExtended	0.967215	0.00176	0.967172	0.00244
WingSpan	1.079481	0.040021	1.078701	0.054751
BodyLength	0.3898	0.005124	0.389929	0.007007
PCH	0.06006	0.009073	0.06025	0.012644
FlightSpeed	7.242055	1.472594	7.200565	1.91039
NocturnalActivity	0.033239	0.004627	0.033195	0.005833

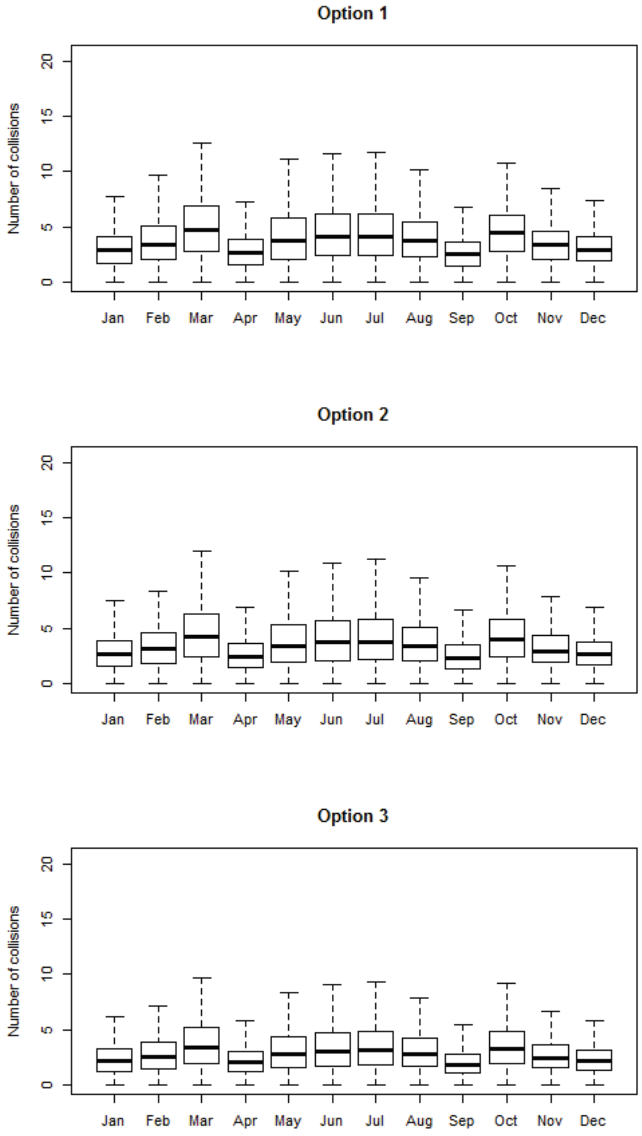
4. 6_Black_legged_Kittiwake_sampledTurbineParameters.csv: Summary of sampled turbine parameters by species, turbine and model option presented as mean and standard deviation (SD), and median and inter quartile range (IQR).

Parameter	Mean	SD	Median	IQR
RotorSpeed	7.8795	1.187502	6.8	2.3
RotorRadius	80.02557	4.641109	79.93026	6.275585
HubHeight	106.5836	4.981272	106.4803	6.57322
BladeWidth	5.492034	0.293631	5.499434	0.414762
Pitch	1.091	2.912594	0	0
JanOp	90.04184	1.992513	90.08147	2.699385
FebOp	90.32209	2.00625	90.27184	2.864814
MarOp	89.53487	1.983321	89.52079	2.567127
AprOp	86.5725	2.050986	86.58052	2.786068
MayOp	84.5539	1.99842	84.5696	2.744052
JunOp	86.04224	2.070166	86.06471	2.915727
JulOp	82.7399	2.025924	82.68036	2.643739

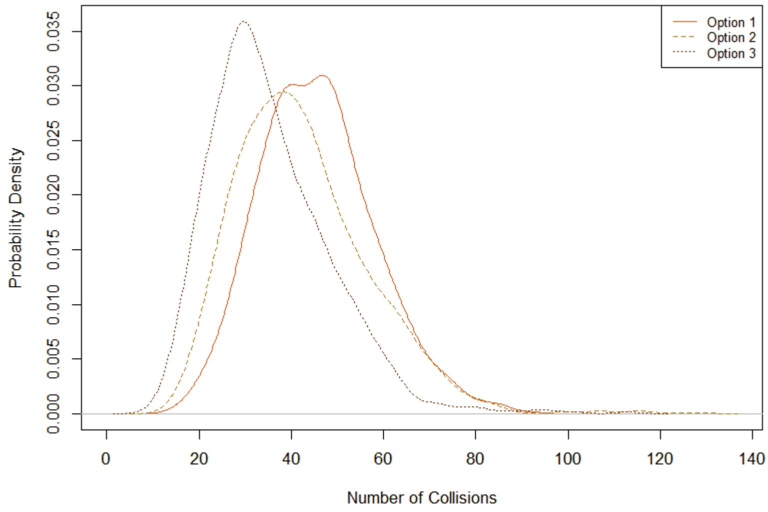
AugOp	83.69396	2.0276	83.71622	2.59691
SepOp	87.46471	2.045078	87.38634	2.880023
OctOp	89.81123	1.95635	89.78423	2.731423
NovOp	90.89083	1.979187	90.93791	2.677976
DecOp	90.04899	2.107647	90.1124	2.786412

Figures

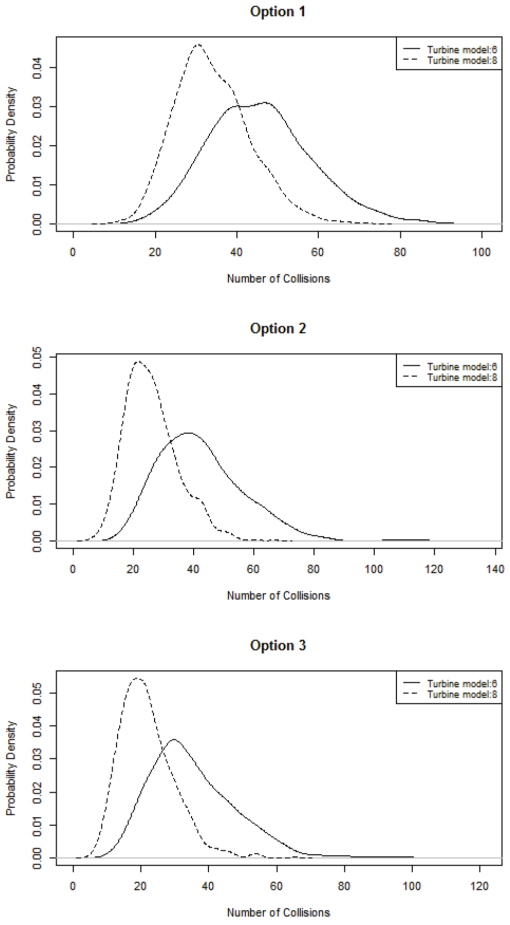
1. 6_Black_legged_Kittiwake .jpg: 3-panel boxplots of monthly collisions for model options 1, 2 and 3 by species, and turbine type (included in the file name).



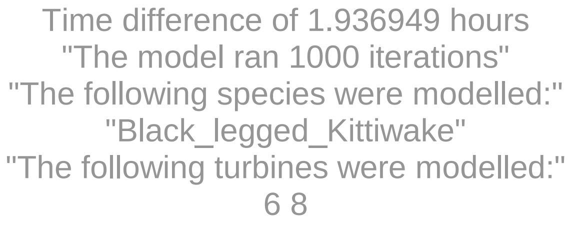
2. 6_Black_legged_Kittiwake_density.jpg: Density plots of numbers of collisions by species, and turbine type (specified in file name). A density curve is plotted for each of the 3 model options.



3. Black_legged_Kittiwake.jpg: If 2 or more turbine models are included, then a 3-panel figure will be produced for each species, with the panels representing model options 1, 2 and 3 and each panel containing probability density plots for the different turbines.



In addition to the collision estimates, the model also saves a copy of the input files which were entered into the model, as well as a summary of the randomly sampled input parameter values. This would therefore allow for the model to be re-run and results verified (if required). It also outputs a text file (run.time.txt) stating the time elapsed between the start and the end of the model, the number of iterations, the species for which the model was run and also the different turbines i.e. 6MW, 8MW, etc. if more than one turbine type was specified.



```
Time difference of 1.936949 hours
"The model ran 1000 iterations"
"The following species were modelled:"
"Black_legged_Kittiwake"
"The following turbines were modelled:"
6 8
```

<u>A note on comparisons of results</u>: Whilst differences in the density curves (specifically the spread) can be compared within each model option, they should not be compared between different model options. This is because of differences in the way in which variation and uncertainty are introduced into each model option. For example, in the basic model (options 1 & 2) uncertainty in the proportion of birds at risk height is only introduced when estimating the flux rate. However, in the extended model (option 3), the uncertainty in the flight height distribution is introduced when calculating the collision integral (the extended model equivalent of the probability of collision).

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Appendix 1: Stakeholder Interviews

Purpose of interviews

To obtain views and opinions of a wide range of stakeholders involved in offshore wind, on collision risk models and modelling, particularly in relation to uncertainty and variability.

Interview questions

Conducted telephone interviews based around the following questions:

1. How much experience do you have, relating to collision risk models/modelling?
2. What collision risk models do you most regularly use or have experience of?
3. What uncertainties exist in the collision risk models that you have used?
4. What are the key uncertainties in input parameters?
5. What parameters do you think have the greatest influence on the outputs of collision risk modelling?
6. If you could, how would you improve collision risk models/modelling?
7. Would the explicit reporting of variability and uncertainty in outputs from collision risk models benefit the consenting process and discussions with regulators?

Interviews were approximately 20-30 minutes each.

Interviewees

I contacted 30 people from a range of stakeholder groups and from those I conducted 20 interviews with people from the following organisations:

BTO
DONG Energy
EDPR
MacArthur Green
Natural England
NIRAS
PMSS
Scottish Natural Heritage
Sue King Consulting

CEH
ECON
Joint Nature Conservation Committee
Marine Scotland Science
Natural Power
Pelagica
Royal Society for the Protection of Birds
Statkraft/Forewind
The Crown Estate
…and Bill Band

Results

Experience of interviewees

Question 1: How much experience do you have, relating to collision risk models/modelling?

The experience of interviewees varied from ‘intelligent client’ to model creator. All interviewees had a good understanding of the general modelling process and the use of model output though not all had conducted the modelling and run the models themselves. One person declined the offer of being interviewed because they thought they didn’t have enough experience to contribute constructively.

Question 2: What collision risk models do you most regularly use or have experience of?

All people interviewed (20) used the Band model and the associated updates. Of these, most people mentioned options 1 and 3 rather than 2 and 4. Additionally, 5 people used the Folkerts model, though less regularly, and one had an understanding of the Tucker model. These were the only models mentioned.

Uncertainties in collision risk modelling

Question 3: What uncertainties exist in the collision risk models that you have used?

This question was targeted at the broader uncertainties surrounding collision risk modelling. The following opinions were given more than once:

- Data collection methods including number and timing of surveys and the fact that surveys only occur in good weather least to a density estimate which may not capture the variability in the environment.
- The use of the Rochdale Envelope and therefore wide ranges for turbine parameters.
- How much precaution should be included?
- Bird behaviour and avoidance
- Which option of the model (or in most cases, which option of Band) is acceptable?
- Little empirical data and also no validation or comparison with post-construction data.
- The appropriate use of the model and output. The collision estimate is considered as definitive and black and white when it is supposed to be a collision risk tool.
- In the case of the Band model, what is the latest version of the model and flight height data sets to use?

Question 4: What are the key uncertainties in input parameters?

All of the input parameters were discussed and raised by the interviewees as a whole but those that occurred more than once and in descending order (most frequently highlighted first):

- Flight height data
- Avoidance
- Density
- Nocturnal activity
- Flight speed
- Rotor speed

Question 5: What parameters do you think have the greatest influence on the outputs of collision risk modelling?

Most of the input parameters were discussed and raised by the interviewees as a whole but those that occurred more than once and in descending order (most frequently highlighted first):

- Avoidance rate
- Flight height data
- Rotor Speed
- Density
- Number of turbines
- Which Band option used
- Operation time

Changes or updates to model

Question 6: If you could, how would you improve collision risk models/modelling?

There were many different opinions on how to improve collision risk modelling but generally they did not involve making large changes to the mechanics of the model itself but rather to the input data or presentation of data and outputs. Comments that were raised more than once and in descending order (most frequently highlighted first) included:

- Present a covering/summary sheet with input data values to ensure parameters are clearly set out and defined.
- Stop presenting single numbers as black and white and also provide context.
- Take data from existing sites to validate the model and also use post-construction monitoring.
- Have a standard approach to derive turbine parameters and bird parameters including consistently defining breeding season periods.
- More studies/data on bird behaviour around turbines and avoidance behaviour.

- More and clearer guidance on the model and model use and intended use, especially on the tidal offset.
- Collect flight height data objectively, not just human observation/estimation but using rangefinders.
- Factor uncertainty into estimates.
- Use R code rather than excel to make modelling process more reproducible.
- Better interpretation of model outputs.
- Single location to have the most up to date version of model and email updates.

These can then be split into comments that were more input data-related:

- Present a covering/summary sheet with input data values to ensure parameters are clearly set out and defined.
- Have a standard approach to derive turbine parameters and bird parameters including consistently defining breeding season periods.
- More studies/data on bird behaviour around turbines and avoidance behaviour.
- Collect flight height data objectively, not just human observation/estimation but using rangefinders.

Or those which were model or output data-related:

- Stop presenting single numbers as black and white and also provide context.
- Take data from existing sites to validate the model and also use post-construction monitoring.
- More and clearer guidance on the model and model use and intended use, especially on the tidal offset.
- Factor uncertainty into estimates.
- Use R code rather than excel to make modelling process more reproducible.
- Better interpretation of model outputs.
- Single location to have the most up to date version of model and email updates.

Question 7: Would the explicit reporting of variability and uncertainty in outputs from collision risk models benefit the consenting process and discussions with regulators?

When asked more specifically about including variability and uncertainty in CRMs interviewees gave a wide range of responses but these were not consistent within different stakeholder groups. Of the 20 people interviewed, 13 agreed that including variability and uncertainty in outputs from collision risk models would benefit the consenting process and discussions with regulators, however 7 people disagreed. Of those 7, all said that they disagreed because of the consenting and assessment process and that in principle it would be better to include variability and uncertainty, but they though that the system did not allow for it. A recurrent comment was that interviewees were unsure of how variability and uncertainty could be included in outputs and still fit in with the Habitats Regulations.

Some comments and themes that were raised in the interviews are listed below:

- Scientifically there is a benefit to making clear what the uncertainties are.
- Accounting for uncertainty in data collection methods and survey data would be useful.
- I am uncomfortable with presenting a value that is apparently so precise.
- There is an absolute fixation on single numbers which is dangerous.
- We need greater acceptance that we live and work in an uncertain world and things are grey, not black and white.
- We need a way of showing that some scenarios are more likely than others.
- Decision makers have to be confident that they are making the right decisions so they need to an understanding of uncertainty around the single numbers.
- We need to weigh up risk (or use a risk assessment process) and we can't do that currently with CRM, though it happens more regularly with PVA.
- The current approach is too precautionary and always uses the most precautionary values.
- If the system were to change, including variability and uncertainty is a more useful approach.
- Any outputs need to be suitable to be taken forward through the assessment process.
- The risk is that it complicates the process even more than already because the more the risks are explicit the more difficult it is to explain to the planning inspectorate.
- There is probably too much uncertainty in the system to make it useful to include it.

There was a wide range of views on some topics, for example opinions on using probability distributions:

- Presenting probability distributions would help a lot because regulators often have a background of understanding risk probabilities.
- Using probability distributions might help with presentation but it might not help with interpretation of outputs, especially if people don't understand how to interpret probability distributions.
- Distributions are probably more helpful but people need to understand them.
- Scientists are used to dealing with probabilities but legislation is binary.

This probably stems from uncertainty and/or inconsistency in (the understanding of) how decisions are made and the lack of a strategic decision on a standard method for presenting data which is most informative for the decision makers.

Appendix 2: Sensitivity analyses

Chamberlain *et al.* (2006) previously documented that the Band model was sensitive to input parameters. Following on from this, the sensitivity of the Band model update produced during the SOSS project (Band 2012) was assessed, both for the basic and extended versions. Similar to Chamberlain *et al.* (2006), the effect of a 10% change in the input parameters was assessed but in addition, a more realistic parameter range was also assessed.

When assessing the effect of a 10% change in the flight height distribution for the extended model, we increased the proportions of birds at heights between the minimum and maximum rotor tip heights by 10%.

The following data sources were used for the input parameters. For turbine-related parameters, expert opinion within the project group was used to assess reasonable parameters ranges and those likely to be built out in the near future.

Bird-related Parameter	**Data description**
Length	Taken from Concise Birds of the Western Palearctic (Cramp and Perrins, 1993) and other sources
Wingspan	Taken from Concise Birds of the Western Palearctic (Cramp and Perrins, 1993) and other sources
Flight speed	RSPB telemetry data (breeding season only)
Nocturnal activity	RSPB telemetry data (breeding season only)
Proportion at collision risk height	Generic flight height curve provided with the Band model and data provided by BTO (Johnston *et al.* 2014).
Flight height distributions	Data provided by BTO (Johnston *et al.* 2014).
Avoidance	‘All gulls’ rate available from Marine Scotland Science avoidance report (Cook et al. 2014)
Bird density	Taken from Creyke Beck A Environmental Statement

Turbine-related Parameter	**Description/Notes**
Rotor radius	Expert opinion
Hub height	Expert opinion
Max. blade chord width	Expert opinion
Rotation speed	Expert opinion (example relationship between wind speed and rotation speed)
Blade pitch	Expert opinion (example relationship between wind speed and pitch)
Turbine operation time	Taken from Inch Cape Environmental Statement

10% change

BASIC MODEL (Option 1)

Input variable	Baseline	Baseline ± 10% (increases mortality)	Collision risk (in absence of avoidance)	Revised number of collisions	% increase in number of collisions
Avoidance rate	0.9893	0.8904	0.065	439	921
Non-avoidance rate	0.0107	0.0118	0.065	47	9
% at collision risk height	6	6.6	0.065	47	9
Bird density (birds/km^2)	9.89	10.879	0.065	47	9
Flight speed (m.s^{-1})	7.26	7.986	0.063	46	7
% nocturnal flight	3.3	3.63	0.065	43	0
Bird length (cm)	39	42.9	0.067	44	2
Wing span (cm)	108	118.8	0.065	43	0
Number of turbines	100	110	0.056	47	9
Rotor radius (m)	80	88	0.061	44	2
Hub height (m)	125	112.5	0.065	43	0
Rotation speed (rpm)	7.74	8.514	0.067	44	2
Blade width (m)	5.5	6.05	0.069	46	7
Blade pitch (degrees)	0	-	-	-	-
% time operational	87.61	96.371	0.065	47	9

Effects of 10% variation in input parameters on predicted mortality rates of black-legged kittiwakes using hypothetical wind farm parameters (100 turbines). Original collision risk was 0.065 and the original number of predicted collisions per year was 43. Collisions are presented as integers.

EXTENDED MODEL (Option3)

Input variable	Baseline	Baseline ± 10% (whichever increases mortality)	Collision risk (in absence of avoidance)	Revised number of collisions	% increase in number of collisions
Avoidance rate	0.9672	0.8705	0.065	9	350
Non-avoidance rate	0.0328	0.0361	0.065	3	50
% at collision risk height	6	6.6	0.065	3	50
Bird density (birds/km^2)	9.89	10.879	0.065	3	50
Flight speed (m.s^{-1})	7.26	7.986	0.063	2	0
% nocturnal flight	3.3	3.63	0.065	2	0
Bird length (cm)	39	42.9	0.067	2	0
Wing span (cm)	108	118.8	0.065	2	0
Number of turbines	100	110	0.065	3	50
Rotor radius (m)	80	88	0.061	5	150
Hub height (m)	125	112.5	0.065	8	300
Rotation speed (rpm)	7.74	8.514	0.067	2	0
Blade width (m)	5.5	6.05	0.069	2	0
Blade pitch (degrees)	0	-	-	-	-
% time operational	87.61	96.371	0.065	3	50

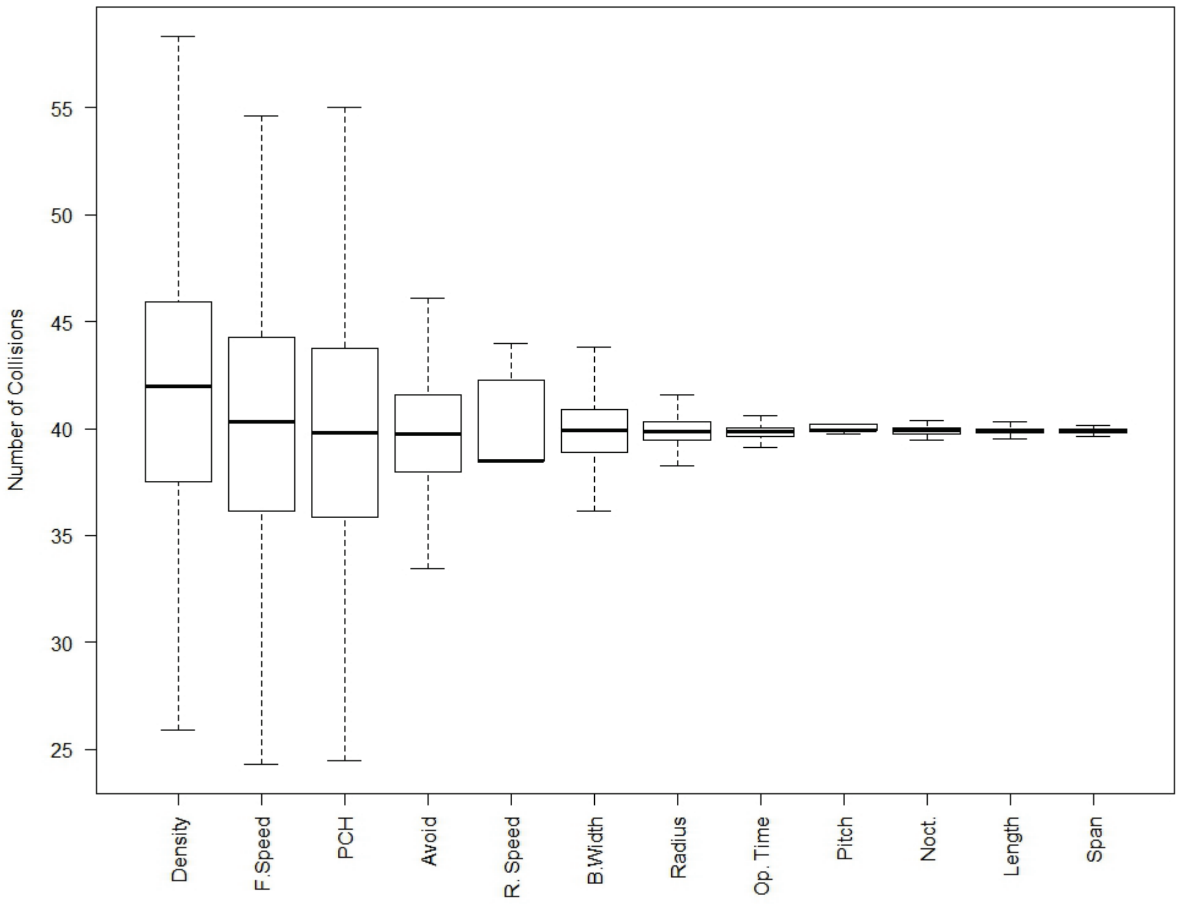
Effects of 10% variation in input parameters on predicted mortality rates of black-legged kittiwakes using the hypothetical wind farm parameters (100 turbines). The original collision risk was 0.065 and the original number of predicted collisions per year was 2. Collisions are presented as integers, therefore the % increase in the number of collisions is greatly influenced by rounding.

Real data range

BASIC MODEL (Option 1)

Input variable	Input variability	Mean collisions (SD)	Median collisions (IQR)
Avoidance rate	N(0.9893,0.0007)	39.76 (2.55)	39.72 (3.61)
% at collision risk height	N(6, 0.9)	39.77 (6.06)	39.77 (7.86)
Bird density (birds/km^2)	tN(monthly mean, monthly SD)	41.86 (6.40)	41.99 (8.39)
Flight speed (m.s^{-1})	N(7.26, 1.50)	40.25 (5.73)	40.30 (8.09)
% nocturnal flight	N(3.3, 0.45)	39.90 (0.19)	39.91 (0.26)
Bird length (cm)	N(39, 0.5)	39.89 (0.15)	39.89 (0.21)
Wing span (cm)	N(108, 4)	39.89 (0.09)	39.89 (0.12)
Rotor radius (m)	N(80, 5)	39.89 (0.67)	39.84 (0.88)
Hub height (m)	Rotor radius + N(26.5, 2)	39.89 (0)	39.89 (0)
Rotation speed (rpm	Relationship to wind speed	40.15 (1.81)	38.51 (3.76)
Blade width (m)	N(5.5,0.3)	39.91 (1.39)	39.90 (1.97)
Blade pitch (degrees)	Relationship to wind speed	40.50 (1.66)	39.89 (0.32)
% time operational	Wind availability-tN(6.3, 2)	39.91 (1.39)	39.90 (1.97)

Effects of variation in input parameters on predicted mortality rates of black-legged kittiwakes using the hypothetical wind farm parameters (100 turbines). 500 iterations. The original collision risk was 0.065 and the original number of predicted collisions per year was 40. N is normal distribution. N(mean, SD). tN is truncated normal distribution. Hub height does not affect calculations in option 1, therefore the values were constant across all iterations.

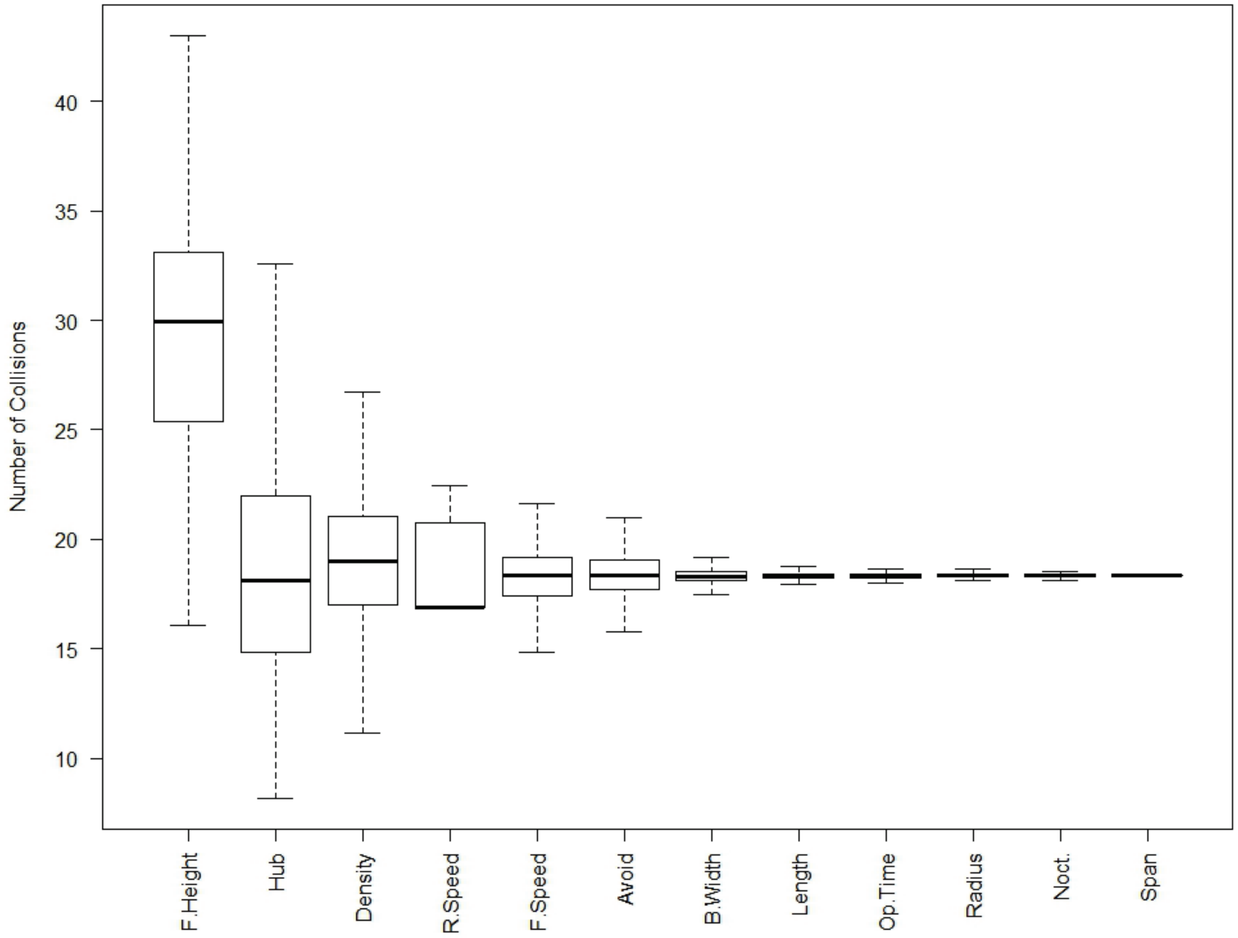


Effects of variation in input parameters on predicted collision mortality of black-legged kittiwakes using the basic Band model. Density values are slightly skewed due to need for use of truncated normal distribution as negative density values are not possible.

EXTENDED MODEL (Option3)

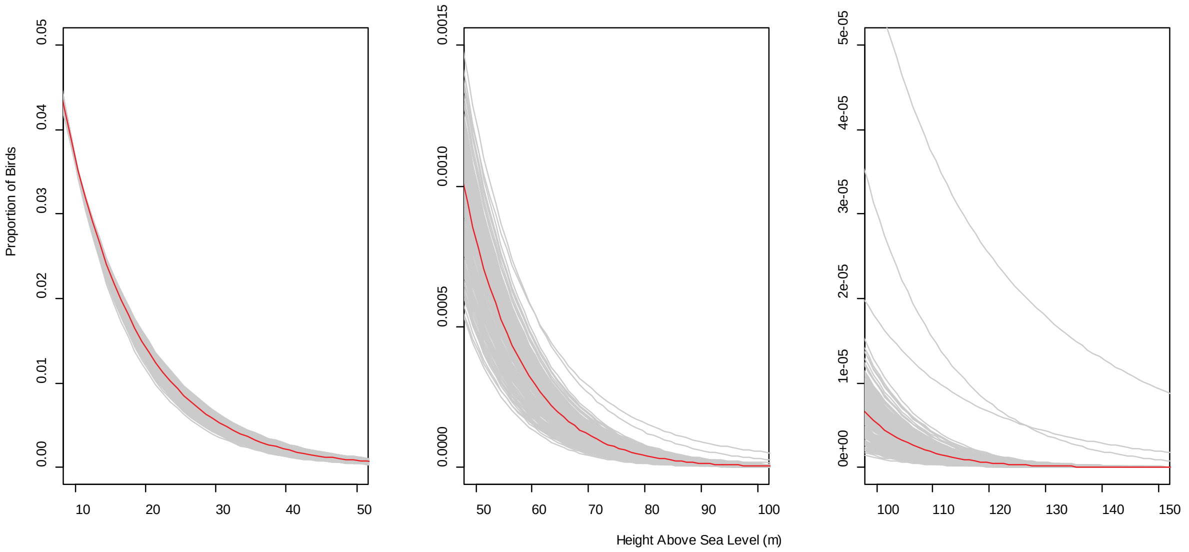
Input variable	Input variability	Mean collisions (SD)	Median collisions (IQR)
Avoidance rate	N(0.9672, 0.0018)	18.34(1.03)	18.33 (1.35)
% at collision risk height	Data from BTO	29.60 (5.92)	29.94 (7.70)
Bird density (birds/km^2)	tN(monthly mean, monthly SD)	19.06 (3.03)	18.97 (4.04)
Flight speed (m.s^{-1})	N(7.26, 1.50)	18.31 (1.38)	18.32 (1.75)
% nocturnal flight	N(3.3, 0.45)	18.32 (0.09)	18.32 (0.12)
Bird length (cm)	N(39, 0.5)	18.32 (0.16)	18.32 (0.22)
Wing span (cm)	N(108, 4)	18.32 (0.16)	18.32 (0.22)
Rotor radius (m)	N(80, 5)	18.35 (0.10)	18.13 (0.14)
Hub height (m)	Rotor radius + N(26.5, 2)	18.72 (5.33)	18.11 (7.08)
Rotation speed (rpm)	Relationship to wind speed	18.57 (1.87)	16.86 (3.89)
Blade width (m)	N(5.5,0.3)	18.31 (0.32)	18.32 (0.44)
Blade pitch (degrees)	Relationship to wind speed	18.32 (0.00074)	18.32 (0.00014)
% time operational	Wind availability-tN(6.3, 2)	18.32 (0.14)	18.32 (0.18)

Effects of variation in input parameters on predicted mortality rates of black-legged kittiwakes using the hypothetical wind farm parameters (100 turbines). 500 iterations. The original collision risk was 0.065 and the original number of predicted collisions per year was 18. N is normal distribution. N(mean, SD). tN is truncated normal distribution.

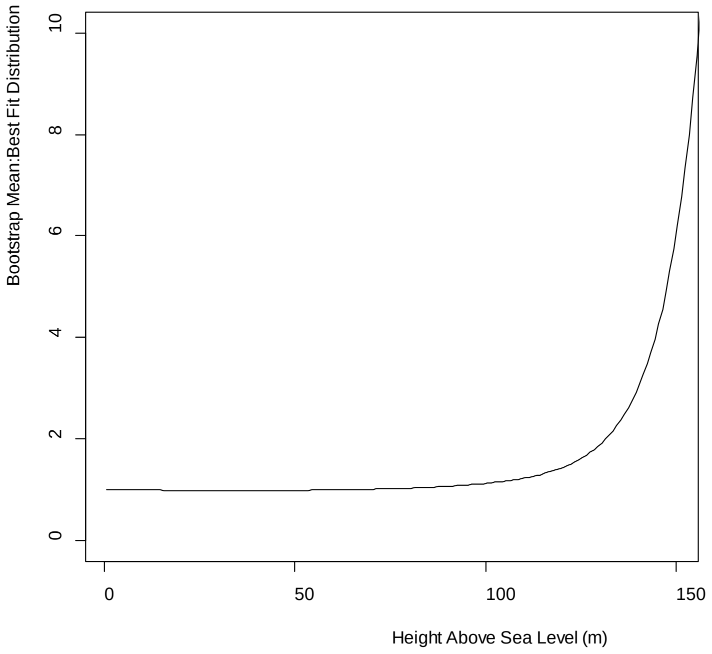


Effects of variation in input parameters on predicted collision mortality of black-legged kittiwakes using the extended Band model. Density values are slightly skewed due to need for use of truncated normal distribution as negative density values are not possible.

A note on variation in flight height: It is noticeable that when variation in the flight height distribution used for the extended model (option 3) is considered, it results in a very different average value to that obtained using the best fit distribution. This should be expected. Flight height distributions are estimated following the methodology set out in Johnston et al. (2014). The best fit distribution is estimated from the complete flight height dataset, and is that which best fits the available data. Confidence intervals were calculated around this distribution using a bootstrapping approach, randomly sampling from the original dataset each time. As a result, each individual bootstrap reflects the shape of the distribution would be if some of the data were excluded. It is not meaningful to compare the mean values obtained from the bootstraps to the best-fit distribution because they are a series of sub-samples. On closer examination, it is clear that the best fit distribution predicts a lower proportion of birds at collision risk height than is obtained from the mean across all bootstraps, and that crucially, this difference is greatest towards the centre of the rotor-swept area, where collision risk is greatest. As a result, the mean collision rate predicted from the bootstraps is greater than collision rate predicted from the best fit distribution.



Comparison of the best fit (red) and bootstrapped (grey) flight height distributions for kittiwake. The best fit distribution does not pass through the centre of the bootstrapped distributions as would be expected if it were directly comparable to the mean. Instead, as height above sea level increases, the proportion of birds predicted by the best-fit distribution moves towards the lower end of the proportion predicted by the bootstraps. The difference is most apparent at heights of around 100 m, which roughly corresponds to the centre of the rotor sweep, the point at which collision risk is greatest. This can be seen more clearly by examining the ratio of the best fit distribution to the mean of the bootstrap distribution at 1 m intervals.


Bootstrap Mean:Best Fit Distribution
0
2
4
6
8
10
0
50
100
150
Height Above Sea Level (m)

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When speed matters: The importance of flight speed in an avian collision risk model

Elizabeth A. Masden [a,*], Aonghais S.C.P. Cook [b], Aly McCluskie [c], Willem Bouten [d], Niall H. K. Burton [b], Chris B. Thaxter [b]

[a] Environmental Research Institute, North Highland College - UHI, University of the Highlands and Islands, Ormlie Road, Thurso KW14 7EE, UK
[b] British Trust for Ornithology, The Nunnery, Thetford, Norfolk IP24 2PU, UK
[c] RSPB Centre for Conservation Science, Royal Society for the Protection of Birds, The Lodge, Sandy SG19 2DL, UK
[d] Theoretical and Computational Ecology, Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Sciencepark 904, 1098 XH Amsterdam, the Netherlands

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ABSTRACT

Renewable energy continues to grow globally, and the number of offshore wind farms is set to increase. Whilst wind energy developments provide energy security and reduced carbon budgets, they may impact bird populations through collision mortality, habitat modification and avoidance. To date, avian collision mortality has received the most attention and collision risk models have been developed to estimate the potential mortality caused by wind turbines. The utility of these models relies not only on their underlying assumptions but also on the data available to ensure the predictions are informative. Using a stochastic collision risk model (sCRM; based on the Band collision risk model) as an example, we explore the importance of bird flight speed and consider how the assumptions of the model influence the sensitivity to flight speed. Furthermore we explore the consequences of using site-specific GPS-derived flight speed rather than a standard generic value, with Lesser Black-backed Gulls *Larus fuscus* as an example, and consider how this generic value is currently used. We found that the model was most sensitive to the parameters of bird density, non-avoidance rate and percentage of birds at collision risk height, as well as bird flight speed. Using site-specific flight speed data derived from GPS tags rather than a standard value reduced the predicted number of collisions. We highlight that within the model, both the estimation of the probability of collision (PColl) and the flux of birds are sensitive to the bird flight speed; this sensitivity acts in opposite directions but the two do not necessarily balance out. Therefore, when the sCRM is used as generally done, there is little difference in collision estimates if airspeeds (bird flight speed relative to air through which it is moving) are used rather than groundspeeds (bird flight speed relative to ground). Estimates of seabird collision rates in relation to offshore wind farms are impacting future offshore wind development. By using site specific flight speed estimates and, accounting for different speeds in relation to wind direction, we demonstrate that cumulative collision estimates can be affected, highlighting the need for more representative flight speed data and where possible site-specific data.

1. Introduction

With increasing global energy consumption and a drive in many countries to move towards renewable sources of energy to achieve net zero, the number of offshore wind farms continues to increase (Soares-Ramos et al., 2020). This is only likely to continue as the development of floating wind opens up more potential development sites that were not previously viable (Jonkman and Matha, 2011). Wind energy developments are considered to affect bird populations through direct mortality of individuals as a result of collisions with turbines, modification of habitat and behavioural responses of bird to turbines (Drewitt and Langston, 2006; Fox et al., 2006). Of these, avian collision mortality has to date, received most attention (Desholm et al., 2006; Douglas et al., 2012; Eichhorn et al., 2012; Johnston et al., 2014; Loss et al., 2013).

A variety of avian collision risk models exist which have been developed to estimate the potential bird mortality caused by wind turbines based on information both on bird numbers and activity and wind turbine design (for a review see Masden and Cook, 2016). The avian

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* Corresponding author.
E-mail address: elizabeth.masden@uhi.ac.uk (E.A. Masden).

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collision risk model most commonly used within the UK was first developed by Band (2000) and is a mechanistic model based on the probability of a turbine blade occupying the same space as a bird flying through the turbine rotor swept volume. It has been further refined (Band, 2012; Band et al., 2007) and developed into a stochastic version (Masden, 2015; McGregor et al., 2018) now known as the sCRM and continues to be the most commonly used avian collision risk model in the UK. In addition, it is frequently used across Europe (Busch and Garthe, 2018; Ministry of Economic Affairs, 2015) and further afield, for example in South Africa, Japan and New Zealand (Christie and Urquhart, 2015; Jenkins et al., 2011; Sugimoto and Matsuda, 2011). Collision risk models are routinely used in environmental impact assessments (EIAs) and the results incorporated into cumulative impact assessment (CIAs). The outputs of collision risk models can also have real consequences for wind farm developments, being at the centre of consenting decisions such as the refusal of Docking Shoal offshore wind farm in the UK (Broadbent and Nixon, 2019) and the judicial review of the decision to grant planning consent to the Firth of Forth Offshore Wind Farms (The Royal Society for the Protection of Birds vs The Scottish Ministers, Inch Cape Offshore Ltd., Neart Na Gaoithe Offshore Wind Ltd., and Seagreen Wind Energy Ltd., 2017). Therefore, it is vital that we understand how collision risk models generate collision estimates and the uncertainties associated with these estimates, if we are to use the outputs as intended.

Collision risk models often require relatively large numbers of parameters. In the case of the Band model, these include parameters related to the wind turbine such as number of turbine blades, rotor radius and blade width and pitch, and others such as wingspan, bird length and flight speed related to the bird (Band, 2012). Parameters related to the turbine structure such as the number of blades generally have a fixed value. However, the majority of parameters related to bird biometrics and flight behaviour have a distribution of possible values, and these values may be uncertain. One parameter which remains uncertain, yet is often included in collision risk modelling, is avoidance rate, ideally the rate at which a bird will take evading action to avoid a collision with a wind turbine (Broadbent and Nixon, 2019; May, 2015). Chamberlain et al. (2006) critically examined the use of avoidance rates in the Band collision risk model (Band et al., 2007) and reported that, “Small variations in avoidance rates result in relatively large changes in predicted collisions, so errors in avoidance rate estimation can have large impacts on estimated mortality rates”. Subsequently, it has been assumed that the most important parameter in collision risk modelling is avoidance rate, and that without more studies (and data) on avoidance behaviour, collision risk models and their estimates are unlikely to be greatly improved. As a consequence, there has been significant investment in large-scale studies aimed at quantifying collision risk and avoidance behaviour (e.g. Skov et al., 2018). However, within collision risk models, avoidance rate is somewhat nuanced and should be considered a correction factor which refers, in part, to the avoidance behaviour of a bird but also includes general model error. Furthermore, avoidance rate is not a factor in collision risk models itself, rather the converse; it is non-avoidance (1 – avoidance rate) which is the parameter with associated risk of collision mortality within the models, and therefore should be the parameter considered in sensitivity analyses such as Chamberlain et al. (2006).

Of the other biological parameters considered in their sensitivity study, Chamberlain et al. (2006) found that the number of birds present and bird flight speed had the largest effects on collisions, after avoidance. To date, little research has focussed on the impact of flight speed on collision. However, improvements in our ability to record the flight speed of birds, using technologies such as radar (Alerstam et al., 2007), biotelemetry (Fijn and Gyimesi, 2018; Kogure et al., 2016; Richardson et al., 2018) and the ornithodolite (Pennycuick et al., 2013), allow us to explore the influence of this parameter on estimates of collision risk in more detail. In particular, Fijn and Gyimesi (2018) highlighted significant differences in the flight speeds of Sandwich Terns *Thalasseus sandvicensis* in relation to behaviour, e.g. foraging vs commuting flight, leading to differences in collision estimates depending on how birds used the area in which a wind farm was proposed.

The aim of this study is to demonstrate the importance of flight speed relative to other parameters in the stochastic collision risk model (sCRM); to consider how the assumptions of the sCRM (Band, 2012; Band et al., 2007; McGregor et al., 2018) influence the sensitivity to flight speed; better understand the consequences of using “real” values in the model; and examine the consequences of this for the assessment of collision risk at the scale of an individual wind farm and cumulatively across multiple wind farms. Whilst our analyses focus on the sCRM, bird flight speed is similarly a key parameter in other collision risk models (Masden and Cook, 2016), and we discuss how our conclusions may apply to these models.

2. Methods

2.1. Sensitivity analysis

Following the methods of Chamberlain et al. (2006) we examined the sensitivity of avian mortality (number of collisions) to variation and uncertainty in input parameters to determine which input parameters caused the largest variation in model output (number of collisions). This was a local sensitivity analysis focussed on variation of input parameters around specific values and followed a ‘one at a time’ methodology i.e. varying one input parameter at a time, while keeping all others fixed (Pianosi et al., 2016). To estimate collision we used the avian stochastic Collision Risk Model (sCRM: McGregor et al., 2018) which at its core uses the following equation to calculate the number of birds that are likely to collide with a wind turbine; the probability of collision for a single transit (PColl) is calculated following Band (2012)

$$\text{Collisions} = \text{Bird transits} \times \text{PColl x } (1\text{–Avoidance})$$

We based our sensitivity analysis calculations around the operational Walney I wind farm off the coast of Cumbria, in the Irish Sea (54.04 degrees N, 3.52 degrees W) which comprises 51 3.6 MW wind turbines. Collision risk was estimated for the Lesser Black-backed Gull *Larus fuscus* during the breeding season (April – August). Mean values of input parameters (Table 1) were varied by ±10% from a baseline value whilst standard deviations were kept constant and the associated change in the numbers of collisions were recorded. Baseline data were taken from published literature where possible, and existing guidance from statutory agencies where published estimates were not available (McGregor et al., 2018). We ran the model for 5000 simulations. Sensitivity of the model outputs was only assessed in relation to biological inputs (avoidance rate, bird density, percentage at collision risk height, flight speed, percentage of nocturnal flight, bird length and wingspan) and not characteristics of the wind turbines, which are more likely to be known with certainty. In addition to avoidance rate, sensitivity was also assessed in relation to non-avoidance i.e. 1 – avoidance rate. All calculations were made using the online sCRM Shiny App http://dmpstats.shinyapps.io/avian_stochcrm/

2.2. Lesser Black-backed Gull tracking data

Fieldwork was carried out within the Lesser Black-backed Gull breeding colony at South Walney (54°40′N, 3°14′W) (Fig. 1), part of the Morecambe Bay and Duddon Estuary Special Protection Area (SPA). The SPA supports nationally and internationally important populations of breeding gulls and terns and wintering waterbirds. The South Walney Lesser Black-backed Gull colony reduced in size by 91% from 19,487 apparently occupied nests (AONs) in 1998–2002 (Mitchell et al., 2004) to 1981 AONs in 2018 (JNCC, 2020) following successive years of poor breeding success likely to be associated with predation, disease and changes in fishing practices (Ross-Smith et al., 2014).

Between 2014 and 2018, GPS tracking data were collected from 44 birds equipped with solar-powered Global Positioning System (GPS) tags

Table 1
Effects of 10% variation in input parameters on predicted mortality rates of Lesser Black-backed Gulls using the Walney I wind farm parameters (51 3.6 MW turbines) (www.4COffshore.com). Parameters were best estimates from scientific literature. The original baseline number of predicted collisions per year was 3.231. Collisions were only estimated during the breeding season months i.e. April – August. % increase in collisions is given as integers. [1] Bowgen and Cook (2018) [2] Bradbury et al. (2014) [3] Cook et al. (2012); Johnston et al. (2014) [4] Alerstam et al. (2007) [5] Garthe and Hüppop (2004).

Input variable	Baseline	Baseline ±10% (whichever increases mortality)	Revised number of collisions (2 d. p.)	% increase in number of collisions
Avoidance rate[1]	0.997	0.8973	108.91	3271
Bird density (birds/ km^2) [2]	0.116	0.1276	3.53	9
Non-avoidance rate [1]	0.003	0.0033	3.50	8
% at collision risk height [3]	0.215	0.2365	3.48	8
Flight speed (m.s^{-1}) [4]	13.1	14.41	3.45	7
% of nocturnal flight [5]	0.5	0.55	3.28	2
Bird length (m)	0.58	0.638	3.26	1
Wing span (m)	1.43	1.573	3.25	1

(www.UvA-BiTS.nl: Bouten et al., 2013) for up to five years (median = 2). Tagging was undertaken under license by the independent Special Methods Technical Panel of the UK Ringing Scheme. The total weight of the device and harness was <21 g, <3.2% of the body mass of tagged individuals. The devices collected high resolution (five minutes or faster) date-time stamped GPS locations throughout the breeding season. As our analysis focussed on flight speed in the marine environment, we restricted our data to GPS points at sea and, following Shamoun-Baranes et al. (2011), we assumed points where measured speed was >4 km/h reflected birds in flight. Following this filtering, we used data from 33 of our 44 GPS tagged birds in our analysis. Previous analysis suggests that this sample size is likely to be sufficient to characterise offshore habitat use by Lesser Black-backed Gulls (Thaxter et al., 2017) and, that neither the tag nor the attachment methodology is likely to have a significant negative effect on the birds (Thaxter et al., 2016).

2.2.1. *Models of Lesser Black-backed Gull flight speed*

In order to derive estimates of flight speed that could be incorporated into collision risk models and, which captured spatial and temporal variation in this parameter, we modelled the instantaneous flight speed (Fijn and Gyimesi, 2018) of Lesser Black-backed Gulls, as measured by the GPS tags, using a General Additive Mixed Model (GAMM) within the R library mcgv (Wood, 2017). As data were obtained from multiple individuals across multiple years, we fitted these as random effects with year nested within individual. Fijn and Gyimesi (2018) identified the potential for spatial variation in flight speed. In order to investigate this, we incorporated latitude and longitude into our model as a spatial smooth following Cleasby et al. (2015). Flight speed is likely to be influenced by wind speed and, this relationship is likely to be mediated by wind direction (Shamoun-Baranes et al., 2007; Spear and Ainley, 1997). Consequently, we included an interaction between wind speed and bird flight direction relative to the wind. For bird flight direction, we followed the definition of Spear and Ainley (1997) with three categories: (i) flight into headwind (difference between wind course and bird course 0–50°); (ii) flight across wind (difference 60–120°) and; (iii) flight with tailwind (difference 130–180°). We obtained data on wind speed and direction from the European Centre for Medium-range Weather Forecasting (ECMWF) (Copernicus Climate Change Service (C3S), 2017). We also considered that flight speed was likely to vary over the course of the day and breeding season, as birds take advantage of changes in air pressure (Shamoun-Baranes et al., 2016); consequently, we fitted these as smoothed variables. Finally, we considered that flight speed was likely to vary in relation to whether the bird was flying away from or towards the colony (McLaren et al., 2016) and whether it was flying within or outside a wind farm, consequently, we fitted these as factors. There was no significant correlation between variables used in our analysis (Table S2). In order to account for potential autocorrelation within the data, we sub-sampled our dataset so that we retained one data point for every five minutes. The fitted model was as follows:

$$\begin{aligned}\text{Flight speed} \sim\ & \text{s(latitude, longitude)} + \text{s(time of day)} + \text{s(day of year)} \\ & + \text{direction of travel relative to coast} + \text{wind speed} \\ & : \text{direction of travel relative to wind} + \text{wind speed} \\ & : \text{inside or outside wind farm}\end{aligned}$$

2.2.2. *Influence of flight speed on collision estimates*

Lesser Black-backed Gulls from the South Walney breeding colony are known to interact with five offshore wind farms – Barrow, West of Duddon Sands, Ormonde, Walney 1 & Walney 2 (Fig. 1: (Thaxter et al., 2018)). At present, when assessing collision risk a single estimate of flight speed would be used within the sCRM across all five sites and current practice is to use flight speed values taken directly from Alerstam et al. (2007). These data comprise 11 tracks of Lesser Black-backed Gulls recorded using radar and totalling 3150 s (Alerstam et al., 2007). However, the values presented in Alerstam et al. (2007) relate to airspeeds whilst, the guidance issued alongside the Band (2012) model, and consequently the sCRM, makes clear that ground speeds should be considered. Accordingly, we use the mean wind speed over the study period from ECMWF to convert the airspeeds presented in Alerstam et al. (2007) into ground speeds for flights with headwinds and tailwinds. We then estimate a mean (and standard deviation) of bird flight speed within each wind farm using GPS data, giving a more realistic perspective, and additionally break down these estimates according to the direction of travel in relation to wind direction (i.e. upwind, downwind and cross wind).

Initially, we estimated the collision rate across all five wind farms following current guidance (McGregor et al., 2018) with air speed taken from Alerstam et al. (2007) and, in the absence of recent data from all five wind farms, density estimates taken from Bradbury et al. (2014) (see Table S1 for full list of parameters). The model derives estimates of both the flux and the probability of collision based on the length of time it takes a bird to cover a given distance (Band, 2012). Consequently, it would be more appropriate to use estimates of ground speed in the model. Using the mean wind speed estimate for the site from ECMWF, we converted the airspeed estimate from Alerstam et al. (2007) into upwind and downwind ground speeds. Following guidance from Band (2012), we assume 50% of flights in each direction. Finally, we investigated the implications of using the flight speeds recorded using GPS within each wind farm. These instantaneous measures of speed reflect ground speed (Fijn and Gyimesi, 2018) and, using the models above, we produced speed estimates for upwind, downwind and crosswind flight. These estimates were then used to recalculate collision rates by running the sCRM with each of the three flight speeds in relation to wind direction for each wind farm. The collision rate accounting for different flight speeds in relation to wind direction for each wind farm was then taken to be the sum of these three collision estimates, weighted by the proportion of time birds were recorded flying in relation to each wind direction.

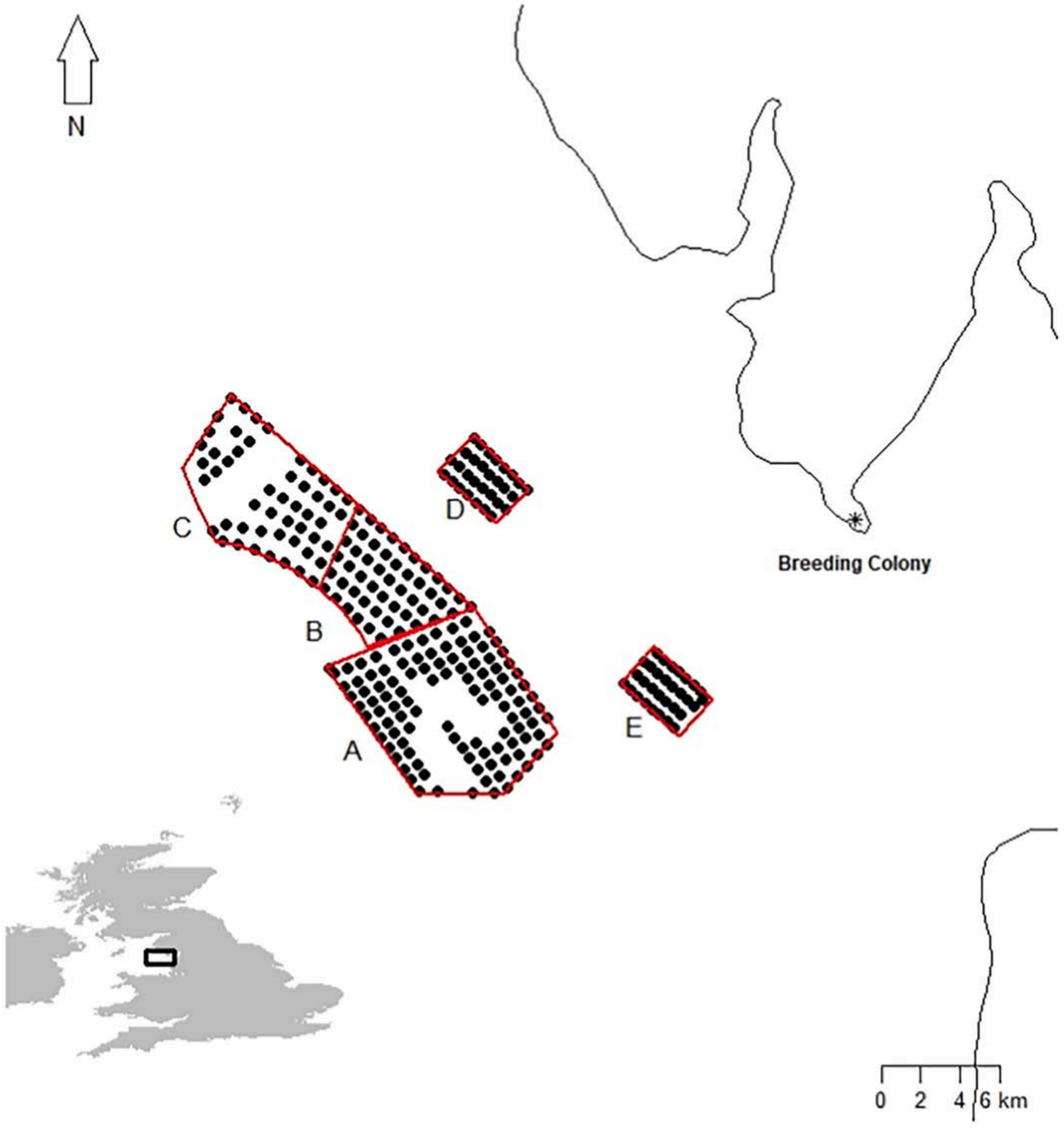

Fig. 1. Location of South Walney Lesser Black-backed Gull breeding colony, with five offshore wind farms in the vicinity. A - West of Duddon Sands; B - Walney 1; C - Walney 2; D - Ormonde; and E - Barrow.

2.2.3. How does flight speed influence the probability of collision (PColl) and flux rate?

As with the Band model (Band, 2012; Band et al., 2007), the sCRM (McGregor et al., 2018) uses flight speed twice when estimating collision risk. Firstly, it is used in the estimation of the number of birds that may pass through a turbine over any given time period, also known as the flux. Secondly, it is used to estimate the probability that a bird which passes through a turbine rotor sweep will collide with the turbine blades. In order to better understand how these two uses may interact with one another, we compared estimates of PColl and flux for the Walney 1 wind farm calculated using the airspeed presented in Alerstam et al. (2007), the upwind and downwind groundspeeds derived from the Alerstam et al. (2007) value and, the speeds recorded using GPS by birds from the South Walney breeding colony. We consider how changes in flight speed may influence these two parameters (PColl and flux) and how these may interact with one another.

All analyses were carried out using R 3.6.0 (R Core Team, 2018).

3. Results

3.1. Sensitivity analysis

In agreement with Chamberlain et al. (2006), avoidance rate had the greatest effect on the number of collisions (Table 1). Bird density, non-avoidance rate, and percentage at collision risk height all had a similar effect on the predicted number of collisions, resulting in 8–9% increases in the estimated number of collisions. Flight speed had the next largest effect, causing a 7% increase in the number of collisions (Table 1).

3.2. Lesser Black-backed Gull flight speed

Our model was a reasonable fit for the data (adjusted-$R^2 = 0.38$). In general, towards the middle of the day birds flew faster and, as the breeding season progressed (Fig. 2, $p < 0.001$ in both cases), likely reflecting birds taking advantage of favourable atmospheric conditions (Shamoun-Baranes et al., 2016; Shamoun-Baranes and Van Loon, 2006). There were clear spatial patterns in flight speed and, birds travelled faster with tail winds than was the case for head or cross winds (Fig. 3, Table 2). Birds also tended to fly faster when travelling towards the colony than when moving away from it (Table 2). However, birds did not appear to adjust their speed when flying within a wind farm (Table 2). Mean speeds within each wind farm and in relation to different wind directions are presented in Table S1.

3.3. Influence of flight speed on collision estimates

Across all five wind farms, there was a negligible difference in the collision estimates based on air speed and ground speed from the data presented in Alerstam et al. (2007) (Table 3). However, using actual speeds recorded using GPS and, accounting for differences in relation to wind direction, resulted in lower estimates of collision risk (Table 3). Within individual wind farms, the proportional decrease in the collision rate predicted when using GPS data, rather than the generic Alerstam et al. (2007) values, varied from 10.2–16.3%, with a 12.4% cumulative decrease across all five.

3.4. How does flight speed influence the probability of collision (PColl) and flux rate?

The use of flight speeds measured instantaneously with GPS or, groundspeeds estimated using Alerstam et al. (2007), resulted in a higher PColl i.e. the probability of collision from a single transit, than using the airspeed value presented in Alerstam et al. (2007) (Fig. 4a). This is because the flight speeds in crosswinds and upwind are noticeably slower than the value reported in Alerstam et al. (2007). Consequently, when birds are flying crosswind or upwind, they take longer to pass through the turbine rotor sweep, increasing the probability that they will occupy the same space as one of the blades.

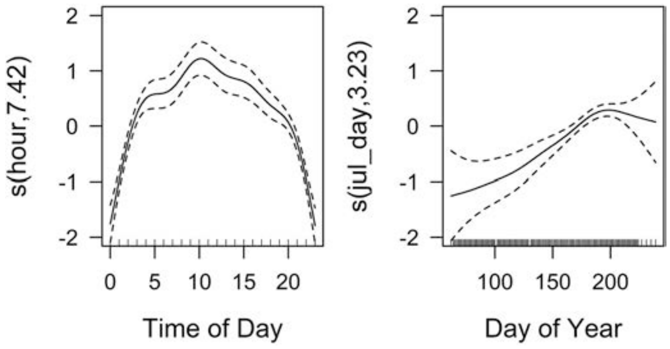

Fig. 2. Smoothed relationships between lesser black-backed gull flight speed and time of day, day of year and distance from coast. Estimated flight speeds (y-axis) are centred on the mean flight speed.

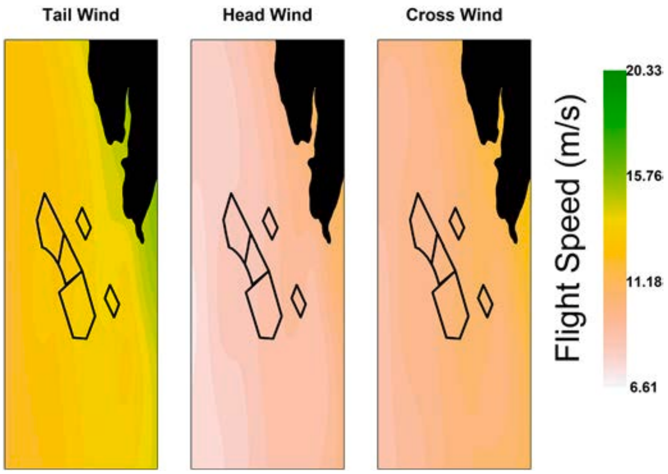

Fig. 3. Modelled variation in Lesser Black-backed Gull flight speed in relation to location and wind direction.

Table 2
Parameter estimates for non-smoothed terms from model of Lesser Black-backed Gull flight speed.

		Coefficient (± Std. Error)	P
Direction of travel			
	Away from Colony	9.52 (0.14)	<0.001
	Towards colony	9.85 (0.15)	<0.001
Wind speed:flight Direction			
	Head wind	−0.46 (0.02)	<0.001
	Tail wind	0.7 (0.03)	<0.001
	Cross wind	−0.08 (0.02)	<0.001
Wind speed:inside/outside wind farm		−0.02 (0.02)	0.39

Estimates of PColl were similar when based on the instantaneous GPS speed and the ground speed estimated from the Alerstam et al. (2007) data (0.91 and 0.90 respectively). However, when the air speed presented in Alerstam et al. (2007) was used to estimate PColl, the figure was ~10% lower at 0.82 (Fig. 4a). By contrast, when considering bird flux, the use of generic air speed from Alerstam et al. (2007) resulted in an estimated flux of 12,974 birds, identical to that estimated when converting the Alerstam et al. (2007) air speed into ground speed but, ~30% greater than the flux estimated using the instantaneous GPS speed (9913, Fig. 4b).

The resulting effect of using generic rather than instantaneous GPS flight speeds when estimating flux presents in the opposite direction to that related to PColl (Fig. 4). However, these effects do not cancel one another out as the impact on the flux exceeds that on PColl. It may seem counterintuitive that the average PColl produced from the ground speed estimated from Alerstam et al. (2007) data is virtually identical to that estimated from the GPS measured speed (Fig. 4a), yet for flux, it is the estimates calculated from groundspeed and airspeed which are identical (Fig. 4b). However, when estimating flux, the differences due to upwind and downwind speeds average out. By contrast, when estimating PColl, the probability of a bird colliding is far greater in relation to upwind flight than downwind flight (Fig. 4a) as it takes longer for a bird to cross the rotor swept area. Correcting the generic air speed values to reflect ground speeds therefore has a noticeable impact on calculations of PColl.

Table 3
Collision estimates in each wind farm based on generic airspeed and groundspeed estimates for Lesser Black-backed Gull (Alerstam et al., 2007) and those measured using instantaneous GPS within each wind farm and correcting for flight direction relative to wind direction.

Wind Farm	Collisions based on current guidance (Alerstam airspeed)	Collisions based on Alerstam airspeed converted to groundspeed	Collisions based on instantaneous GPS speed	% change after converting Alerstam airspeed to groundspeed	% Change using instantaneous GPS speed rather than current guidance
Barrow	15.51	15.57	13.92	<0.1	−10.2
Ormonde	1.04	1.06	0.89	1.9	−14.2
Walney 1	3.23	3.23	2.66	0	−16.3
Walney 2	3.63	3.45	3.06	−4.9	−15.7.
West of Duddon Sands	8	8.50	6.93	−6.3	−13.4
TOTAL	31.41	31.85	27.5	1.3	−12.4

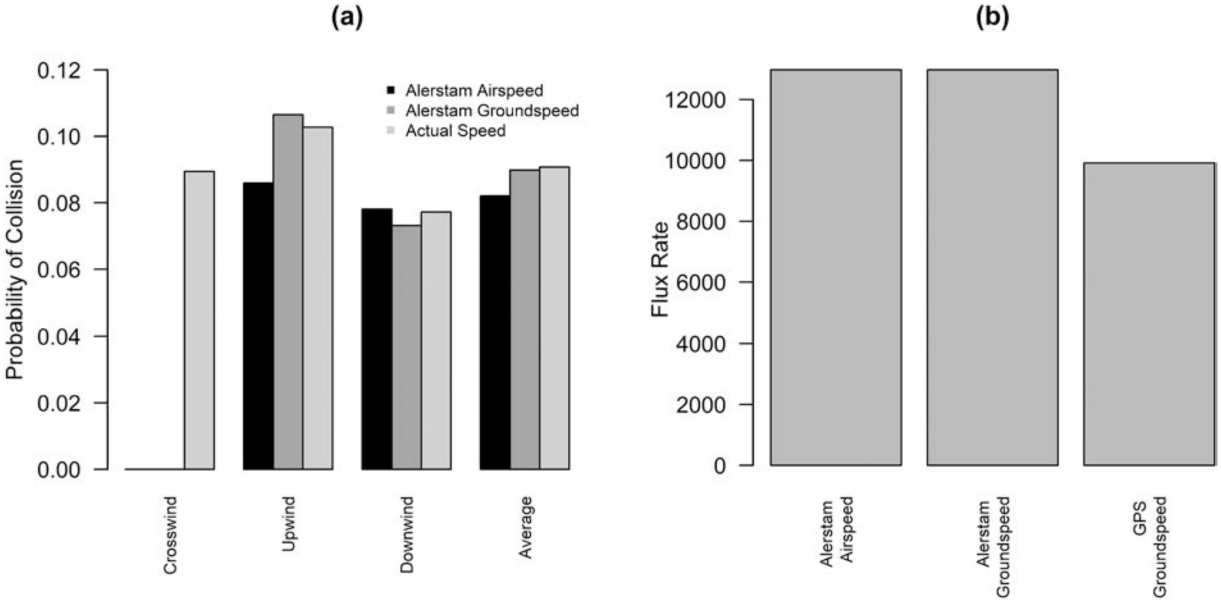

Fig. 4. Comparison of (a) Probability of Collision (PColl) and (b) Flux calculated using upwind, downwind and crosswind speeds derived from instantaneous GPS data within Walney 1 wind farm and airspeeds and ground speeds estimated using the generic data presented in Alerstam et al. (2007). Alerstam airspeed refers to using airspeed values taken from Alerstam et al. (2007) directly within the sCRM (following current practice) and Alerstam groundspeed refers to Alerstam airspeed values converted to groundspeed.

4. Discussion

Avian collision risk models are a useful and necessary tool which aid in the understanding of the environmental impacts of wind energy development (Cook and Masden, 2019; Masden and Cook, 2016). However, all models are sensitive to input data and parameters and our understanding of a system can be influenced by this. In agreement with Chamberlain et al. (2006) we show that the sensitivity of the sCRM to avoidance rate is orders of magnitude greater than for other model input variables (Table 1). To date, this result from Chamberlain et al. (2006) has been used to project the idea that gaining a better understanding of avoidance behaviour is the key to generating more accurate assessments of collision risk. Although a better understanding of bird behaviour with respect to avoidance of wind turbines is important, in relation to collision risk modelling, this idea has evolved into the thinking that avoidance rate is key to model accuracy. However, this is based on a fundamental misunderstanding of how the model operates. Avoidance rates for the sCRM and other versions of the Band model are typically calculated by comparing predicted and observed collision rates (Chamberlain et al., 2006; Cook et al., 2018). Consequently, these rates capture both the behavioural avoidance response of birds to the wind farm and/or turbines and, any error associated with the estimation of the predicted collision rates. As Fig. 4 demonstrates, there may be substantial error associated with the predicted collision rates as a result of how parameters such as flight speed are incorporated. Regarding the sCRM, it is actually non-avoidance rate i.e. 1 - avoidance rate, which is actually used within the model and is the input parameter, therefore should be the parameter assessed in the sensitivity analysis. It is clearly apparent that a 10% change in an avoidance rate of 0.997 would be more substantial than a 10% change in a non-avoidance rate of 0.003, and although the aim of a sensitivity analysis is to identify parameters with small changes that produce changes in the outputs, by including an erroneous parameter it is misleading. Consequently, when evaluating the sensitivity of the sCRM to input factors that contribute to collision risk, non-avoidance is the more appropriate factor to be evaluated.

Within the sensitivity analysis we assessed a 10% change in input parameters; this was to emulate the analysis of Chamberlain et al. (2006) but also due to the fact that there remains much uncertainty around many of the input parameters and obtaining reliable estimates of real world values i.e. the range of all possible values, proved difficult. However, further consideration should be given to whether a 10% change, as typically used in sensitivity analyses, is representative of the level of variation (inherent within a system) or uncertainty (due to a lack of knowledge) in any given parameter. For example, as a result of bird ringing activity, we have a good understanding of bird morphological parameters and can be reasonably confident that a 10% change from a baseline value of 143 cm would encompass all possible values for Lesser Black-backed Gull wingspan (135–150 cm: Cornell Lab of Ornithology, 2019; Robinson, 2005). This may not be the case for other input parameters where there is limited information; to illustrate, little is known about the nocturnal activity of many seabirds meaning there is high associated uncertainty and little understanding of variability, though with increasing amounts of GPS tracking data becoming available, this may change in the near future. Subsequently, it is important to acknowledge that both variation and uncertainty influence the range of possible values and may contribute to differing degrees, however, in complex systems it is often difficult to disentangle the two processes.

Aside from avoidance rate, the sCRM was most sensitive to bird density, non-avoidance rate, percentage of birds at collision risk height, as well as bird flight speed. This agrees with Chamberlain et al. (2006) who found that, of the ornithological parameters included in their sensitivity analysis (excluding avoidance rate), bird density and bird speed had the greatest influence on the model output. Of these, it is flight speed which has received the least attention and for which least is known particularly as speeds are likely to be variable and influenced by both environmental conditions and, what the bird is doing at any given time (Cleasby et al., 2015; Fijn and Gyimesi, 2018; Ross-Smith et al., 2016; Shamoun-Baranes et al., 2007). Whilst changes in outputs of 7–9% may seem irrelevant, in the context of consenting decisions this can make a major difference (Department of Business Energy and Industry Strategy, 2020). Our subsequent analyses therefore focussed on Lesser Black-backed Gull flight speeds. Lesser Black-backed Gull was chosen as the study species primarily due to the availability of fine-scale GPS tracking data but the implications are relevant more broadly where flight speeds collected from specific studies differ from those used more generically, and show heterogeneity due to behaviour, for example Sandwich Terns in Fijn and Gyimesi (2018). At present, flight speed enters the sCRM as one value, albeit with variation, which is an improvement on the original model. For Lesser Black-backed Gulls the accepted flight speed to use in collision risk modelling is 13.1 m.s^{-1} and is taken from Alerstam et al. (2007). However, the flight speeds provided in Alerstam et al. (2007) are airspeeds whereas the sCRM and other versions of the Band model require flight speeds to be presented as groundspeeds. Therefore the airspeed values should be corrected for wind speed before being used in the collision model rather than used directly, which is current standard practice. We estimated collisions using the flight speed provided by Alerstam et al. (2007) directly as well as when converted to groundspeed and found little difference indicating that the way the model is currently used means the distinction between groundspeed and airspeed is unlikely to be important.

At present, flight speed is used within the sCRM to calculate both the probability of collision (PColl) and, also the flux rate. This is true also for earlier versions of the Band model. However, flight speed affects flux and PColl in opposing directions and has a greater influence on flux than on PColl; this means that under current circumstances, using groundspeed rather than airspeed has little impact on the final collision rate. Yet, if we were to estimate flux in a more realistic way and not use flight speed in the calculation, as is current practice (flight speed x density), but measure flux directly using radar for example, this would mean that flight speed would only enter into calculations once, influence only PColl and the difference between ground and airspeed would become much more important (Fig. 4). Furthermore, this highlights that it is not simply a case of improving how flight speed is used within the calculations of the sCRM, rather we need to carefully consider how flux is estimated.

From the GPS data analysed, we found that Lesser Black-backed Gulls flew at speeds ranging from 6 to 20 m.s-^{1} (see Fig. 3), thus including speeds slower than 13.1 m.s-^{1} as taken from Alerstam et al. (2007). These results are consistent with previous studies such as Fijn and Gyimesi (2018) and Lane et al. (2019) which found that flight speeds varied according to environmental conditions and differed significantly from those currently recommended for use in collision risk modelling. Fijn and Gyimesi (2018) showed that for Sandwich Terns there were differences in flight speeds between behavioural stages e.g. commuting vs. foraging, during foraging trips. As a result they concluded that the behaviour of birds should be taken into account when modelling collision rates for a proposed wind farm. We found that for the Lesser Black-backed Gull, birds flew faster towards the middle of the day and, as the breeding season progressed. In addition, Lane et al. (2019) found that Northern Gannets *Morus bassanus* spent more time actively foraging in stronger winds, meaning that bird behaviour is linked to wind speed. In relation to wind, we found that there were clear spatial patterns in flight speed with birds travelling faster in tail winds than in head or cross winds, and also flew faster towards the colony than when moving away from it, however we did not explore flight speed in relation to defined behaviours specifically. Similarly, Fijn and Gyimesi (2018) found that for Sandwich Terns individuals travelled faster during the inbound commute rather than the outbound commute. It is clear therefore flight speed varies spatially and could be related to bird behaviour as well to conditions such as wind speed, therefore using the same flight speed across all behaviours, as is generally the practice within collision risk modelling, is not biologically realistic.

When considering collision risk modelling, the implications of differences in bird flight speeds are that collision estimates can be divergent, as found by Fijn and Gyimesi (2018). Here we present flight speeds of Lesser Black-backed Gulls which are generally slower than those currently used. In this situation, the consequence of using the slower speeds recorded by the GPS is that the bird flux i.e. the number of birds passing through a wind farm, will be reduced; conversely PColl is increased because birds take longer to pass through the area of risk. Overall however, by using the faster Alerstam et al. (2007) flight speed, the collision estimates will be over-inflated because the influence of flight speed on flux overwhelms the influence on PColl. The final collision estimates may therefore be more sensitive to the calculation of flux than they are to the calculation of PColl. These results highlight that both the estimation of PColl and the flux are sensitive to the assumed bird flight speed. However, this sensitivity acts in opposite directions and the two do not necessarily balance each other out, in contrast to the assumptions in Band (2012).

In numeric terms, the cumulative increase in collisions associated with using Alerstam et al. (2007) generic airspeeds rather than instantaneous speeds or ground speeds as measured using GPS observations, may seem minimal (Table 3). However, our analysis focuses on five relatively small (by current standards) wind farms for only four months of the year. At a cumulative scale in the North Sea, the projected collision risk associated with offshore wind farms is considered to be approaching a level that is of significant conservation concern (Brabant et al., 2015; Busch and Garthe, 2018). As was the case in relation to Docking Shoal (Broadbent and Nixon, 2019), these predicted collision rates pose a significant consenting risk to future development of offshore wind farms. By using site specific flight speed estimates and, accounting for different speeds in relation to wind direction, here we reduced the predicted collision estimate associated with these five wind farms by approximately 12% overall, with a range of 10–16% depending on the wind farm concerned. Furthermore, a reduction in uncertainty associated with model input parameters such as flight speed leads to improved collision estimates and allows for increased understanding of the relative risks of windfarms to seabirds set against other pressures, some of which may be related to climate change. Ultimately, this will lead to better-focussed and more effective management of the environment, including seabirds, and the resources on which they rely.

There remain unresolved questions over the assumptions and structure of the sCRM and earlier versions of the Band collision risk model. Key amongst these is how to account for the fact that the influence of flight speed on flux essentially swamps and overshadows any effect of flight speed on PColl. Following on from this, whilst the sCRM makes allowances for the fact that the turbine blade profile varies in relation to upwind or downwind approaches i.e. the collision risk for upwind flight is higher than for downwind due to the geometry of the blade (Band, 2012), these do not account for the fact that flight speeds also differ in relation to approach. To account for this, Band (2012) suggests running the model twice using the different speeds and taking an average of the results weighted by the proportion of time spent in upwind and downwind flight. However, this approach will not address the issue caused by flight speed being used to estimate both PColl and bird flux. Furthermore, it can be argued that flux does not adequately represent the full range of bird behaviour in and around offshore wind farms. The Band collision risk model was initially developed in order to assess the risk of collision posed to wintering geese flying between roost sites and feeding areas each day (Band, 2000). In these circumstances, such simplistic assumptions may be reasonable. It may also be a reasonable assumption in relation to seabird commuting flights between breeding colonies and their foraging areas. However, where birds are engaged in other behaviours, for example area restricted search foraging (Markones et al., 2010), such assumptions are unlikely to be realistic. This may also be relevant to other behaviour-specific parameters such as flight height (Cleasby et al., 2015; Lane et al., 2020), with subsequent consequences for the estimation of collision risk. It may also be unrealistic outside the breeding season, and in relation to immature or non-breeding individuals, when birds are not constrained as central place foragers by their need to provision for chicks. Although the more recent versions of the Band model (Band, 2012) and thus the sCRM were amended to address the issue of flux for the offshore rather than onshore environment, problems relating to the calculation of flux within the model remain. Finally, another challenge of the sCRM and Band model in general is that it remains unvalidated due to the difficulties of obtaining data offshore regarding bird collisions with turbines, especially when these events are likely to be rare and may occur during poor light conditions. Although some progress was made during a recent bird collision avoidance project using a combination of methods (radar, cameras and visual observations; Skov et al., 2018) much remains unresolved.

The Band model (Band, 2012) and more recent sCRM (McGregor et al., 2018) are the most frequently used avian collision risk models in Europe. However, a number of other models are available (Kleyheeg-Hartman et al., 2018; Masden and Cook, 2016), many of which include bird flight speed as an important input parameter (Eichhorn et al., 2012; Holmstrom et al., 2011; Smales et al., 2013; Tucker, 1996). These models differ in that some are focused on the scale of individual turbines (e.g. Tucker, 1996), whilst others consider the scale of a wind farm or, the wider landscape (e.g. Eichhorn et al., 2012). Each of these models uses flight speed in order to estimate the probability of a bird which passes through a turbine rotor swept-area colliding with a blade. Fig. 4a highlights how this estimate is likely to be sensitive to assumptions about bird flight speeds and sensitivity analyses, similar to those we have carried out here, are needed in order to better understand how collision estimates from these models are influenced by assumptions about parameter values. Having estimated the probability of a bird colliding with a rotor blade, it is also necessary to estimate the potential exposure of birds to the risk of collision (Masden and Cook, 2016). In some instances this may be based on individual based modelling informed by GPS tracking data (e.g. Eichhorn et al., 2012) or by scaling up data collected by observing bird movements visually or using technology such as radar (e.g. Smales et al., 2013; Kleyheeg-Hartman et al., 2018). However, in other circumstances (e.g. Tucker, 1996), it may be necessary to use an approach similar to that of Band (2000) to estimate flux rates. In such circumstances, problems similar to those we identify through our analyses are likely to arise.

5. Conclusion

Avian collision risk models are routinely used in environmental impact assessments to understand the potential impacts of wind farms on birds. However, such models are limited by the availability of suitable data. To date, research effort has been focused on improved understanding and quantification of avian avoidance behaviour with large well-funded projects such as the ORJIP Bird Collision Avoidance project (Skov et al., 2018). We show that using more accurate, site-specific data, in this case bird flight speed recorded from GPS, can also have implications for the estimated number of collisions. These estimates are likely to be further improved through wider consideration of patterns in bird behaviour. Whilst some attention has been given to improving methods to determine bird density (e.g. Johnston et al., 2015) and bird flight heights (Ross-Smith et al., 2016), efforts to collect better estimates of flight speed have been overlooked and generic data such as Alerstam et al. (2007) are repeatedly used incorrectly. At present, estimates of seabird collision rates in relation to offshore wind farms are at a level where they may have a significant population level effect (Brabant et al., 2015; Busch and Garthe, 2018); this has repercussions for offshore wind development but often collision estimates are uncertain due to uncertainty surrounding model input parameters. Our analyses suggest that funding should be targeted towards research to better understand bird flight speed and behaviour in order to reduce uncertainty in current collision risk assessments; the increased use of GPS tracking of seabirds means that such data are likely to be widely available (Largey et al., 2021). More generally, it highlights the role that collecting better data can play in increasing the precision of parameters used in EIAs for offshore wind farms and may help reduce the level of precaution used in future assessments.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2021.106622.

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[redacted]

Elizabeth A. Masden is a Research Fellow at the University of the Highlands and Islands. Their research focuses on the potential impacts of human activities such as renewable energy (wind, wave, and tidal), oil and gas developments and marine litter on the environment, and particularly seabirds. Elizabeth also has an interest in cumulative impacts related to renewable energy.

Aonghais S. C. P. Cook is a Senior Research Ecologist in the BTO's Wetland and Marine Research team and has 15 years' experience of seabird research, with a focus on interactions between seabirds and offshore renewable developments being a particular focus in recent years. He has been heavily involved in the development and application of collision risk models and led on the collision risk modelling carried out in relation to the Dogger Bank Offshore Wind Farm Zone. He regularly offers expert advice in relation to assessing the impacts of offshore wind farms on birds.

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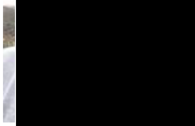
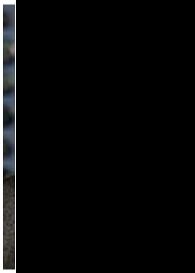
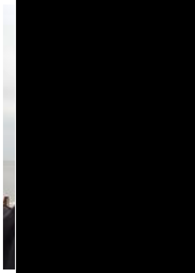
ly McCluskie works within a small team in the RSPB that
ovides scientific support for site conservation. This involves
th active research and review in order to provide the science
quired to underpin policy and casework specifically in rela-
on to the effective conservation of protected sites. In partic-
ar, he examines the interactions between wind farms, both
rrestrial and offshore, and birds. He works with a range of
atutory conservation bodies, government agencies and de-
lopers to best facilitate potential wind farm developments.
e sits and has sat on a large number of expert scientific
eering and advisory groups.



illem Bouten has a chair in Computational Geo-Ecology at
e University of Amsterdam. As a modeller he is currently
volved in interdisciplinary research on the energy transition.
the past 12 years he has developed the UvA-BiTS tracking
stem and has been involved in numerous bird tracking studies
nging from local behavioural studies to migration and
cluding pure science and applied research. In his research he
nks bird behaviour and the energy transition by studying bird
haviour in relation to wind parks.



iall H. K. Burton is Head of the British Trust for Ornithol-
y's Wetland and Marine Research Team. The team's work
plores the range of factors that may affect waterbird and
abird population dynamics, including climate change, habitat
ange and loss and the impacts of coastal and offshore de-
lopments. Niall has >25 year's research experience and >
0 publications, his own work focussed on assessing how
aterbirds and seabirds respond to environmental change.



hris B. Thaxter is a Senior Research Ecologist based at the
itish Trust for Ornithology, UK. His main research interest
s in understanding the ecological drivers of fine-scale animal
ovement and linkages to wider-scale population processes,
abling more effective conservation measures. To do this, he
es a combination of animal-borne telemetry, remote sensing
ta and field observations. With a particular focus on seabirds
is particularly interested in human-wildlife conflicts.
llowing recent expansion in offshore renewable energy,
rrent projects are focusing on how bird species interact with
ind farms, and the consequences this has for effects such as
llision risk.

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A Stochastic Collision Risk Model for Seabirds in Flight

A Stochastic Collision Risk Model for Seabirds in Flight

R.M. McGregor, S. King, C. R. Donovan, B. Caneco, and A. Webb

Authorisations

Responsibility	Name	Signature	Date
Prepared by	Dr Ross McGregor	[redacted]	06/04/2018
Checked by	Martin Scott	[redacted]	06/04/2018
Approved by	Andy Webb	[redacted]	06/04/2018

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Draft 2	30/03/2018	Second draft for review post V2 CRM app release
FINAL	06/04/2018	Final version for release.

Contents

Figures

Executive summary

1 Collision Risk Models (CRM) are used to assess impacts on seabird populations in all offshore wind farms Environmental Impact Assessments ('EIA') and Habitats Regulations Appraisals ('HRA') in the UK. Existing models are unable to properly incorporate uncertainty in the input parameters into calculations of uncertainty in the collision prediction and consequently are not expressed in the outputs.

2 Uncertainty in predicted collision has resulted in the delayed deployment of offshore wind projects, with projects being reduced in size or even cancelled. Not incorporating uncertainty when it is known to occur may be failing to meet the requirement from the European Court of justice to use, "…the best scientific knowledge in the field…".

3 This project aimed to create a CRM that incorporates variability in input parameters correctly into a predicted collision impact with estimated variability. In order to produce a model that was fit for purpose, stakeholders were consulted through a questionnaire-based survey.

4 The survey results section was in seven parts, each asking about different aspects of the CRM. These were: CRM concept, user experience, CRM inputs, CRM operation, CRM outputs, CRM error checking and CRM improvements.

5 The survey, while taking in to account the scope of the project, resulted in the following changes requested by stakeholders:

- Create a user-friendly interface for non-R users;
- Speed up the code;
- The number of turbines should be a user input;
- Output predicted collision probability data;
- Seasonal (as well as monthly & annual) assessment (default + user defined);
- Error checking inputs and collision probability; and,
- Monthly or seasonal flight height inputs.

6 The new stochastic CRM (sCRM) was based on the code written by Masden (2015), but had to be compatible with the Band (2012) offshore CRM. Testing showed that the predictions of the Masden (2015) code matched the predictions of the Band (2012) Excel spreadsheets for Option 1, but that differences in outputs for Options 2 and 3 arose because of a calculation error in Masden (2015) code. Consequently, the sCRM was based on an updated, and streamlined, version of the Masden (2015) code.

The new sCRM was produced in two forms: Firstly, a Shiny app based on the R-code, available as an online tool, which can be run from:

https://dmpstats.shinyapps.io/avian_stochcrm/

Secondly, the Shiny app can be downloaded as a package and run locally in a browser. It can be downloaded from:

https://github.com/dmpstats/stochCRM

1 Introduction

7 Collision Risk Models ('CRMs') have been used to assess impacts on bird populations in all offshore wind farms Environmental Impact Assessments ('EIA') and Habitats Regulations Appraisals ('HRA') in the UK since 2009. These types of models have also been used in onshore wind farm EIA and HRA since the early 2000s, with further models being produced since then to address various issues (Masden & Cook 2016). They have become a *de facto* requirement of Environmental Statements and Appropriate Assessments ('AA') in the United Kingdom.

8 CRMs as an impact assessment tool began with the production of the Scottish Natural Heritage ('SNH') (Band 2000, Band *et al.* 2007) model, which is an application of the concept first published by Tucker (1996). It is a simple mechanical model that calculates the probability of a bird of a certain size moving at a set speed through a wind turbine rotor, being struck by a turbine blade of a certain size and moving at a set speed. Since it is a simple mechanical model of two bodies in motion it does not account for bird behaviour in avoiding the wind farm, or a turbine or the rotor blade itself. These elements of bird behaviour (as well as any errors in the calculation) should, hypothetically, be taken into account by applying an avoidance rate (typically 95% or higher). The Band (2000) model was designed for onshore wind farms where data on bird flight activity is collected by observers carrying out behavioural observations prior to the wind farm be constructed. However, the data required to characterise the ornithological interest in an offshore wind farm makes use of very different data. Boat based or digital aerial surveys are undertaken to estimate species density. It was therefore necessary to adapt the SNH (2000) model to use this type of data.

9 This was undertaken by Bill Band (the original author of the SNH (2000) model), for The Crown Estate Strategic Ornithological Support Services ('SOSS'), under the Round 3 enabling actions. This new model, like the SNH (2000) model, was provided in Microsoft Excel spreadsheets and was deterministic (Band 2012). While the guidance to the Band (2012) model did suggest an approach to incorporate variation around input data, the method was not statistically valid as it assumed that each variable was independent (Masden 2015), and there were errors in the assumed levels of variability around some input values.

10 The limitation of the Band (2012) model in incorporating input value variability and uncertainty led to Masden (2015) developing a stochastic version of the Band (2012) model. In addition to incorporating data uncertainty in to the model, the Masden (2015) version also coded the calculations in to R code ([redacted] However, while Masden (2015) successfully achieved the coding of the Band (2012) model and incorporating uncertainty, users have noted various flaws in running this code. This culminated in a review of the Masden (2015) version of the model by Trinder (2017).

11 The main findings of Trinder (2017) were that the Masden (2015) coded version of Band (2012) has the following constraints:

- The use of only normal distributions or truncated normal distribution for all variables was inappropriate;
- Turbine parameters are modelled with uncertainty, which does not meet the requirement to follow a 'Rochdale envelope' approach to consenting;
- The Masden (2015) code did not allow bird aerial densities to exceed two birds per km^2, which was unrealistic;

- The model *always* uses the generic wind speed, rotor speed, blade pitch relationship provided, and this cannot be 'switched off'; and,
- The method used to generate a range of proportions of birds at collision risk height *can* generate negative values.

12 In most circumstances, the deterministic outputs from the SOSS CRM have been sufficient for determining no likely significant effect on the environment, for EIA, or no adverse effect on site integrity, for an AA. In most cases, for most species, it can be clear that, even with a worst-case scenario used as input parameters, the predicted impacts are relatively small. Uncertainty in CRM can have large impacts on the deployment of offshore wind projects; e.g. the Docking Shoal project was refused consent in July 2012 based on the outputs of CRM, and subsequent population modelling, and it is therefore essential that models are able to be relied upon by developers, regulators and advisers. As the number of developments increases this will be applied increasingly via cumulative impact assessments.

13 However, there have been increasingly frequent situations where CRM predictions have come very close to significant impacts. In these situations, an over-reliance on a single-value CRM prediction can lead to problems, even when a worst-case scenario is presented. Thus, an understanding of the variability around input values and their effects on the potential range of output values can be very important. Existing case law suggests that the approach using a single, precautionary, value may not be wholly compatible with the purpose of the European nature directives.

14 The European Court of Justice ('ECJ') Case C-127/02 states that an appropriate assessment should be made, "…in light of the best scientific knowledge in the field.". It could be argued that a deterministic CRM is not making use of the "best scientific knowledge" as it is known that input values are variable, and the only approach to use in these situations is potentially unrealistic worst-case scenarios. A stochastic CRM would not have these problems, as it would incorporate the variability in the data and present a result with levels of uncertainty. Thus, worst case scenarios can be avoided and the best scientific knowledge in the field can be used appropriately. Outputs from a stochastic CRM can then be used as a mortality input, with known variability, for stochastic population models. These can be used for predicting the importance of the impact on populations for either EIA or HRA.

2 Aims of this project

15 The research aim of this project was to develop a stochastic version of the Band (2012) collision risk model in R that would incorporate the gaps identified by industry and statutory agencies, providing a more robust and transparent method of accounting for uncertainty in the estimation of seabird collision rates.

2.1 Objectives

16 The research objectives for this project were:

- Identify current gaps in Band (2012) model and Masden (2015) code to be addressed in an R-based stochastic version.
- Produce an R-based stochastic version of Band model, tested against the existing Excel version, with R code independently validated.
- Provide advice on the most appropriate parameterisation of the model produced, accounting for limited information that may be available for some variables and the rapidly evolving wind turbine generator technologies.
- Consider end-users' needs and ensure that outputs presented from the model were in an appropriate form.

3 Stakeholder engagement

17 Positive stakeholder management and consultation is the identification, analysis, planning and implementation of actions to allow clear and open engagement with stakeholders. In this instance stakeholders were individuals or groups with an interest in the project, ‘A stochastic collision risk model for seabirds in flight’, because they are involved in work on this topic or may be affected by the outcomes from the consultation process.

18 Stakeholder management, and management of aspirations there-in, is a challenging aspect with any consultation. The overall project can be undermined if there are significant areas of confusion with poor stakeholder commitment and a lack of clear engagement, emphasising the need for clear documented communication.

19 The final draft pro-forma questionnaire was therefore fully discussed with the Project Steering Group (‘PSG’) prior to distribution, with several changes being made.

3.1 Questionnaire

20 A stakeholder questionnaire was designed to capture responses on all the current CRM inputs and outputs, where there are limitations and how stakeholders think these should be addressed. Questionnaires were provided as PDF forms (see Appendix 1), that could be printed and completed by hand or electronically, or via an online survey using Google Forms. Stakeholder responses were also followed up with a telephone interview for a cross-section of stakeholders (Appendix 2).

21 Responses were analysed using descriptive statistics and qualitative analysis, to determine the gaps in existing CRMs and stakeholder needs.

22 Data collected from respondents was anonymised and analysed to determine the key changes needed to be made to the current CRM.

23 Analysis of pro-forma data involved quantitative descriptive statistics and qualitative analysis of free text responses. This included analysis of the response rate, most important concerns about input data, most common concerns about outputs and the most common requested changes to the CRM. These were analysed as a whole for all respondents. Free text was summarised and descriptive assessment of common themes undertaking using word clouds.

24 In addition to the questionnaire a selection of stakeholders were invited to participate in a follow up interview by telephone. This was to ensure that the questionnaire was capturing all of the responses from stakeholders necessary to identify the needed improvements in a stochastic CRM.

3.1 Survey results

25 Survey results were split into seven sections, each asking about different aspects of the CRM. These sections were:

- CRM concept;
- User experience;
- CRM inputs;
- CRM operation;
- CRM outputs;

- CRM error checking; and,
- CRM improvements.

3.1.1 CRM concept

26 There was only one question, Question 1, in this section.

27 Question 1 was in two parts. The first part of the question, 1a, asked, “Do you think that CRM is a useful method for assessing potential impacts from offshore wind farms?”

28 This question was to determine if stakeholders thought that collision risk modelling was a useful method when used for impact assessments. In addition, it provided important context to a stakeholder’s views that could affect their responses to other questions.

29 Stakeholders were provided with three possible responses:

- Yes;
- No; and,
- Don’t know.

30 All responses were “Yes”, though two responses provided qualification on their response. One stakeholder noted that there was too much emphasis on CRM results and that they tended to be taken too “literally”. The other response was similar, noting that the value of CRM output depends on how they are used; if as an absolute measure of risk to birds, CRM was not considered useful, but as a relative measure it was considered useful.

31 The second part of question 1 was a free text option, “If you answered "Yes" to Question 1a, please describe the benefits of CRM. If you answered "No", please describe why you think that CRM is not a useful method.”

32 Most responses were positive (56%) and were mostly in relation to the existing CRM being quantitative, transparent and consistently applied. Many positive responses highlighted the CRMs value in providing relative impact between turbine scenarios or between projects. Its value as a cumulative impact tool was also mentioned several times.

33 A large proportion of responses (40%) provided comments containing both positive and negative comments. Negative comments were focused on issues around too much use of absolute, rather than relative, impact calculations. Many stakeholders were concerned that CRM outputs tended to be considered as more accurate a measure than the input data suggest. Only one comment (4%) was wholly negative.

34 Analysis using a word cloud (Figure 1) highlights that responses were not entirely positive or negative. The words “provides” and “potential” were common, as were “data”, “impacts” and “risk”. This matches the findings that more comments were positive, and that they were focused on CRM being useful for assessing potential impacts on birds.

Figure 1 Word cloud analysis results of responses to Question 1b.

3.1.2 User experience

35 There were four questions in the section on user experience. This was split between questions about experience using the Band (2012) and Masden (2015) models, and general use of R-code.

36 Question 2 was also in two parts. The first part of the question, 2a, asked, “How would you describe your primary role in using the Band (2012) CRM for offshore wind farms? (Tick both user and interpreter boxes if appropriate)”

37 This question was asked to determine stakeholders’ level of understanding of collision risk modelling and their ability to knowledgably answer questions or provide feedback.

38 Stakeholders were provided with two possible responses

- Model user; and,
- Model output interpretation.

39 Valid responses were either of these options or both. The field was not mandatory, so users could provide no response. Stakeholders were then given further options depending on which of the above options they chose. For model users, there were four possible responses:

- Expert;
- Occasional;
- Basic; and,
- None.

40 For model output interpretation, there were three possible responses:

- Supervisory;

- Reviewer; and,
- None.

41 Those that chose "None" were asked to describe their use of the Band (2012) model. Most stakeholders described themselves as both model users and model output interpreters (Figure 2). There were slightly more stakeholders that described themselves as only undertaking model output interpretation (20%), than only model use (12%). Only 2 stakeholders (8%) did not provide a response.

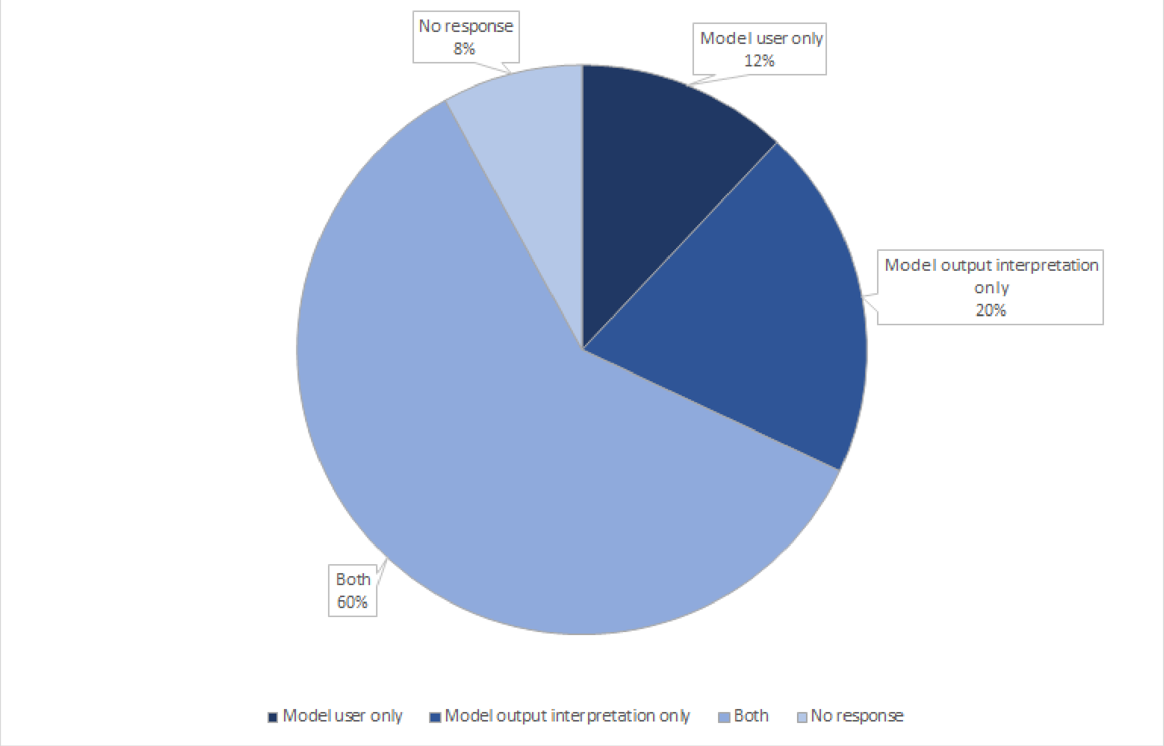


Figure 2 Relative proportion of stakeholder responses to question 2a, Part I.

42 The responses to this part of Question 2 indicated that most stakeholders responding to the survey were well aware of the Band (2012) CRM in some capacity and were therefore likely to provide useful feedback.

43 Among those that described themselves as model users, the majority (46%) described themselves as "Expert" users (Figure 3). Small proportions described themselves as "occasional" or "basic". A relatively large proportion (25%) did not provide a response, but these were mostly stakeholders that described their experience as only with model output interpretation.

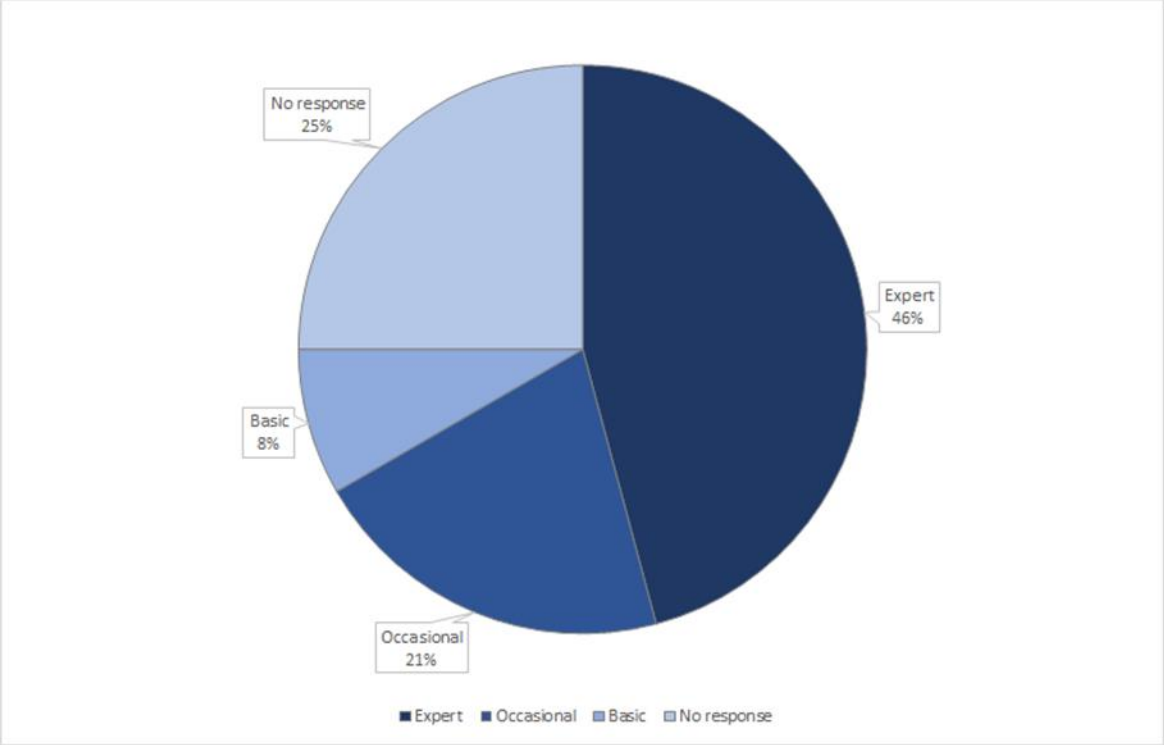


Figure 3 Relative proportion of stakeholder responses to question 2a, Part II.

44 Of those stakeholders that described themselves as being involved with model output interpretation, almost half (48%) were reviewers only of model outputs (Figure 4). Almost one third (28%) were either only supervising model output interpretation or were involved in both reviewing and supervising model output interpretation. Three stakeholders provided the response "other", and three did not provide a response, but these had not selected "model output interpretation" as a response. The free text

responses from three stakeholders only provided confirmation of their status from the categorical responses, so did not provide any further relevant information.

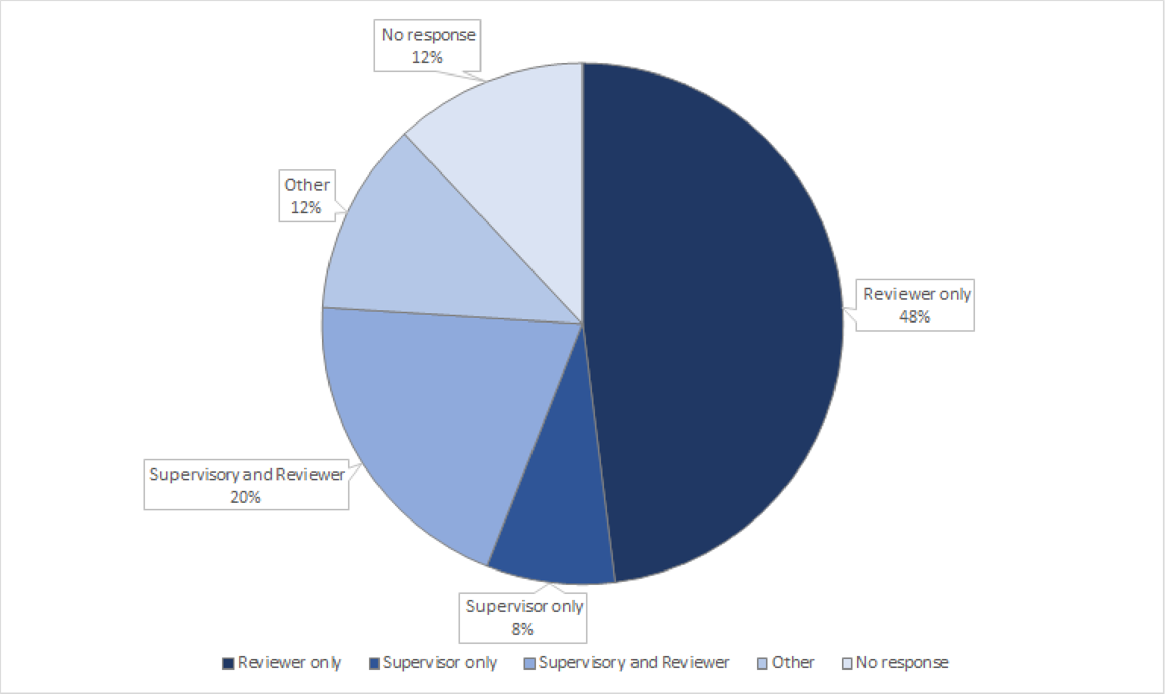


Figure 4 Relative proportion of stakeholder responses to question 2b.

45 Question 3 was a single part question, "What level of R user do you consider yourself to be?". This question aimed to determine stakeholders' level of understanding of the coding language to be used for the stochastic CRM and their ability to knowledgably answer questions or provide feedback.

46 Stakeholders were provided with five possible responses:

- Expert;
- Regular;
- Occasional;
- Never; and,
- Other.

47 Those that chose "other" were asked to provide further information in a free text box. The most common response from stakeholders was that they had no experience of using R (44%), with a relatively high proportion only using it occasionally (24%) (Figure 5). Almost a quarter of responses (24%) were from stakeholders that described themselves as expert or regular users of R.

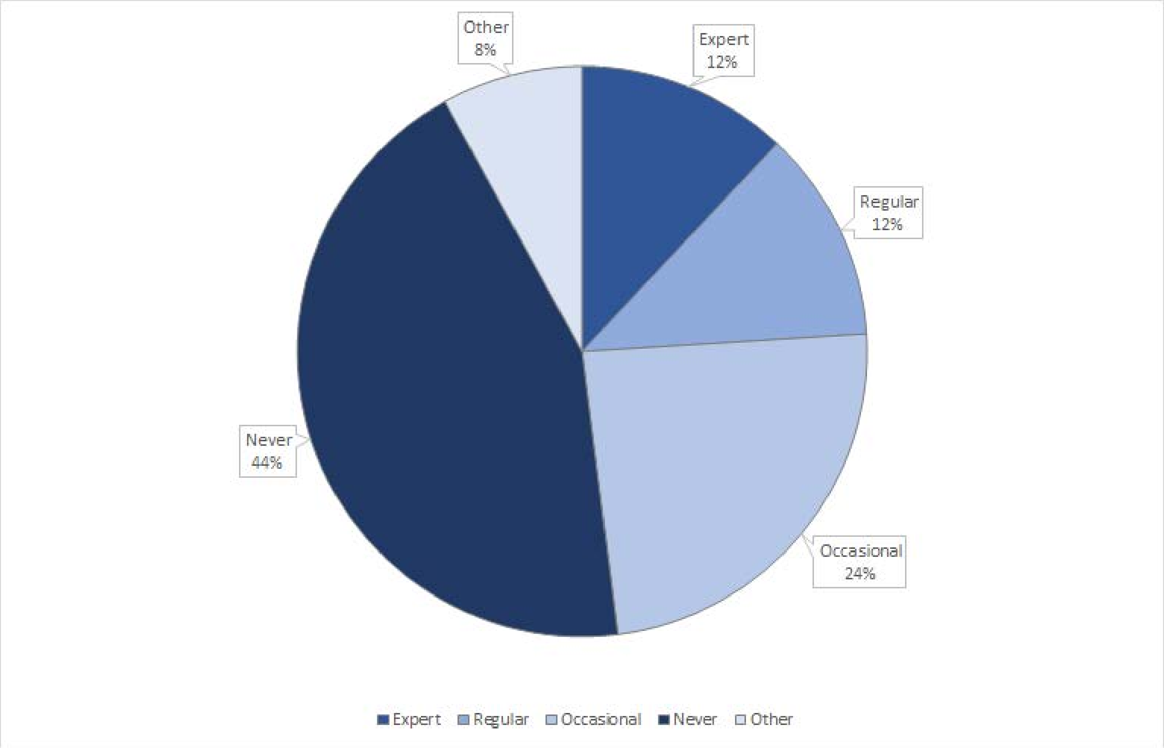


Figure 5 Relative proportion of stakeholder responses to question 3.

48 This made it clear that most stakeholders that responded were unlikely to make a lot of use of an R-code only version of a new stochastic CRM.

49 Question 4 was also a single question, "Have you ever used the Masden (2015) stochastic CRM (or another stochastic CRM) in R?"

50 This question was also to determine stakeholders' level of understanding of CRMs in R, rather than only in Excel, and their ability to knowledgably answer questions or provide feedback. Stakeholders' were provided with four possible responses:

- Yes (Masden (2015) CRM);
- Yes (another stochastic CRM);
- No; and,
- Other.

51 Responses were divided between a majority (60%) that had never used the Masden (2015) CRM, and a large minority (40%) that had. No stakeholders had used any other stochastic CRM, and there were no "other" responses (Figure 6).

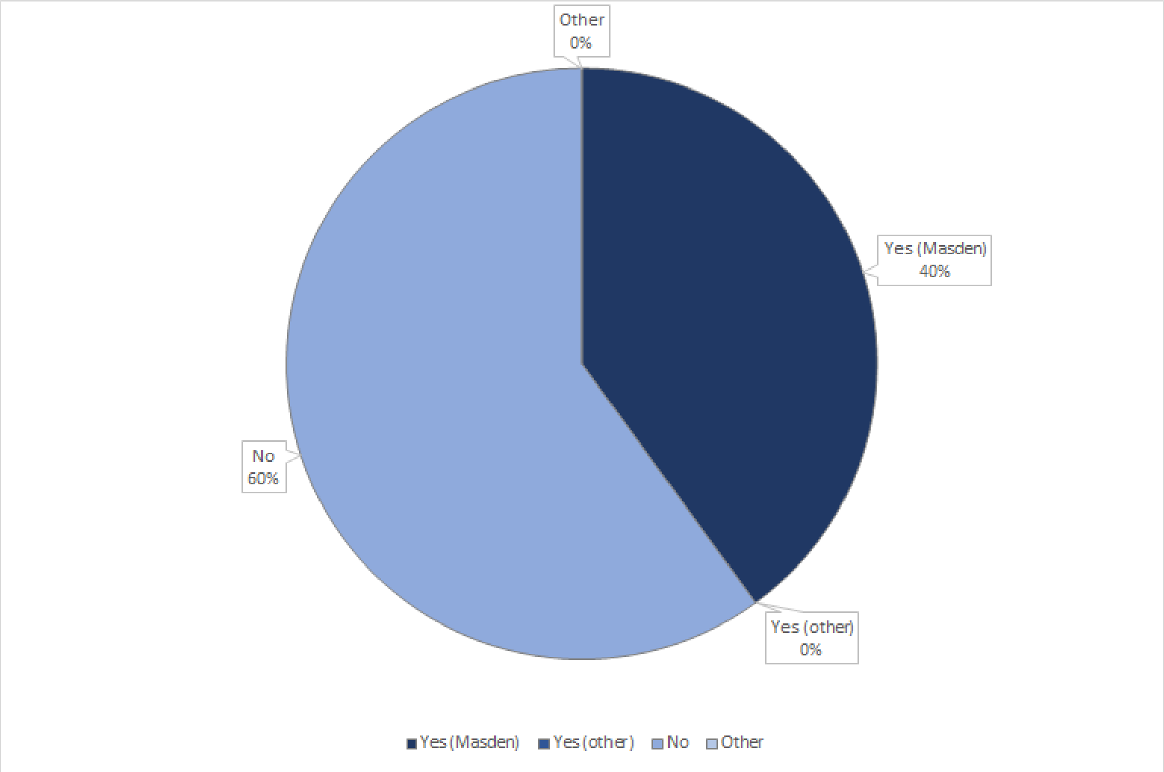


Figure 6 Relative proportion of stakeholder responses to question 4.

52 Question 5 was also a single question, “Have you ever experienced issues running the Masden (2015) stochastic CRM (or another stochastic CRM) in R?” This question aimed to draw out any currently unknown problems with the Masden (2015) version of the CRM.

53 Stakeholders were provided with three possible responses:

- Yes;
- No; and,
- Don’t know.

54 A free text box was provided asking those who responded “Yes” to provide further information.

55 While the majority of responses (Figure 7) were either “Don’t know” or “No response” (36% and 28% respectively), most responders with a known response had experienced problems with the Masden (2015) version of the CRM (28%).

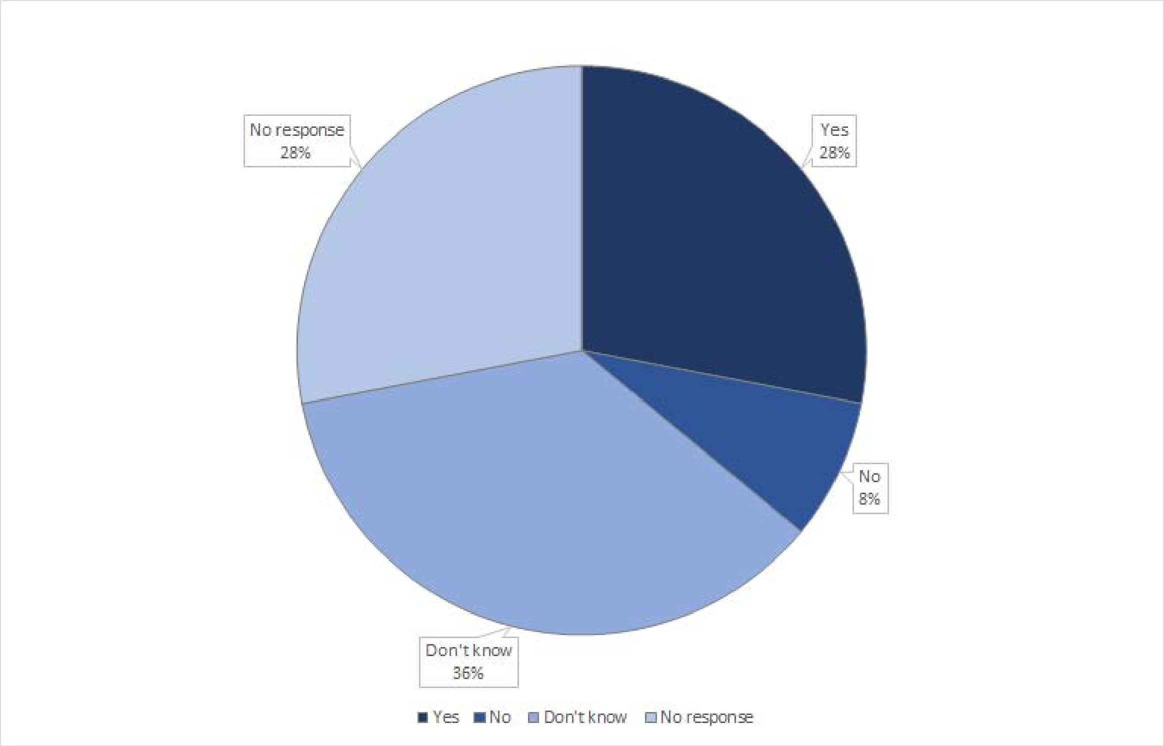


Figure 7 Relative proportion of stakeholder responses to question 5

56 Free text responses were often in relation to bugs in the code, the probability distributions used for count data, the way that the number of turbines is calculated, the assumed relationship between wind speed, rotor speed and blade pitch and the speed to run the model. Useful other comments included issues with selecting appropriate proportions at collision height, variation being present of fixed parameters (e.g. blade length will effectively have no variation around it) and the difficulty experienced when trying to run multiple turbine parameters.

57 Word cloud analysis (Figure 8) of the free text responses agreed with the above assessment with "code", "input" and "parameters", and "problems" being commonly expressed.

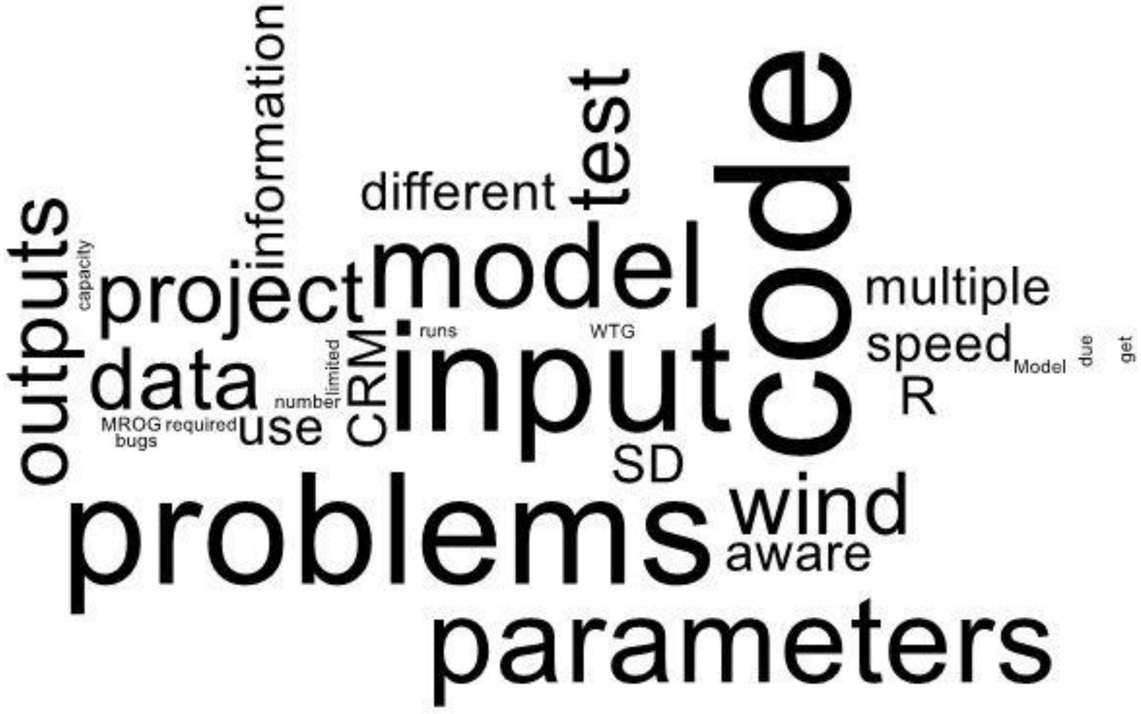


Figure 8 Word cloud of the free text component of question 5

3.1.3 CRM inputs

58 There was only one question in the section on CRM inputs, Question 6.

59 Question 6 was also a single part question, "Are there any Band (2012) input values for birds (e.g. wing span, length, flight speed, nocturnal activity) that you think should be changed, improved or added?"

60 This question aimed to ensure that as many improvements as possible were included in the new model. Stakeholders were provided with three possible responses:

- Yes;
- No; and,
- Don't know.

61 A free text box was provided asking those who responded "Yes" to provide further information. There was a strong, positive, response from stakeholders (76%) to this question (Figure 9). With only 12% stating that there were no changes needed to the bird input parameters.

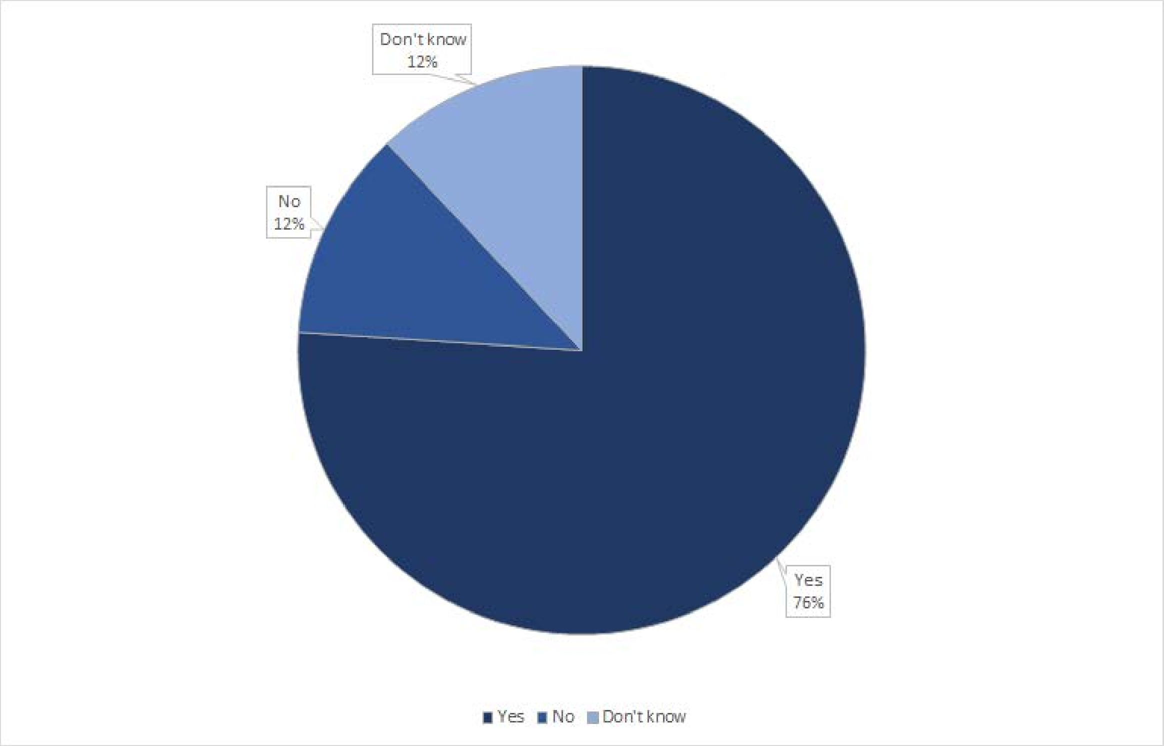


Figure 9 Relative proportion of stakeholder responses to question 6

62 The free text responses from those that stated "Yes" were commonly in relation to flight speed data and nocturnal activity data. Responses suggested that existing data were of poor quality (small sample sizes) or poor resolution (broad categories for nocturnal activity) or both. Other useful comments centred around the lack of behavioural responses in the model (e.g. changes in bird speed, height, etc. in relation to weather). There were also comments that the model is unrealistic in dismissing the effect of different angles of approach to the rotor, though one stakeholder commented that this was not really a bird input parameter issue, but a model calculation issue.

63 Word cloud analysis confirmed much of the above assessment, with "flight", "values", "bird" and "nocturnal" the commonest words used. "Activity", "speed", "model" and "data" were also commonly used.

Figure 10 Word cloud of the free text component of question 6

3.1.4 CRM operation

64 There were three questions in the section on CRM operation. These were related to how the CRM does, or should, predict the number of collisions.

65 Question 7 was also a single part question, “Should the new stochastic CRM retain all of the model Options (1, 2, 3 & 4) described by Band (2012)?”

66 This question aimed to gauge whether stakeholders wish to see changes in the approach used for modelling the different options. Stakeholders were provided with three possible responses:

- Yes;
- No; and,
- Don’t know.

67 A free text box was provided asking those who responded “No” to provide further information. There was a clear response from stakeholders, with 64% wanting to retain the four model Options available in the Band (2012) CRM (Figure 11). Roughly the same number of stakeholders responded “No” as “Don’t know”.

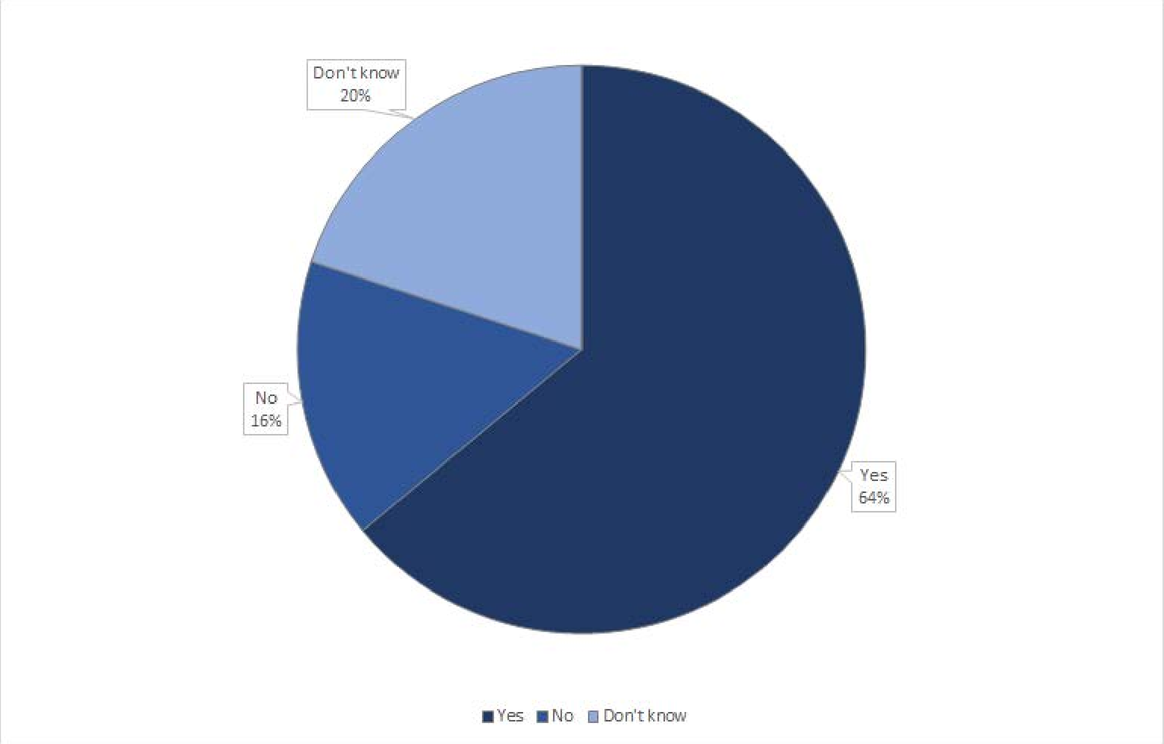


Figure 11 Relative proportion of stakeholder responses to question 7

68 While the questionnaire asked for further information only if the stakeholder responded "No", two of the six responses were from stakeholders who responded "Yes". Both responses noted that all options should be retained for making comparisons with older assessments, so these responses were still very useful. There was no consistent response from stakeholders, with some wanting to drop Option 3 & 4 (extended model), and some wanting only Options 1 & 3. One comment was that if the model is to be stochastic, then only the extended model should be used, as this is the most realistic calculation, as it takes into account the skewed flight height distribution of most seabirds.

69 Question 8 was also a single part question, "The Masden (2015) CRM includes the relationship between wind speed, rotor speed and blade pitch. Given the commercial sensitivity of this information, should a precautionary generic approach be used or should turbine specific data be used for consent applications?"

70 There has been criticism of this approach (particularly the access to suitable turbine data at a pre-consent phase). So was considered important to ask the wider community of stakeholders the implications of either not including this approach, or the potential uncertainties in using generic data.

71 Stakeholders were provided with four possible responses:

- Precautionary generic approach;
- Turbine specific approach;
- Don't know; and,
- Other.

72 A free text box was provided asking for any further information on why the stakeholder gave the response they did.

73 There was roughly an equal split between "precautionary generic approach", "turbine specific approach" and "other". A relatively small proportion (8%) of stakeholders responded "don't' know" (Figure 12).

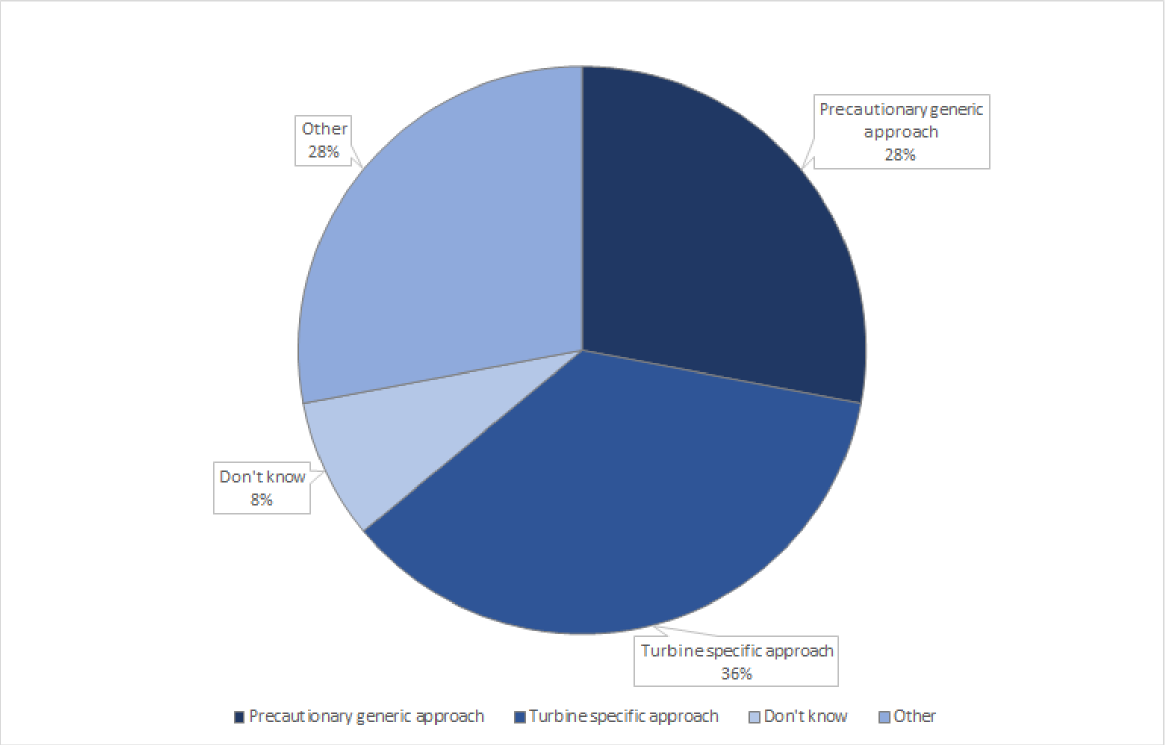


Figure 12 Relative proportion of stakeholder responses to question 8

74 Free text responses were very helpful, with most comments asking for both options to be available, even when stakeholders had selected either a precautionary generic approach or a turbine specific approach. Comments were also provided to highlight the issues around the commercial sensitivity of these data at a pre-construction stage, both from a developer's perspective, and a turbine manufacturer's perspective. Several comments received were about the need to provide these data and how these assessments should be undertaken, were beyond the scope of this project and were issues for regulators and their advisors to consider (e.g. Rochdale envelope approach to a generic or specific approach).

75 In this case, word cloud analysis (Figure 13) did not provide much useful additional value, as most of the commonly used words were from the question itself.

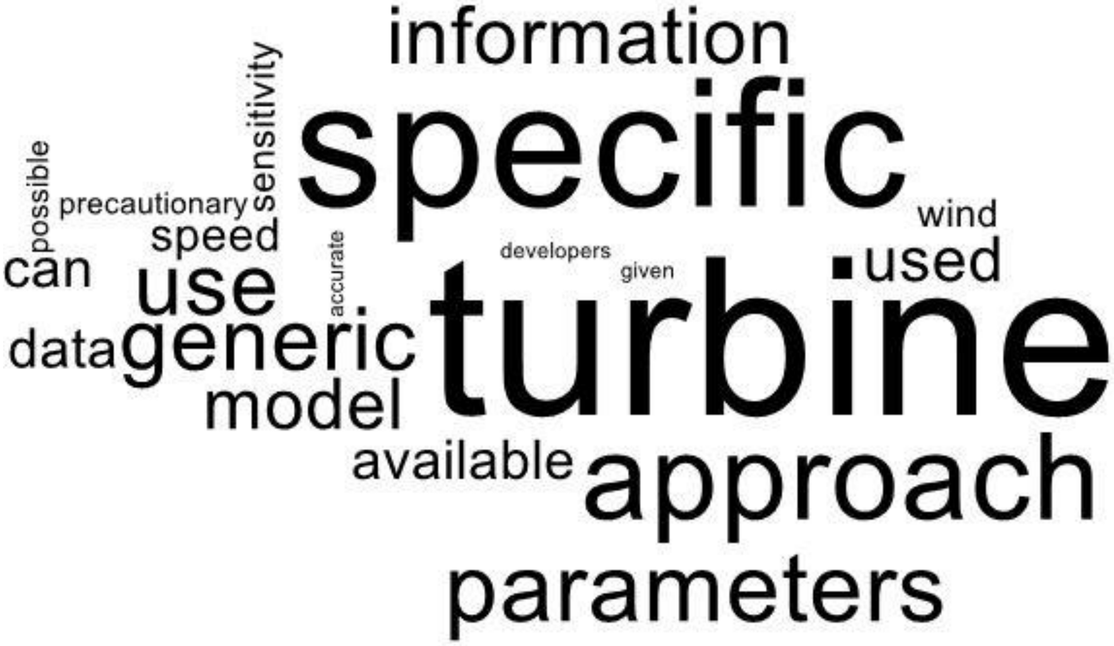


Figure 13 Word cloud of the free text component of question 8

76 Question 9 was also a single part question, “Do you think that the Band (2012) model (& Masden (2015) model) correctly calculates the probability of collision BEFORE avoidance rates are applied?”

77 It has been suggested, several times, in the past that the basic model calculations should be carefully checked by persons with a good understanding of mathematics. This may have been done, so it could be valuable to ask stakeholders this, in case someone has undertaken this check.

78 Stakeholders were provided with three possible responses:

- Yes;
- No; and,
- Don’t know.

79 A free text box asked stakeholders that responded “No” why they think that the model does not make the correct calculation.

80 Almost half (48%) of the responses were “No”, that stakeholders did not think that the model made the correct calculation for the probability of collision (Figure 14). Only 16% responded that the model did make this calculation correctly, and more than a third (36%) did not know.

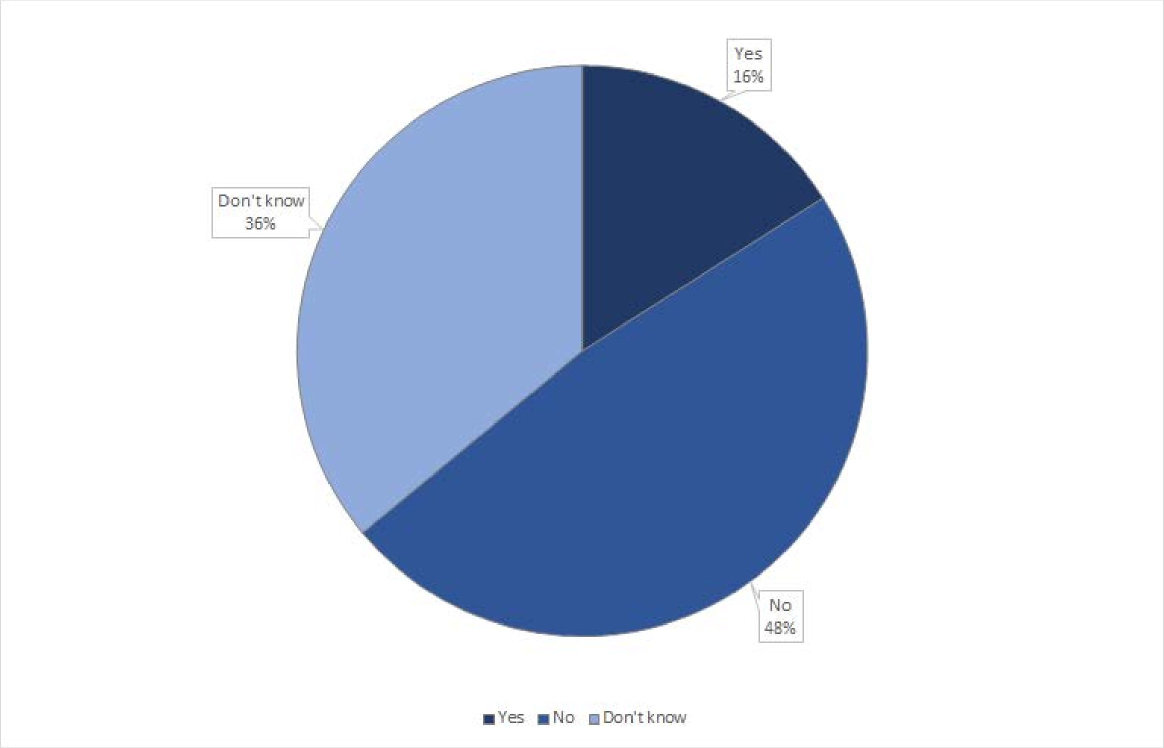


Figure 14 Relative proportion of stakeholder responses to question 9

81 Many of the free text responses commented that the calculation is a simplification and that as it is "just a model" it is by definition, likely to be wrong. Several other comments stated that the model was the best available, so within the assumptions made by the model it was making the correct calculations. Comments also included issues with the assumed 90° angle of approach, the lack of bird behaviour aspects and weather influences captured by the model. One comment suggested that the model flux calculation was likely to be incorrect as it's unbounded (in comparison to flow calculations). Overall, most comments, and the categorical responses, suggest that the question was inappropriately worded, as it was intended to draw out issues with the underlying mathematics, rather than other issues, such as available inputs.

Figure 15 Word cloud of the free text component of question 9

3.1.5 CRM outputs

82 Question 10 was the only question in the section on CRM outputs.

83 Question 10 was also a single part question, “Are there any outputs from the Masden (2015) model not currently provided that may be useful to include in a future model? (A description of the outputs is provided in paragraph 6 of the introduction)”

84 This was an open question to gather information on outputs that have not been considered to date. Stakeholders were provided with three possible responses:

- Yes;
- No; and,
- Don’t know.

85 A free text box asked stakeholders that responded “Yes” to provide the outputs that they considered useful.

86 Almost half of stakeholder responses were “Don’t know” (48%), which is likely a reflection of the relatively small proportion of stakeholders who had used the Masden (2015) model. The remaining half of responses were approximately evenly split between “Yes” (24%) and “No” (28%) responses. All those that responded “Yes” provide some free text responses, and some “Don’t know” responses also provide free text responses. The “Yes” responders requested improved outputs that include tabular data on probabilistic collision outputs (that are currently only provided as plotted data), improved box plot outputs (to include 95% confidence intervals), summarised input information and the predicted number of birds that do not collide in addition to the predicted number that do collide. The “Don’t know” responses were limited to a request for probabilistic outputs rather than a single value (which the Masden (2015) model already does), and for sensitivity testing of the new stochastic CRM.

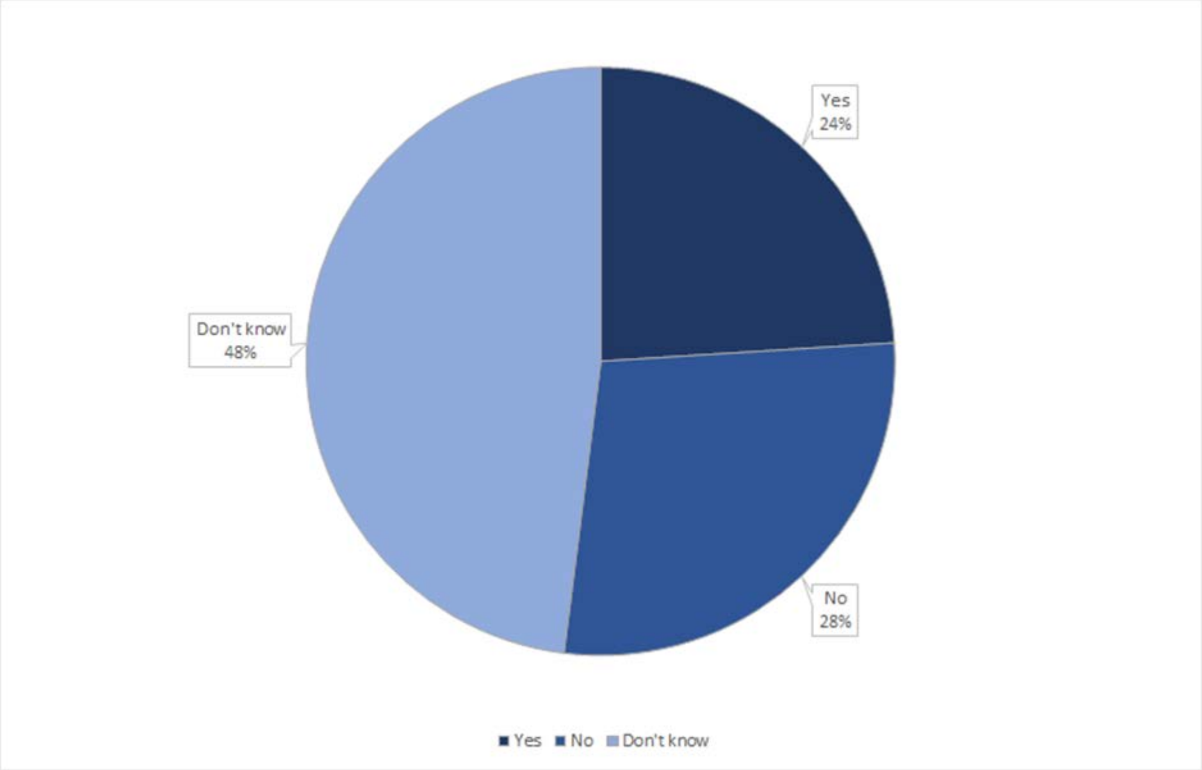


Figure 16 Relative proportion of stakeholder responses to question 10

87 The analysis of free text using a word cloud was not useful for Question 10, as response were too variable to find common themes.

3.1.6 CRM error checking

88 The only question in the section on error checking was Question 11.

89 Question 11 was also a single part question, "The current Band (2012) and Masden (2015) models do not provide any error checking. Is there any turbine specific error checking that would be useful to include in an updated Stochastic CRM?"

90 This question was particularly aimed at developers, hence the focus on turbine error reporting. It was agreed that there was sufficient ornithology expertise within the project steering group to provide advice on matters relating to the bird parameters in the model, but effectively no technical wind turbine experience. Stakeholders were provided with three possible responses:

- Yes;
- No; and,
- Don't know.

91 A free text box asked stakeholders that responded "Yes" to provide examples of useful error checking. Almost two thirds (60%) of stakeholders responded, "Don't know", which was likely a reflection of the nature of the question being turbine specific (Figure 17). About one quarter (28%) of respondents responded "Yes" and only 12% responded "No".

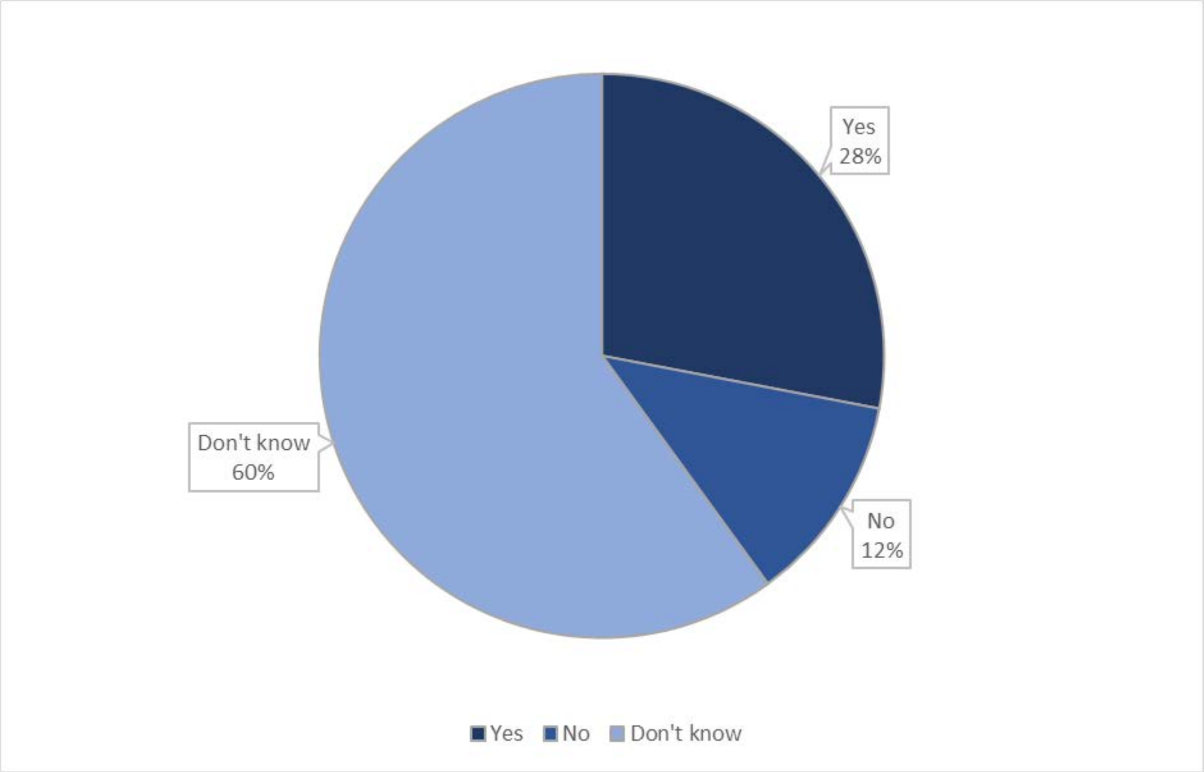


Figure 17 Relative proportion of stakeholder responses to question 11

92 Free text responses included requests for the model to flag up when parameters appear out of range, checking the numbers of birds estimated to pass through the rotor with the available population as a sense check and responses that indicated that the question did not provide an adequate explanation of its intended purpose to stakeholders'.

3.1.7 CRM improvements

93 There were two, free text only, questions in the section on CRM improvements, which were asking general questions and allowed stakeholders to provide any feedback they wished.

94 Question 12 was a single part question, with free text only, "What would be the main improvements you would like to see to a stochastic CRM? Please provide your order of preference/importance (highest first)." This question aimed to draw out practical changes that stakeholders think may be valuable from a new stochastic CRM.

95 There were eight areas where more than one stakeholder provided feedback on possible improvements. There were an additional eight areas where only one stakeholder provided feedback. The most common responses to question 12 were focused on model inputs. While many of these responses were regarding the need for better empirical data on model input values for birds (which was beyond the scope of this project), several were asking for the model to output a summary of the input values used in the model. There were also requests for default values to be provided in the model, but also that users should be able to change these.

96 The second most common comment to question 12, was for a user-friendly approach to modelling. It was clear from other responses that few stakeholders had much experience with using R, and a model

only being available in R could reduce the uptake of the approach among stakeholders. There were also a few appeals for the model to be available as R-code. The next most common response was related to model outputs. There were several recommendations for output summaries, as well as for outputs that provide the error around the estimate and also the probability distribution from the stochastic output.

97 The fourth most common set of recommendations from stakeholders were based around turbine information. Of all the comments provided on turbine inputs or outputs, only one was made by more than one stakeholder. This was in relation to the ability of the Masden (2015) model to use the relationship between wind speed, rotor speed and blade pitch of the turbines. If this element was to be retained in the model, stakeholders expressed a strong preference that default values should be used unless turbine specific parameters are publicly available.

98 A few comments were received about the lack of weather related effects on bird input parameters, though, since the purpose of this project is to create a working stochastic version of the Band (2012) model, this is not within the scope of this project. Similarly, there were a couple of comments regarding avoidance rate data that are used in the model, and this is also not within the scope of this project to address. There were requests for better flexibility in the application of seasonality within the model, though this is relatively easily addressed by users for the point estimates, as predicted collisions are additive, though errors are not.

99 Two comments were also provided regarding the slow speed running the Masden (2015) model, and requests for improved model running speed to be addressed. There were approximately eight different comments that were provided by single stakeholders, which varied greatly. These included comments about the calculations of flux of birds through the wind turbine, use of the oblique approach of birds to the turbine rotor, separate model runs for upwind and downwind flights (which can be done by users anyway) and for model validation.

100 Word cloud analysis (Figure 18) picked up on the multiple recommendations for stakeholders for better bird input values (beyond the scope of this project) and for the model to provide summaries of the model inputs. The requests for different model outputs were also reflected in the word cloud analysis. The word cloud did not pick up on the requests for a user-friendly version of the model, perhaps due to the way that stakeholders described this without using common terms. "Variation" was a relatively common word, which was related to both input values and to outputs. "Speed" was also found relatively frequently, which was related to both model speed, and bird flight speed as a user input.

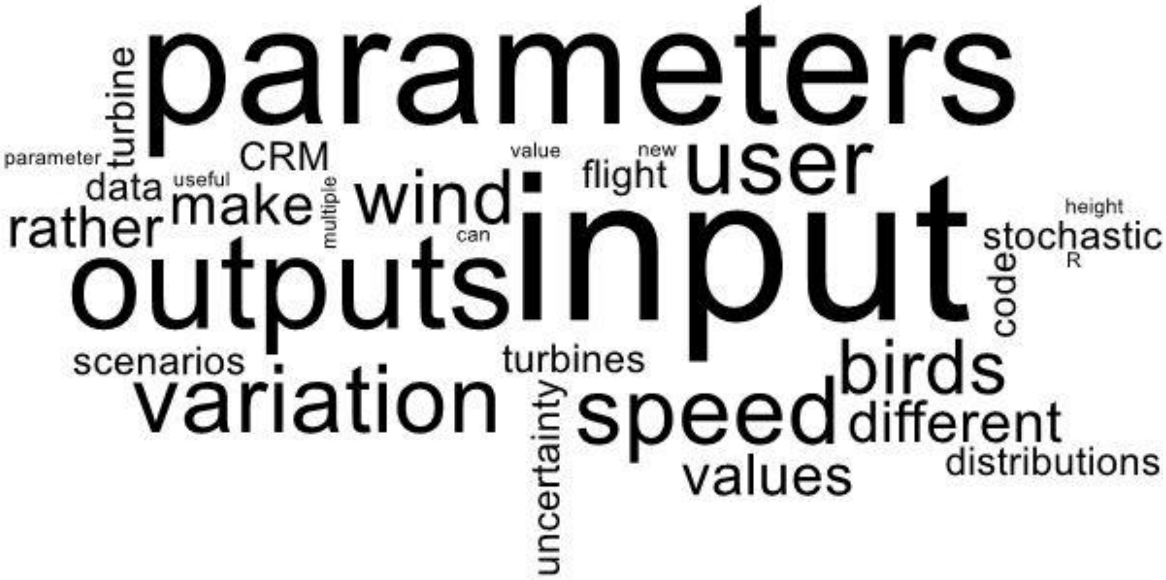


Figure 18 Word cloud of the free text question 12

101 Question 13 was a general free text response question, "Are there any other comments you would like to make about collision risk modelling?", designed as a catch all to ensure that stakeholders were able to provide any other feedback they wished.

102 Responses to question 13 were more variable than other questions, which was expected given the broad question asked. There were few comments made by more than one stakeholder. There were a few comments that the model should be transparent, and related to this a request that the R-code should be freely available. There were also several comments that the CRM is only a model, and there is often both too much precaution used in parameterising it, and too much faith placed in the results, that are often treated as more accurate a prediction than is likely to be true. Other useful comments included a request that single value outputs are no longer used and that only probabilistic outputs are considered, a recommendation is provided for the number of runs needed to produce a useful stochastic output, and that data from the ORJIP project could be used to sense check some of the model calculations. A request was made that care is taken to ensure terms are clear and consistent.

103 There were several other comments that, while useful, were out of scope for this project. These included more use of tracking data to inform bird input parameters, a better understanding of bird aerial density data and more consideration of the difference in weather conditions during surveys with the likely weather conditions when turbines are operational.

104 Word cloud analysis showed that there were many commonly used words (Figure 19), but due to the broad basis for the question there were no key messages that could be better elucidated from the word cloud.

Figure 19 Word cloud from the free text question 13.

3.1.8 Telephone interviews

The telephone interviews were intended to be short (30 – 60 mins) and allow for discussion and exchange of ideas in order to capture any useful additional information. There were four questions:

- Question 1: Did the questionnaire allow you to provide all the feedback you would wish to give? If not, what was missing and what feedback would you want to give?;
- Question 2: When the stochastic CRM is produced do you think you will use it? (If the interviewee is a developer or consultant, then ask: would the new sCRM need to be recommended by the relevant regulator and their SNCB for you to use it?);
- Question 3: Assuming the stochastic CRM is produced and works, what are the next new developments in CRM you would like to see? Are there any other comments you want to make about the survey or CRM for offshore wind farms?; and
- Question 4: How do you think you would implement the results from a stochastic CRM in to an impact assessment and a population model?

105 A total of eight interviews were conducted. Most were with environmental consultants (5), two with developers and one with an NGO. Overall the responses only underlined the comments made in the questionnaire itself.

106 In response to question 1, all of the stakeholders interviewed agreed that the survey was sufficient to allow all the feedback they wished to give. Several provided additional feedback at this stage, with the two most common comments relating to the slow speed of the Masden (2015) model, and the need to provide a user-friendly version as well as a coded version of the model. There were also comments on the value of the outputs including a tabulated summary of the inputs used.

107 Responses to question two all agreed that regulator, and SNCB, approval would be needed to use the model in consent application. However, several consultants noted that they would evaluate the model

anyway and would advise clients accordingly on the value, or otherwise, of the stochastic CRM. One stakeholder noted that the opinion of the RSPB on the model would also have some importance.

108 The most common responses to question three were the need to improve the empirical data on birds used as inputs, and the need to better incorporate information on bird behaviour in relation to weather. There were mixed messages from consultants and developers on the use of the relationship between wind speed, rotor speed and blade pitch. Some consultants noted that they had been provided with these data when asked, while developers noted that under Contracts For Difference ('CFD'), such information would not be readily shared in a public domain, highlighting the need for a generic approach.

109 Responses to question four were the most variable. Issues with the use of a mean and confidence interval around it were noted as problematic for regulators, and that guidance from SNCBs will be needed. One consultant noted that the existing models can give very precise outputs, that is far more than the accuracy of the model, so requested that outputs are always rounded up to the nearest whole bird (at least). Only one stakeholder requested tabular outputs of the collision probability from the model, to be used as an input to a stochastic population model. There were several comments about the CRM and population models being only model, so comparisons being of the most use.

110 Finally, the results of the telephone interviews, while not adding to any stakeholder requested changes to the CRM, did highlight the key messages from the survey.

3.2 Stakeholder requested changes

111 The results of the survey, while taking in to account the scope of the project, results in the following changes that have been requested by stakeholders:

- Create a user-friendly interface for non-R users;
- Speed up the code;
- The number of turbines should be a user input;
- Output predicted collision probability data;
- Provide summary of input values as an output;
- Seasonal (as well as monthly & annual) assessment (default + user defined);
- Error checking inputs and collision probability; and,
- Monthly or seasonal flight height inputs.

4 Comparison of Band (2012) and Masden (2015)

112 The Band CRM is implemented in two distributed forms: a deterministic version in Excel, based on macros and cell-to-cell calculations (Band 2012); and a version with stochastic elements, coded in R (R Core Team, 2016) by Masden (2015).

113 A comparison is presented here, based on general properties and on the outputs when both versions are run for the same scenario. The scenario considered was for a single species (gannet *Morus bassanus*) at a Scottish offshore location. The two implementations will be referred to as the Band and Masden implementations hereafter.

4.1 High level comparison

114 The interfaces to the two models are fundamentally different. The Band implementation is an Excel workbook, with all parameters and data presented cell-wise over numerous spreadsheets. There are effectively no checks on inputs (other than failure to compute), although some elements are protected from alteration. Being a spread-sheet, there is little in the way of an audit trail for presented outputs.

115 Interaction with the Masden implementation is via a main R script file, for high-level parameters, and a series of input files (comma-separated-value: CSV) for data and various parameter sets. Users require an installation of R, appropriate packages and some familiarity with running R code. There are effectively no checks on inputs other than failure to compute i.e. general warnings and errors from R.

116 The data/parameter requirements for the Masden implementation are larger, in keeping with its additional stochastic components e.g. bootstrapped flight heights, parameters governing statistical distributions on CRM parameters. The format of these files, such as column names, must be exactly as expected by the code, so templates need to be followed precisely.

117 Outputs from the Band implementation are tables and graphics within the Excel workbook. Outputs from the Masden implementation are files: CSV for tables and PNG graphics. The input data are also outputted from Masden, giving an audit trail for a particular set of outputs.

118 Calculations using the Band implementation are reasonably fast, on the order of a few seconds to run the imbedded macro for Option 3. However, the spreadsheet requires reconfiguring for each species and speculative turbine configurations. In contrast, the Masden calculations take substantive time. For example, a single species with 1000 Monte-Carlo iterations (a common modest number) might require an hour on a mid-range computer. This scales linearly with the number of species and turbine configurations e.g. two turbine configurations and 10 species might require almost a day of computer time. However, the species-turbine scenarios can be specified in advance, after which the program will iterate over all consecutively.

4.2 Output comparison

119 The principal output from both implementations is the predicted numbers of bird collisions – by month and a yearly total. These are presented for different avoidance rates, large-array corrections, species and “options” for the treatment of bird flight height distributions. The fundamental difference in outputs, is that Masden provides uncertainty in estimates. The uncertainty in collision risk is determined via Monte-Carlo (i.e. resampling of parameter values from statistical distributions on inputs) and expressed by standard deviations, coefficients of variation, inter-quartile ranges, box-plots, etc.

120 The calculations from Band and Masden implementations were compared by using identical inputs for common components and the suppression of Monte-Carlo variability, i.e. the stochastic Masden implementation was forced to provide deterministic predictions for comparability with the Band implementation. This allowed comparison of the basic calculations underpinning both.

121 Using Option 1 (the ‘basic’ Band model), the risk estimates for the Band and Masden models were deemed to be the same, within mild rounding errors. This indicated that the core functions for collision risk were providing effectively identical results.

122 In contrast, Options 2 & 3 (different treatments for flight height distributions) provided different results, with the Masden collisions estimates being somewhat higher and more consistent with Bands estimates with lower avoidance e.g. Masden’s 95% avoidance estimates were similar to Band’s 98% avoidance estimates.

123 The difference in results was mainly attributable to an apparent error in the Masden code, whereby the height of the turbine is incorrectly calculated when relating to the bird flight height distributions – effectively lifting the turbine higher. There may be further, more subtle, differences due to the bespoke visual basic ‘interpolate’ function found in Band, this being implemented differently in Masden.

4.3 Overview

124 Neither implementation is user-friendly, and both are prone to user errors. The current Masden code provides systematically different risk assessments for Option 2 & 3 calculations compared to the Band implementation – which is considered the standard here.

125 The Band implementation benefits from transparency of inputs, but a large, complex interface. There is little to check the validity of inputs, unintended alterations to the spreadsheet are opaque and there is effectively no audit-trail linking inputs to purported outputs.

126 In contrast, the Masden implementation might be considered more direct and efficient in user interaction, but requires interaction with R and is slow to calculate. There is similarly little to check the validity of inputs, but there is a reasonable audit trail linking the code run to the outputs presented. Failure of the code will produce esoteric R errors and would require modest R capabilities to resolve e.g. an error in the input parameter or data files.

5 Coding a new stochastic CRM

5.1 Code review

127 The Masden code was subject to a line-by-line evaluation. Broadly the following was found:

- There is a lack of consistency of coding, suggesting multiple authors, given markedly non-standard approaches.
- The code is inefficient, relying on multiple nested loops for its calculations, rather than vectorised approaches. Related to this, there is a repetition of objects which creates confusion due to synonyms.
- Scoping is poorly conceived in places, where functions rely heavily on global objects.

128 The code benefitted from substantial re-writing for efficiency, consistency and clarity.

5.2 Recoding

129 The Masden code was recoded, with the main goals of improving usability (including speed), transparency and robustness – as well as bug fixes and alterations in light of recent reviews of the code (Trinder 2017 and our detailed code review). These were achieved by creating a user-friendly Graphical User Interface (GUI) to interact with the code and progressively streamlining and improving the structure of the underlying code.

130 The code was moved to a version control system (GIT) and improved in stages. This provides a detailed audit-trail of modifications and reversion to any state is possible. Other developers can collaborate or take over future development relatively seamlessly.

131 There has been vectorisation of many elements to improve speed and readability. Coding consistency has been improved and redundant objects removed. Revised distribution options have been provided for the Monte-Carlo to address the points raised in Trinder 2017.

132 Default parameter values are provided and the inputs are either constrained or flagged to the user if unreasonable. Data can be provided directly through the GUI or from the uploading of template data files. Pop-up help text is provided throughout along with guidance for use.

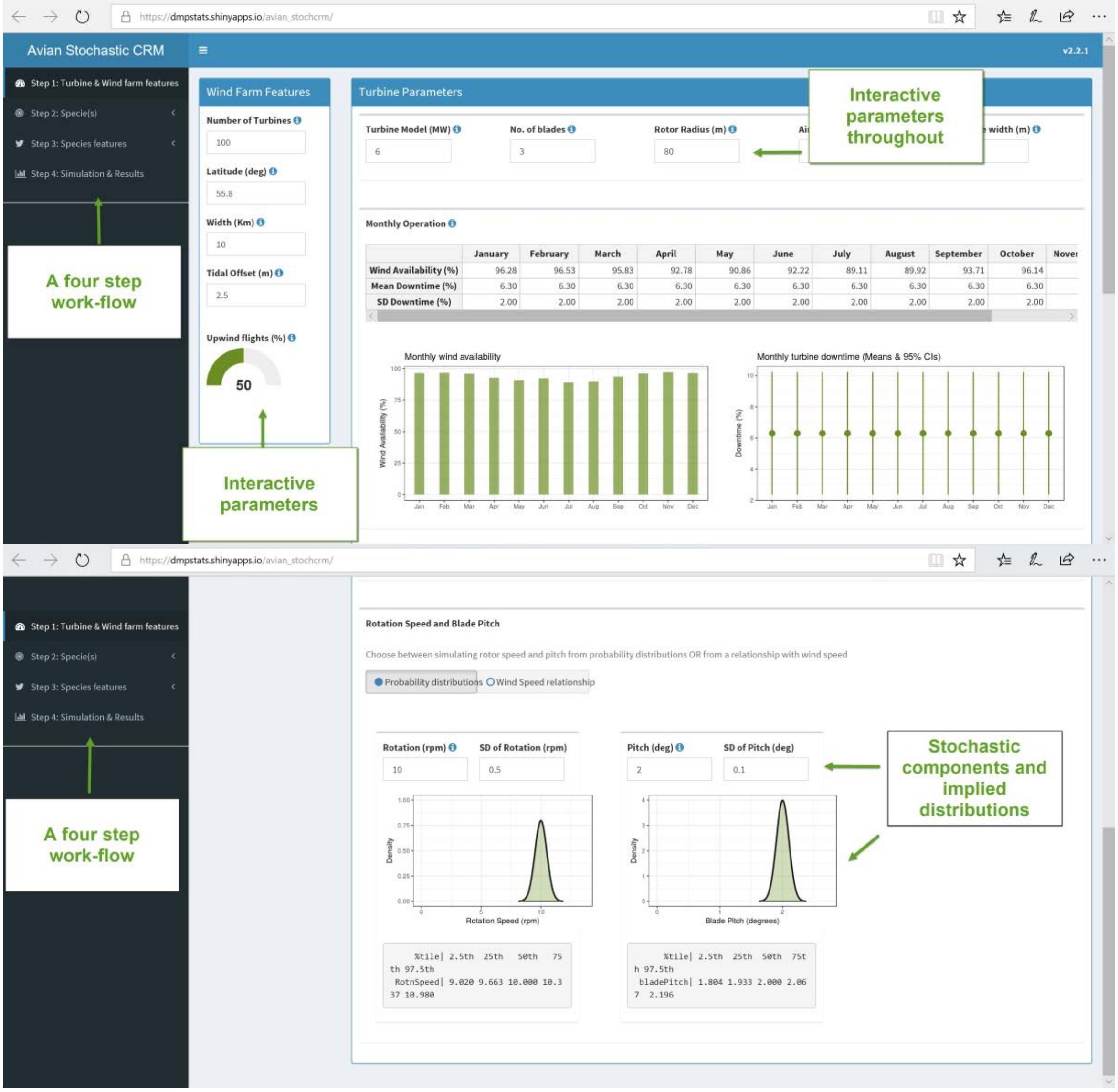
133 The GUI has been developed in Shiny, a set of R tools that create HTML interfaces to R code. This has many benefits:

- It provides a user-friendly GUI that users access through a standard web-browser – all R code is invisible and no direct code interaction is required;
- It is free and open-source, there is no vendor lock-in;
- The underlying R code is maintained on a remote server that all users connect to. Any alterations are immediately realised for all users. No installation or maintenance of R is required by users; and
- There is a wide-range of ways that input and output can be specified, to suit users.

5.3 GUI implementation

134 General information about Shiny can be found on https://shiny.rstudio.com/. The current version of the GUI can be found at https://dmpstats.shinyapps.io/avian_stochcrm/ and the following gives a brief indication of its use.

135 The workflow is broken into four main steps. In the first instance we set turbine parameters for the wind-farm. The GUI provides sliders and fields for all parameters and plots the implied parameter distribution in each case (Figure 20). Default values are presented and where appropriate field values are constrained e.g. counts are non-negative. In addition, ranges of plausible parameter values were solicited from the Project Steering Group (PSG). Entry of values that are not impossible, but outside expected ranges may elicit warning messages.



A four step work-flow

Interactive parameters

Interactive parameters throughout

Stochastic components and implied distributions

Number of Turbines: 100
Latitude (deg): 55.8
Width (Km): 10
Tidal Offset (m): 2.5
Upwind flights (%): 50

Turbine Model (MW): 6
No. of blades: 3
Rotor Radius (m): 80

Monthly Operation

	January	February	March	April	May	June	July	August	September	October	Nover
Wind Availability (%)	96.28	96.53	95.83	92.78	90.86	92.22	89.11	89.92	93.71	96.14	
Mean Downtime (%)	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	
SD Downtime (%)	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	

Rotation Speed and Blade Pitch

Choose between simulating rotor speed and pitch from probability distributions OR from a relationship with wind speed

● Probability distributions ○ Wind Speed relationship

Rotation (rpm): 10
SD of Rotation (rpm): 0.5

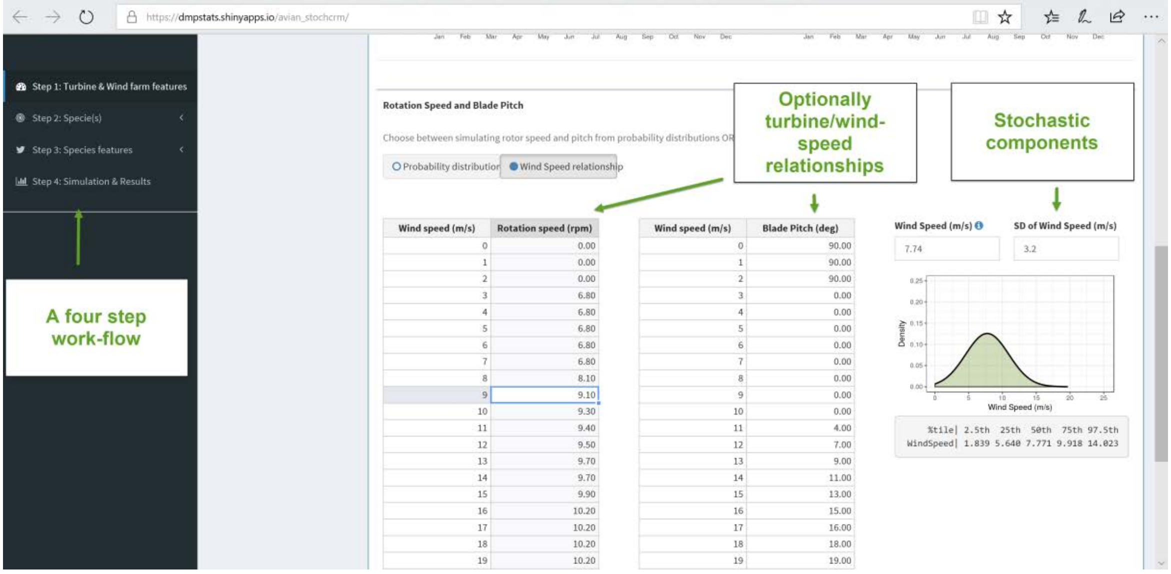
```
    %tile| 2.5th  25th   50th   75
th 97.5th
 RotnSpeed| 9.020 9.663 10.000 10.3
37 10.980
```

Pitch (deg): 2
SD of Pitch (deg): 0.1

```
    %tile| 2.5th  25th  50th  75t
h 97.5th
 bladePitch| 1.804 1.933 2.000 2.06
7  2.196
```

Figure 20 The GUI introduction page. Turbine parameters

136 Additional options have been added for flexibility in portraying relationships between wind-speed and the turbine's rotor pitch and speed.



Rotation Speed and Blade Pitch

Choose between simulating rotor speed and pitch from probability distributions OR

○ Probability distributior ● Wind Speed relationship

Wind speed (m/s)	Rotation speed (rpm)
0	0.00
1	0.00
2	0.00
3	6.80
4	6.80
5	6.80
6	6.80
7	6.80
8	8.10
9	9.10
10	9.30
11	9.40
12	9.50
13	9.70
14	9.70
15	9.90
16	10.20
17	10.20
18	10.20
19	10.20

Wind speed (m/s)	Blade Pitch (deg)
0	90.00
1	90.00
2	90.00
3	0.00
4	0.00
5	0.00
6	0.00
7	0.00
8	0.00
9	0.00
10	0.00
11	4.00
12	7.00
13	9.00
14	11.00
15	13.00
16	15.00
17	16.00
18	18.00
19	19.00

Wind Speed (m/s): 7.74

SD of Wind Speed (m/s): 3.2

```
   %tile| 2.5th  25th  50th  75th 97.5th
WindSpeed| 1.839 5.640 7.771 9.918 14.023
```

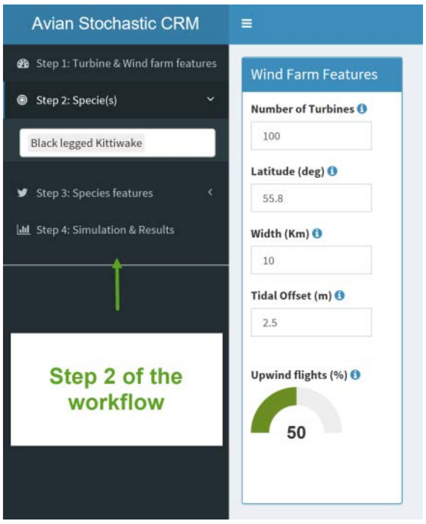
Optionally turbine/wind-speed relationships

Stochastic components

A four step work-flow

Figure 21 The GUI introduction page. Turbine parameters

137 After setting the turbine parameters, noting there may be several proposed turbine setups (Figure 22), the species of interest are selected. Currently these are pre-defined, as there are limited datasets stored for the flight-height distributions, as described in Masden (2015). Further species can be added if equivalent data is available.



Black legged Kittiwake

Wind Farm Features

Number of Turbines: 100

Latitude (deg): 55.8

Width (Km): 10

Tidal Offset (m): 2.5

Upwind flights (%): 50

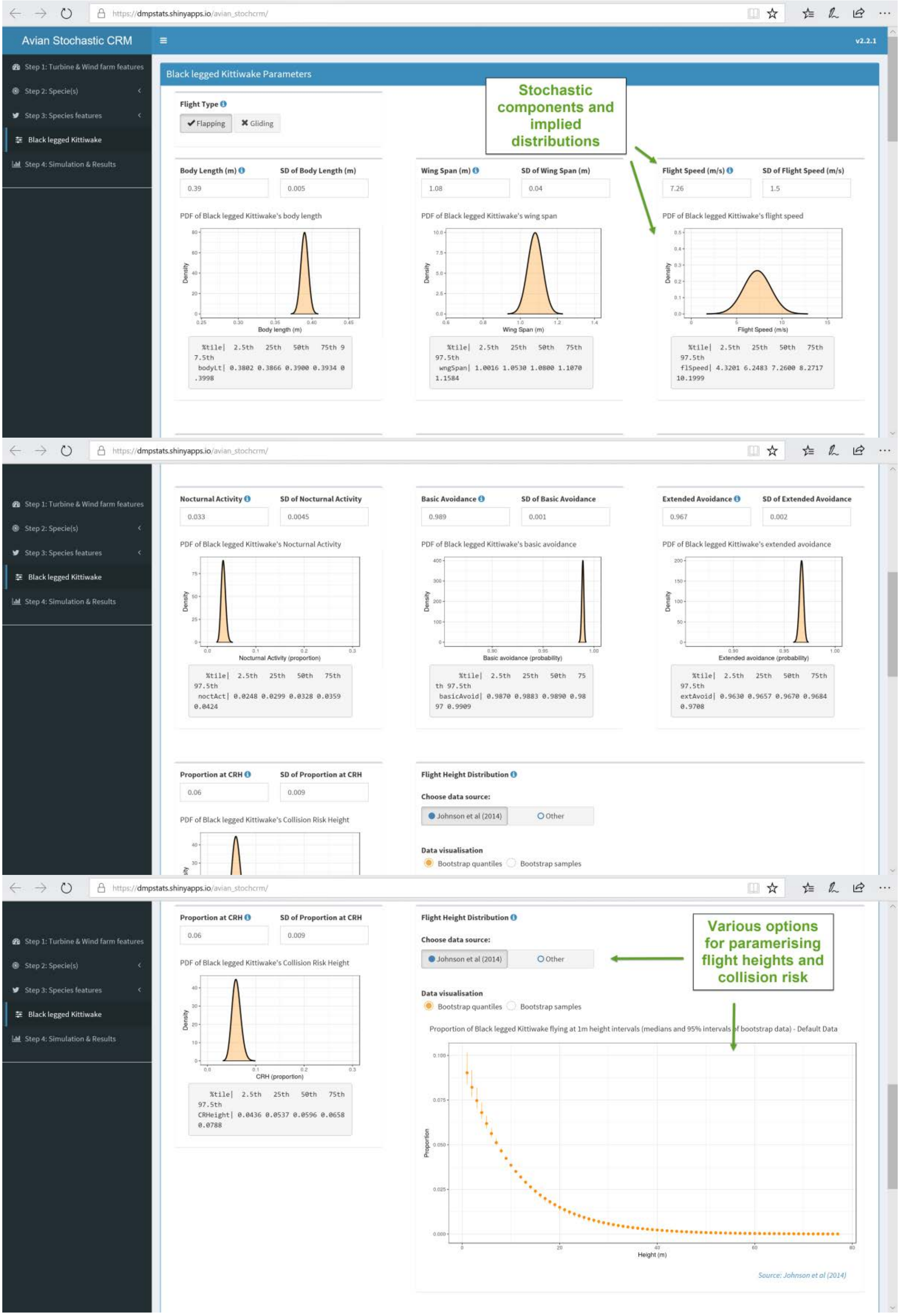
Step 2 of the workflow

Figure 22 There are four basic steps – defining turbine parameters, species to consider, species parameters, then the size of simulation, before results.

138 Each of the species have parameter sets that are defined (Figure 23). As before, parameters for the stochastic components are set and the implied distributions are plotted. Entries are constrained to avoid impossible values and offers warnings if entered values are outside expectations, as per the PSG opinions.

139 A number of modifications have been made with respect to bird densities and their stochastic treatment, in line with the findings of the review by Trinder (2017). The previous default treatment by truncated Normal is retained, but with the upper truncation value removed. Further, users may offer an estimate and confidence bounds or a general series of reference points for whatever distribution they think applies.

140 Bird flight height distributions similarly have a range of options: a single flight height distribution as previously held in the Masden code, or one of the user's choosing; alternatively, bootstrap flight height distributions as previously held in the Masden code, or a set of the user's choosing. Templates can be downloaded from the app to ensure conformity of input data when uploaded.



Black legged Kittiwake Parameters

Stochastic components and implied distributions

Flight Type
✔ Flapping ✖ Gliding

Body Length (m) 0.39
SD of Body Length (m) 0.005

PDF of Black legged Kittiwake's body length

```
  %tile|  2.5th   25th   50th   75th 9
7.5th
 bodyLt| 0.3802 0.3866 0.3900 0.3934 0
.3998
```

Wing Span (m) 1.08
SD of Wing Span (m) 0.04

PDF of Black legged Kittiwake's wing span

```
  %tile|  2.5th   25th   50th   75th
97.5th
 wngSpan| 1.0016 1.0530 1.0800 1.1070
1.1584
```

Flight Speed (m/s) 7.26
SD of Flight Speed (m/s) 1.5

PDF of Black legged Kittiwake's flight speed

```
  %tile|  2.5th   25th   50th   75th
 97.5th
 flSpeed| 4.3201 6.2483 7.2600 8.2717
10.1999
```

Nocturnal Activity 0.033
SD of Nocturnal Activity 0.0045

PDF of Black legged Kittiwake's Nocturnal Activity

```
  %tile|  2.5th   25th   50th   75th
97.5th
 noctAct| 0.0248 0.0299 0.0328 0.0359
0.0424
```

Basic Avoidance 0.989
SD of Basic Avoidance 0.001

PDF of Black legged Kittiwake's basic avoidance

```
     %tile|  2.5th   25th   50th   75
th 97.5th
 basicAvoid| 0.9870 0.9883 0.9890 0.98
97 0.9909
```

Extended Avoidance 0.967
SD of Extended Avoidance 0.002

PDF of Black legged Kittiwake's extended avoidance

```
  %tile|  2.5th   25th   50th   75th
97.5th
extAvoid| 0.9630 0.9657 0.9670 0.9684
0.9708
```

Proportion at CRH 0.06
SD of Proportion at CRH 0.009

PDF of Black legged Kittiwake's Collision Risk Height

```
  %tile|  2.5th   25th   50th   75th
97.5th
CRHeight| 0.0436 0.0537 0.0596 0.0658
0.0788
```

Flight Height Distribution

Choose data source:
● Johnson et al (2014) ○ Other

Data visualisation
● Bootstrap quantiles ○ Bootstrap samples

Various options for paramerising flight heights and collision risk

Proportion of Black legged Kittiwake flying at 1m height intervals (medians and 95% intervals of bootstrap data) - Default Data

Source: Johnson et al (2014)

Figure 23 The interface is similar throughout – interactive parameter setting then a graphic showing what is implied.

141 The simulation is set in motion – the amount of time required being proportional to the number of turbines, species and simulation iterations (Figure 24).

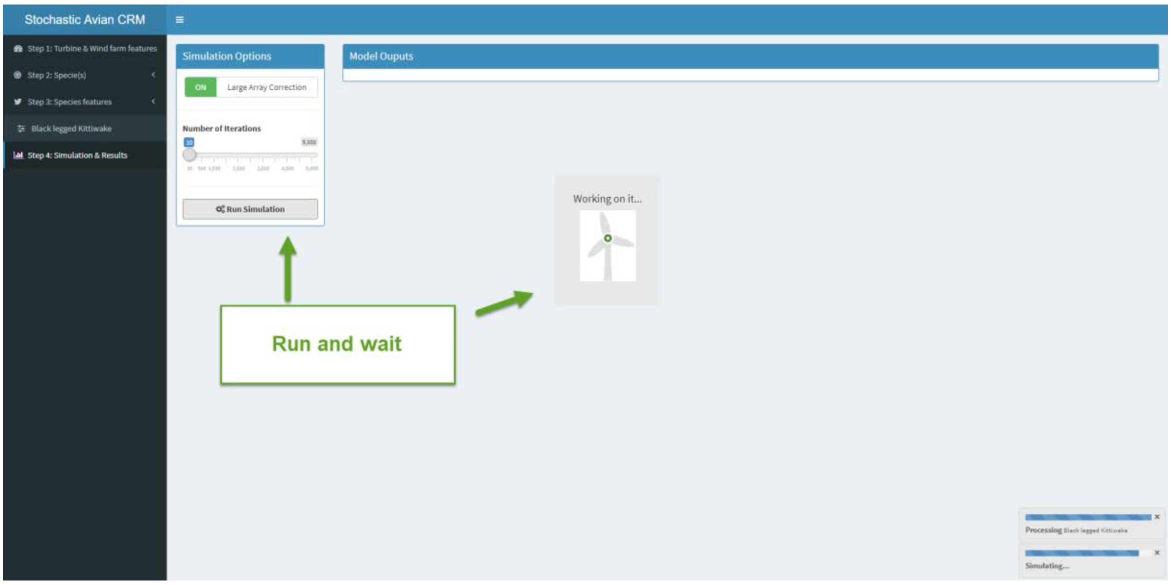
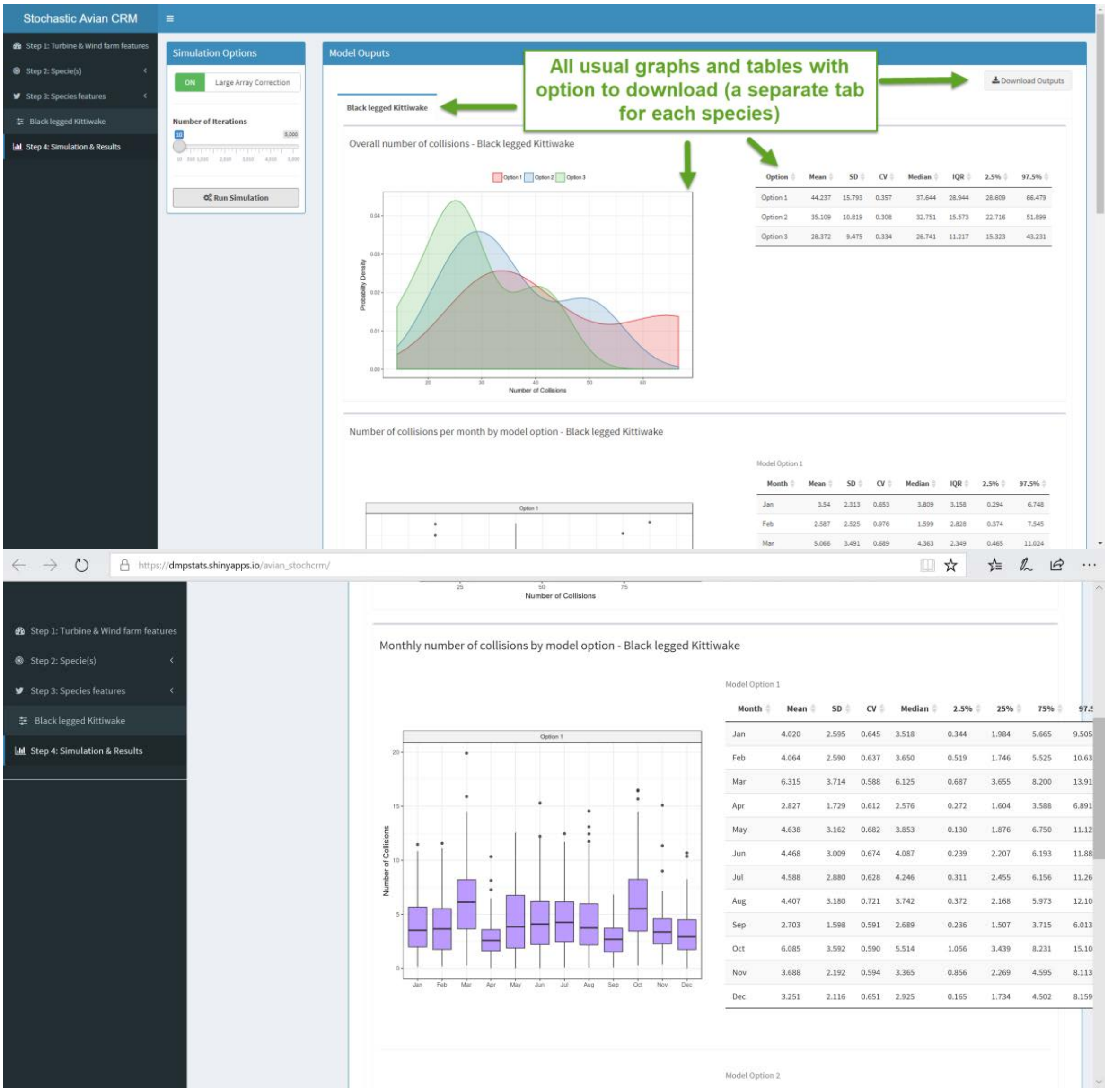


Figure 24 The final step is setting the number of iterations and large-scale corrections.

142 Outputs are extensions of those of Masden, albeit rendered in HTML and available as downloads (Figure 25).



All usual graphs and tables with option to download (a separate tab for each species)

Overall number of collisions - Black legged Kittiwake

Option	Mean	SD	CV	Median	IQR	2.5%	97.5%
Option 1	44.237	15.793	0.357	37.644	28.944	28.609	66.479
Option 2	35.109	10.819	0.308	32.751	15.573	22.716	51.899
Option 3	28.372	9.475	0.334	26.741	11.217	15.323	43.231

Number of collisions per month by model option - Black legged Kittiwake

Model Option 1

Month	Mean	SD	CV	Median	IQR	2.5%	97.5%
Jan	3.54	2.313	0.653	3.809	3.158	0.294	6.748
Feb	2.587	2.525	0.976	1.599	2.828	0.374	7.545
Mar	5.066	3.491	0.689	4.363	2.349	0.465	11.024

Monthly number of collisions by model option - Black legged Kittiwake

Model Option 1

Month	Mean	SD	CV	Median	2.5%	25%	75%	97.
Jan	4.020	2.595	0.645	3.518	0.344	1.984	5.665	9.505
Feb	4.064	2.590	0.637	3.650	0.519	1.746	5.525	10.63
Mar	6.315	3.714	0.588	6.125	0.687	3.655	8.200	13.91
Apr	2.827	1.729	0.612	2.576	0.272	1.604	3.588	6.891
May	4.638	3.162	0.682	3.853	0.130	1.876	6.750	11.12
Jun	4.468	3.009	0.674	4.087	0.239	2.207	6.193	11.88
Jul	4.588	2.880	0.628	4.246	0.311	2.455	6.156	11.26
Aug	4.407	3.180	0.721	3.742	0.372	2.168	5.973	12.10
Sep	2.703	1.598	0.591	2.689	0.236	1.507	3.715	6.013
Oct	6.085	3.592	0.590	5.514	1.056	3.439	8.231	15.10
Nov	3.688	2.192	0.594	3.365	0.856	2.269	4.595	8.113
Dec	3.251	2.116	0.651	2.925	0.165	1.734	4.502	8.159

Model Option 2

Figure 25 The results are tables and plots similar to those in Masden, rendered in the GUI. There are download options.

6 Testing of new stochastic CRM code

143 The new code was tested by its conformity with Masden 2015 outputs and the point estimates of Band 2012. Where disagreement was found between Masden and Band, the Band results were assumed correct and the new CRM code conforms to this.

144 The GUI was further tested by the presentation of extreme and corrupt inputs (including data-files) to ensure sensible behaviour.

7 Conclusions

146 To address the identified need for improved modelling of stochastic variation in collision risk modelling of seabirds for offshore wind farm development applications a stakeholder survey was used to inform the changes needed to create a new stochastic CRM.

147 The stakeholder survey identified seven key changes needed to the currently available CRMs. These included a user-friendly interface, full data outputs, seasonal inputs and assessments, error checking and flexibility for users to change default values.

148 These changes were implemented by experienced R-code developers through the updating and streamlining of the existing Masden (2015) code. The key changes requested by stakeholders were implemented, along with the recommendations of Trinder (2017).

149 A user-friendly interface was developed by coding these models into a Shiny app in R (app version 2.2.1 at time of reporting found at https://dmpstats.shinyapps.io/avian_stochcrm/) that allowed users to easily input values for turbines and birds and incorporated default values and guidance to reduce human error. Flexibility was maintained by allowing users to use non-default values.

150 There are two variants of the revised stochastic CRM, both coded in R. Both provide the full GUI interface via shiny as outlined. The online version runs on the Shiny server, while a downloadable version will run locally on the computer it is installed on, using the internet browser on that computer. It can be downloaded from https://github.com/dmpstats/stochCRM.

151 Data outputs from the Shiny are provided both graphically and as a data download. This provides end users with all the information needed to interpret the collision risk values, and their uncertainty.

152 Both the R-code variants of the sCRM are a highly flexible, stochastic model that provides a prediction of seabird collisions with a correctly calculated error estimate for use in Environmental Impact Assessments.

8 Contributions and Acknowledgements

The project was managed by Dr Ross McGregor (HiDef Aerial Surveying), who also produced and analysed the questionnaire with Sue King (Sue King Consulting). The CRM shiny app and R code were produced by Dr Carl Donovan (DMP Statistical Solutions) and Dr Bruno Caneco (DMP Statistical Solutions). The project was overseen by Andy Webb (HiDef Aerial Surveying).

The authors would like to thank all of those stakeholders who provided a response to the questionnaire, and to those who also agreed to follow up telephone interview. The high response rate to the requests for feedback was greatly appreciated.

The invaluable input to the entire project process from the Project Steering Group greatly aided in the success of this project. The Project Steering Group comprised: Jared Wilson (Marine Scotland Science), Helen Wade (SNH), Julie Black (JNCC), Aly McCluskie (RSPB) and Mel Kershaw (Natural England).

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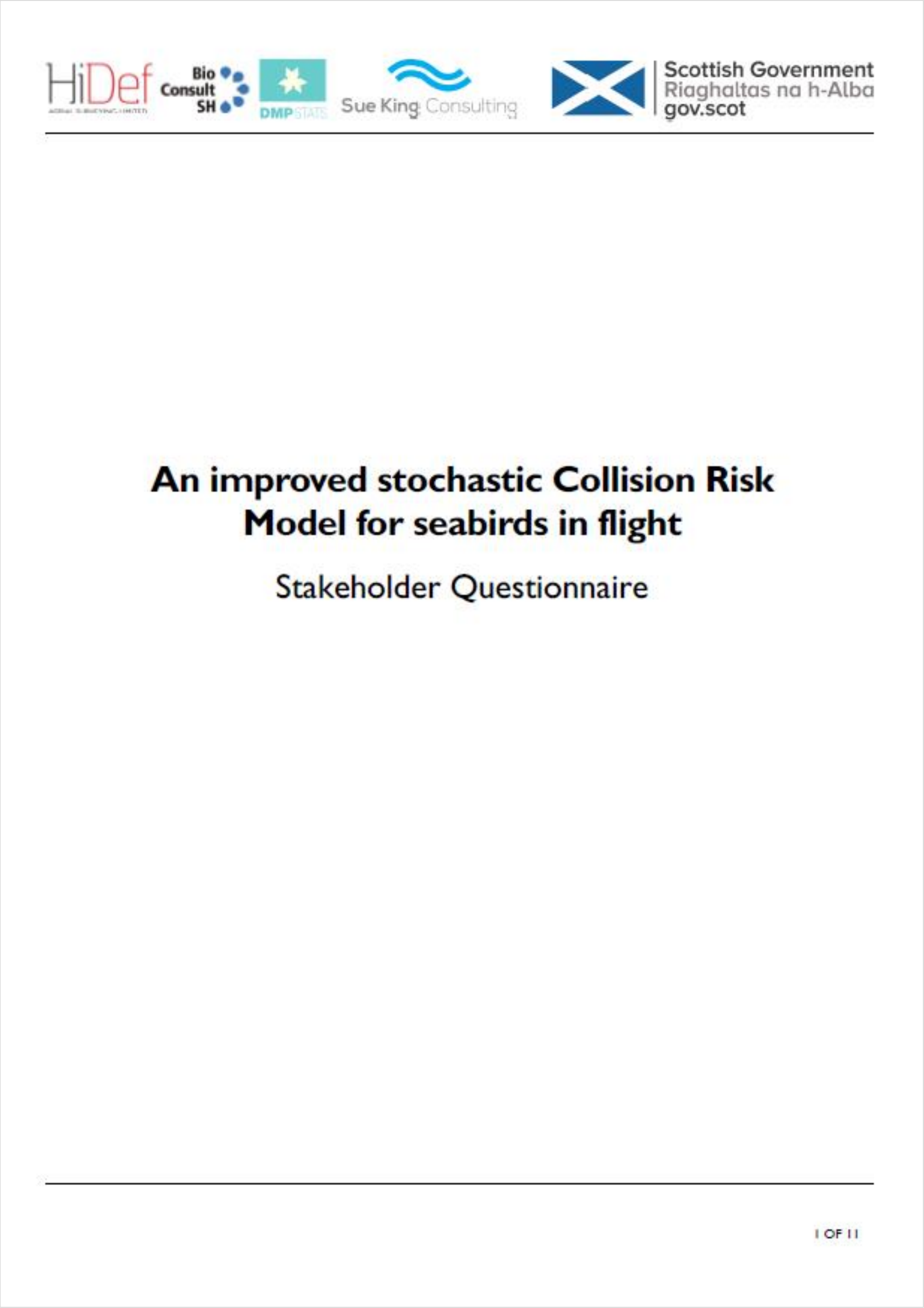
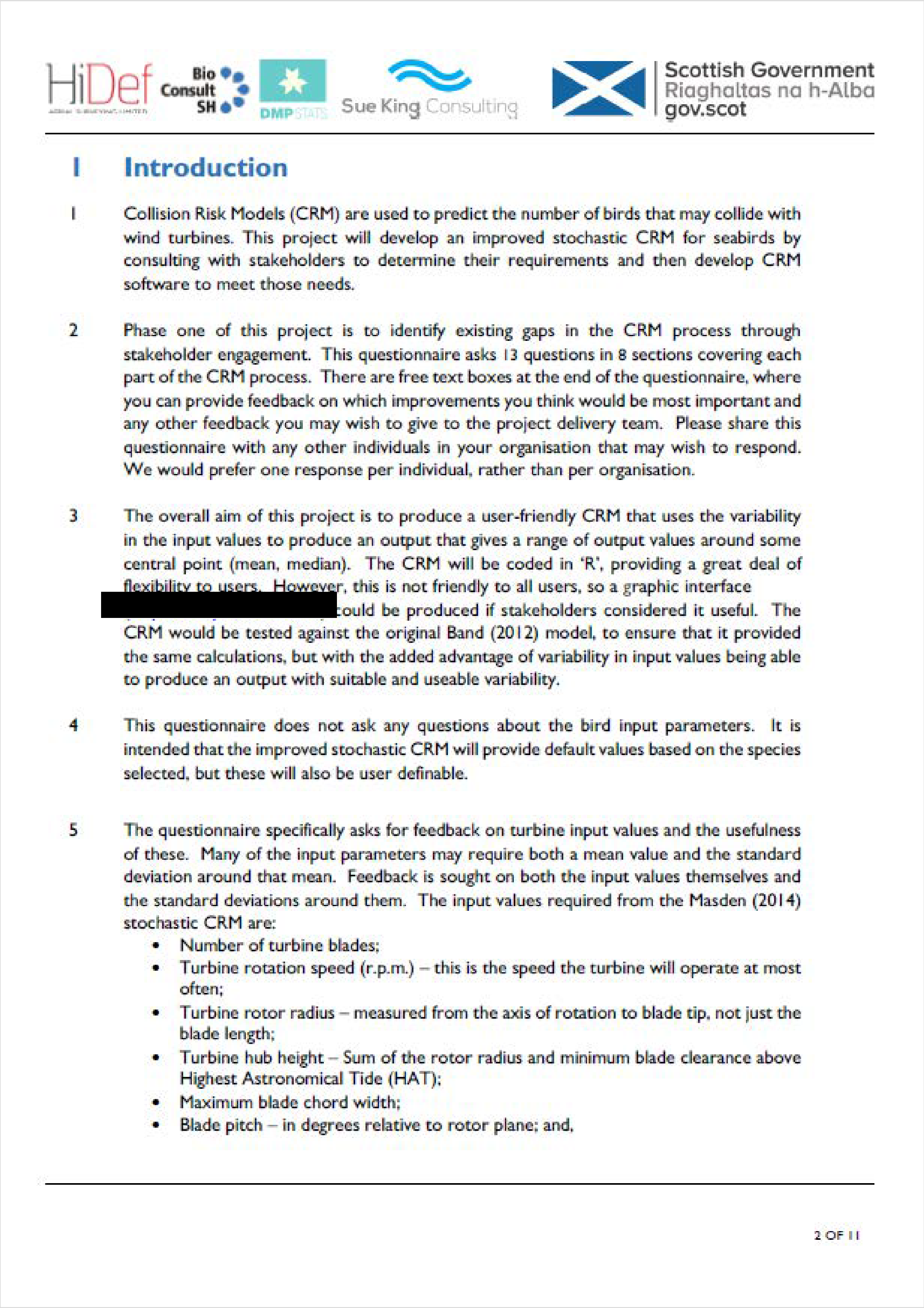
Appendix I Questionnaire *Pro Forma*



An improved stochastic Collision Risk Model for seabirds in flight

Stakeholder Questionnaire

1 OF 11



1 Introduction

1 Collision Risk Models (CRM) are used to predict the number of birds that may collide with wind turbines. This project will develop an improved stochastic CRM for seabirds by consulting with stakeholders to determine their requirements and then develop CRM software to meet those needs.

2 Phase one of this project is to identify existing gaps in the CRM process through stakeholder engagement. This questionnaire asks 13 questions in 8 sections covering each part of the CRM process. There are free text boxes at the end of the questionnaire, where you can provide feedback on which improvements you think would be most important and any other feedback you may wish to give to the project delivery team. Please share this questionnaire with any other individuals in your organisation that may wish to respond. We would prefer one response per individual, rather than per organisation.

3 The overall aim of this project is to produce a user-friendly CRM that uses the variability in the input values to produce an output that gives a range of output values around some central point (mean, median). The CRM will be coded in 'R', providing a great deal of flexibility to users. However, this is not friendly to all users, so a graphic interface [redacted] could be produced if stakeholders considered it useful. The CRM would be tested against the original Band (2012) model, to ensure that it provided the same calculations, but with the added advantage of variability in input values being able to produce an output with suitable and useable variability.

4 This questionnaire does not ask any questions about the bird input parameters. It is intended that the improved stochastic CRM will provide default values based on the species selected, but these will also be user definable.

5 The questionnaire specifically asks for feedback on turbine input values and the usefulness of these. Many of the input parameters may require both a mean value and the standard deviation around that mean. Feedback is sought on both the input values themselves and the standard deviations around them. The input values required from the Masden (2014) stochastic CRM are:

- Number of turbine blades;
- Turbine rotation speed (r.p.m.) – this is the speed the turbine will operate at most often;
- Turbine rotor radius – measured from the axis of rotation to blade tip, not just the blade length;
- Turbine hub height – Sum of the rotor radius and minimum blade clearance above Highest Astronomical Tide (HAT);
- Maximum blade chord width;
- Blade pitch – in degrees relative to rotor plane; and,

- Turbine operation time – this needs to be provided by month, and is the combination of predicted time spent operation from the predicted wind resource, and the planned and emergency maintenance down time.

In addition, the Masden (2014) stochastic CRM requires inputs on the relationship between wind speed (ms^{-1}), rotor speed (rpm) and blade pitch (degrees).

6 The Masden (2014) CRM also provides tabular and figure outputs. These are:

TABLES

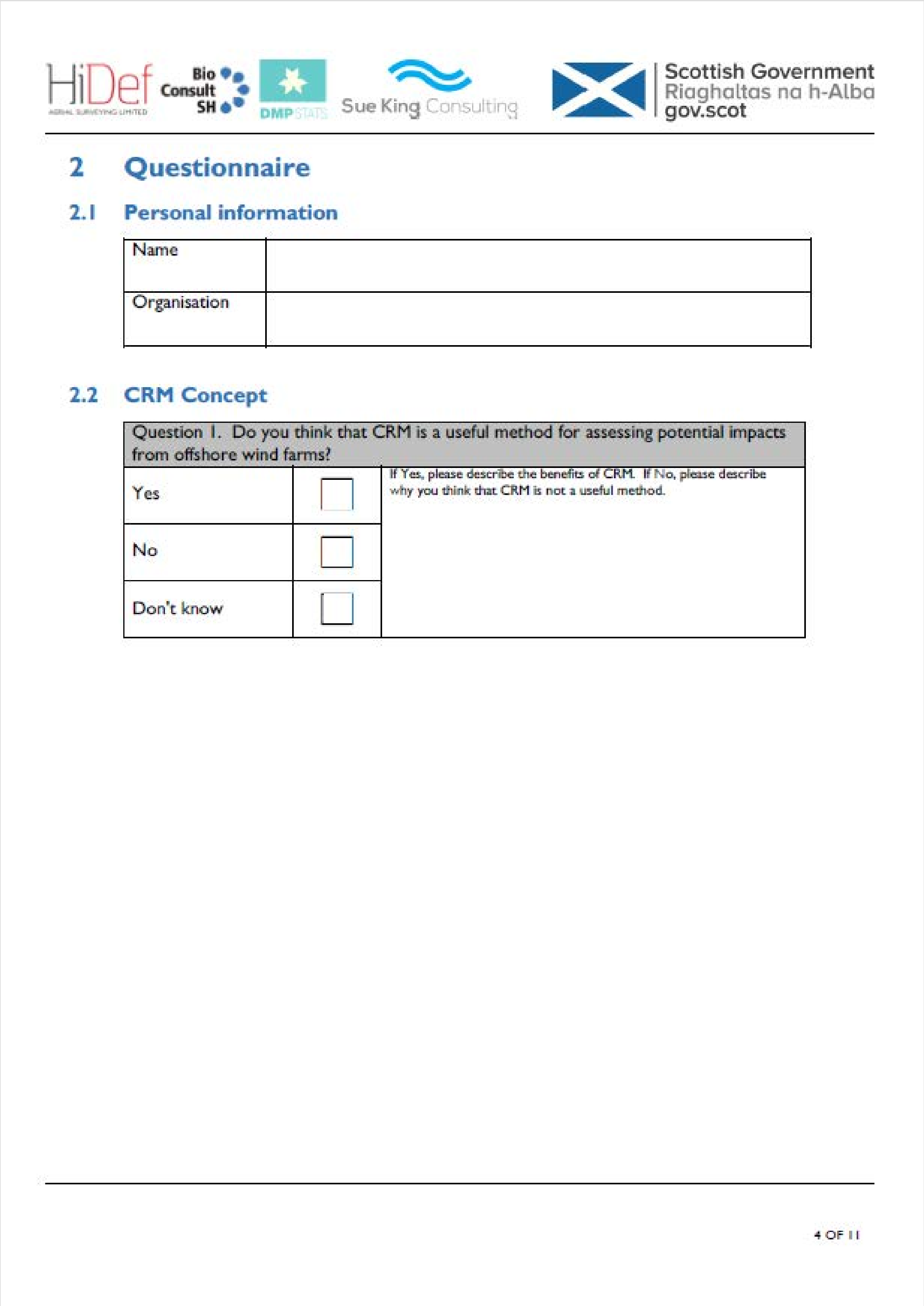
1. Overall summary table of collisions by species, turbine and model option. Results are presented as monthly mean, standard deviation (SD) and coefficient of variation (CV), and median and inter quartile range (IQR).
2. Monthly summaries of collisions. Separate tables are produced according to species, turbine and model option for example 6_Black_legged_Kittiwake_monthlySummaryOpt3.csv. Results are presented as mean, standard deviation (SD) and coefficient of variation (CV), and median and inter quartile range (IQR).
3. Summary of sampled bird parameters by species, turbine and model option presented as mean and standard deviation (SD), and median and inter quartile range (IQR).
4. Summary of sampled turbine parameters by species, turbine and model option presented as mean and standard deviation (SD), and median and inter quartile range (IQR).

FIGURES

1. 3-panel boxplots of monthly collisions for model options 1, 2 and 3 by species, and turbine type.
2. Density plots of numbers of collisions by species, and turbine type. A density curve is plotted for each of the 3 model options.
3. If 2 or more turbine models are included, then a 3-panel figure will be produced for each species, with the panels representing model options 1, 2 and 3 and each panel containing density plots for the different turbines included.

7 To ensure that we fully capture the existing issues stakeholders have with the existing CRMs (i.e. Band 2012 and Masden 2014) a selection of stakeholders will be invited to participate in a short telephone interview.

8 Once completed the survey should be returned to [redacted]



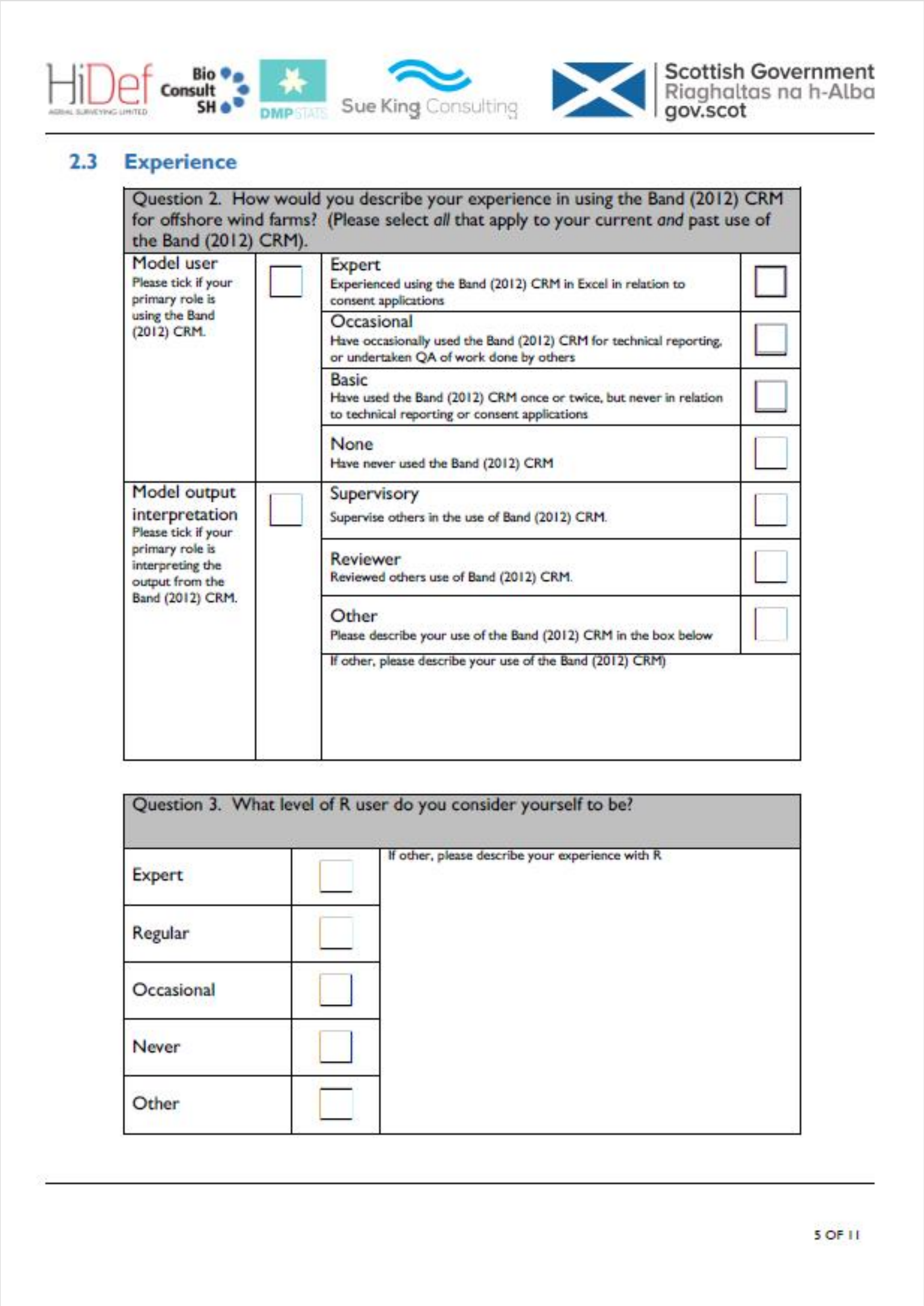
2 Questionnaire

2.1 Personal information

Name	
Organisation	

2.2 CRM Concept

Question 1. Do you think that CRM is a useful method for assessing potential impacts from offshore wind farms?		
Yes	☐	If Yes, please describe the benefits of CRM. If No, please describe why you think that CRM is not a useful method.
No	☐	
Don't know	☐	



2.3 Experience

Question 2. How would you describe your experience in using the Band (2012) CRM for offshore wind farms? (Please select *all* that apply to your current *and* past use of the Band (2012) CRM).			
Model user Please tick if your primary role is using the Band (2012) CRM.	☐	**Expert** Experienced using the Band (2012) CRM in Excel in relation to consent applications	☐
		Occasional Have occasionally used the Band (2012) CRM for technical reporting, or undertaken QA of work done by others	☐
		Basic Have used the Band (2012) CRM once or twice, but never in relation to technical reporting or consent applications	☐
		None Have never used the Band (2012) CRM	☐
Model output interpretation Please tick if your primary role is interpreting the output from the Band (2012) CRM.	☐	**Supervisory** Supervise others in the use of Band (2012) CRM.	☐
		Reviewer Reviewed others use of Band (2012) CRM.	☐
		Other Please describe your use of the Band (2012) CRM in the box below	☐
		If other, please describe your use of the Band (2012) CRM)	

Question 3. What level of R user do you consider yourself to be?		
Expert	☐	If other, please describe your experience with R
Regular	☐	
Occasional	☐	
Never	☐	
Other	☐	

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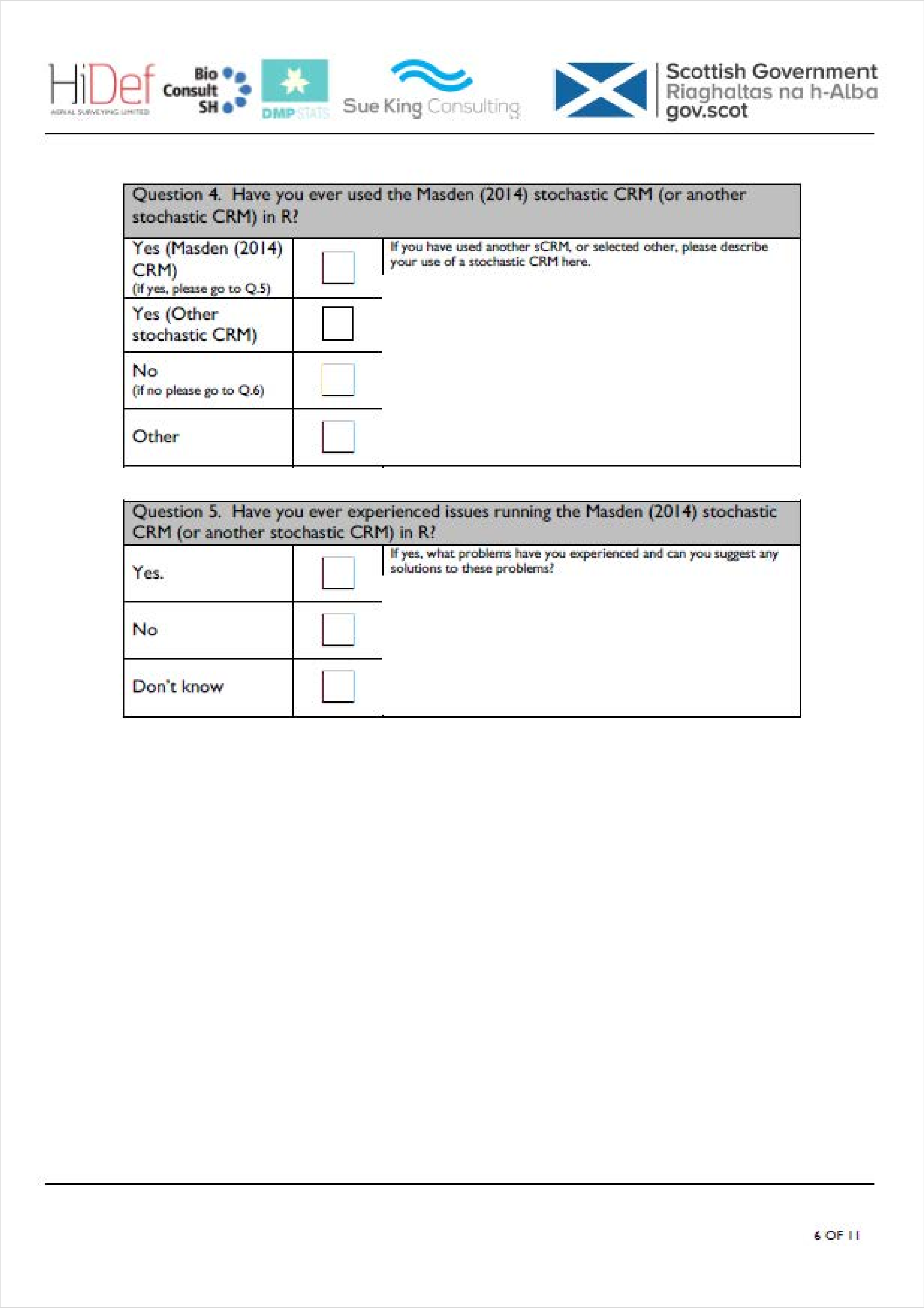
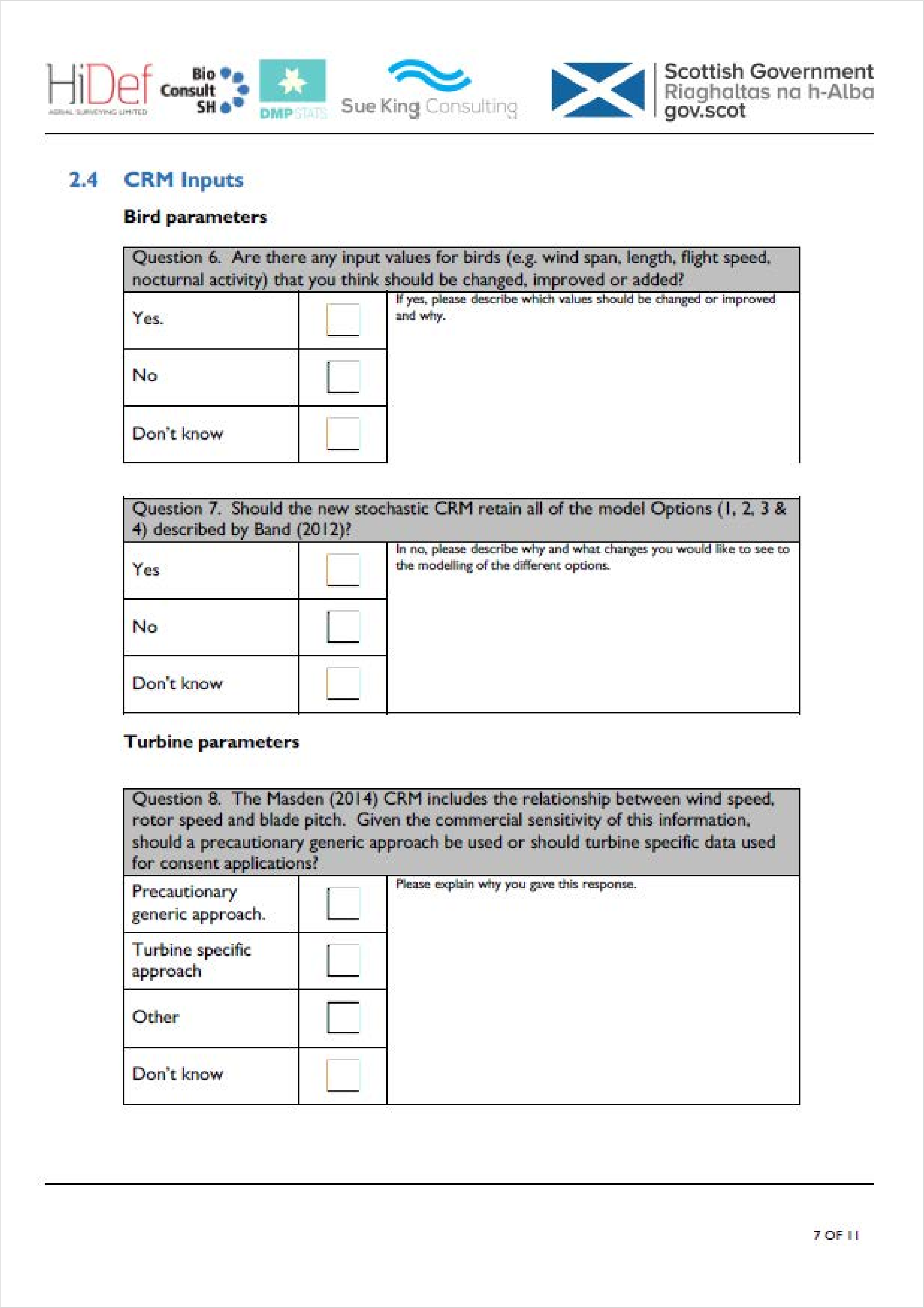


Question 4. Have you ever used the Masden (2014) stochastic CRM (or another stochastic CRM) in R?		
Yes (Masden (2014) CRM) (if yes, please go to Q.5)	☐	If you have used another sCRM, or selected other, please describe your use of a stochastic CRM here.
Yes (Other stochastic CRM)	☐	
No (if no please go to Q.6)	☐	
Other	☐	

Question 5. Have you ever experienced issues running the Masden (2014) stochastic CRM (or another stochastic CRM) in R?		
Yes.	☐	If yes, what problems have you experienced and can you suggest any solutions to these problems?
No	☐	
Don't know	☐	



2.4 CRM Inputs

Bird parameters

Question 6. Are there any input values for birds (e.g. wind span, length, flight speed, nocturnal activity) that you think should be changed, improved or added?		
Yes.	☐	If yes, please describe which values should be changed or improved and why.
No	☐	
Don't know	☐	

Question 7. Should the new stochastic CRM retain all of the model Options (1, 2, 3 & 4) described by Band (2012)?		
Yes	☐	In no, please describe why and what changes you would like to see to the modelling of the different options.
No	☐	
Don't know	☐	

Turbine parameters

Question 8. The Masden (2014) CRM includes the relationship between wind speed, rotor speed and blade pitch. Given the commercial sensitivity of this information, should a precautionary generic approach be used or should turbine specific data used for consent applications?		
Precautionary generic approach.	☐	Please explain why you gave this response.
Turbine specific approach	☐	
Other	☐	
Don't know	☐	

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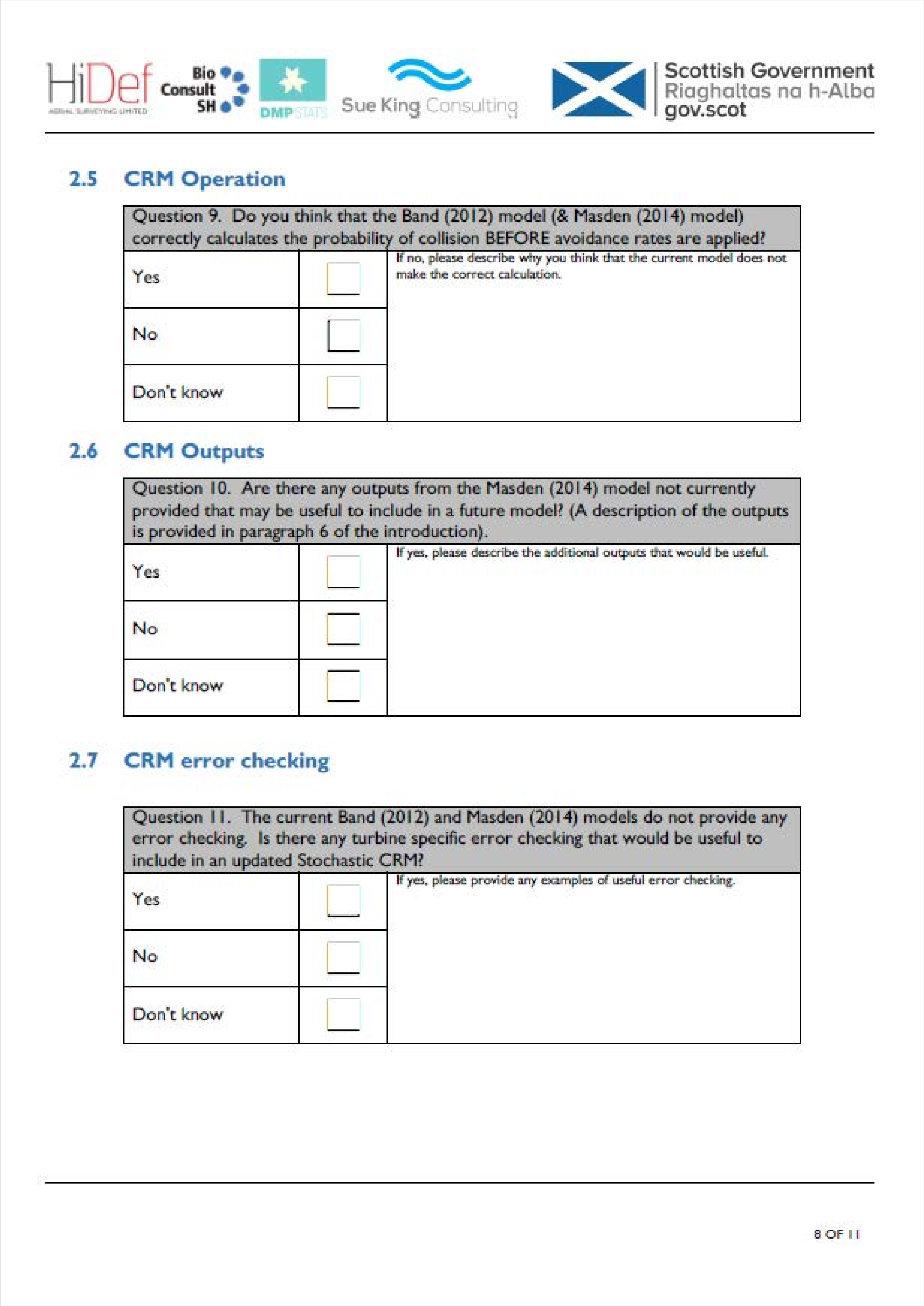

2.5 CRM Operation

Question 9. Do you think that the Band (2012) model (& Masden (2014) model) correctly calculates the probability of collision BEFORE avoidance rates are applied?		
Yes	☐	If no, please describe why you think that the current model does not make the correct calculation.
No	☐	
Don't know	☐	

2.6 CRM Outputs

Question 10. Are there any outputs from the Masden (2014) model not currently provided that may be useful to include in a future model? (A description of the outputs is provided in paragraph 6 of the introduction).		
Yes	☐	If yes, please describe the additional outputs that would be useful.
No	☐	
Don't know	☐	

2.7 CRM error checking

Question 11. The current Band (2012) and Masden (2014) models do not provide any error checking. Is there any turbine specific error checking that would be useful to include in an updated Stochastic CRM?		
Yes	☐	If yes, please provide any examples of useful error checking.
No	☐	
Don't know	☐	

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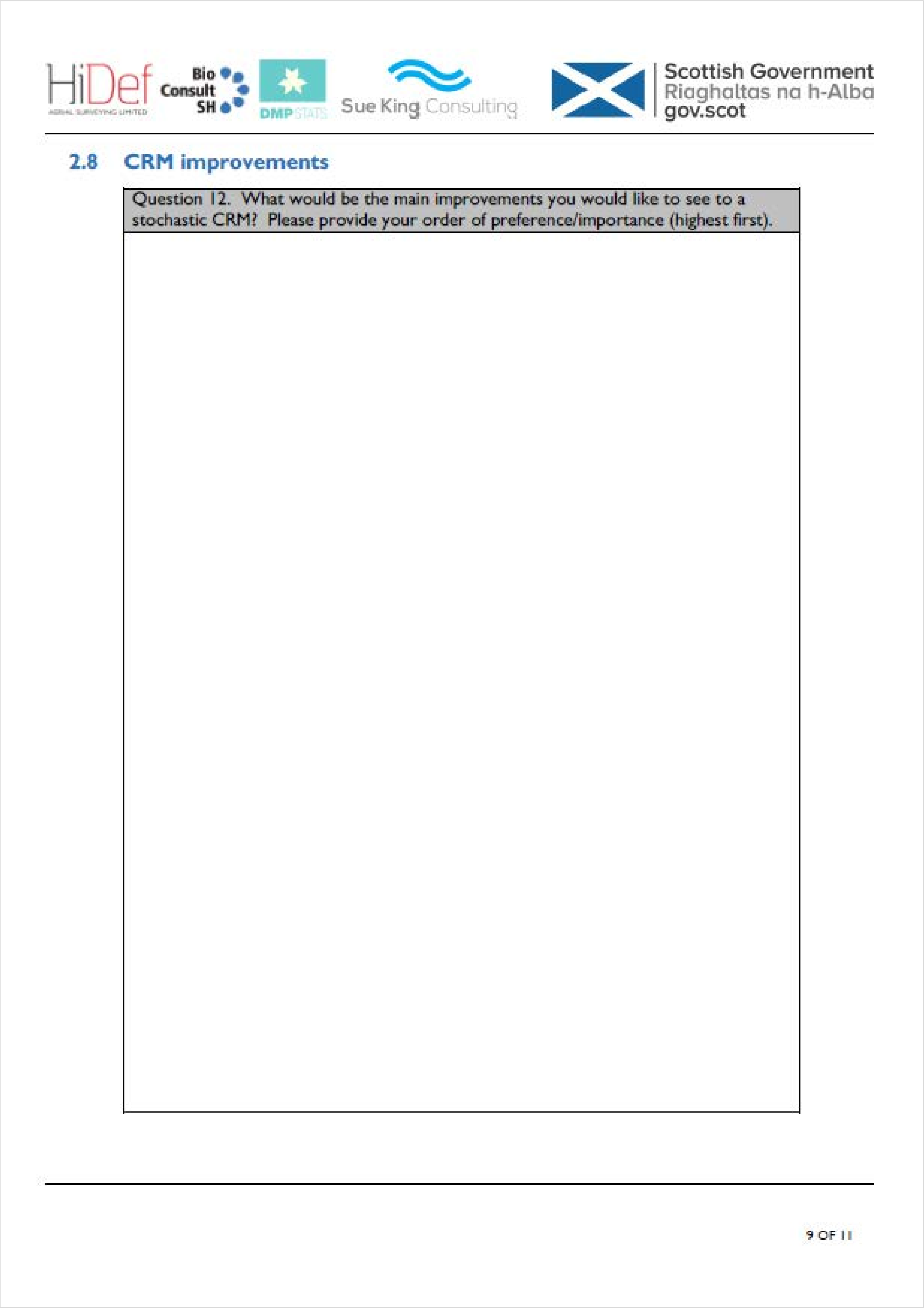
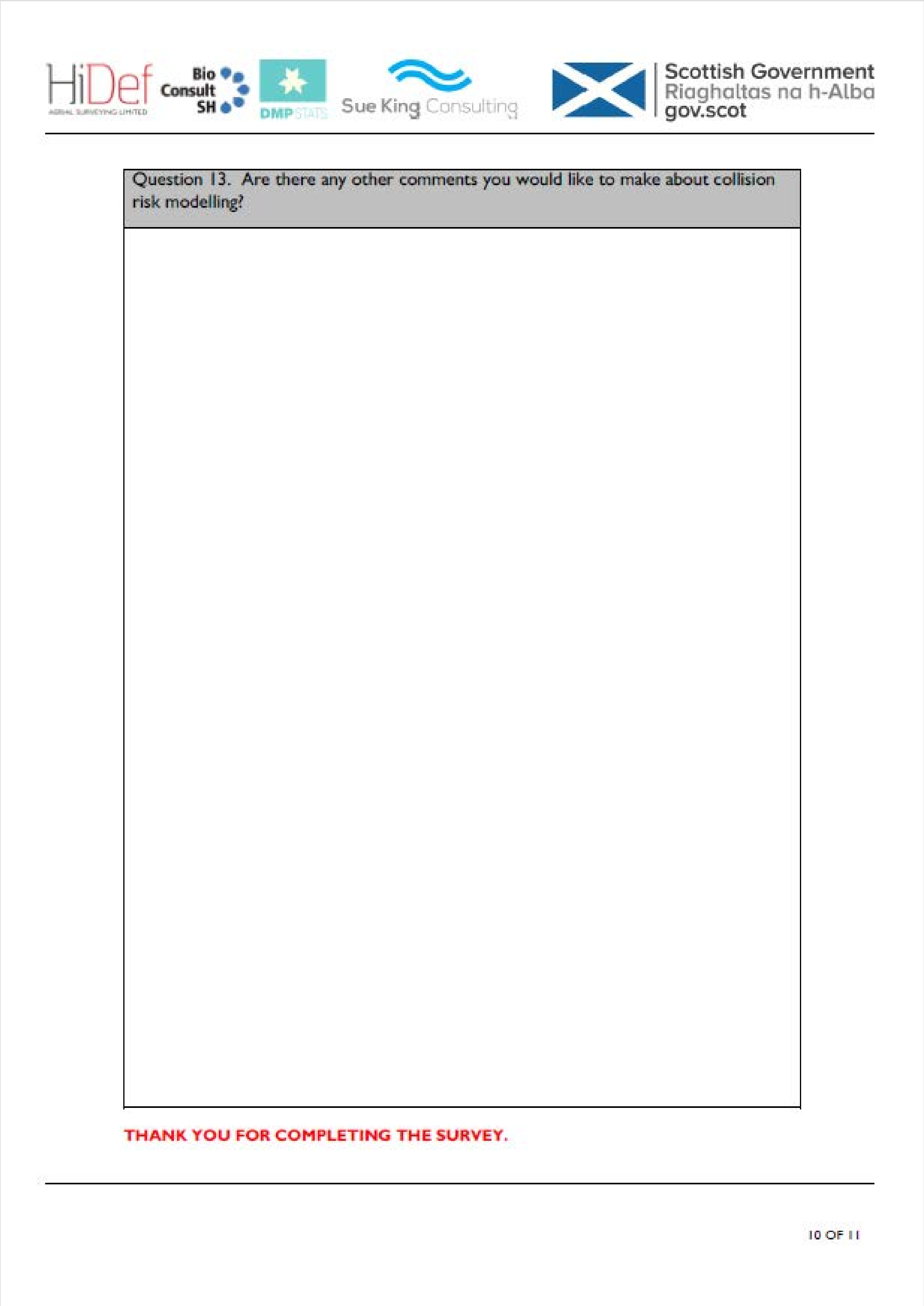


2.8 CRM improvements

Question 12. What would be the main improvements you would like to see to a stochastic CRM? Please provide your order of preference/importance (highest first).



Question 13. Are there any other comments you would like to make about collision risk modelling?

THANK YOU FOR COMPLETING THE SURVEY.

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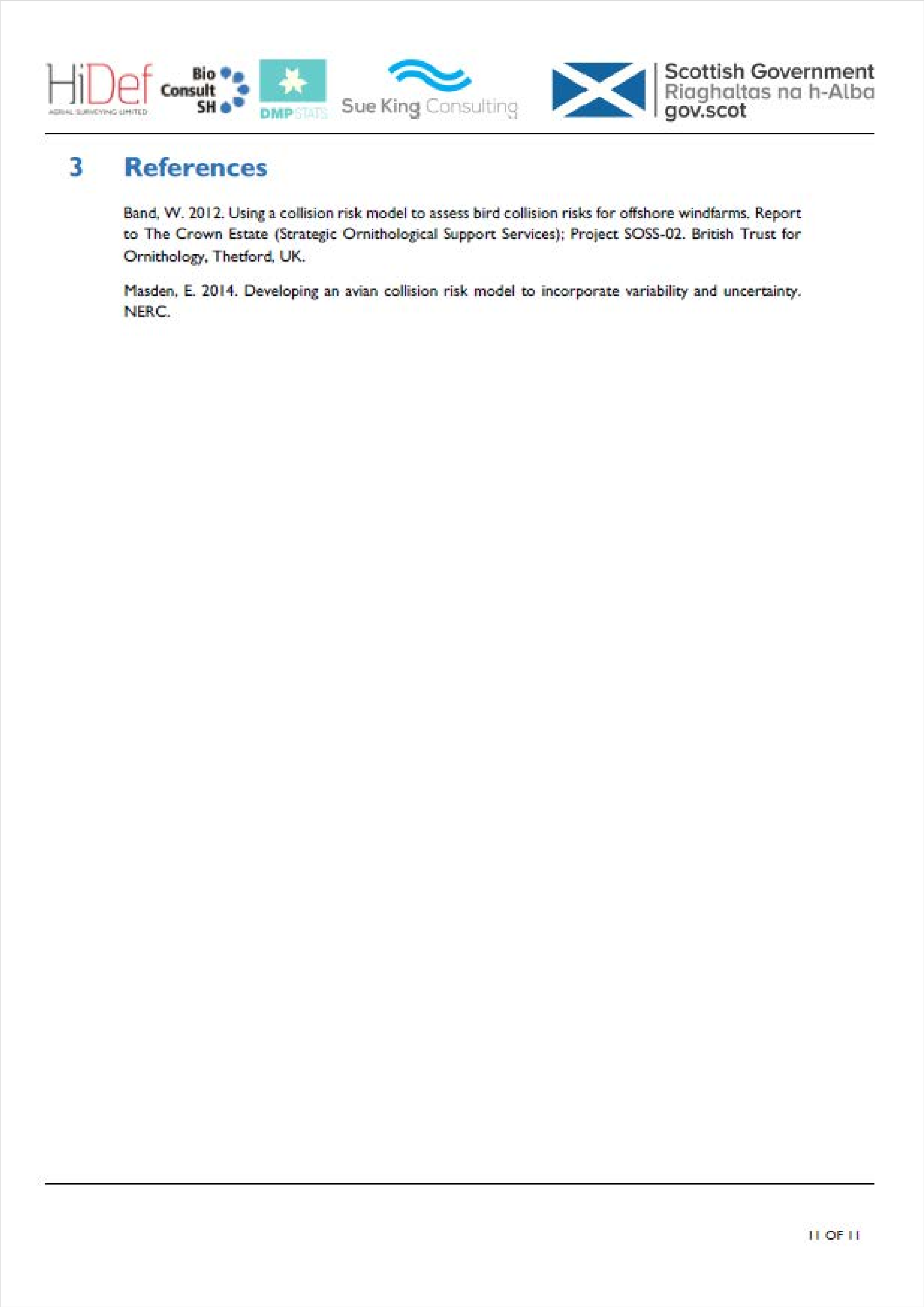

3 References

Band, W. 2012. Using a collision risk model to assess bird collision risks for offshore windfarms. Report to The Crown Estate (Strategic Ornithological Support Services); Project SOSS-02. British Trust for Ornithology, Thetford, UK.

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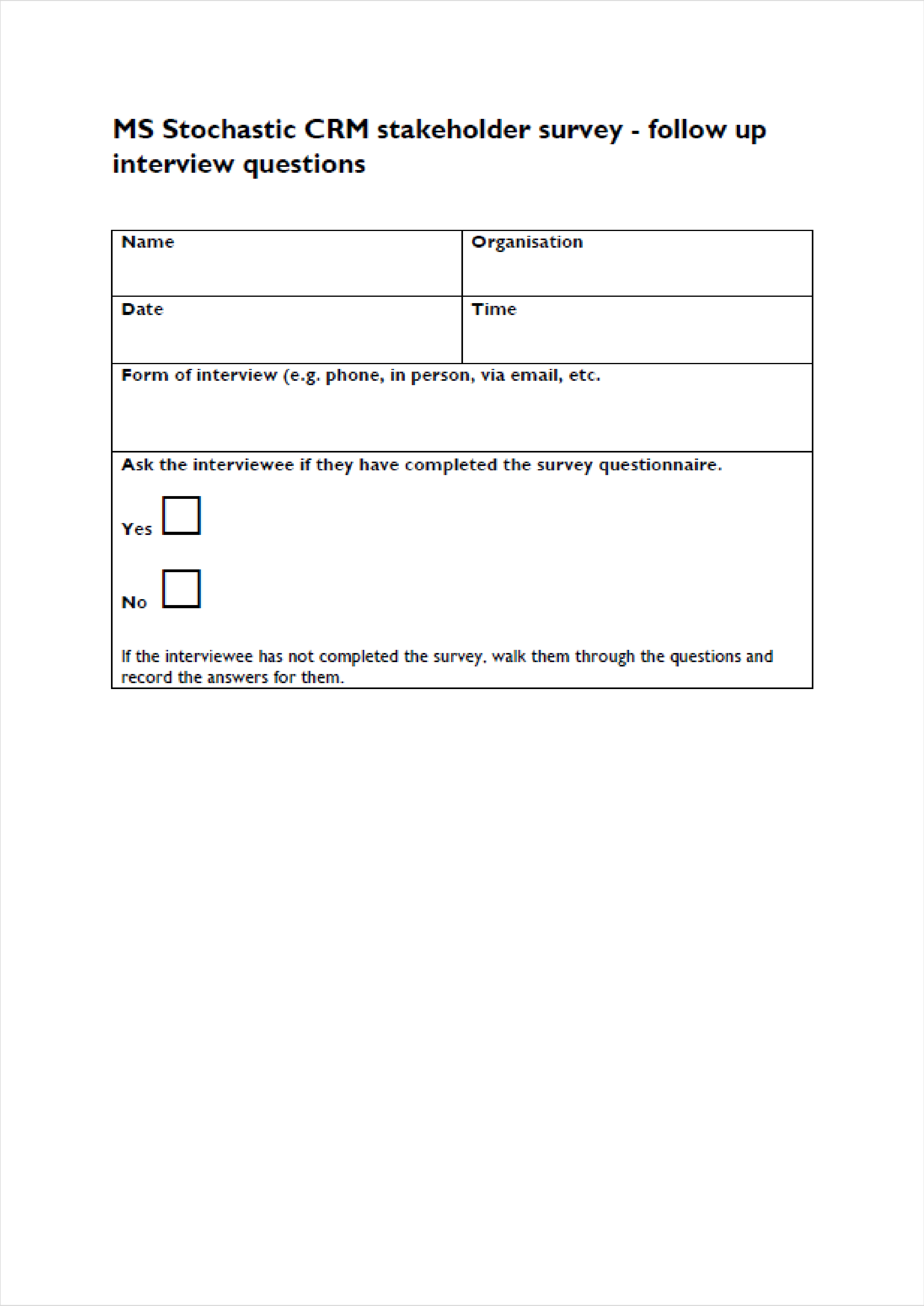
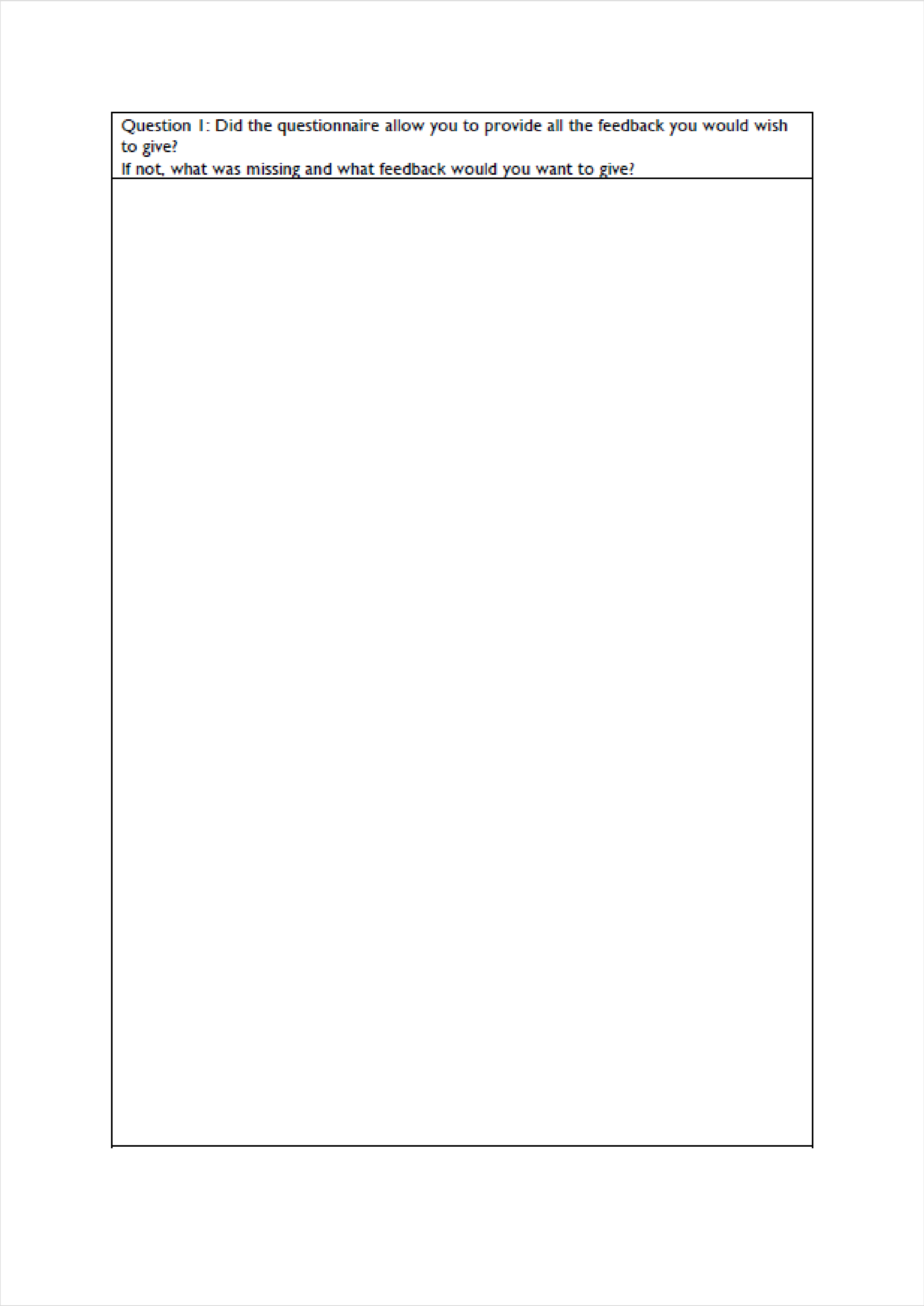
Appendix II Telephone survey *Pro Forma*

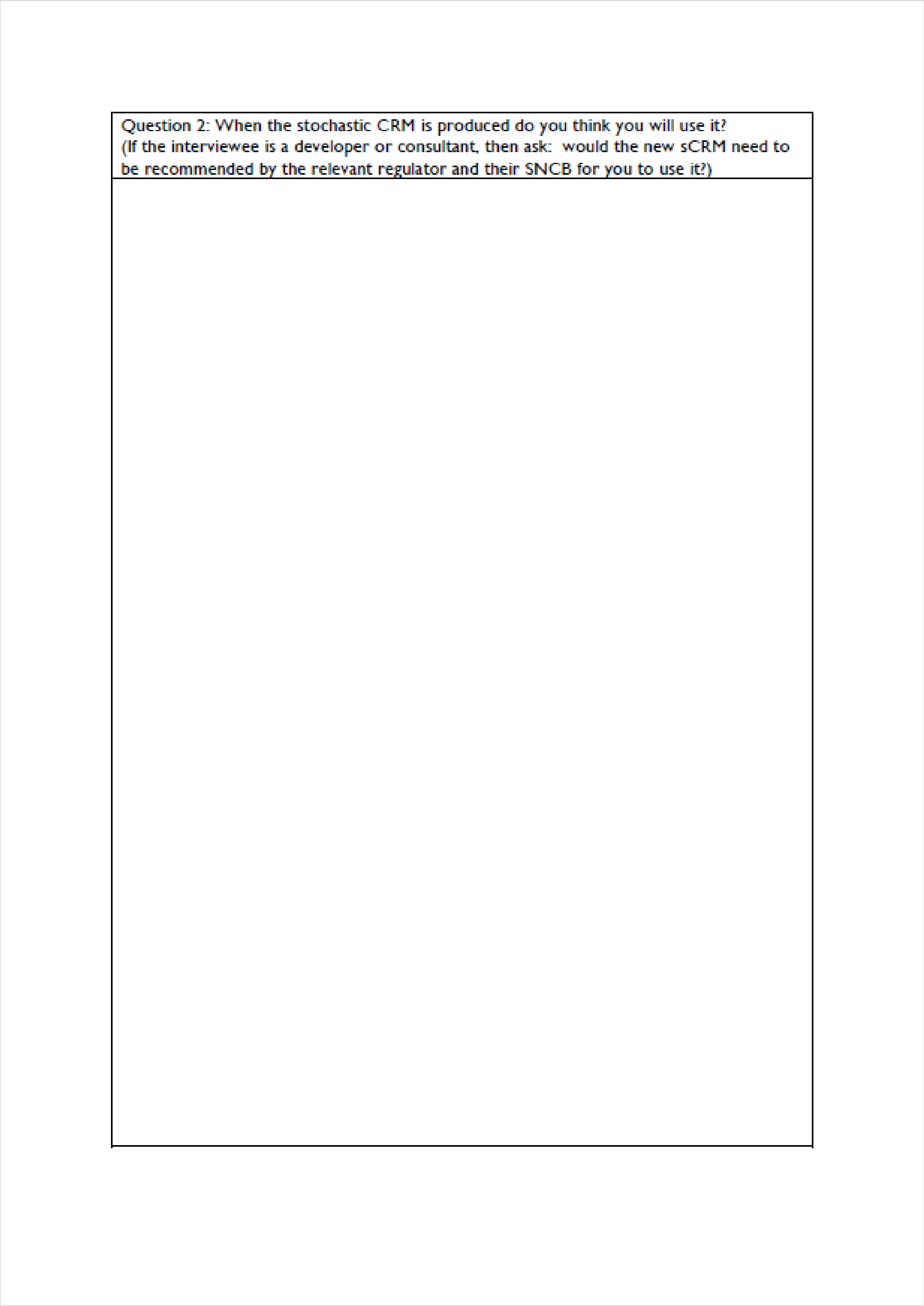


MS Stochastic CRM stakeholder survey - follow up interview questions

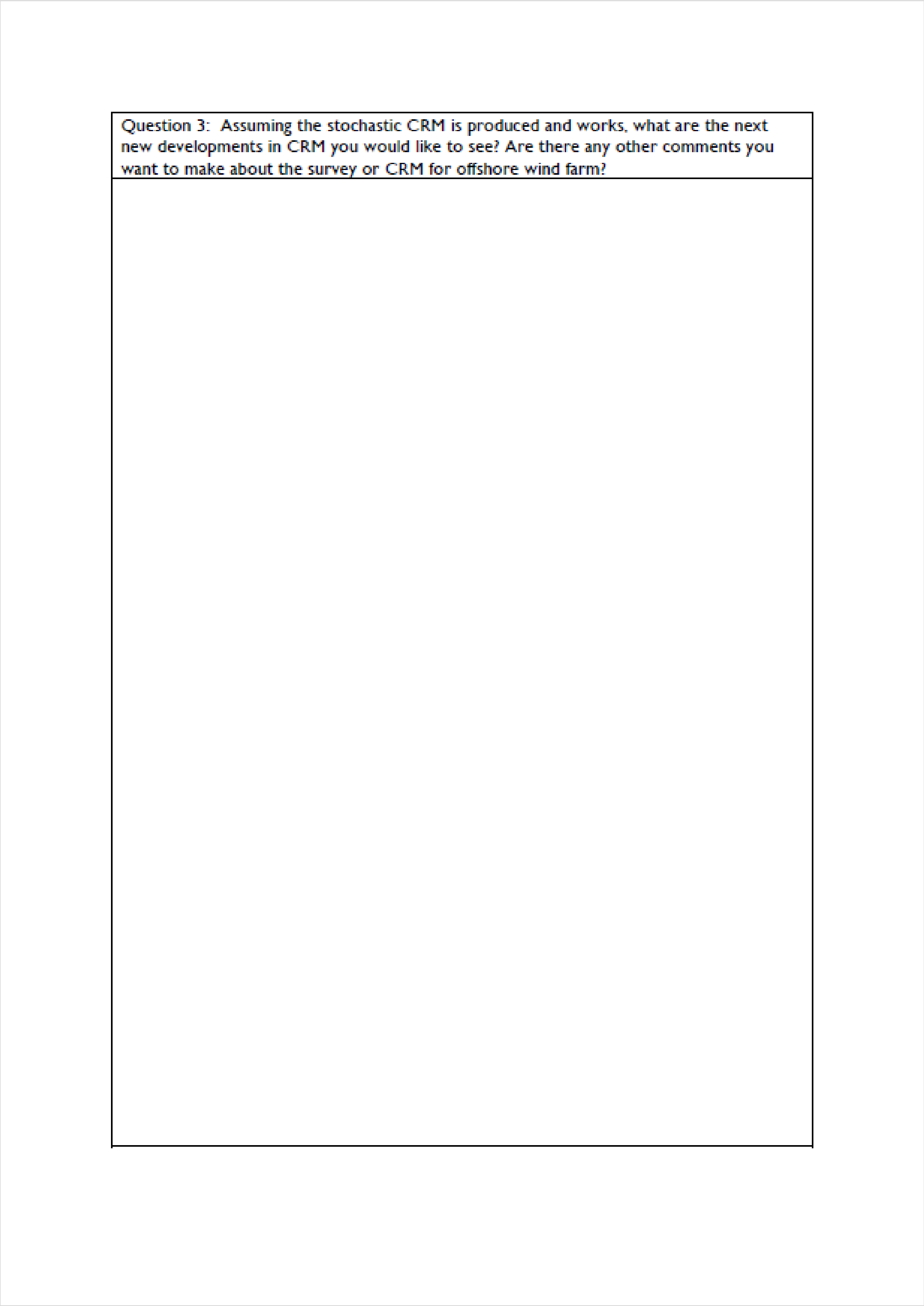
Name	**Organisation**
Date	**Time**
Form of interview (e.g. phone, in person, via email, etc.	
Ask the interviewee if they have completed the survey questionnaire. **Yes** ☐ **No** ☐ If the interviewee has not completed the survey, walk them through the questions and record the answers for them.	



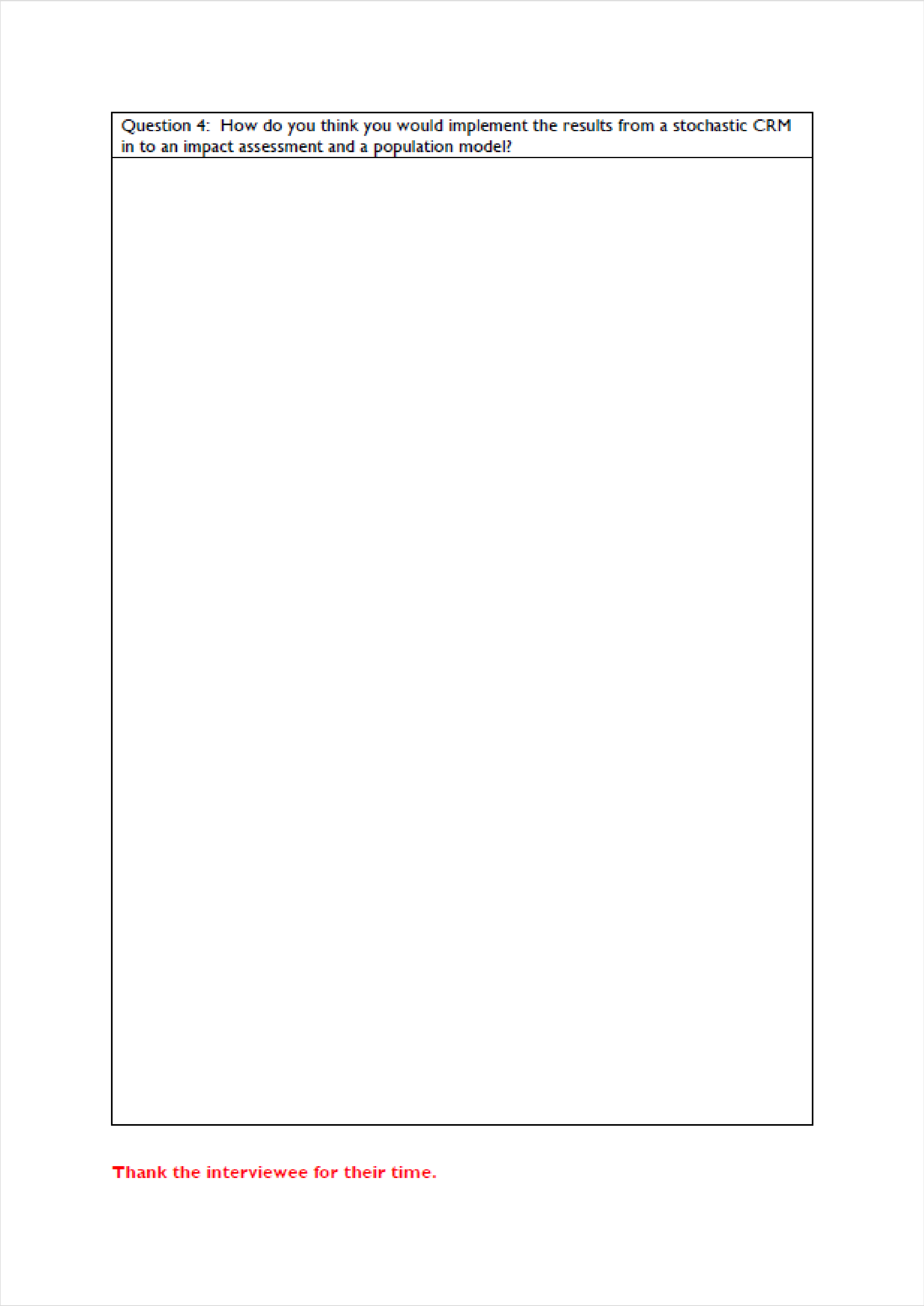
Question 1: Did the questionnaire allow you to provide all the feedback you would wish to give? If not, what was missing and what feedback would you want to give?



Question 2: When the stochastic CRM is produced do you think you will use it? (If the interviewee is a developer or consultant, then ask: would the new sCRM need to be recommended by the relevant regulator and their SNCB for you to use it?)



Question 3: Assuming the stochastic CRM is produced and works, what are the next new developments in CRM you would like to see? Are there any other comments you want to make about the survey or CRM for offshore wind farm?



Question 4: How do you think you would implement the results from a stochastic CRM in to an impact assessment and a population model?

Thank the interviewee for their time.

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Research article

Operational offshore wind farms and associated ship traffic cause profound changes in distribution patterns of Loons (*Gavia* spp.)

Bettina Mendel[a], Philipp Schwemmer[a,*], Verena Peschko[a], Sabine Müller[a],
Henriette Schwemmer[a], Moritz Mercker[b], Stefan Garthe[a]

[a] *Research and Technology Centre (FTZ), University of Kiel, Hafentörn 1, 25761 Büsum, Germany*
[b] *BIONUM - Büro für Biostatistik, Finkenwerder Norderdeich 15 A, 21129 Hamburg, Germany*

ARTICLE INFO

Keywords:
Environmental impact
Marine special protection area
Habitat loss
Management
Red-throated Loon
Avoidance behaviour

ABSTRACT

Seabirds select suitable habitats at sea, but these habitats may be strongly impacted by marine spatial planning, including the construction of offshore wind farms (OWFs) and the associated ship traffic. Loons (*Gavia* spp.) are particularly vulnerable to anthropogenic activities and are also of high conservation status, making them particularly relevant to marine planning processes. We investigated the effects of OWF construction and ship traffic on Loon distributions in the German North Sea on a large spatial scale, using a 'before–after' control impact analysis approach and a long-term data set. Many OWFs were built in or close to core areas of Loon distributions. Loons showed significant shifts in their distribution in the 'after' period and subsequently aggregated between two OWF clusters, indicating the remaining suitable habitat. The decrease in Loon abundance became significant as far as about 16 km from the closest OWF. Ship traffic also had a significant negative impact on Loons, indicating that OWFs deterred Loons through the combined effect of ship traffic and the wind turbines themselves. This study provides the first analysis of the extensive effects of OWFs and ships on Loons on a large spatial scale. The results provide an essential baseline for future marine spatial planning processes in the German North Sea and elsewhere.

1. Introduction

Shallow-shelf sea areas have long been used by humans. The North Sea is amongst the most-intensively utilised sea areas worldwide for activities including fishing, transport, oil and gas drilling, and gravel extraction (Emeis et al., 2015; Halpern et al., 2008). The installation of offshore wind farms (OWFs) in many sea areas throughout Europe and elsewhere represents a relatively new human use requiring considerable attention in terms of the marine planning process. In order to meet their climate goals, many European governments have started to install and plan further OWFs within relatively large sea areas (e.g. Breton and Moe, 2009; Langston, 2010). Germany intends to extend its offshore power generation to 6,500 MW by 2020 and to 15,000 MW by 2030, leading to a large increase in the number of OWF sites, mainly in the German North Sea, making Germany one of the countries with the most extensive plans for OWF installations (Beiersdorf and Radecke, 2014). Seventeen OWFs are currently (2018) in operation, with five further ones under construction and several more being approved in German sea areas (BSH, 2017).

In terms of the process of marine spatial planning, these permanent installations at sea represent a major addition to other types of marine human activities, whilst competing with sea areas assigned for nature conservation (Emeis et al., 2015; Moksness et al., 2009; Nolte, 2010) and potentially overlapping with areas used by resting and foraging seabirds. Previous studies have pointed out contrasting effects (negative or positive) of OWFs on seabirds that vary strongly among areas and species (Dierschke et al., 2016; Drewitt and Langston, 2006; Fox and Petersen, 2006; Furness et al., 2013; Garthe and Hüppop, 2004; Masden et al., 2009). In addition, the construction and maintenance of OWFs is further associated with a strong increase in shipping activities in and around OWFs (Exo et al., 2003).

OWFs may have direct effects on birds such as collision of individuals with the turbines, with subsequent impacts on the whole population (Fox et al., 2006; Goodale and Milman, 2014; Masden et al., 2009). Furthermore, the energy budget and condition of individual birds may also be affected indirectly through the effects of OWFs on habitat loss and reduced food availability (Drewitt and Langston, 2006; Fox et al., 2006; Stienen et al., 2007), though the long-term effects of these indirect effects at the population level are hard to estimate (Fox et al., 2006; Goodale and Milman, 2014; Searle et al., 2017). However,

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* Corresponding author.
E-mail address: schwemmer@ftz-west.uni-kiel.de (P. Schwemmer).

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birds have been shown to lose suitable resting and foraging habitats or to select less suitable sea areas (Stienen et al., 2007). Furthermore, they may need to increase their flight time by flying around OWFs on their way to suitable foraging sites (Drewitt and Langston, 2006; Masden et al., 2009). This study aimed to quantify the indirect effects (i.e. habitat loss by OWFs and associated ship traffic) on Loons (*Gavia* spp.) to provide baseline data for future studies that might address population consequences.

Loons belong to the most sensitive species group with respect to the avoidance of OWFs, as shown for single OWF sites in the North Sea (e.g. Dierschke et al., 2012, 2016; Leopold et al., 2010; Mendel et al., 2014; Petersen et al., 2006a, b; Welcker and Nehls, 2016). Furthermore, Red-throated Loons (*Gavia stellata*) are also very sensitive to ship traffic, demonstrating long flush distances in front of approaching vessels (Bellebaum et al., 2006) and significantly lower densities in areas with permanently higher ship traffic (Hüppop et al., 1994; Schwemmer et al., 2011). Their sensitive nature and the fact that a significant proportion of the biogeographic population occurs in European waters means that Loons are listed in Annex I of the EU Birds Directive and are considered to be particularly threatened with respect to human activities (e.g. Furness et al., 2013; Garthe and Hüppop, 2004). Negative effects on Loons at both the individual and population levels as a result of avoidance of OWFs cannot be ruled out (Dierschke et al., 2016, 2017), and Loons are therefore currently rated as a species group requiring particular consideration with respect to marine spatial planning in Germany and the UK (Busch et al., 2013).

Most Loons in the North Sea are Red-throated Loons (90%), with a minor proportion of Black-throated Loons (*G. arctica*; 10%) (Dierschke et al., 2012; Garthe et al., 2007). The German North Sea represents one of the most important resting sites for Loons with internationally important numbers, especially during spring migration (Garthe et al., 2007, 2015; Mendel et al., 2008; Skov et al., 1995), when around 20,200 Loons use German waters (Garthe et al., 2015). The 'Eastern German Bight' Special Protection Area (SPA) has been established to acknowledge the importance of this resting site and the high sensitivity of Loons with respect to human disturbances (Fig. 1). However, there is a potential conflict with the 'Butendiek' OWF, which was approved before but installed after the establishment of the SPA (Garthe et al., 2012), while further OWFs ('Helgoland Cluster') are located just south of the border of the SPA (Fig. 1).

Information on the long-term and large-scale effects of OWFs on Loons is currently limited and there has been no long-term comparison of their distributions before and after the installation of OWFs. Furthermore, the effects of increasing construction- and maintenance-related ship traffic have rarely been considered (Boon et al., 2010; Christensen et al., 2003).

We therefore hypothesized that Loons would avoid OWF areas and that their distribution patterns would differ before and after the installation of OWFs. We also hypothesized that the ship traffic associated with OWF sites would cause avoidance reactions among Loons. Against this background, this study aimed to shed light on five specific topics. (1) We had access to a long-term dataset covering the 14-year period before the installation of the OWFs ('before'). We therefore aimed to compare this information directly with the distribution of Loons after the installation of OWFs ('after'), using a long-term perspective not achievable in most previous studies. Mandatory operational monitoring of the four offshore windfarms in focus is still ongoing. (2) Most previous studies of the potential effects of OWFs on Loons have focussed on the effects of single OWF sites and their direct vicinities (see Dierschke et al., 2016). These therefore only allowed the reactions of Loons to be studied on a relatively small spatial scale, and could only show that Loon numbers were impacted within the respective site but could not show where they had moved to (Rexstad and Buckland, 2012). In contrast, the current study aimed to analyse the large-scale effects of multiple OWFs on Loon distribution, considering potential shifts between the 'before' and 'after' periods. (3) There is currently a need to disentangle the potential effects of OWFs from the effects of natural habitat characteristics that determine the distribution of Loons (Garthe, 1997; Winiarski et al., 2014). We therefore developed a model including stable natural parameters such as water depth and distance to land, as well as anthropogenic predictors such as distance to closest OWF and shipping traffic. (4) Given that the installation and maintenance of OWFs is associated with large increases in ship traffic, the effects of shipping need to be quantified and separated from the effects of the OWFs themselves. To date, this only has been analysed based on general ship densities (e.g. APEM, 2013; 2016; Leopold et al., 2014), while OWF ships present a dynamic source of disturbance for Loons.

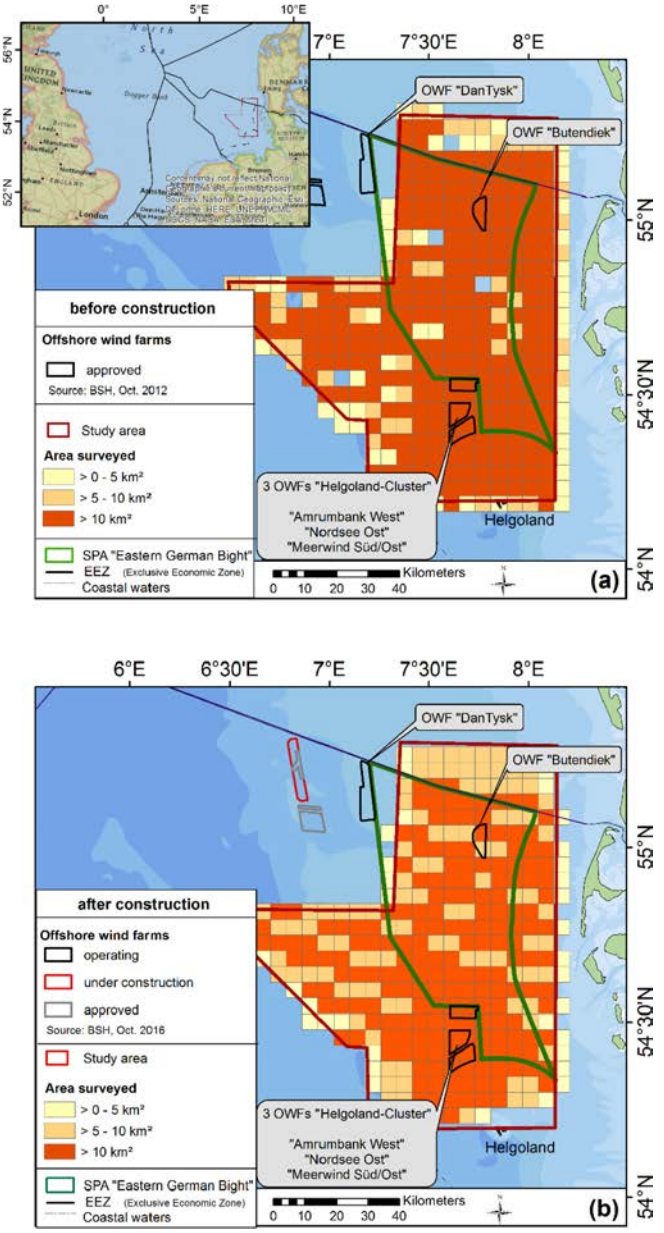

Fig. 1. Location of the study site within the south-eastern North Sea (inserted map in Fig. 1a) and in the eastern German Bight (North Sea) with locations of the different OWFs and the area surveyed for Loon abundance (yellow to red squares) across the 'Eastern German Bight' Special Protection Area (SPA; bold green line) for the 'before' (a) and 'after' periods of the analysis (b). Start of construction: 'Nordsee Ost' OWF during summer 2012; end of all construction works: 'Butendiek' OWF during summer 2015. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This study therefore aimed to relate Loon and ship distributions at very high spatial and temporal scales by relating ship distributions derived from the Automatic Identification System (AIS) with Loon abundance assessed during aerial surveys. (5) Given a negative effect of OWFs on Loons, we aimed to quantify the avoidance distance to OWFs to draw conclusions about the degree of resulting (permanent) habitat loss.

In this study, we adopted two different approaches to analyse different aspects of the effects of OWFs on Loons: we used 'before' data to demonstrate the importance of the OWF areas before construction, and also focused on the simultaneous effects of OWFs and ships associated with OWFs after construction. The combined interpretation of these approaches allowed a comprehensive evaluation of the effects of OWFs on Loons.

2. Methods

2.1. Study area

The study was conducted within the eastern part of the Exclusive Economic Zone of the German North Sea, south of 55°17′ N, north of 54°11′, east of 6°30′ E, and west of 8°9′ E (Fig. 1a). The study site was located within an area 8–100 km off the Wadden Sea islands of northern Germany. The water depth ranged from 10 to 40 m. Loon distribution was recorded within the SPA 'Eastern German Bight' and beyond, and the study site therefore covered the core area of highest Loon densities within German waters (Garthe et al., 2015). The 'Butendiek' OWF is located in the core area of the SPA, while the 'Helgoland Cluster' OWFs are located at the border of the SPA and south of the core Loon distribution (Fig. 1a).

2.2. Recording Loon distribution and data processing

Loon distribution was recorded, both, in the period prior to OWF construction and in the period after construction:

(1) Before construction: These data cover the months of spring migration (i.e. March to April) of the years 2000–2013 and are the similar database as used by Garthe et al. (2015). The records originated from environmental impact assessment studies required for licensing procedures of offshore wind farms in the German EEZ and from seabird monitoring and research programmes (for details see Garthe et al., 2015; Fig. 1a). The data were recorded using visual aerial and ship-based surveys. Briefly, Loons were counted along transects of a known area, which allowed the densities to be computed (see Diederichs et al., 2002; Garthe et al., 2002 for a full description of both recording methods).

(2) After construction: These data also cover the months of spring migration (i.e. mainly March to April, but including the last week of February and the first week of May to enhance the sample size of surveys) of the years 2015–2017. Data originated from ongoing mandatory monitoring of the wind farms during operation, and from the 'Helbird' research project funded by the German Federal Ministry for Economic Affairs and Energy. Overall, data for the after period were based on 10 digital aerial surveys in 2015–2017 (Fig. 1b). Those data were obtained by video-based digital recordings instead of visual observations. Briefly, an aircraft sampled a transect of a known area using a video camera and all seabirds found were recorded and used to compute overall densities (for a detailed description of the method see Buckland et al., 2012; Thaxter and Burton, 2009). A change from visual to digital survey methods was mandatory for safety reasons because the flight altitude needed to be higher during the construction and operational phases of the turbines (168 m, instead of 91 m for visual observations), which excluded visual recordings.

(3) During construction: No data were considered in this study, as disturbance during the construction of the OWF is temporary and mainly associated with construction ships, and its contribution to the overall effect of the OWF on the Loon population was assumed to be of low importance in relation to the expected lifetime of the OWF (Christensen et al., 2003).

Visual observations of seabird distributions are known to underestimate birds in parts of the transect further from the observer (Buckland et al., 2001, 2015). We therefore applied a species-specific correction factor for aerial and ship-based observations, respectively (see Garthe et al., 2015 for details). However, no distance correction was necessary for the video-based digital surveys because the probability of detecting a bird was equal across the whole transect.

All three recording methods relied on the principle that transect sampling of birds could be used to compute densities. However, we did not compare absolute density values between the 'before' and 'after' periods, because the visual and digital methods have not been confirmed to produce the same absolute values (Buckland et al., 2012; Skov et al., 2016); this could only be tested by performing both methods at the same time, and no such dataset is currently available. Thus, both periods were compared by computing the relative deviance from the maximum density in each period in %, and using this to compare the distributions and locations of high-density areas of Loons between the two periods.

Data were spatially pooled in a grid with cells of 2.5 × 2.5 km for the 'before' and 'after' periods, for each of the three methods (visual aerial and ship-based surveys, video-based digital recordings), respectively. Bird numbers and monitored areas were each summed per grid cell, and eventually used to compute mean densities for each period, while geographical coordinates were averaged for each cell.

2.3. Integrating covariates for the 'before–after' control impact (BACI) approach

We related the average distribution data for Loons with environmental variables using ArcGIS (version 10.3; Environmental System Research Institute, 2016). The environmental variables included: (1) *dist_coast* = minimum distance to the mainland and larger islands (except Helgoland); (2) *dist_helgoland* = minimum distance to Helgoland; (3) *dist_owf* = minimum distance to the border of the OWF; and (4) *mean_depth* = mean water depth.

This first model, hereafter named the BACI approach, did not consider the effect of ships because ship data at a sufficiently high spatiotemporal resolution were only available for the 'after' period. To distinguish between the effect of the OWFs and the effect of ship traffic on Loons, we therefore developed a second model (ship model) using only the data from the 'after' period.

To merge the environmental variables with the bird-count data in an optimal way, we first pooled the covariates to a spatial grid of 2.5 × 2.5 km, and then fitted each covariate with a generalised additive model (GAM) using the function gam() in the R-package mgcv (R Core Team, 2017; R version 3.4.2; Wood, 2006). We used only latitude and longitude as a smooth 2D-predictor based on cubic splines with the maximal degree of freedom, so that the result represents a cubing interpolation on the given (possibly irregular) grid. Thirdly, we used the predict() function to predict the values straight to the coordinates as given in the pooled bird-count data. Finally, the additional categorical variable *owf_zone* for 'inside OWF-affected area' vs. 'outside OWF-affected area' was defined for two different zones: 1) inside: ≤ 3 km vs. outside: > 3 km (measured from the nearest turbine), given that OWF-associated ships operate mainly within a 3 km radius around the OWF and this distance class has been used in previous studies of the impact of single OWFs (Vanermen et al., 2015a; Welcker and Nehls, 2016); and 2) inside: ≤ 10 km vs. outside: > 10 km, because an initial analysis showed the greatest decrease in Loon densities up to a distance of 10 km from the turbines.

2.4. Set up and validation of regression models for the BACI approach

The BACI approach is based on surveying a potentially impacted situation and a control situation before the impact (variable '*period*'), and relative comparisons of spatial and temporal differences can then be used to extract the unbiased impact (Schwarz, 2014; Smith, 2002). We formulated the BACI approach within the framework of generalised additive mixed models (GAMMs), which are known to describe biological count data appropriately (Zuur et al., 2007, 2009; 2012). We used a continuous linear or smooth predictor measuring the distance to the border of the next OWF. This allowed us to estimate how the abundance of Loons changed in relation to the distance from the OWF and to estimate avoidance distances. Notably, we introduced a variable for the observation method ('visual ship-based surveys' vs. 'visual aerial surveys' vs. 'digital aerial surveys') as a random intercept to account for differences in detection among these methods. We were aware that this variable was partially collinear with the variable 'period' because only digital aerial surveys were used 'after' and only visual surveys were performed 'before'. Importantly, the estimation of the interaction term 'period x wind_farm' (see below) representing the BACI approach was not influenced by this, because only relative differences in Loon densities were evaluated.

This approach produced the following full model for the BACI approach (not yet thinned regarding its predictors; see below):

$$\begin{aligned}\log(y_{ij}) = \beta_0 + u_i &+ \mathrm{f(mean\_depth_j)} + \mathrm{f(dist\_coast_j)} + \mathrm{f(dist\_helgoland_j)}\\ &+ \mathrm{s(latitude,longitude)} + [\mathrm{wind\ farm_j}] + \mathrm{period_j}\\ &+ [\mathrm{wind\ farm_j}] \times \mathrm{period_j} + \mathrm{offset}(\log(\mathrm{area_j})) + \varepsilon_{ij}\end{aligned} \tag{1}$$

where $\varepsilon_{ij} \sim N(0, \sigma^2)$ and $u_i \sim N(0, \sigma_u^2)$ were independent and identically distributed. Here, y_{ij} is the vector of bird numbers, where the index j refers to the observation number and i is related to the method-ID. *f*() depicts either a linear term or a cubic regression spline *s*() (tested during predictor selection), where, in the case of a spline, the optimal number of knots was estimated via cross-validation. The variable [$wind\_farm_j$] was either considered as a linear term, $dist\_owf_j$ measuring the distance to the next wind turbine, as an additive smoother, $s(dist\_owf_j)$, or as a bivariate variable, owf_zone_j, the latter distinguishing between 'inside OWF-affected area' and 'outside OWF-affected area'. For each model, an appropriate probability distribution was selected for y_{ij} via Akaike Information Criterion (AIC; Akaike, 1973) analysis (see below).

We modified the common selection and validation strategies to validate the optimal GAMM model (Field et al., 2012; Korner-Nievergelt et al., 2015; Zuur, 2012; Zuur et al., 2009, 2010; 2012) using the following steps: (1) Based on the entire model (1), we selected an appropriate probability distribution/stochastic part of the model using the AIC. Namely, we compared Poisson-, negative binomial-, Tweedie-, zero-inflated Poisson distribution, and observation-level random intercept Poisson models. All five probability distributions are known to describe the stochastic part in regression models of (overdispersed) count data reasonably well (Kokonendji et al., 2004; Korner-Nievergelt et al., 2015; Linden and Maentyniemi, 2011; Zuur et al., 2012). (2) The optimal model regarding the set of fixed-effect predictors was selected from the full model by comparing 16 different models. (3) Model validation was carried out by visual inspection of the residual plots to assess all the required model assumptions (Zuur et al., 2010). Corresponding auto-correlation structures were added to the model if required.

AIC favoured a negative-binomial distribution, and subsequent predictor selection produced the following final model:

$$\begin{aligned}\log(y_{ij}) = \beta_0 + u_i &+ \beta_1 \mathrm{dist\_coast_j} + \mathrm{s(latitude,longitude)} + [\mathrm{wind\_farm_j}]\\ &+ \mathrm{period_j} + [\mathrm{wind\_farm_j}] \times \mathrm{period_j} + \mathrm{offset}(\log(\mathrm{area_j})) + \varepsilon_{ij}\end{aligned} \tag{2}$$

Residual analysis revealed no violation of linearity, homogeneity, independence, or normality of the random intercept.

2.5. Integrating covariates for the ship model

Ship traffic has been shown to have a significant effect on Loon distribution (Bellebaum et al., 2006; Schwemmer et al., 2011), and ship traffic in the study area has increased greatly due to the construction and maintenance of OWFs. It is therefore important to disentangle the effects of these two sources of anthropogenic activities (OWFs and ship traffic) on Loons. Ship traffic shows temporal inhomogeneity, with more traffic in the morning and evening hours, and it was therefore necessary to consider the data spatio-temporally instead of purely spatially, as with the BACI approach. Data were only used for five digital-survey flights from the 'after' period because no real-time ship data were available for the 'before' period or for any other survey days during the 'after' period. Bird data were spatially assigned to an optimal grid of 2.5 × 2.5 km for each survey day separately and treated as described above. To consider the time, we also calculated the mean time at which the Loon observations were recorded for each grid cell.

Data on ship distributions were recorded in parallel with the digital-survey flights to record Loon distribution using an AIS spotter (www.aisspotter.com). Because the ship data consisted of irregular position data in terms of time and space, they were linearly interpolated to obtain positions at least every minute. To merge the ship data with the Loon-distribution data, it was assumed that all ships within the time interval $[t - \delta_t, t]$ and within a circle around (x, y) with radius r may influence bird density, for each time point t and each pair of spatial coordinates (x, y). Given that the optimal values δ_t and r are not known *a priori*, we tested all existing combinations between $\delta_t\ \varepsilon\ \{2, 60, 120, 180, 250, 300, 350, 400, 600, \infty\}$ sec and $r\ \varepsilon\ \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}$ km, and created a separate variable counting all ships within the given time and space interval for each of the 100 combinations. Here, $\delta_t = \infty$ depicts a case where all available ship data have only been spatially correlated to bird-count data without considering temporal distance to the observations. We subsequently compared 100 resulting regression models (see below) to find the optimal values of δ_t and r. However, the AIC value was not appropriate for selecting the optimal model because the ship densities and OWF-related variables were collinear, and the model with only one of both variable types would be favoured due to the parsimony of the AIC-based selection. In contrast, we aimed to consider both (collinear) variables to distinguish explicitly between the unique effects of ships and wind turbines on Loon abundance. An appropriate measure should thus relate the effect size of the ship-dependent variable with its reliability. Hence, we selected the model with the highest $|\beta|/SE_\beta$ value, where β is the ship-related regression coefficient and SE_β is its standard error.

2.6. Set up and validation of regression models for the ship model

The GAMMs were set-up as described above for the BACI approach. Notably, the ID of the digital-survey flight was introduced as a random intercept to account for different numbers of birds or different monitoring conditions between surveys.

This produced the following GAMM structure of the ship model (not yet thinned regarding its predictors):

$$\begin{aligned}&\log(y_{ij})\beta_0 + u_i + \mathrm{f(mean\_depth_j)} + \mathrm{f(dist\_coast_j)} + \mathrm{f(dist\_helgoland_j)}\\ &\quad + [\mathrm{wind\_farm_j}] + [\mathrm{ship\_number_j}] + \mathrm{offset}(\log(\mathrm{area_j})) + \varepsilon_{ij}\end{aligned} \tag{3}$$

where $\varepsilon_{ij} \sim N(0, \sigma^2)$ and $u_i \sim N(0, \sigma_u^2)$ were independent and identically distributed. Here, y_{ij} is the vector of bird numbers, where the index j refers to the observation number and i is related to the survey flight ID. *f*() depicts a linear or smooth predictor (tested during AIC-based predictor selection). The variable [$wind\_farm_j$] was either considered as a binomial predictor ('inside' vs. 'outside'), a linear term (distance to the

OWF border), or a cubic regression spline depending on the latter. The variable [*ship_number$_j$*] was considered as the total number of temporally and spatially related ships, additionally depending on the *a priori* defined parameters δ_t and r (see above). In contrast to the BACI approach, we did not consider a spatial smooth because this predictor would interfere with the correct estimation of [*wind_farm$_j$*]. GAMM-model selection and validation strategies were performed as described for the BACI approach (see above), including integration of the appropriate autoregression structures (if required).

AIC-based selection of the probability distribution again favoured a negative-binomial distribution. The optimal values of δ_t and r required to blend the observation and ship data showed that the highest (β/SE)-values (indicating high precision of the ship-related regression coefficient) were $\delta_t = 5$ min and $r = 5$ km. Subsequent predictor selection revealed the following final model:

$$\log(y_{ij}) = \beta_0 + u_i + \mathrm{f(mean\_depth_j)} + \beta_1 \mathrm{dist\_coast_j} + \mathrm{s(dist\_helgoland_j)} \\ + [\mathrm{wind\_farm_j}] + [\mathrm{ship\_number_j}] + \mathrm{offset(log(area_j))} + \varepsilon_{ij} \tag{4}$$

where *s*() depicts the cubic regression splines with optimal degrees of freedom estimated via cross-validation.

Analysis using different sizes of the underlying spatial grid for spatio-temporal pooling revealed an optimal grid size of 2.5 × 2.5 km, leading to a temporal autocorrelation of model residuals of order 2 (in contrast to the model based on raw data, where the autoregressive order (AR order) was > 30). Model-validation plots indicated no violation of linearity or homogeneity, spatial residual plots and a semi-variogram indicated no violation of spatial independence, and a plot of the partial autocorrelation function (pACF-plot) revealed a temporal autocorrelation of approximately order 2, which was integrated as an AR(2)-structure into the model.

3. Results

3.1. Loon abundance before and after OWF installation

The spatial distribution patterns of Loons changed profoundly between the 'before' and 'after periods (Fig. 2). During the 'before' period, the core area with the highest Loon densities clearly overlapped the area of the planned 'Butendiek' wind farm, while moderately high densities stretched out to the area of the planned 'Helgoland Cluster'. In contrast, there was a clear shift to the area located between these two OWF sites during the 'after' period (Fig. 2). The areas of the OWFs themselves, as well as the immediate vicinities, showed extremely low abundances of Loons during the 'after' period. The core area of Loons during the 'after' period was thus still located in the centre of the SPA, but the birds were more aggregated within the still-undisturbed sea area.

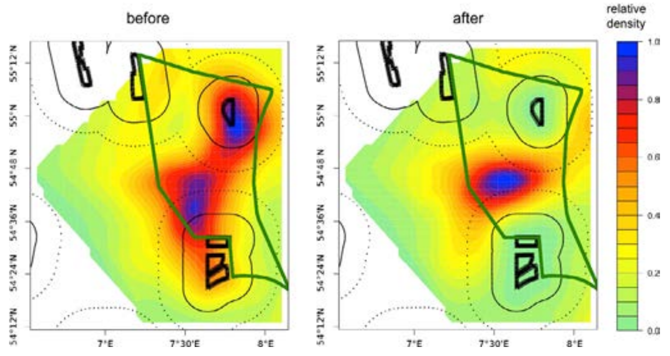

Fig. 2. Spatial density plots of predicted Loon distributions 'before' vs. 'after' the construction of OWFs, based on the BACI-GAMM. Bold black lines: OWFs; thin black lines: 10 km distance buffer; dotted black lines: 20 km distance buffer; bold green line: Special Protection Area.

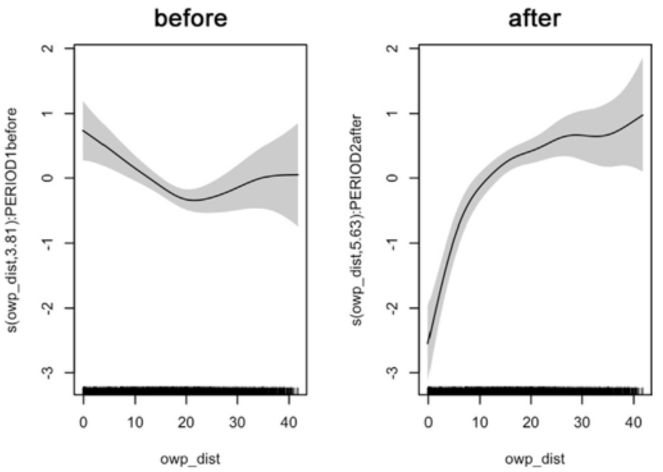

Fig. 3. Change in Loon abundance in relation to distance from the closest OWF site 'before' (left) and 'after' construction of the OWFs. Smoothed curve: predicted number of Loons at a given distance from the closest OWF; shaded area: 95% confidence interval; small lines on the x-axis: observations of Loons at a given distance from the OWF.

We also introduced the distance from the wind farm as a smooth term, estimated separately for each period. This revealed a striking difference between the two periods (Fig. 3): the 'before' plot suggested that the future wind farm areas were sites with naturally increased Loon abundance, while the 'after' plot showed a strong decline in Loon abundance due to the OWFs (Fig. 3). The start of this decline was already visible at > 20 km from the OWFs (see also dotted black lines in the 'after'-plot in Fig. 2b). To determine the distance from the wind farm at which the decline in abundance was significant, we approximated the first derivative of the corresponding smooth (Fig. 3 'after') by calculating its first finite difference.

To determine the distance at which the change in Loon density became significant, we calculated confidence intervals for the first derivatives via bootstrap analysis and subsequently evaluated where the lower confidence interval intersected with zero. This occurred at around 16.5 km from the OWFs (Fig. 4). However, the greatest decline in density was at distances within 10 km from the OWF (Figs. 3 and 4). Avoidance of wind farms within 10 km was also clearly visible in the distribution maps (solid black lines in Fig. 2b).

Additionally, the binomial wind farm-related variable *owf_zone* was highly significant for both radii (3 or 10 km, respectively). The abundance of Loons decreased highly significantly by 94.5% inside the 3 km zone around the OWFs within the study site (interaction term in Table 1; $\beta = -2.9$, $p < 0.001$), while the abundance was still decreased by 83.7% inside the 10 km zone (Table 2, $\beta = -1.8$, $p < 0.001$). The distance to land (*dist_coast*) had no significant effect on Loon densities (Table 1; Table 2).

3.2. Distinguishing between effects of ships and OWFs

Loon densities were still reduced if ships were included in the overall model as a predictor for the 'after' period, as was the case without considering the effect of ships, as shown above. Applying a 3 km radius around the wind farms, OWFs alone reduced the Loon density by 70.8% compared with the sea areas outside the OWFs ($p < 0.001$; Table 3). If the radius was extended to 10 km around the OWFs, the Loon density was still reduced by 44.5% ($p < 0.001$) by the OWFs alone.

When ships as single predictor were removed from the model, the estimated effect of OWFs (now combined with the effect of the ships) on Loons was 84% using a 3 km radius ($p < 0.001$). This suggested that

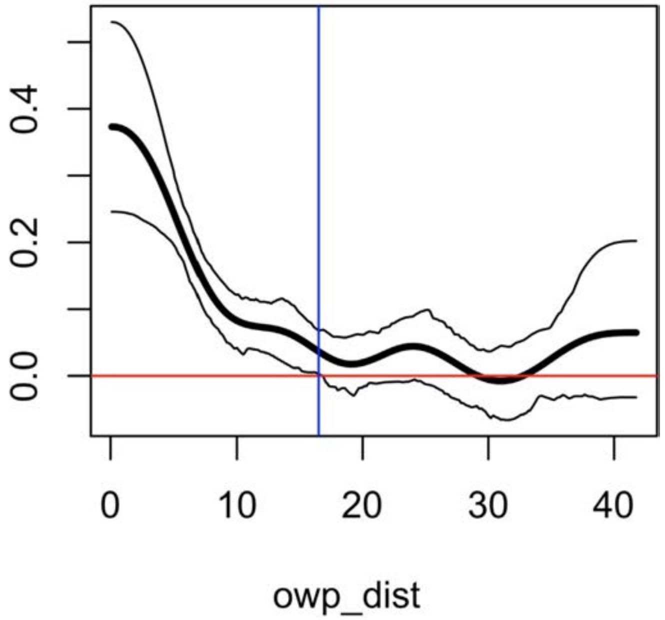

Fig. 4. First finite difference of the smooth depending on the distance from the closest OWF, partially evaluated for the 'after' period. Red line indicates a derivative of zero, blue line indicates distance at which the derivative was significant. Thick black line corresponds to the first derivative; thin black lines depict 95% confidence intervals.

Table 1
Regression results of the BACI approach–GAMM using the binomial variable 'inside wind farm' vs. 'outside wind farm' (*owf_zone*) for a radius of 3 km.

	Estimate	Std. Error	z value	Pr(> |z|)
(Intercept)	−1.05	1.17	−0.90	0.37
period[after]	0.40	0.85	0.47	0.64
owf_zone[a][inside]	0.70	0.13	5.07	< 0.001
dist_coast[b]	0.02	0.02	0.70	0.43
period[after]xowf_zone[inside]	−2.90	0.22	−13.16	< 0.001

[a] Offshore wind farm zone.
[b] Distance to coast.

Table 2
Regression results of the BACI approach–GAMM using the binomial variable 'inside wind farm' vs. 'outside wind farm' (*owf_zone*) for a radius of 3 km.

	Estimate	Std. Error	z value	Pr(> |z|)
(Intercept)	−1.41	1.17	−1.21	0.23
period[after]	0.73	0.95	0.76	0.45
owf_zone[a][inside]	0.66	0.12	5.59	< 0.001
dist_coast[b]	0.02	0.02	1.01	0.31
period[after] xowf_zone[inside]	−1.81	0.12	−15.26	< 0.001

[a] Offshore wind farm zone.
[b] Distance to coast.

Table 3
Regression results for the *ship-owf*-approach–GAMM distinguishing between the effect of ships and the effect of OWFs in the 'after' period for a radius of 3 km.

	Estimate	Std. Error	z value	Pr(> |z|)
(Intercept)	0.29	0.58	0.5	0.62
owf_zone[a][inside]	−1.23	0.31	−4.03	< 0.001
dist_coast[b]	−0.01	0.01	−0.55	0.58
n_ships[c]	−0.37	0.08	−4.82	< 0.001

[a] Offshore wind farm zone.
[b] Distance to coast.
[c] Number of ships.

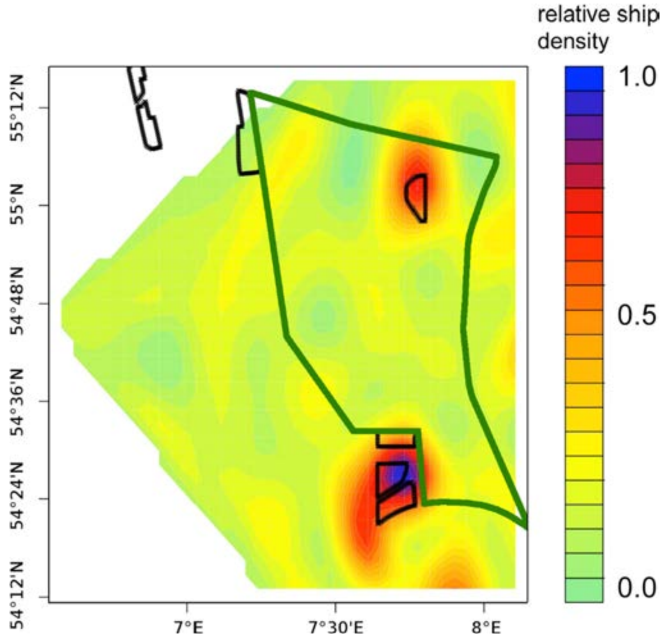

Fig. 5. Spatial density plot of ship distribution in the 'after' period based on AIS data.

ships also had a strong negative effect on Loon abundance, accounting for at least 14% of the joint OWF–ship effect.

Thus, in the ship model, the effect of OWFs alone was not as strong as estimated by the BACI approach (i.e. without considering ship traffic; > 94% and > 84%, respectively). There are two possible explanations for these different estimations. (1) the ship model was only fitted using data from the 'after' period because no ship data were available for the 'before' period. Hence, the estimated reduction in effect does not take account of the fact that bird densities within the OWFs showed the highest Loon abundances before the construction of the farms (see above), leading to a strong underestimation of the reduction effect. (2) Although the ship model considered the effect of ships, these were at least partially correlated with OWF location (Fig. 5). Thus the BACI approach actually estimated the joint reduction effect of OWFs and ships, whereas the ship model evaluated both impacts separately, which may have led to a reduction in the OWF effect compared with the BACI approach.

Indeed, the ship model showed a significant negative impact of ships on Loon abundance (Tables 3–4), with a highly significant decline of 31% in abundance for each additional ship in the spatio-temporal range of the Loons (i.e. 5 min and 5 km from the Loon sighting; see Methods) ($p < 0.001$). This suggests that one in three Loons left the area as one ship approached. The spatial component of ship disturbance was much stronger than the temporal component; i.e. our regression models selecting for the optimal δ_t and r revealed that ships within 5 km had a strong impact on Loon abundance, whereas the time lag between

Table 4
Regression results for the *ship-owf*-approach–GAMM distinguishing between the effect of ships and the effect of OWFs in the 'after' period for a radius of 10 km.

	Estimate	Std. Error	z value	Pr(> |z|)
(Intercept)	0.73	0.58	1.26	0.20
owf_zone[a][inside]	−0.59	0.17	−3.51	< 0.001
dist_coast[b]	−0.01	0.01	−1.00	0.32
n_ships[c]	−0.48	0.07	−6.44	< 0.001

[a] Offshore wind farm zone.
[b] Distance to coast.
[c] Number of ships.

the Loon sighting and the AIS signal of the ship was less relevant (with an optimum at approx. 5 min). This suggests that ships may affect Loons most strongly at a distance of ≤5 km.

As seen with the BACI approach, the distance to land had no significant influence on Loon abundance (Tables 3–4).

4. Discussion

4.1. Distribution patterns before and after OWF installation

Our results demonstrated that the distribution patterns of Loons, which had remained stable over a period of many years (Garthe et al., 2015), were substantially altered at both small and large spatial scales by the installation of OWFs in the German North Sea. We developed our BACI approach on a solid database including 14 years of large-scale surveys in the period 'before' OWF installation. To the best of our knowledge, all previous reports have been based on a maximum of 1–3 years of data prior to the construction of OWFs, and have mostly focused on the effect of a single OWF (e.g. Leopold et al., 2013; Petersen et al., 2014). Although we were unable to compute absolute differences in Loon populations between the two periods due to a change in survey methods, our results demonstrated profound large-scale shifts in distribution patterns, as well as significant avoidance of the OWF areas.

We observed a shift in the Loon-abundance hotspot to the western–central area of the SPA that remained undisturbed by OWFs in the 'after' period. This hotspot is located about 20 km distant from all surrounding OWFs. Several previous studies have highlighted the environmental parameters that are most important for determining Loon distribution patterns. Frontal systems are expected to increase prey availability for Loons (Skov and Prins, 2001), while nearshore and shallow sandy sea areas also play a major role (O'Brien et al., 2008; Skov and Prins, 2001; Skov et al., 2016). Our results suggest that the area of the 'Butendiek' OWF, which was installed in the northern part of the SPA, was of particular importance for Loons before the construction of this OWF, given that this was the area of maximum Loon abundance during the 'before' period. The 'Helgoland-Cluster' OWFs are located south-west of the border of the SPA, and our results showed that, in contrast to the 'Butendiek' area, Loon abundances in the 'before' period were significantly lower compared with abundances within the SPA. However, Loons are known to occur here regularly (Garthe et al., 2015).

One aim of this study was to disentangle the importances of natural habitat structures and anthropogenic pressures on Loons. Our modelling approach showed that natural habitat predictors, such as distance to the coast/Helgoland and water depth did not play major roles compared with the effects of OWFs and shipping (see below). This suggests that anthropogenic pressures are the most important factors driving the distribution patterns of Loons within their natural hot spots.

Still, we cannot completely rule out that undetected changes in ecological conditions might have additionally led to the shift in distribution patterns. For instance, it could be assumed that Loons might have followed shifts in their prey community. However, given that Loons are known to feed on a variety of fish species (Guse et al., 2009), a shift in fish distribution that could account for the change in Loon distribution seems highly unlikely. The reef effect is even known to likely increase benthic and fish communities inside OWFs (e.g. Vandendriessche et al., 2015; Vanermen et al., 2015a) which in turn may enhance the quality of these sites for piscivorous seabirds. However, given that these sites were avoided by Loons, despite of a likely higher fish availability and as Loon distribution patterns had been stable over a period of many years in the 'before' period (Garthe et al., 2015), it seems to be convincing that OWFs and associated ship traffic are the main factors explaining the shifts in distribution patterns.

Incorporating distance from the nearest OWF as a smoothed term in the model allowed us to highlight the fact that Loons reacted as far as 20 km from OWFs, with significant changes in densities at a distance of 16.5 km and the greatest changes in abundance within 10 km. These values were higher than those reported in previous studies (summarized in Dierschke et al., 2016; Welcker and Nehls, 2016). However, most previous studies only investigated local avoidance effects (often only up to 4 km distance; Leopold et al., 2013; Petersen and Fox, 2007, Petersen et al., 2006a,b; Welcker and Nehls, 2016) and were therefore unable to detect any larger-scale avoidance reactions. This highlights the importance of a sufficiently large-scale approach and the inclusion of multiple OWF sites (Rexstad and Buckland, 2012), as in the current study. To emphasize the importance of scale, we quantified the effects of OWFs on Loons by defining the affected sea areas by both 3 km and 10 km radii.

The 3 km distance class was chosen based on previous studies that showed avoidance distances for single OWFs up to this value (Vanermen et al., 2015a; Welcker and Nehls, 2016). However, our results suggest that this distance was too short, based on the effects of multiple OWFs on a larger spatial scale.

The reason for the relatively large-scale effect of OWFs on Loons detected in the current study is not completely clear. It is possible that visual cues are not the only reason for the large disturbance distance. Previous studies showed that OWFs not only affected seabirds and other marine wildlife directly (Bergström et al., 2014; Goodale and Milman, 2014; Lindeboom et al., 2011), but may additionally cause changes in the abiotic environment, such as sediment properties and water stratification due to turbulence caused by the piles (Carpenter et al., 2016; Nagel et al., 2018). Carpenter et al. (2016) pointed out that an individual OWF may enhance mixing of the water column, with a cascade of effects on the whole ecosystem in an area of 10–20 km from the OWF, though the physical–biological interactions remain unclear. This was in accordance with the disturbance distance of Loons found in the current study. Petersen et al. (2014) also showed significantly lower Loon abundances up to 13 km from OWFs, which also matched the results of the current larger-scale approach.

Finally, it is important to critically explore the question of the power of the data used in this study. For the type of data used, previous investigations have shown that high survey intensities are required to safely trace declines in seabird populations, mainly as a result of high variability in distribution patterns (e.g. MacLean et al., 2013; Vanermen et al., 2015b). However, compared to our study that was conducted over a large sea area, both studies mentioned above focussed on rather small study sites, likely enhancing small-scale variability in counting data. According to Vanermen et al. (2015b) the statistical power after 10 years of survey was sufficiently high to detect reliable changes. For the 'before' period, 13 years of data were available for our BACI approach, indicating a valid data base. In contrast, the 'after' period only consists of 10 aerial surveys over a period of three years, suggesting that the data base for the 'after' period may still be too weak. However, the significant negative and consistent effects of OWFs and associated ship traffic on Loon distribution during all surveys of the 'after' period indicates that the data base is sufficient to yield valid results. Nevertheless, it will be necessary to enhance the data base for the 'after' period by future surveys to confirm the results and to enhance the statistical power.

4.2. Distinguishing between the effect of ships and OWFs

The installation of OWFs causes a substantial increase in ship traffic in the surrounding area due to maintenance and service activities (Exo et al., 2003). Although ship traffic is known to affect the distribution patterns of seabirds and particularly of Loons (Bellebaum et al., 2006; Schwemmer et al., 2011), the combined effect of OWFs and their associated ship traffic has rarely been reported; however, the few available studies noted a significant impact of ship traffic on Loon distribution (APEM, 2013, 2016; Leopold et al., 2014; Skov et al., 2016). Loons have been shown to exhibit a behavioural response to approaching ships, and flight distances of up to 2 km have been documented (Bellebaum et al., 2006; Schwemmer et al., 2011). This corresponds to the current results, which suggested a significant reduction in Loon densities within a radius of up to 5 km from the vicinity of ships, with the temporal aspect of ship distribution having little effect.

Inclusion of ship abundance in the model showed a reduced density of Loons of up to 70% based on the 3 km distance zone. This reduction could be considered to reflect the effect of the OWFs alone. In contrast, the joint effect of OWFs and ships led to a reduction of 84%, indicating the additional negative impact of ships on Loon densities. The exact reduction in densities due to ships alone could not be computed reliably because of the collinearity of ship traffic and OWFs. Importantly, their mobile nature means that ships are both spatially and temporally variable predictors, and a reliable estimation of their overall effects on birds will always be biased. This issue will remain difficult to address even in future studies, given that ships aggregate strongly in the vicinity of OWFs and present no fixed predictor.

The greater reduction in Loon densities following inclusion of ship traffic in the model demonstrates the importance of reviewing the cumulative impact of multiple anthropogenic pressures in the marine environment. Previous studies have focussed on cumulative effects simply by investigating the combined effects of multiple OWFs (Busch et al., 2013; Desholm, 2009; Dierschke et al., 2003, 2006, Fox et al., 2006; King et al., 2009; Mendel and Garthe, 2010). However, given the strong effect of ships on Loon abundance, it seems necessary to include other anthropogenic pressures in estimates of cumulative effects on Loon abundance in general.

4.3. Conclusions

The large-scale avoidance effects of OWFs (and ships) on Loons suggest that Loons are unlikely to suffer from enhanced direct mortality, e.g. because of collisions (Leopold et al., 2010; Petersen et al., 2006a,b; this study). Furthermore, a low flight altitude of only up to 10 m above the sea surface (Van Bemmelen et al., 2011) reduces the collision risk for Loons. Indirect effects, such as habitat loss, are thus likely to be key factors affecting Loons in relation to OWFs. However, the consequences of such indirect effects e.g. on population levels of seabirds, and density-dependent effects are hard to assess, and appropriate methodologies are largely lacking (Green et al., 2016; Horswill et al., 2017). When assessing the consequences of habitat loss due to the installation of OWFs and the associated enhancements in ship traffic, it is essential to consider which alternative sea areas could be used as resting and foraging grounds. In the current case, alternative sites seemed to be very limited because the SPA was virtually surrounded by OWFs. This might explain why Loons tended to concentrate in the centre of the SPA rather than moving outside it.

Although it was not possible to compute absolute differences in abundance between the 'before' and 'after' periods in this study, it is hoped that this issue will be resolved when enough data become available from parallel digital and visual surveys of sea areas where visual observations are still allowed. However, the relative reduced densities of Loons with respect to OWFs and ship traffic as well as the avoidance distances provided in the current study will serve as a baseline for further studies. A suitable approach for quantifying the overall habitat loss for Loons would involve computing the relative proportion of habitat loss within a certain area (e.g. within the SPA). Dierschke et al. (2006) suggested summing the total OWF areas and adding an additional buffer zone to assess the overall habitat loss. Applying this approach to the current study allowed the minimum habitat loss due to the OWFs in the SPA to be computed, indicating that complete loss of the sea area within a 3 km radius around the OWFs for Loons (as strongly supported by the current study) would equate to a loss of 8.8% of the SPA (overall size 3,135 km^2) for Loons. This should be regarded as an absolute minimum, given that our results clearly showed that the density of Loons was greatly reduced beyond 3 km from the nearest OWF.

Although we are not able to compare absolute density values between the 'before' and 'after' periods, our results indicated that Loons aggregated in the centre of the SPA after OWF installation, representing an increase in Loon density in a much smaller sea area. Given that Loons tend to occur in comparatively small flocks, only occasionally exceeding 5–10 individuals/km^2 (Garthe et al., 2015; O'Brien et al., 2012), this change in distribution might promote density-dependent effects (Blanc et al., 2006; Horswill et al., 2017; Lewis et al., 2001). A possible shift towards suboptimal habitats may lead to suboptimal body conditions prior to breeding, which could in turn reduce the reproductive success and enhance mortality in adult birds (Coulson et al., 1983; Hüppop, 1995). Even a slight increase in the mortality of adult Loons of only 0.3% can have significant negative effects on population levels (Rebke, 2005).

To assess the role of habitat loss on Loons, it is crucial to know if habituation to OWFs will occur or if the habitat loss will be permanent. Although studies from the UK and The Netherlands have indicated slight (though insignificant) increases in Loon abundances after 4–5 years since construction, studies from Denmark have shown no signs of habituation (Petersen and Fox, 2007; Petersen et al., 2008). Similarly, the current study found no habituation 3 years after construction. However, the monitoring of the operating wind farms is still ongoing and thus results on habituation are preliminary. Given that the degree of habituation remains very unclear, we strongly recommend the need for long-term monitoring to assess any potential large-scale effects of cumulative anthropogenic drivers on Loon distribution, particularly within the most relevant sea areas for Loons (e.g. Vanermen et al., 2015a,b).

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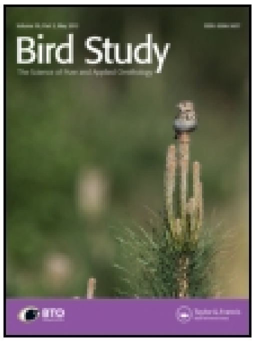

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Effects of artificial lights and moonlight on petrels at St Kilda

WILL MILES[1]*, SARAH MONEY[2], RICHARD LUXMOORE[3] and ROBERT W. FURNESS[1]
[1]Faculty of Biomedical and Life Sciences, Graham Kerr Building, University of Glasgow, Glasgow, G12 8QQ, UK, [2]Raintree House, Church Lane, Drayton St Leonard, Wallingford, Oxfordshire, OX10 7AU, UK and [3]The National Trust for Scotland, Wemyss House, 28 Charlotte Square, Edinburgh, EH2 4ET, UK

Capsule When moonlight levels are low, shearwaters and storm-petrels are attracted to artificial lighting at night at St Kilda and may be killed, but impacts are lessened by deliberate light reduction measures.
Aims To determine the scale and impacts of attraction of petrels to artificial lights at St Kilda, investigate influences of the lunar cycle, and assess effects of reducing artificial light emissions.
Methods Nightly numbers of Manx Shearwaters *Puffinus puffinus*, Leach's Storm-petrels *Oceanodroma leucorhoa* and European Storm-petrels *Hydrobates pelagicus* attracted by artificial lights were recorded in September and October from 2005 to 2008. Effects of experimental reductions to light emissions in 2007 and 2008 were assessed, together with variation in annual moonlight, mortality rates, and age of birds found.
Results Reductions to light emissions caused a decrease in numbers of Leach's Storm-petrels attracted, but had less effect on attraction of Manx Shearwaters. Only juveniles were found, the majority after nights with little or no moonlight, and mortality was extremely infrequent. Only one European Storm-petrel was found, and Leach's Storm-petrel and Manx Shearwater totals were small compared with estimated breeding totals at St Kilda.
Conclusions Numbers of petrels attracted to artificial lights on St Kilda were low. However, reductions to light emissions were still beneficial in reducing numbers of young that became disorientated, grounded, or died during fledging periods. Therefore, reductions to light emissions should be encouraged. A review of this phenomenon across the UK found it to be rare in breeding areas away from St Kilda.

Attraction to artificial lights has been observed in many different species of birds (Saunders 1930, Herbert 1970, Avery *et al.* 1976, Dick & Donaldson 1978, Harris *et al.* 1998). Among seabirds, burrow-nesting and nocturnal species such as petrels (Procellariiformes) are particularly vulnerable (Klomp & Furness 1992, Jones & Francis 2003, Montevecchi 2006). Widespread mortality of petrels has been reported in many situations where these birds are attracted to artificial lights, especially on islands with large breeding populations of shearwaters, storm-petrels, and gadfly petrels (Reed *et al.* 1985, Muirhead & Furness 1988, Brooke 1990, Warham 1996, Brooke 2004, Imber *et al.* 2005, Montevecchi 2006, Salamolard *et al.* 2007, Rodríguez & Rodríguez 2009). Tens of thousands of light-disorientated and grounded petrels have been recorded, and many birds found dead, including threatened, endangered, and endemic species (Reed *et al.* 1985, Stewart *et al.* 1996, Jones 2001, Le Corre *et al.* 2002, Le Corre *et al.* 2003, Montevecchi 2006). On several islands, conservation measures have been implemented to reduce the impacts on petrels of artificial light from buildings and to decrease further threats to grounded petrels from mammalian predators (Le Corre *et al.* 2002, Montevecchi 2006). For example, on the island of Kauai, Hawaii, large numbers of Newell's Shearwaters *Puffinus newelli*, Madeiran Storm-petrels *Oceanodroma castro* and Dark-rumped Petrels *Pterodroma sandwichensis* have been attracted to bright lights of coastal resorts, but by shielding lights to prevent upwards radiation in the largest resorts, the number of birds attracted decreased by 40% (Reed *et al.* 1985). On Tenerife, Canary Islands, public awareness and civil cooperation with care and release schemes for petrels found around the heavily-lit resorts have resulted in the

*Correspondence author. Email: willtsmiles@hotmail.com

successful release to sea of 95% of nearly 10 000 petrels found between 1998 and 2006, including Cory's Shearwaters *Calonectris diomedea borealis*, Bulwer's Petrels *Bulweria bulwerii* and White-faced Storm-petrels *Pelagodroma marina* (Rodríguez & Rodríguez 2009).

In the UK at St Kilda, Outer Hebrides, Manx Shearwaters *Puffinus puffinus* and Leach's Storm-petrels *Oceanodroma leucorhoa* have been found grounded within the inhabited area of the only village, on the island of Hirta, annually since 1969 (*St Kilda Rangers' Reports* 1969–2004, St Kilda Rangers pers. comm.). Although records have not been systematically documented every year, it is certain that in excess of 10 000 shearwaters, storm-petrels, and Atlantic Puffins *Fratercula arctica* have been found, and that these species are strongly attracted in autumn to the lights of buildings at night in the village, and formerly to streetlamps that were on at night along the shorefront (*St Kilda Rangers' Reports* 1969–2008, Harris 1984, Harris *et al.* 1998, St Kilda Rangers pers. comm., Miles & Money pers. obs.). In a successful attempt by the Ministry of Defence (MoD) and The National Trust for Scotland (NTS) to reduce numbers of puffins found grounded on Hirta, these streetlamps were turned off by the St Kilda MoD base staff through the late 1990s, and have remained turned off to date. The village on Hirta faces the island of Dùn, across Village Bay, and it is assumed that young Manx Shearwaters and Leach's Storm-petrels attracted to the village lights are mostly fledglings from the large breeding colonies on Dùn, since these species do not breed on Hirta within sight of the village. Unlike puffins (Harris *et al.* 1998), storm-petrels and shearwaters attracted to artificial lights in the village on Hirta have not been studied and, until now, mortality rates, ages of all birds, and influences of the moon on the attraction of petrels to lights at St Kilda were unknown. Dùn holds the largest breeding colony of Leach's Storm-petrels in Britain and Ireland (Mitchell *et al.* 2004). Recent declines in this colony have been reported, from an estimated 27 704 apparently occupied sites (AOS) in 1999 to 14 490 AOS in 2003 and 12 770 AOS in 2006 (Newson *et al.* 2008). Predation of Leach's Storm-petrels by Great Skuas *Stercorarius skua* has been proposed as the most likely cause of a decline, but other possible mortality factors for petrels should not be ignored. This study aimed to assess the numbers, ages and mortality of petrels attracted to the lights in the village on Hirta between 2005 and 2008; to determine the possible mitigating effects of reduced artificial lighting in the village at night; and to investigate the influence of the lunar cycle on storm-petrels and shearwaters found on Hirta.

METHODS

Study site, species, and collection of grounded petrels

St Kilda (57°47′N, 08°33′W) is located in the Outer Hebrides 66 km west of Harris. This study was carried out on the largest island in the archipelago, Hirta, in the inhabited area (0.25 km^2) of Village Bay. Petrels found grounded were Leach's Storm-petrels, European Storm-petrels and Manx Shearwaters. No other species of petrel has ever been found grounded on St Kilda owing to light attraction, and these three are the only breeding petrels on the islands, other than Northern Fulmar *Fulmarus glacialis* (Murray 2002, Mitchell *et al.* 2004), which differs in not being an exclusively nocturnal visitor to land. In all years from 2005 to 2008, the entire perimeter of every inhabited building was systematically checked for grounded petrels, within the hour after dawn, every morning between 1 September and 16 October. These dates were chosen because the vast majority of grounded petrels found prior to this study had been recorded within this period (*St Kilda Rangers' Reports* 1969–2004). Searches also included thorough examination of all potential hiding places for grounded petrels, including pipe systems, nearby vehicles, and extraction vents. All birds examined were fledglings with newly grown fresh feathers and sometimes tufts of chick down still present. When estimating the ages of Leach's Storm-petrels reference was made to photographs of known adults examined during ringing and known juveniles from burrows, examined pre-fledging at St Kilda under license. Birds examined were temporarily sheltered in the dark and on the same day released to sea at dusk. Sheltering the birds prevented any chance of otherwise exposed individuals being found by skuas, which commonly hunted within the village area during daylight (Miles & Money pers. obs.). The timing of release aimed to minimize this threat, but also to reduce the likelihood of the birds flying back towards artificial lights in the village, which were much less glaring at dusk than later in the night.

Artificial lighting and reduction measures

In 2005–2008, total artificial lighting at night in the village on Hirta included: 32 fixed outside lights, indoor lighting permanently on in two utility buildings (for access safety), and indoor lights left on at night with windows uncovered in up to 15 rooms used for accommodation. Eleven buildings in the village were used or inhabited with lighting on during nights of this study, all but two being MoD buildings of the radar base facility. The small power station for the island was the most densely-lit building, with 24-hour indoor lighting and eight outside lights. In 2005 and 2006, many indoor lights in the village were left on at night, many left uncovered, outdoor lights left on, and no reductions to light emissions made. In 2007, at our request, measures to reduce light emissions to the absolute minimum in the village were kindly implemented by staff of the radar base and NTS. These changes included all outside lights being turned off and the windows of the majority of rooms being shielded at night by curtains, blinds, or custom-made boarding. However, effects of these measures on petrels were somewhat unclear from one year's trial (see Results). In 2008, light-reduction methods were repeated as in 2007, but with an experimental period of 20 nights of no light reduction in the village, starting from the night of 22 September. The exact start date was determined by the day most convenient to the radar base staff for changing all light reduction measures on their buildings, and because of this could not be chosen entirely at random (see Discussion). The timing and short duration of the 20-day control period were considered preferable to lights being left on and uncovered for the entire late summer and autumn in 2008, because attraction of fledgling puffins would be minimized in the late summer, and numbers of petrels attracted in different light conditions would potentially be comparable within years as well as between years.

Influence of moon phase and position

We investigated possible effects of moonlight on numbers of petrels found attracted to lights in the village using two explanatory variables: the phase of the moon and the length of time that the moon was above the horizon at night. Data of percentage of the moon's face illuminated (moon phase) and percentage total duration that the moon was above the horizon at sea level between sunset and sunrise were calculated for the years of this study using annual and daily data for St Kilda from the US Naval Meteorology and Oceanography Command (www.usno.navy.mil [accessed April 2009]). Effects of the moon on daily numbers of Leach's Storm-petrels and Manx Shearwaters found in the village were investigated using a GLM with a log-link function, and arcsine transformations for proportional data were used for moon variables. All analyses were performed using R version 2.8.1.

RESULTS

Numbers, ages, and mortality of grounded petrels

Over the four years we collected 59 Manx Shearwaters, 45 Leach's Storm-petrels and 1 European Storm-petrel (Table 1). Fewer than 3% of birds were found dead in this study, all in 2006 (Table 1). They included one Leach's Storm-petrel which had become trapped in an open drain-hole and drowned, another which had landed in an open and partially-full diesel sump and become entirely saturated in fuel, and, exceptionally, one Manx Shearwater found hanging next to an outside light with its head lodged in a ventilation grill and its neck broken. Subsequently the drain-hole was covered and the diesel sump kept drained and dry at all times. All other birds (>97%) were found alive, and successfully released to sea on the same day.

Between- and within-year differences in petrel numbers and artificial light

Numbers of Leach's Storm-petrels found in the village (Table 1) differed significantly between years

Table 1. Numbers of Leach's Storm-petrels *Oceanodroma leucorhoa*, European Storm-petrels *Hydrobates pelagicus* and Manx Shearwaters *Puffinus puffinus* found between 1 September and 16 October around buildings in the village on Hirta, St Kilda, in different conditions of artificial lighting, from 2005 to 2008. Counts given in parentheses are numbers of birds found dead.

		Number of birds found			
Year	Village night lighting	Leach's Storm-petrel	European Storm-petrel	Manx Shearwater	Total
2005	On	11	0	5	16
2006	On	28(2)	0	10(1)	38
2007	Reduced	0	0	27	27
2008	Reduced (1 Jul–21 Sept) (12 Oct–16 Oct)	0	0	0	0
	On (22 Sept–11 Oct)	6	1	17	24
Total		45	1	59	105

(test for homogeneity: $\chi^2_3 = 38.65$, $P < 0.01$). The only year that none were found was 2007, when village lighting was reduced for the entire autumn period. In 2008, numbers of Leach's Storm-petrels differed significantly between periods with and without light reduction measures in place (test for homogeneity: $\chi^2_1 = 4.16$, $P < 0.05$); however, the total number of individuals found was very small (Table 1). Birds were found only during the period when light reduction measures were not in use, and the first individuals were discovered on the morning of 23 September, immediately following the first night that outdoor lights were on and lighting left uncovered in the village (Fig. 1). Leach's Storm-petrels were never found during any time in this study when measures to minimize artificial light emissions were in place. Numbers of Manx Shearwaters found in the village (Table 1) also differed significantly between years (test for homogeneity: $\chi^2_3 = 18.48$, $P < 0.01$). Unlike Leach's Storm-petrels, Manx Shearwaters were found in all years, including 2007 (Table 1 & Fig. 1). In 2008, numbers of Manx Shearwaters differed between periods with and without light reduction measures implemented at night (test for homogeneity: $\chi^2_1 = 15.06$, $P < 0.01$). Manx Shearwaters were found only within the 20-night period that no light reduction measures were in place and the first on the morning of 23 September, immediately following lights first going on (Fig. 1). Also during this period, on 4 October, the only European Storm-petrel of the study was found.

Effects of the moon on petrels and shearwater responses to artificial light

The number of Leach's Storm-petrels and Manx Shearwaters found in the village attracted to lights was influenced significantly by the percentage of the moon's face illuminated at night (GLM: $z = -3.768$, $P < 0.001$) and by the percentage of the night that the moon was above the horizon (GLM: $z = -2.243$, $P < 0.05$), with no significant interactions. Species was tested in the model as an additional explanatory variable and effects found to be non-significant. Figure 1 shows that, overall, the vast majority of Leach's Storm-petrels and Manx Shearwaters were found at times of very low moonlight, for example after nights when less than 20% of the moon's face was illuminated and after nights when the moon was above the horizon at sea level for less than 20% of the time between sunset and sunrise.

DISCUSSION

Assessment of numbers and ages of petrels attracted to artificial lights

Total numbers of Leach's Storm-petrels, European Storm-petrels and Manx Shearwaters found during this study (Table 1) were very low compared with the estimated combined total of over 60 000 individuals of these species which have annually bred at St Kilda (Mitchell *et al.* 2004, Newson *et al.* 2008). Adult breeding activity of these species may continue at the colonies until November (Brooke 2004), but only juvenile petrels were found during the study period. This strongly suggests that, in September and October, adults are not normally influenced by artificial lighting at night on Hirta. Outside of this period, it is likely that effects of the lighting on adults are also minimal. Only Manx Shearwaters have ever been found attracted to lights on St Kilda outside of the species' normal fledging times. Fewer than ten have been reported in total, and all were thought to be early or late fledglings, based on the time of year (all broadly within the autumn period) and presence of chick down in their plumage (S. Murray pers. comm. 2009, *St Kilda Rangers' Reports* 1969–2008, Snow & Perrins 1998, Brooke 2004).

Juveniles were the only age group attracted by artificial lights on Hirta in this study, but it is difficult to state the scale of effects precisely. Measures of Leach's Storm-petrel, European Storm-petrel and Manx Shearwater productivity do not exist for all years of the study, so estimates of the proportions of the total number of fledged juveniles that were attracted to lights each year cannot be determined for all species. However, it is very likely that such estimates would be extremely small, as very low numbers of petrels were found in comparison to the most recent estimates of breeding population sizes at St Kilda (Mitchell *et al.* 2004, Newson *et al.* 2008).

Effects of artificial light reduction and moonlight

Between-year differences in numbers of Leach's Storm-petrels found in the village were probably because of deliberate reductions in light emissions rather than other unknown year effects. There was a significant within-year difference in numbers of Leach's Storm-petrels found in 2008, between the times when light reduction methods were in place and the deliberate control period when light emissions were not reduced.

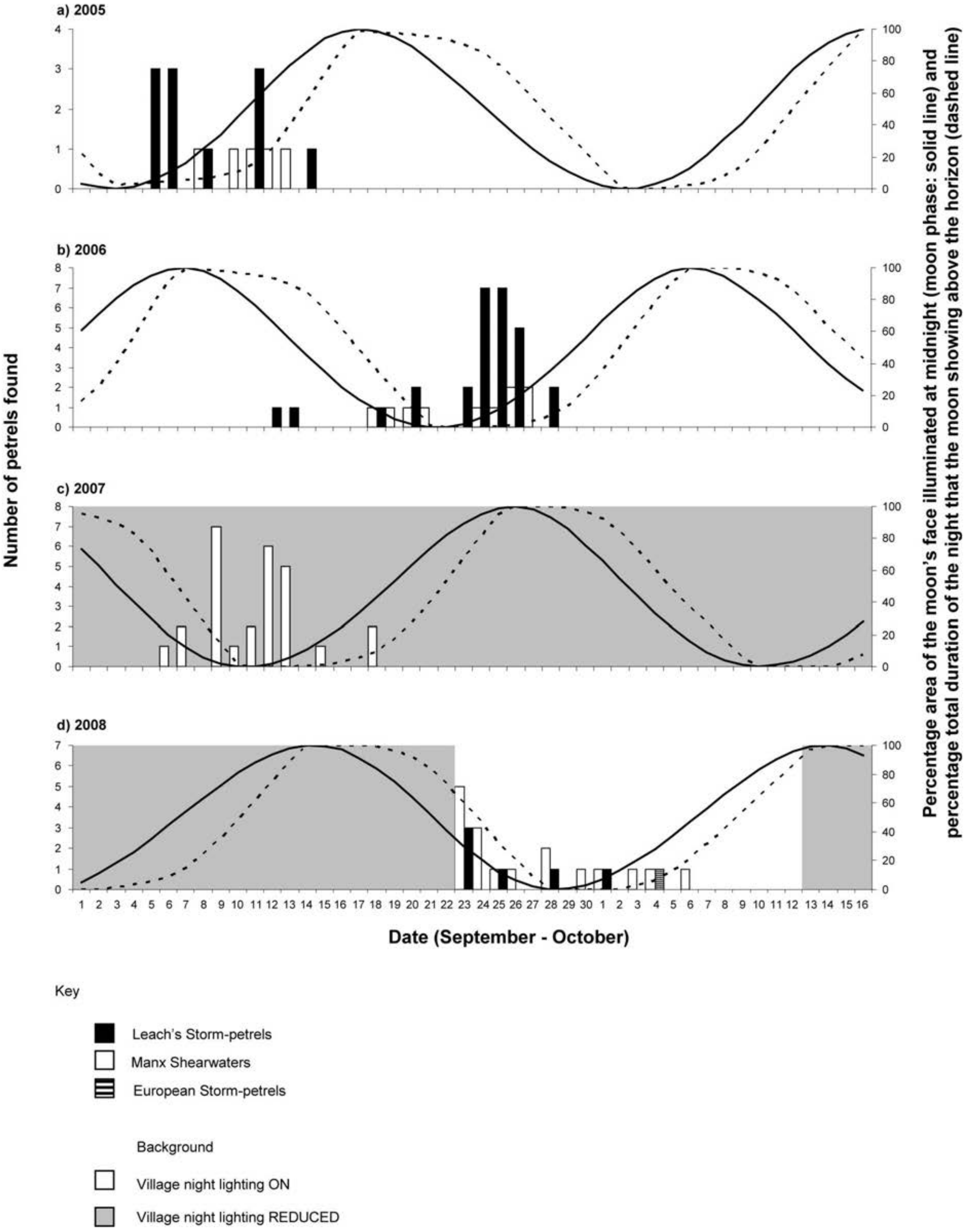

Figure 1. Distribution of numbers of Manx Shearwaters *Puffinus puffinus*, Leach's Storm-petrels *Oceanodroma leucorhoa* and European Storm-petrels *Hydrobates pelagicus* found around buildings in the village on Hirta, St Kilda, between 1 September and 16 October, with different conditions of artificial lighting (background), moon phase (solid line), and total duration that the moon was above the horizon at sea level at night (dashed line) from 2005 to 2008.

Also, numbers of Leach's Storm-petrels found in the village differed significantly between 2007, when lights were off, and the period in 2008 when lights were on (test for homogeneity: $\chi^2_1 = 4.16$, $P < 0.05$). These differences are very suggestive that differences in numbers of birds found in different years occurred in response to deliberate changes in artificial light conditions. Considering the two most obvious possible other influences (annual productivity and annual weather effects), there is little to suggest that differences in numbers were not due to the deliberate changes in light reduction measures. Productivity estimates for the species in 2007 and 2008 were not significantly different (Money *et al.* 2008, Money unpublished data) and although particularly high numbers of seabirds are found during foggy weather (Harrow 1976, Verheijen 1981, Warham 1990, Jones 2001), low-visibility and extreme weather conditions in the village on Hirta were recorded very infrequently in 2007 and 2008 (*St Kilda Ranger's Report* 2007, 2008). It was unfortunate that, owing to practical limitations, the start of the period with lighting on in 2008 could not be chosen entirely randomly, so experimental control was not perfect in this respect. However, the results showed no indication of being an artefact of experimental design and, considering this potential bias alongside the other three years' data, overall, the data seemed strongly indicative and convincing that deliberate reductions to light emissions during this study reduced attraction of Leach's Storm-petrels.

Unlike Leach's Storm-petrels, a high number of Manx Shearwaters was found in 2007, and effects of reducing light emissions on the numbers of birds attracted to the village were apparently not the same for Manx Shearwaters as for Leach's Storm-petrels that year. Given the measures in place to reduce lighting to the absolute minimum throughout 2007, it seems possible that Manx Shearwaters may still be attracted by very weak lighting, even the extremely low-level emissions on St Kilda in 2007 which did not affect the smaller species of petrel breeding at the site. Greater sensitivity to artificial lights in larger species of petrels has been suggested in other studies, for example differences between shearwaters and storm-petrels in Hawaii and in the Canary Islands (Telfer *et al.* 1987, Rodríguez & Rodríguez 2009). Additional evidence for this theory at St Kilda is that European Storm-petrels are the smallest species to breed on Hirta and nest in walls next to the MoD base (unlike Leach's Storm-petrels and Manx Shearwaters), yet have hardly ever been found grounded around buildings at any time of year, and are apparently the least sensitive to light (*St Kilda Rangers' Reports* 1969–2008, Murray 2002, Miles & Money pers. obs.). One other possibility, however, is that Manx Shearwaters may be more attracted by sounds at night than storm-petrels and that certain noises continue to attract shearwaters at times when artificial lighting is minimal or even non-existent. On Hirta, Manx Shearwaters have most frequently been found close to extractors and generators that were continuously emitting low frequency sounds, including in all years of this study. It seems likely that attraction to these sound emissions could be one explanation as to why Manx Shearwaters were found in 2007 during reduced light conditions.

Effects of the lunar cycle and position of the moon above the horizon on numbers of grounded petrels were similar in this study to those found in other studies: most petrels were found at times of least moonlight (Verheijen 1980, Telfer *et al.* 1987, Le Corre *et al.* 2002, Rodríguez & Rodríguez 2009). In 2008, a separate study was carried out on the phenology of Leach's Storm-petrels at St Kilda, in which fledging dates were recorded (Money unpublished data). Thirteen birds, out of 28 studied, fledged between the first and last quarter of the lunar cycle (7–22 September), including three on nights around the full moon (14–16 September). In other studies on light attraction of petrels, the possibility has been suggested that fewer juveniles have been found at times of greatest moonlight (e.g. full moon) because fledging was inhibited on these nights (Imber 1975, Rodríguez & Rodríguez 2009). However, for Leach's Storm-petrels at St Kilda in 2008, the phenology study suggested this was not so. The lack of grounded Leach's Storm-petrels at times of greatest moonlight was perhaps more probably because of the relative glare and attraction of artificial lights diminishing on nights when ambient light from the moon was particularly bright and long-lasting.

Occurrences of light-induced mortality of petrels at St Kilda and in the UK

Mortality of petrels found attracted to lights was very low at St Kilda (<3%). This has also been found in similar studies on much larger and more populated islands (more petrels and more people), for example Réunion Island (<10%) and Tenerife (<6%) (Le Corre *et al.* 2002, Rodríguez & Rodríguez 2009). Considering the decline in Leach's Storm-petrels reported from Dùn (Newson *et al.* 2008), in relation to our results, the possibility that high mortality of breeding and non-breeding storm-petrels may have occurred in the UK away from St Kilda was reviewed, by searching all regional bird reports and county avifaunas for records of light-induced effects and mortality of Leach's and European Storm-petrels, for all areas of the UK with storm-petrel breeding colonies (Mitchell *et al.* 2004), in all years from 1990 to 2006 (Table 2). Most frequent were records of attraction to lighthouses and harbour lighting, but unusual records included: individuals coming to flashes from a garden fireworks display (Egilsay, Orkney, 5 November 2005); attraction to oil terminal flares (Sullom Voe, Shetland, 3 November 2000); and several individuals attracted to moth traps (Skaw, Shetland, 30 July 2004). Given the time period and area covered (Shetland, Orkney, all regions of the UK north and west coasts, Scillies, and the Channel Islands), records were surprisingly few in total (<120 individuals). However, the proportion of all records of storm-petrels found dead (21%) was high in comparison with our study at St Kilda (<2%). Perhaps because records from regions of the UK other than St Kilda were not all made systematically, they were possibly biased by a greater likelihood of dead birds being found during casual observations than live and potentially transitory individuals. Even with this consideration, the results of this search strongly suggest that in areas of the UK with storm-petrel breeding colonies away from St Kilda, mortality of Leach's Storm-petrels and European Storm-petrels owing to light attraction has also been very low in comparison to estimated UK breeding population sizes (Mitchell *et al.* 2004). It was notable that the highest proportions of all Leach's Storm-petrel and European Storm-petrel records (70% and 86.6%, respectively) came from Bardsey lighthouse. This may partly be explained by relatively high observer coverage at this light source, but even taking this into account, this site has a high attraction power to birds in comparison with other intensively watched sites with lighthouses, such as North Ronaldsay and Fair Isle (Bardsey, Fair Isle, North Ronaldsay, and Orkney *Bird Reports* 1990–2006). Possible reasons suggested for this have included differences in lighthouse beam characteristics (e.g. light frequency and rotation rate), as well as site location differences relative to species' migration routes and breeding areas, migration bottlenecks, seabird foraging ranges, and seasonal and local weather patterns (Saunders 1930, Herbert 1970, Verheijen 1981, *BardseyBird Reports* 1990–2006, Brooke 1990, Jones 2001, Jones & Francis 2003, D. Shaw pers. comm. 2009). Overall, in areas of the UK with breeding storm-petrels, it seems that very low numbers of individuals are affected by artificial lighting relative to estimates of total breeding population sizes, and light attraction is not a cause of high mortality.

Table 2. Total annual numbers and mortality of Leach's Storm-petrels *Oceanodroma leucorhoa* and European Storm-petrels *Hydrobates pelagicus* recorded at artificial light sources in regional bird reports and avifaunas for all regions of the UK with storm-petrel breeding colonies other than St Kilda, for all years from 1990 to 2006.

Year	Leach's Storm-petrels found	European Storm-petrels found
1990	2	8
1991	0	2
1992	1	2
1993	0	2
1994	3	8
1995	2	3
1996	0	2
1997	4	0
1998	2	2
1999	1	6
2000	3	3
2001	0	0
2002	8	16
2003	0	1
2004	3	16
2005	1	9
2006	0	2
Total	30	82
Total found dead	8 (26.7%)	15 (18.3%)

The status of St Kilda as a Site of Special Scientific Interest, Special Protection Area, and World Heritage site means that increases in the number of brightly-lit buildings on the archipelago are unlikely. The inhabited village is the only area of Hirta with lighting on at night, with the exception of one MoD building on the hilltop, which has outside lighting occasionally left on. Petrels have been discovered near this building during the daytime by staff of the radar base, but very few birds have been found, less than annually, and the vast majority of these were alive. There are no other sources of artificial light on land at St Kilda and it is rare for brightly-lit ships to anchor for long near the islands. In conclusion, numbers of petrels attracted to artificial lights on St Kilda are low, very few are killed by the phenomenon, but reductions to artificial light emissions should be encouraged since they are beneficial in reducing numbers of fledglings that are grounded.

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Research article

Northern gannets (*Morus bassanus*) are strongly affected by operating offshore wind farms during the breeding season

Verena Peschko [a,*], Bettina Mendel [a], Moritz Mercker [b], Jochen Dierschke [c], Stefan Garthe [a]

[a] *Research and Technology Centre (FTZ), University of Kiel, Hafentörn 1, 25761, Büsum, Germany*
[b] *Bionum GmbH - Consultants in Biostatistics, Finkenwerder Norderdeich 15a, 21129, Hamburg, Germany*
[c] *Institute of Avian Research, An der Vogelwarte 21, 26386, Wilhelmshaven, Germany*

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ABSTRACT

Northern gannets (*Morus bassanus*) have been ranked as one of the most vulnerable species in terms of collision with offshore wind farm (OWF) turbines, and strong avoidance of OWFs has been documented for this species. Gannets increasingly encounter OWFs within the ranges of their largest breeding colonies along the European coasts. However, information on their actual reactions to OWFs during the breeding season is lacking. We investigated the possible effects of OWFs located 23–35 km north of the colony on Helgoland in the southern North Sea on breeding gannets. GPS tags were applied to 28 adult gannets breeding on Helgoland for several weeks over 2 years. Most gannets (89%) predominantly avoided the OWFs in both years, but 11% frequently entered them when foraging or commuting between the colony and foraging areas. Flight heights inside the OWFs were close to the rotor-blade zone, especially for individuals predominantly avoiding the OWFs. Gannets preferred distances of 250–450 m to the turbines when being inside the OWF. A point process modelling approach revealed that the gannets resource selection of the OWF area compared with the surroundings (outside OWF = up to 15 km from the OWF border) was reduced by 21% in 2015 and 37% in 2016. This study provides the first detailed characterisation of individual reactions of gannets to OWFs during the breeding season and one of the first comprehensive studies of OWF effects on this species based on telemetry data. The documented effects need to be considered during the planning processes for future OWFs, especially those located close to large seabird breeding colonies.

1. Introduction

Seabirds increasingly encounter offshore wind farms (OWFs) in European waters, especially over the past 10–15 years (Perveen et al. 2014; Windeurope 2020; Bórawski et al. 2020). Seabirds such as northern gannets (*Morus bassanus*, hereafter gannet), depend on offshore areas for foraging, and also for resting and moulting (Schreiber and Burger 2001). It is therefore necessary to study and understand the potential OWF effects, especially during the breeding season when birds have a restricted foraging range and choice of foraging habitats, and are under increased pressure to find enough prey to raise their offspring (Orians and Pearson 1979). However, few studies have explicitly investigated the reactions of seabirds towards OWFs during this stage of their life cycle (Masden et al. 2010; Thaxter et al. 2015, 2018).

Seabirds show different behavioural reactions towards OWFs ranging from complete avoidance to attraction (Drewitt and Langston, 2006; Furness et al. 2013; Dierschke et al. 2016). As a wide-ranging seabird species, gannets can encounter OWFs with increasing frequency in range of their largest breeding colonies along the European coasts (Grecian et al. 2012; Bradbury et al. 2014). Their flight height and manoeuvrability make gannets one of the most vulnerable species in terms of collision with turbines (Garthe and Hüppop, 2004; Furness et al. 2013). In Scottish waters, it was predicted that the gannet population on the Bass Rock could be affected due to a relatively high number of predicted collisions with future OWFs (Cleasby et al. 2015). Furthermore, strong avoidance of OWFs was found for gannets in most studies (reviewed in Dierschke et al. 2016). At the Blight Bank OWF for example, an 85% reduction in gannet density was detected in the OWF (Vanermen et al. 2015), while a study at the Alpha Ventus OWF in German waters found a reduction of 75% inside the OWF (Welcker and

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* Corresponding author.
E-mail addresses: peschko@ftz-west.uni-kiel.de (V. Peschko), mendel@ftz-west.uni-kiel.de (B. Mendel), info@bionum.de (M. Mercker), jochen.dierschke@ifv-vogelwarte.de (J. Dierschke), garthe@ftz-west.uni-kiel.de (S. Garthe).

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Nehls 2016). Displacement and collision effects of OWFs may thus have different consequences for gannets in terms of habitat loss and direct mortality.

Although some knowledge on the general avoidance of OWFs by gannets is available, very little is known on the individual reaction and movement patterns in and around the OWFs, the behaviour of the gannets close or inside the OWFs as well as their flight height compared to the turbine height. GPS tracking can generate valuable data on fine- and large-scale habitat use and behaviours (Garthe et al. 2007; Thaxter et al. 2018), as well as changes in these with regard to changing environmental conditions (Garthe et al. 2011; Paredes et al. 2014). However, few studies to date have used GPS tags to investigate effects of operating OWF on seabirds (Thaxter et al. 2015, 2018; Garthe et al. 2017a; Peschko et al. 2020). In a recent pilot study, for example, Garthe et al. (2017a) showed that three gannets equipped with GPS tags largely avoided the operating OWFs north of Helgoland. Based on flight heights collected before OWF construction, Cleasby et al. (2015) predicted the possible collision risk of breeding gannets with respect to future OWFs.

Three wind farms, covering an area of 105 km^2, are currently operating only 23–35 km north of Helgoland. However, the only gannet colony in the southern North Sea is located on Helgoland, highlighting the need to assess the possible effects of these nearby OWFs on the local gannet population. We therefore applied GPS tags on adult gannets for several weeks during two consecutive breeding seasons to generate a unique, extensive, and detailed dataset of gannet movements and behaviours to address the following questions: Do gannets breeding on Helgoland react to the presence of OWFs close to their colony? Are gannets displaced or attracted by the OWFs and can we quantify their reactions? Are there individual differences between the birds' reactions towards the OWFs? How do the gannets behave in the vicinity of or inside the OWFs in terms of foraging and flight heights? Do they behave similarly in consecutive years? We approached these questions by visualizing and quantifying the reactions of gannets towards OWFs based on recorded foraging trips, behaviours, and altitudes. We also applied a state-of-the-art modelling approach for telemetry data (spatio-temporal point process model; PPM) to investigate if resource selection of the OWF area was reduced in comparison with the areas outside the wind farm.

2. Materials and methods

2.1. Fieldwork and data collection

Gannets were caught on the island of Helgoland (54°11′ N, 7°55' E) in the south-eastern North Sea. Gannets started to breed on Helgoland in 1991 and the colony increased to 1071 breeding pairs in 2017 (Dierschke et al. 2018). Using a noose pole, we caught 28 incubating or chick-rearing gannets during the breeding seasons in 2015 and 2016. GPS devices were attached to the base of the four central tail feathers using TESA® tape (Beiersdorf AG GmbH, Hamburg, Germany). Sixteen gannets each received a Bird Solar GPS logger (e-obs GmbH, Munich, Germany, 39 g), eight were equipped with OrniTrack-25 loggers (Ornitela, Vilnius, Lithuania, 25 g), and four with both a CatLog-S GPS logger (Catnip Technologies, Hong Kong SAR, China) and a precision temperature–depth (PTD) logger (Earth and OceanTechnologies, Kiel, Germany, CatLog-S plus PTD: 64 g). The attached devices represented 0.8%–1.9% of the mean gannet body mass of 3286 g (Wanless and Okill 1994), which was well below the recommended threshold of 3% (Phillips et al. 2003). Although attachments to the tail may have negative effects on flight behaviour (Vandenabeele et al. 2014), most pairs successfully incubated their eggs and/or raised their chicks, similar to non-handled nests. The mean handling time was 17 min, and the birds were released in close proximity to their nest. Eggs were observed during the handling period to prevent nest predation. Individuals were either re-caught after 3–4 weeks to remove the devices, or the devices fell off during moulting. All GPS devices recorded the date, time, and geographic position with a sampling interval of 2–5 min. When the battery was low, the solar devices reduced the sampling interval to 15–30 min. In 2016, at each regular sampling interval, the e-obs devices were additionally programmed to record positions continuously for 15 s to generate reliable flight-height measurements (see below). The Bird Solar GPS devices transmitted data via a UHF connection to a base station, and the OrniTrack-25 devices transmitted data via GSM. Recapture was thus only mandatory for CatLog-S devices.

Gannet catching and tagging were conducted in accordance with the German Protection of Animals Act and with the permission of the Ministry of Energy, Agriculture, the Environment, Nature and Digitalization (file number V 242-7224.121-37).

2.2. Foraging trips

We did not interpolate the birds' positions because we focused on their reactions to OWFs and therefore chose to use the original data points, representing the true positions of the individuals. Some devices recorded at 1-s intervals during different periods of the data collection and we excluded these data points from the trip identification, the behavioural analysis and the statistical modelling, but used them for the analyses of flight heights and the distance of the birds to the single turbines. Based on the number and duration of tracks passing through the OWFs, we classified birds which have entered the OWFs on more than three occasions and stayed for more than 30 min inside the OWFs during each occasion as 'attracted' to the OWFs. The remaining birds were classified as 'predominantly avoiding individuals'.

All trips with a duration of $>$20 min and $\geq$1 km distance from the nest were classified as foraging trips, using an R code provided by Lascelles et al. (2015) which also estimated the duration (h) and total and maximum distance (km) of the foraging trips. We applied linear mixed models (LMM; R-package lme4 (Bates et al. 2015)) to test if the duration (h) and total and maximum distance (km) differed between the years, controlling for by-individual variability. Subsequently we performed a likelihood ratio test for the full compared to the null model applying an ANOVA.

To find out if there was an overall difference in the amount of trips crossing and positions in the OWFs between the years, we calculated the percentage of trips and positions within the OWFs for each individual bird. We estimated the percentage of trips inside the OWF for trips with $>$ 3 positions in the OWF and the overall percentage of positions inside the OWFs. We then applied LMMs to test if the percentage inside the OWF changed depending on the year, controlling for by-individual variability. Subsequently we performed a likelihood ratio test for the full compared to the null model applying an ANOVA. We furthermore grouped the results in different categories: 0%, 0.01–10%, $>$ 10% of trips passing through an OWF and 0%, 0.01–1%, $>$ 1–2% and $>$ 2% of positions inside the OWFs.

2.3. Behavioural classification

Behavioural states were identified by expectation-maximization binary clustering (EMbC, Garriga et al. 2016), as a robust non-supervised multivariate clustering algorithm that minimises prior assumptions and favours a semantic interpretation of the final clustering by splitting the input features into low and high values of speed and turning angle (Garriga et al. 2016). This offers a new approach to the classification of behavioural states and has already been successfully applied in several studies (Mendez et al. 2017; Jones et al. 2018). The algorithm assigns each location to one of the following four clusters (see Supporting Information S1, Table S1): high velocity/low turn (HL), high velocity/high turn (HH), low velocity/low turn (LL), and low velocity/high turn (LH). HL was interpreted as 'travelling/commuting' behaviour, the two states with low speeds (LL, LH) were merged into one and interpreted as 'resting', and HH was identified as 'foraging' behaviour (see Supporting Information S1, Table S1). EMbC analysis was conducted using the R package EMbC v2.0.1 (Garriga et al. 2018), and a smoother function was applied to account for temporal association in behavioural states.

The areas in which the different behavioural states were shown were visualized by assigning kernel densities of the positions to each category in ArcGIS using the ArcMET tool (version 10.2.2v3; Wall 2014). We furthermore investigated how close the gannets approached the single wind turbines during the different behavioural states, and we additionally used the 1-s intervals of the GPS bursts (c.f. below) to investigate which distances to the single turbines the gannets preferred while being in the OWF. For further details on both approaches, see Supporting Information S3.

2.4. *Flight heights*

Altitude estimates are improved by increasing the satellite-connection time (e.g. Corman and Garthe 2014). The e-obs devices were thus programmed to record GPS positions every second during bursts of 15 s duration (if the tag battery allowed), in addition to the normal GPS schedule. Variability of altitude measurements was quantified by conducting tests at two locations of known height, a rooftop (13.5 m) and nest (53 m), which showed mean values of 12.8 m (±2.3 m SD) and 53.4 m (±5.8 m SD), respectively. After inspection of the data, we decided to use bursts of $\geq$ 11 s duration for flight-height analysis. Appropriate data were available for eight gannets tagged in 2016. We analysed flight heights as described by Garthe et al. (2017b), with slight modifications. Briefly, if the last flight height measurement in a burst differed by $>$ 5 m from the preceding one, probably indicating a flight manoeuvre, we used the preceding measurement rather than the last one and assumed the best altitude estimate. We excluded the positions of resting birds using the EMbC method (see 'behavioural classification'). Using ArcGIS (version 10.3; Environmental Systems Research Institute (ESRI), 2016) we retrieved the information if a GPS-position with an associated flight height measurement was located inside the OWF (no buffer around OWF borders) or outside the OWF (= *owf_yn_height*). To find out if the gannets changed their flight heights inside compared to outside the OWF, we applied a generalised additive mixed model (GAMM) with the flight height as dependent variable and *owf_yn_height* as predictor. The appropriate probability distribution was chosen based on the AIC. We furthermore included the individual bird-ID as random factor to control for by-individual variability, and finally added the relevant autocorrelation terms. We additionally investigated the possible effect of the distance to single wind turbines on the flight height inside the OWFs (for further details, see Supporting Information S3).

2.5. *Statistical modelling*

2.5.1. *Preparation of covariates*

The means of the spatial covariates for a grid with a spatial resolution of 200 × 200 m were calculated using ArcGIS (version 10.3; Environmental Systems Research Institute (ESRI), 2016). The variables used for modelling included (1) *owf_yn* = a categorical variable indicating if the grid cell lies inside the OWF (no buffer around OWF borders) or outside the OWF, (2) *dist_Helgoland* = minimal distance of the grid cell to the island of Helgoland, (3) *depth* = mean water depth in the grid cell, and (4) *slope* = inclination of the seabed in the grid cell.

2.5.2. *PPMs*

We determined if the habitat use by gannets was affected by the presence of OWFs by applying a spatio-temporal-PPM (realized within the GAMM framework) to a dataset consisting of 49,185 raw data points collected in 2015 and 38,581 data points collected in 2016. We concentrated the analysis on an area of up to 15 km from the OWF border (Fig. 2a and b) as we aimed to understand the gannets reactions in close vicinity of the OWFs. Limiting the size of the study area to a 15 km buffer around the OWFs furthermore helped to minimize a possible bias by other factors (e.g. fishing vessels) which could not be included in the model, and moreover reduced possible influences of the natural high-density area very close to the colony (Fig. 2). Finally, we considered different covariates within the analysis (such as distance from the colony, depth, or slope), in order to distinguish between the OWF effect and the partial effect of these factors which could have influenced the spatial distribution within the chosen radius. Thus, the size of 15 km was the optimal compromise comprising enough data on the one hand and minimizing the possible influence of external factors on the other hand. We have furthermore chosen to concentrate our analysis on the OWF cluster close to Helgoland as we aimed to investigate how gannets react towards OWFs in close vicinity of their colony. For a sound analysis of the reactions to OWFs further apart from the colony, data were too sparse for the current analysis. Each year was analysed separately as the construction status of the OWFs was different in 2015 and 2016. Only the fully commissioned and operating OWFs were considered in the analysis.

Statistical analysis of telemetry data investigating resource selection is often challenging, and various modelling strategies have been developed, including (integrated) step selection functions (Thurfjell et al. 2014; Avgar et al. 2016) and point process approaches (Johnson et al. 2013; Renner et al. 2015). Both approaches use contrasting points (e.g., 'dummy points', 'pseudo-absences', or 'available steps') in addition to true tracking locations, making it possible to compare selected versus available resources. Methods using contrasting points tend to produce better results than techniques using presence points alone (Brotons et al. 2004; Elith et al. 2006; Barbet-Massin et al. 2012).

In the following analysis, we used and extended the spatio-temporal PPMs presented by Renner et al. (2015), which naturally and automatically resolve many of the questions and pitfalls associated with alternative approaches (Warton and Shepherd 2010; Warton and Aarts 2013; Renner et al. 2015). For example, the role and number of dummy points is not *ad hoc*, but can be deduced mathematically by the efficient estimation of an integral as a part of the PPM likelihood (Warton and Shepherd 2010; Warton and Aarts 2013). Additionally, PPMs represent a generalisation of many other frequently used methods (Johnson et al. 2008; Warton and Shepherd 2010; Aarts et al. 2012). Finally, the PPM likelihood can be approximated by a mathematical method using standard generalised linear or additive mixed modelling-regression software (Johnson et al. 2013; Renner et al. 2015), ensuring flexible and individual implementation. Details of the modifications of the PPMs compared with the spatio-temporal PPMs are presented by Johnson et al. (2013) (see Supporting Information S2).

2.5.3. *Model selection.*

When applying the GAMM-PPM to the tracking raw data, convergence of the log-likelihood was approached after two cycles of refinement of the dummy point mesh in 2015 and one cycle of refinement in 2016 leading to 357,252 respectively 43,607 dummy points.

The optimal model regarding the set of fixed-effect predictors was selected by comparing 12 different models for each year, based on the Akaike Information Criterion (AIC; Akaike 1973). Inspection of the results of the best models showed that all models revealed similar patterns in the data, indicating that our main results were robust across different models. We first inspected a basic model only including autocorrelation terms, random effects, and the variable *owf_yn*, which was the main focus of the analysis:

$$Z \sim \beta + te\left(log_{d_t}, log_{d_s}, angle,\ k = c(5,5,5)\right) + s(trip_{id}, bs = \text{'}re\text{'}) + s(bird_{id}, bs = \text{'}re\text{'}) + owf\_yn \tag{1}$$

where β is the intercept and *te()* a tensor-product regression spline considering temporal, spatial and directional autocorrelation, where the optimal number of knots (maximal 5 per variable to avoid over-smoothing) has been estimated via generalised cross-validation. $Trip_{id}$ and $bird_{id}$ where included as random effects, indicated by the term *s(…, bs = 're)*. In order to approximate the PPM likelihood based on standard

GAMM software, a weighted regression Poisson model has been fitted, using regression weights W and observations Z, where $Z = 1/W$ has been defined for tracking points, and $Z = 0$ for dummy points. Especially, W are appropriate quadrature weights based on the 2D rectangle rule (for more technical details see for example Johnson et al. 2013).

We subsequently added other variables to the basic model to find the best model for our data. We restricted the number of variables added to the basic model to a maximum of three to keep the models interpretable. The best model was then selected via the AIC. For the data collected in 2015 the best model additionally included the covariates *dist_Helgoland* and *depth*:

$$\begin{aligned} Z \sim \beta + te\left(log_{d_t}, log_{d_s}, angle,\ k = c(5,5,5)\right) + s(trip_{id}, bs = \text{'}re\text{'}) \\ + s(bird_{id}, bs = \text{'}re\text{'}) + owf\_yn + dist\_Helgoland + deph \end{aligned} \tag{2}$$

For the data collected in 2016 the best model additionally included the covariates *dist_Helgoland* and *slope:*

$$\begin{aligned} Z \sim \beta + te\left(log_{d_t}, log_{d_s}, angle,\ k = c(5,5,5)\right) + s(trip_{id}, bs = \text{'}re\text{'}) \\ + s(bird_{id}, bs = \text{'}re\text{'}) + owf\_yn + dist\_Helgoland + slope \end{aligned} \tag{3}$$

2.5.4. Model validation, numerical realisation, and software

PPM model-validation plots for the final GAMM-PPM were generated based on PPM-Pearson residuals (Baddeley and Turner, 2005; Baddeley et al. 2005). All statistical analyses were performed using the free statistical software R (R Core Team 2017). Spatial statistics were performed using *spatstat* (Baddeley and Turner, 2005), dummy-point meshes and trapezoid rule-based quadrature weights were created using *mvQuad* (Weiser 2016), GAMM and GAM fits were performed using the package *mgcv* (Wood 2006). All the codes were programmed such that the main parts of the code could be run using parallel computing, using the *parallel* package and the *bam()* function from the *mgcv* package.

3. Results

3.1. Overview of foraging trips

We recorded a total of 1182 individual foraging trips by 28 gannets (12 females and 16 males) in 2015 and 2016 (Table 1). Only the mean duration was significantly higher in 2016 than in 2015 (Table 1). The same large-scale area was used for foraging in both years (Fig. 1).

3.2. Avoidance of and attraction by OWFs

3.2.1. Foraging trips

Most individuals mainly avoided the OWFs north of Helgoland ('predominantly avoiding individuals', n = 25, 89% of individuals; Fig. 2) and most foraging trips passed the OWFs at the south-west border (Fig. 2a and b). However, two individuals in 2015 and one in 2016 (all males) frequently entered the OWFs north of Helgoland ('attracted individuals', n = 3, 11% of individuals, Fig. 2c and d) and also visited other OWF areas further from the colony (Fig. 2e and f). Of all individuals tagged in 2015, eight (= 67%) did not enter the OWFs during their foraging trips (Table 2, considering trips with ≥ 3 positions in OWF), two (= 17%) entered the OWFs during 0.01%–10%, and two (= 17%) entered them during > 10% of their foraging trips (Table 2). In 2016, eight (= 50%) did not enter the OWFs, seven (= 44%) entered on 0.01%–10% and one (= 6%) on > 10% of their foraging trips. In 2015, five (= 42%) of the tagged individuals recorded no positions in the OWFs (two = 13% in 2016), four (= 33%) recorded 0.01%–1% (12 (= 75%) in 2016), two (= 17%) recorded > 1%–2% (one = 6% in 2016), and one (= 8%) recorded > 2% of their positions in the OWF (one = 6% in 2016) (Table 2). When comparing the individual amount of trips crossing and positions in the OWFs between the two years, no significant difference in either %-trips or %-positions in OWFs between 2015 and 2016 was found (Table 2).

3.2.2. Behaviour

Differentiating among the behavioural categories foraging, travelling, and resting, showed that individuals 'predominantly avoiding' the OWFs mainly used areas west and north-west of Helgoland (i.e. south-west or west of the OWFs) to commute to and from the colony (Fig. 3a). They seldom entered the OWFs when travelling between the colony and foraging areas. These individuals used many different areas for foraging, some north-west and some north-east of Helgoland, and some located south and north-east of the OWFs (Fig. 3b), but very few located in the OWFs. Additionally, they did not enter the OWFs while resting (Fig. 3c). In contrast, the gannet that was attracted to the OWFs mainly used an area between the island and the OWFs for commuting to and from the colony and frequently entered the OWFs when travelling (Fig. 3d). For this individual, most of its foraging area was located in the OWFs or nearby, north-west of the OWFs (Fig. 3e). In 2015 the individuals attracted to the OWF also used it intensely for foraging, however they additionally foraged outside the OWF (see Supporting Information S4). Only individuals attracted to the OWF in 2015 entered the wind farms while resting (see Supporting Information S4), in 2016 individuals only entered the OWFs rarely or not at all when resting (Fig. 3f). Only data for the 2016 breeding season are shown here, but similar patterns were detected in 2015 (see Supporting Information S4).

The kernel densities of the core foraging areas (25% foraging percentile) of the individuals attracted to the OWFs overlapped with the operating OWFs by 12.5% in 2015 and by 33% in 2016 with one more OWF operational (Table 3). Only 6.5% (7.1% in 2016) of the core travelling and 2.6% (0% in 2016) of the core resting areas of these individuals overlapped with the OWFs in 2015. For individuals predominantly avoiding the OWFs in both years, < 1% of the kernel densities of each behaviour overlapped with the OWFs.

In all three behavioural states and also when analysing the 1-s intervals of the GPS bursts, a preference for the area between 250 and 450 m distance from the turbines was revealed for the gannets when they were inside the OWF (Fig. 4, and Supporting Information S3, Fig. S3; distance between single wind turbines = 600–1200 m). The strongest avoidance was found between 0 and 250 m distance from the turbines (Fig. 4, and Supporting Information S3, Fig. S3). A slightly higher preference for closer distances to the turbines appears for the foraging behaviour, though it was not found to be significant (for further details see Supporting Information S3). The separate visualization of the distance to the turbines for 'attracted' and 'predominantly avoiding' individuals furthermore shows, that when being inside the OWFs, attracted individuals approached the turbines more than individuals avoiding the OWFs (Fig. 4b).

Table 1

Total number of foraging trips in 2015 and 2016, as well as mean values for: duration, maximum distance, and total distance.

	2015	2016	χ^2	*p*-value
Trips (n)	580	602	–	–
Duration (h)	7.83 (0.33–61.23)	10.93 (0.33–116.87)	6.7134	<0.01
Max. distance (km)	38.37 (1.10–388.36)	53.11 (1.10–392.67)	1.9879	0.16
Total distance (km)	110.28 (2.33–1021.17)	139.61 (2.77–1118.53)	0.312	0.58

$\chi^2$and *p*-values for LMMs. Values in brackets indicate the minimum and maximum.

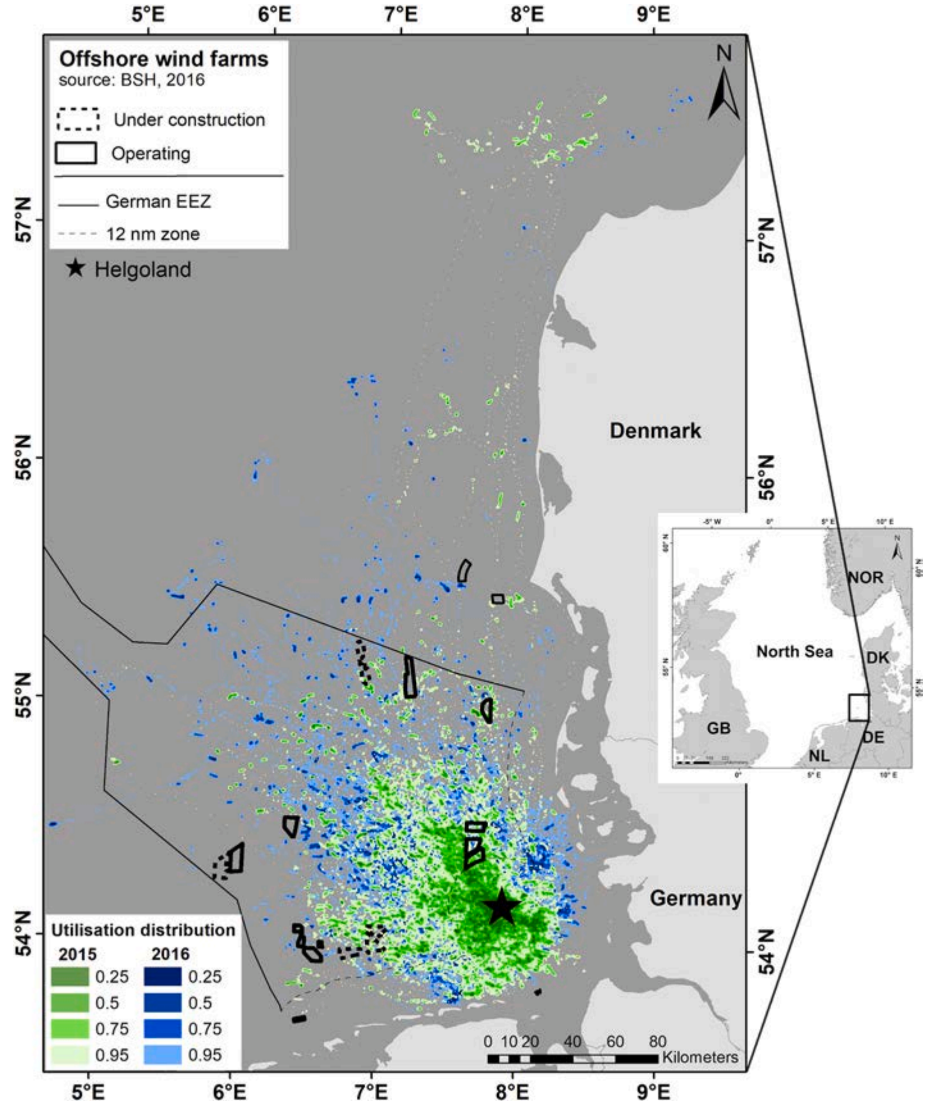

Fig. 1. Kernel densities of northern gannets tagged in 2015 (green) and 2016 (blue). OWF status in 2016: dashed black line = under construction, solid black line = operating. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2.3. *Flight heights*

Gannets flew at significantly higher altitudes inside compared with outside the OWFs (mean height 17.9 m (n = 209) vs 14.4 m (n = 2640), respectively, $p = 0.082$) (Table 4, Fig. 5). Flight heights were mostly below the rotor-blade zone (RBZ; 30–150 m) (Fig. 5). Individuals ‘predominantly avoiding’ the OWFs showed higher flight heights inside compared to outside the OWFs (mean height 27.3 m (n = 60) vs 14.7 m (n = 2200), respectively, with their mean altitude inside the OWFs just below the RBZ, however the GAMM did not detect a significant effect ($p = 0.287$). The individual ‘attracted’ to the OWFs flew at significantly higher altitudes inside than outside the OWFs ($p = 0.059$), but mainly used altitudes below the RBZ. Flight heights during travelling were not significantly higher inside than outside the OWFs (mean 17.9 m (n = 91) vs 12.8 m (n = 1645), respectively, $p = 0.157$). There was no significant difference in flight heights during foraging behaviour ($p = 0.413$). Altitudes were significantly higher during foraging compared with travelling (mean 17.8 m (n = 1113) vs 13.7 m (n = 1736), respectively, $p < 0.001$). In most distances to the turbines ‘attracted individuals’ tended to use lower flight heights than the ‘predominantly avoiding’ individuals, the latter tending to use increased flight heights with distance to the turbines (Fig. 6). However, no significant change of the flight height with distance to the turbines was revealed (all p-values > 0.1).

3.2.4. *Avoidance strength*

Both the basic and best models revealed a significantly reduced selection of the OWFs compared with the surrounding area in 2015 (basic model, Table 5; best model, Table 6, variable ‘inside OWF’, estimate = −0.240, p = < 0.001, response = exp(estimate) = 21% reduced selection inside the OWF compared with outside, lower confidence interval (CI) = 30% reduction, upper CI = 11% reduction). Both the basic and best models revealed a significantly reduced selection of the OWFs compared with the surrounding area in 2016 (basic model, Table 7; best model, Table 8; variable ‘inside OWF‘, estimate = −0.461, $p = < 0.001$, response = exp(estimate) = 37% reduced selection inside the OWF compared with outside, lower confidence interval (CI) = 45% reduction, upper CI = 28% reduction).

4. Discussion

This study provides the first detailed characterisation of the reactions of gannets during the breeding season to OWFs, and is one of the first comprehensive studies of these effects based on telemetry data. Gannets' reactions indicated that they were susceptible to OWF effects such as habitat loss, increased flight distances, and collisions, with potential effects on their energy budget and mortality. These findings add to our

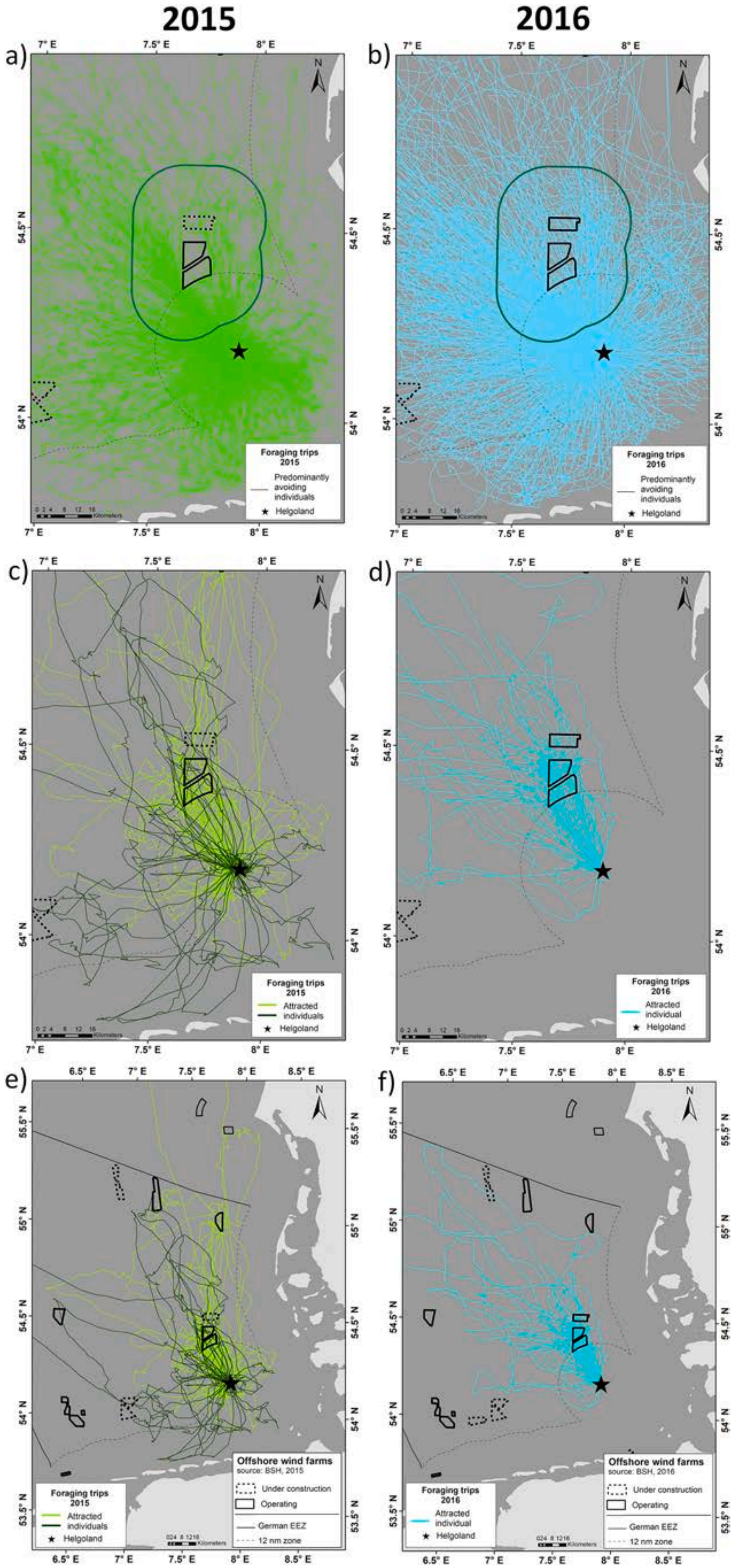

Fig. 2. Flight behaviours of gannets tagged in 2015 (n = 10) (a) and 2016 (n = 15) (b) that 'predominantly avoided' the OWFs (all individuals shown in the same colour). Gannets tagged in 2015 (n = 2) (c) and 2016 (n = 1) (d) that were classified as 'attracted individuals' (individuals shown in different colours). (e) & (f) Large-scale movements of individuals shown in (c) and (d). OWFs: dashed black = under construction, solid black = operating, dark green line = 15 km buffer applied for PPM analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Percentages of individuals in relation to their use of OWFs.

		No. and (%) of individuals		Linear mixed model	
	%	*2015*	*2016*	χ^2	*p*
Trips with ≥ 3 positions in OWF	***0***	8 (67)	8 (50)	0.4069	0.524
	0.01–10	2 (17)	7 (44)		
	> 10	2 (17)	1 (6)		
Positions in OWF	***0***	5 (42)	2 (13)	0.0053	0.942
	0.01–1	4 (33)	12 (75)		
	> 1–2	2 (17)	1 (6)		
	> 2	1 (8)	1 (6)		

OWF = 0 m distance to border of the OWF.

current knowledge regarding the vulnerability of gannets to OWFs in close vicinity to their breeding colonies, and should thus be included in models of collision risks and population-level effects.

Using a PPM approach, we showed that the gannets resource selection of the OWF area was significantly reduced compared with the surroundings in both breeding seasons. The reduction was lower than that reported by line-transect surveys (Vanermen et al. 2015; Welcker and Nehls 2016); however, these studies were estimated for the entire yearly cycle rather than focussing on the breeding period. Gannets might be more flexible in their choice of habitat when they are not bound to their colony and do not need to feed their offspring. In contrast, gannets may accept passing through OWFs more during the breeding season if it reduces their travel time and costs considerably. However, avoidance estimated from survey data (investigating effects on density or abundance of species) cannot be compared directly with values estimated from tracking data (inferring resource selection), and the resulting

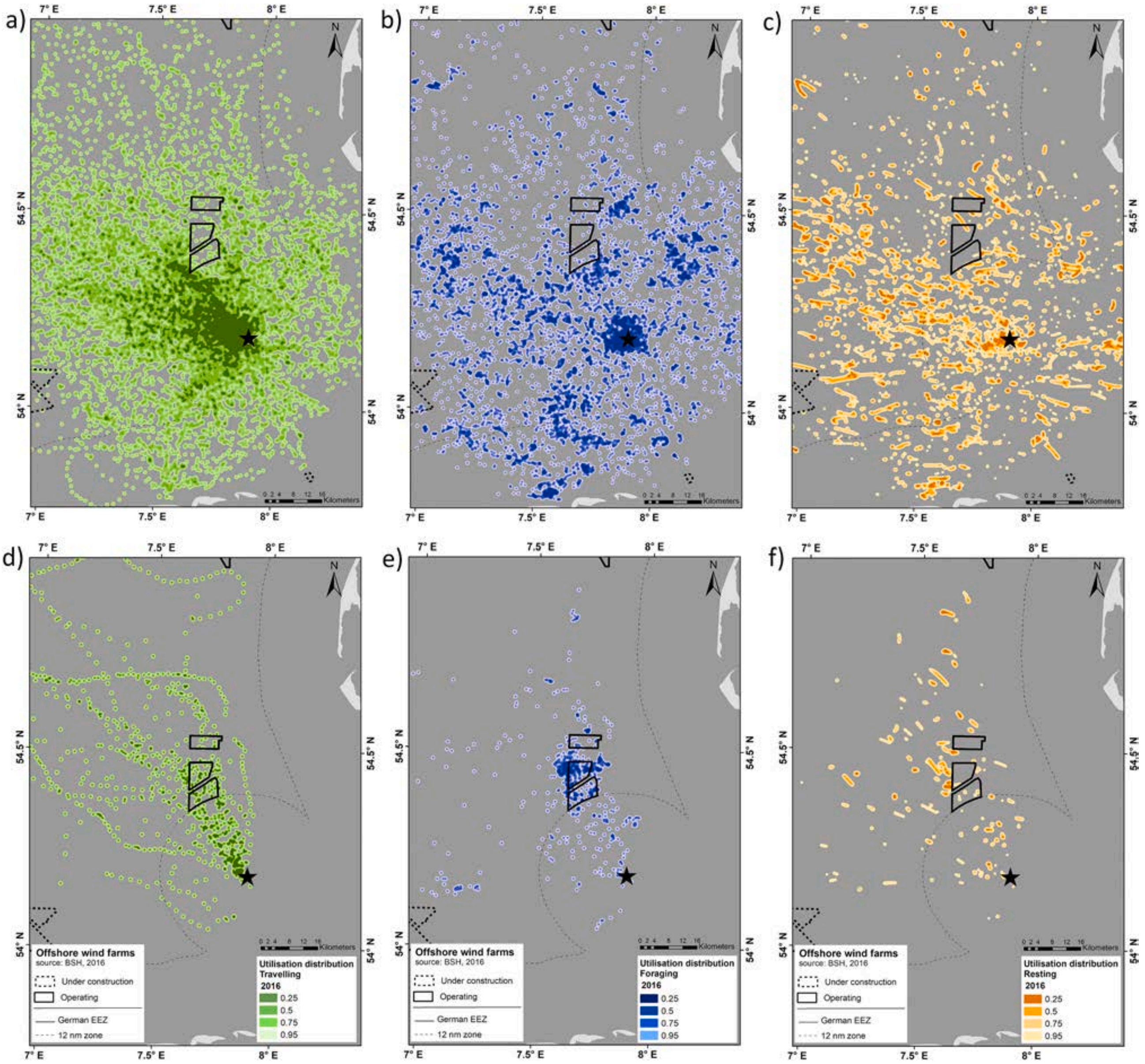

Fig. 3. Kernel densities of travelling (a, d), foraging (b, e), and resting (c, f) positions of gannets tagged in 2016 visualized as percentiles. Dark colour = 25% percentile, light colour = 95% percentile. (a, b, & c) Individuals 'predominantly avoiding' the OWFs, and (d, e, & f) individual 'attracted' to OWFs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Percent overlap with OWFs (no buffer around the OWFs) for each behaviour and individuals often using (= 'attracted') or predominantly not using (= 'predominantly avoiding') the OWFs in 2015 and 2016.

		Foraging		Travelling		Resting	
Year	Percentile	Ind. using OWFs	Ind. not using OWFs	Ind. using OWFs	Ind. not using OWFs	Ind. using OWFs	Ind. not using OWFs
2015	**25%**	12.47	0.00	6.50	0.00	2.61	0.00
	50%	8.32	0.00	4.76	0.00	2.39	0.00
	75%	5.61	0.05	3.71	0.15	2.77	0.01
	95%	4.16	0.13	2.71	0.33	2.80	0.03
	99%	3.44	0.19	2.17	0.38	2.70	0.06
2016	**25%**	33.39	0.05	7.10	0.05	0.00	0.06
	50%	27.59	0.21	5.86	0.13	0.03	0.20
	75%	18.76	0.36	5.42	0.46	1.09	0.20
	95%	13.32	0.49	4.67	0.60	2.57	0.24
	99%	10.88	0.55	4.12	0.64	2.86	0.26

reduction in resource selection is not readily comparable to the reduction in abundance.

Our study also showed that 89% of gannets predominantly avoided the OWFs, which thus created a barrier effect and/or habitat loss. Displacement could lead to an increase in foraging-trip length and energy expenditure, especially during the breeding season, with consequent effects on energy and time budgets (Masden et al. 2010; Searle et al. 2014). This could in turn reduce adult condition or survival (Masden et al. 2010) and lead to a decrease in chick growth rates and survival, ultimately reducing reproductive success (Langton et al. 2014). We can currently only speculate on how the strength of the reaction towards the OWFs affects the birds' energy budgets and reproductive success. However, if individuals in other colonies react similarly to OWFs in the vicinity, this could for example have a strong impact on the world's largest breeding colony on the Bass Rock in Scotland, UK (~75, 000 breeding pairs in 2014; Murray et al. 2015). Effects on (sub)populations thus need to be considered.

Behavioural analysis showed that birds avoiding OWFs predominantly used areas to the south-west of the OWFs for commuting between the colony and foraging areas. These areas were already intensely used before the OWF construction (Garthe et al. 2017a). However, the close proximity of the intensely used areas to the south-western tip of the OWFs strongly underlines the influence of the OWF on the gannets' flight directions.

Birds avoiding the OWFs are less prone to collide with turbines. However, they sometimes entered the OWFs, and although no significant difference was found between inside and outside the OWFs for gannets predominantly avoiding the OWFs, flight heights measured on these occasions showed that they flew at altitudes just below or inside the RBZ. Thus, gannets that predominantly avoid the OWFs appear to fly at altitudes inside the OWFs that could increase their collision risk. The reason why birds tended to fly higher inside compared with outside the OWFs remains unclear and should be investigated in future studies with larger sample sizes. However, when gannets were inside the OWFs flight heights of individuals predominantly avoiding the OWFs tended to increase with the distance to the turbine (though no significant change was found). Individuals predominantly avoiding the OWFs did not approach the turbines closely (shortest distance = 79 m), but preferred to stay between 250 and 450 m distance to the turbines (similar to the attracted individuals, spacing between turbines = 600–1200 m), which correlates with half the distance between neighbouring turbines. Gannets hence preferred to stay in areas which were as far as possible from the turbines, predominantly in the middle between the turbine rows. It can thus further be concluded, that gannets which predominantly avoided the OWFs used flight heights inside the OWFs which increased their risk to collide with the turbines, but also preferred distances to the turbines which would in turn reduce their collision risk. These findings hence suggest, that actual collision risk inside the OWFs is moderate, however, further studies with larger sample sizes of flight height and distance to turbines are needed to confirm the here presented findings. Moreover, bad weather conditions decrease manoeuvrability of flying birds, which can lead to higher collision risk during such periods.

In contrast to the avoidance behaviour shown by most gannets, three

Table 4
Flight heights of eight gannets tagged in 2016 inside and outside the OWFs.

			Altitude (m)			GAMM
Bird	Location	n	Mean	SD	Median	*p-value*
All	inside OWF	209	17.9	17.9	15.9	0.082
	outside OWF	2640	14.4	18.0	10.7	
Attracted	inside OWF	149	14.2	12.3	14.3	0.059
	outside OWF	440	12.7	15.4	9.6	
Avoiding	inside OWF	60	27.3	24.9	23.3	0.287
	outside OWF	2200	14.7	18.5	10.7	
Travelling	inside OWF	91	17.9	19.2	14.3	0.157
	outside OWF	1645	12.8	17.6	7.4	
Foraging	inside OWF	118	18.0	16.8	16.5	0.431
	outside OWF	995	16.9	18.4	14.9	

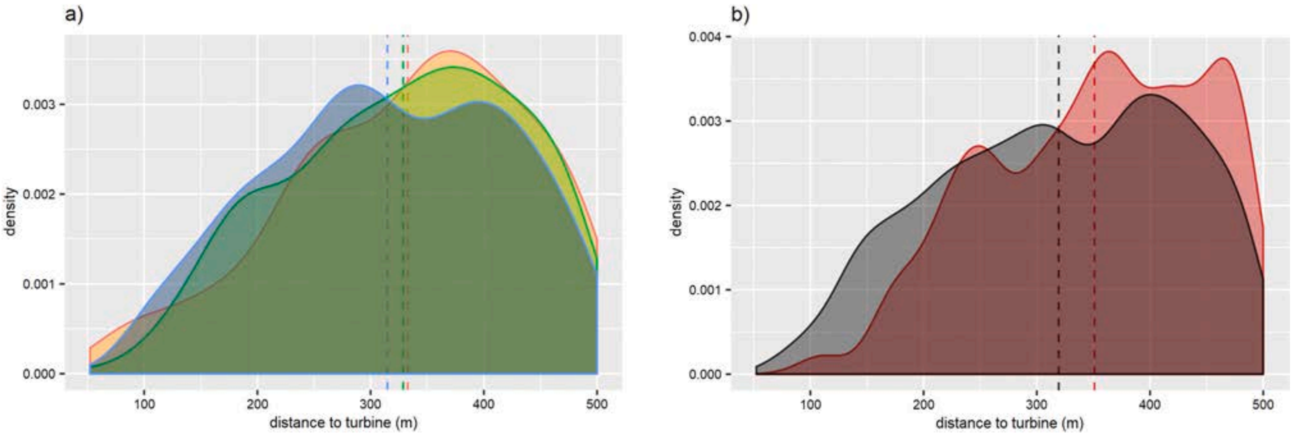

Fig. 4. Density plots of the distance to the single wind turbines when gannets were inside the OWFs for a) based on all positions in 2015 and 2016 for which behavioural states were detected (n = 959); Orange = resting, green = travelling, blue = foraging. b) Density plot based on 1-s interval GPS-positions collected in 2015 and 2016 (n = 5146) for individuals 'attracted' to the OWF (dark grey, no. positions = 2994) and individuals 'predominantly avoiding' the OWF (red, no. positions = 2152). Dashed lines indicate the mean values. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

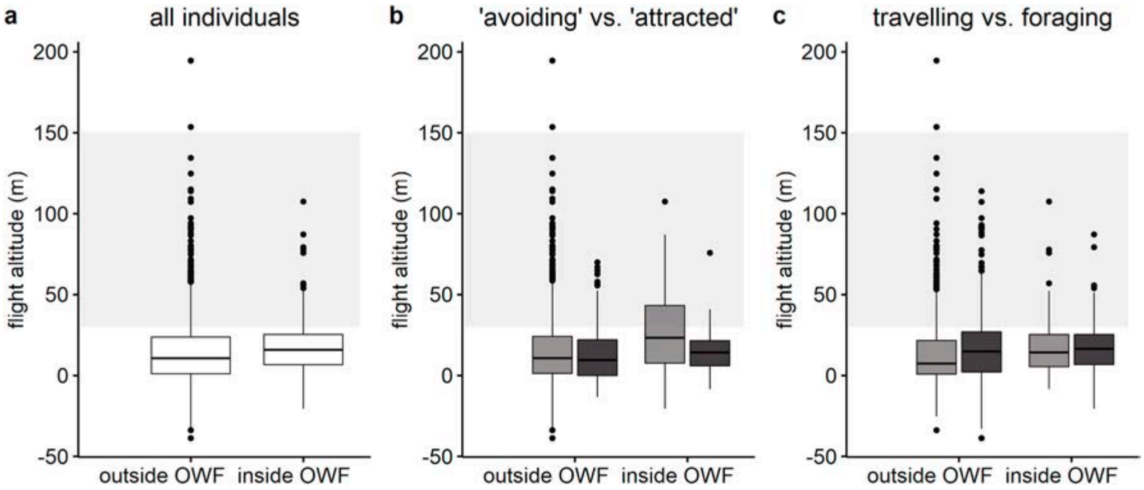

Fig. 5. Flight heights outside and inside OWF for (a) all birds, (b) 'predominantly avoiding' (light grey) and 'attracted' (dark grey) individuals, and (c) travelling (light grey) and foraging (dark grey). Grey background = rotor-blade zone.

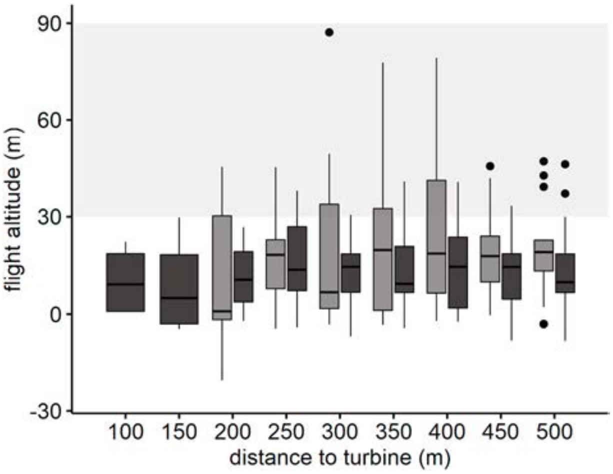

Fig. 6. Flight height with distance to the turbines for the individual 'attracted' to the OWF in 2016 (dark grey, n = 1) and individuals 'predominantly avoiding' the OWF in 2016 (light grey, n = 15). Grey background = rotor-blade zone.

Table 5
Results of basic point process model for 2015.

Parametric coefficients	Estimate	Standard Error	z value	Pr(>|z|)
(Intercept)	2.805	0.098	28.598	<2e-16
inside_OWF	**−0.231**	**0.062**	**−3.704**	**< 0.001**
Smooth term	edf	Ref.df	χ^2	*p*-value
te(log_ds,angle, log_dt)	73.893	83.840	35113	<2e-16
s(trip_id)	147.508	166.000	7393	<2e-16
s(bird_id)	1.769	11.000	1250	0.005

Parametric coefficients and smooth terms are shown. Terms relevant to the analysis of OWF effects indicated in bold.
edf = estimated degrees of freedom; Ref.df = reference degrees of freedom.

Table 6
Results of the best model for 2015.

Parametric coefficients	Estimate	Standard error	z value	Pr(>|z|)
(Intercept)	3.293	0.230	14.315	<2e-16
inside_OWF	**−0.240**	**0.063**	**−3.825**	**<0.001**
dist_Helgoland	0.017	0.002	6.837	<0.001
depth	0.036	0.007	5.039	<0.001
Smooth terms	edf	Ref.df	χ^2	*p*-value
te(log_ds,angle, log_dt)	73.944	83.900	35386	<2e-16
s(trip_id)	147.439	166.000	7276	<2e-16
s(bird_id)	1.737	11.000	1193	0.005

Parametric coefficients and smooth terms are shown. Terms relevant to the analysis of OWF effects indicated in bold.
edf = estimated degrees of freedom; Ref.df = reference degrees of freedom.

Table 7
Results of basic point process model for 2016.

Parametric coefficient	Estimate	Standard error	z value	Pr(>|z|)
(Intercept)	0.587	0.099	5.941	<0.001
inside_OWF	**−0.423**	**0.066**	**−6.392**	**<0.001**
Smooth term	edf	Ref.df	χ^2	*p*-value
te(log_ds,angle, log_dt)	72.061	83.220	13801.300	<2e-16
s(trip_id)	114.992	139.000	11642.400	<2e-16
s(bird_id)	0.916	15.000	124.600	0.141

Parametric coefficients and smooth terms are shown. Terms relevant to the analysis of OWF effects indicated in bold.
edf = estimated degrees of freedom; Ref.df = reference degrees of freedom.

individuals entered the OWFs frequently. These birds foraged intensely, and in 2016 even predominantly, in the OWFs. Foraging conditions close to or inside the OWFs might be good due to the so called 'reef effect' (Lindeboom et al. 2011), which leads to an increase in benthic structures and hence increased fish diversity and abundance at the turbines (e.g. Stenberg et al. 2015; Vandendriessche et al. 2015). However, we did not find a significant preference for closer distances to the turbines while foraging. Moreover, birds preferred to stay between 250 and 450 m distance to the turbines, and it is currently unknown if the food accessibility is comparable to undisturbed areas, or if foraging in these areas is beneficial and can sustain breeding success.

The individuals that were attracted to the OWFs were not prone to displacement, but their risk of colliding with the turbines was generally increased as they often entered the OWFs and stayed there for foraging. The flight height of the bird that frequently entered the OWFs in 2016 was higher inside compared to outside the OWFs but generally below the RBZ both while inside and outside the wind farm. This could indicate an individual preference for flying at this height, irrespective of the presence of the OWF, and a larger sample size is therefore needed to determine if birds attracted to and using OWFs might adapt their flight height to altitudes below the RBZ.

Gannet flight heights were measured as part of a recent study

Table 8
Results of the best model for 2016.

Parametric coefficients	Estimate	Standard error	z value	Pr(>|z|)
(Intercept)	1.207	0.110	10.997	<2e-16
inside_OWF	**−0.461**	**0.067**	**−6.874**	**<0.001**
dist_Helgoland	−0.017	0.001	−14.275	<2e-16
slope	−1.711	0.375	−4.567	<0.001
Smooth terms	edf	Ref.df	χ^2	*p*-value
te(log_ds,angle, log_dt)	73.297	84.420	13284	<2e-16
s(trip_id)	114.984	139.000	12033	<2e-16
s(bird_id)	0.932	15.000	132	0.124

Parametric coefficients and smooth terms are shown. Terms relevant to the analysis of OWF effects indicated in bold.
edf = estimated degrees of freedom; Ref.df = reference degrees of freedom.

modelling gannet collision risks with future OWFs located <50 km from breeding colonies in Scotland, UK (Cleasby et al. 2015). They revealed that predominantly foraging birds would be at risk of collisions because they flew at rotor-blade height, whereas commuting birds flew below the rotor blade height. We also found higher flight heights during foraging compared with travelling. However, although gannets breeding on Helgoland generally flew at higher altitudes inside OWFs compared with outside, they predominantly flew below the rotor blades. The turbines may exert wake effects that could potentially affect the birds' flight manoeuvrability (Stevens and Meneveau, 2017), which potentially causes them to avoid the area close to the rotor blades. The tendency to fly higher inside OWFs nevertheless increases their risk of colliding with the turbines. A larger sample of flight heights inside OWFs is needed to clarify the gannets' behaviours and draw conclusions about the actual collision risk. More data on other parameters, like the position of the birds with respect to the single turbines as well as their distance to the turbines during the different behavioural states, are furthermore needed to better understand the gannets risk to collide with the turbines.

During this study, individuals tagged in both years showed no distinctive patterns in their reaction towards OWFs to allow any conclusions to be drawn on a possible change with time. The resource selection of the OWF areas decreased from 2015 to 2016. This could indicate an increased avoidance of the OWFs and thus an increasing habitat loss with time. However, as the values did not differ significantly, future studies including more years are needed to demonstrate if and how the gannets' reactions towards OWFs change over time, at both the individual and sub-population (Helgoland) levels.

The effects documented in the current study are of considerable relevance to other gannet colonies, and should be considered during the planning of future wind farms, especially when located close to large seabird colonies (e.g. the Bass Rock, Scotland, UK), with the potential to affect large numbers of individuals. This study provides fundamental information that will improve models of collision risk and population-level effects in relation to seabirds and OWFs.

Credit author statement

VP, SG & BM developed the idea for the manuscript. VP, SG, JD conducted fieldwork in 2015 and 2016. MM and VP developed the statistical modelling approach. VP analysed the data. VP wrote the manuscript. SG, BM, JD and MM reviewed and approved the manuscript. BM, SG and VP acquired the financial support of the project.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.111509.

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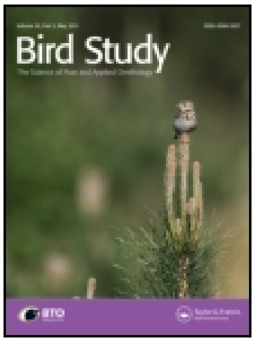

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Observations of seabirds at offshore wind turbines near Blyth in northeast England

PETER ROTHERY[1]*, IAN NEWTON[1] and BRIAN LITTLE[2]
[1]*Centre for Ecology and Hydrology, Monks Wood, Abbots Ripton, Huntingdon, Cambridgeshire, PE28 2LS, UK and* [2]*AMEC Wind Energy, Bridge End, Hexham, Northumberland, UK*

Capsule No obvious effects were detected, except for reduced Cormorant *Phalacrocorax carbo* presence after construction.

Aim To check for differences in the numbers and behaviour of seabirds following construction of two turbines 1 km offshore.

Methods Shore-based two-hour watches were conducted several times per month during 26 months before turbine construction, seven months during construction, and 32 months after construction. Numbers, flight heights and directions of all passing seabirds were noted, as were weather and tidal conditions. No watches were made under darkness or in poor daytime visibility.

Results In summer, numbers of Cormorants declined post-construction, while Sandwich Terns *Sterna sandvicensis* and Great Black-backed Gulls *Larus marinus* increased. Otherwise no meaningful changes in bird numbers and behaviour were recorded, and no collision mortality was witnessed during 352 hours of daytime watches post-construction. Most seabirds flew below the height of the rotor blades.

Conclusion Apart from possibly causing decline in summer usage of the locality by Cormorants, the turbines seem to have had no adverse effects on the local seabirds in the periods and conditions covered by our watches. We advise against extrapolating our findings to conditions of poor visibility or darkness, or to larger windfarms.

Plans to build large numbers of wind turbines off British coasts have raised questions about their possible impact on bird populations, either by causing mortality or by deterring birds from feeding areas (Langston & Pullan 2003, Kingsley & Whitham 2005, Petersen *et al.* 2006, de Lucas *et al.* 2007). As yet, however, only limited information is available on the behaviour of birds with respect to offshore wind farms, or on the frequency of collisions. This study was planned to provide information relevant to addressing these questions, by recording the numbers and behaviour of birds flying near two turbines situated about 1 km off the Northumbrian coast, in northeast England. We report the findings from daytime observations conducted at this site over a 65-month period, beginning about 26 months before the turbines were built in June–December 2000, and ending about 32 months after. Findings concern mainly the flight behaviour of passing seabirds, for no collisions were witnessed in the period of study.

One of the bird species of particular interest, and the most numerous near the Blyth turbines, was the Sandwich Tern *Sterna sandvicensis*, which fed in the inshore waters of Newbiggin Bay and Blyth Bay around Blyth harbour, along with the estuary of the River Blyth. The main breeding area was on Coquet Island, 15 km to the north of Blyth, which during the study held around 1700 breeding pairs (RSPB unpubl. data). When the young terns fledged in July, they accompanied the adults to the Blyth estuary, where they were closer to the local concentrations of small fish on which they fed. Some terns may have come to the Blyth area from further afield, including the Farne Islands, situated 25 km north of Blyth.

Previous studies have shown that the biological impact of wind turbines depends largely on the location of the turbines with respect to the nesting, resting and foraging areas of birds, and their main movement corridors. In addition, flight height and function, light values and weather conditions all appear to influence collision frequency, as does the direction of flight relative to the lay of the turbines. In conditions of good

*Correspondence author. Email: pro@ceh.ac.uk

visibility, birds usually change direction long before they reach the vicinity of the turbines, avoiding the windfarm altogether or flying in the corridors between the turbines (Desholm & Kahlert 2005, Petersen *et al.* 2006). If they get close, they may still avoid the rotors, or fall victim to the rotors through near-turbine turbulence (Winkelman 1992, Pettersson 2005). In general, impacts can be site-specific as well as species-specific (for site-specific impacts on terns see Everaert & Stienen 2007).

METHODS

Observations

The two turbines (2.0 MW capacity) were spaced 200 m apart on a permanently submerged spit. They were on solid-sided conical steel towers, with a hub height of 59.4 m above mean sea level (amsl), and rotor diameter of 66 m. The rotor blades thus extended 26.4–92.4 m amsl. Observations of passing birds were made from the shore over the period 18 April 1998 to 30 August 2003. All birds could be seen at the 1 km range, even small passerines. Before turbine construction, the watch point was located on top of a low cliff, east of the middle silo at Alcan, 5 m asl; after construction of the turbines the watch point was moved about 150 m to the north end of the pier. Observations covered a 600 m scan area, and were made with 10 × 40 binoculars, and a ×30 wide-angle telescope mounted on a tripod. All birds passing within two-hour watches were recorded. Such watches were initially conducted about twice per month, but they were increased to six to eight times per month (Table 1).

After initial trials, observations were focused on the zone 1 km from shore, around the proposed turbine site. The focus of the telescope was first calibrated to objects 1 km to the north, along the shore, and kept at this setting during watches. The watches were done at pre-planned times, regardless of weather and other conditions, provided that both towers were visible. Every bird passing close through the tower area was recorded to species, as was its approximate height above sea level and its direction of flight, mostly either northward or southward, more or less parallel to the coast. Wind was recorded at the start of each watch as predominantly offshore or onshore, and the state of the tide was noted retrospectively from tide tables. Some watches were ended prematurely, owing to worsening weather and poor visibility. At these times, virtually no flight activity could be seen offshore, and during severe gales many birds moved closer to shore, presumably for protection.

Table 1. Number of standard watches in each month and year, 1998–2003.

Month	1998	1999	2000	2001	2002	2003	Total
January	–	0	2	4	4	8	18
February	–	0	1	3	4	7	15
March	–	2	2	5	3	6	18
April	2	2	2	7	2	6	21
May	3	2	2	4	6	8	25
June	2	2	**2**	6	8	7	27
July	2	2	**2**	5	6	8	25
August	2	1	**2**	5	4	8	22
September	0	1	**4**	3	5	–	13
October	0	2	**1**	5	7	–	15
November	0	2	**3**	6	7	–	18
December	0	2	**5**	4	6	–	17
Total	11	18	28	57	62	58	234

Watches during the construction period (June–December 2000) are in bold.

Before construction of the towers, flight heights of birds were judged against various objects of known height around the harbour area, but some error was expected in the estimates. After construction, flight heights could be recorded with greater accuracy by reference to the nearby towers. Each bird seen was placed within one of four height zones: C, from sea level to the top of the access platform (9.1 m amsl, 6.5–11.7 m according to tide); B, from the top of the access platform to the bottom of the rotor sweep (26.4 m amsl); A, within the rotor sweep (26.4–92.4 m amsl); A+, above the rotors (>92.4 m amsl).

Most of the birds seen were seabirds, mainly Herring Gull *Larus argentatus*, Great Black-backed Gull *Larus marinus*, Black-headed Gull *Larus ridibundus*, Black-legged Kittiwake *Rissa tridactyla*, Sandwich Tern, Common Eider *Somateria mollissima*, Common Scoter *Melanitta nigra*, Cormorant *Phalacrocorax carbo* and Gannet *Morus bassanus*. Most individuals were presumed to be on local flights between breeding and feeding areas, or between roosting and feeding areas, but in spring and autumn there are likely to have been some migrants. For purposes of analysis, species were examined individually, taking the numbers seen per watch as the unit of observation. The small numbers of land-birds that were seen passing the towers included mainly Common Pigeons *Columba livia*, and a few shorebirds and passerines (see Appendix), all of which were also excluded from analysis.

In addition, the counts from one watch were excluded altogether from analysis because they were so exceptionally high that they would have greatly distorted the picture. On this two-hour watch on 14 January 2000, a massive northward movement of gulls occurred, mainly Black-legged Kittiwakes, totalling at least 1422 individuals. This total was 5.5 times higher than the next highest count, and about 50 times higher than the average count (see later). These birds flew only a few metres above sea level, and their flight behaviour in all respects appeared 'normal'.

Statistical analysis

The main aim was to compare pre- and post-construction periods in terms of the number of birds seen passing per hour, the proportion of birds flying at height category C (as opposed to higher), and the proportion flying south (as opposed to north), parallel to the local coastline. The analysis used statistical models to test and estimate differences in these three respects between pre- and post-construction periods, allowing for seasonal patterns and year-to-year variation in counts. Details of the models used are given in Endnote a.

These basic models were augmented to include effects of start time of watch, time from high tide (linear and quadratic trends) and wind direction (north/south). The models were then used to test for effects of these variables, and to estimate differences between pre- and post-construction periods, allowing for possible confounding effects and time, tide and wind.

For some species, counts differed markedly between the 'summer' breeding season (April–September) and the 'winter' non-breeding season (October–March). For example, Sandwich Terns were absent over winter. We therefore analysed and reported results for these two periods separately. For each of the main species, we present the observed overall means for numbers per hour, proportion of birds flying in height category C, and proportion flying south, together with tests and estimates of the effects of pre- and post-construction periods based on the statistical models.

RESULTS

The numbers and distribution of watches over the study period are shown in Table 1. Some 38 watches were conducted in the period 18 April 1998 to 18 May 2000 (pre-construction), 19 in the period 9 June to 29 December 2000 (during the construction process), and a further 177 in the period 12 January to 30 August 2003 (post-construction, with working turbines). This gave 234 watches in all, extending over 352 hours of observation (Tables 1 & 2). Some 2031 birds were counted near the turbines by watches during the pre-construction period, 689 birds during the construction period, and 9866 during the post-construction period, with a grand total of 12 687 individual seabird sightings. Counts for the nine main species are given in Table 2.

The distribution of watches through the day (GMT) is shown in Table 3, along with details of concurrent tide and wind directions (onshore or offshore). The main point is that, taken overall, watches were comparable in these respects in the pre- and post-construction periods, as well as during construction. Because not all observation periods lasted exactly two hours, data are presented as 'numbers per hour' in Tables 4, 5 and 6.

The average number of birds seen per hour during the entire study period was 28.1, with an estimated standard deviation of 32.1, a coefficient of variation (CV) of 114%, and a range of 1 to 260. For the nine main species only, the equivalent figures were: mean = 23.4, sd = 29.5, CV = 126%, range 1–260.

Seasonal variations

The numbers of birds seen at the turbines varied greatly from watch to watch, but with regular seasonal abundance patterns that varied between species. Some species were seen only in summer, others chiefly in winter, and yet others year-round, but with regular seasonal fluctuations in abundance. For example, Sandwich Terns were present only during April–September each

Table 2. Total number of birds counted in daytime watches for each species in each construction period.

		Construction phase		
Species	Total	Pre	During	Post
Gannet	578	137	9	432
Cormorant	530	135	43	352
Common Scoter	473	77	55	341
Common Eider	1288	163	51	974
Black-headed Gull	1119	73	68	978
Herring Gull	1755	265	82	1408
Great Black-backed Gull	794	130	100	564
Black-legged Kittiwake	1617	140	127	1350
Sandwich Tern	2398	218	45	2135
Total other species	2135	694	109	1332
Overall total	12 687	2032	689	9866
Total observation time (h)	457.9	70.3	36.0	351.6

Table 3. Summary of distribution of observational periods in relation to start time, end time, time from high tide and wind direction.

		Construction phase		
Variable	Statistic	Pre	During	Post
Start time (GMT)	Median	12:45	13:00	13:00
	sd (h)	2.0	1.7	1.9
	Lower quartile	10:00	11:00	11:30
	Upper quartile	13:50	13:00	14:00
End time (GMT)	Median	14:40	15:00	15:00
	sd (h)	1.9	1.9	1.7
	Lower quartile	11:55	12:45	13:30
	Upper quartile	15:30	15:00	16:00
Time from high tide (h)	Median	–2.3	0.4	–0.9
	sd	4.4	4.2	4.3
	Lower quartile	–5.5	–3.5	–3.1
	Upper quartile	2.3	4.2	3.5
High tide (m)	Median	4.8	4.5	4.6
	sd	0.45	0.42	0.41
	Lower quartile	4.5	4.3	4.4
	Upper quartile	5.2	5.1	5.0
Wind direction	Percentage offshore	50	58	51

Table 4. Number of birds per hour counted during the three construction phases in summer (April–September) and winter (October–March), and estimated ratio (*R*) of post-construction to pre-construction counts (95% confidence interval).

	Construction phase			Post versus pre	
Species	Pre	During	Post	*R* (95% CI)	*P*
April–September					
Gannet	3.0	0.5	2.2	0.8 (0.4, 1.6)	0.51
Cormorant	2.3	0.7	1.3	0.6 (0.4, 0.9)	0.005^{**}
Common Scoter	1.3	0	1.2	1.8 (0.2, 3.8)	0.78
Common Eider	0.5	0.1	0.3	0.5 (0.1, 1.8)	0.30
Black-headed Gull	0.2	0	0.1	0.2 (0.1, 1.9)	0.17
Herring Gull	3.9	2.4	2.6	0.9 (0.4, 1.8)	0.77
Great Black-backed Gull	0.5	2.2	1.3	2.5 (1.2, 5.5)	0.020^{*}
Black-legged Kittiwake	2.9	6.4	5.8	2.0 (0.8, 5.2)	0.15
Sandwich Tern	4.7	2.4	10.9	2.3 (1.1, 4.9)	0.033^{*}
October–March					
Gannet	0	0	0.1	na	na
Cormorant	1.3	1.7	0.6	0.6 (0.3, 1.1)	0.11
Common Scoter	0.6	3.2	0.7	0.8 (0.3, 3.8)	0.78
Common Eider	5.8	2.9	5.9	1.2 (0.4, 3.9)	0.78
Black-headed Gull	2.4	4.0	6.2	1.5 (0.3, 7.6)	0.65
Herring Gull	3.3	2.1	5.7	1.6 (0.7, 3.7)	0.28
Great Black-backed Gull	0.8	3.5	2.0	2.3 (0.8, 6.6)	0.14
Black-legged Kittiwake	0.2	0.4	1.4	8.7 (0.3, 20)	0.30
Sandwich Tern	0.1	0	0	na	na

Analysis is based on a statistical model allowing for monthly differences and random year-to-year variation (see statistical methods). na, Analysis not appropriate. *P*-values for Wald tests: $^{**}P < 0.01$, $^{*}P < 0.05$.

year, showing a marked peak in numbers during May–July (Fig. 1a). Common Scoters showed three peaks in seasonal abundance each year, coinciding with periods of spring migration (March–April), summer moult migration (June–August) and autumn migration (November) (Fig. 1b). Cormorants were present year-round, but were most abundant in the period March–October (Fig. 1c). In Fig. 1, the data are shown separately for the three periods, pre-construction, during construction and post-construction. Both

Table 5. Percentage (*number*) of birds flying in height category C in the three construction phases in summer (April–September) and winter (October–March), and estimated odds ratio of post-construction to pre-construction counts (95% confidence interval).

	Construction phase			Post versus pre	
Species	Pre	During	Post	Odds ratio (95% CI)	*P*
April–September					
Gannet	99 (*137*)	44 (*9*)	72 (*424*)	0.03 (0, 1.3)	0.069
Cormorant	87 (*105*)	93 (*14*)	69 (*261*)	0.3 (0.1, 0.9)	0.027*
Common Scoter	100 (*62*)	– (*0*)	100 (*225*)	1.0 (–)	na
Common Eider	100 (*24*)	100 (*1*)	100 (*58*)	1.0 (–)	na
Black-headed Gull	9 (*11*)	– (*0*)	53 (*17*)	na	na
Herring Gull	68 (*179*)	35 (*46*)	31 (*516*)	0.3 (0.1, 1.3)	0.12
Great Black-backed Gull	68 (*22*)	49 (*41*)	24 (*257*)	0.2 (0.1, 0.7)	0.015*
Black-legged Kittiwake	72 (*136*)	12 (*121*)	68 (*1135*)	0.5 (0.1, 3.7)	0.52
Sandwich Tern	83 (*216*)	78 (*45*)	50 (*2133*)	0.2 (0.1, 0.9)	0.037*
October–March					
Gannet	– (*0*)	– (*0*)	13 (8)	na	na
Cormorant	77 (*30*)	66 (*29*)	63 (*91*)	0.5 (0.1, 2.2)	0.37
Common Scoter	100 (*15*)	– (0)	100 (*116*)	1.0 (–)	na
Common Eider	99 (*139*)	74 (*74*)	97 (*976*)	0.2 (0, 80)	0.61
Black-headed Gull	98 (*62*)	81 (*68*)	84 (*961*)	0.01 (0, 28)	0.25
Herring Gull	76 (*86*)	25 (*36*)	36 (*892*)	0.2 (0.1, 0.6)	0.005**
Great Black-backed Gull	84 (1*9*)	34 (*59*)	28 (*307*)	0.03 (0, 0.7)	0.026*
Black-legged Kittiwake	100 (*4*)	83 (*6*)	71 (*215*)	na	na
Sandwich Tern	– (*2*)	– (*0*)	– (*2*)	na	na

Analysis is based on a statistical model allowing for monthly differences and random year-to-year variation (see statistical methods). na, Analysis not appropriate. *P*-values for Wald tests: $^{**}P < 0.01$, $^{*}P < 0.05$.

Table 6. Percentage (*number*) of birds flying south during the three construction phases, in summer (April–September) and winter (October–March), and estimated odds ratio of post-construction to pre-construction counts (95% confidence interval).

	Construction phase			Post versus pre	
Species	Pre	During	Post	Odds ratio (95% CI)	*P*
April–September					
Gannet	1 (*137*)	89 (*9*)	41 (*424*)	47 (2, 999)	0.016*
Cormorant	60 (*98*)	64 (*14*)	49 (*261*)	0.6 (0.3, 1.4)	0.27
Common Scoter	52 (*62*)	– (*0*)	48 (*225*)	na	na
Common Eider	80 (*15*)	– (*1*)	61 (*36*)	0.4 (0.3, 5.9)	0.50
Black-headed Gull	64 (*11*)	– (*0*)	6 (*17*)	0.1 (0, 1.8)	0.10
Herring Gull	26 (*164*)	59 (*46*)	49 (*515*)	2.5 (1.0, 6.6)	0.12
Great Black-backed Gull	47 (*17*)	46 (*41*)	55 (*256*)	1.3 (0.2, 7.1)	0.77
Black-legged Kittiwake	22 (*136*)	96 (*121*)	37 (*1005*)	1.6 (0.5, 5.2)	0.38
Sandwich Tern	27 (*216*)	60 (*45*)	40 (*2077*)	1.8 (0.6, 5.3)	0.27
October–March					
Gannet	– (*0*)	– (*0*)	– (*8*)	na	na
Cormorant	65 (*31*)	72 (*29*)	49 (*89*)	0.7 (0.2, 2.9)	0.59
Common Scoter	0 (*15*)	0 (*0*)	100 (*116*)	na	na
Common Eider	53 (*19*)	16 (*50*)	33 (*226*)	0.4 (0, 9.1)	0.44
Black-headed Gull	16 (*62*)	89 (*38*)	74 (*410*)	6.6 (0.6,69)	0.12
Herring Gull	38 (*84*)	50 (*36*)	68 (*873*)	2.8 (0.7, 12)	0.16
Great Black-backed Gull	32 (*19*)	47 (*51*)	55 (*303*)	1.5 (0.2, 11)	0.71
Black-legged Kittiwake	75 (*4*)	33 (*6*)	38 (*215*)	na	na
Sandwich Tern	– (*2*)	– (*0*)	– (*1*)	na	na

Analysis is based on a statistical model allowing for monthly differences and random year-to-year variation (see statistical methods). na, Analysis not appropriate. *P*-values for Wald tests: $^{**}P < 0.01$, $^{*}P < 0.05$.

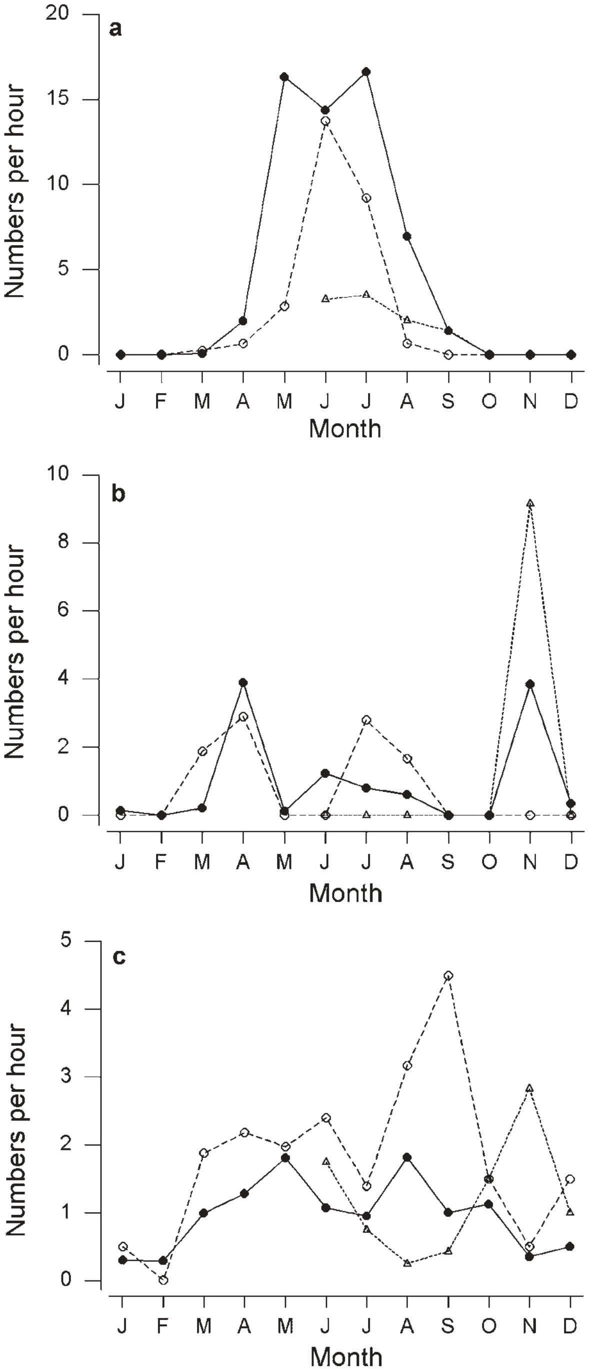

Figure 1. Mean number of birds per hour versus month in different periods of construction (○, pre-construction; △, during construction; ●, post-construction) for Sandwich Tern (a), Common Scoter (b) and Cormorant (c).

Sandwich Terns and Common Scoters showed reduced numbers during the six-month construction period, but counts of Cormorants were more variable. It would not be surprising if human activity around the towers reduced bird activity there, but because only 17 counts were made during the construction period, little weight could be put on the findings.

Annual variations

Annual variations in mean summer and winter counts are shown for the main species in Fig. 2. No great annual changes occurred in most of the species between the pre- and post-construction periods. However, increased numbers of Sandwich Terns were seen in the summers of 2002 and 2003, and of Black-legged Kittiwakes in the summers of 2000 to 2003; increased numbers of Black-legged Kittiwakes occurred in winter 2001/02 and of Common Eiders in winter

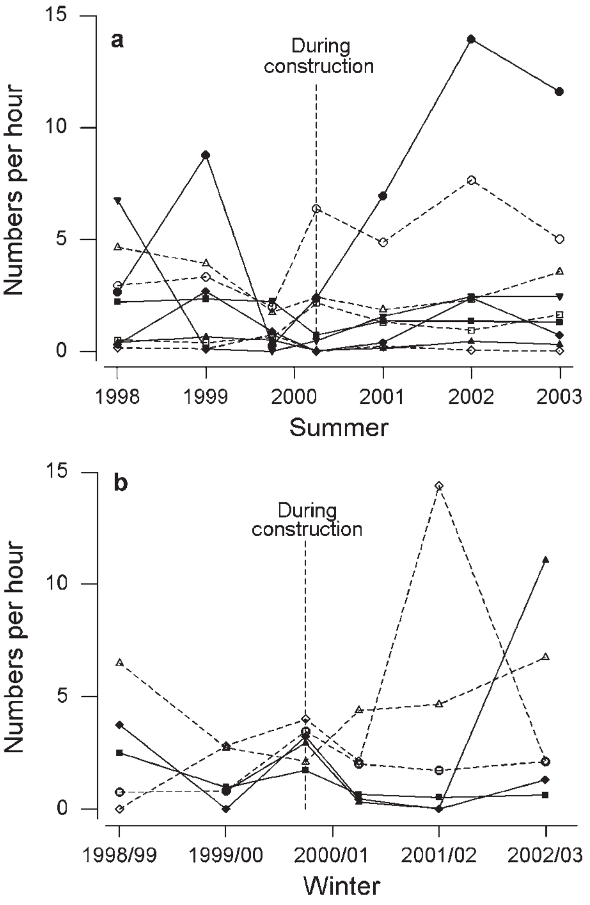

Figure 2. Number of birds per hour versus year for different species during (a) summer (April–September) and (b) winter (October–March). ▼, Gannet; ■, Cormorant; ◆, Common Scoter; ▲, Common Eider; ◇, Black-headed Gull; △, Herring Gull; □, Great Black-backed Gull; ○, Kittiwake; ●, Sandwich Tern. (Note: there are no Gannets or Sandwich Terns for winter; for winter 1998/99 a value of 38 per hour for Common Eiders has been omitted to improve the resolution.)

2002/03. All of these increases occurred in the post-construction period, when the turbines were operational.

For the year 2000, the summer data were split into pre-construction (April–May) and construction (June–September) periods. The apparent low numbers of several species in the pre-construction period of 2000 were not unusual, as they were comparable to April–May counts in other years. Similarly, numbers for June–September, when construction was underway, did not differ markedly from June–September counts in other years, apart from the Sandwich Terns mentioned above. For the winter counts, data were split between the construction period (October–December) and post-construction period (January–March), but showed no striking differences, apart from the reduction in Common Scoters during construction, mentioned above (Fig. 2).

Comparison between pre- and post-construction periods

For the nine commonest species, the mean number of birds counted per hour is shown in Table 4 for the three construction periods, and for summer (April–September) and winter (October–March) separately. Too few counts were made during the construction period to draw firm conclusions for this period, and the emphasis here is on comparison between pre- and post-construction periods. Only three species showed a statistically significant change (5% level) in summer numbers between these periods. The Cormorant showed a stepwise drop of about 43% between pre- and post-construction, so could have been influenced to some extent by the presence of the turbines, whereas the Great Black-backed Gull and Sandwich Tern showed more progressive but substantial increases extending over several years. The average numbers of both these species more than doubled between 1998–2000 and 2001–03. The apparent substantial increase in Black-legged Kittiwakes between the pre- and post-construction periods was not statistically significant (Table 4).

Turning to the winter counts, no species showed significant change between the pre- and post-construction periods, although in the Black-headed Gull the increase seemed substantial. The lack of statistical significance was associated with great variation from count to count, which led to wide confidence intervals on the post-construction to pre-construction ratios.

Flight heights

An important question in assessing the vulnerability of different species to turbine-inflicted mortality concerns the heights at which they normally fly. These heights (in the four categories C to A+), as measured post-construction, are summarized for the nine main species in Table 5. All species flew either entirely (two species) or largely (seven species) below the height of the rotor blades (zones B and C); that is, less than 26.4 m amsl. Species that flew within the height band of the rotor blades included Gannet (13% of all records), Cormorant (13%), Black-headed Gull (4%), Herring Gull (33%), Great Black-backed Gull (44%), Black-legged Kittiwake (11%) and Sandwich Tern (3%). Hence, on this basis alone, the two duck species could be judged least vulnerable to collision mortality by day, and the two large gulls as most vulnerable. Very few birds were seen above the height of the rotor blades (Table 7).

For further analysis, comparing pre- and post-construction periods, we pooled the three highest height categories, giving two categories for analysis,

Table 7. Percentage (*number*) of birds of each species observed in each height category (see text) during the post-construction phase.

	Height category			
Species	C	B	A	A+
Gannet	71 (*306*)	17 (*54*)	13 (*54*)	0 (*0*)
Cormorant	67 (*236*)	18 (*65*)	13 (*47*)	1 (*4*)
Common Scoter	100 (*341*)	0 (*0*)	0 (*0*)	0 (*0*)
Common Eider	97 (*941*)	3 (*341*)	0 (*0*)	0 (*0*)
Black-headed Gull	84 (*821*)	12 (*113*)	4 (*42*)	0 (*2*)
Herring Gull	34 (*484*)	32 (*449*)	33 (*460*)	1 (15)
Great Black-backed Gull	26 (*146*)	28 (*160*)	44 (*249*)	2 (*9*)
Black-legged Kittiwake	68 (*924*)	21 (*280*)	11 (*146*)	0 (*0*)
Sandwich Tern	51 (*1080*)	46 (*988*)	3 (*69*)	0 (*0*)

below and above the height of the turbine platform (mean 9 m, range 6.5–11.7 m depending on tide) respectively; Table 5 shows the percentage of all sightings within the lowest category. In the two sea-ducks (Common Eider and Common Scoter), all individuals seen were in the lower height band, but in all other species some individuals flew higher, the proportion varying between species, as described above.

In the summer months, three species showed statistically significant (5% level) differences between pre- and post-construction periods, with smaller proportions in the lower height band post-construction. In the winter months, the same held for two of these species (the large gulls). However, doubt hangs over these results because, whereas in the post-construction period, flight heights could be estimated fairly accurately from comparison with the nearby turbines, in the pre-construction period these heights were estimated without reference to any close physical structure. The apparent changes in flight heights between pre- and post-construction periods may therefore have resulted from observer judgement errors, rather than from genuine changes in flight heights. Even allowing for error, however, it was clear that most seabirds seen throughout the study flew within 5 m of the sea surface, and well below the height of the moving rotor blades.

Flight directions

Almost all flight directions were recorded as north or south, roughly paralleling the coast; Table 6 shows the percentage flying south, separately for summer and winter. For some species, the differences between pre- and post-construction periods seemed substantial, but samples were often small, and only in the Gannet in summer did the difference between these periods emerge as statistically significant, with many fewer birds moving south in the pre-construction period than in the post-construction period. Three other species, namely Cormorant, Herring Gull and Great Black-backed Gull, also showed substantial change in the proportion of southward flights between pre- and post-construction periods that were consistent in summer and winter. Combining the summer and winter data led to statistical significance only in the Herring Gull (odds ratio 2.8, 95% CL = 1.1, 6.8, $P = 0.026$). Outside the migration seasons, most movements were interpreted as local feeding flights, and it could be assumed that most birds moved up and down the coast on a loop, passing close to the turbines in one direction but not in the other. We have no explanation for the changes in directional frequencies recorded between pre- and post-construction periods.

Winds and tides

Most of the variation in the count data within species could be interpreted in terms of seasonal changes that were unaffected by the presence of turbines. However, it was important to assess to what extent winds and tides may have influenced the numbers and behaviour of birds seen. Using the methodology described earlier, in various species significant effects of time of day, tidal state and wind direction were detected on the numbers seen per hour, and on flight heights and directions (Tables 8, 9 and 10). However, in no species, in summer or winter, did these effects make any material difference to the ratio of post- to pre-construction counts. In other words, after taking account of variability in time of day (GMT), tidal state and wind direction, no effects on earlier conclusions on pre- and post-construction comparisons were apparent.

Mortality

During 352 hours of observation in the post-construction period, no birds were seen to be struck by the blades. Birds avoided the rotors mainly by veering around them, but their normal low flight heights could have given further protection. Large gulls flew within the height band of the rotors much more often than the other species; terns seldom flew within the height band of the rotors, and sea-ducks were never seen within that band.

Despite the lack of mortality incidents during the watches, two Gannets that had apparently been killed by collision were found during systematic weekly searches for carcasses conducted on nearby shorelines (B. Little, unpubl. data). They indicated that some turbine-caused mortality probably did occur, but we had no way of knowing the total killed (not all casualties are likely to have washed up locally, Seys *et al.* 2001), nor whether those found were from local or more distant turbines.

DISCUSSION

This study was based on daytime observations of mainly passing birds in clear weather, and involved a 'windfarm' comprising only two turbines. We advise against

Table 8. Effect of start time (T), time of start time from high tide (THT = T – high tide time) and wind direction on the number of birds per hour, and estimated ratio (*R*) of post- to pre-construction counts per hour, after adjustment for effects of start time, time from high tide and wind direction.

		April–September			October–March		
Species	Adjusting variable	Effect	*R*	*P*	Effect	*R*	*P*
Gannet	None	na	**0.78**	**0.51**	na	na	na
	T	–	0.78	0.51	na	na	na
	T^2	–	0.79	0.54	na	na	na
	THT	+	0.74	0.43	na	na	na
	THT^2	–	0.69	0.33	na	na	na
	Wind	+	0.74	0.42	na	na	na
Cormorant	None	na	**0.60**	**0.005****	na	**0.57**	**0.14**
	T	–	0.60	0.005**	–	0.57	0.11
	T^2	+	0.60	0.006**	–	0.58	0.13
	THT	+	0.63	0.013*	+	0.58	0.14
	THT^2	+	0.64	0.015*	–	0.57	0.12
	Wind	–	0.62	0.011*	–	0.55	0.087
Common Scoter	None	na	**0.80**	**0.78**	na	**0.80**	**0.78**
	T	–	0.81	0.80	–	0.81	0.80
	T^2	–*	0.76	0.75	–*	0.76	0.75
	THT	–	0.81	0.80	–	0.81	0.80
	THT^2	+**	0.85	0.84	+***	0.85	0.84
	Wind	+	0.77	0.75	+	0.77	0.75
Common Eider	None	na	**0.51**	**0.30**	na	**1.18**	**0.78**
	T	–*	0.53	0.32	–	1.24	0.72
	T^2	+	0.46	0.27	–	1.42	0.56
	THT	–	0.52	0.32	–	1.18	0.78
	THT^2	+***	0.53	0.41	–	1.13	0.84
	Wind	–	0.43	0.22	+**	0.90	0.86
Black-headed Gull	None	na	**0.21**	**0.17**	na	**1.46**	**0.65**
	T	+	0.21	0.17	+**	0.39	0.29
	T^2	+	0.20	0.16	+	0.39	0.29
	THT	–	0.21	0.17	+***	0.73	0.70
	THT^2	–	0.29	0.25	+**	0.87	0.85
	Wind	–	0.36	0.40	–	1.66	0.55
Herring Gull	None	na	**0.90**	**0.77**	na	**1.59**	**0.28**
	T	+	0.90	0.79	–	1.74	0.20
	T^2	+	0.91	0.80	–	1.76	0.18
	THT	+	0.86	0.67	–	1.65	0.24
	THT^2	+	0.86	0.67	–	1.62	0.26
	Wind	+	0.89	0.77	–	1.93	0.19
Great Black-backed Gull	None	na	**2.33**	**0.020***	na	**2.25**	**0.14**
	T	+	2.06	0.039*	–*	2.82	0.054
	T^2	+	2.07	0.038*	–*	2.61	0.068
	THT	–	2.35	0.019*	–	2.32	0.12
	THT^2	–	2.21	0.027*	+	2.33	0.13
	Wind	+*	2.20	0.028*	–	2.63	0.15
Black-legged Kittiwake	None	na	**2.00**	**0.15**	na	**8.71**	**0.20**
	T	–	2.05	0.13	–	11.1	0.15
	T^2	–	2.10	0.11	–*	10.5	0.14
	THT	–*	2.18	0.096	+*	7.10	0.20
	THT^2	–	2.16	0.10	+	7.01	0.20
	Wind	–	1.94	0.18	+*	23.2	0.30
Sandwich Tern	None	na	**2.28**	**0.033***	na	na	na
	T	+	2.27	0.051	na	na	na
	T^2	+	2.28	0.050*	na	na	na
	THT	–	2.30	0.034*	na	na	na
	THT^2	–*	2.17	0.056	na	na	na
	Wind	+*	3.07	0.007**	na	na	na

For linear trend, +/– indicates an increase/decrease with time, or north/south for wind direction; for quadratic effect, +/– indicates increase/decrease in the *rate* of increase. Unadjusted values are shown in bold. Analyses are based on statistical models which allow for monthly differences and random year-to-year variation (see statistical methods). na, Statistical analysis not appropriate. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

Table 9. Effect of start time (T), time of start time from high tide (THT = T – high tide time) and wind direction on the percentage of birds flying in height category C, and estimated odds ratio (*R*) of post- to pre-construction percentages.

		April–September			October–March		
Species	Adjusting variable	Effect	Odds ratio	*P*	Effect	Odds ratio	*P*
Gannet	None	na	**0.03**	**0.069**	na	na	na
	T	–	0.03	0.085	na	na	na
	T^2	–*	0.08	0.091	na	na	na
	THT	+	0.03	0.076	na	na	na
	THT^2	–	0.03	0.062	na	na	na
	Wind	+	0.03	0.088	na	na	na
Cormorant	None	na	**0.32**	**0.027***	na	**0.52**	**0.37**
	T	+	0.32	0.031*	–**	0.74	0.70
	T^2	–	0.32	0.032*	+	0.57	0.45
	THT	+	0.35	0.042*	+	0.53	0.37
	THT^2	–	0.32	0.033*	–	0.55	0.41
	Wind	+	0.35	0.049*	+	0.47	0.36
Black-headed Gull	None	na	na	na	na	**0.01**	**0.25**
	T	na	na	na	–	0.01	0.30
	T^2	na	na	na	+	0.01	0.31
	THT	na	na	na	–	0.01	0.27
	THT^2	na	na	na	+	0.03	0.16
	Wind	na	na	na	+	0.01	0.25
Herring Gull	None	na	**0.34**	**0.12**	na	**0.18**	**0.005****
	T	+	0.34	0.12	+	0.16	0.004**
	T^2	–***	0.31	0.079	–	0.16	0.005**
	THT	–*	0.39	0.20	+	0.16	0.004**
	THT^2	–	0.38	0.18	+	0.17	0.006**
	Wind	–**	0.31	0.093	–	0.20	0.016**
Great Black-backed Gull	None	na	**0.19**	**0.015***	na	**0.05**	**0.026***
	T	+	0.17	0.013*	–	0.05	0.027*
	T^2	–	0.16	0.011*	–	0.05	0.028*
	THT	+**	0.12	0.004**	+	0.04	0.024*
	THT^2	–	0.10	0.004**	+	0.04	0.026*
	Wind	+	0.18	0.016*	+	0.06	0.058
Black-legged Kittiwake	None	na	**0.53**	**0.52**	na	na	na
	T	+	0.42	0.37	na	na	na
	T^2	–***	0.30	0.20	na	na	na
	THT	+	0.52	0.52	na	na	na
	THT^2	+	0.61	0.64	na	na	na
	Wind	–	0.51	0.52	na	na	na
Sandwich Tern	None	na	**0.21**	**0.037***	na	na	na
	T	+*	0.22	0.032*	na	na	na
	T^2	–	0.22	0.033*	na	na	na
	THT	+	0.21	0.036*	na	na	na
	THT^2	+	0.22	0.050*	na	na	na
	Wind	–***	0.26	0.12*	na	na	na

For linear trend, +/– indicates an increase/decrease with time, or north/south for wind direction; for quadratic effect, +/– indicates increase/decrease in the *rate* of increase. Unadjusted values are shown in bold. Analyses are based on statistical models which allow for monthly differences and random year-to-year variation (see statistical methods). na, Statistical analysis not appropriate. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

extrapolating our findings to conditions of darkness or poor visibility, or to larger windfarms involving multiple rows of turbines. Moreover, we were unable to set up a parallel count site on another section of local coast not subject to windfarm development. Compared to the simple before-and-after comparison adopted, such a BACI (before–after control impact) design could have provided greater statistical confidence in the conclusions, as it would have better allowed for any changes in bird numbers that might have occurred independently of turbine construction over the study period.

The numbers of seabirds seen in the observation area varied more than 25-fold in different count periods, but

Table 10. Effects of start time (T), time of start time from high tide (THT = T – high tide time) and wind direction on percentage of birds flying south, and estimated odds ratio (*R*) of post- to pre-construction percentages.

		April–September			October–March		
Species	Adjusting variable	Effect	Odds ratio	*P*	Effect	Odds ratio	*P*
Gannet	None	na	**46**	**0.016***	na	na	na
	T	–	47	0.017*	na	na	na
	T^2	–	52	0.016*	na	na	na
	THT	+	57	0.014*	na	na	na
	THT^2	+	65	0.011*	na	na	na
	Wind	+	54	0.013*	na	na	na
Cormorant	None	na	**0.63**	**0.27**	na	**0.67**	**0.59**
	T	+**	0.65	0.20	+	0.57	0.43
	T^2	–	0.65	0.20	–	0.62	0.49
	THT	+	0.71	0.40	–	0.66	0.58
	THT^2	+	0.74	0.46	–	0.69	0.6`
	Wind	+	0.64	0.29	–	0.81	0.80
Common Scoter	None	na	na	na	na	na	na
	T	na	na	na	na	na	na
	T^2	na	na	na	na	na	na
	THT	na	na	na	na	na	na
	THT^2	na	na	na	na	na	na
	Wind	na	na	na	na	na	na
Common Eider	None	na	**0.39**	**0.50**	na	**0.44**	**0.60**
	T	+	0.48	0.62	+**	0.01	0.14
	T^2	–	0.46	0.62	+**	0.02	0.033*
	THT	+	0.25	0.38	+	0.63	0.78
	THT^2	–	0.24	0.39	–	0.16	0.39
	Wind	–	0.39	0.51	+**	0.08	0.10
Black-headed Gull	None	na	**0.04**	**0.096**	na	**6.61**	**0.12**
	T	+	0.00	0.046*	–	8.03	0.11
	T^2	–	0.00	0.046*	–	5.81	0.15
	THT	+	0.02	0.16	–	7.21	0.11
	THT^2	+	0.01	0.27	+	8.28	0.11
	Wind	+	0.02	0.11	–	8.14	0.09
Herring Gull	None	na	**2.53**	**0.12**	na	**2.83**	**0.16**
	T	+	2.63	0.12	–	3.54	0.11
	T^2	–	2.71	0.079	–	3.58	0.10
	THT	+	2.43	0.20	–	3.05	0.15
	THT^2	+	2.42	0.18	–	2.57	0.22
	Wind	+*	2.53	0.093	+	4.36	0.070
Great Black-backed Gull	None	na	**1.29**	0.77	na	**1.47**	**0.71**
	T	+	1.02	0.98	–*	1.70	0.58
	T^2	–	1.02	0.98	–*	1.73	0.55
	THT	–	1.35	0.74	–	1.66	0.61
	THT^2	–	1.36	0.73	+	1.74	0.59
	Wind	+*	1.14	0.88	+	1.95	0.54
Black-legged Kittiwake	None	na	**1.65**	**0.38**	na	na	na
	T	+	1.64	0.40	na	na	na
	T^2	–	1.59	0.44	na	na	na
	THT	–	1.85	0.31	na	na	na
	THT^2	+	2.32	0.19	na	na	na
	Wind	–	1.63	0.40	na	na	na
Sandwich Tern	None	na	**1.82**	**0.27**	na	na	na
	T	+	1.87	0.25	na	na	na
	T^2	–	1.86	0.26	na	na	na
	THT	+	1.82	0.27	na	na	na
	THT^2	–	1.73	0.30	na	na	na
	Wind	+***	1.49	0.48	na	na	na

For linear trend, +/– indicates an increase/decrease with time, or north/south for wind direction; for quadratic effect, +/– indicates increase/decrease in the *rate* of increase. Unadjusted values are shown in bold. Analyses are based on statistical models which allow for monthly differences and random year-to-year variation (see statistical methods). na, Statistical analysis not appropriate. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

regular seasonal patterns in numbers were apparent in most of the species seen. These seasonal fluctuations were the main source of systematic variation within the counts. Most birds flew low over the waves, within about 9 m of the sea surface (the average level of the access platform), and well below the lower sweep of the rotors. The main exceptions to these generalizations were the large gulls which flew at rotor height more often than other species.

Too few counts were made during the construction period to draw firm conclusions on effects, but comparing pre- and post-construction periods, three significant differences emerged. In the summer period, the numbers of Cormorants declined significantly, while the numbers of Sandwich Terns and Great Black-backed Gulls increased significantly. In the winter months, no significant changes were detected. Because the Cormorants underwent a step-change in summer abundance following construction of the turbines, they may have been avoiding the area to some extent. However, the increase of other species was gradual, and thus probably occurred independently of the turbines. The increase in counts of Sandwich Terns was not associated with any increase in the colony size on Coquet Island, as nest counts for the years 1998–2003 were 2897, 1676, 1726, 1190, 1689 and 1238, respectively (RSPB unpubl. data). They may therefore have resulted from changes in the use of different feeding areas. Post-construction, small flocks of Sandwich Terns were on several occasions seen fishing around and between the turbines, raising the possibility that the underwater parts of these structures were attractive to small fish. Terns were not seen to forage in these areas before the turbines were built there.

The height distributions recorded for passing birds at Blyth were broadly similar to those recorded elsewhere (Garthe & Hüppop 2004, Petersen *et al.* 2006), but off the Danish coast waterbirds (mainly Eiders) flying within a windfarm area reduced their flight heights compared with outside the area, passing more often below the height of the rotors (Petersen *et al.* 2006). Although some apparent changes in the height distribution of passing birds were detected at Blyth (with more birds flying higher than 9 m post-construction), these changes may not have been real because of the difficulty of measuring flight heights before turbine construction. The Black-headed Gull passed the turbines mainly in a southward direction pre-construction, and in a northward direction post-construction. This difference was statistically significant, but being based on small samples (11 and 17) it was hard to interpret.

Of the various changes observed between the pre- and post-construction periods, the only ones that we would place confidence in are the numerical changes: decrease in one species and increase in two others. From the nature of the study, we could not infer causal changes that were unequivocally attributable to the construction of the turbines. However, as the decline in Cormorant counts occurred rapidly, in stepwise manner, between pre- and post-construction periods, it may have been because the presence of turbines deterred birds from feeding locally (but we had no independent evidence of this). The increases in Sandwich Terns and Great Black-backed Gulls were more gradual, and probably occurred independently of the presence of the turbines. Another change apparent in some species concerned the ratio of southward to northward flights recorded between pre- and post-construction periods. We have no explanation for why this change might have occurred, and it may again have been unconnected with the turbines. No other meaningful effects of the turbines on bird behaviour were detected. No mortality was recorded in the daytime watch periods, but two Gannets, apparently killed by the rotor blades, were found during systematic weekly searches of the nearby shoreline. Some differences between our findings and another study involving terns (Everaert & Stienen 2007) are discussed in Endnote b.

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ENDNOTES

a. The unit for statistical analysis was the watch period, while the corresponding count was taken as the response variable. Let y_{ijk} denote the count for the *k*th watch of the *i*th month, in the *j*th year. The corresponding mean count (μ_{ijk}) is assumed to be proportional to the duration of the watch with multiplicative effects of month, year and period, that is: $\mu_{ijk} = D_{ijk} \exp(\alpha_i + \beta_j + \theta_m + \alpha\beta_{ij})$. D_{ijk} denotes the duration of the watch, α_i is a *fixed* effect for the *i*th month, β_j is a *random* effect for the *j*th year and $\alpha\beta_{ij}$ is a *random* month × year interaction effect. The effect of construction period is denoted by θ_m (pre, $m = 1$; during, $m = 2$; post, $m = 3$) depending on the particular month and year (see Table 1). Construction period effects are additive on a logarithmic scale, i.e. a multiplicative effect measured as the ratio $R = \exp(\theta_3 - \theta_1)$. Random variation of counts about the mean was assumed to increase in proportion to the mean count, that is $\mathrm{var}[y_{ijk}] = c\mu_{ijk}$, where c denotes the overdispersion factor. The model was fitted as a generalized linear mixed model with log link function and Poisson error distribution using the statistical package Genstat 7.

For the analysis of birds flying at height category C (or flying south), let r_{ijk} denote the number of birds flying at height C out of the n_{ijk} birds observed in the *k*th watch of the *i*th month, in the *j*th year. The corresponding mean count is $\mu_{ijk} = n_{ijk}\, p_{ijk}$, where p_{ijk} is the event probability which includes effects for month, year and construction period; that is $p_{ijk} = \exp(\alpha_i + \beta_j + \theta_m + \alpha\beta_{ij})/[1 + \exp(\alpha_i + \beta_j + \theta_m + \alpha\beta_{ij})]$, where α_i is a *fixed* effect for the *i*th month, β_j is a *random* effect for the *j*th year and $\alpha\beta_{ij}$ is a *random* month × year interaction effect. Random variation of counts about the mean was assumed to follow the binomial variance; that is $\mathrm{var}[r_{ijk}] = cn_{ijk}p_{ijk}(1 - p_{ijk})$, where c denotes the overdispersion factor. Construction period effects are additive on a logit scale, that is $OR = \exp(\theta_3 - \theta_1)$ corresponds to the odds ratio for the event probabilities (namely $Odds = P/[1 - P]$). The model was fitted as a generalized linear mixed model with logit link function and binomial error distribution. In a few cases it was not possible to fit logistic models because of small sample sizes or a limited range of variation. For example, the Common Scoters and Common Eiders flew only at height category C, and were never seen at greater heights.

b. It is instructive to compare our findings with those of another study on terns, including Sandwich Tern, Common Tern *Sterna hirundo* and Little Tern *S. albifrons*. The study was based on 25 'small to medium' turbines located on a breakwater in Zeebrugge harbour, Belgium (Everaert & Stienen 2007). In this locality, the turbines were found to inflict considerable collision mortality, estimated at about seven terns per turbine per year and about 13 other species per turbine per year during 2004 and 2005. However, in this situation a nesting area for terns and other birds had been constructed immediately adjacent to some pre-existing turbines, as a mitigation measure to offset the loss of nesting habitat elsewhere. The terns were thus vulnerable during their display and other high flights around the colony, and on foraging trips they had to pass repeatedly through the line of turbines. This was completely different from the situation at Blyth, where the turbines were located many kilometres from the nearest breeding colony, and where the birds were flying mainly parallel to the rotor blades, rather than through them. The Blyth turbines did not intercept major flight lines. Also, our study was observational and restricted to conditions of good visibility, while the Belgian study was based partly on carcass searches on the ground below the turbines, so could have revealed casualties occurring in all weather conditions, day and night (although the terns did not normally fly at night). Our carcass searches were on nearby shoreline, about 1 km from the offshore turbines, but revealed no terns (unpubl. data). At the least, the Belgian study illustrates the likely consequences of constructing turbines close to seabird nesting colonies (or, as in this case, of constructing nesting areas close to pre-existing turbines).

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APPENDIX

Alphabetical list of species and numbers counted during the study (species selected for analysis are shown in bold).

Species	Number counted	Species	Number counted
Arctic Skua *Stercorarius parasiticus*	13	Lesser Black-backed Gull *Larus fuscus*	13
Arctic Tern *Sterna paradisaea*	26	Little Gull *Larus minutus*	10
Barnacle Goose *Branta leucopsis*	240	Long-tailed Duck *Clangula hyemalis*	1
Black-headed Gull *Larus ridibundus*	**1119**	Mallard *Anas platyrhynchos*	15
Black-tailed Godwit *Limosa limosa*	8	Manx Shearwater *Puffinus puffinus*	18
Black-throated Diver *Gavia arctica*	4	Meadow Pipit *Anthus pratensis*	26
Common Gull *Larus canus*	268	Mediterranean Gull *Larus melanocephalus*	1
Common Scoter *Melanitta nigra*	**473**	Mute Swan *Cygnus olor*	5
Common Tern *Sterna hirundo*	125	Oystercatcher *Haematopus ostralegus*	24
Cormorant *Phalacrocorax carbo*	**531**	Peregrine Falcon *Falco peregrinus*	1
Great Crested Grebe *Podiceps cristatus*	1	Pink-footed Goose *Anser brachyrhychus*	121
Curlew *Numenius arquata*	54	Puffin *Fratercula arctica*	25
Dunlin *Calidris alpina*	21	Razorbill *Alca torda*	1
Common Eider *Somateria mollissima*	**1208**	Red-breasted Merganser *Mergus serrator*	8
Feral/Racing Pigeon *Columba livia*	180	Red-throated Diver *Gavia stellata*	34
Fieldfare *Turdus pilaris*	3	Redshank *Tringa totanus*	9
Fulmar *Fulmarus glacialis*	268	Ringed Plover *Charadrius hiaticula*	2
Gannet *Morus bassanus*	**578**	Roseate Tern *Sterna dougallii*	3
Garganey *Anas querquedula*	1	Sand Martin *Riparia riparia*	1
Golden Plover *Pluvialis apricaria*	2	**Sandwich Tern *Sterna sandvicensis***	**2398**
Goldeneye *Bucephala clangula*	56	Scaup *Aythya marila*	70
Goosander *Mergus merganser*	2	Shag *Phalacrocorax aristotelis*	35
Great Black-backed Gull *Larus marinus*	**725**	Shelduck *Tadorna tadorna*	5
Great Northern Diver *Gavia immer*	1	Shoveller *Anas clypeata*	2
Greylag Goose *Anser anser*	1	Swallow *Hirundo rustica*	1
Guillemot *Uria aalge*	170	Swift *Apus apus*	1
Heron *Ardea cinerea*	2	Teal *Anas crecca*	24
Herring Gull *Larus argentatus*	**1755**	Tufted Duck *Aythya fuligula*	2
Kestrel *Falco tinnunculus*	1	Velvet Scoter *Melanitta fusca*	2
Kittiwake *Rissa tridactyla*	**1667**	Whimbrel *Numenius phaeopus*	51
Knot *Calidris canutus*	4	Whooper Swan *Cygnus cygnus*	3
Lapwing *Vanellus vanellus*	3	Wigeon *Anas penelope*	162

The diving behaviour of the Manx Shearwater

Shoji, A. [1], Dean, B. [1], Kirk, H. [1], Freeman, R. [2,3,4], Perrins, C.M. [1] & Guilford, T.C. [1]

[1]Department of Zoology, South Parks Road, Oxford, OX13PS, UK

[2]Centre for Mathematics and Physics in the Life Sciences and Experimental Biology, University College London, Gower Street, London WC1E 6BT, UK

[3]Computational Ecology and Environmental Science, Microsoft Research Limited, 7 JJ Thomson Avenue, Cambridge CB3 0FB, UK

[4]Zoological Society of London, Regent’s Park, London, NW1 4RY, UK

Key Words: Diving behaviour; Shearwater; Bio-logging

Running Head: Shearwater diving

Summary

The diving capabilities of *Procellariformes* remain the least understood component of avian diving physiology. Due to their relatively small size shearwaters may have high oxygen consumption rates during diving relative to their available oxygen stores. Dive performance in this group should be strongly limited by the trade-off between oxygen consumption and oxygen stores, and shearwaters could be a good model group for testing predictions of dive theory. Many earlier measurements of shearwater dive behaviour relied on observations from the surface or potentially biased technology, and it is only recently that diving behaviour has been observed using electronic recorders for many of the clades within the family. To rectify this issue, the diving behaviour of Manx Shearwaters (*Puffinus puffinus*) breeding in Wales, United Kingdom, was studied on a large sample of birds using bird-borne time-depth-temperature recorders deployed on chick-rearing shearwaters in July and August over three years (2009-2011). Light availability apparently limited diving as dives only occurred between 4:00 and 19:00 in GMT. All individuals routinely dive deeper than traditional assumptions, to a mean maximum depth of 31m and down to nearly 55m. We compiled all available data for a comparison of the dive depth across shearwater species. There was a positive allometric relationship between maximum dive depth and body mass across *Puffinus* and *Ardenna* shearwater species, as expected, but only if samples of < 2 individuals were excluded. The large intra-specific range in maximum dive depth in our study illustrates that apparent diversity in diving performance across species must be interpreted cautiously.

Introduction

In breath-holding diving animals, oxygen stores are generally increase with body mass ^1.00, while metabolic rate increases only with body mass ^0.75 (Halsey *et al.* 2006). Therefore body mass determines capacity for long and deep dives in breath-hold divers (Kooyman & Kooyman, 1995). Procellariiform seabirds often exceed the dive depth limit expected from allometry, exemplifying adaptation for a pelagic life-style, and widely varied diving performance. Albatrosses, with their long wings, are not morphologically adapted for diving and typically performe shallow (<5m) dives (Prince et al. 1994), while diving petrels (*Pelecanoides*), morphologically adapted for underwater pursuit using wing propulsion, can reach meanmaximum diving depths of 10-18 m (Navarro *et al*. 2014, Dunphy *et al*. 2015). The diving behaviour of shearwaters (*Puffinus, Ardenna* and *Calonectris)* possess several anatomical adaptations for swimming under water, including a robust sternum and pelvis, laterally compressed “streamlined” tarsi, flattened humeri and relatively short wings compared with many other Procellariiformes (Warham 1977). Some petrel species are known to engage in pursuit plunging and pursuit diving (Warham 1990). However, information on dive performance in shearwater species consists of mixed data from maximum depth gauges (Burger & Wilson 1988) and low-sampling rate archival pressure loggers (Rayner *et al*. 2011). The use of high-sampling-rate dive loggers is critical for capturing fine-scale diving behaviour and accurately calculating dive parameters. Lower sampling rates lead to under estimation of the number of dives performed, overestimation of dive duration and potentially underestimation of dive depth (Wilson *et al*. 1995, Elliott *et al*. 2009). To help fill this gap in knowledge we report detailed diving behaviour in a ca. 400 g representative of the group (range: 148-850 g, Table 1), the Manx Shearwater *Puffinus puffinus*, a trans-equatorial migrant predominantly breeding in the UK (Guilford et al. 2009). Knowledge of the feeding ecology of marine top predators is essential to understand their potential role in the marine ecosystems, and to conserve and manage those ecosystems (Ashmole, 1971, Hunt and Schneider, 1987), and there is a need for more data for those species that have been seldom studied to date (Phalan et al., 2007). Our goal is two-fold: to describe the diving behaviour of Manx Shearwaters for the first time with a large sample using 1 Hz time-depth recorders (TDR), and to explore whether there is an allometric relationship between body mass and dive depth for shearwater species using currently available published data (including analysis of sample size).

Methods

To gain a representative sample of diving behaviour, TDRs were deployed on Manx shearwaters rearing chicks during July and August over three years (2009-2011) at Skomer Island, Wales (51° 44′ N, 5° 17′ W). Equipped birds were selected from our study plots, all of whom were caring for young during the normal chick-rearing period at this site. With alarge number of birds tracked for multiple years and by comparing breeding success with unmonitored plots, our samples are representative of the population as a whole. 2.7g CEFAS G5 TDRs were attached for seven days maximum to four central tail feathers with Tesa marine cloth tape (Wilson & Wilson 1989), configured at 1 Hz recording in pressure and temperature, with a resolution of <0.1 m,. As part of another study, birds also carried a GPS logger on their back and leg-mounted geolocator-immersion logger: total attachment mass was 17.5-19.0g (4.0-4.8% body mass based on individual body weights; see Dean et al. (2012) for methods, which reported that there was no measurable effects in breeding parameters). Birds were taken from study nests by hand, weighed, devices deployed (or removed), and returned within 15 minutes. Birds were sexed by cloacal inspection (Gray & Hamer 2001) and sex information was recorded as unknown if we missed the laying date. To determine food load from parents to their chicks, we weighed chicks every evening at 8pm before Manx Shearwaters arrived at the colony and checked study burrows every 20 min through the night (typically between 23:00-04:00). To reduce disturbance, we used knock-down sticks at the entrance (Shoji & Gaston, 2010), only checking nests when sticks were displaced. When we found an adult in a study burrow, we blocked the nest and left at least 20 min to allow parents to feed young before weighing both parent and chick. This visual inspection also allowed us to determine trip duration.

All analyses were performed in R 3.1.2 (R Development Core Team 2014). Weextracted dive depth, dive duration and surface interval duration for each dive, after accounting for device drift, using diveMove (Luque & Fried 2011). Depth measurements were calibrated using a ‘moving quantile’ zero-offset correction method (details in Luque & Fried 2011), and each dive event was classified using a dive threshold of 1 m. Behavioural aerobic dive limit (bADL) was estimated by following the method provided in Kooyman & Kooyman (1995). Dive duration with the minimum post-dive duration was identified by fitting a spline regression with segmented relationship in post-dive durations (“segmented” package in R). We applied Burger’s (1991) method for other diving seabirds to develop the allometric relationship between maximum dive depth and body mass averaged across individuals using data from published studies (values from other literatures was used for some species when body mass was not presented in the references) as the estimated slope of the $\log_{10}$-$\log_{10}$ linear regression. As there are intra-specific variations in dive depth in seabirds (Halsey *et al*. 2006) and sample sizes varied among studies, we further tested whether absolute maximum dive depth is related to sample size, by using the residual of absolute maximum dive depth on body mass against number of individuals used in each study. We tested for normality and homoscedasticity prior to the analysis and data were transformed if necessary. To analyse the relationship between dive duration (s) and dive depth (m) in Manx Shearwaters, we used linear mixed models with individual as a random effect to include multiple dives per individual. Model selection was based on minimising Akaike's information criterion (AIC) and we calculated ΔAIC relative to the null model (intercept-only). Unless otherwise stated, means ± 1 SD are presented.

Results

We deployed loggers on 18 birds in 2009 (5 males, 11 females, 2 unknown), 9 in 2010 (4 males, 4 females, 1 unknown), and 10 in 2011 (8 males, 2 females). Corrupted data from 4 TDRs (1 male in 2009, 2 males and 1 female in 2011) were discarded. Mean deployment period (duration of device attachment) was 3.8 ± 1.2 days (range 2-10). The median recorded foraging trip was 1 day (interquartile range 1-3, range 1-8) after which tracked parents fed chicks a meal with a mean mass of 48.1 ± 20.7 g, and 56 g for parents carrying devices <1% body mass (Gray & Hamer 2001). In total we recorded 3,329 dives during 122 bird-days from 33 deployments: 1,209 dives in 53 days from 17 birds in 2009, 733 dives in 28 days from 9 birds in 2010; and 1,387 dives in 41 days from 7 birds in 2011. One female was tracked in both 2009 and 2010 so the first deployment was excluded. Mean mass of tracked males (419.3 ± 23.5 g) and females (419.3 ± 31.8 g) was similar (t_{27} = 0.001, P = 0.99), and mean dive depth and dive frequency per day did not differ between sexes (mean dive depth: male = 34.4 ± 9.4 m, female = 31.0 ± 6.9 m, pooled = 32.7 ± 8.2 m, t_{27} = 1.33, P = 0.19; dive frequency: male = 256.6 ± 130.5 dives day^{-1}, female = 184.6 ± 156.9 dives day^{-1}, pooled = 219.3 ± 146.8 dives day^{-1}, t_{27} = 1.11,

$P = 0.28$). There was a clear diurnal pattern to diving behaviour (Fig. 1a, b), showing that diving activities in this species occurred during the daytime between 04:00 - 19:00 GMT ($n = 3{,}329$). Dive duration increased with dive depth (ΔAIC = - 5477, GLMM: Estimate = 1.55 ± 0.01 s, Fig. 1_{C}). Maximum dive depth across individuals averaged 31.0 ± 9.9 m (range: 9.6 - 54.9m), while the maximum individual dive duration averaged 46.2 ± 16.0 s (range: 23 – 84 s). To determine the relationship between surface-pause duration and dive duration, we related each dive time to the shortest succeeding surface time needed for that dive time, and found a break point identified by fitting a spline regression (30.02 ± 14.51 (95 % CI) s; Fig. 2). Surface times rose steeply for dives longer than 30 s ($y = 9.45 \times 1.04^x$, $P < 0.0001$) ;. Approximately 10 % of dives exceeded the behavioural ADL (Fig. 1d).

To develop an allometric relationship we collected reported averaged maximum dive depths of 14 species (11 *Puffinus* including *Ardenna* and 3 *Calonectris* shearwaters; Table 1, Fig. 3). For presentation purposes, we included *Ardenna* species in the same category as *Puffinus* in this manuscript. The two genera appeared to differ, with *Calonectris* species showing only shallow diving (Fig. 3) compared with the *Puffinus* group. Across all studies (by combining species), residuals of absolute maximum dive depth on body mass increased with sample size (estimate = 0.93 ± 00.37 $t = 2.55$, $R^2 = 0.29$, $P = 0.02$, $N = 13$). Since maximum achievable depths may be missed in small samples we excluded the species with the smallest sample size (Great Shearwaters *Ardenna gravis*, $N = 2$), and found that maximum dive depth then increased with body mass across *Puffinus* species (exponent ± $SE = 0.59 \pm 0.19$, $R^2 = 0.53$, $t = 3.16$, $P = 0.01$, $N = 11$).

Discussion

Manx Shearwawter diving behaviour

Manx Shearwaters breeding at the world's largest colony have a striking diurnal foraging pattern and dive much deeper than reported dive depth in other groups of *Procellariiformes* (e.g. Dunphy *et al*. 2015). These data provide the first insights into the diving behaviour of the Manx Shearwater based on a large dataset providing detailed information for a *Puffinus* species. The use of high-sampling-rate dive loggers (1 Hz in this study; <10% of median dive duration), as recommended by Wilson et al. (1995) captured fine-scale diving behaviour and allowed accurate calculation of dive parameters. As with above-surface movement patterns associated with foraging in Manx Shearwaters (Dean *et al*. 2012), we found that diving behaviour was highly constrained to daylight and twilight hours, strongly suggesting visual pursuit of prey. Diurnal diving is typical of birds dependent on ambient light to forage, such as some albatrosses and prions, though some visual-based predation can occur at night under strong moonlight (Brooke 2004), or at high latitudes when days are too short (Grémillet *et al*. 2005), while some *Pterodroma* species use nocturnal foraging (Rayner *et al*. 2008). The difference could reflect the diet selection or whether or not birds search for prey in flight or sit on the water, which may be more effective at night (Phalan *et al*. 2007). Furthermore, Clupeid fish make diel vertical migrations within the water column in response to ambient light levels (Hays 2003), so diving at dawn and dusk might enhance foraging efficiency despite reduced ambient light because prey can be found at shallower depth at those times. In our study, dive frequency peaked in early evening (17:00 - 18:00 GMT), which may reflect a trade-off between increased prey availability and foraging efficiency during low-light conditions (Elliott & Gaston 2015) or perhaps reflecting a strategy to minimise the cost of transporting large food loads to the colony or nocturnal resting at sea. About half of all dives were less than 7 m, consistent with traditional views (Brooke 1990) that Manx Shearwaters rely on pursuit diving for shallow pelagic prey. Nevertheless, all individuals routinely dived much deeper, to a mean maximum depth of 31m with some diving down to nearly 55m. While deep dives were reliably recorded with TDR, foraging related shallow dives may be missed out because we have currently no way to identify uncertain dive events such as bathing, socializing and other non-foraging associated activities from genuine short, shallow dives so shallow dives were excluded from the analyses. Future studies to investigate the role of those dives will allow the nature of shallow dives to be better understood.

Sex-specific differences in diving behaviour (dive frequency, depth and duration) have been found in several species of seabird where there is sexual size dimorphism (Quillfeldt *et al*. 2011, Gomez Laich *et al*. 2012), reversed sexual size dimorphism (Lewis *et al*. 2005, Weimerskirch *et al*. 2006), or where the sexes are similar in size (Lewis *et al*. 2002, Pech & Congdon 2006, Elliott *et al*. 2010). Manx Shearwaters show little sexual size dimorphism: <1 mm difference in wing length and bill length, and 1 mm difference in tarsus length between the sexes (Brooke 1990) and the diving profiles of males and females in this study was similar.

Similarly, as all telemetric methods can impact behaviour (Phillips *et al*. 2003), for example by reducing provisioning rate or meal sizes (Saether *et al*. 1993), the biologgers in the current study may have impacted where and how birds foraged. Nevertheless, in our study, foraging trip length (median 1 day) and food delivery to chick (48g) were reasonably representative of normal behaviour (56 g for parents carrying devices <1% body mass, Gray & Hamer 2001; 49 g for untagged parents, Hamer & Hill 1997). In a comparison of birds with the same or similar devices with control birds , there were no measurable impact of carrying the device on reproductive success, chick-growth rates or foraging trip lengths (Dean *et al.* 2012).

Since seabirds are limited by the oxygen they take with them, stored in the respiratory and circulatory systems and muscles, there must be a dive duration (the aerobic dive limit, ADL (but see Butler 2006)) beyond which accumulated blood lactate must subsequently be metabolised during surface recovery (Burger, 2001). Early reports of calculated anaerobic dive limits (cADL) underestimated ADL by about a factor of three (e.g. Croll *et al.* 1992) because they used values for oxygen consumption derived from shallow dive tanks, which overestimated oxygen consumption by a factor of three (Hansen & Ricklefs 2004, Elliott *et al.* 2013). One reason behavioural ADL (bADLs), such as the bADL measured in our study, may be preferable is because they avoid inaccuracies in the measurement of oxygen consumption during diving. Calculated ADL has been reported for several species of diving seabird: 48 s for Brünnich's Guillemot *Uria lomvia* (Croll *et al.* 1992), 78-120 s for Gentoo Penguin *Pygoscelis papua* and 126 s for King Penguin *Aptenodytes patagonicus* (Butler 2001). Estimated bADL was 27-29 s for Imperial Shags *Phalacrocorax atriceps* (Quillfeldt *et al.* 2011) and 240 s for Crozet and Kerguelen Shags *Phalacrocorax melanogenis* and *Phalacrocorax verrucosus* (Tremblay *et al.* 2005, Cook *et al.* 2008), though it seems improbable that there is one order magnitude difference in the bADL among these species, because these three species are closely related (Hackett *et al.* 2008). Rather the inconsistency is likely to reflect ecological or physical differences or is due to a difference in sample sizes. Our estimate for the Manx Shearwater bADL of 30 s, falls within this range and high correlation between dive depth and dive duration suggests that the Manx Shearwaters use their lengthy dives to achieve deeper depth, rather than extending the bottom time of each dive. Only 10 % of dives exceeded 30 s duration, suggesting that Manx Shearwaters rarely dive beyond their aerobic limit, which agrees with the previous report that few dives for most animals exceed their ADL (Butler & Jones 1997). Overwhelmingly most (90%) of Manx Shearwater diving is therefore aerobic, although occasional longer anaerobic dives are also used, perhaps to exploit dense, but mobile and hard-to-find concentrations of prey before they escape or become depleted (Ydenberg & Clark 1989).

Allometric relationship

Maximum dive depth in wing-propelled divers is allometrically related to body mass (Burger 1991), and we found that the relationship across *Puffinus* and *Ardenna* shearwater species was significant after removing the smallest sample. The allometric scaling exponent for dive depth (0.59) in this study was higher than the exponent for dive duration (0.37; Halsey *et al*. 2006). This suggests that *Puffinus* species were using long dive duration to increase their transit times (= deeper depth), rather than to stay longer at the bottom. The high value of the exponent could represent real range in diving behaviour in relation to body size, but the cross-study effect of sample size on apparent maximum dive depths with mass suggests caution. Perhaps because *Puffinus* shearwaters often dive much lesser depth than they are able (as we have shown here for the Manx Shearwater), maximum achievable depths may be missed in small samples making some studies unreliable. Similarly, the due to poorly resolved phylogeny in *puffinus* species (Pyle *et al*. 2011), we were unable to account for phylogeny which could be a potential issue. Nevertheless, our results show that dive depth scales with body mass in shearwaters, but that strong conclusions require reliable data.

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SPECIES	Binary	N	mass	Max depth (m)	Ave. Max depth (m)	Ave. depth (m)	Ave. Max duration (g)	Ave. duration (g)	Method	Reference
Barolo shearwater	*Puffinus baroli*	6	174.1	23.1	14.8	-	-	-	MDG	Neves et al., 2012
Flesh-footed shearwater	*P. carneipes*	23	632	28.7	13.6	-	-	-	MDG	Taylor, 2008
Black-vented shearwater	*P. opisthomelas*	18	406	52	21	-	-	-	MDG	Keitt et al., 2000
Yelkouan shearwaters	*P. yelkouan*	10	500	30.2	25.7	17.8	-	-	TDR	Peron et al., 2013
Audubon's shearwater	*P. Iherminier*	7	168	35	15	-	-	-	MDG	Burger, 2001
Manx shearwater	*P. puffinus*	36	421	55	33.06	9.6	46.22	13.49	TDR	This study
Hutton's shearwater	*P. huttoni*	13	380	36.6	23	-	-	-	MDG	Taylor, 2008
Balearic shearwater	*P. mauretanicus*	18	500	28.04	16.35	-	-	-	TDR	Meier et al., 2015
Balearic shearwater	*P. mauretanicus*	3	500	26	-	5.6	66	17.6	DL	Aguilar et al., 2003
Great shearwater	*Ardenna gravis*	2	864	18.9	14.9	3	6.9	31	TDR	Ronconi et al., 2010
Fluttering shearwater	*A. gavia*	1	148	29.4*	-	-	-	-	MDG	Taylor, 2008

Sooty shearwater	*A. griseus*	9	850	69.9	48	15.9	-	-	TDR	Shaffer et al., 2009
Sooty shearwater	*A. griseus*	20	850	68.2	-	12.5	-	-	TDR	Shaffer et al., 2006
Sooty shearwater	*A. griseus*	16	850	92.9	42.7	-	-	-	MDG	Taylor, 2008
Sooty shearwater	*A. griseus*	10	847	55.1	-	6.93	-	39.73	TDR	Dunphy et al., 2015
Sooty shearwater	*A. griseus*	35	850	67	-	38.7	-	11.5	MDG	Weimerskirch and Sagar, 1996
Short-tailed shearwaters	*A. tenuirostris*	22	588	70.6	35.5	-	12	-	MDG	Weimerskirch and Cherel, 1998
Flesh footed shearwater	*A. carneipes*	3	700	66.5	44.1	3.2	-	-	TDR	Rayner et al., 2011
Wedge-tailed shearwaters	*A. pacificus*	19	426	66	13	-	-	-	MDG	Burger, 2001
Cory’s shearwater	*C. borealis*	22	770	9.8	7.35	1.95	3.95	24.5	TDR	Paiva et al., 2010
Streaked shearwaters	*C. leucomelas*	14	513	6	2.53	1.06	4.43	8.64	TDR	Matsumoto et al., 2012
Scopoli’s shearwaters	*C. diomedea*	10	657	5.4	4.45	1.8	7.95	11.7	TDR	Grémillet et al., 2014

Table 1. Raw data used in this study on sample size, body mass, dive depth and duration in shearwater species.

Note: N = number of individuals, Max depth = absolute maximum dive depth, Ave Max depth = maximum dive depth averaged across individuals, Ave depth = mean depth, Ave. Max duration = maximum dive duration averaged across individuals, Ave duration = mean duration. Method: MDG = maximum depth gage, TDR = temperature-depth recorders, DL = combined depth sensor and depth logger. * indicates median value.

Figure legends

Figure 1. (a) Number of dives and (b) mean dive depths (04:00 - 19:00) as a function of hour of day;(c) relationship between dive depth (m) and dive duration (s); (d) Frequency of dive durations (s) in the Manx Shearwater. Dashed line indicates the behavioural ADL (30 s).

Figure 2. Dive duration and the shortest succeeding surface pause duration in a given dive duration in the Manx Shearwater. The black solid line represents the segmented regression line with an identified breakpoint (30 s) on dive duration and the two vertical grey broken lines are 95 % confidence intervals (15.69-44.34 s).

Figure 3. Average maximum dive depth (m) against body mass (g). Grey dots indicate *Puffinus* and *Ardenna* species (*N* = 11) and black dots indicate *Calonectris* (*N* = 3). Black square indicates the smallest sample (Great Shearwater, *Ardenna gravis*; *N* = 2) which was excluded from the analysis. The line is the linear regression for *Puffinus* and *Ardenna* species after removing the smallest samples (*N* = 11). Closed grey dot indicates the value of the Manx Shearwater.

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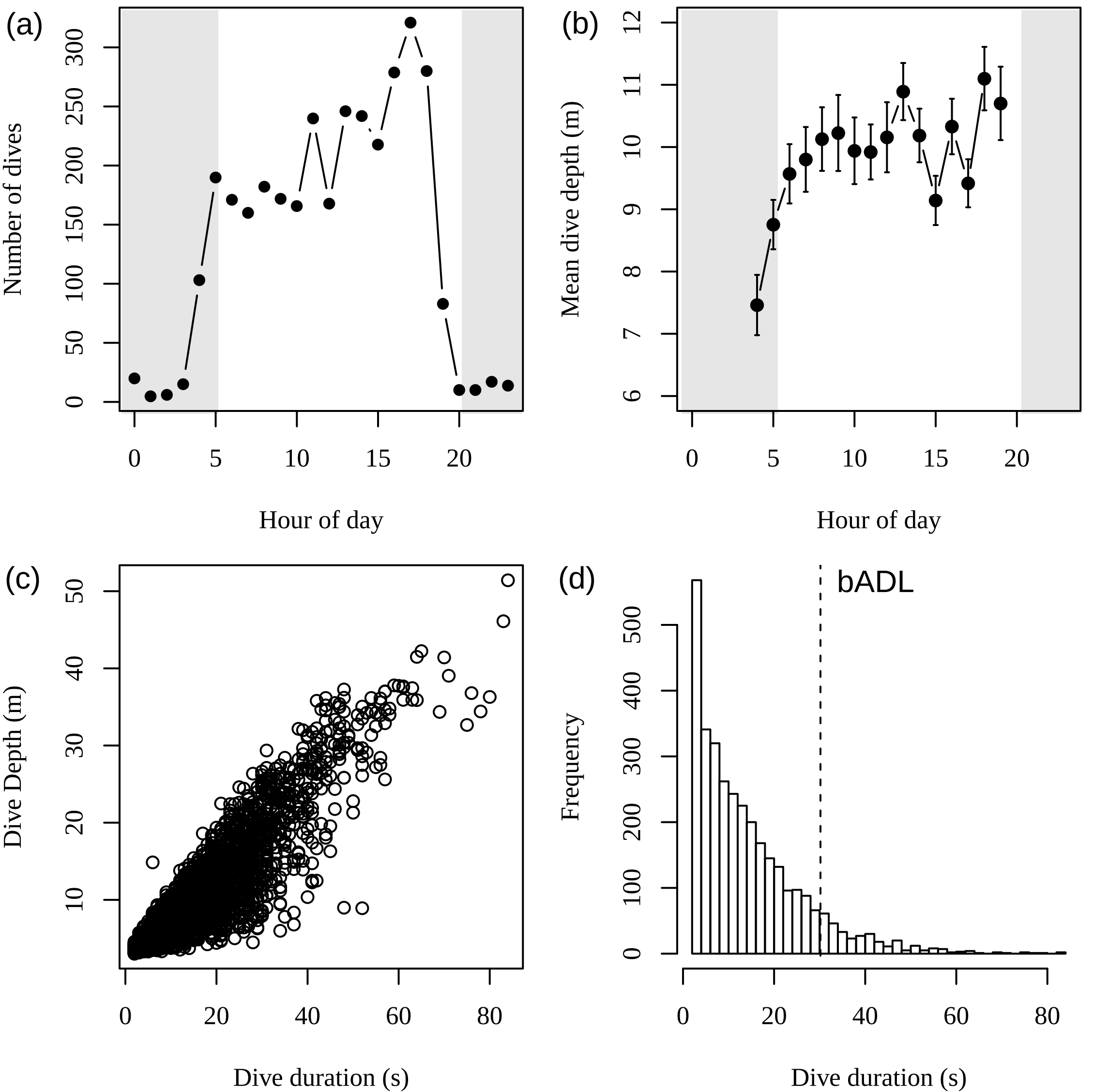
(a)
Number of dives
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50
100
150
200
250
300
0
5
10
15
20
Hour of day
(b)
Mean dive depth (m)
6
7
8
9
10
11
12
0
5
10
15
20
Hour of day
(c)
Dive Depth (m)
10
20
30
40
50
0
20
40
60
80
Dive duration (s)
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Frequency
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60
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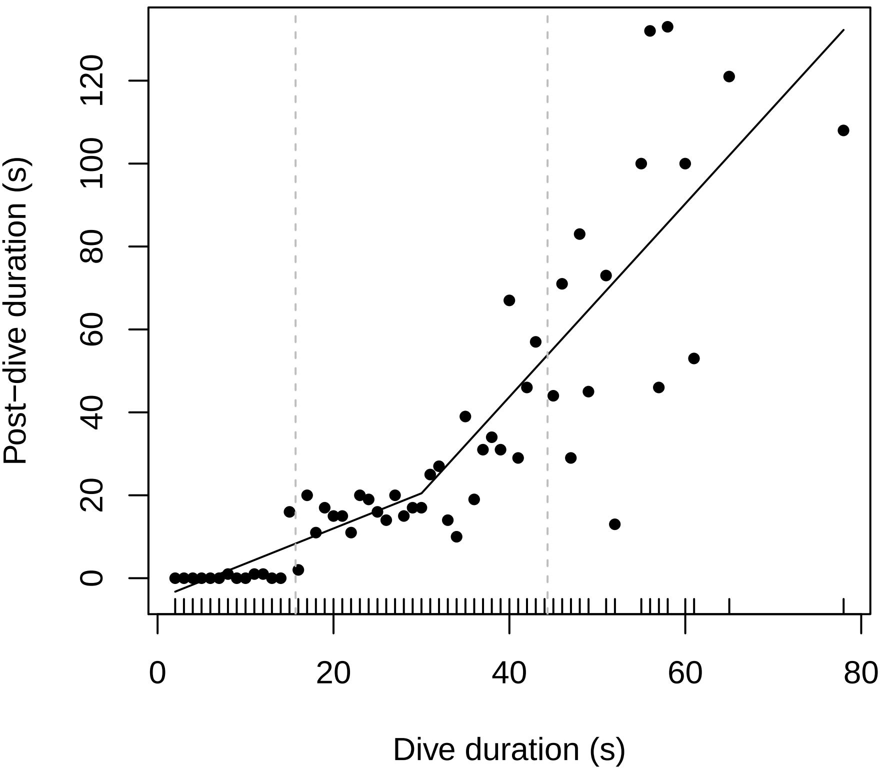
Dive duration (s)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0
20
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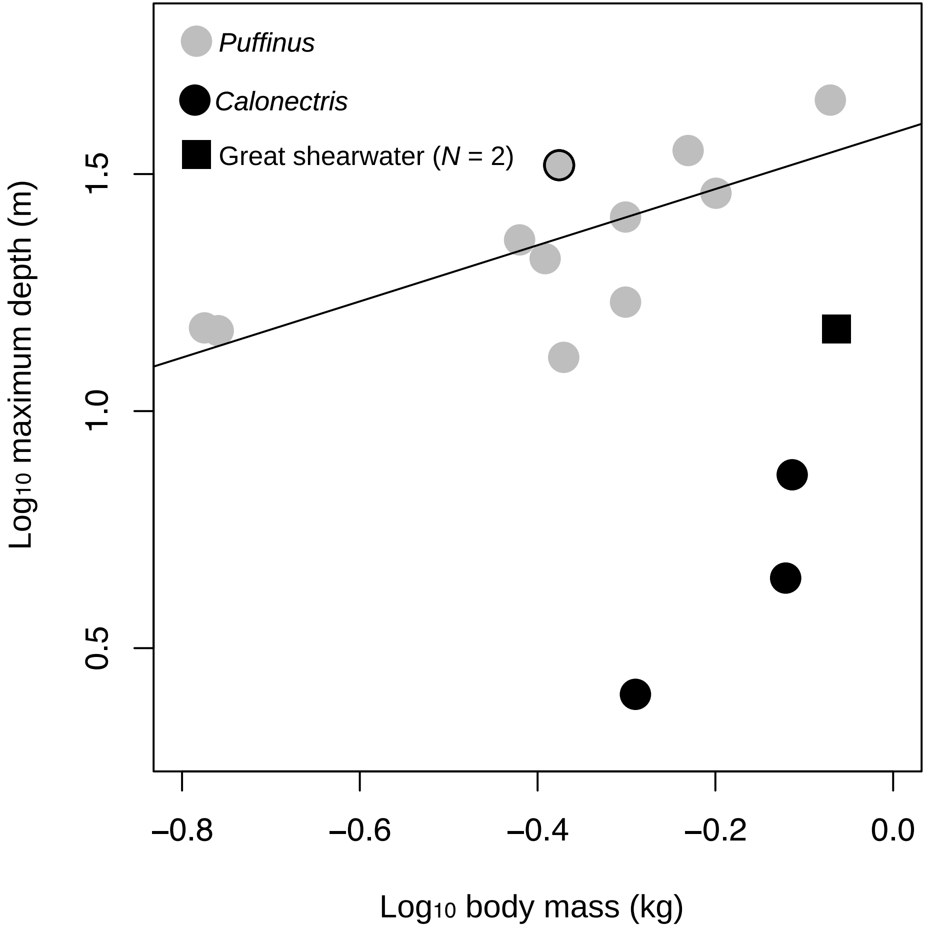
60
80
Dive duration (s)


Puffinus
Calonectris
Great shearwater (N = 2)
Log10 maximum depth (m)
0.5
1.0
1.5
Log10 body mass (kg)
−0.8
−0.6
−0.4
−0.2
0.0

Flight behaviour of seabirds in relation to wind direction and wing morphology

LARRY B. SPEAR & DAVID G. AINLEY
H.T. Harvey & Associates, PO Box 1180, Alviso, CA 95002, USA

We studied flight direction relative to wind direction (hereafter referred to as "flight direction"), the relation between wing morphology and flight behaviour and interspecies relationships in flight behaviour among all major seabird taxa. We calculated wing loading and aspect ratios for 98 species from 1029 specimens. Species were sorted into 13 groups on the basis of similarity in patterns of flight direction. The primary flight direction of Pelecaniformes and Charadriiformes was into and across headwinds. The most common flight direction of Procellariiformes was across wind. Seabirds avoided flying with tailwinds. Wing loading and aspect ratios were positively correlated in Procellariiformes, Pelecaniformes and alcids but negatively correlated in larids. In Procellariiformes, incidence of headwind flight and that of tailwind flight were significantly correlated with wing loading and aspect ratio; species with higher wing loading and aspect ratios flew more often into headwinds and less often with tailwinds. In contrast, the proportion of Pelecaniformes and Charadriiformes flying with tailwinds increased significantly with increased wing loading. Our results demonstrate a close link in seabirds between flight behaviour, wing morphology and natural history patterns in terms of distribution, colony location, dispersal and foraging behaviour.

Over the ocean environment, wind is a strong, persistent force to which seabirds are exposed nearly continuously. Most species of seabirds fly long distances to feeding areas, fly while searching for food and also migrate long distances over wide expanses of open ocean. As a result, they must continually navigate in winds while flying to and from the breeding colony, to which they are usually highly faithful. The effect of wind, therefore, must have a strong bearing on their morphology and natural history patterns, and understanding the effect of wind direction on flight behaviour of seabirds should be basic to understanding their life history strategies (Pennycuick 1989, Ballance 1995). A better understanding of flight behaviour in relation to wind direction also will allow better assessment of how seabirds' movements are affected by large-scale meteorology (Alerstam *et al.* 1993).

Considerable information is available on seabird wing morphology and aerodynamics of flight (Pennycuick 1975, 1989; Warham 1977), but we are aware of only one field study (see below) that has examined the possible relation between wing morphology and patterns of flight direction relative to wind direction (hereafter referred to as "flight direction"). Even so, deviations between measured and expected values of daily energy expenditure (based on aerodynamic theory) are thought to reflect adaptations in wing morphology and flight behaviour to make better use of the energy of the wind (Ballance 1995). The need for more information on the effect of environmental factors on flight performance is obvious and has also been noted by Pennycuick (1989) and Alerstam *et al.* (1993).

We conducted research among the range of seabird taxa to determine (1) whether seabirds demonstrated preferred flight direction and (2) the relation between wing morphology and patterns of flight direction. Previously we showed that wing morphology, preferred flight direction and natural history patterns are linked among four taxa of procellariids (Spear *et al.* 1995).

METHODS

Wind speed and flight direction

During cruises in the Pacific and Southern Oceans (1980–1992), we used continuous strip sampling to survey seabirds during 7581 h. We recorded over 130,000 birds that were flying in a steady direction (and where winds were ≤1.5 m·s^{-1}), or 91,000 birds after adjusting counts for the effect of bird movement relative to that of the ship (Spear *et al.* 1992a). (The latter adjustment is necessary when studying flight direction from a moving vessel because any patterns in ship direction will bias analyses. For example, if birds flew east and west in equal numbers, unadjusted counts from a ship transiting westward would show greater numbers flying east because the observer would count more who were flying east compared to those flying west as a result of relative movements of the ship and birds.)

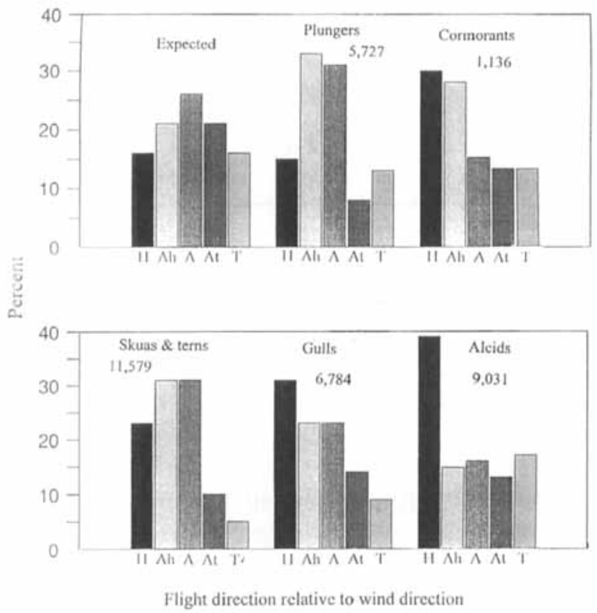


Figure 1. Flight direction relative to wind direction of five groups of Pelecaniformes and Charadriiformes. Expected distribution shown at top left. Numbers given above flight direction distributions are sample sizes. H = headwind, Ah = across headwind, A = across wind, At = across tailwind, T = tailwind.

We divided surveys into 30-min segments and recorded wind direction and ship speed at the beginning of each segment and flight direction to the nearest 10° for all birds in transit. We recorded an average flight direction for groups of birds flying in directions varying $\leq 10°$. Following Pennycuick (1982, 1987a) and Alerstam *et al.* (1993), we scored flight style of each bird according to four categories: gliders, flap gliders, flappers and glide flappers (details in Spear & Ainley 1997). Flight style of each species was categorized on the basis of averaged data for individuals observed during all surveys (L.B. Spear & D.G. Ainley, unpubl.).

Wing morphology

We examined wing morphology of 978 individual seabirds representing 84 species that we collected, captured, or retrieved from drift nets, although measurements for eight species were provided mostly or entirely by other researchers. Wing morphology for 51 birds representing arespecies are from Pennycuick (1982, 1987a) and Ballance (1995). In all, 1029 birds of 98 species were considered. Following Pennycuick (1989), we calculated wing loading and aspect ratios. All measurements were of birds that had dry feathers and that were healthy at death or when captured. To obtain measurements of wing span (length from tip to tip of fully extended wings) and wing area of birds with *rigor mortis*, we relaxed the *pectoralis* muscles before extending the wings. This was done by extending the wings forward and upward with a thumb placed on the ventral side of the humerus just above the base of the wing (where the wing is attached to the body). The Latin names of all species examined except those appearing only in the text are given in the Appendix.

Analyses

χ^2 tests were used to compare flight direction data among seabird taxa. Significance was assumed at $P < 0.001$ to adjust for multiple tests. We used five categories of flight direction (keeping in mind that flight direction and wind direction are reversed 180°): (1) flight into headwinds (difference between bird course and wind course of $\leq 20°$), (2) flight across headwinds (difference of 30° to 60°), (3) flight across wind (difference of 70° to 110°), (4) flight across tailwinds (difference of 120° to 150°), and (5) flight with tailwinds (difference of 160° to 180°). Under the null hypothesis that flight direction is not related to wind direction, the proportion of birds flying in each of the five directions would be 3:4:5:4:3, respectively. Significant deviation from those ratios would indicate a response in bird flight direction to wind direction.

Linear regression was used to examine relations between flight direction and wing morphology. To simplify presentation of these analyses, we used three categories of flight direction instead of the five given above. The directions were (1) flight into headwinds (difference between bird course and wind course of 0° to 50°), (2) flight across wind (difference of 60° to 120°), and (3) flight with tailwinds (difference of 130° to 180°).

RESULTS

Relation between flight direction and wind direction

χ^2 tests were used to compare flight direction among the 25 seabird groups identified in Spear and Ainley (1997) on the basis of morphology and flight speed. Flight direction varied insignificantly among subgroups composing each of the 12 larger groups ($P > 0.001$, analyses not shown) but varied significantly among the larger groups (χ^2 tests, all $P < 0.001$, Figs 1 and 2). Groups whose species members were separated from other closely related species on the basis of size and/or morphology included the "large gadfly petrels" (*Pterodroma* with mass >250 g); "small gadfly petrels" (*Pterodroma* with mass <250 g and Bulwer's Petrels); "diving shearwaters" (procellariids that feed by wing-propelled diving, including Sooty Shearwaters, Short-tailed Shearwaters, Antarctic Petrels and "Manx-type Shearwaters," [the later hereafter termed "Manx Shearwaters", i.e., all members of the *Puffinus puffinus* superspecies, including Little Shearwaters *P. assimilis*, Audubon's Shearwaters and, for the purposes here, the morphologically similar Christmas Shear-

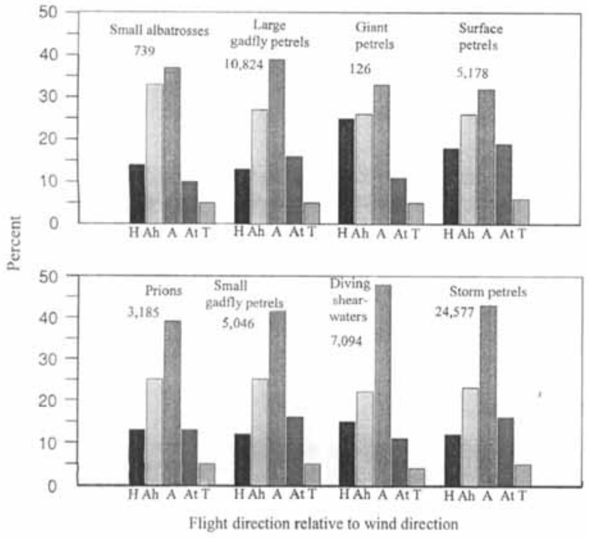


Figure 2. Flight direction relative to wind direction of eight groups of Procellariiformes. See Figure 1.

water]); "surface-feeding petrels" (procellariids that feed mostly on the ocean surface, hereafter referred to as "surface petrels," including *Procellaria*, fulmarine petrels [Warham 1990] and surface-feeding shearwaters, including Buller's Shearwaters Wedge-tailed Shearwaters Pink-footed *P. creatopus*, Flesh-footed *P. carneipes*, Great *P. gravis*, Cory's *Calonectris diomedea* and Streaked Shearwaters *C. leucomelas*); "prions" (including the closely related Blue Petrel [Warham 1990] and "plungers" (boobies, pelicans and tropicbirds) (Appendix).

The flight direction most often flown by Pelecaniformes and Charadriiformes was across and into headwinds (Fig. 1), and that of Procellariiformes was across wind (Fig. 2). Flight direction of each category of Pelecaniform and Charadriiform differed significantly from that of each of the Procellariiform groups (χ^2 tests, $P < 0.001$). Flight direction also varied significantly between each group of Pelecaniform and Charadriiform (χ^2 tests, $P < 0.001$; Fig. 1). Flight direction most often taken by gulls, cormorants and especially alcids was into headwinds; those of plungers, skua and terns were across headwinds and across wind.

Compared with other Procellariiformes, albatrosses and large gadfly petrels flew significantly more often across headwinds (Fig. 2), whereas diving shearwaters flew more often acrosswind, surface petrels more often across tailwinds, and surface petrels and especially giant petrels more often into headwinds. Flight direction of small gadfly petrels differed insignificantly from that of storm petrels and prions. Flight direction of prions was similar to that of large gadfly petrels, as was flight direction of giant petrels compared with that of albatrosses and surface petrels.

All taxonomic groupings avoided tailwind flight, especially Procellariiformes (Figs 1 and 2).

Wing loading and aspect ratios

Aspect ratio decreased significantly with increased wing loading among larids (Fig. 3). In contrast, the relation was significantly positive among species of Procellariiformes and alcids. The relation was also significant among Pelecaniformes ($F_{2,10} = 5.94$, $P < 0.05$, β coefficient = 0.022, s.e. ± 0.0088), when controlling for differences in regression slope

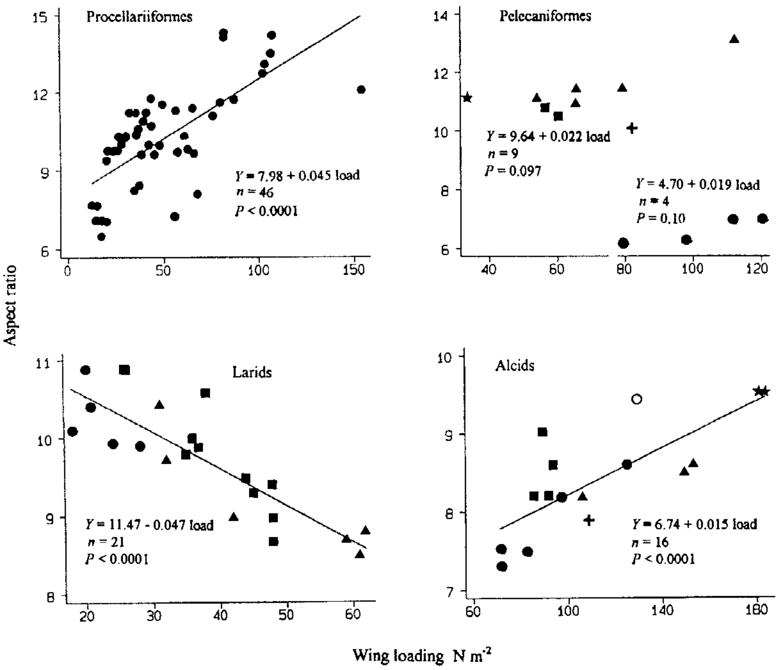


Figure 3. Relation between wing loading and aspect ratio of four groups of seabirds. Each point denotes the average for a given species (Appendix). Lines indicate the best regression fit. Values of n are numbers of sea cies, and P values indicate the level of sight icance by which slopes deviated from zero. Among Pelecaniformes, the cormorants (circles) were considered as distinct from six species representing pelicans (crosses), tropicbirds (squares), boobies (triangles) and frigatebirds (stars). Larids included terns (circles), skuas (triangles) and gulls (squares). Alcids included auklets (solid circles), murrelets (squares), puffins (triangles), Pigeon Guillemot (crosses), Razorbill (open circles) and *Uria* spp. (stars). See Figure 4 for species delineations among Procellariiformes.

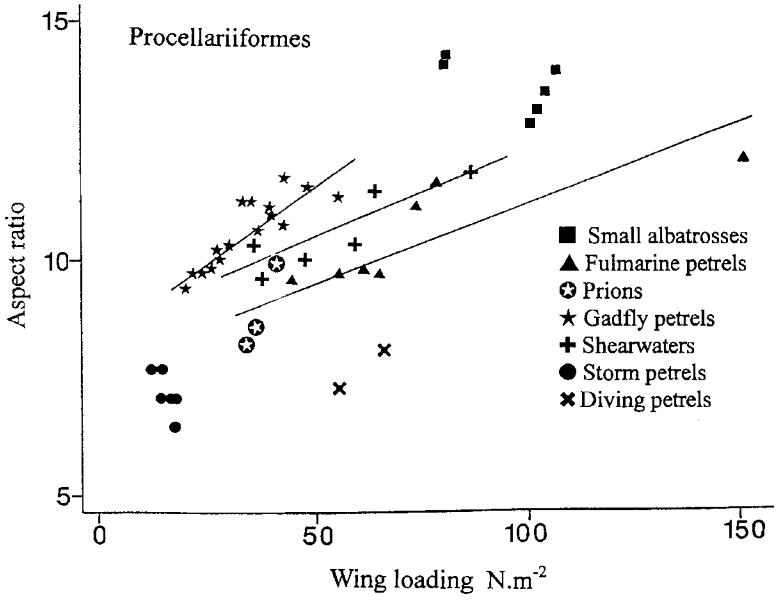


Figure 4. Average relation between wing loading and aspect ratio in different taxonomic groups of Procellariiformes. Lines of best fit are shown for gadfly petrels (top line), shearwaters (central line) and fulmarine petrels (bottom line). The fulmarine petrel (triangle) on the far right is the Giant Petrel.

elevation between the two groups including plungers, (i.e., species with high aspect ratios, including tropicbirds, boobies, pelicans and "surface-snatching" frigatebirds) and pursuit divers (i.e., cormorants which have very low aspect ratios (Fig. 3)). The relation was not significant for separate comparisons of species within each of the two Pelecaniform groups.

Four taxa of Procellariiformes were visually distinct (Fig. 4): (1) albatrosses had the highest wing loading and aspect ratios; (2) storm petrels had the lowest values; (3) diving petrels had low aspect ratios relative to wing loading; and (4) gadfly petrels, shearwaters and fulmarine petrels had intermediate values. Linear regression analyses for aspect ratio, including the terms wing loading and group (groups were gadfly petrels, shearwaters and fulmarine petrels) revealed highly significant effects of the term group on aspect ratio in comparisons among the three groups (Table 1). Thus, for a given value of wing loading, aspect ratios were higher in gadfly petrels compared with shearwaters and fulmarine petrels and higher in shearwaters compared with fulmarine petrels.

Relation between wing morphology and flight direction

For this comparison, we divided seabird species into two major groups, Procellariiformes and Pelecaniformes/Charadriiformes, on the basis of taxonomy and flight mode. To increase the number of sample groups, we further divided Procellariiformes into ten subgroups and Pelecaniformes/Charadriiformes into eight subgroups on the basis of inconsistency in the relation of aspect ratio to wing loading among species members. Subgroup classifications are the same as given in Figures 1 and 2, with exception of surface petrels, which were split into fulmarine petrels (with higher wing

Table 1. *Regression analyses for the relation between aspect ratio and wing loading in fulmarine petrels (n = 7 species), gadfly petrels (n = 16) and shearwaters (n = 6) (see Appendix for morphometrics). Each line reports on a distinct analysis. Models a, b and c included the independent term wing loading; models d, e and f included the independent terms wing loading and group, the latter analyzed as categorical. The dependent term is aspect ratio*

Term	β Coefficient	s.e.	*F*	d.f.	*P*
Wing loading					
a. Gadfly petrels	0.0615	0.0094	43.1	1	<0.0001
b. Shearwaters	0.0383	0.0103	13.9	1	<0.02
c. Fulmarine petrels	0.0235	0.0074	10.2	1	<0.03
d. All groups	—	—	10.1	2	<0.001
e. Gadfly petrels *v* fulmarine petrels	—	—	15.4	1	<0.001
f. Gadfly petrels *v* shearwaters	—	—	18.3	1	<0.001
g. Shearwaters *v* fulmarine petrels	—	—	10.2	1	<0.03

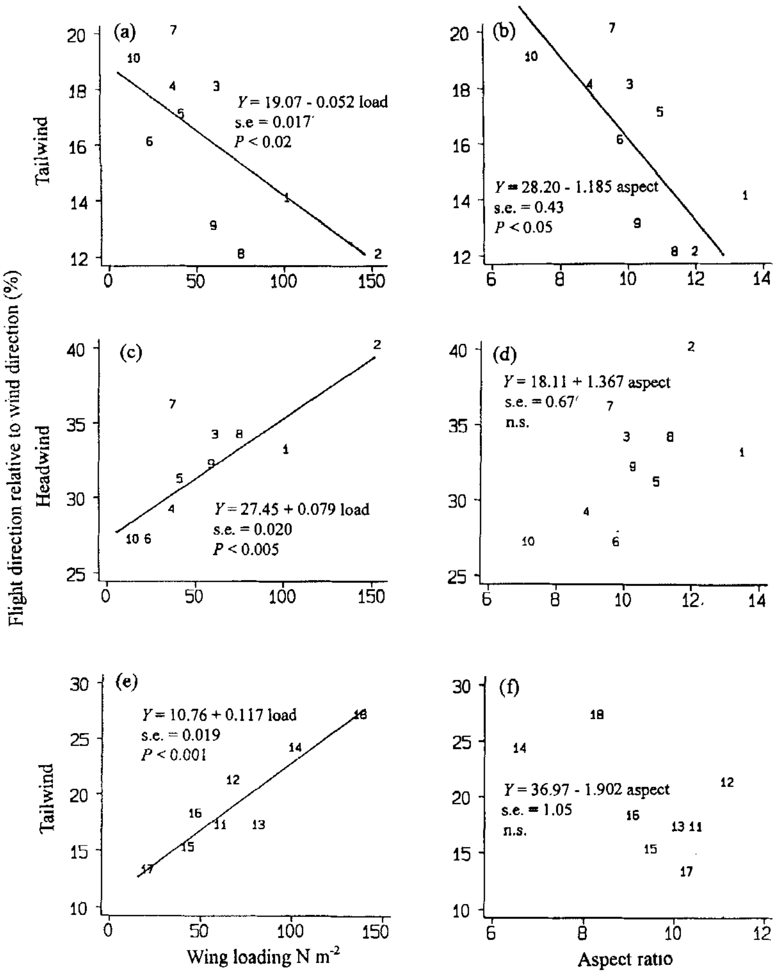


Figure 5. Flight direction as a function of wing loading and aspect ratio in ten groups of Procellariiformes (a–d) and eight groups of Pelecaniformes and Charadriiformes. Values for flight direction are the number of birds seen flying in a given direction divided by the total seen, multiplied by 100. Wing loading and aspect ratio are the averages among species for (1) small albatrosses, (2) Giant Petrels, (3) fulmarine petrels, (4) prions and Blue Petrels, (5) large gadfly petrels, (6) small gadfly petrels, (7) surface shearwaters, (8) diving shearwaters, (9) Manx shearwaters, (10) storm petrels, (11) tropicbirds, (12) boobies, (13) pelicans, (14) cormorants, (15) skuas, (16) gulls, (17) terns and (18) alcids (see also Appendix). See Figures 1 and 2 for sample sizes.

loading and aspect ratios) and surface-feeding shearwaters (hereafter referred to as surface shearwaters, with lower wing loading and aspect ratios); Manx shearwaters (with lower wing loading and lower aspect ratios), which were separated from diving shearwaters; plungers, which were split into boobies (with higher wing loading and aspect ratios), pelicans (with higher wing loading and lower aspect ratios) and tropicbirds (with lower wing loading and aspect ratios) and skuas (with higher wing loading and lower aspect ratios), which were split from terns (see the Appendix for morphometrics).

The proportion of Procellariiformes that flew with tailwinds decreased significantly with increased wing loading, and the proportion of birds flying into headwinds increased significantly with decreased in wing loading (Fig. 5a and c). Similar relationships were indicated in analyses on aspect ratio and flight direction, except the proportion of Procellariiformes flying into headwinds was insignificant (Fig. 5b and d). Similarity in the relations of flight direction with both aspect ratio and wing loading resulted from the significant relation between wing loading and aspect ratio (Fig. 3).

Unlike Procellariiformes, the proportion of Pelecaniformes and Charadriiformes flying with tailwinds *increased* significantly with increased wing loading (Fig. 5e). The relation between aspect ratio and proportion of these birds flying with tailwinds was insignificant (Fig. 5f).

DISCUSSION

Factors affecting flight direction

Seabirds flew across wind, across headwinds, and into headwinds more often than expected. In particular, they avoided flying with tailwinds, which was unexpected because flying downwind is, per distance flown, seemingly more energy efficient than flying upwind (Pennycuick 1989). There are at least two possible explanations. First, birds who slope/soar on rising air pushed in front of sea waves must stay in front of the wave (Pennycuick 1975). Minimum flight speed usually will not allow this; they must fly faster by moving at an angle along the wave front (Pennycuick 1989). "Sailing" (Spear & Ainley, 1997) directly downwind also would be difficult because the wind force must be applied perpendicular to the wing surface.

Second, maximizing the probability of detecting prey could explain the high incidence of headwind flight if birds that we recorded as "in transit" were foraging. Because the air speed of birds flying downwind must be greater than that of the wind, ground speeds are likely too fast for effective detection of prey if the birds are searching directly below (Alerstam *et al.* 1993). Flying upwind may allow seabirds to maintain adequate air speeds whilst flying at slower ground speeds, possibly increasing the probability of detecting prey. Flying upwind would also decrease response time when elusive prey are located. To respond, birds flying downwind must turn and backtrack upwind, whilst a bird flying upwind can check its flight while over the prey and thus make a quicker response.

Foraging habitat

The higher incidence of headwind and across-headwind flight in Pelecaniformes and Charadriiformes compared with Procellariiformes might also be explained by the prey detection hypothesis. We suspect that Pelecaniformes and Charadriiformes, more than Procellariiformes, are likely to benefit from headwind and across-headwind flight because the majority use neritic waters (waters over the continental shelf and slope), where prey are more abundant than in the less productive pelagic waters used by most Procellariiformes (Murphy 1936, Harrison 1983). Pelecaniformes and Charadriiformes, then, feed more often where prey can be located by searching below, or within easy view of, the flight path. In contrast, finding prey in pelagic waters usually requires searching a wider radius through olfactory sensing or by visual scanning of the horizon for schools of predatory fish or cetaceans and/or feeding flocks of other seabirds (c.f. Ashmole 1971, Ainley 1977, Ainley & Boekelheide 1983, Au & Pitman 1986, Prince & Morgan 1987, Croxall & Prince 1994, Nevitt *et al.* 1995). The higher incidence of across-wind flight in Procellariiformes is likely also to be related to greater reliance on efficient use of energy provided by the wind and waves when foraging over wide ocean expanses, where prey densities are low (Weimerskirch *et al.* 1993).

The different flight patterns of Charadriiformes compared with Pelecaniformes also support the ideas given above. Predominantly neritic species (gulls, cormorants and alcids) flew more often into headwinds than did less neritic species (skuas, terns, boobies, pelicans and tropicbirds). The latter group also included many glide flappers, which use a style of flight similar to that of Procellariiformes (see also Ballance 1995).

Migration

One would expect consistent patterns in flight direction relative to wind direction in migrating birds because wind directions are likely to be consistent within a given area. Studies on migration of terrestrial species such as Passerines and shorebirds indicate that these birds generally make transoceanic migrations at high altitude with extensive use of tailwinds (Richardson 1978, Alerstam 1979, Williams & Williams 1990).

Extensive low-altitude transoceanic migration by seabirds (Gudmundsson *et al.* 1992, Alerstam *et al.* 1993) may be related to opportunistic foraging along the migration route (see above), which would require consistent low-altitude flight. If this is true, migrating seabirds should respond to the wind in a way that would result in a compromise between optimal foraging and efficient flight. Consistent with this idea, Arctic Terns migrating in the Antarctic flew mostly into headwinds (a flight direction similar to that of terns and skuas we observed over a much wider geographic range, many of which were in migration) and foraged along the migration route (Gudmundsson *et al.* 1992). This finding suggests that headwind flight is acceptable or even preferred during migration. The only explanation that we can imagine for headwind flight in seabird migrants, besides the unlikely possibility that there was no other choice, is improvement of foraging opportunities. An important determinant of migration routes, then, may be the effect of predominant wind direction in a given area in relation to foraging methods and flight behaviour of different seabird taxa.

Colony location

Optimal colony location is downwind of the feeding area, facilitating tailwind flight on the return trip of birds carrying heavy prey loads (Pennycuick 1989). However, if colony location is not optimal, the location of favourable feeding areas relative to the colony may influence flight direction more than wind direction if net energy gain is greater (e.g. effect of wind on condition of Arctic Terns; Monaghan *et al.* 1989). Therefore, flight direction relative to wind direction should vary among birds breeding at different colonies, and we might expect flight direction of breeders to vary compared with that of free-ranging nonbreeders (e.g. variable results on flight direction of albatrosses; Pennycuick 1982, 1987a, Alerstam *et al.* 1993, Weimerskirch *et al.* 1993, this study).

Our observations indicating preference for across-wind flight by gadfly petrels (breeding and nonbreeding birds) are consistent with those for Barau's Petrels *Pterodroma baraui* foraging from the breeding colony at Reunion Island in the Indian Ocean (Stahl & Bartle 1991); however, our results (see also Pennycuick 1982) indicating higher incidence of headwind and across-headwind flight in nonbreeding albatrosses are different from those indicating a high incidence of across-tailwind flight found by Weimerskirch *et al.* (1993) for breeding Wandering Albatrosses *Diomedea exulans* foraging from the Isles de Crozet (see also Alerstam *et al.* 1993).

It is unknown whether the findings of Weimerskirch *et al.* (1993) for Crozet albatrosses represent true preference in terms of flight efficiency (a theory proposed by these authors) or constraints imposed by colony location in relation to favourable feeding areas. Comparisons with other populations should reveal key information on the pelagic ecology of Procellariiformes in general and this species in particular. Wandering (and Royal *D. epomophora*) albatrosses are unique among seabirds in that they are the largest, fly almost exclusively by soaring, and are restricted to oceans where wind velocities are consistently the highest worldwide (Abrams *et al.* 1981, van Loon & Rogers 1984, Prince *et al.* 1992, Weimerskirch *et al.* 1993).

Relation between wing morphology and flight direction

The lower incidence of tailwind flight and higher incidence of headwind flight with increased wing loading and aspect ratio among Procellariiformes may be related to factors discussed above. Procellariiformes with higher aspect ratios and wing loadings are faster fliers, have less profile drag and glide more (as opposed to flapping) than do those with lower wing loading and aspect ratios (Pennycuick 1982, 1989). Hence, we might expect a higher incidence of headwind flight among Procellariiformes with heavier wing loads because they would be more likely to benefit from decreased ground speed to increase prey detection and because of their more energy efficient flight.

In contrast to the Procellariiformes, Charadriiformes and Pelecaniformes (mainly glide-flappers and flappers) with higher wing loading had a higher incidence of tailwind flight compared to those with lower wing loading. This pattern was likely related to the lower energy efficiency of flapping flight among larger species, which generally have higher wing loading (Pennycuick 1989, Program 1).

Wing morphology in relation to reproductive strategies and dispersal

Aspect ratio increased significantly with increased wing loading in Procellariiformes, Pelecaniformes and alcids but decreased significantly with increased wing loading in larids (skuas, gulls and terns). These patterns are probably related to interaction of flight mechanics with reproductive strategies (Pennycuick 1987b) and dispersal.

Larids with lower aspect ratios (larger skuas and gulls) breed in temperate to polar latitudes, which have high oceanic productivity, facilitating shorter foraging distances, whereas many larids with higher aspect ratios (terns and smaller gulls) breed mostly in temperate latitudes, where productivity is lower and foraging distance is greater (Flint & Nagy 1984, Gabrielson *et al.* 1987, Spear 1988, Zhao-Qin 1990, Hamer *et al.* 1991). More importantly, perhaps, most smaller larids (including smaller skuas) are also trans-equatorial migrants, whilst most larger larids are not (Harrison 1983). Thus, the former would benefit more from higher aspect ratios, increasing flight efficiency and ability to carry larger food loads (Pennycuick 1989).

In contrast to larids, larger Procellariiformes generally make longer foraging trips than smaller ones, both temporally and spatially (Furness & Todd 1984, Pennycuick *et al.* 1984, Brooke 1990, Montevecchi *et al.* 1992, Weimerskirch *et al.* 1993, Spear *et al.* 1995), as do larger alcids (Gaston & Nettleship 1981, Schneider & Hunt 1984, Cairns *et al.* 1987, Gabrielson *et al.* 1991). This pattern could explain the positive relationship between wing loading and aspect ratio in these species.

The significant between-species difference in aspect ratios for procellariids and Pelecaniformes of similar wing loading is also consistent with adaptation for different patterns of migration and for exploiting prey occurring in different densities. Among three taxa of procellariids, gadfly petrels have the highest aspect ratios and inhabit waters where prey densities are low. They make long foraging trips during the breeding season (Warham 1990, Stahl & Bartle 1991, Spear *et al.* 1995), and most migrate long distances after breeding (Pitman 1986, Spear *et al.* 1992b, Bartle *et al.* 1993). Fulmarine petrels, however, with low aspect ratios, forage exclusively in the highly productive polar to subpolar waters, have shorter foraging trips when breeding (Coulson & Horobin 1971, Obst & Nagy 1992) and disperse into adjacent seas after breeding (Harrison 1983, Ainley & Boekelheide 1983). Shearwaters, with intermediate aspect ratios, inhabit mostly temperate to subpolar waters, where productivity is moderate to high. Most shearwaters are also highly migratory (Warham 1990). It follows that gadfly petrels should be the most highly adapted of the three taxa for efficient flight, fulmarine petrels should be least adapted and shearwaters should be intermediate. These relations among Pelecaniformes were similar. Boobies, pelicans and tropicbirds, with high aspect ratios, often feed in less productive waters than do cormorants (Nelson 1978, Schneider & Hunt 1984, Ainley & Boekelheide 1990, Harrison 1990), which have markedly lower aspect ratios.

In conclusion, the close relationships demonstrated here between flight behaviour, wing morphology and natural history patterns among seabirds indicate that flight energetics is of major importance in shaping trophic-related energetics and, ultimately, ecological adaptations.

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APPENDIX

Morphological data for 98 species of seabirds. Wing area was calculated as the area of the wings plus the area of the body lying between the wings (Pennycuick 1989). Values are mean ± one s.d. given for sample sizes >2. Values of n *are sample sizes. Asterisks denote data from Pennycuick (1987a); # denotes data from Ballance (1995). Wing loading given in newtons per square meter.*

Species	*n*	Mass (g)	Wing span (mm)	Wing area (cm^2)	Body area (cm^2)	Wing load (N·m^{-2})	Aspect ratio
Small albatrosses							
Black-browed Albatross* (*Diomedea melanophris*)	3	3790	2160	3560	—	104	13.1
Grey-headed Albatross* (*D. chrysostoma*)	1	3790	2180	3520	—	106	13.5
Waved Albatross (*D. irrorata*)	1	2920	2215	3455	535	82	14.2
Black-footed Albatross (*D. nigripes*)	2	3980	2265	3607	581	108	14.2
Laysan Albatross (*D. immutabilis*)	1	3375	2020	3215	560	103	12.7
Light-mantled Sooty Albatross* (*Phoebetria palpebrata*)	1	2840	2180	3380	—	82	14.1
Fulmarine petrels							
Giant Petrel* (*Macronectes* spp.)	4	5190	1990	3310	—	154	12.0
White-chinned Petrel* (*Procellaria aequinoctialis*)	2	1370	1400	1690	—	80	11.6
Northern Fulmar (*Fulmarus glacialis*)	8	693 ± 49	1035 ± 44	1095 ± 65	150 ± 16	62 ± 5	9.8 ± 0.5
Southern Fulmar (*Fulmarus glacialoides*)	10	776 ± 86	1062 ± 37	1169 ± 76	154 ± 22	66 ± 6	9.7 ± 0.4
Cape Petrel (*Daption capense*)	10	444 ± 65	873 ± 55	785 ± 66	128 ± 50	56 ± 7	9.7 ± 0.5
Snow Petrel (*Pagodroma nivea*)	37	329 ± 47	826 ± 35	711 ± 62	84 ± 23	45 ± 5	9.6 ± 0.5
Antarctic Petrel (*Thalassoica antarctica*)	27	733 ± 79	1035 ± 30	963 ± 43	143 ± 22	75 ± 8	11.1 ± 0.6
Blue Petrels and prions							
Blue Petrel (*Halobaena caerulea*)	12	203 ± 22	699 ± 17	491 ± 16	64 ± 8	41 ± 4	10.0 ± 0.5
Antarctic Prion							
(*Pachyptila vittata desolata*)	5	168 ± 5	621 ± 5	467 ± 13	60 ± 5	35 ± 1	8.3 ± 0.2
(*Pachyptila vittata desolata**)	5	168	626	460	—	36	8.5
Slender-billed Prion (*Pachyptila belcheri*)	2	150	592	411	52	36	8.6

APPENDIX
Continued

Species	*n*	Mass (g)	Wing span (mm)	Wing area (cm^2)	Body area (cm^2)	Wing load (N·m^{-2})	Aspect ratio
Large gadfly petrels							
Juan Fernandez Petrel (*Pterodroma externa*)	110	421 ± 42	1067 ± 22	1041 ± 42	164 ± 21	40 ± 3	10.9 ± 0.3
White-necked Petrel (*P. cervicalis*)	7	412 ± 29	1053 ± 14	998 ± 46	179 ± 13	40 ± 3	11.1 ± 0.4
Tahiti Petrel (*P. rostrata*)	75	411 ± 40	1047 ± 30	938 ± 50	147 ± 18	43 ± 4	11.7 ± 0.4
Phoenix Petrel (*P. alba*)	16	287 ± 34	947 ± 23	803 ± 39	114 ± 15	35 ± 5	11.2 ± 0.3
Herald Petrel (*P. heraldica*)	4	266 ± 29	934 ± 16	778 ± 26	138 ± 20	34 ± 5	11.2 ± 0.1
Mottled Petrel (*P. inexpectata*)	2	358	842	633	102	56	11.3
Kerguelen Petrel (*P. brevirostris*)	3	340 ± 16	883 ± 24	681 ± 42	105 ± 18	49 ± 2	11.5 ± 0.1
Murphy's Petrel (*P. ultima*)	7	374 ± 29	962 ± 11	867 ± 39	134 ± 7	43 ± 4	10.7 ± 0.4
Kermadec Petrel (*P. neglecta*)	12	369 ± 34	1010 ± 12	968 ± 34	172 ± 20	37 ± 3	10.6 ± 0.4
Small gadfly petrels							
Bonin Petrel (*P. hypoleuca*)	6	172 ± 8	766 ± 18	551 ± 28	97 ± 12	30 ± 3	10.3 ± 0.2
White-winged Petrel (*P. leucoptera*)	63	160 ± 16	748 ± 25	559 ± 25	85 ± 13	28 ± 3	10.0 ± 0.4
Collared Petrel (*P. brevipes*)	1	121	713	524	69	23	9.7
Black-winged Petrel (*P. nigripennis*)	55	151 ± 11	756 ± 14	559 ± 25	86 ± 14	27 ± 2	10.2 ± 0.4
Stejneger's Petrel (*P. longirostris*)	27	143 ± 9	718 ± 11	529 ± 21	82 ± 11	26 ± 1	9.8 ± 0.3
Pycroft's Petrel (*P. pycrofti*)	1	112	693	495	68	22	9.7
Bulwer's Petrel (*Bulweria bulwerii*)	34	90 ± 11	650 ± 18	450 ± 30	61 ± 8	20 ± 2	9.4 ± 0.4
Surface-feeding shearwaters							
Wedge-tailed Shearwater (*Puffinus pacificus*)	34	385 ± 38	1040 ± 39	1051 ± 83	173 ± 35	36 ± 3	10.3 ± 0.5
Buller's Shearwater (*P. bulleri*)	2	397	997	1036	173	38	9.6
Diving shearwaters							
Sooty Shearwater (*Puffinus griseus*)	20	799 ± 88	1026 ± 16	893 ± 33	160 ± 9	88 ± 9	11.8 ± 0.4
Slender-billed Shearwater (*P. tenuirostris*)	15	502 ± 77	930 ± 28	763 ± 47	122 ± 10	65 ± 9	11.4 ± 0.5
Manx shearwaters							
Newell's Shearwater (*Puffinus newelli*)	20	378 ± 31	800 ± 13	623 ± 33	109 ± 23	60 ± 5	10.3 ± 0.5
Christmas Shearwater (*P. nativitatis*)	2	335	831	694	127	48	10.0
Oceanites							
Wilson's Storm Petrel* (*Oceanites oceanicus*)	3	38	393	219	—	17	7.1

APPENDIX
Continued

Species	n	Mass (g)	Wing span (mm)	Wing area (cm^2)	Body area (cm^2)	Wing load (N·m^{-2})	Aspect ratio
Frigate petrels							
White-faced Storm-Petrel (*Pelagodroma marina*)	2	41	434	266	24	15	7.1
White-throated Storm Petrel (*Nesofregetta fuliginosa*)	6	70 ± 5	515 ± 13	409 ± 25	48 ± 5	17 ± 1	6.5 ± 0.5
White-bellied Storm Petrel (*Fregetta grallaria*)	9	45 ± 5	447 ± 13	283 ± 17	30 ± 7	16 ± 2	7.1 ± 0.1
Oceanodroma							
Leach's Storm Petrel (*Oceanodroma leucorhoa*)	26	41 ± 3	469 ± 11	286 ± 13	36 ± 5	14 ± 1	7.7 ± 0.3
Wedge-rumped Storm-Petrel (*O. tethys*)	32	24 ± 1	394 ± 13	202 ± 15	23 ± 4	12 ± 1	7.7 ± 0.4
Diving petrels							
Common Diving Petrel (*Pelecanoides urinatrix*)	2	150	425	221	41	67	8.1
South Georgia Diving Petrel* (*Pelecanoides georgicus*)	3	114	381	200	—	56	7.3
Tropicbirds and pelicans							
Red-tailed Tropicbird (*Phaethon rubricauda*)	3	765 ± 120	1133 ± 16	1228 ± 51	228 ± 16	61 ± 11	10.5 ± 0.7
Red-billed Tropicbird (*Phaethon aethereus*)	1	638	1005	1095	215	57	10.8
Brown Pelican (*Pelecanus occidentalis*)	21	4120 ± 531	2224 ± 87	4920 ± 310	454 ± 19	82 ± 9	10.1 ± 0.5
Boobies							
Northern Gannet* (*Sula bassanus*)	1	3010	1850	2620	—	113	13.1
Masked Booby (*S. dactylatra*)	3	1750 ± 132	1563 ± 15	2148 ± 63	408 ± 7	80 ± 8	11.4 ± 0.3
Red-footed Booby (*S. sula*)	5	1195 ± 145	1526 ± 42	2119 ± 104	396 ± 19	55 ± 7	11.0 ± 0.5
(*S. sula*)#	10	1069 ± 135	1510 ± 32	2000 ± 95	—	52 ± 6	11.3 ± 0.3
Brown Booby (*S. leucogaster*)	2	1348	1475	1995	390	66	10.9
Blue-footed Booby (*S. nebouxii*)	2	1428	1555	2126	392	66	11.4
Cormorants and frigate birds							
Shag* (*Phalacrocorax aristotelis*)	4	1810	1040	1580	—	112	6.9
Imperial Shag* (*P. atriceps*)	1	2230	1130	1830	—	120	7.0
Brandt's Cormorant (*P. penicillatus*)	7	1869 ± 267	1083 ± 54	1865 ± 159	340 ± 34	98 ± 11	6.3 ± 0.3
Pelagic Cormorant (*P. pelagicus*)	8	1156 ± 80	954 ± 58	1450 ± 199	267 ± 26	79 ± 10	6.3 ± 0.4
Great Frigatebird (*Fregata minor*)	3	1230 ± 169	1980 ± 36	3540 ± 82	499 ± 38	34 ± 4	11.1 ± 0.6
Phalaropes							
Grey Phalarope (*Phalaropus fulicaria*)	3	39 ± 1	424 ± 15	228 ± 23	38 ± 3	17 ± 2	7.8 ± 0.9
Red-necked Phalarope (*P. lobatus*)	3	37 ± 4	352 ± 8	195 ± 18	35 ± 3	18 ± 2	6.4 ± 1.1

APPENDIX
Continued

Species	*n*	Mass (g)	Wing span (mm)	Wing area (cm^2)	Body area (cm^2)	Wing load ($N \cdot m^{-2}$)	Aspect ratio
Skuas							
Great Skua* (*Catharacta skua*)	6	1350	1370	2140	—	62	8.8
Brown Skua (*C. lonnbergi*)	3	1440 ± 44	1370 ± 35	2286 ± 124	387 ± 13	61 ± 3	8.5 ± 0.1
South Polar Skua (*C. maccormicki*)	6	1237 ± 103	1340 ± 20	2070 ± 69	338 ± 25	59 ± 5	8.7 ± 0.3
Pomarine Skua (*Stercorarius pomarinus*)	4	654 ± 24	1176 ± 34	1533 ± 78	231 ± 9	42 ± 3	9.0 ± 0.4
Arctic Skua (*S. parasiticus*)	6	367 ± 81	1038 ± 30	1115 ± 57	156 ± 10	32 ± 6	9.7 ± 0.2
Long-tailed Skua (*S. longicaudus*)	7	275 ± 41	956 ± 31	880 ± 63	144 ± 18	31 ± 3	10.4 ± 0.7
Large gulls							
Great Black-backed Gull* (*Larus marinus*)	1	1560	1690	3170	—	48	9.0
Western Gull (*L. occidentalis*)	21	1037 ± 178	1436 ± 62	2235 ± 192	232 ± 35	45 ± 5	9.3 ± 0.6
Herring Gull (*L. argentatus*)	10	1102 ± 170	1486 ± 60	2284 ± 156	279 ± 45	48 ± 6	9.4 ± 0.5
Glaucous-winged Gull (*L. glaucescens*)	7	1176 ± 177	1458 ± 52	2458 ± 188	288 ± 61	48 ± 7	8.7 ± 0.6
Thayer's Gull (*L. thayeri*)	3	897 ± 238	1376 ± 68	1993 ± 179	196 ± 25	44 ± 9	9.5 ± 0.3
Medium-sized gulls							
California Gull (*Larus californicus*)	1	560	1210	1478	177	37	9.9
Heermann's Gull (*L. heermannii*)	11	469 ± 40	1135 ± 35	1308 ± 109	161 ± 39	35 ± 6	9.8 ± 0.4
Swallow-tailed Gull (*L. furcatus*)	2	690	1368	1878	188	36	10.0
Black-legged Kittiwake (*Rissa tridactyla*)	2	368	1038	1015	144	38	10.6
Small gulls							
Franklin's Gull (*Larus pipixcan*)	1	255	1015	945	95	26	10.9
Terns							
Sooty Tern (*Sterna fuscata*)	14	176 ± 15	840 ± 20	712 ± 33	70 ± 9	24 ± 3	9.9 ± 0.5
Arctic Tern (*S. paradisaea*)	2	103	733	495	49	20	10.9
Forster's Tern (*S. forsteri*)	2	141	782	589	60	21	10.4
White Tern (*Gygis alba*)	1	95	725	522	70	18	10.1
Inca Tern (*Larosterna inca*)	1	219	870	765	81	28	9.9
Large alcids							
Brunnich's Guillemot (*Uria lomvia*)	10	1033 ± 37	727 ± 33	560 ± 5	143 ± 22	182 ± 15	9.5 ± 0.3
Guillemot (*U. aalge*)	1	1050	730	560	148	184	9.5

APPENDIX
Continued

Species	*n*	Mass (g)	Wing span (mm)	Wing area (cm^2)	Body area (cm^2)	Wing load (N·m^{-2})	Aspect ratio
Medium-sized alcids							
Razorbill* (*Alca torda*)	3	620	661	462	—	132	9.5
Pigeon Guillemot (*Cephus columba*)	12	470 ± 32	578 ± 21	422 ± 24	63 ± 8	109 ± 8	7.9 ± 0.5
Rhinoceros Auklet (*Cerorhinca monocerata*)	7	560 ± 56	615 ± 34	440 ± 28	89 ± 12	126 ± 17	8.6 ± 0.7
Atlantic Puffin* (*Fratercula arctica*)	3	398	549	369	—	106	8.2
Horned Puffin (*F. corniculata*)	10	663 ± 46	607 ± 22	434 ± 28	97 ± 11	150 ± 12	8.5 ± 0.3
Tufted Puffin (*F. cirrhata*)	25	799 ± 62	662 ± 28	512 ± 37	119 ± 15	153 ± 13	8.6 ± 0.4
Small alcids							
Ancient Murrelet (*Synthliboramphus antiquus*)	1	215	446	244	54	86	8.2
Xantus' Murrelet (*S. hypoleuca*)	1	200	421	207	36	94	8.6
Craveri's Murrelet (*S. craveri*)	1	172	412	189	37	89	9.0
Marbled Murrelet (*Brachyramphus marmoratus*)	3	226 ± 19	443 ± 19	240 ± 23	50 ± 9	92	8.2
Cassin's Auklet (*Ptychoramphus aleuticus*)	26	190 ± 18	441 ± 10	262 ± 14	49 ± 3	71 ± 7	7.5 ± 0.3
Parakeet Auklet (*Cyclorrhynchus psittacula*)	1	282	502	334	80	83	7.5
Crested Auklet (*Aethia cristatella*)	4	277 ± 11	480 ± 29	283 ± 34	63 ± 9	97 ± 11	8.2 ± 0.5
Least Auklet (*A. pusilla*)	3	104 ± 2	325 ± 25	144 ± 9	28 ± 3	71 ± 3	7.3 ± 0.8

The energetics of flapping flight and its feasibility in exoplanetary atmospheres.

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Robin Spivey
Bangor University

The energetics of flapping flight and its feasibility in exoplanetary atmospheres.

Critical Analysis of Published Works

Submission by Robin James Spivey

For the degree of Doctor of Philosophy (Published Works)

School of Biological Sciences
Bangor University

2015

Abstract

Flapping flight is an energetically demanding yet remarkably effective mode of locomotion exhibited by various species of vertebrates and invertebrates. It demands coordination and spatiotemporal awareness, particularly when contending with adverse weather conditions and airborne predators. Simultaneously, flight imposes stiff constraints on the brain to body mass ratio, thereby demanding the evolution of efficient neural processing. As relatively modest changes in either atmospheric density or gravity can render flight impractical, it is important from an astrobiological perspective to be able to quantify the athleticism of the Earth's various flying animals. Recently, two approaches have been advanced capable of measuring the instantaneous power expended during flapping flight in wild-ranging animals. The first involves translation of heart-rate measures to oxygen consumption estimates via a universal scaling law (Bishop & Spivey, 2013) and the second utilises a mathematical translation of triaxial accelerometry data captured from body mounted transducers (Spivey & Bishop, 2013). Indeed, technological advances now permit the design of unobtrusive instruments capturing year-long data from migratory birds (Spivey & Bishop, 2014). These systems have been successfully deployed while investigating the high altitude trans-Himalayan flights of bar-headed geese, uncovering and unexpectedly steep rise in flight costs with altitude (Bishop et al, 2015). The pelagic foraging excursions of Manx Shearwaters, which regularly profit from environmental assistance, have also been scrutinised in conjunction with high resolution GPS data (Spivey et al, 2014). A potentially significant outcome of the present work is a novel hypothesis concerning the hitherto puzzling lack of evidence for extraterrestrial life (Spivey, 2015), perhaps the first to rigidly adhere to the scientific method by yielding testable predictions for particle physics. The model suggests that complex lifeforms may not be altogether scarce within the Milky Way. This is reinforced by recent progress in astrometry, which has established that potentially habitable planets are commonplace within the galaxy, their mass spectrum concentrated within the range 5–10 Earth-masses. Building upon these developments, opportunities are evaluated for animals of comparable physiology to birds to sustain horizontal flight in higher gravity environments than we are accustomed to on Earth. For animals that must generate their own weight support and forward propulsion, how is the traditional circumstellar habitable zone constrained by a planet's gravitational field and atmospheric density? A definition of a 'habitable flying zone' is derived and its potential significance for future space missions discussed.

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Signature

Date 30th April 2015

A flight corridor popular with migrating bar-headed geese as they traverse the Himalaya is visible from Everest (8848m), lying between the prominent foreground peak of Makalu (8481m) and, in the distance on the left, Kangchenchunga (8586m).

Acknowledgements

Field studies of bar-headed geese migrating across the Himalayan mountain range have observed this species flying continuously for periods in excess of 24 hours. The energy expended by a goose in a typical day's flight is comparable to the energy required in order to elevate the same goose to an altitude of 100km, the edge of space. Based on NASA's present-day rocket technology, the additional launch cost associated with transporting a bar-headed goose alongside a crew of astronauts is comparable to the tuition fees payable by UK students throughout the course of their undergraduate studies. The aeronautical capabilities of bar-headed geese are but one of many astonishing evolutionary achievements in the natural history of life on Earth, a history that may have a wider cosmological significance than has been hitherto suspected. This work is dedicated to all those who participated in the epic struggle for existence that, despite the challenges involved, has brought with it so much progress. Finally, I would like to thank my father for dissuading me at an early age from following pursuits lacking in direction or purpose and my mother for convincing me that, in any walk of life, history provides guidance regarding the avoidance of past mistakes.

R. J. Spivey

April 2015.

This submission in candidature of a PhD is based upon Bangor University's 'Regulations for the Award of the Degree of PhD by Published Works (Regulation 05 2009 Version 01)' ('the Regulations').

In this submission the Published Works comprise a series of six papers published in peer-reviewed academic journals. Details of these papers are presented in Table 1. Throughout the text, papers submitted as Published Works will be referred to by their numbering in Table 1 (e.g. 'Paper IV'), rather than conventional academic referencing style. The numbering adopts the chronological order in which they were published and copies of the full papers are provided as Appendices.

Our situation on this earth seems strange.
Every one of us appears here involuntarily and uninvited for a short stay,
without knowing the whys and the wherefore.

Albert Einstein

Man's greatest concern is to know how he shall properly fill his place in the universe.

Immanuel Kant

Apparently, there is hope that something worthwhile will develop from us. They know better.
We doubt, but they know. We can bring a new and wonderful stream of life that will renew
and supplement their already perfected life.

Konstantin Tsiolkovsky

Le savant doit ordonner;
on fait la science avec des faits comme une maison avec des pierres;
mais une accumulation de faits n'est pas plus une science qu'un tas de pierres n'est une maison.

Henri Poincaré

Concern for man and his fate must always form the chief interest of all technical endeavors.
Never forget this in the midst of your diagrams and equations.

Albert Einstein

The energetics of flapping flight and its feasibility in exoplanetary atmospheres.

Table of Contents

Preamble:

Summary of Published Works

Table 1: Details of peer-reviewed academic journal papers submitted as Published Works.

Paper	Reference	DOI
I	Bishop C.M., **Spivey R.J.** (2013) Integration of exercise response and allometric scaling in endotherms. Journal of Theoretical Biology **323**, 11–19.	[redacted]
II	**Spivey R.J.**, Bishop C.M. (2013) Interpretation of body-mounted accelerometry in flying animals and estimation of biomechanical power. Journal of The Royal Society Interface, **10**(87), 20130404.	[redacted]
III	**Spivey R.J.**, Bishop C.M. (2014) An implantable instrument for studying the long-term flight biology of migratory birds. Review of Scientific Instruments, **85**, 014301.	[redacted]
IV	**Spivey R.J.**, Stansfield S., Bishop C.M. (2014) Analysing the intermittent flapping flight of a Manx Shearwater, *Puffinus puffinus*, and its sporadic use of a wave-meandering wing-sailing flight strategy. Progress in Oceanography **125**, 62-73.	[redacted]
V	Bishop C.M., **Spivey R.J.**, Hawkes L.A., Batbayar N., Chua B., Frapell P. B., Milsom W. K., Natsagdorj T., Newman S. H., Scott G. R., Takekawa J. Y., Wikelski M., Butler P.J.(2015) The roller coaster flight strategy of bar-headed geese conserves energy during Himalayan migrations. Science **347**(6219), 250-254.	[redacted]
VI	**Spivey R. J.** (2015) A cosmological hypothesis potentially resolving the mystery of extraterrestrial silence with falsifiable implications for neutrinos. Physics Essays, **28**(2), 254-264.	[redacted]

Structure of this document

As outlined in the *Table of Contents*, this document is arranged in three chapters. The Published Works all fall within the compass of the life sciences and have some pertinence to the biology and astrobiology of flying animals. The first chapter provides a brief overview of the fields covered, with particular emphasis on the evolution of bird flight, the challenges involved in aerial locomotion and its sensitivity to fundamental environmental variables. The second chapter contains critical analysis of the Published Works, providing details of my personal contributions to each paper. In the third chapter, many of the findings of the Published Works are drawn together, examining the potential for self-powered flight in extraterrestrial settings and, in particular, its feasibility on extrasolar planets where surface gravities and atmospheric densities may be considerably different to those encountered at sea level here on Earth.

Chapter 1: Introduction

Birds, mammals, insects and pterosaurs have independently evolved solutions to the formidable challenges of airborne locomotion, an intensely demanding form of locomotion (Tucker, 1970; Schmidt-Nielsen, 1972). The ability to fly enables lengthy foraging excursions and, in many species, impressive seasonal migrations, oscillating between the northern and southern hemispheres. Although long-range migration requires considerable physical endurance and navigation skills, it can increase daylight hours and afford high quality feeding opportunities (Dingle, 1996). The longest migrations witnessed in nature are those undertaken by birds, animals that habitually relocate over truly planetary distances (Egevang et al, 2010). However, due to the constant need for weight support to combat gravity when airborne, actively-powered flapping flight calls for significantly higher mass-specific power than other modes of locomotion (Ellington, 1991; Butler, 1991; Tobalske, 2007).

Pterosaurs first appeared on Earth over 200 million years ago (Wang & Zhou, 2004). Feathered species, such as *Archaeopteryx*, can be traced back some 150-160 million years (Alonso et al, 2004). The original impetus for the evolutionary development of winged animals is still the subject of much conjecture amongst biologists. It may have originated with attempting to glide from tree to tree to evade predators, the need to silently pounce upon prey from a distance (Garner et al, 1999) or gain weight support or traction (Padian & Chiappe, 1998), particularly in animals running up inclined slopes or tree trunks (Dial, 2003). The first flying insects date back some 300 million years to the Carboniferous period: the evolution of flight appears especially likely during hyperoxic episodes in the Earth's history (Dudley, 2000).

Freedom to explore all three dimensions of space during flight comes with both hefty power demands and the requirement for precise control of wing kinematics (Gatesy & Dial, 1996). The frequency, amplitude and angle of attack of the wingbeats, the partial retraction of the wings during the upstroke (and possibly also on the downstroke), the degree of supination/pronation and the relative force on each wing must all be centrally coordinated. Additionally, birds need a high degree of visual acuity in order to avoid obstacles, home in on prey and evade predators (Jones et al, 2007). Executing these various tasks concurrently demands considerable skill and attentiveness. Furthermore, take-off and landing are fraught with hazards, particularly at night, in adverse weather or in especially windy conditions.

The need for complex motor functions and sophisticated three-dimensional trajectory control in birds must be balanced against the need to minimise weight which, in turn, constrains brain size (Pearson, 1972). Adaptation to changing environments is a driving force for evolutionary growth in brain size (Sol et al, 2005). During long-range migrations, navigation skills are vital (Griffin, 1952; Griffin, 1969; Stapput et al, 2008; Thorup & Holland, 2009; Holland et al, 2009). Birds are known to use magnetoception (Mouritsen & Ritz, 2005; Witschko et al 2006), solar compassing, ground landmarks, the polarization patterns of the sky at sunrise and sunset (Able, 1982; Muheim, 2006), orientation with reference to the night-time stars and olfaction (Schmidt-Koenig, 1987). Bats use echolocation at night both for navigation (Norberg & Rayner, 1987) and for catching insects (Griffin et al, 1960). More so than any other locomotory medium, efficient neural control is paramount.

Modern birds are the sole descendants of theropod dinosaurs of the Jurassic era. Most dinosaur species perished in the aftermath of one or more asteroid strikes during the Cretaceous-Paleogene extinction event some 65 million years ago (Renne et al, 2013). A high degree of speciation in birds compared to other tetrapod classes (Weir & Schluter, 2007) may have been a contributing factor. Also potentially relevant is brain size. The brain masses of birds are, in general, an order of magnitude larger than in reptiles (Martin, 1981). In some species, the encephalisation quotient (or the ratio of brain mass to body mass) rivals that of primates (Iwaniuk & Nelson, 2003). Indeed, despite radical differences in neuroarchitecture, after 280 million years of independent evolution, a degree of convergence in cognitive functioning can be appreciated between corvids and apes (Emery & Clayton, 2004). The most developed sections of the avian brain perform flight-related functions, closely tied to which is an acute visual system (Hart, 2001) handling information from retinae with high photoreceptor densities (Meyer, 1977). Analysis of the braincase of Archaeopteryx suggests it too had a sophisticated vision system, a large inner ear and expanded auditory perception: neurological and sensory adaptations consistent with an ability to fly (Alonso et al, 2004).

Factors relevant to the feasibility of flight

The Earth’s tallest pinnacle, Everest, protrudes high into the upper atmosphere. Such large mountains significantly deform the underlying crust and so can only exist for geologically short periods of time (Schmidt & Montgomery, 1995). Although many species inhabit or migrate across mountainous regions, there has been almost no evolutionary pressure for birds to fly as high as the stratosphere. Because flight is reliant on an atmospheric medium, which becomes exponentially more rarefied with altitude, it is unlikely that any flying animal will ever evolve an innate ability to escape the gravitational field of its home planet. The movement of life everywhere in the universe is thus constrained by gravity and the inhospitable vacuum of space. Nevertheless, evolution recently succeeded in bridging the gap between the Earth and its nearby satellite, the Moon. The solution was in many respects ingenious but entirely reliant on evolution first cultivating a species possessing some intelligence and technological aptitude (Bilstein, 1999).

All non-parasitic lifeforms are reliant upon respiration to tap the energy reserves of their surroundings. Metabolic activity involves chemical transformations typically catalysed by enzymes within cells. For all species capable of flight, oxygen drawn from the atmosphere is used for oxidative phosphorylation (Rich, 2003) in which adenosine diphosphate is converted into adenosine triphosphate, a molecule capable of intracellular energy transfer. A fuel substrate is also required, though the replenishment of nutrients through feeding and drinking is generally impractical during flight – except for hovering insects and birds.

Besides its ability to supply a combustible gas, flying animals also use the atmosphere for propulsion and to generate forces counteracting their body weights (Tobalske et al, 2003). Unless the beating of wings, whether feathered or membranous, occurs within some medium capable of transporting momentum away from a bird, the laws of gravitational inertia apply. Were it not for the atmosphere, any bird initially flying horizontally at an altitude lower than the summit of Everest would ballistically trace out a geodesic trajectory and collide with the Earth within 42 seconds. Some maintain that Archaeopteryx could not sustain flight for even this length of time due to an inability to raise its own wings rapidly without assistance (Senter, 2006), as might be possible when gliding downwards. However, others contend that its wings could have been passively elevated during horizontal flight at sufficiently high speeds (Pennycuick, 1968), a possibility with some support as its cranial characteristics closely resemble those of modern birds (Alonso et al, 2004).

Body weight is the product of body mass and the acceleration due to gravity. Atmospheric density is a function of gravity, altitude and atmospheric mass trapped in a planet's gravitational field. Air density is maximised at low altitude, minimising the costs of weight support near the ground. A planet's surface gravity is proportional to its mass divided by its radius. This simple relationship was first deduced by Newton and is independent of radial variations in the composition and density of the planet. Therefore, providing the atmosphere is breathable and not composed of caustic chemicals, such as the sulphuric acid present in the Venusian atmosphere, knowledge of a planet's mass and surface air density alone are sufficient for evaluating the feasibility of flight. Temperature, though capable of influencing air density, need not affect the minimum costs of flight as the body temperature of an animal can be somewhat adapted both to its environment and its power budget during flight.

The estimation of flight power in free-ranging birds has traditionally been restricted to wind tunnel work involving relatively small species or techniques lacking satisfactory temporal resolution. Others have pioneered an alternative approach based upon heart-rate (Woakes et al, 1995). However, in recent years, enormous strides in electronics and transducer technologies are increasingly enabling the design of sophisticated instruments continuously collecting electrocardiography alongside additional data such as triaxial acceleration. Such instruments can be sufficiently compact, lightweight and energy-efficient to enable year-long deployments, especially in larger species of birds. This permits more comprehensive studies of flight power than were hitherto possible.

Comfortable environmental temperatures

Lifeforms require temperatures compatible with condensed fluids, most notably liquid water. In cold conditions matter will solidify or freeze. Excessively hot environments cause liquids to evaporate and solids to sublimate. At extreme temperatures, atomic matter disintegrates to produce plasma, thereby prohibiting all chemistry. The electromagnetic flux density due to the Sun at the Earth's mean orbital radius is known as the solar constant and has a value of 1361 Watts per square metre (Kopp et al, 2011). Because the Earth subtends a small solid angle from the Sun it intercepts less than one billionth of the Sun's total irradiance. Similar figures apply to other habitable planets of comparable size orbiting main sequence stars, irrespective of variations in stellar mass or luminosity. Thus, stars are an inefficient means of sustaining planetary life. Alternatives have been proposed such as the tidal heating of satellites by their host planets (e.g. Jupiter's moon Europa), radioactive decay of unstable isotopes such as Uranium-238 and Thorium-232 which are known to be present in the Earth's mantle and outer core (Araki et al., 2005) and the retention of the primordial heat of planet formation by dense hydrogen atmospheres (Stevenson, 1999). However, none of these proposals are promising from the perspective of the efficient sustainment of life over the ultra-long-term.

The extent of the circumstellar habitable zone (CHZ) is still the subject of ongoing debate (Kasting et al, 1993; Vladilo et al, 2013). Its definition is susceptible to variations in such things as atmospheric density, the chemical composition of the atmosphere, a planet's orbital eccentricity and rotation rate, albedo, the obliquity of the rotational axis, the strength and orientation of its magnetosphere, internal radiogenic decay and tidal interactions with satellites. However, the presence of liquid water is considered essential (Kasting et al, 1993; Lineweaver & Chopra, 2012). On Earth, microbial life is pervasive, even several kilometres into the rocky crust (Mason et al, 2010). It seems to thrive wherever liquid water can penetrate. This is why the CHZ is occasionally referred to as the 'liquid water belt' and NASA has stated that the strategy of its astrobiological programmes is to "follow the water".

Within the Solar System, Venus has a mean surface temperature (MST) of 735K and orbits at 0.723 Astronomical Units (AU) from the Sun while the MST for

Mars, which orbits at 1.523 AU, is 218K. In comparison, Earth's MST is about 288K. From the Stefan-Boltzmann law, the power radiated by a black body is proportional to the fourth power of its surface temperature, whereas the power intercepted by a planet from a star is inversely proportional to the square of its orbital radius. Hence, to a first approximation, one would expect a planet's temperature to be inversely related to the square root of its orbital radius. This naïve expectation can, however, be very inaccurate. At 737K, Venus is much hotter than the 338K this would predict and, at 210K, Mars is slightly cooler than the implied 232K. These discrepancies are primarily attributable to thermal runaway, colloquially known as the greenhouse effect: Venus has a dense insulating atmosphere whereas Mars does not (Earth's being intermediate). A simple estimate of the width of the CHZ can therefore be obtained by neglecting the influence of atmospheric insulation, which only serves to narrow the CHZ for some prototypical planet, giving $R_2/R_1 = T_2^2/T_1^2$ where R and T respectively denote planetary radii and temperatures. Although the boiling point of water increases with pressure, even hyperthermophiles cannot tolerate temperatures above 122ºC (Takai et al, 2008). Thus, one would generally expect that $R_2 \lesssim 2R_1$. If the Earth were centrally located within the CHZ then the inner edge would be at 0.732 AU and the outer edge at 1.366 AU. Although this span is relatively narrow (less than 14% of the logarithmic difference between the orbits of Mercury and Neptune), it suggests a high fraction of stellar systems may possess a habitable planet.

A planet located within the CHZ is by no means guaranteed to cultivate complex life, the formerly habitable yet barren planet Mars is proof of that. Although life on Earth arose rather swiftly once the primordial heat had dissipated, it took several billion years for multi-cellularity to subsequently emerge. Since this time period is comparable to the Earth’s age, it is entirely plausible that the evolution of multicellular organisms is an extremely unlikely event on any life-hosting planet. Approximately speaking, stellar lifetimes are inversely proportional to the cube of a star's mass so the most massive stars are the soonest to die. They also radiate strongly at ultraviolet wavelengths capable of disrupting biochemical processes. Stars of low mass are longer lived than the Sun but any planets within the CHZ are so close to their host stars that they are vulnerable to tidal-locking well before their host stars expire. The mechanism of tidal locking is responsible for drawing the Moon into synchronous rotation with the Earth so that one lunar hemisphere remains permanently invisible. Thus, the CHZ is restricted to the hydrogen-burning class F, G and K stars of 0.45 to 1.4 solar masses. Collectively, they account for about a quarter of all stars. Therefore, it would seem that in order to cultivate intelligent life through abiogenesis and evolution, planets must occupy quite circular orbits at a comfortable distance from a star of moderate size and maintain a reasonable rotation rate to inhibit the day/night contrast. The mechanisms underpinning abiogenesis are still the subject of debate but it the landmark Miller-Urey experiment has conclusively demonstrated the possibility of fabricating organic molecules from inorganic chemistry (Miller, 1953). This falls under the umbrella of the prebiotic soup from a reducing atmosphere proposal (Oparin, 1924). However, an alternative gaining adherents is that life began in hydrothermal vents (Martin et al, 2008), one argument being that DNA is intrinsically tolerant of relatively high temperatures. A minority favour *panspermia*, the idea that life came from space, where it is supposedly pervasive. This appears to be at odds with the lack of evidence of fossilised microbial life on Mars, a formerly habitable planet where water was abundant.

Most stars within the Milky Way are members of binary systems (Mattieu et al, 2000). Depending on the exact separation of the two stars, gravitational perturbations could destabilise the orbit of an otherwise habitable planet orbiting one of the stars, or at least episodically upset its climate so as to prohibit the development of complex intelligent life. However, circumbinary planets, which simultaneously orbit a pair of tightly bound stars, may fare better. Habitable planetary orbits are considered possible in roughly half of the binary systems (Quintana, 2006).

Planetary habitability and gravity

Animals locomote either by swimming, flying, walking, running, hopping or brachiation. Some animals use multiple modes of locomotion. For example, Razorbills can walk using their legs and fly or swim using their wings, inevitably demanding some degree of compromise (Piatt & Nettleship, 1985). Aquatic animals are generally very buoyant in water and thus their locomotion costs are relatively immune to the effects of gravity. Even so, aquatic birds and mammals which surface regularly to inspire air must overcome some excess buoyancy at the start of each dive as the air in their lungs is compressed.

As for surface-dwelling animals that walk or run, weight support comes via limbs in direct contact with the ground. The heavier the animal, the sturdier the skeletal framework has to be and hence the more costly locomotion becomes. The compressive strength of a material is proportional to its cross-sectional area and so the diameter of a leg bone should approximately scale with the square root of the weight it must support. A sauropod dinosaur, the quadrupedal *Amphicoelias fragillimus*, is estimated to have weighed as much as 122 tonnes (Carpenter, 2006), a mass comparable to some of today's blue whales. This cumbersome herbivorous creature would have struggled to walk, and might have been obliged to spend much of its time partially submerged in water.

While an increased surface gravity may only moderately limit the opportunities for land-based lifeforms, and is largely irrelevant as far as aquatic species go, flying creatures are more vulnerable to its effects. On Earth, most birds are capable of take-off from level ground without assistance from a headwind (Sato et al, 2009) but aerobically sustained hovering is limited to hummingbirds and pied kingfishers (*Ceryle rudis*). The Earth is a planet where hovering flight is merely difficult, as opposed to impossible. However, hovering is somewhat like standing still, and not a true mode of locomotion as such. Its aerodynamics differ from the aerodynamics of forward flight (Warrick et al, 2005).

Locomotion in rarefied air

The phenomenon of bird flight is observed primarily at low altitudes, consistent with the presence of relatively dense air there. Temperature is another contributory factor as it declines steadily with altitude within the troposphere. Nevertheless, most birds are very well insulated by a downy layer of feathers and heat production is naturally elevated during flapping flight. The metabolic power associated with flight primarily manifests itself initially as thermal energy which has to be actively dissipated to the environment if thermoregulation is to be maintained (Wu et al, 2009). High altitude flight in cool air may therefore even be potentially advantageous to some species.

Airlines transport passengers within the stratosphere, minimising the fuel they require to complete their journeys. Aviation theory is sufficiently developed that the power required by aircraft flying at various altitudes and speeds can be accurately predicted so as to optimise travel times and fuel costs. The drag incurred by aircraft is reduced in lower density air. Providing the engine intakes collect sufficient oxygen to burn fuel at the same rate, high altitude flight is then possible at greater airspeeds. The cost of first ascending to a high cruising altitude can be handsomely offset by the resulting fuel savings.

Although birds might have adopted a similar high altitude flight strategy to reduce their travelling or migration costs, there are other factors to consider. An uncomfortably low ambient air temperature at higher altitudes is only one. Flying low over the ground allows flight to be safely terminated should fog, mist or cloud begin to form or drift into the flight path. Wings must be sufficiently strong to cope with take-off in dense air, limiting the scope for lighter, larger area wings that might be preferable at higher altitudes. These issues will be returned to and quantitatively analysed later.

Thus, we should not be surprised if birds are reluctant to fly or incapable of flying at extreme altitudes. Indeed, birds are very rarely witnessed at the cruising altitudes of aircraft unless they were assisted by strong thermals, they were obliged to ascend in order to traverse mountain ranges or they were attempting to profit from strong tailwinds that are occasionally present in the upper atmosphere (Alerstam, 1993; Altshuler & Dudley, 2006). Nevertheless, some species of bird are habituated to life well above sea level. In temperate conditions near the equator, hummingbirds are known to live at altitudes of up to 5000m (Chai & Dudley, 1995; Rahbek & Graves, 2000).

Perhaps most notable amongst the birds that regularly traverse high altitude mountain ranges during their seasonal migrations are bar-headed geese, *Anser indicus,* whose flight is almost entirely self-powered (Black et al, 1978). Like other geese, this species does not dawdle hoping for environmental assistance (Hawkes et al 2013) but tends to flap its wings continuously throughout flight. It spends many weeks each year at altitudes approaching 5000m on the Tibetan plateau and heads across the Himalaya as winter approaches to arrive in India where the weather is more pleasant (Butler 2010; Hawkes et al, 2011). Summer is spent wading, foraging and breeding on lakes in China or Mongolia. The geese can be readily captured during July when their feathers moult. Unlike brent geese, which struggle to cross the Greenland ice-caps at altitudes of 2500m (Gudmundsson et al, 1995), bar-headed geese will reach 2–3 times that altitude during their trans-Himalayan migrations (Zhang et al 2011; Hawkes et al, 2013). Their tolerance of hypoxia in treadmill experiments (Hawkes et al, 2014) comfortably surpasses that of a lowland species, the barnacle goose, *Branta leucopsis*. This athleticism is at least partially attributable to a small genetic adaptation in their haemoglobin (Rollema & Bauer, 1979; Perutz, 1983).

General aims

The presence of liquid water is by now widely considered a prerequisite for planetary habitability (Lineweaver & Chopra, 2012). However, planets within the CHZ may or may not be compatible with aerial locomotion. Self-powered flight is the primary mode of transport for most of the Earth’s ten thousand avian species (Codron et al, 2013) and therefore the potential importance of flight to the diversity and evolutionary development of extraterrestrial biospheres should not be overlooked. Mass-specific flight costs are known to increase with body mass (Pennycuick, 1992) yet bar-headed geese are relatively heavy birds, making their migrations all the more impressive. Nevertheless, there are heavier species. This thesis will draw on published works to develop a quantitative model for evaluating flight athleticism in very general circumstances. This will first be used to perform inter-species comparisons capable of identifying which birds are the most proficient aeronauts. By considering the influence of such factors as atmospheric density and planetary gravity, the limits of flight in extraterrestrial settings shall then be determined. Thus, a central focus of this thesis is the astrobiology of flight and the derivation of criteria capable of discriminating between planets where flight is potentially feasible and those where the degree of athleticism required exceeds what can be credibly extrapolated from observations of Earth’s flying birds.

Chapter 2: Critical analysis of Published Works

Paper I: Integration of exercise response and allometric scaling in endotherms.

The metabolic rate of any living animal largely depends on its level of physical activity and rate of heat escape. Due to photosynthetic processes operating over geological timescales dating back some 2.3 Gyr (Bekker et al, 2004), oxygen exists in the Earth's present day atmosphere at a volumetric concentration of approximately 21%. From a biological perspective, this combustible diatomic gas serves as a readily available energy source (Kasting & Siefert, 2002).

Birds are the direct descendants of dinosaurs but their cardiopulmonary systems are functionally comparable to those of mammals, and their body temperatures closely resemble those of mammals. In both clades, oxygen is extracted from inhaled air by a pair of lungs and mechanically pumped around an endothermic body by a single organ along arteries and veins. Despite these similarities, no coordinated program of research has previously set out to investigate whether the general variation of metabolic rate within birds and mammals might follow some unified relationship. The allometric scaling of basal metabolic rate or maximal metabolic rate continues to attract considerable interest (Kleiber, 1932; Bishop & Butler, 1995; West et al, 1997; White et al 2009) and it is known that their scaling laws differ (Koteja, 1987; Bishop, 1999; Glazier, 2008) yet the intervening activity spectrum has not received the same scrutiny. Indeed, no theoretical relationship describing the aerobic exercise spectrum has been previously advanced, whether for an individual species of bird or mammal, or across multiple species of birds and mammals.

Locomotion is an especially demanding form of physical activity that all animals are evolutionarily adapted to perform. Many species are adept at multiple modes of movement. For example, razorbills, *Alca torda*, are able to walk on land, fly through the air and hunt for food by swimming underwater. Nevertheless, for each species, there will typically be a preferred, primary mode of locomotion which is most able to probe the limits of aerobic athleticism for which $\dot{V}_{O_2} \to \dot{V}_{O_2}^{max}$. This primary mode of locomotion will lend itself to the characterisation of the exercise response spectrum by imposing the most stringent demands on the most critical muscle of all, the heart (Bishop, 1997).

This paper contributes to the field of physiology by uncovering a previously unknown power law relationship linking heart-rate, f_h, the rate of oxygen consumption, $\dot{V}_{O_2}$, body mass, m_b, and heart mass, m_h, in endothermic birds and mammals undergoing primary mode locomotion. It was possible to both theoretically justify the existence of this relationship and verify its existence using empirical data drawn mainly from existing published studies.

The initial impetus for this work came from wind tunnel experiments involving bar-headed geese (Ward et al, 2002) in which f_h and $\dot{V}_{O_2}$ had been simultaneously collected. Dr Bishop had appreciated that these quantities seemed to follow a power law relationship, approximately quadratic in f_h. As few birds were willing to sustain flight for any length of time in the wind tunnel, much of the data was acquired from a juvenile bird which, having been reared in captivity, was unaccustomed to flight initially. This resulted in the bird attempting to hone its skills by flying somewhat inconsistently, often adjusting its position within the wind tunnel. As the bird matured, it was better able to maintain station, speed and effort level. The collected data therefore exhibited greater variability in both heart-rate and $\dot{V}_{O_2}$ in earlier flights than in later flights. This was somewhat fortunate in that a wide variation in exercise intensity was useful in establishing the existence of the power law relationship and constraining its exponent, yielding $\dot{V}_{O_2} \propto f_h^{1.88}$. The large aerobic scope of the bar-headed goose and the fluctuations in flight power associated with learning to fly both contributed positively to this finding.

It was then interesting to know whether a similar near-quadratic relationship might generally describe the heart-rate response of all endotherms undergoing primary mode locomotion. When Dr Bishop drew my attention to this matter he had already collated results drawn from numerous species and confirmed that, although there was some spread in the results, the power law exponents seemed to be clustering around the value of two. Our analysis initially focused on the Fick equation which describes oxygen consumption as the product of arteriovenous oxygen difference and cardiac output, the latter quantity being the product of heart-rate and cardiac stroke volume (the volume of blood delivered by each heart beat). However, although this equation was known to have validity both allometrically (Bishop & Butler, 1995) and for individual animals (Butler et al 2004; Green, 2011), it did not furnish any explanation as to why a quadratic power law $\dot{V}_{O_2} \propto f_h^2$ might apply during exercise.

I realised that if the quadratic relationship is valid, one could deduce from the Fick principle that heart-rate and arteriovenous oxygen difference should be linearly related, $f_h \propto C_aO_2 - C_vO_2$. Although this had not been previously reported it was possible to show, using data from elite human athletes already present in the literature for both males (Crisafulli et al., 2007) and females (McCole et al., 1999) undergoing exercise at varying intensities, that this expectation was upheld to a remarkable degree of precision (r^2>0.99). In fact, the same analysis led to a prediction of a power law relating four physiological variables including also body mass and heart mass. This was able to elucidate some curious patterns Dr. Bishop had already noticed in the data which previously had no explanation. Further data were then gathered for species in which multiple measurements of heart-rate, oxygen consumption, heart mass and body mass were available. In all, data were obtained for 24 species (12 mammals and 12 birds) spanning 5 orders of magnitude in body mass.

Until this time Dr Bishop had been using a spreadsheet for data analysis which lacked the capability for multiple regression. In any case, just as a single bad sample can skew the arithmetic mean of a dataset, least-squares methods are vulnerable to the outliers that are commonly encountered in biological data. I therefore decided to try a more robust approach, a multidimensional generalisation of the least absolute deviation method. Since the magnitude operator is non-linear, the process is not analytically tractable and thus calls for a numerical approach. This can be awkward to implement since there may exist local minima distracting from the desired global minimum. To counter this, I employed an adjustable grid when iterating towards a solution. Although computationally time-consuming, the results exhibited good stability and were relatively insensitive to the random exclusion of some of the original 24 species. The results were in keeping with the predictions of the modelling efforts, as was later confirmed independently by multiple least-squares regression due to requests by reviewers unfamiliar with its limitations. Not only was the quadratic power law observed at the level of an individual or a species, it was also upheld allometrically at the inter-species level, just as the modelling work had anticipated. Furthermore, the results affirmed the expected dominance of heart mass over body mass, though knowledge of both heart mass and body mass provided superior predictions of oxygen consumption from heart-rate.

Nevertheless, to a useful approximation, the 4-variable power law could be reduced to a 3-variable power law in which the body mass term was discarded. By taking logarithms of heart-rate, heart mass and $\dot{V}_{O_2}$ it was possible to plot the data in 3 dimensions and visually confirm that the points clustered on a plane. This plane could be mathematically decomposed into two orthogonal axes: one being heart mass (the allometric scaling axis) and the other corresponding to a quantity we termed 'cardiac activity', the product $\dot{V}_{O_2}^2 f_h$ which is loosely related to exercise intensity. One might instinctively expect that increases in either f_h or $\dot{V}_{O_2}$ will take one further up the cardiac activity scale. Whilst generally correct, exceptions are possible. For instance, an elevated heart-rate, f_h, can sometimes correspond to a drop in cardiac activity. If $\dot{V}_{O_2}$declines in percentage terms by more than half the percentage increase in f_h then the cardiac activity will fall. This might occur when an animal is frightened and its adrenaline levels rise, causing a rapid and shallow pulse. At such times, the animal would be poised for action, yet simultaneously conserving energy, potentially in readiness of an evasive manoeuvre.

This work establishes for the first time a firm theoretical basis for the conversion of heart-rate to oxygen consumption estimates without the need for prior calibration either in the field or laboratory. Since heart-rate can be measured with high temporal resolution, this approach also permits near-instantaneous estimates of metabolic rate. However, despite these notable advantages, the technique is not without some potential drawbacks. Heart-rate is susceptible to emotional factors (fear, excitement etc), seasonally/hormonally induced changes in heart size and the inherent flexibility to vary stroke volume independently of heart-rate, especially in animals that may lack physical conditioning such as those emerging from hibernation. Nevertheless, the technique has definite merits and appears especially well-suited to assessing relative metabolic rates during the long-range migratory flights of individual birds, particularly in those species that flap their wings continuously when airborne, and which therefore have relatively stable heart-rates.

Irrespective of whether the primary mode of locomotion was running, swimming or flying, or whether the data was taken from birds or mammals, it clustered around a single plane. Thus, a remarkable and hitherto unknown unification of cardiovascular response had been uncovered.

Since birds and mammals have radically different lineages, it is possible that extraterrestrial endotherms which are also reliant on oxygen for respiration and have comparable body temperatures might not deviate far from the same plane, even though their physiology may be distinctly different. A shift in body temperature would likely cause a perpendicular shift in the data but would likely fall on another plane parallel to the one we have uncovered. This conjecture could be investigated without expenditure on interstellar missions and associated delays by collecting comparable data from ectotherms, such as reptiles, exercising over a range of ambient temperatures, compensating for any ensuing activity-related rises in body temperature.

Paper II: Interpretation of body-mounted accelerometry in flying animals and estimation of biomechanical power.

Microelectromechanical accelerometers are a relatively recent technological innovation typically fabricated from silicon using etching techniques similar to those used for integrated circuitry. Silicon is an excellent choice of material for such applications, exhibiting little mechanical hysteresis or fatigue. This permits the design of fiducial proof masses mounted on cantilever beams whose vibrational displacements reflect applied accelerations. Initial applications for accelerometers included pedometers, the parking of hard disk drives as dangerous free-fall conditions are sensed and airbag activation during vehicle collisions. More recently, accelerometers have been incorporated into games controllers for user input, still/video cameras for image stabilisation and smartphones for display orientation. Concurrently, these transducers have found increasing use in animal research (Weimerskirsch et al, 2005; Taylor et al, 2008), although their potential was apparent several decades ago (Bilo, 1984). Accelerometry allows the determination of measures descriptive of locomotion such as stride rate or flipper beat frequency. Due to various commercial pressures, accelerometers have increased in bandwidth whilst becoming more frugal energetically. This makes them a highly attractive technology for deployment in a wide variety of modern, long-term biological studies.

Prior to this work, somewhat ad hoc measures obtained from accelerometry data had been extensively used as proxies for an animal's rate of energy expenditure. The field had attracted relatively little focus from technologists due to the small size of the research market for accelerometers compared to the demands of the consumer electronics industry. Thus, a theoretical basis underpinning the usage of accelerometers in animal monitoring studies went largely unexplored. The measures adopted by biologists had proven useful as correlates of metabolic rate but they lacked the appropriate units. Also, the independent measures of oxygen consumption used to empirically assess correlations typically had very poor temporal resolution. One such method is the doubly-labelled water technique which calculates the mean field metabolic rate (FMR) from the elimination rates of water containing low concentrations of isotopes (Lifson et al., 1955; Nagy, 1980; Speakman, 1997; Butler et al 2004; Elliot et al 2012).

In conjunction with a doctoral student, Dr. Bishop had been studying free-ranging bird flight for several years using accelerometers and GPS modules (Tyson, 2013). These systems were mounted on flexible fibreglass backplates and attached to homing pigeons via elasticated harnesses in fixed orientations. The pigeons were reared and attended to in a loft in Treborth near Bangor and tended to use the Menai Straits for guidance during return flights. The systems deployed on pigeons were rather power hungry, with a battery life of just a few hours. This was adequate for short-range homing flights but not for long-term monitoring purposes. Investigation of the annual migrations of bar-headed geese would necessitate the design of much lower power implantable instruments recording accelerometry and heart-rate.

At the commencement of the pigeon project, although accelerometry had previously been widely used to monitor animal movements, very few of those studies had involved flying birds, whether in the wild or in wind tunnels. Accelerometry not only allows the direct measurement of wingbeat frequency but also the intensity of the vibrations transmitted to the body during each wingbeat cycle. It seemed probable that this information could assist the estimation of biomechanical power expended by a bird during flapping flight. Both pigeons and geese tend to flap their wings continuously during homing flights, and therefore make excellent study animals for research into the biomechanics and energetics of flight, particularly steady horizontal flight.

Preliminary analysis of data collected from the body of a flying pigeon began with Fourier processing of the upward component of the acceleration from a section of flight in which the bird was beating its wings consistently and periodically. As might be expected, the frequency spectrum possessed a very prominent spike at the frequency corresponding to the beating of the wings. The sample rate of the accelerometer was 187 Hz so, for a wingbeat frequency of around 7 Hz, it was possible to observe quite high (up to 9th or 10th) order harmonics, albeit of a relatively low amplitude.

This information provided the basis for a mathematical exploration of the energy fluctuations visible to an accelerometer anchored to the body of a bird undergoing flapping flight. Simplifying assumptions were adopted, such as horizontal flight in a straight line at constant mean airspeed and constant wingbeat frequency. Since the experimental data suggested the power of the body vibrations was quite tightly concentrated at the (fundamental) wingbeat frequency, a sinusoidal pattern of horizontal and vertical oscillations was imposed, with freedom to vary their individual amplitudes and the relative phase between them. The analysis showed that, if the horizontal vibrations were used for temporary storage and return of energy during each wingbeat cycle, then power would be minimised if the horizontal and vertical vibrations occurred in quadrature phase i.e. with a 90 degree phase lag between the two. Physiological considerations suggested that for quadrature phase flapping, the upward acceleration should lead the forward acceleration. This expectation was later confirmed with publically accessible video footage of flying birds.

Several experimental groups had sought to uncover correlations between acceleration and energy expenditure (Hendelman et al, 2000; Wilson et al, 2006; Halsey et al, 2009; Green et al, 2009). In these works, accelerometry data was typically processed by separating the acceleration into two components, namely the static acceleration (typically calculated as the mean acceleration obtained over several seconds with a fixed duration rectangular sampling window) and the dynamic acceleration (the raw acceleration after subtracting the static acceleration thus obtained). The dynamic acceleration was then further processed by taking its three components and, after inverting negatively valued components and performing summation, averaging over the same time window. Despite its crude nature, this measure, known in the literature as Overall Dynamic Body Acceleration (ODBA), was found to be somewhat correlated with energy expenditure — even though no solid theoretical basis existed.

Dissatisfaction with this approach provided further motivation for a mathematical assessment of the mechanics underlying the vibrations detectable to a body-mounted accelerometer during flight. Three energy components were considered: (i) the kinetic energy in the forward horizontal axis (ii) the kinetic energy in the vertical axis and (iii) the gravitational energy. For convenience, the bird's frame of reference was used. It was found that the calculation of body power first had to discriminate between three cases according to the relative amplitude of the horizontal and vertical vibrations. Whichever case applied, it was possible to translate root-mean-square (rms) dynamic accelerations of the forward and vertical axes into power estimates in dimensionally correct units, $[ML^{2}T^{-3}]$. This was an improvement over ODBA whose units are simply those of acceleration, $[LT^{-2}]$.

This formally established for the first time a firm theoretical connection between dynamic acceleration and locomotory power requirements, in this specific case the biomechanical power required during flight. An appendix explored the relationship between rms dynamic acceleration with both ODBA and an alternative to it that took into account the Pythagorean theorem called VeDBA (McGregor, 2009). It was pointed out that the error due to ODBA's incorrect handling of vector length varies between zero and 73% according to orientation, with a mean error of 50%. VeDBA is free of this error but, like ODBA, is not a true measure of power and is not identical to rms acceleration, even for purely linear vibrations along a single axis.

Since birds are capable of executing many wing-strokes and several banking turns in the space of a few seconds, a superior method of disentangling the static and dynamic acceleration than had been used by ODBA advocates was also described. This used Fourier processing to separate the two components in the frequency domain before transforming back to the time domain. Furthermore, a technique for decomposing the dynamic acceleration into vertical, forward and lateral components from an arbitrarily orientated accelerometer, perhaps located within the abdomen, was presented.

This approach enabled the near-instantaneous assessment of flight power. The results of Paper I could be used to obtain estimates of flight power from heart-rate with a similar temporal resolution and so these two methods could be directly compared by calculating their statistical correlations. By the time these papers had been published, instruments capable of collecting the necessary data had already been designed, manufactured and deployed on wild geese during a field trip to Mongolia. Even in ancient times, bird flight fascinated scientists such as Aristotle, da Vinci and Galileo (Rayner, 2001). However, the direct measurement of the energetic costs of free-ranging flight has had to await some relatively recent technological advances.

Paper III: An implantable instrument for studying the long-term flight biology of migratory birds.

This paper describes the design of a system which was used to study the high altitude migrations of bar-headed geese across the Tibetan plateau and the Himalayas. The central component of this embedded system was a 16/32-bit microcontroller, the Microchip PIC24FJ128, chosen for its combination of peripherals, processing capability, compact size and low power consumption. A primary consideration was its low latency when recovering from sleep mode, helping to minimise power consumption when regularly collecting physiological data. Simultaneous maximisation of battery life and minimisation of weight was vitally important to this project.

Year-round heart-rate monitoring had never been accomplished before in any bird due to the complication of limited battery life in a compact instrument (Woakes et al, 1995; Butler et al, 1998; Butler & Woakes, 2001). However, a telemetric system equipped with a large external battery had previously been used in long-term deployments on land animals (Arnold et al, 2004). The strategy adopted here broke with the long-standing tradition in biological experimentation of processing an ecg signal in real-time to detect QRS complexes and subsequently either emitting a telemetric pulse or storing to memory the time intervals of individual/multiple heartbeats. An earlier generation instrument designed by Andrew Davies had employed such a beat-averaging approach to ease the memory requirements and although it was possible to adapt the firmware of that logger to extend battery life to cover a full year, it had no capability to capture accelerometry, and multiple false beat detections were impossible to correct in post-processing due to the summation of consecutive beat times.

At the outset of this project, before work had commenced on Papers I and II, it was unclear what information might be gleaned from a body-mounted accelerometer other than wingbeat frequency or measures of the ubiquitous measure called ODBA. The instrument was to be packaged in an implantable cylindrical housing, implantation being considered less harmful to animals for long-term deployments (White et al, 2008). I proposed using stainless steel end caps as ecg electrodes to boost reliability compared to flying leads. Some time later, the decision was taken to use titanium electrodes, perhaps in an attempt to minimise weight. Due to the cylindrical shape of the implanted instruments, the risk of rotation within the abdomen during flights could not be discounted. Reorientation of the sensor in real time was deemed impractical due to the large computational overhead. Hence, it was attractive to record raw accelerometry for post-processing and analysis following the return of instruments from the field. A similar approach had been previously adopted, but was intended only for very short deployments on lighter birds (Tucker, 1999).

The possibility of using a mass storage device to not only hold the incoming accelerometry but also the ecg samples was therefore investigated. To this end, a micro SD card was selected for its compact size and its acceptable current draw, providing power was completely withdrawn between memory transfers. An ultra-low power parallel SRAM of 1MB capacity was chosen as an intermediate data buffer – serial SRAM was limited to 32 kB and serial FLASH was rejected due to excessive current draw. Given the space constraints, layout necessitated a dense four layer printed circuit board design. The processor, SRAM and glue logic were placed on an upper board (Figure 1) and joined to a double-sided lower board via a 22 pin header. The micro SD card, sandwiched between the two boards, mated with a connector on the lower board. The ecg circuitry, the accelerometer, voltage regulators, a magnetometer and a connector leading to a third, circular board, were mounted on the underside of the second board. The circular board was mounted perpendicularly to the others and equipped with high resolution sensors monitoring pressure and temperature. While the other two boards were internally positioned within the logger, this board sat within the recess of an external electrode. This allowed exposure to atmospheric pressure, essential for altitude estimation.

Although the system was capable of recording an ecg signal continuously for almost 3 years from a 1/2AA sized lithium thionyl chloride battery, the accelerometer would totally discharge the battery in some three months if permanently enabled at the target rate of 100 Hz. Continuous triaxial accelerometry at 12 bits per channel required 39MB per day or 14 GB per year. The maximum capacity of the SD cards at the time was 8GB. Some 5.7GB of each card was dedicated to the ecg signal which was digitised at 180 samples per second during interrupt service routines. A compromise was achieved by activating the accelerometer for 18 seconds every two minutes (15% duty cycle). In this way, there was just enough battery and memory capacity to last a full year without need for a larger capacity memory card. Some allowance was made for premature discharge of the battery, 10-11 months operation being deemed sufficient to capture the return migration from India to Mongolia.

Firmware development occupied the bulk of the work for this project. The deadline was both tight and inflexible due to the brief moulting period of the geese, the only time of the year when they could be readily captured. The facility within the processor to enable and disable specific modules in order to reduce power consumption, change clock rates and remap pin functions, though undoubtedly useful for power reduction, also introduced additional complexities which delayed the completion of the firmware development.

The design deadline also had to be met while attempting to coordinate the manufacture and assembly of instruments. This relegated system testing to a weekend spent in the mountains of Snowdonia wearing a logger whilst attempting to complete the 14 peaks challenge. After some further refinements to the firmware, the loggers were finally assembled. Unfortunately, late in the evening on the day before the field workers left for Mongolia, a troubling glitch was observed in some units. After a few short hours of sleep and some frantic head scratching, the cause of the problem was pinpointed the following morning. Its rectification required the disassembly of all loggers for reprogramming to overcome an incompatibility between the format of newly sourced micro SD cards and those used during development work. A field worker from another institution was planning on departing the UK slightly later and, in the end, it proved possible to courier the loggers to him at the airport.

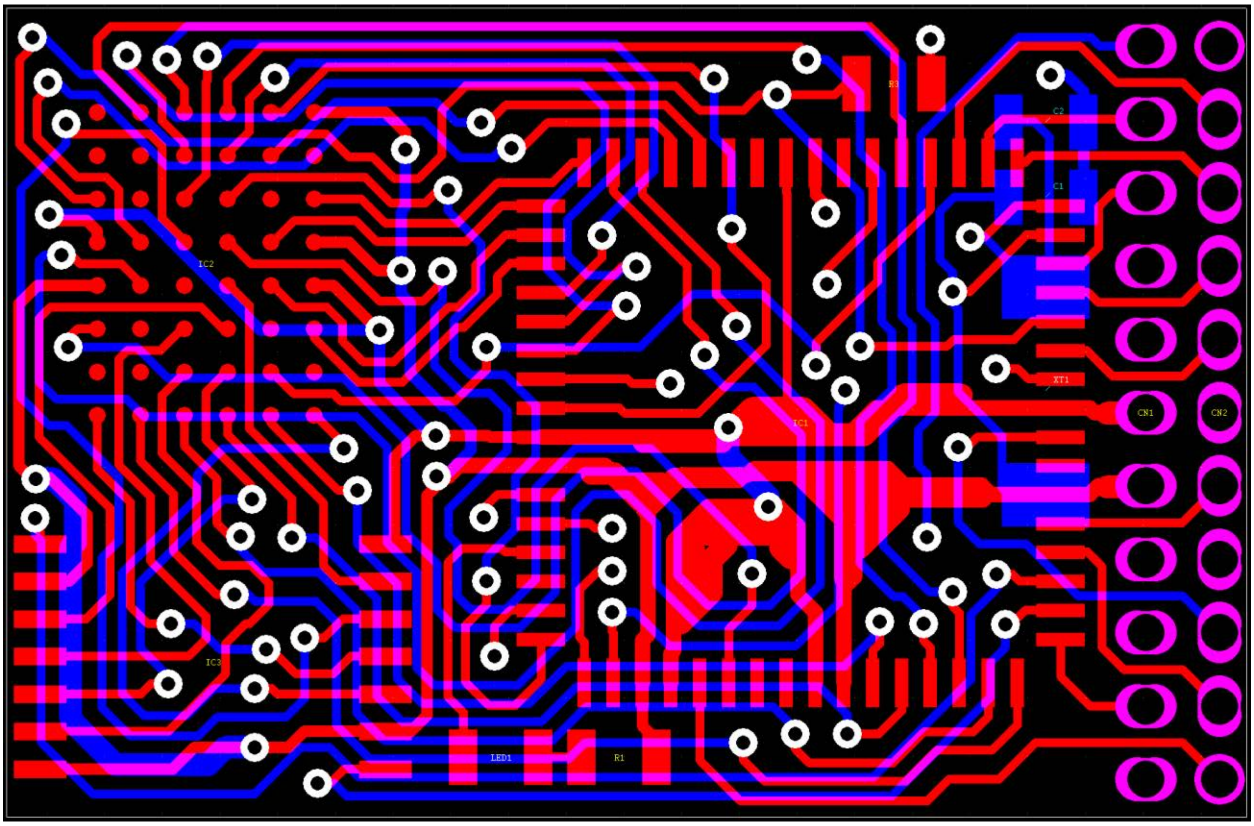

Figure 1. The outermost layers of the hand-tracked processor board which accommodated a PIC microcontroller (centre, right) and parallel static RAM (ball grid array, top left).

A surplus logger which had been identically configured was left standing on a bookshelf for almost a year. Prior to the recovery of loggers from Mongolia the following season, the anxious decision was taken to see whether it had in fact collected all the data it was expected to, which it had. Alas, the loggers that eventually returned from the field had not fared so well. This was partially due to their immersion in the hostile environment of a living animal. It appears that an epoxy resin bond between the pressure sensor and the titanium electrode it sat within was not hermetically sound, allowing the gradual ingress of vapour from the abdomen into the instruments. Although the loggers were not flooded, some of the gold-flashed contacts were visibly tarnished. The compounds responsible were sufficiently aggressive to attack the battery, entering through the vents intended to allow the discharge of gas in the event of a fault. This unfortunately led to the accelerated degradation of battery charge, evident from declining voltage measurements taken by the instruments. This, it seems was why no recaptured unit had succeeded in collecting data for more than 7 months, even though the unit kept on a bookshelf had performed flawlessly.

Could this be avoided in the future, especially if pressure measurements are required once more within the abdomen? Titanium is a difficult metal to adhere to without specialist adhesives. Stainless steel electrodes may have eliminated the problem. Alternatively, a separate neck collar system could handle altitude estimation, perhaps alongside informative measurements of other parameters such as external temperature and air speed. In fact, an air speed sensor with built-in temperature sensing was designed, based on a thermistor bridge circuit with a pulsed heating element. However, these were never fitted to geese due to lack of time for the completion and testing of firmware. Biocompatible O-rings might have helped, but we only became aware of their availability after the final instruments had been assembled and deployed. Future projects would do well to allow time for testing within a captive animal prior to field work. This need not necessarily delay the development of hardware or firmware as basic checks for corrosion and battery discharge would likely suffice for checking housing integrity, with functional tests being performed externally, as they were here.

This instrument represented a significant technological advance compared to existing biologgers such as the 'Daily Diary' (Wilson et al, 2008). However, since its design, technology has moved further forwards in several ways, each of which would have a significant bearing on the design choices and compromises if a future generation of instruments were to be commissioned. For instance, there are now serial memory devices that deliver performance competitive with parallel SRAM. A single stage operational amplifier could be used for ecg amplification/signal conditioning, indeed one such circuit was prototyped and shown to obtain reliable heart-rate data from flying pigeons. Perhaps the main advances, however, are seen in the enhanced performance of accelerometers. Power consumption has dropped dramatically in the latest generation devices, and some (marginally higher powered devices) now offer some built-in digital signal processing capabilities. These innovations are opening up a variety of exciting possibilities from real-time detection and classification of behavioural activity to intelligent activity triggered data collection to on-the-fly results compression. It is conceivable that in coming years, highly sophisticated instruments could provide a wealth of data that requires little in the way of post-processing following recapture. However, since the market will remain relatively small, this is likely to require both foresight and investment from those eager to see continued progress in animal studies.

Paper IV: Analysing the intermittent flapping flight of a Manx Shearwater, Puffinus puffinus, and its sporadic use of a wave-meandering wing-sailing flight strategy.

Due to its reconfigurable firmware, the logger described in Paper III has been adapted for use on several projects involving horses, carp, trout, bass, mackerel, barnacle geese, frigate birds, kittiwakes, lobsters, penguins, pigeons, razorbills and humans, mostly on behalf of other researchers and students at Bangor University. This article describes a project we undertook ourselves in collaboration with Steven Stansfield, the warden for Bardsey Island. He kindly obtained the necessary permits to study the flights of Manx Shearwaters over the Irish Sea in June 2013 and helped with datalogger deployment/recovery from subterranean burrows where chicks are reared (Brooke, 1990).

This species undertakes huge migrations each year from South America to the Irish Sea (Guilford et al, 2009; Freeman et al, 2013; Dean et al, 2013). It tends to intermittently flap and glide during flight (Tobalske, 2001), executing characteristically tortuous aerial movements close to the sea surface (Pennycuick, 2002). This complex flight pattern departs significantly from the assumptions employed in the analysis of Paper II such as level flight at a steady speed with constant wingbeat frequency. It was therefore interesting to know whether it might be possible to glean useful information concerning flight in this species by extending existing approaches (Paper II; Halsey et al 2009; Duriez et al, 2014). It was also desirable to augment accelerometry with detailed information concerning the flight trajectory. To this end, location fixes via the global positioning system (GPS) seemed the only realistic option.

Size, weight and battery life were once again prime concerns. Programmable GPS modules measuring 16x16x5mm with built-in memory and antenna were sourced. An electronic board capable of communicating with and configuring these modules was designed. It was also used to evaluate a yet more compact GPS module from the same supplier which could operate with a short wire antenna. The prototyping was successful and demonstrated our ability to design a future generation of unobtrusive flight monitoring instruments mounted on a neck collar for year-round study of birds weighing as little as 100 grams. Several systems were programmed for Dr. Bishop to take with him to Bardsey on a student field trip. Unfortunately, no instruments were deployed on arrival and fewer instruments were eventually deployed than originally planned. Nevertheless, some useful data was collected, in particular from one bird that was carrying both an accelerometer and GPS module.

The Manx Shearwater belongs to the order of seabirds known as procellariiformes, a family of remarkably adept aeronauts. This particular species generally weaves its way across sea waves, rarely gaining much height.

Recognising in advance that separation of gliding and flapping would be crucial to the success of this project, loggers had been programmed to collect accelerometry at 400Hz. ECG collection was not attempted but could be considered for any future studies. However, despite the formidable complexity associated with processing accelerometry compared to ecg, it does encode far more information concerning the flight motions of a bird. Therefore, ecg collection may be useful in terms of independent power estimates, but it cannot compete with the wealth of data obtainable through accelerometry.

Albatrosses, which belong to the same order, rarely flap their wings when airborne. Unlike the Manx Shearwater, albatrosses seem incapable of aerobically sustaining horizontal flight for any length of time without wind assistance. Their metabolic rate during flight has attracted some interest in the past (Bevan et al, 1995; Pennycuick, 1982). There was an opportunity here to investigate whether shearwaters might be similarly capable of harvesting energy from the wind and, if so, under what circumstances.

Fortuitously, the weather conditions were near ideal for addressing this very question on the morning of June 23rd 2013. Data from several weather stations indicated that there had been a moderately strong wind blowing for many hours whose orientation remained approximately constant during that period. This allowed the accurate estimation of sea conditions such as wave heights and lengths. Other researchers have observed that shearwaters tend to fly perpendicularly to the wind. Such a strategy can be useful in that headwinds need not be combated either during the outward or return leg of a foraging excursion, assuming unchanging wind conditions. This work suggests that, especially on windier days, there can be a further advantage to that strategy.

Although albatrosses are almost entirely reliant on dynamic soaring to remain aloft (Rayleigh, 1883; Sachs et al, 2012; Sachs et al, 2013; Richardson 2011), this work indicates that although Manx Shearwaters are not, they can greatly reduce the fraction of time they spend flapping their wings (the duty cycle) in other ways. Rather than exploiting a vertical wind gradient, they can profit from interactions between the wind and the waves. Out at sea, waves tend to move in the same direction as a sustained wind. Following the trough of a wave can then provide welcome respite from a crosswind. However, due to the motions of the waves, course corrections are occasionally necessary if a bearing perpendicular to the wind is to be maintained. Fortunately, the possibility of extracting free energy arises on abandoning one wave and flying windward to another.

Shearwaters may accomplish this in two ways. The first involves flying low over the trailing edge of a wave with the wings outstretched so as to maximise the lift gained from the passage of wind forced up over the wave. Supposing the wind has a speed $v_w = 10$ m/s and is deflected upwards 30 degrees by the wave then the wind will have an upward velocity of at least $v_w \sin(30) = 5$ m/s. If the bird takes full advantage of this it could be launched upwards, gaining $v_w^2 \sin^2(30)/2g$ in height: in this example about 1.3 metres.

A second and more potent mechanism for extracting energy comes from changes in the airspeed, v_{air}, of the shearwater caused by its turning into a headwind. The bird may be flying along in the trough of a wave at a relative speed of v_t. If the wave comes to an end then, if the bird does not change its direction or height, its airspeed rapidly increases from $v_{\text{air}} = v_t$ to $v_{\text{air}} = (v_t^2 + v_w^2)^{1/2}$. If it then banks hard, turning 90 degrees to directly face the wind, it can gain further airspeed, $v_{air} = v_t + v_w$. In circumstances where $v_t \approx v_w$ it is therefore possible that the kinetic energy of the bird doubles or even quadruples without much expenditure of effort. This injection of energy can be converted to a height gain of $\Delta h \approx (v_{\text{air}}^2 - v_t^2)/2g$, which for $v_t \approx v_w \approx 10$ m/s could be in the range 5 to 15 metres, depending on the skill of the bird.

The shearwater meandered with a cycle time of 12–16 seconds. A lift/drag ratio of 12 is plausible for this species in which case these birds could sustain meandering flight at zero duty cycle with a prevailing wind of 10 m/s. This is entirely consistent with our observation that, during a flight in similarly windy conditions, the bird was meandering about half the time. Occasional lulls in the wind would result in the bird following a straighter course to conserve energy.

Wingbeat frequency is an important parameter for characterising bird flight (Pennycuick, 1996). Unlike pigeons and geese, which vary both their wingbeat frequency and amplitude (and to some extent independently) during flight, the primary means by which Manx Shearwaters adjust their effort level is through modulating their flapping duty cycle. On windy days, they can interact with the wind and waves to reduce their flight costs. In this way, they can potentially treble their foraging range and conserve a great deal of energy during migration.

This work demonstrates the utility of recording accelerometry even from a bird that intermittently beats its wings and tends to follow a convoluted three dimensional flight path. It describes the associated methodology, quantifies the superiority of the wingbeat frequency determination approach over a cruder existing method (Sato et al, 2003; Watanuki et al, 2005), shows in quantitative terms that this species can handsomely benefit from environmental assistance and interprets the flight patterns in terms of a comprehensible flight strategy in which the birds interact with the wind and the waves to minimise their effort, allowing longer-range foraging missions perpendicular to the wind. This rather intricate flight strategy, which is quite distinct from dynamic soaring and gust soaring, is summarised schematically in Figure 11 of the paper.

Paper V: The roller coaster flight strategy of bar-headed geese conserves energy during Himalayan migrations.

A BBSRC grant was awarded to investigate the trans-Himalayan flights of bar-headed geese during one of the most spectacular migrations in the animal kingdom. At extreme altitudes birds must meet the challenges of weight support and ventilation in an unusually cold and low density atmosphere. The Himalayas are located 28 degrees above the equator, somewhat north of the Tropic of Cancer. At this latitude, the tropopause has an altitude of around 11km. Temperatures near -19 ºC are typical at 6000m and -32 ºC at 8000m. Soaring birds, e.g. vultures, have occasionally been observed at these altitudes, but regularly make use of thermals during their ascents. In still air conditions, bar-headed geese are contenders for the title of the world's highest fliers.

Anecdotal reports of geese traversing the 22km wide Annapurna massif suggest that these geese may be able to fly at altitudes approaching 8000m (Blum, 1980) although the highest altitude obtained via satellite tracking is 7290m (Hawkes et al, 2013). Even if most geese are capable of reaching such altitudes, there is generally no need to owing to the presence of many valleys running transversely across the Himalaya. Navigation along some well-chosen routes is possible at altitudes barely exceeding 5000m (Takekawa et al, 2009).

Apart from my previously described contributions – designing the electronics and firmware for the implantable loggers (Paper III), collaborating on the development of a heart-rate based power predictor (Paper I) and modelling the relationship between flight power and body-mounted accelerometry (Paper II) – my input here involved extracting and processing data from recovered loggers, analysing that data by writing R scripts, probing theoretical models, conception and generation of all figures and assisting the writing of the manuscript.

The collected data permitted scrutiny of the theoretical models in Papers I and II through comparison of biomechanical body power with heart-rate derived metabolic rate estimates. Due to the complexity of the mechanical coupling between wings and body it was unclear at first whether body mounted accelerometry would yield reliable estimates of flight power. Uncertainty shrouded the fraction of the total biomechanical power being communicated to the body and its potential susceptibility to flight effort, rate of ascent/descent, air speed, air density and so forth. It was also possible that the birds might not utilise energy storage on the forward axis during wingbeat cycles to mask other (vertical axis kinetic and gravitational) energy fluctuations since inefficiencies in forward axis kinetic energy recovery might outweigh the advantages.

In accordance with initial expectations at the outset of the modelling work it transpired that the dominant consideration with regard to flight power is the supply of kinetic energy to the wings which displace air during each downstroke. Correlations with heart-rate power were maximised by discarding all terms except $\ddot{z}_{\mathrm{rms}}^2/f_w$, where $\ddot{z}_{\mathrm{rms}}$ is the rms dorsoventral acceleration and f_w the wingbeat frequency. Adding or subtracting terms involving $\ddot{y}_{\mathrm{rms}}^2/f_w$ was unhelpful, implying that the birds made little use of temporary energy storage on the forward axis. An alternative power estimator term, $g\ddot{z}_{\mathrm{rms}}/f_w$, which modelling efforts suggested was also worthy of consideration, could be dismissed for the geese. Analysis indicated that flight was often executed with a phase lag of approximately 90 degrees between the upward and forward accelerations, in accordance with our theoretical and physiological expectations. This is puzzling, hinting at the option of energy storage and retrieval, even if it might be no more than an evolutionary legacy. Invariably, forward horizontal accelerations were smaller in amplitude than vertical accelerations, compatible with the wings primarily providing weight support as opposed to propulsion.

Using the $\ddot{z}_{\mathrm{rms}}^2/f_w$ estimator for biomechanical power from Paper II, excellent agreement was obtained with rates of oxygen consumption obtained via ecg using the quadratic $\dot{V}_{O_2} \propto f_h^2$ relationship of Paper I. This was especially so in the case of longer duration flights where more data points were available. In fact, the majority of flights exhibited correlations in excess of 90%. High statistical correlations were also observed between wingbeat frequency, rms dorsoventral acceleration and heart-rate, the strongest being obtained between $\ddot{z}_{\mathrm{rms}}$ and f_h. However, were it not for changes in air density with altitude, the correlation between f_w and f_h could well have been superior. Wingbeat frequency can be very accurately estimated using a zero-crossing method presented in Paper IV. In contrast, the derivation of $\ddot{z}_{\mathrm{rms}}$ is prone to various inaccuracies due to changes in the location or orientation of the accelerometer within the abdomen, non-linear oscillations of the accelerometer during each wingbeat cycle due to muscle movements, viscous damping, the challenge of separating the static and dynamic accelerations during banked turns and other manoeuvres, and coping with random gusts of wind from all angles having a power spectrum spanning both static and dynamic frequency bands.

Using a global three-dimensional analysis covering all lengthier flights (N=77) I obtained pairwise relationships between the $\ddot{z}_{\mathrm{rms}}$, f_w and f_h variables. 3D fits were obtained from logarithmically transformed data via principal component analysis. I then pooled results for individual flights for each bird before taking averages across multiple birds. A consistent pattern of behaviour emerged and it was possible to infer a steep exponential relationship in which P_m was approximately proportional to f_w^7. Such a steep power law, which had not been theoretically anticipated or experimentally measured before, implied that the angular travel of the wingbeats varied with wingbeat frequency. Further analysis then indicated that both wingbeat frequency and wingbeat amplitude generally increased in tandem with one another.

Wingbeat frequency was far more vulnerable to changes in altitude and air density than $\ddot{z}_{\mathrm{rms}}$, rising by some 0.1 Hz per vertical km from about 3.78 Hz at sea level. At altitude, the wings must beat more rapidly in order to impart the same momentum to air of reduced density. Even though air of reduced density is more easily deflected, it is difficult to generate the same lift from the same pair of wings in rarefied air. In some instances, flights by the same bird at a similar altitude and time of year showed a marked difference in wingbeat frequency. Although data from additional sensors would be required to confirm the following speculations, this may have either been caused by the presence/absence of flock formation flight or the presence/absence of cloud. Reductions in flight power are possible during formation flight but require synchrony of wingbeat frequencies to those of adjacent birds. Alternatively, condensing humidity within a cloud can load the wings, increasing their effective mass and thereby suppressing wingbeat frequency.

A useful means of detecting examples of environmental assistance during flight was to plot rate of ascent against either heart-rate, wingbeat frequency or dorsoventral acceleration and look for departures from a general trend. For some flights, there was good clustering of the data points but on others, particularly high altitude flights where jet stream disturbances may been influential, it was visibly degraded. For a minority of flights, episodes of environmental assistance/hindrance were clearly witnessed as departures from normality. These events were generally brief, usually occurring in pairs of opposite polarity, with assistance followed by hindrance or vice versa. This is indicative perhaps of crosswinds while flying low across mountain ridges. In terms of the total migratory energy budget, however, it appeared that environmental assistance was almost completely irrelevant.

Heart-rates of 430 bpm could apparently be sustained for several hours. However, heart-rates above 460 bpm tended to cause steep rises in body temperature within minutes, almost irrespective of altitude. This would usually be followed by a sharp reduction in flight intensity. On occasion, cessation of flight occurred during descending flight in which heart-rates were alarmingly elevated, suggesting emergency landings due to strong orographic downdrafts.

A surprising finding was that heart-rates as low as 260 bpm were capable of sustaining horizontal flight near sea level, well below those recorded in wind tunnel work. Analysis of the flight data at low rates of ascent/descent suggested that horizontal flight would demand a heartrate of 459 bpm at 8000m (see Figure 2), a height consistent with daytime sightings by a mountaineer on a windy day (Blume, 1980) when orographic lift may have provided assistance. The night-time honking of geese was also heard from the vague direction of Makalu's summit (altitude 8463m) by a climber walking at 5000m on the Barun Glacier (Swan, 1970). Such romanticised accounts and television documentaries prone at times to extravagant hyperbole have by now convinced many laypeople that bar-headed geese can and regularly do traverse the summit of Everest.

A heart-rate of 430 bpm is estimated to translate to a total metabolic power of 152 W which, for a 23% mechanochemical conversion efficiency, equates to a total biomechanical power of some 35 W (an impressive 14 W/kg). Bar-headed geese are very well-adapted to high altitude flight but they are not entirely in a class of their own. Other birds, such as mallards, steppe eagles, condors and cranes, have also been known to fly at altitudes above 6000m (Fedde et al, 1985). In all, some twenty species of birds are thought to spend a major portion of their lives at altitudes exceeding 4000m (Black & Tenney, 1980).

I was particularly interested to investigate the relationship between flight energetics and altitude, along with the sensitivity of wingbeat frequency to flight power. Careful attention was given to the ascents onto the Tibetan plateau which demanded sustained effort for several hours. This analysis revealed that the geese could conserve energy by a somewhat counter-intuitive strategy of undulating flight which often involved discarding previously hard-won altitude gains only to later recoup them, typically during the same flight. Existing aerodynamic theory had predicted that flight power would scale with air density to the power -0.54 (Pennycuick, 1996) but the global analysis favoured an exponent twice as large. This large discrepancy which, contrary to some misconceptions (Levesque, 2015), was neither previously suspected nor obvious from wind tunnel work, had a profound qualitative impact on the optimal flight strategy. Flight costs increased so rapidly with altitude that the geese could conserve energy by discarding any excess height above the ground at their earliest opportunity. Undulating flight in geese had originally been interpreted simply in safety terms, allowing rapid landings due to e.g. fatigue or changes in weather. Only after it occurred to me to integrate the flight costs along actual and simulated flight paths (almost two years after the first batch of dataloggers were recovered) did it emerge that for typical plateau ascents this peculiar strategy could actually provide energy savings (around 12% in the specific example presented). In contrast, the costs of plateau ascent flights would have *increased* had the expectations of aerodynamicists been upheld, integrating along the actual flight paths. There were no GPS location fixes in this study so there was no way of knowing how high or low above the ground the geese were actually flying at any time. However, that in no way contradicts or invalidates the surprising finding that energy was conserved relative to steady ascent or descent, a conclusion that justifies a general strategy of ground hugging flight for this particular species of goose.

That self-powered flight is possible at all at altitudes resembling the highest mountain peaks is remarkable when one considers that unacclimatised, sedentary humans suffer from symptoms of hypoxia after just ten minutes at 6100m (Tucker, 1972). It would seem that the same is true of mice (Fedde et al, 1985). In contrast, bar-headed geese resting within a hypobaric chamber have endured a simulated altitude of 10,668m without any discernible adverse effects or any perceptible changes in behaviour (Black & Tenney, 1980).

A number of evolutionary adjustments can facilitate high altitude flight (Altshuler & Dudley, 2006; Scott & Milsom, 2006) including high ventilation rates (Tucker, 1968), improved tolerance of respiratory alkalosis (Scheid, 1990), haemoglobin of higher O_2 affinity (Petschow et al, 1977), elevated cardiac output (Black & Tenney, 1980), hormonally induced cardiac hypertrophy during the migratory seasons and tissue enhancements such as greater capillary density and mitochondrial abundance (Fedde et al, 1985).

The results here reaffirm the advantages of triaxial accelerometry as a tool capable of quantitatively estimating flight power with excellent temporal resolution. Its accuracy rivals that obtainable by the heart-rate method whilst offering considerable invulnerability to its intrinsic emotional susceptibilities. Accelerometry also obviates the technical challenges of reliably extracting heart-rate from the noisy electrocardiographic data so typical of self-powered energetic flight at high altitudes. Furthermore, as Paper IV demonstrated, it can be readily collected from a flying bird in a non-invasive manner.

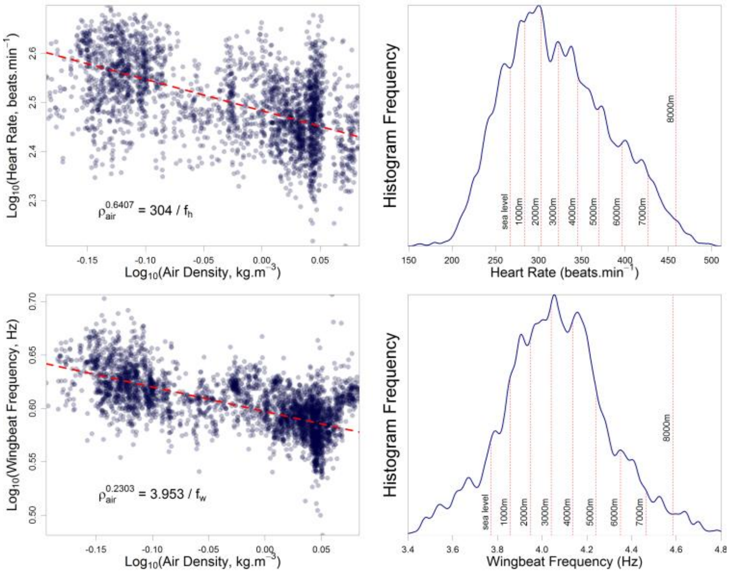

Figure 2. Flight data excluding rates of ascent outside the range ±0.1m/s for three geese that successfully crossed the Himalaya. Trend lines were obtained by iteratively reweighted least squares to converge to a result approximating that of least absolute deviation. Altitudes in excess of 8000m cannot be achieved with heart-rates below 459 bpm. Ascents to higher altitudes seem impractical without significant and sustained environmental assistance.

Paper VI: A cosmological hypothesis potentially resolving the mystery of extraterrestrial silence with falsifiable implications for neutrinos.

The previous articles have touched upon some of the extremes of atmospheric locomotion after several billion years of laboured evolutionary struggle here on Earth, eliciting curiosity in the limits of aerial athleticism elsewhere in the universe. Bodyweight is a significant factor when considering the potential for self-powered exoplanetary flight but the majority of the exoplanets discovered to date have surface gravities greater than Earth's. Hence, it would be useful to first know the range of planetary masses to consider.

Another long-standing complication has been the astonishing lack of evidence for extraterrestrial life, aerial or otherwise. The majority of the stars in the Milky Way resembling the Sun in mass and composition are significantly older than the Earth. SETI has failed to detect any convincing incoming transmissions and its public funding was withdrawn two decades ago. No artefact of alien visitation has ever been discovered anywhere within the Solar System. Yet, according to a recent estimate, the Milky Way alone hosts some 40 billion habitable Earth-like planets (Petigura et al, 2013). It seems incongruous that such a vast and ancient galaxy could be totally devoid of intelligent life. The lack of plausible explanations for this mystery has led to it being colloquially referred to as the '*Fermi paradox*', due to the now legendary bewilderment expressed by the physicist Enrico Fermi, amongst many others (Finney et al, 2000).

Planetary habitability of various forms has been extensively debated in the literature (Lineweaver & Chopra, 2012) but the question of cosmic habitability has gone largely unexplored. This article was the result of contemplating some major outstanding mysteries in cosmology; the remarkable fine-tuning of the laws of physics, the long-standing puzzle concerning extraterrestrial silence and the question of the long-term opportunities for life within the universe. It summarises the outcome of my investigations, describing what appears to be the first falsifiable hypothesis on this topic that, short of brute force exploration or reception of an artificially generated signal from an alien civilisation, can claim to adhere to the scientific method. It yields several testable predictions concerning particle physics beyond the Standard Model which can be put to the test today.

In the distant future, providing dark energy decays to low mass fermions at a suitable juncture, oceanic planets of a mass up to around 15 times that of the Earth could offer remarkably efficient habitats for aquatic lifeforms. More specifically, the 4s electrons of the hexagonally close-packed (hcp) phase of iron present within rocky planets (Stixrude, 2012), could mediate the annihilation of electron neutrinos, converting most of their rest mass energy into bioavailable warmth. This mechanism involves heat percolating from the iron core of a planet through a silicate mantle and crust of hot ice into subglacial oceans. In this way, comfortable liquid environments for aquatic life can be maintained with high efficiency. In essence, oceanic planets would reprocess electron neutrinos into infrared photons, a form of spent energy as far as life is concerned.

By implication, rocky planets containing hcp iron may represent the likeliest locations where the universe might currently be cultivating intelligent lifeforms, a subset of which may eventually serve as interstellar colonists. Unlike previous conjectures attempting to resolve Fermi's paradox, the model does not conform to any conventional category (Hart, 1975). Rather, it is a *cosmological* explanation for the mystery of extraterrestrial silence, one that challenges the diktat within modern science that nature is lacking in purpose, regardless of the accumulating evidence to the contrary (Dyson, 1979).

Although the presence of dark matter was originally inferred through the peculiar gravitational retention of rapidly moving nebulae within galaxy clusters (Zwicky, 1933), concerted efforts to experimentally capture dark matter or study its interactions have since failed. Astronomers have for many years considered the possibility that cold dark matter particles might mutually annihilate within galactic cusps (Stecker et al, 1985; Gondolo & Silk, 1999; Stoehr et al 2003). Despite occasional claims in the literature, it has not yet been convincingly argued that any of the features observed in the electromagnetic spectrum can only be explained by annihilating cold dark matter particles, even though the Fermi Gamma-ray Space Telescope has been operational for seven years now.

Following Zwicky's original deduction that dark matter exists, some eighty years elapsed before it was suggested that its annihilation within oceanic planets might sustain aquatic life (Hooper & Steffen, 2011). This was almost a novel suggestion, appearing just a few days after it had first been proposed on the same research preprint web server (Spivey, 2011). The main developments since that early work have been an appreciation of the importance of dark energy and how two forms of dark matter could have synergistic biological roles.

A particle whose existence was correctly inferred by Wolfgang Pauli in 1930, just a few years before Zwicky realised the need for cluster dark matter, remains today the only dark matter candidate actually known to exist – the neutrino. Evidence that neutrinos possess mass first came from the solar neutrino anomaly which was eventually resolved when they were shown to undergo flavour oscillations (Fukuda et al, 1998). Since then, curious anomalies in oscillation studies have hinted at the existence of sterile neutrinos, somewhat heavier yet highly inert counterparts of the familiar active neutrinos. Recent astronomical evidence supporting this view comes from reconstruction of the mass distribution responsible for the gravitational lensing of the Abell 1689 cluster, which is uniquely compatible with the presence of a condensed halo of 1.5eV fermions

(Nieuwenhuizen, 2009). The inferred mass exceeds cosmological bounds on active neutrinos, but their sterile counterparts (which differ in mass and chirality) are a very plausible match, particularly given the finding that degenerate active neutrinos can efficiently transfer their energy to hcp iron, with sterile neutrinos potentially enabling the continuance of late time heating (Spivey, 2013).

In recent generations, the rate of scientific progress has vastly accelerated due to rapid technological advances. Electrical engineers have devised countless transducers, integrated circuits and instruments capable of measuring natural phenomena with unprecedented detail and precision. The discipline of electronics now harnesses electricity and magnetism for innumerable ends. Whilst design engineers have found many ingenious solutions to problems by manipulating the force of electromagnetism, there has been little industrial demand for engineers skilled in the manipulation of either gravity, the strong nuclear force or the weak interaction. But what might a team of design engineers conversant with all four forces of nature be capable of? A possible answer could be the conceptual design of a simulated life-hosting universe. If at all possible, the configuration of a universe would ideally pay very careful heed to ethical concerns and attempt to safeguard the welfare of the hosted lifeforms.

The laws of physics must be in many respects very finely-tuned to allow for the emergence of complex lifeforms (Barrow & Tipler, 1986; Davies, 2003). The weak anthropic principle demands that the laws of physics be compatible with human presence but it cannot account for an arbitrarily large degree of fine-tuning. If neutrinos, particles hitherto suspected to have no biological importance whatever, can provide an effective long-term solution to the challenge of sustaining life after the stars cease to shine, selectively heating planets containing hcp iron in a thermally regulated manner scaling according to planet mass, the weak anthropic principle is irrelevant. A universe tailored towards aquatic lifeforms would represent another victory for the Copernican Principle responsible for the revolution that overturned the ancient Ptolemaic system.

This hypothesis can also help elucidate the accelerating cosmic expansion driven by dynamical dark energy: time is required during the early universe for planet formation, abiogenesis, evolution and the cultivation of lifeforms sufficiently intelligent to take command of their own biology. Ethical considerations suggest that the widespread provision of habitats would be reckless at this time due to, for instance, the harrowing nature of predation. Carnivorism is virtually unavoidable on any life hosting planet where evolution is still operating. Furthermore, civilisations adept at bioengineering are required to populate dark, anoxic oceans of the future kept warm via neutrino annihilation. Without exception, habitable planets are ultimately purged of all vestiges of life (including subterranean microbial life) as their host stars swell to become red giants. If this is no mere coincidence, the belief that extraterrestrial lifeforms are all currently following Darwinian evolution (Lineweaver & Chopra, 2012) is misplaced. Timing estimates for the future decay of dark energy to neutrinos can be obtained purely via energetic arguments. The results satisfy the demand of allowing ample time for colonist recruitment and galactic mergers within clusters whilst ensuring that some life-cultivating stars remain active until planetary heating by dense neutrino haloes can commence.

This paper models how a strategy of sporadic life cultivation and colonist recruitment could operate. Galaxy mergers within clusters can robustly assure that habitats of the aquatic era are competently colonised. If the universe is thus arranged, the probability with which typical galaxies generate colonising civilisations as a function of time would be rather tightly constrained. Even so, it remains unclear whether ours might be the first technological civilisation of the Milky Way (even ignoring self-destruction scenarios). Had a more advanced civilisation ever appeared here, it would likely have relocated to the neighbouring Virgo galaxy cluster where long-term survival prospects would be vastly improved. Rather counter-intuitively, the absence of evidence for alien life could presently offer the most compelling evidence of a universe expressly configured to efficiently sustain life – and one that is currently very much in its infancy.

Should neutrinos continue to bear the hallmarks of cosmic design once their properties have been more accurately determined, focus would naturally shift to the question of how the decay of dark energy to active neutrinos might proceed. Although a definitive answer cannot be given at this stage, a brief critique of some relevant facts might highlight some options worthy of further scrutiny.

The targeted delivery of neutrinos to galaxy clusters could be strategically advantageous to the welfare of future aquatic lifeforms. A dense neutrino halo might function as an energy source for around 10^{25} years but the scavenging of neutrinos by a gargantuan black hole produced via coalescence following galaxy mergers could considerably foreshorten that timescale. This is hard to reconcile with planetary heating being almost 99% efficient during the early universe. Moreover, black hole thermodynamics indicates that the entropy of a black hole is colossal, being a quarter of the event horizon area in Planck units. Thus, the combined entropy of all the stars in the visible universe could be eclipsed by just one supermassive black hole. The second law of thermodynamics insists that entropy is a non-decreasing function of time but energy is generally/always conserved. Thus, it may be better to interpret the efficiency of planetary heating by neutrinos in terms of entropy management than energetic economy. If so, the squandering of entropy on black holes could be strategically catastrophic.

Originally referred to as ‘frozen stars’ (Landau & Lifshitz, 1975), the term black hole was coined in an attempt to popularise a number of solutions to the equations of general relativity. However, event horizons cannot be observationally detected

(Abramowicz et al, 2002). It has been said that the scientist must guard against becoming the "dupe of his own definitions" and discovering "creations of his own caprice" (Poincaré, 1905). The notoriously stubborn black hole information paradox (Susskind, 2008) can be traced to the common expectation that physical information will permanently disappear on entering a black hole. Furthermore, any classical rotating (Kerr or Kerr-Newman) black hole possesses closed timelike curves within their event horizons. It is difficult to conceive of a clearer signal that a physical theory has been extended beyond its range of validity than the abandonment of causality: without it physics can describe nothing.

A less widely appreciated difficulty, inspired by astronomical observations, is the apparent violation of topological censorship (Friedman et al, 1993) implied by the curious characteristics of quasars (Spivey, 2000; Pompilio et al, 2000). Electrically charged toroidal black holes accreting plasma would be expected to generate ultrarelativistic streams of charged particles, stably aligned with their axis of rotation. The poloidal magnetospheres of these black holes would provide stiff resistance to charge neutralisation, electromagnetism being far stronger than gravity. However, the sealing of the central aperture as accretion gradually subsides would cause a topological transition that abruptly eradicates this defence. With flux lines suddenly leading directly towards the black hole, accreting plasma could spiral along lines of magnetic flux, swiftly neutralising the black hole. This could naturally account for the finite lifetime riddle of active galactic nuclei despite the ample supply of free gas in low redshift galaxy clusters. The simple alternative of gas starvation is now ruled out (Hopkins & Hernquist, 2008). An earlier model of quasar energetics (Blandford & Znajek, 1977) relied on strong magnetisation of a primordial accretion disk largely composed of hydrogen and helium, an assumption understandably regarded as contentious (Ghosh & Abramowicz, 1997; Livio, Ogilvie & Pringle, 1999).

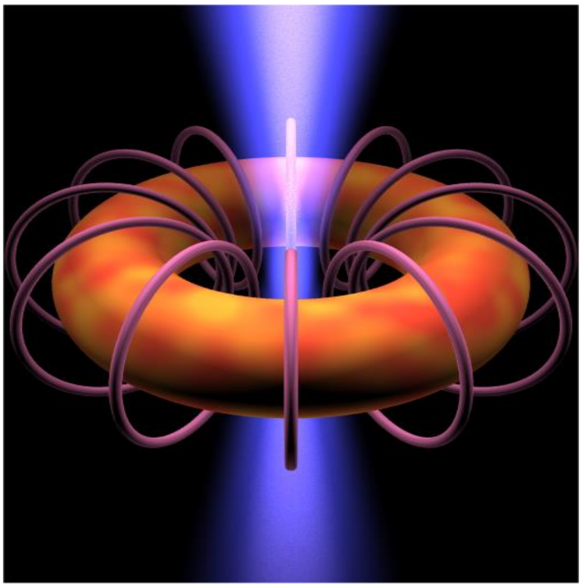

Figure 3. A depiction of a poloidal field generated by an electrically charged toroidal black hole stabilised by rotation. Plasma from a surrounding accretion disk is siphoned into the central aperture, spiralling along flux lines. Only near the axis of rotation do lines of magnetic flux lead directly away from the black hole. This severely constrains the directions in which escaping charged particles can travel, thereby eludicating the origin of the biaxial jets associated with quasars. When the torus eventually collapses, the flux lines then lead directly to the black hole, allowing the otherwise curious extinction of quasar activity during the early universe to be understood.

According to external observers, infalling matter hovers indefinitely above the event horizon of a black hole (Misner et al, 1973). The architect of general relativity considered this reason enough to dismiss notions that black holes ever form in nature (Einstein, 1939). He expressed this physical intuition long after the discovery of a spherically symmetric metric (Schwarzschild, 1916) describing a stagnant black hole spacetime. The dynamical 'formation' of a black hole was first described in a seminal work that same year. It showed that, from any exterior perspective, the event horizon of a (worst case) spherical black hole takes an aternity to form (Oppenheimer & Snyder, 1939). Although time is a relative concept, the relative rate of passage of time between two worldlines is well-defined in general relativity providing they both remain exterior to a black hole's event horizon. As one worldline penetrates the event horizon, however, the ratio first grows without limit and then becomes undefined, consistent with the impossibility that proper time or distance along any worldline can become transfinite. Since the satisfaction of this requirement cannot be guaranteed by Einstein's field equations alone, there is a need to exercise caution whenever the solutions to those equations exhibit event horizons. The singularity theorems and topological censorship apply only to spacetimes possessing trapped surfaces. Thus, evidence from quasars that toroidal black holes are stable structures suggests that these structures do not literally possess event horizons.

Black hole evaporation processes (Hawking, 1975) generate purely thermal radiation, lacking in information content, and are far too slow to eliminate the risk of neutrino confiscation. The mechanism underlying Hawking radiation is an acceleration-related effect in quantum field theory (Unruh, 1976). The temperature of the vacuum is observer-dependent, being proportional to the acceleration perceived, $T = \hbar a/2\pi c k_b$. Accelerations approaching the Planck scale, $\sqrt{c^7/\hbar G} \sim 10^{52}$ m·s^{-2} might arise deep within a frozen star lacking an event horizon. That could give rise to significant Unruh radiation at a power level approaching the Planck scale, $c^5/G \sim 10^{53}$ W. Such radiation could conceivably discharge the energy of the vacuum, i.e. dark energy, on a timescale comparable to stellar lifetimes, bringing a timely end to accelerating cosmic expansion.

Reminiscent of the extreme conditions within core collapse supernovae (Woosley & Janka, 2005), radiation is most likely to emerge from a high density environment in the form of weakly interacting neutrinos. Escaping from a minuscule region of extreme time-dilation deep within a frozen star or incipient black hole (Vachaspati et al, 2007), the formation of neutrino haloes, virtual from the 'dark hole' perspective but nonetheless functional, could ensue. With gravitational confinement from the surrounding galaxy, the haloes would be supported by degeneracy pressure. Given these various considerations one wonders whether, in the years following Einstein's departure, the dismissal of his misgivings concerning objects with event horizons may have been overly hasty.

Summary of contributions

Paper	Authors & Title	Contributions
I	C.Bishop & R.Spivey. *Integration of exercise response and allometric scaling in endotherms.*	Development of a quantitative model that unified the cardiovascular response to exercise with an allometric relationship. Statistical analysis of raw data to confirm the utility of 3 and 4 variable power laws. Conception and generation of figures. Providing assistance with the writing of the manuscript. Fielding referee comments.
II	R.Spivey & C.Bishop. *Interpretation of body-mounted accelerometry in flying animals and estimation of biomechanical power.*	Signal processing of preliminary data from pigeons. Mathematical analysis of the biomechanics of flapping flight. Derivation of expressions for body power during flight based upon decomposed rms accelerations. Manuscript preparation and generation of all figures. Fielding comments obtained during peer review.
III	R.Spivey & C.Bishop. *An implantable instrument for studying the long-term flight biology of migratory birds.*	Electronic design of the instrument and the writing of the firmware in C and assembly language. Processing and analysis of data collected. Description of the design methodology and preparation of a firmware flowchart and system block diagram. Writing of the manuscript.
IV	R.J.Spivey, S.Stansfield & C.M.Bishop. *Analysing the intermittent flapping flight of a Manx Shearwater, Puffinus puffinus, and its sporadic use of a wave-meandering wing-sailing flight strategy.*	Design of an interface board for custom configuration of the GPS modules deployed. Recovery, processing and analysis of recovered GPS and accelerometry data. Description of techniques for processing accelerometry in birds that intermittently flap their wings. Evaluation of the flight of the Manx Shearwater over a turbulent sea in windy conditions and identification of a strategy by which it can harvest energy from the environment. Generation of all figures. Writing of the manuscript and fielding of referee comments.
V	Bishop, Spivey, Hawkes, Batbayar, Chua, Frapell, Milsom, Natsagdorj, Newman, Scott, Takekawa, Wikelski & Butler. *The roller coaster flight strategy of bar-headed geese conserves energy during Himalayan migrations.*	Design of instruments used (Paper III). Processing and analysis of collected data. Testing of two theoretical approaches to flight power estimation (Papers I and II). Discovery that flight power is exquisitely sensitive to wingbeat frequency and increases far more steeply with altitude than anticipated. Analysis of long-range flights showing that, contrary to prevailing theory, discarding hard-won height gains is usually an effective strategy for energy conservation when traversing mountainous terrain. Preparation of all figures. Assisting Dr. Bishop with the writing of the manuscript as co-lead author.
VI	R.J.Spivey. *A cosmological hypothesis potentially resolving the mystery of extraterrestrial silence with falsifiable implications for neutrinos*	I was the sole author of this work which describes an evidence-based cosmological model capable of reconciling the intriguing fine-tuning of the natural constants with the bewildering lack of evidence for extraterrestrial life. Manuscript preparation included physical calculations, sociological modelling of colonist recruitment, figure generation and the logical induction of an ethical cosmic strategy for life from diverse data.

Chapter 3: The Astrobiology of Flight

Research on bar-headed geese was perhaps initially stimulated by interest in the question of whether these birds might actually be capable of reaching the summit of Everest, as it were, ‘under their own steam’, a possibility which has occasionally been alluded to (e.g. Swan, 1970). Although Everest is the world’s highest pinnacle, flight may be more difficult at sea level on planets with a more rarefied atmosphere and/or a greater surface gravity. There is therefore a need for a way to compare the feasibility of flight in different astrobiological settings.

Paper I showed both theoretically and empirically that, with knowledge of heart and body masses, heart-rate can be used to obtain reasonably accurate estimates of instantaneous metabolic rate in endotherms of a similar body temperature. Whether aerial, aquatic or terrestrial, the animals studied closely conformed to a general, unified, relationship during primary mode locomotion.

In Paper II a theoretical model was developed facilitating the estimation of the biomechanical costs of continuous flapping flight from a body-mounted triaxial accelerometer under certain simplifying assumptions. The technique was intended primarily for birds that flap their wings continuously and can be applied whether or not the transducer orientation is fixed, providing reorientation only occurs at frequencies below the beating of the wings.

Paper III described the design of instruments whose electronics was capable of simultaneously capturing the data required by both of the techniques described in the first two papers. Optimised for both size and weight reduction, it was small enough to be implanted into the abdomen of a goose with a battery life capable of recording annual migrations.

In Paper IV these instruments were deployed on birds that are adept at harnessing environmental assistance, whenever available. A technique for accurately measuring wingbeat frequency after Fourier processing was described, and its advantages over an existing method quantified. The versatility of the accelerometry technique was demonstrated, even in a species that beats its wings intermittently. Details of a meandering wind and wave exploitation strategy were teased from the data. It appears that Manx Shearwaters can, even in moderate prevailing winds, reduce their long-range foraging costs approximately three-fold by dynamically interacting with deflections of atmospheric airflow across an undulating sea surface.

Paper V built upon the previous works, analysing data collected from the implantable instruments after recapture from geese migrating towards and across the Himalaya. Excellent correlations were obtained between instantaneous power estimates independently obtained by the heart-rate and accelerometry techniques. The tendency of flight power to increase more rapidly with altitude than theoretically anticipated was used to demonstrate the viability of a ‘roller-coaster’ flight strategy over undulating terrain. It was also found that unrealistically high heart-rates are needed for bar-headed geese to fly at altitudes above 8000m, unless significant environmental assistance is available. Some continuous sections of flight lasted over 24 hours. A day’s migratory flight can demand 11 MJ, equivalent to the energy an efficient climbing animal of identical body mass would need to scale a ladder tall enough to reach the notional Kármán line – an altitude 100 km above the Earth’s surface regarded as the threshold of outer space.

Paper VI presented a novel cosmological framework within which the absence of evidence for extraterrestrial life need no longer be regarded as paradoxical, despite the vast size and age of the Milky Way. It nevertheless suggests that many planets in our galaxy are likely to host complex life, primarily rocky Earth-like planets containing hcp iron whose outer electrons are potentially receptive to the annihilation energy of degenerate neutrinos. In an astrobiological context, this implies that rocky planets of up to 15 Earth masses are the likeliest sites for the cultivation of intelligent life at the present time.

Collectively, the articles presented here help address the following question: on what subset of habitable planets would the Earth’s most athletic birds be capable of atmospheric propulsion? Alternatively stated, what criteria need to be satisfied in order that exoplanets might be host to flying animals and can a practical definition of a Habitable Flying Zone (HFZ) be derived?

Animals that fly tend to impose more restrictive demands on their environments than those employing other modes of locomotion. Since the evolution of neutral buoyancy is trivially accomplished, aquatic lifeforms are likely to be immune to changes in planetary gravity. Surface dwelling creatures support their own weight courtesy of direct contact with the ground and their skeletal framework will be adapted to their local gravitational fields. The weight a leg bone can support is proportional to its cross-sectional area. The human femur is about 40mm in diameter so a leg bone diameter of 90mm should suffice for bipedal animals on planets whose surface gravity is five times that of the Earth’s. Additional limbs can also assist with weight support in higher gravity environments. There may be some postural costs for a standing animal but these can be dwarfed by the weight support costs of a flying animal. This analysis is primarily concerned with super-Earth planets up to 15 times the mass of the Earth for the reasons discussed in Paper VI. This is large enough to encompass the majority of rocky exoplanets and all those whose internal pressures are compatible with the presence of hcp iron at their cores.

Birds are not only generally more tolerant of hypoxia than mammals but also less vulnerable to the adverse effects of hyperventilation (Black & Tenney, 1980).

Avian lungs utilise a cross-current airflow assisted by a complementary vasculature allowing for efficient gas exchange, advantageous during high altitude flight where the partial pressure of oxygen is reduced (Scott, 2011). A single base-pair mutation converting the amino acid proline to alanine is responsible for the unusually high oxygen affinity of haemoglobin in bar-headed geese (Weber et al, 1993). This analysis concerns exoplanets with breathable atmospheres, the exact chemical composition of which is of secondary concern. One can envisage efficient flow-through breathing arrangements, similar perhaps to the way fish obtain oxygen when swimming by the passage of water through their gills. The mechanical costs of respiration may therefore be largely avoidable, though there may be some additional aerodynamic drag to overcome.

Despite their need to migrate at high altitudes, it has been pointed out that both wing morphology and wingbeat frequency of bar-headed geese are not appreciably altered compared to lower altitude species (Lee et al, 2008). Perhaps this can be understood because, due to the months spent in India each winter, they must also regularly take-off and fly in the dense air encountered near sea level. Their wings must therefore be strong enough to cope with the same dense air as lower altitude geese encounter. Conversely, flying animals on worlds of higher surface gravity may not need to fly over a wide range of altitudes since the stronger gravity would tend to swiftly erase topographical features such as mountain ranges. It is possible that some alien lifeforms might be capable of flying over Everest but that their wings would be too large and fragile to permit flight and especially take-off nearer sea level on this planet.

Flight Power and Athleticism

Scaling laws applicable to flight have been extensively discussed over the years (Pennycuick, 1968; Peters, 1983; Schmidt-Nielsen, 1984; Pennycuick, 1992; Pennycuick, 2008). This analysis shall focus mainly on flying animals capable of supporting their own weight in still air conditions, building upon an established result from aerodynamic theory pertaining to hovering flight (Pennycuick, 2008). If a bird's wings have combined area A_{wing} and the air they sweep is on average accelerated to a downward velocity v_a then the volume of air being swept in unit time is $v_a A_{wing}$. In an atmosphere of density ρ, the mass of air being accelerated from rest to velocity v_a per unit time is $\rho v_a A_{wing}$ and so the rate of change of momentum in the air is $\rho v_a^2 A_{wing}$. For a bird of body mass m_b, Newton's second law requires that this equals the bird's body weight $m_b g$. This allow the downward velocity of the air to be obtained as $v_a = \sqrt{m_b / \rho A_{wing}}$. The power required during hovering is simply the rate at which kinetic energy is imparted to the air

$$P_{hov} = \frac{\rho A_{wing} v_a^3}{2} = \frac{1}{2}\sqrt{\frac{m_b^3 g^3}{\rho A_{wing}}}$$

We are primarily concerned here with the feasibility of flight as opposed to the possibility of rapid aerial locomotion. Considering also the possibility of wind assistance, the limit of relatively low airspeeds is applicable in which only a small fraction of the power relating to forward horizontal flight, P_f, is required to overcome the drag associated with forward motion. In such circumstances one would expect P_f and P_{hov} to scale similarly.

If avian anatomy scales isometrically (an assumption revisited shortly) and one assumes linearity of body volume and body mass (i.e. constant body density) then $A_{wing} \propto m_b^{2/3}$ and

$$P_f \propto \left(\frac{m_b^7 g^9}{\rho^3}\right)^{1/6}$$

A density term reflecting body composition could be used to convert this proportionality to a dimensionally valid equation but it is customary in discussions of biological scaling laws to use proportionalities for simplicity. For an individual animal whose body mass does not vary significantly during flight this further reduces to $P_f \propto \sqrt{g^3/\rho}$, a term which concisely encapsulates the relevant environmental conditions. Thus, flight becomes more challenging on planets with stronger gravitational fields and reduced atmospheric densities, as expected (Altshuler & Dudley, 2006). On Earth, the value of $\sqrt{g^3/\rho}$ at sea level is 27.7 $m^3s^{-3}kg^{-1/2}$. The ability to fly when $\sqrt{g^3/\rho} \geq 27.7$ $m^3s^{-3}kg^{-1/2}$ is therefore what delineates flying birds from flightless birds.

Departures from isometry are likely (Rayner, 1985; Rayner, 1998; Rayner, 2001) and the allometrically neutral relationship $A_{wing} \propto m_b^{2/3}$ is only marginally compatible with empirical data – actual wing measurements suggest that $A_{wing} \propto m_b^{0.780 \pm 0.112}$ (Hedenstrom, 2008). This implies the following modification involving the exponent $\alpha = 0.11 \pm 0.056$,

$$P_f \propto m_b^{1+\alpha}\sqrt{g^3/\rho}\,.$$

Since $\alpha > 0$, mass-specific flight power, P_f/m_b, generally increases with body mass in accordance with theoretical expectations (Pennycuick, 2008). Due to experimental complications, this has yet to be confirmed by empirical data drawn from a range of species. This analysis proceeds by defining flight athleticism, χ, with reference to the mass-specific power needed to fly horizontally in still air according to the expression

$$\chi = \left(\frac{m_b}{\widetilde{m}}\right)^{\alpha} \sqrt{\frac{g^3}{\rho}}$$

where $\widetilde{m}$ is a fiducial mass term used for normalisation purposes and can be arbitrarily chosen. In particular, heavier animals capable of flight in hypodense air would score well on this measure and have thus come under the most evolutionary pressure to be both anatomically and physiologically well-adapted to flight. Aerodynamic drag is of less concern to large birds, in keeping with the earlier assumption that $P_f \propto P_{hov}$.

Aeronautical Extrema

At least three species of bird appear to be capable of entirely self-powered flight at altitudes exceeding 7000m, bar-headed geese being an iconic example. Despite a body mass placing them in the 98th percentile of bird species (Codron et al, 2013), multiple individuals have been observed flying in formation at almost 8000m by mountaineers climbing the Annapurna massif (Blum, 1980). Alpine choughs, *Pyrrhocorax graculus*, also inhabit the Himalaya. Nesting as high as 6500m, there are reports of them following climbers on Everest at altitudes approaching 8200m – within the mountaineering ‘death zone’.

Small birds such as choughs readily take to the air but swans are much larger and typically require 15-20 forceful wingbeats to become aloft when taking off from water, even though they can obtain some acceleration and weight support by patting the water with their webbed feet. On becoming airborne they continue to gain speed and gradually start to ascend, which necessitates continued effort (Tobalske & Dial, 2000). Thus, unlike smaller birds for which a period of anaerobic exertion is adequate for take-off, swans require considerable aerobic athleticism at the commencement of most flights. This applies also to juveniles – cygnets only start to fly at 4–5 months of age. The athleticism demanded by take-off may confer upon swans an ability to sustain high altitude flight, even if they are not ecologically coerced to do so. Lowland species may be incapable of take-off in hypodense air but that does not preclude, per se, an ability to fly high – even though swans tend not to fly high during migration (Pennycuick et al, 1996). In still air conditions, flying low in dense air facilitates flight and, as paper V shows, can also conserve energy even if this strategy incurs additional costs when height must be regained. However, strong tailwinds capable of drastically curtailing migration times and total energy expenditure are sometimes available, especially after ascending to higher altitudes. During lengthier migratory flight, the additional costs of ascent and high altitude cruising can easily be recovered in the presence of a favourably-oriented wind. In the cold and featureless seascape of the north Atlantic, which is neither conducive to the generation of strong thermals nor orographic updrafts, a large flock of whooper swans, *Cygnus cygnus*, was once detected by radar then visually identified by a pilot to be flying at 8200m with a ground speed of 38 m s^{-1} towards the end of a ~1000 km migration (Stewart, 1978, see also Liechti & Schaller, 1999).

The air density at 8200m is 0.513 kg m^{-3}. Setting $\tilde{m} = m_w = 11$ kg, the mass of a whooper swan, and making allowances for variations in α, the maximum value of χ at which flight is possible at this altitude is 42.8 m^3 s^{-3} kg$^{-1/2}$ (whooper swans), 34.1-39.8 m^3 s^{-3} kg$^{-1/2}$ (bar-headed geese) and 22.4-34.6 m^3 s^{-3} kg$^{-1/2}$ (Alpine choughs). Results for various species are presented in Figure 4. Whooper swans appear to top the list for avian athleticism, making them well-suited for astrobiological extrapolations. To compete, bar-headed geese would need to be capable of flight at altitudes of 9433-11704m, which seems unrealistically high even for well-conditioned individuals (Paper V).

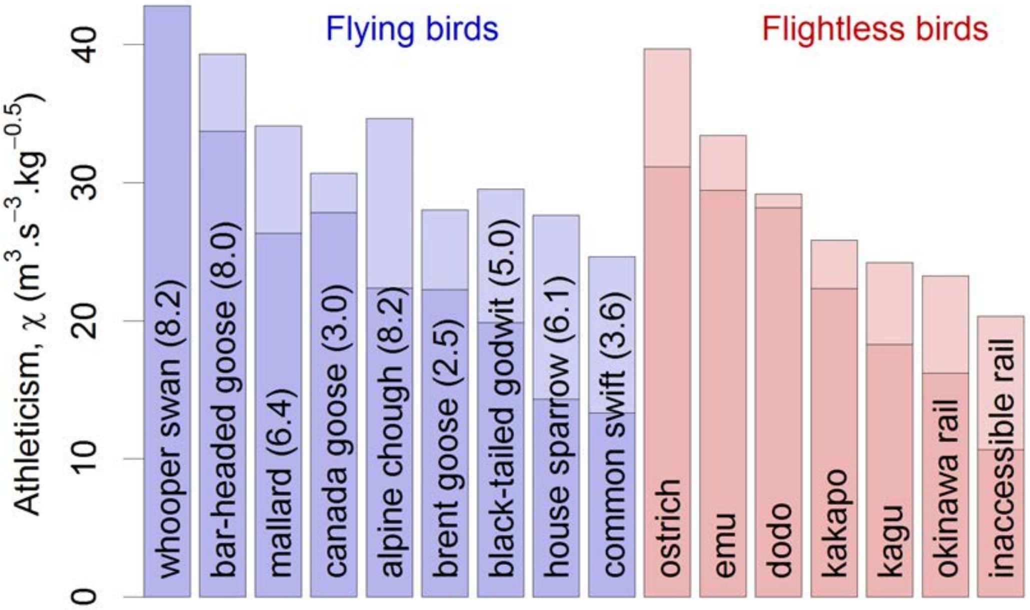

Figure 4. Flight athleticism, χ, for various species. Estimated maximum flight altitudes are given in km (in parentheses) for unassisted flight. Results are also provided for selected flightless birds under the optimistic assumption that they might be capable of flight in slightly denser air than the Earth provides. Lightly shaded areas represent the uncertainty in the allometric scaling exponent, 0.054< α < 0.166, using a fiducial mass of $\tilde{m} = 11$ *kg.*

Planetary Environments

Space telescopes are now simultaneously monitoring thousands of stars for changes in brightness during planetary transits (Marcy et al, 2014). Gravitational microlensing searches imply that the majority of the Milky Way's stars harbour planets (Cassan et al, 2012). NASA's Kepler mission has to date identified over 3500 planets, finding a bias towards smaller planets of 1–2 Earth radii (1 to 12.5 Earth-masses) orbiting about one in five stars within the CHZ (Petigura et al,

2013) implying that the Milky Way is probably home to around 40 billion habitable planets.

The 5 Earth-mass exoplanet Gliese 581c is thought to have a radius 1.5 times that of the Earth's (Valencia et al, 2007), consistent with the mass-radius relationship $R/R_{Earth} = (M/M_{Earth})^{0.274}$ which has been suggested for dense terrestrial planets (Sotin et al, 2007). Since gravity obeys an inverse square law relationship, this would imply that surface gravity, g_s, scales with planet mass as $(M/M_{Earth})^{0.452}$. The surface gravity for a 5 Earth-mass planet would therefore be $2.07g$ whereas that of a 15 Earth-mass planet would be $3.4g$. On Earth, a whooper swan can fly in air of density as low as $\rho_w = 0.513$ km m^{-3}. Since athleticism is not an environmental variable, the minimum air density required by whooper swans on other planets is $\rho_{min} = \rho_w(M/M_{Earth})^{1.356}$. For a 15 Earth-mass planet, $\rho_{min} = 20.18$ kg m^{-3}.

One would expect that on evolutionary timescales, a breathable atmosphere on a super-Earth planet would be invulnerable to '*Jeans escape*' (Jeans, 1925; see also Gross, 1974). This is not the case for planets of very low mass, which can rapidly lose their atmospheres due to random thermal collisions being better able to impart escape velocities to the particles. Non-breathable lighter gases, such as helium and diatomic hydrogen, are more vulnerable to escape. This is why they are only present in the Earth's atmosphere in very low concentrations.

The Earth's oceans cover an area of 362 million km^2 – some 71% of its entire surface area (total 511 million km^2). The mean ocean depth is 3682m (Charette & Smith, 2010) so the total volume of the Earth's oceans, V_O, is 1.33 billion km^3. It is interesting to consider Earth-like analogues with a very similar water fraction to the Earth so that ocean volume scales with planet mass, $V \propto M$. Earth is predominantly covered in water and little land would remain if the water fraction were to double. Therefore, to a reasonable approximation, any additional water is here taken to be evenly distributed over the entire surface area of the planet. In such circumstances, the relative increase in sea level, Δd, of a super-Earth's oceans with respect to Earth's would be:

$$\Delta \mathrm{d} = \frac{V_O}{4\pi R_{\mathrm{Earth}}^2}\left[\left(\frac{M_{\mathrm{Earth}}}{M}\right)^{0.452} - 1\right]$$

If, instead, water were to be delivered entirely through cometary bombardment and, furthermore, one assumes that the spatial density of comets is largely independent of galactic location then the water fraction will scale with the cross-sectional area of a planet, $V \propto A \propto R^2 \propto M^{0.548}$. In this case ocean depth would not vary at all with planet mass. The results for $V \propto M$ are plotted in Figure 5. For a 5 Earth-mass planet, $\Delta\mathrm{d} = 4.32$ km, and the water fraction would be roughly doubled. From Figure 6, one would then expect some small islands to remain. However, for a 15 Earth-mass planet ($\Delta d = 6.24$ km) only a small number of mountain peaks would evade submersion.

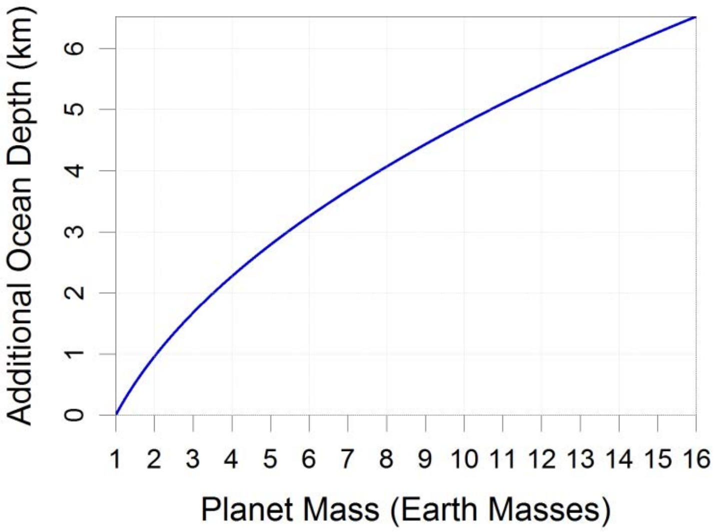

Figure 5. Super-Earth planets with an identical water fraction to the Earth would have correspondingly deeper oceans. The influence this would have on the Earth's land masses can be assessed by referring to Figure 6. Note, however that no change in ocean depth would be expected if water were delivered to planets entirely by cometary bombardment because the water fraction would then be proportional to planet area rather than planet mass.

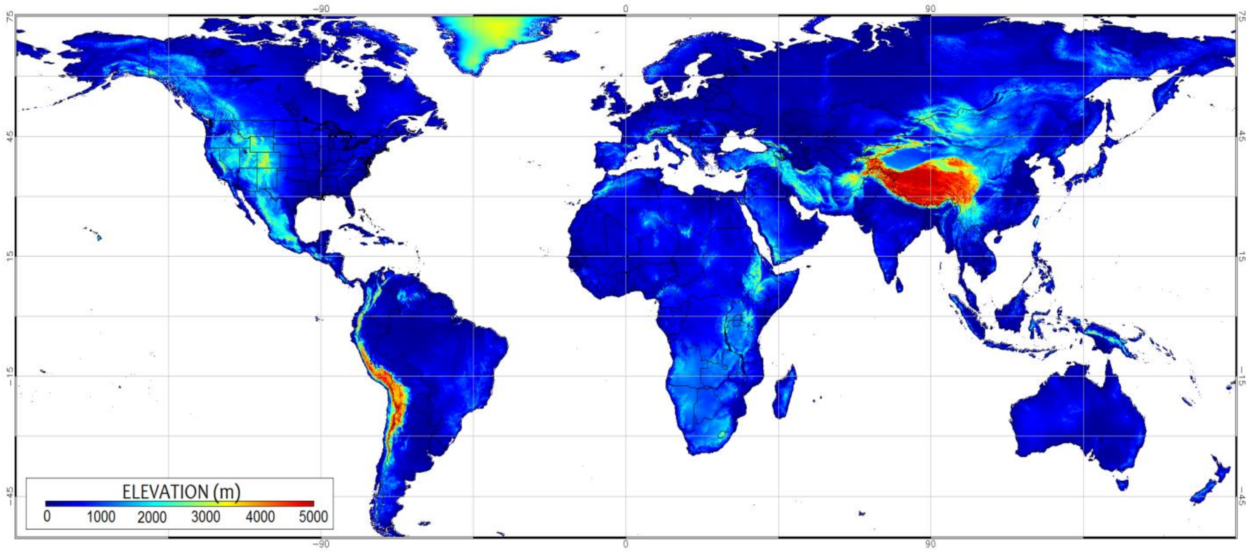

Figure 6. Global elevation data for the Earth highlights the formidable barrier to seasonal migration represented by the Tibetan plateau and the Himalayas. This map also shows that some land would remain if water from comets and asteroids were to result in a doubling of the Earth's water fraction. Data courtesy of NOAA.

As with discussions of circumplanetary habitable zones, some simplifying assumptions will be helpful here. Due to uncertainties such as cloud cover, humidity levels and fluctuations in atmospheric heating due to planetary rotation, an isothermal atmospheric model is adopted. In hydrostatic equilibrium the ideal gas law predicts that air density, ρ, is proportional to air pressure. According to the International Standard Atmosphere, the constant of proportionality, $\beta = p/\rho$, has a value of about 82714 m^2 s^{-2} for a temperature of 15ºC at sea level (ρ=1.225 kg m^{-3}). Gravity is taken to be insensitive to changes in altitude, z. By considering the weight of a thin horizontal layer of air,

$$\frac{dp}{dz} = \frac{dp}{d\rho} \times \frac{d\rho}{dz} = \beta \frac{d\rho}{dz} = -\rho g_s.$$

The air density at height h is obtained by integration from $z = 0$ to $z = h$

$$\beta(\ln \rho - \ln \rho_s) = -g_s h$$

where ρ_s represents the surface air density. Thus, $\rho = \rho_s e^{-g_s h/\beta}$ and the total mass contained by the atmosphere below height h is

$$M_h = 4\pi R^2 \int_0^h \rho(z)dz = 4\pi R^2 \rho_s \int_0^h e^{-g_s z/\beta} dz = \frac{4\pi\beta\rho_s R^2}{g_s}\left(1 - e^{-\frac{g_s h}{\beta}}\right).$$

M_h converges as $h \to \infty$ to yield the total mass of the entire atmosphere,

$$M_{\text{atm}} = \frac{4\pi R^2 \rho_s K}{g_s}.$$

For an isothermal atmosphere, under the assumption of spherical symmetry, half the air mass lies below a scale height, $\hat{\mathrm{h}}$, given by

$$\hat{\mathrm{h}} = \frac{\beta \ln 2}{g_s} = \frac{\beta \ln 2}{g_{Earth}}\left(\frac{M_{Earth}}{M}\right)^{0.452}$$

This expression is entirely independent of ρ_s. Plots of surface gravity, planetary radius and atmospheric scale height against planetary mass are provided in Figure 7. Everest’s summit is well above the Earth’s atmospheric scale height. According to the International Standard Atmosphere, the air density becomes half that at sea level at 6700m, an altitude at which it had been formerly considered unlikely that a bird could sustain flight (Pennycuick, 2008).

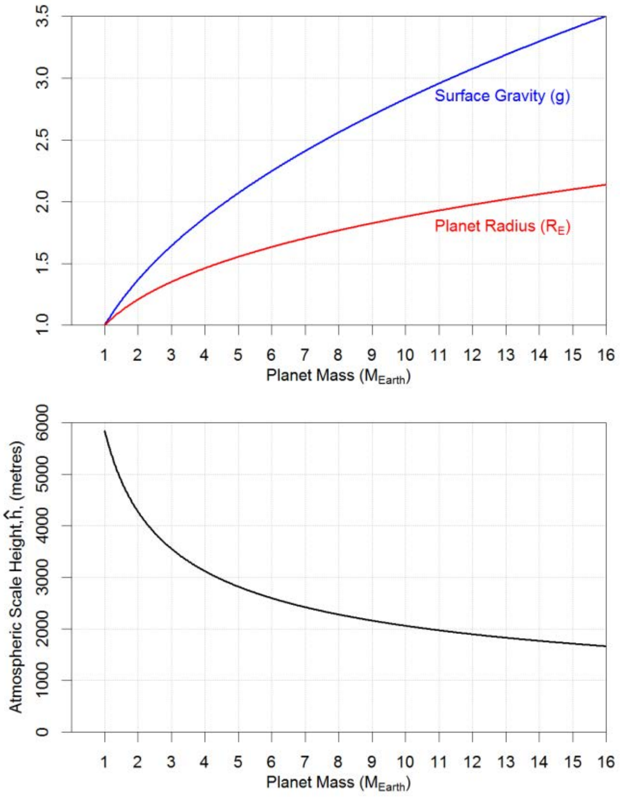

Figure 7. The upper plot shows how surface gravity (blue) and planet radius (red) are expected to vary (with respect to the values for Earth) with planet mass for terrestrial planets. The lower plot depicts the atmospheric scale height $\hat{h}$ *for super-Earth planets, showing that higher gravity tends to compress the atmosphere.*

As Figure 7 indicates, although super-Earth planets have high gravitational fields making weight support more difficult for flying animals, this can be partially offset by their enhanced confinement of an atmosphere above a planetary surface, flight being assisted by denser air. Venus, a planet of lower surface gravity than the Earth, has a very much denser atmosphere, $\rho_s = 65$ kg/m^3. However, even in the case of Venus, an animal whose density is comparable to water would hardly benefit at all from the small buoyancy effect of the thicker atmosphere.

A Definition of Aerial Habitability.

From the earlier expression for M_{atm}, we have $\rho_s = g_s M_{atm}/4\pi\beta R^2$. Using $g_s \propto M^{0.452}$ and $R \propto M^{0.274}$,

$$\rho_s = \frac{g_{Earth} M_{atm} (M/M_{Earth})^{0.452}}{4\pi\beta R_{Earth}^2 (M/M_{Earth})^{0.548}} \propto M^{0.904}\left(\frac{M_{atm}}{M}\right).$$

Clearly, at a fixed atmospheric fraction, the surface air density scales as $M^{0.904}$. Since $g_s \propto M^{0.452}$, we also have

$$\frac{g_s^3}{\rho_s} = \frac{4\pi\beta R_{Earth}^2 \left(\frac{M}{M_{Earth}}\right)^{0.096}}{g_{Earth} M_{atm}} \left[g_{Earth}\left(\frac{M}{M_{Earth}}\right)^{0.452}\right]^3$$

$$\frac{g_s^3}{\rho_s} = \frac{4\pi\beta R_{Earth}^2 g_{Earth}^2}{M_{atm}} \left(\frac{M}{M_{Earth}}\right)^{1.452}$$

$$\sqrt{\frac{g_s^3}{\rho_s}} = \gamma \left(\frac{M}{M_{Earth}}\right)^{0.226} \sqrt{\frac{M}{M_{atm}}}$$

The constant γ is equal to $2g_{Earth}R_{Earth}\sqrt{\pi\beta/M_{Earth}}$ and has a value of about 0.026 m^3 s^{-3} kg$^{-1/2}$. This result will be useful later.

The maximum mass of a planet at which a swan can fly at zero altitude can be obtained by requiring that ρ_{min} and ρ_s be equal, giving $\rho_w(M/M_{Earth})^{1.356} = \rho_{Earth}(M/M_{Earth})^{0.904}$. Thus, for an isoatmospheric planet (i.e. one whose M_{atm}/M ratio is identical to that of the Earth) the limiting planet mass compatible with a flying whooper swan is

$$\frac{M}{M_{Earth}} = \left(\frac{\rho_{Earth}}{\rho_w}\right)^{1/0.452} \approx 6.86\ M_{Earth}.$$

The surface gravity of a planet of this mass would be $2.388g$ and the surface air density would be 6.985 kg m^{-3}.

Since $P_f \propto m_b^{1+\alpha}\sqrt{g^3/\rho}$ and $\rho_s \propto M^{0.904}$, the flight power at zero altitude on isoatmospheric planets scales as $P_f \propto M^{0.226}$. Because surface gravity scales as $M^{0.452}$ one can write $M/M_{Earth} = (g_s/g_{Earth})^{1/0.452}$ from which it is apparent that $g_s/g_{Earth} = \rho_{Earth}/\rho_s$ for the limiting planet mass. Therefore, for isoatmospheric planets, there exists a simple relationship, $\rho_{eq} \propto 1/g_s$, allowing translation of surface gravity to the Earth-equivalent air density and hence altitude via the International Standard Atmosphere – see Figure 8.

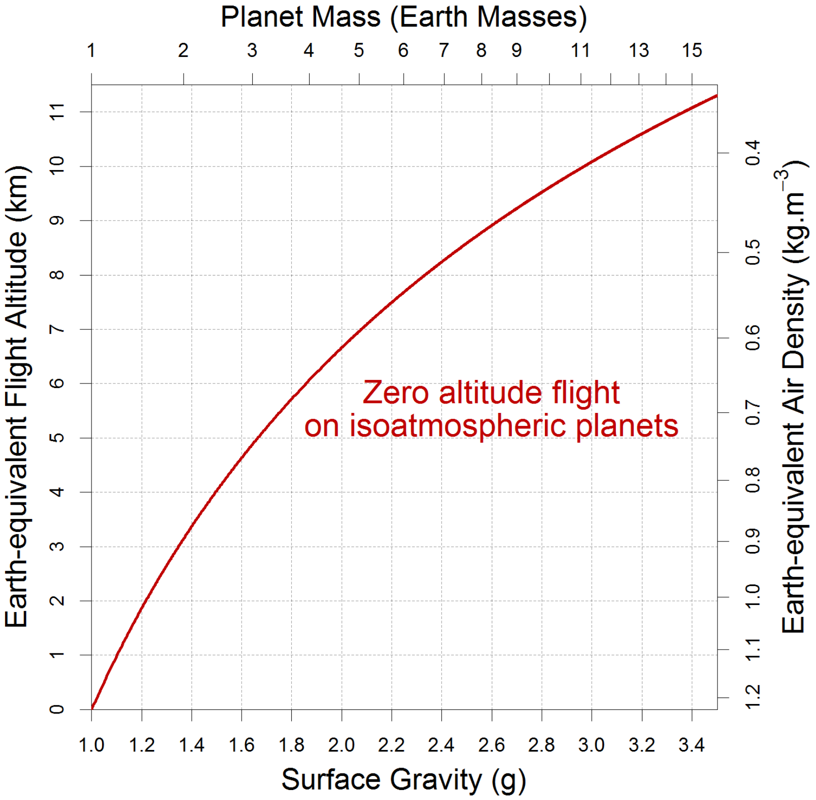

Figure 8. For isoatmospheric planets the Earth-equivalent air density required for flight at zero altitude is inversely related to the surface gravity of a planet, $\rho_{eq} \propto 1/g_s$.

Might smaller birds be capable of flight on an isoatmospheric planet of 15 Earth masses? The surface air density would scale as $1.225(M/M_{Earth})^{0.904}$ giving $\rho_s = 14.17$ kg m^{-3}, lower than the minimum air density required by whooper swans for the same planet mass, $\rho_{min} = 20.18$ kg m^{-3}. Since $P_f \propto \rho_s^{-1/2}$, power would have to be boosted by a factor of 1.1934. To achieve this, body mass could be reduced $(m_b < m_w)$ and flight would become feasible on a 15 Earth-mass planet if $m_b = m_w \times 1.1934^{-1/\alpha}$. Hence, flying animals of 0.42–3.8 kg or less in body mass (according to the value of α) may be capable of aerial locomotion on a 15 Earth-mass planet. A histogram of adult body masses in almost ten thousand bird species (Codron et al, 2013) is presented in Figure 9. Some 88% of bird species have a body mass below 0.42 kg whereas around 99% have a body mass below 3.8 kg.

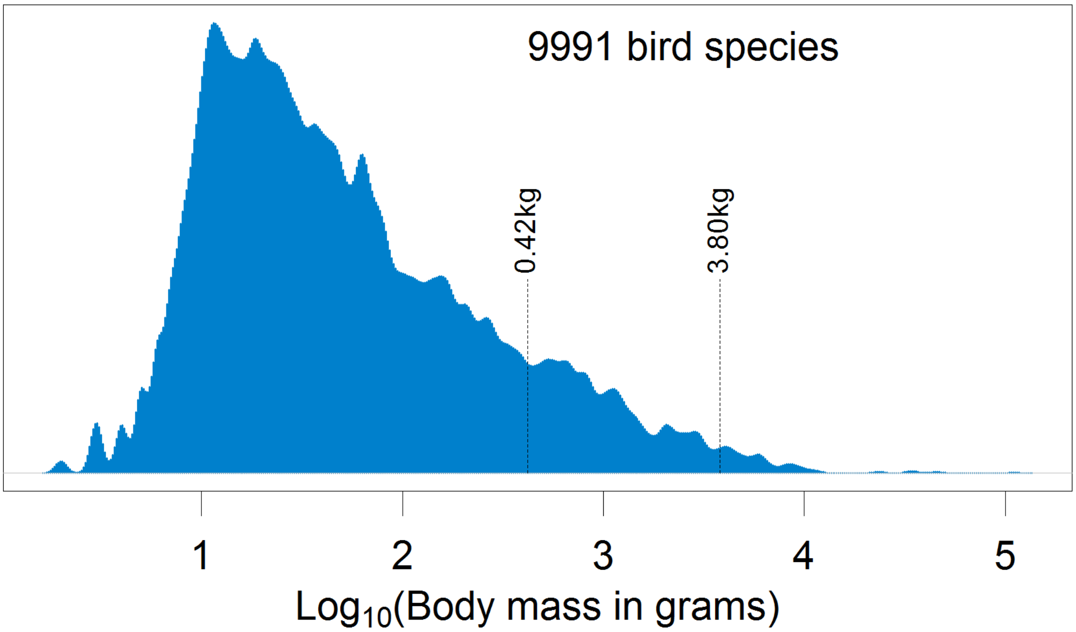

Figure 9. The distribution of adult body masses in 9991 bird species. It is likely that most of the Earth's species have the potential to adapt to oxygenated super-Earth planets with an atmospheric fraction comparable to that of the Earth. The median body mass is 37g. Some 88% of birds have a body mass less than 0.42kg, 98% have a body mass lower than 2.6kg, which is typical of the body mass for a bar-headed goose. and 99% lie below 3.8kg.

For an isoatmospheric 15 Earth-mass planet, $\sqrt{g_s^3/\rho_s} > 51.1$ m^3 s^{-3} kg$^{-1/2}$. On Earth this is equivalent to $\rho < 0.36$ kg m^{-3} and altitudes >11 km. Even if smaller birds lack the athleticism of whooper swans, some may be able to fly in such rarefied air. The possibility could be investigated using a hypobaric wind tunnel operated at a temperature the birds would find comfortable.

Hovering birds are relatively easy to study experimentally. Mixtures of helium and oxygen can be used to assess whether hummingbirds are capable of flying in normoxic conditions at a range of different air densities. Results suggest that ruby-throated hummingbirds, which have a body mass of only 2–6 grams, can sustain hovering at air densities down to 47% that of sea level, or approximately 0.576 kg/m^3 (Chai & Dudley, 1995; Chai & Dudley, 1996). This corresponds to a value of $\sqrt{g_s^3/\rho_s}$ of 40.5 m^3·s^{-3}·kg$^{-0.5}$. In forward flight, this species is likely to be capable of flying in air that is yet more rarefied. However due to its relatively low body mass, it is unlikely to challenge whooper swans for athleticism. Body masses are lower still in flying insects. The hovering flight of male alpine bumble bees (*Bombus impetuosus*) captured in China at an altitude of 3250m has also been investigated. Some individuals (mass ~ 0.4g) were capable of hovering briefly in a hypobaric chamber at equivalent altitudes exceeding 9000m (Dillon & Dudley, 2014). These insects have been not been observed at altitudes above 5600m so the reason for the surplus athleticism could be some occasional demand for intensely energetic behaviour, such as mating, predator evasion or combating gusts of wind.

Sufficient information has now been collected to describe circumstances compatible with self-powered circumplanetary flight in which the effect of atmospheric buoyancy can be neglected. A planet would ideally occupy an orbit within the 'conventional' continuously habitable zone (Kasting et al, 1993) and, in addition, the following criterion should be satisfied:

$$\left(\frac{m_b}{m_w}\right)^{\alpha}\sqrt{g_s^3/\rho_s} \lesssim 42.8\ \mathrm{m^3 s^{-3} kg^{-1/2}} \qquad \text{(HFZ1)}$$

A previous expression for $\sqrt{g_s^3/\rho_s}$ can be substituted here to arrive at an alternative formulation involving only normalised mass terms:

$$\left(\frac{m_b}{m_w}\right)^{\alpha}\left(\frac{M}{M_{Earth}}\right)^{0.226}\sqrt{\frac{M}{M_{atm}}} \lesssim 1663 \qquad \text{(HFZ2)}$$

The molar mass of the air, M_{air} = 0.029 kg mol^{-1}, the air temperature, T_{air}, and the universal gas constant for air, R_{air} = 8.314 N m mol^{-1} K^{-1}, obey the relationship $\beta = R_{air}T_{air}/M_{air}$. Since both γ and M_{atm} are linearly dependent on β, the value of $\sqrt{g_s^3/\rho_s}$ is proportional to $\sqrt{\beta}$. Therefore, any variations in temperature can be accommodated by applying a correction factor of $\sqrt{288.15/T_{air}}$ to the right hand sides of these inequalities (HFZ1 and HFZ2)

One should also be aware that changes in atmospheric composition can occur over geological timescales. Thus, even if an atmosphere is not currently caustic or toxic, it may have been in the past, hindering opportunities for evolution. The results of this analysis are presented graphically in Figures 10 and 11. Note that these results are likely to err a little on the side of caution. On Earth, birds that fly at high altitudes must generally also be capable of take-off at sea level, necessitating a degree of compromise. However, flying animals on other worlds lacking high land may have no need to fly much higher than sea level.

VARIATION OF FLIGHT POWER WITH ATMOSPHERIC DENSITY

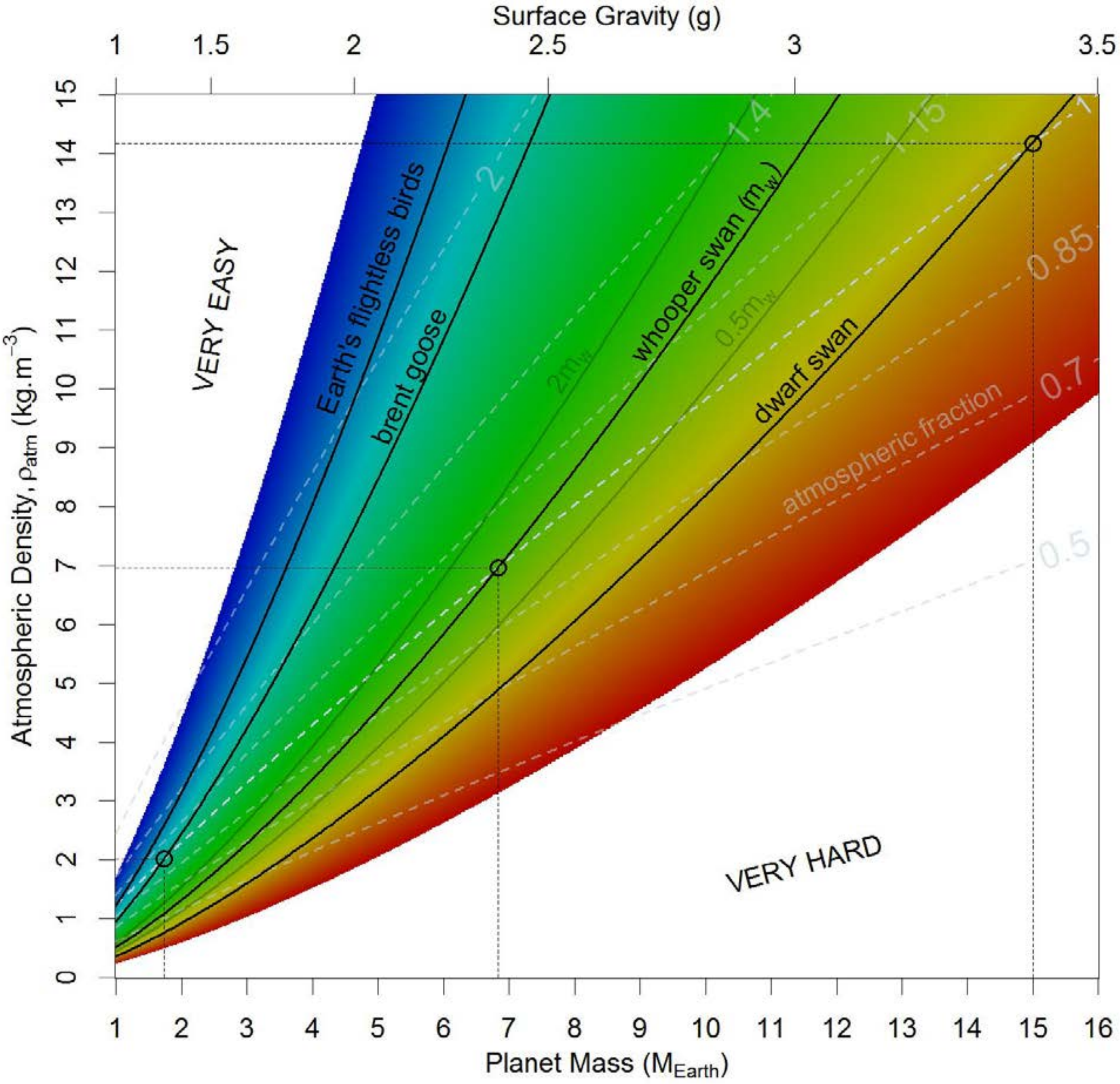

Figure 10. Flight power (colour coded from red to blue with increasing effort) is a function of planet mass/surface gravity and atmospheric density. The HFZ lies upward of the solid contours. An 11kg whooper swan would struggle to fly on an isoatmospheric planet exceeding 6.86 Earth masses. The influence of doubling or halving body mass relative to the whooper swan is shown for $\alpha = 0.11$*. The trace marked "dwarf swan" corresponds to a hypothetical flying animal of the same mass-specific athleticism as a whooper swan but with a reduced body mass of 0.04-0.34*m_w *(corresponding to the range* $0.054 < \alpha < 0.166$*). Dashed contours here represent the relative atmospheric mass content relative to the Earth's fraction (862 parts per billion).*

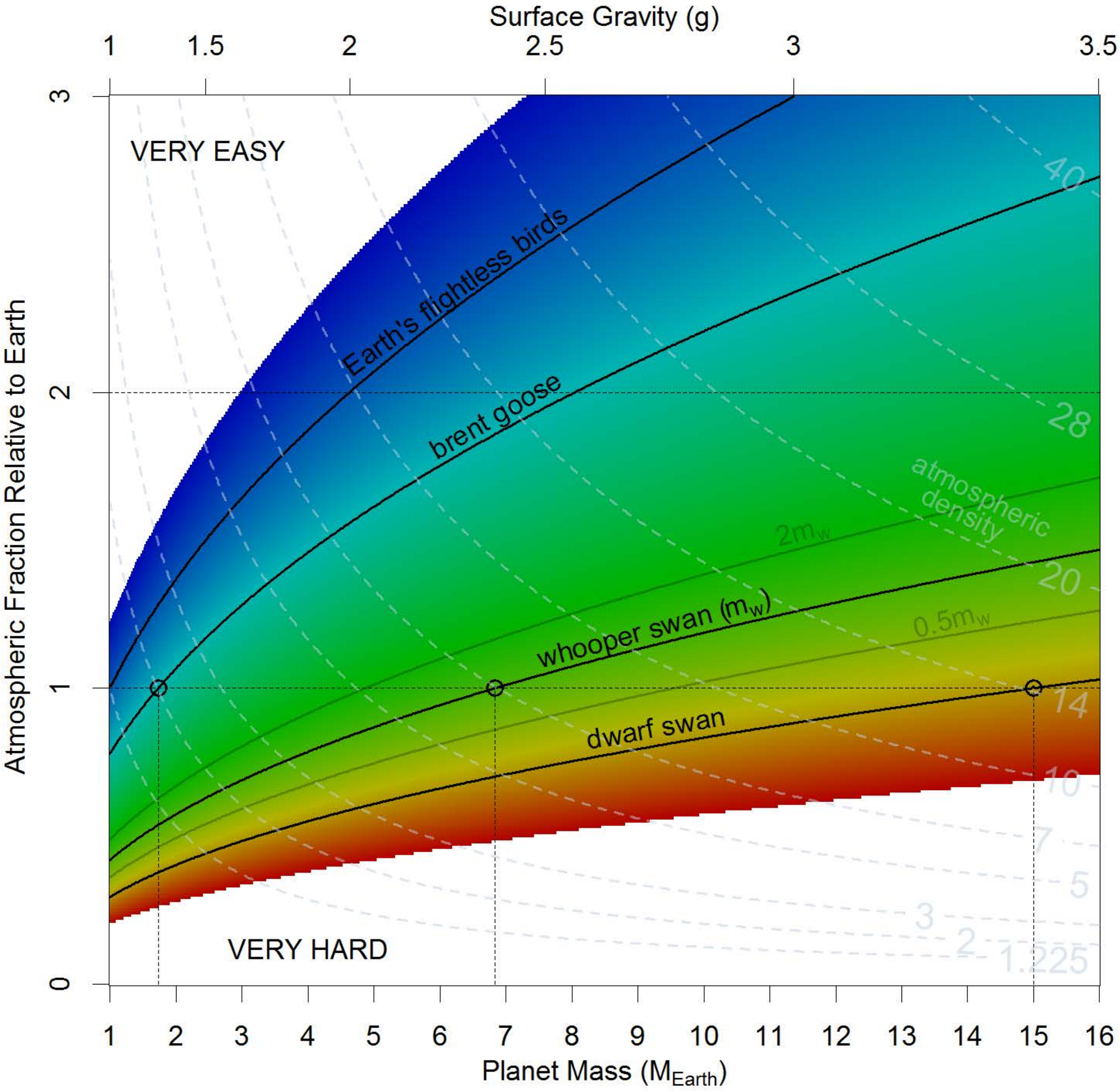

Figure 11. Flight power colour coded from blue (low effort) to red (high effort) expressed in terms of planet mass/surface gravity and the relative atmospheric fraction compared to that of the Earth. The HFZ again lies upward of the solid contours. Here, the dashed contours represent the surface density of the atmosphere (in kg·m^{-3}), and correspond to isobars for the isothermal model used here. On Earth, the "dwarf swan" would be capable of attaining altitudes of 11km.

Conclusions

When Lord Kelvin averred in 1895 that “heavier than air flying machines are impossible”, it was as though he had never laid eyes on a bird in flight. Living organisms may not be technically classed as machines but they abide by the usual rules of physics and, like machines, are constructed from atoms. Aerial locomotion is one of the greatest marvels of the animal kingdom, an ability whose evolutionary origins still remain a topic of considerable debate.

The Himalayas are a geologically recent barrier to bird migration. Somehow, bar-headed geese have evolved means of negotiating this formidable obstacle, raising the question of why so few species have been able to emulate their achievement. This puzzle is accentuated by the discovery that their flight costs rise far more rapidly with altitude than had been theoretically predicted (as low altitude flight facilitates emergency landings it is not impossible that inefficiency at higher altitudes is an evolutionary quirk enhancing survival prospects by encouraging the geese to remain low). Another consideration which may deter other species from following the same migration path is that numerous high altitude stopovers are needed on the Tibetan plateau. Larger birds may struggle to take off in rarefied air, especially from water. Swans from Mongolia avoid the Himalays, heading to China or Korean for the winter. Conversely, the absence of smaller avian migrants may be due to their need for a plentiful supply of food in order to maintain adequate thermoregulation in cold environments, the plateau offering rather poor foraging opportunities. On other planets, however, the most comfortable temperatures may often be found well above sea level with conditions at lower altitudes excessively hot. Smaller flying animals may then be abundant at higher elevations, where they might evade larger predators.

Some species of birds are far less reliant on self-powered flight, harnessing the assistance of sunlight-driven thermals or using dynamic soaring to harvest energy from the wind. Paper IV shows that seabirds can profit from the interplay between the wind and the ocean waves. Such strategies are potentially important on other worlds too. Nevertheless, climate systems undergo chaotic fluctuations, so environmental assistance is unreliable. Although super-Earths may generally provide denser atmospheres to partially offset the difficulty of weight support, winds are then likely to be relatively gentle because denser atmospheres are better at redistributing energy. Venus, for example, may have a super-rotating atmosphere but, at the surface where the atmosphere is most dense, the winds rarely exceed 1 m/s.

In very dense atmospheres, buoyancy effects may come into play. Inflatable air sacs containing metabolically generated gases of low density such as hydrogen or methane can be imagined. As the density of the medium increases further, the wings would have to become so sturdy that they might resemble fins. The distinction between swimming and flight may then be somewhat blurred (*flimming?*). In a supercritical fluid the temperature and pressure are so high that the liquid and gas phases coexist. It may therefore be helpful to tighten the definition of flight to locomotion through a medium of sufficiently low density that the effects of buoyancy are negligible. There will be worlds where flight can only be anaerobically sustained. Running might then be interspersed with transient powered leaps through the air. The possibility of flying very low to benefit from ground effect would also be important in such circumstances.

Gravity is not the only long-range force that nature provides and electromagnetism is intrinsically stronger than it. One can therefore imagine an exotic alien animal equipped with electrocytes, similar to those found in electric eels, capable of generating electrical currents. Superconductivity, if achievable at body temperature, could support essentially lossless current loops giving rise to magnetic dipoles. In the presence of a planetary magnetosphere, such fields could, if appropriately oriented, provide forces of attraction or repulsion like those between bar magnets. Such an exotic mode of locomotion harvesting the rotational energy of a planet need not necessarily be confined to the atmosphere. Brief excursions into space may be possible, akin to the temporary dives of mammals underwater.

In the presence of a breathable atmosphere, winged animals of a body mass comparable to the majority of the Earth's avian species could fly on isoatmospheric planets of 15 Earth-masses ($g_s = 3.4g$), spanning the full range of super-Earth planets containing hcp iron at their cores. However, if the air density on other planets equalled that at sea level here then even whooper swans would struggle to fly on planets exceeding twice the mass of the Earth.

The oxygen in our atmosphere is almost entirely of biological origin. Although the Earth is denser and 44 times more massive than Saturn's moon Titan, its atmosphere is thicker. The quantity $\sqrt{g_s^3/\rho_s}$ has a value of 1.18 there. Setting aside the complication of its very different atmospheric composition and cold temperature, whooper swans would find flight there 36 times easier than at 8200m altitude here. Because the value of α is small and positive, animals larger than any that have ever graced this planet could be envisaged flying in such conditions. However, transport costs (or the energy/distance ratio), should approximately scale as $m_b^{0.7}$ during flight but only $m_b^{0.6}$ for running (Schmidt-Nielsen, 1972). Thus, above a certain body size, terrestrial locomotion would be energetically favoured to flight, even though transit times might increase.

This analysis has resulted in concise definitions of a habitable flying zone (HFZ1 and HFZ2) for animals capable of atmospheric locomotion in still air conditions. It can be regarded as another variation on how planetary habitability is defined but it is a non-trivial and remarkably important one that has somehow been ignored (Lineweaver & Chopra, 2012). Its potential significance to us is apparent when considering the possibility that in the future we may embark on programmes of interstellar exploration. Doubtless, we will want to study planets which have the best chance of hosting complex and intelligent lifeforms. Evolutionary pressure for an efficient solution to the challenges of 3-D locomotion in environments where gravity must be continuously combated may be highly relevant to the emergence of intelligent life elsewhere in the universe. Hence, there is a need to understand the influence that planetary size, mass and atmosphere can have upon possible ecosystems. Planetary rotation may also have a significant bearing. Habitable planets with the most stable temperatures will tend to rotate quite rapidly, driving volatile weather conditions. Water can unexpectedly condense from the air to form mist, fog and cloud, quite possibly hampering visibility and rendering aerial locomotion perilous at times.

It is increasingly evident that several species of bird exhibit a remarkable range of cognitive functions ranging from complex long-range navigation to problem-solving abilities on a par with young children (Lefebvre et al, 2002). Corvines are known to imaginatively fashion and utilise tools (Hunt, 1996; Hunt & Gray, 2004). Psittacines are capable of mimicry, communication, dialogue (Pepperberg, 1981; Emery, 2006) and even have some numerical ability (Pepperberg, 1994). Such intellectual feats are rarely encountered in other animals of comparable brain size (Pearson, 1972). Moreover, Eurasian Magpies (*Pica pica*) have demonstrated self-recognition when confronted with a mirror, a trait commonly associated with high intelligence (Prior et al, 2008).

Any animals undertaking seasonal migrations are able to transport seeds via their digestive tracts, thereby accelerating the spread of botanical life. The threat of airborne predation can also provide a stimulus for the evolution of intelligence in fauna such as the small ground-based mammals from which our own species descended and birds no doubt preyed upon. Volant organisms of all kinds have likely played an important and perhaps even crucial role in shaping the Earth's biosphere and enriching its biodiversity. Furthermore, birds demonstrated considerable resilience in the face of a mass extinction that wiped out their dinosaur relatives. Following oblique asteroid strikes that spatter debris high up into the stratosphere, incandescent rocks can rain down sparking global fires on land with devastating and lasting effects on the food chain. Widespread fires may well have been at the root of the extinction of the pterosaurs. Cumbersome on land, if forced to take to the sea for refuge they would have struggled to take off again after alighting on water. As soaring animals, even take-off on land may have required the assistance of trees, cliffs or favourable winds (Sato et al, 2009). At times of elevated oxygen concentrations in the atmosphere, fires will readily ignite quite spontaneously. Short-lived technological civilisations can wage devastating wars and pollute the environment. In the context of long-term survival prospects, during times of adversity an ability to swiftly and efficiently relocate over planetary distances and flexibly forage on land and sea should not be underestimated. The viability of flapping flight on a planet may therefore be a far more important long-term consideration than the feasibility of soaring flight.

Accurate determination of the HFZ may facilitate shrewder selection of exoplanetary destinations in any future space missions to nearby star systems that are intent on maximising the chances of encountering complex lifeforms – perhaps even extraterrestrial civilisations of comparable sophistication to our own. However, this is likely to first necessitate the development of highly advanced techniques for remotely assessing the composition and density of extrasolar planetary atmospheres. It is unclear at present whether this will eventually become practical via improved spectroscopic analysis and telescopes or whether it will necessitate the deployment of autonomous probes on reconnaissance missions. A potential overriding consideration is that as our knowledge of particle physics further matures, a point in time may arrive when our civilisation may need to carefully reconsider its perspectives concerning the cosmos in ways that may impact long-term goals and policy-making. Rather than being obliged to scour the galaxy on interstellar missions looking for extraterrestrial life, we may be presented with the intriguing possibility of being able to estimate the rarity and spatial distribution of intelligent life to reasonable accuracy by deductive means. In that eventuality, there may no longer be much appetite for exploration of the Milky Way. In the meantime there is a need for caution to guard against undesirable contamination of extant alien biospheres either with life, technology or discoveries that originated here.

Whatever might transpire, one can already appreciate that since the fate of the Sun is to become a red giant, life cannot thrive here on Earth indefinitely. Furthermore, relocation to colonies on Mars or other planets and satellites of the Solar System can only provide fleeting respite against the expansion of the Sun before it collapses to a white dwarf. In the shorter term, it may also fail to guard against detonations of nearby supernovae within the Milky Way. There are also more imminent political threats to contend with. If our descendants are to have any hope of surviving until the end of the stelliferous era, at least a thousand times the age of the universe into the future, interstellar relocation will be required. In order to establish a colony elsewhere capable of hosting all the Earth's species, the importance of aerial habitability must not be ignored when selecting planetary destinations.

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Paper I

Integration of exercise response and allometric scaling in endotherms.

Charles M. Bishop & Robin J. Spivey

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Integration of exercise response and allometric scaling in endotherms

Charles M. Bishop*, Robin J. Spivey

School of Biological Sciences, Bangor University, Deiniol Road, Gwynedd, LL57 2UW, UK

HIGHLIGHTS

- ▸ A novel relationship links rate of oxygen consumption, heart rate and heart mass.
- ▸ Oxygen consumption during primary locomotion is proportional to heart rate squared.
- ▸ Marine endotherms show a similar relationship to that of terrestrial endotherms.
- ▸ Endotherms may be similarly constrained by their relatively high blood pressure.

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ABSTRACT

The relationship between heart beat frequency and the rate of oxygen consumption for different species of birds and mammals is influenced by body size, the type of exercise being undertaken and its intensity. Here a model is presented combining allometric scaling and exercise-induced variations in oxygen consumption and blood flow, when birds and mammals undergo their primary mode of locomotion. Novel relationships, common to the regulatory systems of all endotherms, are found to relate the rate of oxygen consumption, heart-rate, body and heart mass in 24 species of endotherms spanning 5 orders of body mass. We show that these relationships can be derived from linearity between heart-rate and the arteriovenous oxygen difference, present in data from exercise-attuned humans. We find that the metabolic rate of endotherms undergoing their primary mode of locomotion across a range of exercise intensities is quadratically related to heart-rate and that body mass is inferior to heart mass as a predictive scaling variable. The model facilitates graphical comparisons between species, and enables metabolic costs to be extrapolated from heart-rate data whenever direct measurements of oxygen consumption prove prohibitively challenging.

1. Introduction

The scaling of maximal metabolic rate (MMR) and especially basal metabolic rate (BMR) with body mass has been the focus of much investigation (West et al., 1997; Glazier, 2010; Agutter and Tuszynski, 2011; White et al., 2009; Kolokotrones et al., 2010). Scaling exponents for body mass are generally observed to be higher for MMR than BMR in birds and mammals (Koteja, 1987; Bishop, 1999; Savage et al., 2004; Weibel et al., 2004; Glazier, 2008) and are frequently determined by measurements of the rate of oxygen consumption ($\dot{V}_{O_2}$). The Fick principle describes the transport of oxygen around the body and relates heart rate (f_h) to metabolic rate. Therefore, MMR and BMR should also be related to f_h (Green et al., 2005). Accordingly, allometric scaling of $\dot{V}_{O_2}$ can be regarded as a function of f_h, with both body mass (M_b) and heart mass (M_h) serving as scaling parameters (Bishop, 1999). From this perspective, more is known about the extreme limits of the exercise spectrum, but there is no known unifying physiological relationship linking metabolic rates of different species from BMR through intermediate levels of exercise to MMR. We set out to develop and quantitatively test a model combining the cardiovascular response to exercise with the effect of allometric scaling. The two scaling variables M_b and M_h are considered and their relative scaling influence compared.

2. A blood circulation model

The Fick principle is summarised by the following equation:

$$\dot{V}_{O_2} = f_h V_s (C_aO_2 - C_{\bar{v}}O_2) \qquad (1)$$

where V_s is cardiac stroke volume and $C_aO_2 - C_{\bar{v}}O_2$ is the arteriovenous oxygen difference. In the steady-state, this is applicable both in an allometric scaling context (Bishop and Butler, 1995; Bishop, 1997) and when considering functional changes in blood flow of individual animals (Butler et al., 2004;

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* Corresponding author. Tel.: +44 1248 382315; fax: +44 1248 370731.
E-mail address: c.bishop@bangor.ac.uk (C.M. Bishop).

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Green, 2011). The allometric scaling of heart rate with body mass M_b is usually expressed as a bivariate power law in which $f_h \propto M_b^{-\alpha}$ with exponents reported between $0.16 \leq \alpha \leq 0.37$, apparently depending on whether MMR or BMR is under consideration and the particular species involved (Bishop, 1999; Bishop and Butler, 1995). At least some of this variation has been attributed to greater heat retention in the muscles of larger animals (Gillooly and Allen, 2007), which they argue may indicate that there is only a single fundamental mechanism underlying these exponents. Given this observation, along with the general paucity of relevant experimental data, our model simply assumes that α is constant during primary mode locomotion. Heart-rate may typically vary some 3–6 fold between rest and sustained near-maximal exercise, according to species (Bishop and Butler, 1995; Butler et al., 2004; Green, 2011), while heart-rate differences >8-fold have been recorded in wild-living geese (Spivey, Hawkes, Butler and Bishop, unpublished observations) and aerobic scopes of around 60-fold have been estimated for the pronghorn antelope *antilocapra Americana* (Lindstedt et al., 1991; Bishop, 1999).

Variable	Units	Meaning
$\dot{V}_{O_2}$	ml min^{-1}	Oxygen consumption
f_h	beats min^{-1}	Heart rate
$\mathbf{M_b}$	kg	Body mass
$\mathbf{M_h}$	kg	Heart mass
V_s	ml beat^{-1}	Cardiac stroke volume
$C_aO_2-C_{\bar{v}}O_2$	ml oxygen per ml blood	Arteriovenous oxygen difference
κ, κ_i, κ_g	ml min kg$^{-1-\alpha}$	Constants of proportionality
α, β, μ, ν, ξ, ζ	Dimensionless	Scaling exponents
OP	ml beat^{-1}	Oxygen pulse
CA	ml^2 min^{-3}	Cardiac activity

Acquisition of some of the variables in the Fick equation required for inter-species comparisons necessitates invasive procedures, often impractical or difficult to accomplish accurately compared to that of cooperative human subjects. Thus, the modelling process begins with the observation that data from human males engaging in regular exercise (Crisafulli et al., 2007) and from elite female athletes (McCole et al., 1999) exhibit a hitherto unappreciated linearity between f_h and $C_aO_2-C_{\bar{v}}O_2$ during sustained aerobic exercise (Fig. 1). It is, therefore, assumed for now that the cardiovascular systems of animals undergoing their primary modes of locomotion (whether running, hopping, swimming or flying) are regulated as in healthy humans and that one can arbitrarily extrapolate this linearity to other species. As neither C_aO_2 nor $C_{\bar{v}}O_2$ should scale systematically with body mass (Bishop, 1997), neither should $C_aO_2-C_{\bar{v}}O_2$. Because M_b and $C_aO_2-C_{\bar{v}}O_2$ are completely independent variables in a mathematical, scaling and functional sense, the linearity of both $C_aO_2-C_{\bar{v}}O_2$ and $M_b^{-\alpha}$ with f_h allows the expressions to be combined:

$$M_b^{\alpha} f_h \propto C_aO_2-C_{\bar{v}}O_2 \tag{2}$$

It can be seen that when either of the two input variables are held fixed, both of the original linear relationships with heart rate are recovered, respectively. Thus, for an individual animal, M_b will be constant and one recovers $f_h \propto C_aO_2-C_{\bar{v}}O_2$, while for individuals and/or species of animal performing exercise of a given intensity (i.e. a constant value of $C_aO_2-C_{\bar{v}}O_2$) one recovers $f_h \propto M_b^{-\alpha}$. A rigorous mathematical derivation of this is provided in Appendix A. Multiplication of both sides of the relationship by f_h and V_s gives:

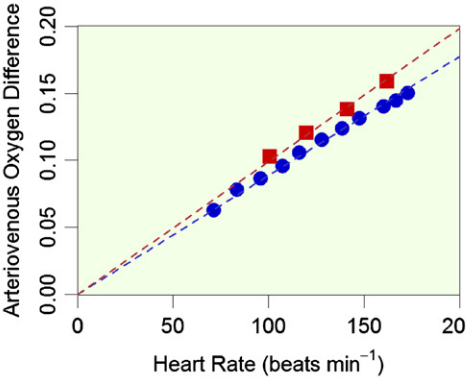


Fig. 1. Linear relationship between heartrate and arteriovenous oxygen difference. In exercise-attuned humans, the linearity of the f_h, $C_aO_2-C_{\bar{v}}O_2$ relationship is demonstrated by Pearson correlations $r \approx 0.996$ for males (blue circles) and $r \approx 0.995$ for females (red squares). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$M_b^{\alpha} V_s f_h^2 \propto f_h V_s (C_aO_2-C_{\bar{v}}O_2) \tag{3}$$

With reference to Eq. (1), each side must be proportional to $\dot{V}_{O_2}$. Whilst the measurement of f_h is quite practical in free-ranging animals (Butler et al., 2004), the measurement of V_s is exceedingly difficult. Laboratory experiments have nevertheless demonstrated that V_s can be relatively invariant between exercise states for a number of species (Butler et al., 1997; Vatner and Boettcher, 1978), rising only slightly at the onset of exercise (Grubb, 1982; Crisafulli et al., 2007). Stroke volume should be approximately linear with body mass (Lindstedt and Calder, 1981), giving:

$$\dot{V}_{O_2} \propto M_b^{\alpha} V_s f_h^2 \propto M_b^{1+\alpha} f_h^2 \tag{4}$$

However, we would expect that V_s should correlate better with heart mass, M_h, than body mass, M_b (Bishop and Butler, 1995). Since M_h can vary adaptively up to 4-fold within birds and mammals of similar body mass (Bishop, 1997), the assumption that M_h and V_s scale linearly should offer improved accuracy:

$$\dot{V}_{O_2} \propto M_b^{\alpha} M_h f_h^2 \tag{5}$$

This quadrivariate power law combines allometric scaling with the physiological response to exercise. However, for visualisation purposes, it is usually more convenient to work with only three variables. We could use Eq. (4) but, since α is predicted to lie between 0.16 and 0.37 (i.e. is significantly smaller than one), it is likely to be preferable to use M_h as a proxy for M_b than the alternative of using M_b as a proxy for M_h. This also has the advantage of accounting for differences in heart mass between individuals or between different species. Thus, an alternative trivariate power law is:

$$\dot{V}_{O_2} \propto M_h^{1+\alpha} f_h^2 \tag{6}$$

This function represents a curved surface in three dimensions which simplifies to a plane in logarithmic space:

$$\log \dot{V}_{O_2} \approx \log \kappa + (1+\alpha) \log M_h + 2 \log f_h \tag{7}$$

where κ has been introduced as a general constant of proportionality.

3. Methods and results

Using data drawn from published sources for 24 species spanning 5 orders of magnitude in body mass (2.4 g–492 kg—Appendix B), we tested the hypothesis that Eqs. (4–6) accurately model experimental data for exercising endotherms. Samples consisted of body mass and estimates of heart mass along with rates of oxygen consumption and heart beat frequency measurements taken at rest and during the primary mode of aerobic locomotion, defined as the mode of locomotion that yields the maximum possible $\dot{V}_{O_2}$ for each particular species. Given the current scarcity of published data suitable for this study, the data was primarily analysed using a robust numerical method based on least-absolute-deviations, yielding a near-optimal fit for the exponent values of M_h, f_h and M_b suitable for use by experimentalists. Weighting coefficients were incorporated in the numerical analysis in order to compensate for the different numbers of sample points for each species. The robustness of the results was quantitatively assessed using a Monte Carlo iterative approach, further details of which are presented in Appendix C. We also employed least squares (LS) fitting in order to further confirm our results and perform model comparisons in Appendix D. It is well known that LS methods allow outliers to unduly influence results, but that closed-form expressions for confidence limits are then available. We, therefore, utilise both methods (which are in good agreement, see Appendix D) but prefer the numerical approach due to its improved robustness, which resulted in the following best fits for the three models:

$$\dot{V}_{O_2} = 0.000476\, M_b^{1.196 \pm 0.015} f_h^{2.090 \pm 0.03} \tag{8}$$

$$\dot{V}_{O_2} = 0.0402\, M_b^{0.328 \pm 0.05} M_h^{0.913 \pm 0.045} f_h^{2.065 \pm 0.03} \tag{9}$$

$$\dot{V}_{O_2} = 0.18\, M_h^{1.257 \pm 0.015} f_h^{2.094 \pm 0.03} \tag{10}$$

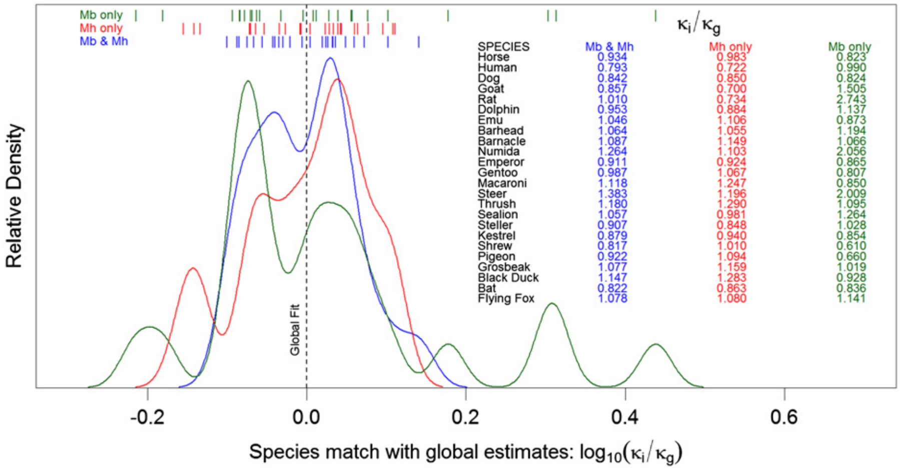
For each of these expressions, values of κ were then obtained for each individual species (κ_i) and referred to global values ($\kappa_g = 0.000476$, 0.0402 or 0.18, respectively). Error terms for the exponents are based on Monte Carlo sub-sampling of 20 species chosen at random from the 24 species and repeated 50 times (see Appendix C). Deviations between the ratios κ_i/κ_g and unity reflect the disagreement between each model and these data. These error estimators were logarithmically transformed and used to generate the density histograms of Fig. 2. This approach provides a detailed visual representation of the spread around the global best fit and preserves the species-specific identification for each of the three models. The quadrivariate power law Eq. (9) exhibits the lowest level of scatter, with a mean departure of κ_i from κ_g of 12%. Hence, Eq. (9) is generally recommended for estimating $\dot{V}_{O_2}$ from measurements of f_h when both M_h and M_b are known. However, the trivariate power law Eq. (10) is nearly as accurate, with a mean error of 14.2%, confirming that it offers a useful alternative, well suited for visualisation purposes. Use of M_b on its own (Eq. (8)), is clearly inferior having several extreme outliers and an overall error of 30.6%.

The relative accuracy of the trivariate expression affirms the anticipated correlation between M_b and M_h, while the numerical fitting method was sensitive enough to resolve the potential degeneracy between the exponents of the two variables in the quadrivariate expression—apparent in the good agreement with the empirically determined exponents of Eq. (9) and the theoretically predicted ones of Eq. (5). This upholds the expectation of the modelling of $\dot{V}_{O_2}$ dependency that the exponent of M_b is comparable to the experimentally observed values of α, the relationship with M_h is approximately linear and that with f_h close to quadratic. Despite the expected degeneracy between the exponents of M_b and M_h, the sum of their exponents was tightly constrained by the data (e.g. $0.328+0.913=1.241$ from Eq. (9), compared to $M_b^{1.196}$ from Eq. (8) and $M_h^{1.257}$ from Eq. (10)), as were the exponents of f_h (range 2.065 to 2.094). Thus, Eq. (9) encapsulates a new and potentially informative biological relationship with broad applicability.

If we assume that the relationship with respect to f_h is precisely quadratic (as modelled in Eq. (6)), then the best fit for Eq. (10) becomes:

$$\dot{V}_{O_2} = 0.290 M_h^{1.245 \pm 0.015} f_h^2 \tag{11}$$

Utilising the trivariate result from Eq. (11) facilitates graphical representation of combined allometric scaling and exercise intensity relationship in the form of a plane tilted in 3-D logarithmic space. Parallel lines exist on the plane, along which any one of the three variables remain constant. It is convenient to view this plane perpendicularly and orientated such that one of the variables is identified with the horizontal axis—we choose here the allometric scaling variable $\log M_h$ for this. For constant M_h, one has from Eq. (11) that $\dot{V}_{O_2} \propto f_h^2$ and hence a slope of two in the logarithmic $\dot{V}_{O_2}$, f_h plane. Lines perpendicular to this and in the same plane will hence have a slope of $-1/2$. It follows that within the plane of the trivariate power law $\dot{V}_{O_2} \propto f_h^{-1/2}$ and hence $\dot{V}_{O_2}^2 f_h$



SPECIES	Mb & Mh	Mh only	Mb only
Horse	0.934	0.983	0.823
Human	0.793	0.722	0.990
Dog	0.842	0.850	0.824
Goat	0.857	0.700	1.505
Rat	1.010	0.734	2.743
Dolphin	0.953	0.884	1.137
Emu	1.046	1.106	0.873
Barhead	1.064	1.055	1.194
Barnacle	1.087	1.149	1.066
Numida	1.264	1.103	2.056
Emperor	0.911	0.924	0.865
Gentoo	0.987	1.067	0.807
Macaroni	1.118	1.247	0.850
Steer	1.383	1.196	2.009
Thrush	1.180	1.290	1.095
Sealion	1.057	0.981	1.264
Steller	0.907	0.848	1.028
Kestrel	0.879	0.940	0.854
Shrew	0.817	1.010	0.610
Pigeon	0.922	1.094	0.660
Grosbeak	1.077	1.159	1.019
Black Duck	1.147	1.283	0.928
Bat	0.822	0.863	0.836
Flying Fox	1.078	1.080	1.141

Fig. 2. Density histograms of $\log_{10}(\boldsymbol{\kappa_i}/\boldsymbol{\kappa_g})$. Green trace: body mass fitting only; red trace: heart mass fitting only; blue trace: combined body and heart mass fitting; vertical bars: ratios for individual species κ_i relative to the global best fit κ_g; numerical results tabulated to the right. A smoothing bandwidth of 0.02 has been applied.

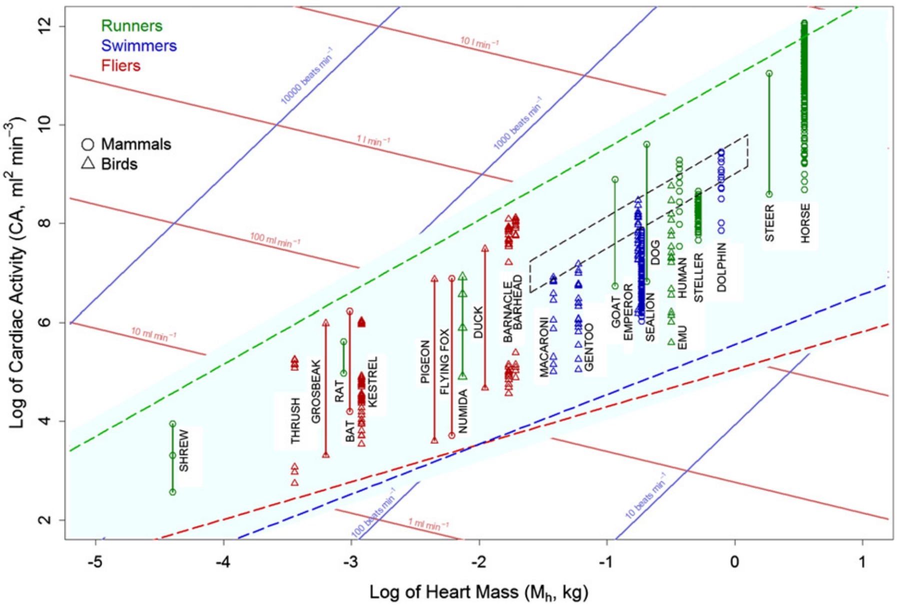


Fig. 3. Scaling plane. The logarithmic plane of the trivariate power law $\dot{V}_{O_2} \propto M_h^{1.245} f_h^2$ is viewed perpendicularly. The horizontal axis corresponds to allometric scaling and the vertical axis corresponds to cardiac activity or exercise spectrum scaling $\left(\log \dot{V}_{O_2}^2 f_h\right)$. Dashed lines represent $\dot{V}_{O_2} \propto M_h^{\beta}$ contours: green ($\beta = 0.90$), blue ($\beta = 0.75$) and red ($\beta = 0.67$). Maximal metabolic rates are consistently lower in breath-holding marine species (region enclosed by dashed black parallelogram). Unbroken contour lines represent constant f_h (blue) and constant $\dot{V}_{O_2}$ (red).

will be constant along the M_h-axis and lines parallel to it. Thus, $\dot{V}_{O_2}^2 f_h$ constitutes a conceptually new quantity that is orthogonal to heart mass and referred to here as 'cardiac activity' (*CA*). Hence, the plane plotted in Fig. 3 represents variations in *CA* vertically and M_h horizontally, with data from the 24 species being superimposed for comparison purposes. We also note that, in the special case of $\dot{V}_{O_2} \propto f_h^2$, $CA \propto f_h^5$ and $CA \propto \dot{V}_{O_2}^{5/2}$.

Any straight line in the plane presented in Fig. 3 can be decomposed into multiple bivariate relationships. For example, the allometric scaling of maximal metabolic rate (MMR) for several species appears to fall close to the dashed green line (fitted by eye). This line simultaneously represents the following three power-laws:

$$\dot{V}_{O_2}^{\max} \propto M_h^{0.9} \tag{12}$$

$$\dot{V}_{O_2}^{\max} \propto \left(f_h^{\max}\right)^{-5.3} \tag{13}$$

$$f_h^{\max} \propto M_h^{-0.17} \tag{14}$$

4. Discussion

We have modelled and empirically confirmed the existence of novel trivariate and quadrivariate power laws, interrelating f_h, M_b, M_h and $\dot{V}_{O_2}$, which simultaneously describe the metabolic response of endotherms according to both exercise intensity and allometric scaling. The scaling of either MMR and/or BMR with respect to body mass has historically been the focus of intensive debate (West et al., 1997; Glazier, 2010; Agutter and Tuszynski, 2011; White et al., 2009; Kolokotrones et al., 2010). An innovation of the present model is the identification of a generalised exercise spectrum for birds and mammals during their primary modes of locomotion, in which $\dot{V}_{O_2}$ is approximately proportional to f_h^2 across a range in body mass spanning five orders of magnitude. For the trivariate relationship (e.g. Eqs.(10 and 11)), data from each species lies clustered on a plane in logarithmically transformed space (Fig. 3). This scaling behaviour may be more readily observable at the inter-species level, when data from multiple species are considered, since there is likely to be some flexibility for each individual species to deviate to some degree from the general global best fit pattern. By rescaling $\dot{V}_{O_2}$ with respect to the global scaling exponents of M_b and M_h (Fig. 4), it is possible to generate a two dimensional plot that can be likened to an edge-on projection of the three-dimensional plane of Fig. 3. Note, however, that in this plot $\dot{V}_{O_2}$ has been rescaled using both M_b and M_h, in accordance with the quadrivariate model of Eq. (9), which we find to be slightly superior to the trivariate model of Eq. (10) (i.e. heart mass only). Thus, the linearity of f_h with $C_aO_2 - C_{\bar{v}}O_2$, as seen in humans (Fig. 1), appears to be a fundamental regulatory phenomenon during periods of primary locomotion, which spans the range of heart-rates studied here from 60 to over 1000 beats min^{-1}. While lacking theoretical explanation at present, it may be that the blood flow of birds and mammals is regulated in a

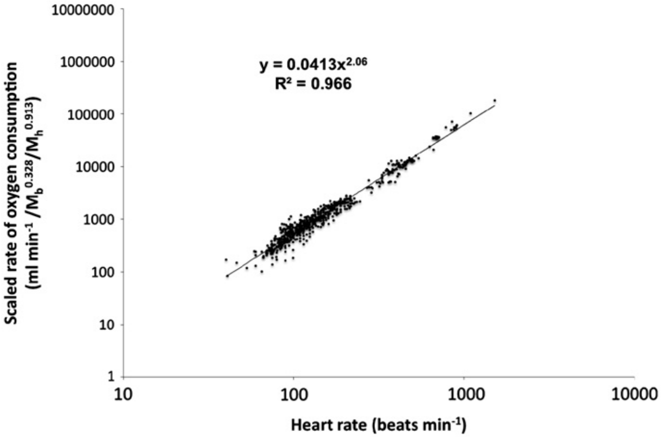


Fig. 4. Rescaled oxygen consumption versus heart rate. Using Eq. (9), $\dot{V}_{O_2}$ is adjusted for both body mass and heart mass for all sample data and plotted logarithmically against unadjusted heart rate. The rescaled relationship between oxygen consumption and heart rate is approximately quadratic ($\xi = 2.060 \pm 0.033$).

similar way as a result of common selection processes arising from their closed circulatory systems which operate at relatively high systemic and pulmonary pressures (Painter, 2005).

The processing of electrocardiogram signals in order to extract heart rate is an informative method in the study of vertebrate energetics and behaviour, especially in free-ranging animals (Butler et al., 2004; Green, 2011). Unfortunately, the requirement to experimentally calibrate the relationship between $\dot{V}_{O_2}$ and f_h for different study species has potentially limited the use and interpretation of f_h measurements. However, the present model offers a means of providing reasonable estimates of energetic costs for species performing primary locomotion without calibration data. For example, a study on great white pelicans (*Pelecanus onocrotalus*) found that the heart-rate of birds flying alone was 17% higher than those of birds flying in V-formation (Weimerskirch et al., 2001). The present model suggests the V-formation strategy represents a metabolic saving of some 27% relative to unaccompanied flight. As a further example, bee-eaters (*Merops apiaster*) migrating through Israel exhibited a mean f_h of 513 beats min^{-1} during periods of flapping flight compared to 230 beats min^{-1} during periods of soaring-gliding flight (Sapir et al., 2010). The present model estimates the cost of soaring-gliding in this species to be approximately five times less than flapping flight.

It is concluded that the linearity demonstrated in Fig. 1 generalises to non-human species. The Fick principle can alternatively be expressed as $\dot{V}_{O_2} = f_h \times OP$ where *OP* is the oxygen pulse or amount of oxygen consumed per heartbeat. Thus, a regulatory mechanism seems to exist in endotherms engaged in their primary mode of locomotion where changes in oxygen pulse are mirrored by changes of equal degree in heart-rate. There are indications in Fig. 3 that the measured maximum cardiac index ($\dot{V}^2_{O_2} f_h$) values for marine animals are considerably lower than those for "terrestrial" endotherms. Breath-holding birds and mammals appear to have a curtailed capacity for strenuous exercise, possibly due to the lack of evolutionary opportunity to simultaneously swim and ventilate rapidly. While $f_h^{\max}$ is noticeably lower in marine animals than in similarly sized terrestrial animals, nevertheless, their oxygen pulse remains similar to those of other endotherms for a given value of M_h and f_h. The blue whale has the largest body and heart mass in all the animal kingdom. Obtaining oxygen consumption and heart rate from this species during exercise would be extremely challenging experimentally. However, given knowledge only of its heart mass (around 320 kg), this model predicts that the blue whale's maximal f_h is around ~52 beats min^{-1} and maximal $\dot{V}_{O_2} \sim 960$ l min^{-1}, comparable to an existing estimate of 700 l min^{-1} (Lockyer, 1981).

For some species, the relationship between $\dot{V}_{O_2}$ and f_h may be available for non-primary modes of locomotion, e.g. penguins running on a treadmill (Green et al., 2005), geese running on a treadmill (Ward et al., 2002), cold-stimulation of metabolic activity in resting animals (Sapir et al., 2010) or with exercise restrictions (Dechmann et al., 2011). In the case of the penguins, the overall relationship appears similar to Eq. (8). However, in the other examples, we note that $\dot{V}_{O_2}$ has a strongly sub-quadratic response f_h^{ζ}, with an exponent $1 \le \zeta \ll 2$ and the oxygen pulse would then vary as $f_h^{\zeta-1}$ rather than f_h. In terms of stroke volume regulation, this would suggest $V_s \propto f_h^{\zeta-1}/(C_aO_2 - C_{\bar{v}}O_2)$ such that when the value of ζ approaches 1, V_s is proportional to the inverse of $(C_aO_2 - C_{\bar{v}}O_2)$. For example, a study of the neotropical bat *Molossus molossus* (Dechmann et al., 2011) used $\dot{V}_{O_2}$ and f_h data to predict daily energy expenditure from non-primary locomotion calibration data. The bats flew with an average f_h of 847 ± 171 beats min^{-1} but the metabolic rate, $\dot{V}_{O_2} =$ 0.83 ± 0.17 ml min^{-1}, suggested by the calibration was implausibly low. However, given a resting f_h of 110 beats min^{-1} and $\dot{V}_{O_2} = 0.1$ ml min^{-1}, the present model predicts $\dot{V}_{O_2} =$ 5.9 ± 2.7 ml min^{-1} at $f_h = 847$ beats min^{-1}, comparable to an allometric extrapolation of $\dot{V}_{O_2} =$ 4.6 ml min^{-1} for 13 species of bats during flight (Winter and von Helversen, 1998). Hence, non-primary locomotion data can be highly misleading when attempting to estimate primary locomotion $\dot{V}_{O_2}$.

It has previously been observed that animals of the same total mass but whose hearts are of different sizes tend to have the same maximal heart rate (Weibel et al., 1991). In the present model, M_h was incorporated to represent stroke volume, with the M_b component modelling the allometric influence on heart rate. This accords with our numerical analysis of a range of exercise data since the optimal exponent of M_b in Eq. (11) is around 1/3 whereas that of M_h is close to unity. Thus, our model allows the scaling relationship $f_h \propto M_b^{-\alpha}$ to be directly related to familiar allometric scaling relationships for BMR and MMR, by substitution in Eq. (5):

$$\dot{V}_{O_2} \propto M_b^{\alpha} M_h f_h^2 \propto M_b^{\alpha} M_h M_b^{-2\alpha} \propto M_h M_b^{-\alpha} \propto M_b^{1-\alpha} \tag{15}$$

This highlights the connection between the scaling of f_h and the differential scaling of metabolic rate. It confirms that $\dot{V}_{O_2} \propto f_h^2$ is more appropriate for animals during primary locomotion, while $\dot{V}_{O_2} \propto f_h$ may be more appropriate for endotherms either undergoing non-primary locomotion or spending the majority of time in a relatively immobile state. In this regard, care should be taken during calibration experiments to avoid mixing data from both primary and non-primary modes of locomotion. In closing, we note from the unified scaling relationship in Eq. (9) that, at least when attention is not confined purely to basal metabolism, heart mass serves as a superior predictor of oxygen consumption than does body mass.

Acknowledgements

We would like to thank the support of Bangor University.

Appendix A

Given knowledge that heart rate scales allometrically according to

$$f_h \propto M_b^{-\alpha}$$

and that heart rate scales with exercise intensity according to

$$f_h \propto C_aO_2 - C_{\bar{v}}O_2$$

it is clear that heart rate is sensitive both to body mass and arteriovenous oxygen difference. One can infer from these two expressions that

$$f_h M_b^{\alpha} \propto C_aO_2 - C_{\bar{v}}O_2.$$

Proof. Let $p = M_b^{-\alpha}$ so that $f_h \propto p$, and let $q = C_aO_2 - C_{\bar{v}}O_2$ so that $f_h \propto q$. Since p and q represent two entirely different forms of scaling (allometric and exercise intensity), they are independent variables. If $f_h \propto pq$ then the partial derivatives read:

$$\frac{\partial f_h}{\partial p} \propto q \equiv const, \quad \frac{\partial f_h}{\partial q} \propto p \equiv const$$

Integrating these, one obtains

$$f_h = \int df_h = \int \frac{\partial f_h}{\partial p} dp = \int const\, dp$$

$$f_h = \int df_h = \int \frac{\partial f_h}{\partial q} dq = \int const\, dq$$

By setting the constants of integration to zero one recovers both $f_h \propto p$ and $f_h \propto q$, from which it is clear that

$$f_h \propto M_b^{-\alpha} \quad \text{and} \quad f_h \propto C_aO_2 - C_{\bar{v}}O_2.$$

Since these expressions are none other than the two original proportionalities, it follows that $f_h \propto pq$ and hence one can deduce

$$f_h M_b^{\alpha} \propto C_aO_2 - C_{\bar{v}}O_2.$$

To illustrate the possible point of confusion here, consider a rectangle of area A, width w and height h. Because $A = w \times h$, we can write $A \propto w$ and $A \propto h$, which could then suggest that $A = k_1 w$ and $A = k_2 h$ and that $w/h = k_2/k_1$. However, this approach seems to constrain the geometry of the rectangle as well as suggest that $A^2 = k_1 w \times k_2 h$ and $A \propto \sqrt{w \times h}$. The latter is clearly a contradiction and we know area is not calculated in this way since the units would be incorrect. The confusion arises because what we mean by $A \propto w$ and $A \propto h$ is that $\partial A/\partial w$ and $\partial A/\partial p$ are each constant. Similarly, $\partial f_h/\partial\{M_b^{-\alpha}\}$ and $\partial f_h/\partial\{C_aO_2 - C_{\bar{v}}O_2\}$ are also constant, which is why it is possible to infer that $f_h M_b^{\alpha} \propto C_aO_2 - C_{\bar{v}}O_2$.

Appendix B

Source data for 24 species (body mass in kg, heart mass in g)

1) Greater spear-nosed bat (*Phyllostomas hastatus*), (n=1 ind.), mean rest and flight data (n=2 data pts.), M_b=0.101, M_h=0.968, (Ref. 27).
2) Grey-headed flying fox (*Pteropus poliocephalus*), (n=1 ind.), mean rest and flight data (n=2 data pts.), M_b=0.75, M_h=6.1, (Refs. 2, 8).
3) Thoroughbred horse (*Equus caballus*), (n=5 ind.), data from figure, rest and running (n=182 data pts.), M_b=492, M_h=3,530, (Refs. 9, 14).
4) Steer (*Bos taurus*), (n=3 ind.), mean rest and max run (n=2 data pts.), M_b=449, M_h=2,038, (Refs. 19, 21).
5) Human (*Homo sapiens*), (n=8 ind.), mean rest and cycling (n=11 data pts.), M_b=70.4, M_h=367, (Refs. 9, 10).
6) Dog (*Canis familiaris*), (n=3 ind.), mean rest and max run (n=2 data pts.), M_b=28, M_h=205, (Refs. 21, 27).
7) Goat (*Capra hircus*), (n=3 ind.), mean rest and max run (n=2 data pts.), M_b=30, M_h=116, (Refs. 21, 27).
8) Wistar rat (*Rattus norvegicus*), (n=6 ind.), mean submax run and max run (2 data pts.)(1), M_b=0.28, M_h=0.87, (Ref. 16).
9) Common dolphin (*Tursiops truncatus*), (n=2 ind.), data from figure (n=13 data pts.), M_b=145, M_h=783, (Refs. 26, 31).
10) California sea lion (*Zalophus californianus*), (n=1 ind.), data from figure (n=95 data pts.), M_b=32.3, M_h=187(2), (Refs. 7, 11).
11) Steller sea lion (*Eumetopias jubatus*), (n=1 ind.), data from figure (n=71 data pts.), M_b=89, M_h=516(2), (Refs. 11, 24).
12) Etruscan shrew (*Suncus etruscus*), (n=7 ind.), rest, submax and max independent f_h and $\dot{V}_{O_2}$ reported. (n=3 data pts.), M_b=0.0024, M_h=0.04, (Refs. 1, 30).
13) Bar-headed goose (*Anser indicus*), (n=2 ind.), rest and flight (n=16 data pts.), M_b=2.66, M_h=21, (Ref. 29).
14) Barnacle goose (*Branta leucopsis*), (n=4 ind.), rest and flight (n=27 data pts.), M_b=1.98, M_h=18, (Ref. 29).
15) American kestrel (*Falco sparverius*), (n=1 ind.), rest, flight and postflight (n=56 data pts.), M_b=0.12, M_h=1.2, (Refs. 15, 18).
16) Emperor penguin (*Aptenodytes forsteri*), (n=3 ind.), data from figure (n=25 data pts.), M_b=23, M_h=175, (Refs. 12, 22, 23).
17) Gentoo penguin (*Pygoscelis papua*), (n=1 ind.), data from figure (n=20 data pts.), M_b=6.21, M_h=59.6(3), (Refs. 6, 12).
18) Macaroni penguin (*Eudyptes chrysolophus*), (n=1 ind.), rest and swim (n=11 data pts.), M_b=3.56, M_h=38.1(4), (Refs. 12, 32).
19) Guinea fowl (*Numida meleagris*), (n=5 ind.), mean rest and run (4=4 data pts.), M_b=1.48, M_h=7.4, (Refs. 13, 18).
20) Emu (*Dromiceius novaehollandiae*), (n=2 ind.), data from figure (n=17 data pts.), M_b=37.5, M_h=319, (Ref. 17).
21) Swainson's thrush (*Catharus ustulatus*), (n=5 ind.), rest and flight (n=10 data pts.), M_b=0.032, M_h=0.36, (see Table below). Average heart-rate (beats min^{-1}) and rate of oxygen consumption (ml min^{-1}) for Swainson's thrush (*Catharus ustulatus*) at rest and while flying in a wind tunnel. Data kindly provided courtesy of Wikelski, M.C. and Bowlin M.S.

Heart rate (beats min^{-1})	**Oxygen consumption (ml min^{-1})**
367.8	1.218
371.1	1.218
393.7	1.184
406.6	1.506
416.3	1.686
869.4	11.72
891.9	12.44
870.8	12.87
899.8	13.73
904.6	14.08

22) Grosbeak (*Hesperiphona vespertina*), (n=12 ind.), rest and flight (2 data pts.), M_b=0.0593, M_h=0.63, (ref. 4, 18).
23) Black duck (*Anas rubripes*), (n=3 ind.), rest and flight (n=2 data pts.), M_b=1.026, M_h=11.1, (ref. 4, 5)
24) Pigeon (*Columba livia*), (n=7 ind.), mean rest and flight (n=2 data pts.), M_b=0.34, M_h=4.48, (ref. 25).
25) (1)Resting data ignored as f_h showed animals were severely stressed
    (2)Mean %M_h taken for 6 species of seal.
    (3)Mean %M_h taken for *Pygoscelis adeliae* and *Pygoscelis antarctica*.
    (4)Mean %M_h taken for *Eudyptes chrysocome*.

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Appendix C

Eqs. (4, 5 and 6) can be generalised using a power law of the form:

$$\dot{V}_{O_2} = \kappa M_b^{\mu} M_h^{\nu} f_h^{\xi}$$

A numerical iteration method was used to search for the values of the parameters μ, ν and ξ that minimised the total absolute deviation across the entire data set. This was particularly important due to the need to resolve the potential degeneracy in the relative proportions of the mass exponents μ and ν caused by the general correlation between heart mass and body mass. The procedure was then repeated both for $\mu = 0$ (Eq. (6)) and $\nu = 0$ (Eq. (4)). For each individual sample, the value of κ was calculated. In the case of perfect agreement between experimental data and the model for some optimal values of μ, ν and ξ, this would yield the same value of κ each time. Since the number of sample points per species differed, a global estimate κ_g was obtained using a weighted median approach. A normalised error estimator Δ_κ was calculated for each discrete combination of μ, ν and ξ according to the following recipe:

$$\Delta_\kappa = \frac{1}{N\,\kappa_g} \sum_{i,j} w_i \left| \kappa_{ij} - \kappa_g \right|$$

where i identified the species, j enumerated a particular sample for species i, N was the total number of species considered and weights w_i were inversely proportional to the square root of the number of sample points for species i. By using these square root weightings, a compromise was achieved between biasing the outcome towards species with the most data points and attaching excessive importance to those species with fewest data points. The process was then repeated by varying the exponents μ, ν and ξ until a reliable minimum of Δ_κ was obtained.

The estimation of confidence limits is not tractable analytically for this numerical procedure. Therefore, in order to assess the reliability of the exponents obtained, data for the 24 species were randomly sub-sampled at the species level and the fitting process repeated, generating a population of results from which a measure loosely analogous to a standard deviation could be gauged, a measure corresponding to a confidence interval of 68.3%. The fitting was repeated 50 times in each case, obtaining fresh estimates for μ, ν and ξ. These results were accumulated and used to determine the median deviation about the mean for each exponent in turn. For subsets of 12, 16 and 20 species (respectively 1/2, 2/3 and 5/6 of the total number of species for which data was available), the results obtained were:

12 species : $\mu = 0.309 \pm 0.130$, $\nu = 0.943 \pm 0.170$, $\xi = 2.102 \pm 0.068$

16 species : $\mu = 0.319 \pm 0.081$, $\nu = 0.931 \pm 0.080$, $\xi = 2.084 \pm 0.059$

20 species : $\mu = 0.336 \pm 0.050$, $\nu = 0.912 \pm 0.045$, $\xi = 2.071 \pm 0.030$

These results confirm the robustness of the results, tally with one another and find good agreement with the result presented in Eq. (9). The deviations are larger for μ and ν than for ξ. This is consistent with degeneracy arising due to the strong correlation between heart mass and body mass. In order to investigate this more closely the fitting was repeated with only μ and ν allowed to vary, keeping ξ fixed at its value in Eq. (9). Drawing 16 species at a time, the fitting was repeated 1000 times from which the values of μ and ν, once again with estimated errors of one standard deviation, were:

$\mu = 0.336 \pm 0.067$, $\nu = 0.914 \pm 0.061$

The scatter in the results was also studied by allowing just one of the three exponents to deviate from the values presented in Eq. (9). Repeating the fits 1000 times for each variable, and fitting to 16 randomly drawn species once more the following results were obtained:

$\mu = 0.329 \pm 0.013$

$\nu = 0.916 \pm 0.011$

$\xi = 2.060 \pm 0.033$

The scatter in the individual ranges of μ and ν is improved here due to the elimination of the degeneracy between μ and ν. This degeneracy can also be avoided when considering the sum $\mu + \nu$ and fitting with ξ held fixed, in which case by randomly drawing 16 species over 1000 trials once more the outcome was: $\mu + \nu = 1.248 \pm 0.015$.

The variables present in Eq. (9) are far more practical to measure than stroke volume, cardiac output or arteriovenous oxygen difference. The model predicts that, during primary mode locomotion, these vary as follows:

$$V_s \propto \frac{\dot{V}_{O_2}}{M_b^{\alpha} f_h^2}$$

$$CO \propto \frac{\dot{V}_{O_2}}{M_b^{\alpha} f_h}$$

$$C_aO_2 - C_{\bar{v}}O_2 \propto M_b^{\alpha} f_h$$

These expressions involve only readily obtained quantities. The model also assists with estimating the costs of primary locomotion for a species where it is only practical to measure BMR and f_h, from which the remaining exercise spectrum can be extrapolated.

Appendix D

Here we present results obtained using multiple linear regression based on weighted least squares minimisation, using the same weightings as before. This approach was disfavoured from the point of view of obtaining the optimal global fit to the data because of the quadratic sensitivity to outliers. However, linear modelling is far more convenient from an implementation perspective. The results, along with 68% confidence intervals, are tabulated below for all 24 species:

Model	κ	μ	ν	ξ	AIC
M_b only	$0.0076 \pm^{0.0013}_{0.0011}$	1.175 ± 0.007	–	2.001 ± 0.028	-451.8
M_b and M_h	$0.070 \pm^{0.019}_{0.015}$	0.265 ± 0.042	0.972 ± 0.044	2.020 ± 0.021	-801.8
M_h only	$0.275 \pm^{0.029}_{0.027}$	–	1.251 ± 0.006	2.013 ± 0.022	-764.8

The AIC scores above confirm that least squares regression also marginally favours the use of both body mass and heart mass over heart mass alone, whereas body mass alone provides clearly inferior results.

It is possible to subdivide the 24 species into two equally-sized groups, namely birds and mammals. Since the number of data points used in the regression then varies, it is inappropriate to use AIC for comparisons purposes. In the results presented below, either zero or one or two of the exponents are held fixed while regression is used to

Subset	κ	μ	ν	ξ	Species
All	$0.0775 \pm^{0.0183}_{0.0148}$	0.263 ± 0.042	0.970 ± 0.044	2	24
All	$0.0892 \pm^{0.0012}_{0.0012}$	0.235 ± 0.003	1	2	24
All	$0.2916 \pm^{0.0043}_{0.0042}$	0	1.248 ± 0.004	2	24
Birds	$0.0831 \pm^{0.0590}_{0.0345}$	0.317 ± 0.112	0.899 ± 0.119	1.923 ± 0.040	12
Birds	$0.0745 \pm^{0.0530}_{0.0310}$	0.272 ± 0.110	0.967 ± 0.115	2	12
Birds	$0.0869 \pm^{0.0018}_{0.0017}$	0.241 ± 0.009	1	2	12
Birds	$0.2807 \pm^{0.0131}_{0.0125}$	0	1.250 ± 0.046	2	12
Mammals	$0.0436 \pm^{0.0143}_{0.0108}$	0.257 ± 0.044	0.987 ± 0.045	2.129 ± 0.025	12
Mammals	$0.1139 \pm^{0.0283}_{0.0227}$	0.188 ± 0.044	1.036 ± 0.045	2	12
Mammals	$0.0956 \pm^{0.0019}_{0.0019}$	0.222 ± 0.004	1	2	12
Mammals	$0.2972 \pm^{0.0038}_{0.0038}$	0	1.230 ± 0.004	2	12

obtain fits for the undefined parameters, along with 68% confidence limits:

It can be seen that in each case the exponents are in close accordance with theoretical expectations. Thus, although body temperatures tend to be somewhat elevated in birds compared to mammals, there is good agreement between the two groups. Whether those differences that exist are due to experimental error and the paucity of experimental data or truly reflect fundamental differences between the two groups is presently unclear.

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Paper II

Interpretation of body-mounted accelerometry in flying animals and estimation of biomechanical power.

Robin. J. Spivey & Charles. M. Bishop

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Interpretation of body-mounted accelerometry in flying animals and estimation of biomechanical power

R. J. Spivey and C. M. Bishop

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Author for correspondence:
R. J. Spivey
e-mail: r.spivey@bangor.ac.uk

Interpretation of body-mounted accelerometry in flying animals and estimation of biomechanical power

R. J. Spivey and C. M. Bishop

School of Biological Sciences, Bangor University, Bangor, Gwynedd LL57 2UW, UK

An idealized energy fluctuation model of a bird's body undergoing horizontal flapping flight is developed, focusing on the biomechanical power discernible to a body-mounted accelerometer. Expressions for flight body power constructed from root mean square dynamic body accelerations and wingstroke frequency are derived from first principles and presented in dimensionally appropriate units. As wingstroke frequency increases, the model generally predicts a gradual transition in power from a linear to an asymptotically cubic relationship. However, the onset of this transition and the degree to which this occurs depends upon whether and how forward vibrations are exploited for temporary energy storage and retrieval. While this may vary considerably between species and individual birds, it is found that a quadrature phase arrangement is generally advantageous during level flight. Gravity-aligned vertical acceleration always enters into the calculation of body power, but, whenever forward acceleration becomes relevant, its contribution is subtractive. Several novel kinematic measures descriptive of flapping flight are postulated, offering fresh insights into the processes involved in airborne locomotion. The limitations of the model are briefly discussed, and departures from its predictions during ascending and descending flight evaluated. These findings highlight how body-mounted accelerometers can offer a valuable, insightful and non-invasive technique for investigating the flight of free-ranging birds and bats.

1. Introduction

Birds flap their wings in order to achieve weight support and locomotion [1–3]. Experiments using high-frame-rate video footage to monitor wing and body motions of birds or bats flying in wind tunnels have combined the findings with aerodynamic results and accelerometry to estimate overall energy expenditure during flight [4–6]. Such approaches have been experimentally valuable and theoretically illuminating, enabling the refinement of aerodynamic theory, but in studies involving free-ranging animals where trailing wires and heavy equipment cannot be used, ambulatory recording of body acceleration offers a viable and practical alternative. Accelerometry was initially restricted to wind tunnel work [7], but has now been miniaturized and demands relatively little electrical power. Commercially available micro-electromechanical transducers are now capable of faithfully recording high-frequency vibrations, offering a new means of studying the characteristics, kinematics and energetics of free-ranging avian flight [8,9] and, indeed, animal locomotion in general [10]. Because the long-term study of birds in the wild is becoming increasingly feasible, there is new scope to assess some of the difficult choices birds face during long-range migrations [11,12].

Traditional techniques for monitoring the metabolic rate or power input of free-ranging vertebrates include doubly labelled water [13,14] and heart rate, f_h, derived from electrocardiography [15,16]. The latter approach offers good temporal resolution but has historically necessitated calibration of f_h against measurements of oxygen consumption, $\dot{V}_{O_2}$. However, the direct translation of f_h to $\dot{V}_{O_2}$ may now be possible for endotherms undergoing primary mode locomotion if augmented

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by knowledge of heart and body mass [17]. Accelerometry has a similar potential to monitor instantaneous biomechanical power output [18] during locomotion, and strong correlative relationships between body acceleration and $\dot{V}_{O_2}$ have been found in animals running on treadmills [18,19]. As one might expect, body accelerations during flight are generally elevated compared with other forms of locomotion [14,20–22]; however, a theoretical understanding of how body acceleration relates to the biomechanical power of flapping flight has not yet been elucidated. This study aims to address this by setting out a mathematical model that assists the interpretation of accelerometry data captured from birds during flight. Novel measures descriptive of flight kinematics, integral to this modelling, shall also be derived.

Instruments that log acceleration are, for practical reasons, generally attached to the torso of a flying animal. As wings are coupled to the body, this offers much promise as a non-invasive tool that can help estimate the biomechanical power (and indirectly or proportionally, the metabolic costs) associated with flight [18,19,23], with the potential to augment or replace existing methods [15,24]. Activity-related accelerations can be decomposed into the sum of dynamic and static accelerations which can be respectively derived by high- and low-pass filtering either in the time or the frequency domain. To date, biologists have found the dynamic component most informative with regard to correlations with energy expenditure. Two time-averaged measures of dynamic body acceleration (DBA) have been used when studying the energetics of animals [18,25]. Overall dynamic body acceleration (ODBA) is a running average of the L^1-norm of the dynamic acceleration [10,18]. The variant using the L^2-norm, which accurately encapsulates vectorial length, is known as vectorial dynamic body acceleration (VeDBA) [26,27]. An immediate difficulty with using any acceleration measure as a proxy for estimating biomechanical power in the absence of empirical calibration is that the fundamental units of acceleration, namely LT^{-2}, are different both to those of power, $\mathrm{ML}^2\mathrm{T}^{-3}$, and those of mass-specific power, $\mathrm{L}^2\mathrm{T}^{-3}$. Overcoming this inevitably requires the development of some theoretical model descriptive of the biomechanics of bird flight with respect to body acceleration.

Under the hypothesis that DBA is closely related to overall metabolic costs, accelerometry has been successfully applied to a wide variety of other animals [10]. Consequently, it is not unreasonable to expect that a correlation could also exist between DBA and the biomechanical power directly discernible using a body-mounted accelerometer (*body power*) during steady horizontal flight and the metabolic rates of birds during flight (subject to the additional uncertainties of the value for the mechanochemical conversion efficiency of muscle [28]). Therefore, the ansatz is adopted here that the kinetics of the body should reflect the kinetics of the wings, thereby ultimately allowing the biomechanical costs incurred during avian locomotion to be estimated. This work primarily focuses on the interpretation of data from accelerometers attached to the body of a flying bird in the absence of additional information, a constraint demanding the development of some mathematical model to theoretically bridge the divide between body vibrations and overall biomechanical costs. The relationship between decomposed vertical and horizontal dynamic accelerations, and the various components of the energy associated with the body are investigated, lateral components being neglected due to the symmetrical beating of the wings. Birds must find ways of contending with the weight of gravity when airborne and flapping flight demands significant energy expenditure [1,3]. Motions of the body on the vertical axis differ from motions within the horizontal plane as they involve changes in gravitational potential. Thus, if the biomechanical power during flight is to be estimated solely from accelerometry, then it is essential to pay heed to the direction of gravity and hence also the absolute orientation of the transducer. The ultimate aim of this work is to derive estimates of acceleration-based biomechanical body power during flapping flight from first principles, potentially leading to the future interpretation of accelerometry from flying animals without the need for direct calibration. Novel statistical measures derived here may also be informative of flight kinematics, pertaining to energetically significant transitions in the wingstroke frequency, such as the relative phase and amplitude of forward and vertical body oscillations.

2. Developing a model

2.1. Preliminaries

Due to the pulsatile character of avian flight associated with the periodic contraction of powerful wing muscles, the energy associated with each wingstroke is delivered sporadically. Efficient flight confers evolutionary advantages, so the effort required by a bird to flap its wings is likely to achieve useful goals such as forward propulsion against aerodynamic drag, the countering of gravity, changes in velocity, ascent/descent and general manoeuvring. The mechanical energy of a bird will fluctuate in time and in still air there is a metabolic cost when the total energy increases. When it decreases, the dissipation of mechanical energy into the surrounding air is used to accomplish these various flight goals [29]. In the absence of gravity and an atmospheric medium, the mean mechanical power required by a vibrating but dissipationless mechanical system is precisely zero, because the total energy of the system is constant at all times. However, energy will necessarily be transformed or exchanged between different elements of the system within individual vibration cycles. Birds, on the other hand, remain airborne and sustain forward momentum despite air resistance by doing mechanical work which they never recover. Notwithstanding this, birds may be able to temporarily store and retrieve energy within individual wingbeat cycles in a similar manner to an idealized dissipationless system, so this should be considered when developing the model, as such a mechanism may provide significant flexibility to execute flight more efficiently under certain circumstances.

We assume a triaxial accelerometer of negligible mass securely affixed to the body of a bird undergoing horizontal flight at a steady air speed. It has been known for several decades that, provided adequate consideration is given to harness design, accelerometers can be externally mounted to birds with negligible oscillation relative to the body [30]. Raw data from an accelerometer can be reoriented using mathematical transformations, an issue returned to later, so this analysis proceeds by taking the z-axis to be oppositely aligned to gravity and the y-axis to correspond to the direction of forward motion. An inertial frame of constant velocity comoving with the bird is considered. The majority of the power in the measured accelerations resides at the fundamental wingstroke frequency f, the angular frequency of the wingstrokes being $\omega = 2\pi f$. This is a

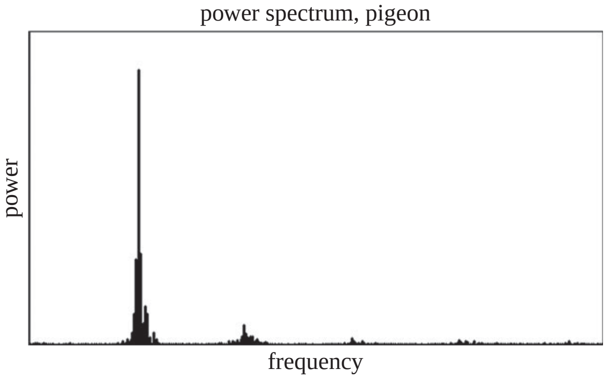

Figure 1. A typical power spectrum derived from the Fourier decomposition of about 10 s of vertical axis accelerometry data captured by the authors at 400 s s^{-1} from the body of a freely flying homing pigeon during horizontal, straightline flight while returning to a loft. The peak at the fundamental wingstroke frequency (at around 6.5 Hz) dominates over that of higher harmonics, suggesting that the acceleration on the bird's body is not only periodic but essentially sinusoidal.

crucial assumption, backed up by the acceleration power spectrum obtained via accelerometry experimentally collected from a flying pigeon, as presented in figure 1. Because power is concentrated at the fundamental frequency, the oscillations of the body in the vertical axis can be accurately approximated by a sinusoid with maximum excursion B relative to the mean altitude. The vertical displacement z and vertical velocity $\dot{z}$ therefore vary as follows:

$$z = B\cos(\omega t) \tag{2.1}$$

and

$$\dot{z} = -B\omega\sin(\omega t). \tag{2.2}$$

It is assumed that no energy is stored either elastically or as rotational kinetic energy, leaving the gravitational potential energy $U = m_b gz$, the kinetic energy associated with the vertical axis $K_z = m_b\dot{z}^2/2$, and the kinetic energy associated with the forward axis $K_y = m_b\dot{y}^2/2$ to be considered. Here, m_b is the mass of the body of the bird, and g is the gravitational acceleration. The beating of both wings is assumed to always be in phase with one another. Because of the bilateral symmetry in birds, we neglect any kinetic energy associated with the x-axis.

The wings also have gravitational and kinetic energies (both vertical and horizontal). However, these are not directly estimable from a body-mounted accelerometer, so terms for these quantities are not explicitly included in the analysis. Instead, it is assumed that the activity detected by the accelerometer will, to a first approximation, be an attenuated reflection of the total biomechanical output of the bird. It is reasonable to think that energy associated with the wings can be subsumed into existing terms by constructive or destructive superposition. This follows from the fact that the addition of two arbitrarily scaled sinusoids of the same frequency, but different phase results in a rescaled sinusoid of the same frequency:

$$a\sin(\omega t) + b\sin(\omega t + \phi) = c\sin\left[\omega t + \arctan\left(\frac{b\sin\phi}{a + b\cos\phi}\right) + \pi H(-a - b\cos\phi)\right], \tag{2.3}$$

where $c = \sqrt{a^2 + b^2 - 2ab\cos\phi}$ and H is the Heaviside step function in which $H(\xi) = 1$ if $\xi \geq 0$, otherwise $H(\xi) = 0$. It can be seen that the resultant sinusoid will generally have an intermediate phase shift.

2.2. Relative phase between vertical and horizontal oscillations of the body

Vibrations on both axes will exhibit simple harmonic motion with both K_y and K_z varying at the same frequency. However, before an expression for the variation in y can be written as a sinusoid, there is a need to carefully consider its relative phase θ with respect to z. Even if the bird has considerable freedom to adjust the phase of its motion on the horizontal axis, arrangements that minimize the power required in order to sustain flight confer evolutionary advantages. Introducing a horizontal vibration amplitude A, the counterpart to B for the vertical axis, one can write

$$y = A\cos(\omega t + \theta) \tag{2.4}$$

and

$$\dot{y} = -A\omega\sin(\omega t + \theta). \tag{2.5}$$

The convention is adopted that neither A nor B can be negative. The total energy associated with the bird's body, $E_b(t)$, is

$$E_b(t) = U + K_z + K_y = m_b gz + \frac{m_b\dot{z}^2}{2} + \frac{m_b\dot{y}^2}{2} \tag{2.6}$$

and

$$E_b(t) = m_b gB\cos(\omega t) + \frac{m_b B^2\omega^2\sin^2(\omega t)}{2} + \frac{m_b A^2\omega^2\sin^2(\omega t + \theta)}{2}. \tag{2.7}$$

During each wingstroke, the flight muscles of the bird must supply energy when E_b is increasing. An important aspect of the present model is the assumption that when E_b decreases, energy is irrecoverably lost to the environment and exploited so as to achieve propulsion and weight support. This can be compared with aerodynamic models which assume the kinetic energy of the wings is never recovered [31,32]. The mean power associated with the body, $\langle P_b\rangle$, can then be determined according to

$$\langle P_b\rangle = \frac{\omega}{2\pi}\int_0^{2\pi/\omega} E_b(t)H(\dot{E}_b(t))\,dt. \tag{2.8}$$

Consider, for now, the case in which $A = 0$. One then has $K_y = 0$ and $E_b = U + K_z$. Gravitational potential energy attains a minimum at $t = \pi/\omega$ when $z = -B$ and a maximum at $t = 0$ when $z = B$. At both these times, K_z reaches its minimum of zero. Because $\sin^2\omega t = (1 - \cos 2\omega t)/2$, the vertical kinetic energy varies sinusoidally at twice the frequency of the gravitational energy. Thus, $E_b(t = \pi/\omega)$ is always a minimum. Although U is always a maximum at $t = 0$, it is possible that E_b is not a maximum at that time if K_z thereafter increases more rapidly than U decreases. This possibility is apparent upon inspection of the time derivatives of E_b, the roots of which correspond to stationary points:

$$\dot{E}_b(t)|_{A=0} = m_b B\omega\sin(\omega t)[B\omega^2\cos(\omega t) - g] \tag{2.9}$$

and

$$\ddot{E}_b(t)|_{A=0} = m_b B\omega^2[B\omega^2\cos(2\omega t) - g\cos(\omega t)]. \tag{2.10}$$

Owing to the $\sin(\omega t)$ term, stationary points exist at $t = 0$ and $t = \pi/\omega$. At $t = \pi/\omega$, one has $\ddot{E}_\mathrm{b} = m_\mathrm{b} B\omega^2(B\omega^2 + g^2) > 0$, so this stationary point is always a minimum. However, $\ddot{E}_\mathrm{b} = m_\mathrm{b} B\omega^2(B\omega^2 - g)$ for the stationary point at $t = 0$, which corresponds to a maximum when $\omega^2 < g/B$ and a minimum when $\omega^2 > g/B$. If both these are minima, additional stationary points occur when $\cos(\omega t) = g/B\omega^2$. Using $\cos(2\omega t) = 2g^2/B^2\omega^4 - 1$, one then finds that at those times $\ddot{E}_\mathrm{b} = m_\mathrm{b}(g^2 - B^2\omega^4) < 0$, confirming that these points correspond to maxima of E_b.

Therefore, when $\omega^2 < g/B$, the mean body power is simply $\langle P_\mathrm{b}\rangle = (\omega/2\pi)\,(E_\mathrm{b}^{\max} - E_\mathrm{b}^{\min})$, where $E_\mathrm{b}^{\max} = E_\mathrm{b}(0) = m_\mathrm{b} gB$ and $E_\mathrm{b}^{\min} = E_\mathrm{b}(\pi/\omega) = -m_\mathrm{b} gB$. However, when $\omega > g/B$, then due to the existence of a new maximum in E_b at $t \neq 0$, $E_\mathrm{b}^{\max}$ will exceed $E_\mathrm{b}(0)$, and the mean power will inevitably rise. During intense flight, there will be a high wingstroke frequency, and for each wingstroke the variation in kinetic energy will increase and the variation in gravitational energy will decrease, allowing the variations in kinetic energy to become dominant. However, if it were possible to temporarily store some of the vertical kinetic energy as horizontal kinetic energy, and retrieve it later in the wingstroke cycle, then this elevated maximum in E_b could be avoided, and the concomitant increase in power is eliminated.

The transition between the two regimes occurs at $g = B\omega^2$, corresponding to the peak gravitational energy $U^{\max} = m_\mathrm{b} gB$ being equal to twice the peak vertical kinetic energy $2K_z^{\max} = m_\mathrm{b} B^2\omega^2$. Clearly, if the total kinetic energy $K_{yz} = K_y + K_z$ did not fluctuate at all, then K_z could be arbitrarily large without incurring any additional increase in mean power. The total kinetic energy is

$$K_{yz} = \frac{m_\mathrm{b}\omega^2}{2}\left[A^2\sin^2(\omega t + \theta) + B^2\sin^2(\omega t)\right] \tag{2.11}$$

and

$$K_{yz} = \frac{m_\mathrm{b}\omega^2}{4}\left[A^2 + B^2 - A^2\cos(2\omega t + 2\theta) - B^2\cos(2\omega t)\right]. \tag{2.12}$$

If K_{yz} is constant, then its derivative

$$\dot{K}_{yz} = \frac{m_\mathrm{b}\omega^3}{2}\left[A^2\sin(2\omega t + 2\theta) + B^2\sin(2\omega t)\right] \tag{2.13}$$

must be zero at all times. It is apparent from this expression and (2.3) that K_{yz} varies sinusoidally. The amplitude of these fluctuations vanishes when

$$A^2\sin 2\omega t\cos 2\theta + A^2\cos 2\omega t\sin 2\theta + B^2\sin 2\omega t = 0 \tag{2.14}$$

and

$$\tan 2\omega t = \frac{\sin 2\omega t}{\cos 2\omega t} = \frac{-A^2\sin 2\theta}{A^2\cos 2\theta + B^2}. \tag{2.15}$$

Because θ is constant, this would demand that t is also constant. However, K_{yz} can be zero, if the $\sin 2\omega t$ and the $\cos 2\omega t$ terms are simultaneously zero. One then finds that the $\cos 2\omega t$ term vanishes if $\sin 2\theta = 0$, which is satisfied when $\theta = n\pi/2$ $(n \in \mathbb{Z})$. The $\sin 2\omega t$ term is zero when $A^2\cos 2\theta + B^2 = 0$, which yields $\theta = \arccos(-B^2/A^2)/2$. When $\theta = n\pi$, one has $\cos 2\theta = 1$ which must be rejected as it predicts $A^2 = -B^2$. However, $\theta = (n \pm 1/2)\pi$ yields $A^2 = B^2$, which is acceptable. Therefore, for K_{yz} to remain constant requires $A = B$ and $\theta = \pm\pi/2$. This can be seen in the following

$$\begin{aligned} K_{yz} &= K_z + K_y \\ &= \frac{m_\mathrm{b}\omega^2}{2}\left[B^2\sin^2(\omega t) + A^2\sin^2(\omega t \pm \pi/2)\right] \end{aligned} \tag{2.16}$$

and

$$K_{yz} = \frac{m_\mathrm{b}\omega^2}{2}\left[B^2 + (A^2 - B^2)\cos^2(\omega t)\right] = \frac{m_\mathrm{b}\omega^2 B^2}{2}. \tag{2.17}$$

A relative phase shift of $\pm\pi/2$ between the horizontal and vertical axes corresponds to what is commonly termed a quadrature phase arrangement. Only in this circumstance does it hold that K_y is a maximum when K_z is a minimum, and vice versa. This maximizes the potential for shuttling energy back and forth between the two axes, a useful property that the bird might be able to exploit to decrease its mean power. Although K_y will be maximal at $t = 0$ and $t = \pi/\omega$, because these maxima are equal, they have no effect on the difference $E_\mathrm{b}(t = 0) - E_\mathrm{b}(t = \pi/\omega)$. In fact, this holds for any value of θ because $\sin^2 x = \sin^2(x + \pi)$, but K_{yz} is constant only when K_y and K_z are in antiphase. As the kinetic energies vary at double the fundamental wingstroke frequency, this occurs when $\theta = \pm\pi/2$.

While variations in K_{yz} can be completely eliminated, it may not be necessary for the bird to do so because, as will be shown, the bird can in some cases also minimize power when $A/B < 1$ with excessive fluctuations in K_z being completely tamed by smaller fluctuations in K_y. This may be preferable as it reduces extraneous energy losses and ameliorates the vibrations transmitted to the head of the bird, which might otherwise make flight an unnecessarily uncomfortable experience compromising visual acuity [33]. Note also that if $A/B > 1$, then fluctuations in K_y may not be adequately absorbed by fluctuations in K_z.

Because birds are expected to have a maximum forward velocity at the end of the downbeat, the phase that makes $\dot{y}(0)$ maximal is chosen $(\theta = -\pi/2)$. Hence, θ can be eliminated from the expressions for y and $\dot{y}$ by writing

$$y = A\sin(\omega t) \tag{2.18}$$

and

$$\dot{y} = A\omega\cos(\omega t). \tag{2.19}$$

The upbeat commences at $t = 0$ when $\dot{y}$ is maximal. The body is then at its maximum height above the ground. The body and the wings are in antiphase on the vertical axis, and the same should also be approximately true of the forward axis. To summarize the findings of this section, power reduction is possible only when $g/B\omega^2 < 1$ and is best achieved by a quadrature phase arrangement.

2.3. Quadrature phase flight

Unless expressly stated otherwise, the analysis now proceeds by assuming quadrature phase applies. In order to assess the biomechanical power in the body, one is interested in determining the maxima and minima (stationary points) of the body energy, necessitating looking for roots of the first-time derivative and inspecting their signs by taking the second-time derivative. Both K_{yz} and U vary sinusoidally but because they do not vary at the same frequency their sum is not a simple sinusoid, demanding that calculus be used. Body energy now reads

$$E_{\mathrm{b}}(t) = \left(\frac{m_{\mathrm{b}}}{2}\right)[2gB\cos(\omega t) + B^2\omega^2\sin^2(\omega t) + A^2\omega^2\cos^2(\omega t)], \tag{2.20}$$

and the first derivative is

$$\dot{E}_{\mathrm{b}} = m_{\mathrm{b}}\omega^3(B^2 - A^2)\sin(\omega t)\cos(\omega t) - m_{\mathrm{b}}gB\omega\sin(\omega t) \tag{2.21}$$

and

$$\dot{E}_{\mathrm{b}} = m_{\mathrm{b}}\omega\sin(\omega t)[\omega^2(B^2 - A^2)\cos(\omega t) - gB]. \tag{2.22}$$

Stationary points exist when either $\cos(\omega t) = gB/\omega^2(B^2 - A^2)$ or $\sin(\omega t) = 0$. The first condition has real solutions only if $\omega^2 \geq gB/|B^2 - A^2|$. When $\omega^2 > g/B$, the smallest value of A that prevents a maximum in E_{b} from arising anywhere but at $t = 0$ occurs when $\cos(\omega t) = 1$, from which the smallest value of A that minimizes the power can be determined. If this is an overriding consideration with the need to maintain visual acuity a secondary concern, this value of A would seem to be optimal:

$$A_{\mathrm{opt}} = B\sqrt{1 - g/B\omega^2}. \tag{2.23}$$

Note that A_{opt} must be real (because $\omega^2 > g/B$) and because $A^2_{\mathrm{opt}} \leq B^2$ at all times, birds have no need to fly with $A > B$. Moreover, for given values of A and B, the optimum angular frequency comes to $\omega_{\mathrm{opt}} = \sqrt{gB/(B^2 - A^2)}$ which exceeds the critical frequency $\omega_{\mathrm{c}} = \sqrt{g/B}$ above which power can be reduced if $A \neq 0$. The optimum ratio of A/B ensures fluctuations in K_y are sufficiently large to avoid excessive fluctuations in K_z, its value depending only on the ratio $\omega/\omega_{\mathrm{c}}$:

$$\frac{A_{\mathrm{opt}}}{B} = \frac{\sqrt{\omega^2 - \omega_{\mathrm{c}}^2}}{\omega}. \tag{2.24}$$

This is plotted in figure 2. The second derivative of the body energy is

$$\ddot{E}_{\mathrm{b}} = m_{\mathrm{b}}\omega^4(B^2 - A^2)\cos(2\omega t) - m_{\mathrm{b}}gB\omega^2\cos(\omega t). \tag{2.25}$$

The condition that $\ddot{E}_{\mathrm{b}} = 0$ at $t = 0$ yields $A = A_{\mathrm{opt}}$, showing that the maximum at $t = 0$ is then also a stationary point of inflection. Now, consider the stationary points that arise when $\cos(\omega t) = gB/\omega^2(B^2 - A^2)$. Using the identity $\cos(2\omega t) = 2\cos^2(\omega t) - 1$, one finds that

$$\ddot{E}_{\mathrm{b}} = 2m_{\mathrm{b}}\omega^4(B^2 - A^2)\frac{g^2B^2}{\omega^4(B^2 - A^2)^2} - m_{\mathrm{b}}\omega^4(B^2 - A^2) - \frac{m_{\mathrm{b}}g^2B^2\omega^2}{\omega^2(B^2 - A^2)} \tag{2.26}$$

and

$$\ddot{E}_{\mathrm{b}} = \frac{m_{\mathrm{b}}}{B^2 - A^2}\left[g^2B^2 - \omega^4(B^2 - A^2)^2\right]. \tag{2.27}$$

If $A^2 < B^2$, the sign of $\ddot{E}_{\mathrm{b}}$ must be negative if $gB < \omega^2(B^2 - A^2)$. This satisfies the condition required for the stationary points to exist, establishing that those corresponding to $\cos(\omega t) = gB/\omega^2(B^2 - A^2) < 1$ must be maxima if $A^2 < B^2$. Considering the alternative situation in which $A^2 > B^2$, the sign of $\ddot{E}_{\mathrm{b}}$ must be positive if $gB < \omega^2(A^2 - B^2)$. Hence, the stationary points at which $\cos(\omega t) = gB/\omega^2(B^2 - A^2) < 1$ must then correspond to minima.

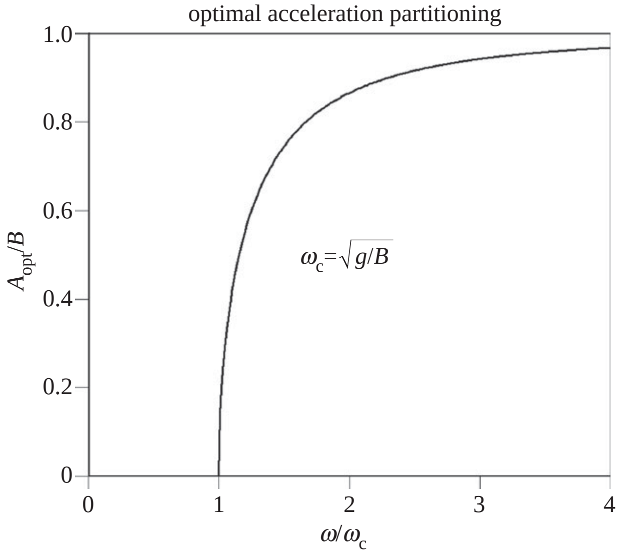

Figure 2. The optimum value of A/B, the ratio of the horizontal and vertical vibration amplitudes, at which body power is minimized and dynamic acceleration on the forward axis attains its smallest acceptable value, see equation (2.24).

Note that the stationary point in E_{b} at $t = \pi/\omega$ has second derivative

$$\ddot{E}_{\mathrm{b}}(\pi/\omega) = m_{\mathrm{b}}\omega^2[(B^2 - A^2)\omega^2 + gB]. \tag{2.28}$$

This is negative if $gB < \omega^2(A^2 - B^2)$ so that when $A^2 > B^2$, which gives rise to stationary points at $\cos(\omega t) = -gB/\omega^2(A^2 - B^2)$, the stationary point at $t = \pi/\omega$ becomes a maximum. This is a point of inflection when $gB = \omega^2(A^2 - B^2)$ corresponding to the maximum value of A at which power is minimized:

$$\frac{A_{\max}}{B} = \sqrt{1 + \frac{g}{B\omega^2}} = \frac{\sqrt{\omega^2 + \omega_{\mathrm{c}}^2}}{\omega}. \tag{2.29}$$

This has a similar form to the earlier expression $A_{\mathrm{opt}} = \sqrt{\omega^2 - \omega_{\mathrm{c}}^2}/\omega$. The bird has minimized its mean body power if $A_{\mathrm{opt}} \leq A \leq A_{\max}$ or equivalently if $\omega^2 < gB/|B^2 - A^2|$. When this condition is satisfied and $\omega^2 > g/B$, flapping flight demands less power than when forward axis vibrations are absent altogether ($A = 0$). For a fixed value of B, this is illustrated in figure 3.

3. Estimation of body power

The calculation of mean body power here involves the integration of E_{b} only as it increases according to (2.8). This can be easily accomplished by subtracting the minima of E_{b} from successive maxima of E_{b}. If $t = 0$ at $t = t_0$, $t = \pi/\omega$ at $t = t_1$ and $t = \pm\arccos[gB/\omega^2(B^2 - A^2)]/\omega$ at $t = t_*$ then only these times need be considered in order to determine the minima and maxima of the body energy variation. With reference to figure 4, it can be seen that there are three distinct cases to consider with stationary points located at the following times:

case 1: $t = t_0$ and $t = t_1$: $\{gB > \omega^2|B^2 - A^2|\}$,
case 2: $t = t_0$, $t = t_1$ and $t = t_*$ $\{gB < \omega^2(B^2 - A^2);\ A^2 < B^2;\ E_{\mathrm{b}}(t_*) > E_{\mathrm{b}}(t_0)\}$ and
case 3: $t = t_0$, $t = t_1$ and $t = t_*$ $\{gB < \omega^2(A^2 - B^2);\ A^2 > B^2;\ E_{\mathrm{b}}(t_*) < E_{\mathrm{b}}(t_1)\}$.

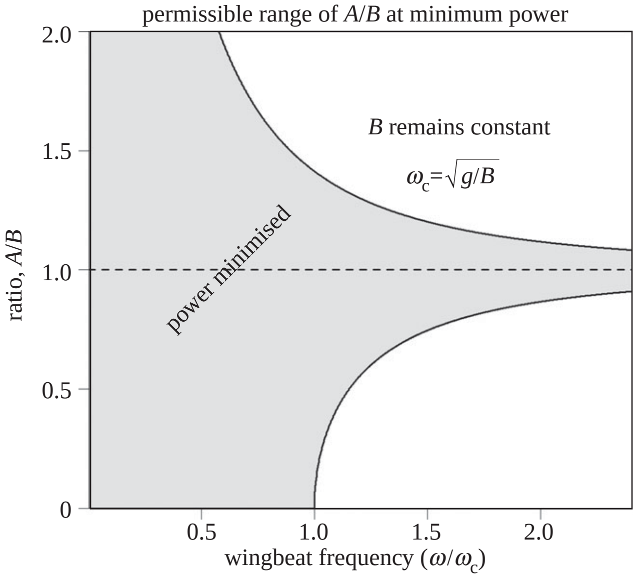

Figure 3. Body power is minimized providing the ratio A/B falls within the interval $\left(B\sqrt{1-\omega_c^2/\omega^2}, B\sqrt{1+\omega_c^2/\omega^2}\right)$ if $\omega > \omega_c$ or $\left(0, B\sqrt{1+\omega_c^2/\omega^2}\right)$ if $\omega \le \omega_c$. The upper and lower limits to A/B each approach unity as $\omega/\omega_c \to \infty$ (see text).

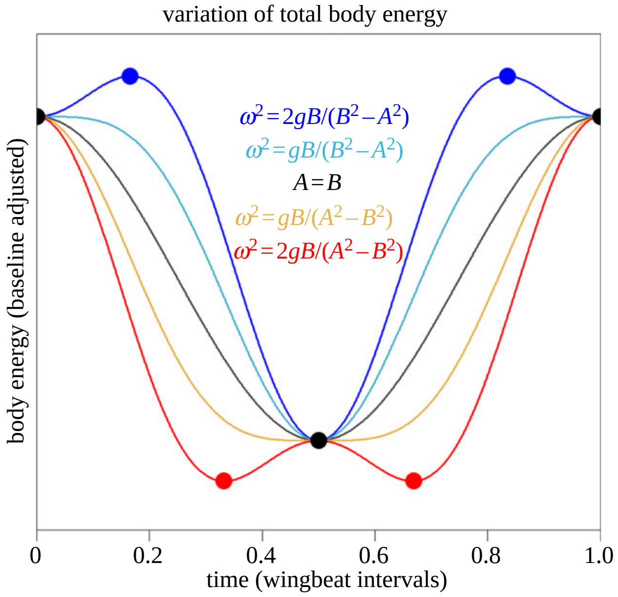

Figure 4. Variation of body energy assuming motions on the forward and vertical axes are in quadrature phase (see text). In this model, the bird provides the energy required for the traces to increase with time but does not recover that energy when it declines. Thus, differences in energy between the stationary points (marked by dots) allow the calculation of mean power. There are two limiting cases: (i) $\omega^2 = gB/(B^2 - A^2)$, when $B^2 > A^2$, and (ii) $\omega^2 = gB/(A^2 - B^2)$, when $A^2 > B^2$ (both plotted) delineating three modes of flight. The case $A = B$ bisects the range in which the mean power attains a minimum, which becomes narrower as wingstroke frequency increases (figure 3). Outside this range, stationary points appear at times intermediate between the midpoint and the start/end points of a wingstroke cycle (at $t = t_*$, upper and lower traces provide examples). (Online version in colour.)

The body energy at t_0 and t_1 is simply

$$E_b(t_0) = \left(\frac{m_b}{2}\right)(A^2\omega^2 + 2gB) \tag{3.1}$$

and

$$E_b(t_1) = \left(\frac{m_b}{2}\right)(A^2\omega^2 - 2gB), \tag{3.2}$$

When $t = t_*$, $\sin^2(\omega t_*)$ is obtained as $1 - \cos^2(\omega t_*)$:

$$\sin^2(\omega t_*) = 1 - \left[\frac{gB}{\omega^2(B^2 - A^2)}\right]^2. \tag{3.3}$$

After some algebra, the total energy of the body when $t = t_*$ is found to be

$$E_b(t_*) = \frac{m_b g^2}{2\omega^2}\left[\frac{B^2\omega^4}{g^2} + \frac{B^2}{B^2 - A^2}\right]. \tag{3.4}$$

3.1. Case 1

This case corresponds to the shaded region in figure 3 and the central traces of figure 4 for which the calculation of mean power is particularly simple:

$$\langle P_{b1}\rangle = \frac{\omega}{2\pi}[E_b(t_0) - E_b(t_1)] = \frac{m_b g B\omega}{\pi}. \tag{3.5}$$

3.2. Case 2

This case corresponds to the zone below the shaded region in figure 3 (see also the uppermost trace in figure 4). The stationary point at t_0 is now a minimum and two new maxima arise at $t = t_*$. Recalling that in this case, $B^2 > A^2$, the power is

$$\langle P_{b2}\rangle = \frac{\omega}{2\pi}[E_b(t_*) - E_b(t_0) + E_b(t_*) - E_b(t_1)] \tag{3.6}$$

and

$$\langle P_{b2}\rangle = \frac{m_b}{2\pi\omega}\left[\omega^4(B^2 - A^2) + \frac{g^2B^2}{B^2 - A^2}\right] \tag{3.7}$$

3.3. Case 3

This case corresponds to the zone above the shaded region in figure 3 (see also the lowermost trace in figure 4). The stationary point at t_1 is now a maximum and new minima arise at $t = t_*$. One has $A^2 > B^2$, and the power now comes to

$$\langle P_{b3}\rangle = \frac{\omega}{2\pi}[E_b(t_0) - E_b(t_*) + E_b(t_1) - E_b(t_*)] \tag{3.8}$$

and

$$\langle P_{b3}\rangle = \frac{m_b}{2\pi\omega}\left[\omega^4(A^2 - B^2) + \frac{g^2B^2}{A^2 - B^2}\right]. \tag{3.9}$$

The poles appearing in the expressions for $\langle P_{b2}\rangle$ and $\langle P_{b3}\rangle$ as $A \to B$ are avoided because when $\omega^2 > gB/|B^2 - A^2|$ one has $A^2 \neq B^2$. It is apparent that the results for cases 2 and 3 are equivalent but for the reversal of sign in the $B^2 - A^2$ terms. Therefore, it would be acceptable to take the modulus of either expression without expressly checking whether $A^2 > B^2$. In the limiting cases where $gB = \omega^2|B^2 - A^2|$, the prediction of case 1 coincides with that of case 2 or 3. For instance, when $A = A_{\text{opt}} = B\sqrt{1 - g/B\omega^2}$ then $B^2 - A^2 = gB/\omega^2$ and it can be seen that $\langle P_{b2}\rangle$ reduces to $\langle P_{b1}\rangle$:

$$\langle P_{b2}^{\text{opt}}\rangle = \frac{m_b}{2\pi\omega}\left[\frac{\omega^4 gB}{\omega^2} + \frac{g^2B^2}{gB/\omega^2}\right] = \frac{m_b g B\omega}{\pi} = \langle P_{b1}\rangle. \tag{3.10}$$

The importance of correctly distinguishing between case 1 and cases 2 and 3 is stressed, because $\langle P_{b2}\rangle$ and $\langle P_{b3}\rangle$ overpredict the true power when $gB > \omega^2|B^2 - A^2|$ and $\langle P_{b1}\rangle$ underpredicts the true power when $gB < \omega^2|B^2 - A^2|$.

3.4. Deriving body power using data from accelerometers

The root mean square (or r.m.s.) value of a quantity is a measure commonly used in physics and engineering and can lend itself to the description of DBA (table 1). As such, it offers an alternative to ODBA and VeDBA. The r.m.s. value of a discrete set of N dynamic single axis accelerations a_dyn is $a_\mathrm{rms} = \sqrt{a^2_\mathrm{dyn}/N}$, and that of a simple sinusoid such as $\psi = \beta \sin(t)$ is

$$\psi_\mathrm{rms} = \sqrt{\langle \psi^2 \rangle} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} (\beta \sin t)^2 \mathrm{d}t} = \sqrt{\frac{\beta^2}{4\pi}\int_0^{2\pi} (1 - \cos 2t) \mathrm{d}t} = \frac{\beta}{\sqrt{2}}. \tag{3.11}$$

Static and dynamic accelerations can be respectively derived from raw acceleration data using low-pass and high-pass filtering techniques. While the static acceleration is useful in determining the vertical, gravity-aligned axis, there are many circumstances where the direction of the forward axis is more ambiguous. However, birds will generally adjust the roll of their bodies during flight so that the static acceleration vector remains dorsally aligned. It is therefore likely that the r.m.s. value of the dynamic sway, $\ddot{x}_\mathrm{rms}$, will be appreciably smaller than the r.m.s. value of the dynamic surge, $\ddot{y}_\mathrm{rms}$. In principle, this allows for reorientation of accelerometry data during post-processing by application of a rotation matrix whose components can be inferred by analysis of the data. A method for achieving reorientation is outlined in appendix A. Estimates of the dynamic surge, $\ddot{y}_\mathrm{rms}$, and the dynamic heave, $\ddot{z}_\mathrm{rms}$, are readily obtained after high-pass filtering of the reoriented acceleration components. These relate to ω, A and B as follows:

$$\ddot{y}_\mathrm{rms} = \sqrt{\langle \ddot{y}^2 \rangle} = \sqrt{\langle (A\omega^2 \sin \omega t)^2 \rangle} = \frac{A\omega^2}{\sqrt{2}} \tag{3.12}$$

and

$$\ddot{z}_\mathrm{rms} = \sqrt{\langle \ddot{z}^2 \rangle} = \sqrt{\langle (B\omega^2 \cos \omega t)^2 \rangle} = \frac{B\omega^2}{\sqrt{2}}. \tag{3.13}$$

Hence, body power can be directly evaluated from r.m.s. heave and surge:

$$\langle P_\mathrm{b1} \rangle = \frac{\sqrt{2} m_\mathrm{b} g \ddot{z}_\mathrm{rms}}{\pi \omega} \tag{3.14}$$

and

$$\langle P_\mathrm{b2,3} \rangle = \frac{m_\mathrm{b}}{2\pi\omega} \left| 2\ddot{z}^2_\mathrm{rms} - 2\ddot{y}^2_\mathrm{rms} + \frac{g^2 \ddot{z}^2_\mathrm{rms}}{\ddot{z}^2_\mathrm{rms} - \ddot{y}^2_\mathrm{rms}} \right|. \tag{3.15}$$

These expressions conveniently obviate the need to double integrate acceleration data in order to obtain the values of A and B directly, which is generally challenging due to the baseline drift introduced when integrating. However, A and B each feature in the true-or-false test $gB < \omega^2 |B^2 - A^2|$ that determines which expression for power is valid. Therefore, a reformulation of the discriminant is also desirable, and because $\ddot{y}_\mathrm{rms}/\ddot{z}_\mathrm{rms} = A/B$ it

Table 1. Variables used in this study.

variable	units	description
$\boldsymbol{a}$	m s^{-2}	acceleration vector
a_rms	m s^{-2}	r.m.s. acceleration
a_dyn	m s^{-2}	dynamic acceleration
A	m	relative forward displacement amplitude
A_opt	m	smallest value of A that minimizes power
B	m	relative vertical displacement amplitude
E_b	J	body energy
$\dot{E}_\mathrm{b}$	J s^{-1}	first-time derivative of body energy
$\ddot{E}_\mathrm{b}$	J s^{-2}	second-time derivative of body energy
f	Hz	wingstroke frequency
f_h	beats min^{-1}	heart-rate
g	m s^{-2}	Earth's gravitational acceleration
K_y	J	relative forward kinetic energy
K_z	J	relative vertical kinetic energy
K_{yz}	J	total kinetic energy
$\dot{K}_{yz}$	J	first-time derivative of total kinetic energy
L	m	dimension of length
M	kg	dimension of mass
m_b	kg	body mass
ODBA	m s^{-2}	overall dynamic body acceleration
ω	rad s^{-1}	wingstroke angular frequency
ω_opt	rad s^{-1}	optimal value of ω
ω_c	rad s^{-1}	first critical value of ω
ω_0	rad s^{-1}	second critical value of ω
P_b	W	biomechanical body power
$P_\mathrm{b}^\mathrm{opt}$	W	optimal biomechanical body power
ϕ	rad	rotation angle
T	s	dimension of time
t	s	time
θ	rad	relative phase angle
U	J	gravitational potential energy
VeDBA	m s^{-2}	vectorial dynamic body acceleration
$\dot{V}_{\mathrm{O}_2}$	ml min^{-1}	oxygen consumption rate
y	m	relative forward displacement
$\dot{y}$	ms^{-1}	relative forward velocity
$\ddot{y}$	m s^{-2}	forward acceleration
$\ddot{y}_\mathrm{rms}$	m s^{-2}	r.m.s. forward acceleration
z	m	relative vertical displacement
$\dot{z}$	m s^{-1}	relative vertical velocity
$\ddot{z}$	m s^{-2}	vertical acceleration
$\ddot{z}_\mathrm{rms}$	m s^{-2}	r.m.s. vertical acceleration

follows that

$$\frac{gB}{\omega^2|B^2-A^2|}=\frac{gB/\sqrt{2}}{|B\ddot{z}_{\mathrm{rms}}-A\ddot{y}_{\mathrm{rms}}|}=\frac{g/\sqrt{2}}{|\ddot{z}_{\mathrm{rms}}-(A/B)\ddot{y}_{\mathrm{rms}}|}=\frac{g\ddot{z}_{\mathrm{rms}}}{\sqrt{2}|\ddot{z}^2_{\mathrm{rms}}-\ddot{y}^2_{\mathrm{rms}}|}. \tag{3.16}$$

It is therefore possible to determine, without knowledge of either A or B, nor indeed ω, the regime in which the bird is flying. $\langle P_{\mathrm{b1}}\rangle$ should be used when $g\ddot{z}_{\mathrm{rms}} > \sqrt{2}|\ddot{z}^2_{\mathrm{rms}}-\ddot{y}^2_{\mathrm{rms}}|$, otherwise $\langle P_{\mathrm{b2,3}}\rangle$ is applicable.

The critical frequency ratio, ω/ω_c, can similarly be translated using (3.13) and the knowledge that $\omega_c=\sqrt{g/B}$

$$\left(\frac{\omega}{\omega_c}\right)^2=\frac{\sqrt{2}\,\ddot{z}_{\mathrm{rms}}}{g}. \tag{3.17}$$

It is also possible to express $\omega/\omega_{\mathrm{opt}}$ using only r.m.s. accelerations:

$$\left(\frac{\omega}{\omega_{\mathrm{opt}}}\right)^2=\frac{\sqrt{2}\,\ddot{z}_{\mathrm{rms}}}{g}\left(1-\frac{A^2}{B^2}\right)=\frac{\sqrt{2}\,\ddot{z}_{\mathrm{rms}}}{g}\left(1-\frac{\ddot{y}^2_{\mathrm{rms}}}{\ddot{z}^2_{\mathrm{rms}}}\right). \tag{3.18}$$

3.5. Relative body power

According to this model, body power retains linearity with wingstroke frequency until, and as illustrated in figure 5, the angular frequency exceeds

$$\omega_0=\sqrt{\frac{gB}{|B^2-A^2|}}. \tag{3.19}$$

This can also be conveniently gauged from r.m.s. accelerations alone because

$$\left(\frac{\omega}{\omega_0}\right)^2=\frac{\sqrt{2}\,|\ddot{z}^2_{\mathrm{rms}}-\ddot{y}^2_{\mathrm{rms}}|}{g\ddot{z}_{\mathrm{rms}}}. \tag{3.20}$$

The expressions for $\langle P_{\mathrm{b2}}\rangle$ and $\langle P_{\mathrm{b3}}\rangle$ can be recast as

$$\langle P_{\mathrm{b2,3}}\rangle=\frac{m_{\mathrm{b}}}{2\pi\omega}\left(\omega^4|B^2-A^2|+\frac{g^2B^2}{|B^2-A^2|}\right) \tag{3.21}$$

and

$$\langle P_{\mathrm{b2,3}}\rangle=\frac{m_{\mathrm{b}}g^2\omega_0^2}{2\pi\omega_{\mathrm{c}}^2}\left(\frac{1+\omega^4/\omega_0^4}{\omega}\right). \tag{3.22}$$

It is now apparent that when $\omega \gg \omega_0$, the response becomes asymptotically cubic at higher wingstroke frequencies, i.e. $\langle P_{\mathrm{b2,3}}\rangle \propto \omega^3$. However, at lower wingstroke frequencies, flight proceeds within the linear regime of (3.5). For case 1, it is possible to write $\langle P_{\mathrm{b1}}\rangle = mg^2\omega/\pi\omega_{\mathrm{c}}^2$, allowing the ratio of $\langle P_{\mathrm{b1}}\rangle/\langle P_{\mathrm{b2,3}}\rangle$ to be expressed in a particularly simple form

$$\frac{\langle P_{\mathrm{b1}}\rangle}{\langle P_{\mathrm{b2,3}}\rangle}=\frac{2\omega^2/\omega_0^2}{1+\omega^4/\omega_0^4}. \tag{3.23}$$

The response is plotted in figure 6 and can be compared with figure 5 where the wingstroke frequency is expressed in units of $\omega/\omega_{\mathrm{c}}$. If $\omega < \omega_0$, then the expression for $\langle P_{\mathrm{b2,3}}\rangle$ is not physically meaningful, and the mean power is always given by $\langle P_{\mathrm{b1}}\rangle$. When $\omega > \omega_0$, power can always be reduced, because the ratio $\langle P_{\mathrm{b2,3}}\rangle/\langle P_{\mathrm{b1}}\rangle$ then exceeds unity. Furthermore, it grows without limit as $\omega \to \infty$.

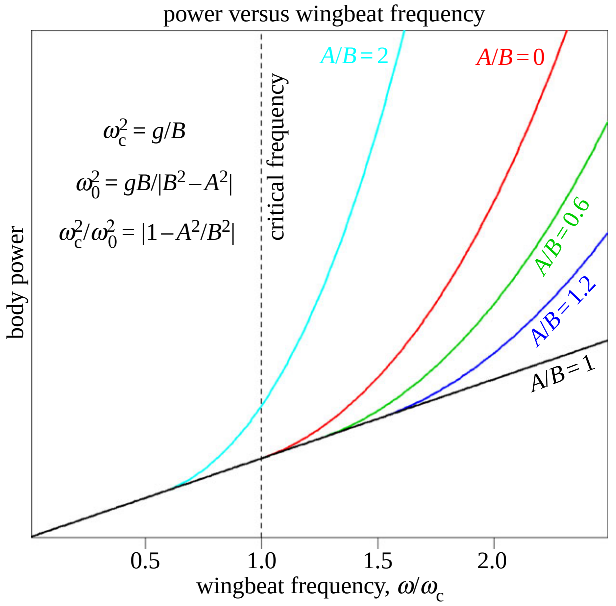

Figure 5. Above a threshold frequency that depends on the ratio A/B, when $A \neq B$ an asymptotically cubic response is inevitable at high frequencies. However, body power is always minimized when $A = B$. See equations (3.5), (3.7), (3.9) and (3.22). (online version in colour.)

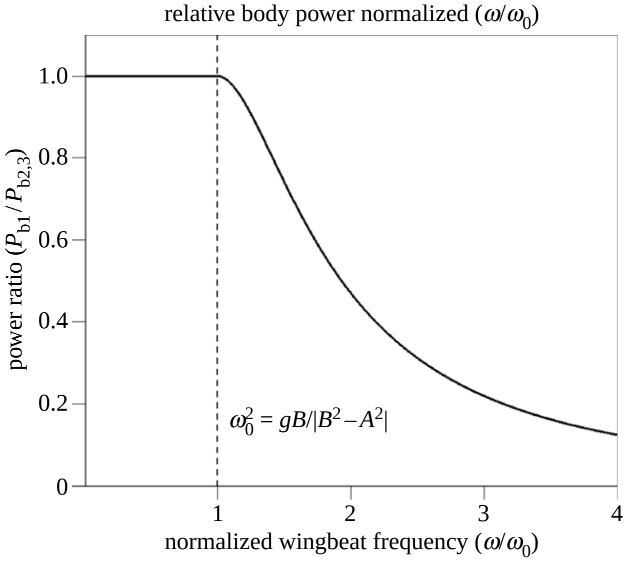

Figure 6. The ratio $\langle P_{\mathrm{b1}}\rangle/\langle P_{\mathrm{b2,3}}\rangle$ as a function of normalized wingstroke frequency ω/ω_0. When $\omega < \omega_0$, forward vibrations are incapable of reducing the mean body power. Note that $\langle P_{\mathrm{b1}}\rangle$ never exceeds $\langle P_{\mathrm{b2,3}}\rangle$.

Power is always minimized when $A = B$ but it is interesting to know how the ratio $\langle P_{\mathrm{b2,3}}\rangle/\langle P_{\mathrm{b1}}\rangle$ grows for other values of A/B when $\omega > \omega_0$. First, note that ω_0 is related to ω_{c} according to

$$\omega_{\mathrm{c}}^2=\omega_0^2\left|1-\left(\frac{A}{B}\right)^2\right|. \tag{3.24}$$

The relative flight cost ratio $\langle P_{\mathrm{b2,3}}\rangle/\langle P_{\mathrm{b1}}\rangle$ can be expressed either in terms of ω/ω_0 or A/B and $\omega/\omega_{\mathrm{c}}$:

$$\frac{\langle P_{\mathrm{b2,3}}\rangle}{\langle P_{\mathrm{b1}}\rangle}=\frac{1}{2}\left(\frac{\omega}{\omega_0}\right)^2+\frac{1}{2}\left(\frac{\omega_0}{\omega}\right)^2 \tag{3.25}$$

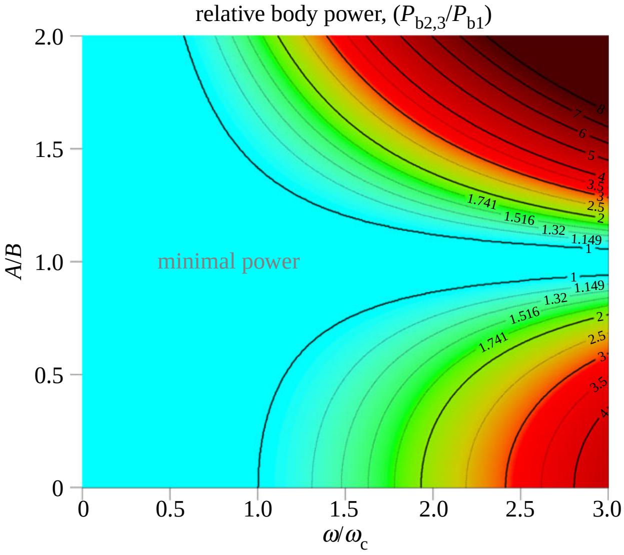

Figure 7. The relative cost of flapping flight normalized to that possible when $A = B$. For example, at a constant wingstroke frequency $\omega/\omega_c = 2$, flight costs more than double when $A/B < \frac{1}{2}\sqrt{2-\sqrt{3}}$ or $A/B > \frac{1}{2}\sqrt{6+\sqrt{3}}$. (Online version in colour.)

and

$$\frac{\langle P_{b2,3}\rangle}{\langle P_{b1}\rangle} = \frac{1}{2}\left[\left(\frac{\omega}{\omega_c}\right)^2 \left|1-\left(\frac{A}{B}\right)^2\right| + \frac{1}{(\omega/\omega_c)^2\,|1-(A/B)^2|}\right]. \tag{3.26}$$

A colour-coded contour plot of this function is presented in figure 7 (online).

4. Non-quadrature phase

We reiterate that this modelling pertains to steady, horizontal flight. The possibility exists that departures from quadrature phase may be advantageous during ascent or descent, but the mathematics in such cases is considerably more involved. Nevertheless, these situations were numerically investigated under the assumption that $A = B$ with an additional power component representing the change in gravitational energy with time, whose mean value can be estimated using an altimeter or GPS device [34,35]. The results are presented in figure 8. It can be seen that predictions of the quadrature phase model are still accurately upheld in most circumstances involving realistic rates of ascent or descent.

Although the optimal arrangement is never far from quadrature phase, the error is sensitive to the rate of ascent, and is asymmetrical in that it grows faster with descent than ascent. This is evident from the plot presented in figure 9. It has been reported that the power requirements of moderate ascending and descending flight in pigeons can be accurately estimated by summing the power required for level flight with the rate of change of gravitational potential [36]. Interestingly, the same study found that a discrepancy did arise for high descent rates but not for high climb rates, descent being clearly more expensive than anticipated. When flying steeply downwards at a descent angle of −60°, the pigeons flew at a horizontal velocity of 3.6 $\mathrm{m\,s^{-1}}$ and a vertical rate of descent exceeding 3 $\mathrm{m\,s^{-1}}$. Hence, one possible explanation for this could be that flight costs during rapid descent are so minor and so rarely encountered that there is little need for birds to acquire biomechanical flexibility that would allow significant deviations from quadrature phase. However, this descent rate is more rapid than that which would be expected if the bird were simply gliding (typically no more than 2 $\mathrm{m\,s^{-1}}$ for a pigeon).

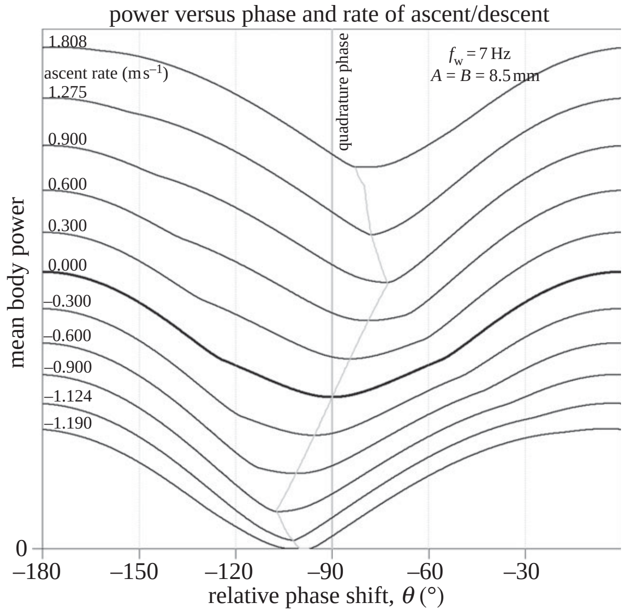

Figure 8. When the bird is ascending or descending, the quadrature phase arrangement is not always optimal. However, the phase θ for which the power is minimized only deviates significantly from −90° during extreme rates of ascent or descent. The results here simulate a bird with a wingstroke frequency, $f_w = 7$ Hz and equal amplitude oscillations on both forward and vertical axes of amplitude 8.5 mm. The locus of points at which the power is minimized at climb rates intermediate between those of the marked traces is also shown.

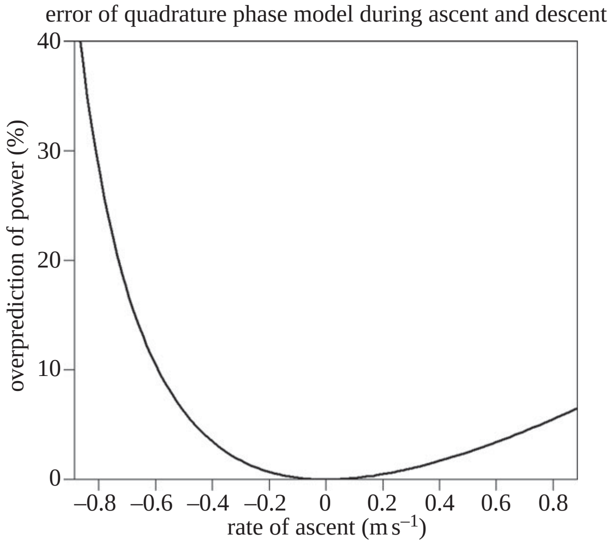

Figure 9. The quadrature phase assumption potentially overpredicts the body power for ascending or descending flight. The error is plotted here for climb rates within the range ±0.9 $\mathrm{m\,s^{-1}}$, where the optimum phase appears to deviate linearly from $\theta = -90°$ in figure 8. The model is relatively accurate for sustainable rates of ascent but errors grow rapidly for high rates of descent.

If more accurate estimates of biomechanical power are required then direct integration is an option, obtaining relative velocities and displacements for the forward and vertical axes from which the individual energy terms can be derived, combining this information with altitude data (if available) to obtain body energy, and calculating power by numerically evaluating the mean rate of energy increase with time, being careful to ignore periods when the total energy of the bird is decreasing. This approach may offer improved precision, particularly when power is not all concentrated at the fundamental wingstroke frequency or when large departures from quadrature phase are expected.

5. Discussion

Despite the considerable complexities involved in flapping flight, by focusing on the consequences for the mechanical motions of the body, this oscillatory energy fluctuation model provides a useful initial step in theoretically underpinning the use of body-mounted accelerometers to estimate the relative costs of horizontal flapping flight in birds or bats. Acceleration-based proxies for the power detectable in the body of an animal during flight have been derived from first principles ((3.5), (3.7) and (3.9)) and in the appropriate units of $\mathrm{ML}^2\mathrm{T}^{-3}$. Within these equations, the DBA formalism is encapsulated very naturally via r.m.s. acceleration ((3.14) and (3.15)), or aRMS. These expressions represent a substantial improvement over attempting to estimate the biomechanical energy expenditure or metabolic rate of flying animals from ODBA or VeDBA alone. The magnitude of ODBA varies with orientation, and different rescaling factors must be applied to single axis projections of ODBA and VeDBA if they are to be used to estimate $\ddot{y}_{\mathrm{rms}}$ or $\ddot{z}_{\mathrm{rms}}$ (appendix B). We point out that aRMS, which is more closely related to VeDBA than ODBA, is just as straightforward to calculate. Furthermore, aRMS may be more universally applicable in future mathematical and empirical studies of animal locomotion. DBA measures lack the units of power and so will always require a direct calibration against the rate of energy turnover. Their use in estimating the biomechanical costs of flapping flight has generally lacked a firm theoretical basis, pays no heed to sensor orientation relative to gravity, ascribes undue significance to accelerations in the horizontal plane and overlooks the significance of wingstroke frequency. As can be seen in (3.22), body power is rather sensitive at times to wingstroke frequency, so may in itself provide a valuable means of gauging flight effort independently of body power estimation.

This analysis furnishes several novel parameters that may provide insights into the kinematics of flight. In particular, it predicts that there may be two regimes of flight with regard to power production and wingstroke frequency and that there may be a transition from slow to moderate intensity flight, when equation (3.23) and figures 6 and 7 suggest power savings may sometimes be possible. For steady horizontal flight involving sinusoidal vibrations on the forward and vertical axes, it has been shown that a quadrature phase arrangement is potentially advantageous. If flight strategies could exploit this, temporarily storing and retrieving energy during each wingbeat cycle, it might be possible for some species to avoid or curb what would otherwise be a third-order sensitivity in mean body power to wingstroke frequency. Due to the ubiquity of predators, the need to catch airborne prey and the general requirement for economy of locomotion, there may have been considerable evolutionary pressure for birds to waste very little energy at wingstroke frequencies exceeding ω_0. Nevertheless, body-mounted accelerometry is not privy to the subtleties of wing flexion, angle of attack and feathering, so this model leaves open the possibility that birds have considerable scope to adjust their flight style without necessarily compromising efficiency.

When birds are flying in the linear regime then equation (3.14), which reflects the costs of combating gravity, shows that only the vertical, gravity-aligned component of the acceleration should enter into the calculation of body power. Although forward accelerations become relevant to power estimation for the asymptotically cubic regime, equation (3.15) shows that their contribution to body power is *subtractive*. This somewhat counterintuitive need to subtract $\ddot{y}_{\mathrm{rms}}$ from $\ddot{z}_{\mathrm{rms}}$ in (3.7) stems from the fact that variations of gravitational energy do not always mask variations in kinetic energy. However, quadrature oscillations in K_y tend to erase fluctuations in K_{yz}, not reinforce them.

While the model directly considers vibrations only on the body of the bird, owing to mechanical coupling, the same kind of oscillations and trade-offs should also apply to the horizontal and kinetic components of the wings. However, because the centre of mass of the wings must travel a much greater distance during each wingstroke than the centre of mass of the body, for any given wingstroke frequency, fluctuations in wing kinetic energy grow quadratically with wingstroke excursion, but variations in wing gravitational potential grow only linearly. Therefore, the onset of the transition between the linear and asymptotically cubic flight power regimes might be generally expected to occur at a lower frequency for the wings than for the body. The kinematics of the wings, which cannot be directly measured by the accelerometer, should generally dominate the overall biomechanical costs of flight. Indeed, kinetic energy fluctuations might easily become a more important consideration than compensating for the gravitational energy losses of each wingbeat. If the gravity terms are neglected, then (3.7) and (3.9) simplify somewhat and predict $\langle P_{\mathrm{b}}\rangle \approx 4\pi^2 m_{\mathrm{b}} f_w^3 |B^2 - A^2|$. This could be especially true of energetic high-speed flight, even though there may then be significant wing retraction and supination to avoid undue aerodynamic drag [37,38]. Because the forces involved in wing retraction tend to cancel on the body due to bilateral symmetry, the costs are hidden from body-mounted accelerometers. Hence, the ratio of perceived body power to true total biomechanical power might be somewhat reduced during intense flight for some species, which may well require the tailoring of flight models to each species in the future, following empirical observations and extensions of the modelling.

A number of other original summary statistics could prove useful to the interpretation of body-mounted accelerometry data obtained from flying birds. The ratio A/B may help to characterize the mode of flight performance and perhaps also evaluate the skill and dexterity of individual birds. With the possible exception of hovering flight when birds may be able to recoup some of the kinetic energy stored in the air during the previous half-stroke, flying animals generally have no means of recovering energy lost to the environment. However, vibrations on the forward axis offer convenient energy storage which may also be exploited to reduce pitching of the body. Many birds use various reflex mechanisms during flight to subdue head vibrations and thereby avoid vision impairment [33]. Body accelerations have a total amplitude $\sqrt{\ddot{y}^2 + \ddot{z}^2} = \omega^2\sqrt{A^2 + B^2}$ which for small A/B can be approximated by $\omega^2 B(1 + A^2/2B^2)$. Hence, the additional loss of visual acuity due to a small A/B ratio would be relatively imperceptible, implying little need for $A/B \rightarrow 0$.

The ratio A/B may also be particularly sensitive to effort in realistic situations, correlating with wingstroke frequency and increasing at higher forward velocities. The relative phase lag θ between the vertical and forward axes may act as a marker of ascending or descending flight, or reflect efforts to synchronize wingstroke frequency with other birds during V-formation flight. We also expect the ratios ω/ω_c, $\omega/\omega_{\text{opt}}$ and ω/ω_0 to be informative regarding flight intensity and flight efficiency. Collectively, these measures may also crudely encode hints as to the altitude at which the bird is flying. Due to the complexities of wing kinematics and anatomical constraints, it is very likely that no simple unifying pattern will adequately summarize all species, but departures from normality are often the most interesting aspects of biological research and so additional parameters can prove very useful in highlighting departures from non-conformity. Therefore, these flight variables may be particularly valuable in helping to unpick the challenges involved in flying efficiently. The static acceleration also offers a potentially illuminating variable for flying animals which has been largely ignored to date. Birds can sustain prolonged banking when circling or jostling for position within a cluster flock [39], and any drift in the mean direction of the momentum vector induces a non-gravitational contribution to the static acceleration. Thus, when the static acceleration deviates appreciably from gravity, it would suggest that the bird is not undergoing steady horizontal flight. However, the converse is not true, because one also expects the static acceleration to tally with gravity during steady non-banking ascending or descending flight. Therefore, the distribution and time variability of the static acceleration can be informative.

Dimensional considerations may allow the results obtained here to be extrapolated to some degree, particularly regarding the estimation of biomechanical power from accelerometry for aquatic animals. Due to the buoyancy afforded by water, the estimation of inertial costs for aquatic species during swimming is not encumbered by gravitational considerations [2]. This invulnerability to gravity suggests that the cost of swimming should correlate with the product of body mass, the period of the swimming stroke and some function of the square of the decomposed r.m.s. accelerations, dependent upon the anatomy of the species under consideration. Locomotion costs in terrestrial animals are likely to be more complex: weight support can either be provided continuously or episodically by the ground.

Naturally, there are limitations to what a body-mounted accelerometer alone can glean about flight. During free-ranging flights, there could be circumstances where basic inferences may be misleading, particularly if the rate of ascent or descent is unknown. In addition, special care may be needed when attempting to disentangle the static and dynamic accelerations for birds using intermittent modes of flight such as flap-gliding or flap-bounding. Accelerometers cannot infer absolute velocities in any direction, and many birds exploit the assistance of thermals, following winds and airflow over uneven terrain, all of which are capable of drastically altering the power requirements of flight. Nevertheless, the present model offers a practical and non-invasive method of extracting from accelerometry a variety of parameters that could be informative concerning flight style and performance, while also providing an explicit procedure for determining biomechanical body power in free-flying birds which may be generally proportional to overall flight power. In the complex processes that transform the biochemical energy of birds into atmospheric vortices, turbulence and heat, aerodynamic costs lie downstream of the biomechanical costs. While it might eventually be possible to incorporate them within an extended model, the formidable challenges of contending with complicated wake patterns, vortex interactions and chaotic flow patterns continue to plague theoretical models, and quasi-static approximations to the Navier–Stokes equations commonly used in aerodynamic analysis inherently limit their accuracy and usefulness [40]. A more realistic near-term goal would be to broaden the present modelling to include wing kinematics and morphology. This will inevitably necessitate the input of anatomical information allowing the body power relationship to accommodate allometric differences between species and also address wing-propelled locomotion in the media of differing densities. Due to the intrinsic complexities, we anticipate that experimental data collected from a variety of species will be required. Birds are graceful aeronauts, skilfully adjusting their posture and technique in ways we have only started to perceive [41]. However, a battery of physiological, biomechanical and aerodynamic techniques can augment and refine one another when quantifying flight costs. These complementary approaches to studying avian energetics hold much promise in arriving at a more unified understanding of the compromises involved when animals fly—whether they are foraging for food, migrating, chasing airborne quarry or evading predators.

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Appendix A. Reorientation during post-processing

When flying in a straight line, the static acceleration $\boldsymbol{a}_s = (\bar{a}_1, \bar{a}_2, \bar{a}_3)$, where $\bar{a}_k$ represents the time-averaged mean of the kth accelerometer channel, should equal the gravitational acceleration, $\boldsymbol{g}$. When this does not hold, it is possible that the bird is turning, undulating, bounding or flying through zones containing vertical air currents. Centripetal acceleration combines with gravity during turns, the direction of the resultant vector determining the degree of banking necessary in order that the bird experiences the net acceleration dorsally so that the forces on the wings are symmetrically balanced. At such times, the increase in the static acceleration relative to gravity is a useful guideline as to the departure from linear motion. For uniform rectilinear motion, the mode of the distribution of the static acceleration magnitude can be identified with gravity. To some degree, this allows for the self-calibration of accelerometry data.

When $||\boldsymbol{a}_s|| \approx ||\boldsymbol{g}||$, a condition that is easily checked, it is straightforward to calculate the vertically aligned component of the acceleration a_{vert} using the scalar projection of $\boldsymbol{a}$ onto $\boldsymbol{a}_s$:

$$a_{\text{vert}} = \frac{a_1\bar{a}_1 + a_2\bar{a}_2 + a_3\bar{a}_3}{\sqrt{\bar{a}_1^2 + \bar{a}_2^2 + \bar{a}_3^2}} \approx \frac{a_1\bar{a}_1 + a_2\bar{a}_2 + a_3\bar{a}_3}{g}. \tag{A 1}$$

This vertical acceleration is the combination of both static and dynamic components, so the dynamic vertical acceleration a_z can be obtained by subtracting the time-averaged value of a_{vert} using

$$a_z = a_{\text{vert}} - \bar{a}_{\text{vert}}. \tag{A 2}$$

Projections of $\boldsymbol{a}$ orthogonal to the vertical axis will then lie in the horizontal plane:

$$a_{\text{hor}_1} = \frac{a_1\bar{a}_2 + a_2\bar{a}_3 + a_3\bar{a}_1}{g} \tag{A 3}$$

and

$$a_{\text{hor}_2} = \frac{a_1\bar{a}_3 + a_2\bar{a}_1 + a_3\bar{a}_2}{g}. \tag{A 4}$$

As before, the dynamic acceleration is obtained by subtracting the static acceleration ($a_{\text{h}1} = a_{\text{hor}_1} - \bar{a}_{\text{hor}_1}$ and $a_{\text{h}2} = a_{\text{hor}_2} - \bar{a}_{\text{hor}_2}$). A means of determining a_x and a_y from $a_{\text{h}1}$ and $a_{\text{h}2}$ is then required. By symmetry, one expects the dynamic acceleration of the forward (y) axis to exceed that on the lateral (x) axis. One way to proceed would be to first determine the fundamental wingstroke frequency using a_z then bandpass filter $a_{\text{h}1}$ and $a_{\text{h}2}$ using fast Fourier transforms so that only frequencies near the fundamental wingstroke frequency are retained. Following this, one could compute the angles $\phi = \arctan(a_{\text{h}2}/a_{\text{h}1})$, compile a circular histogram of the results and use the angle corresponding to the peak in the histogram Φ, to reorient $a_{\text{h}1}$ and $a_{\text{h}2}$ as follows:

$$a_x = a_{\text{h}1}\sin\Phi - a_{\text{h}2}\cos\Phi \tag{A 5}$$

and

$$a_y = a_{\text{h}1}\cos\Phi + a_{\text{h}2}\sin\Phi. \tag{A 6}$$

There is a potential ambiguity in this result concerning the polarities of a_x and a_y. It arises due to the fact that one expects two peaks in the angular histogram separated by π. Therefore, one should also evaluate a_x and a_y using $\Phi \leftarrow \Phi + \pi$. In practice, there may be no need to calculate a_x because it is unlikely to represent interesting information, but the polarity of a_y is potentially important if one is eager to know, for example, how the phase shift between the forward and vertical axes varies with time. This model expects that the displacement on the y-axis will always lag behind that of the z-axis, and hence a_z should always lead a_y, resolving the ambiguity. One can again apply bandpass filtering to a_y and a_z around the detected wingstroke frequency in order to test which value of Φ is appropriate. The phase shift can be accurately measured in the recovered time domain after bandpass filtering using linear interpolation between samples in the vicinity of the positive/negative going zero crossings. If the orientation of the accelerometer is fixed with respect to the body of the bird, then this process need only be performed once, and the value of Φ can then be reused without recalculation.

Appendix B. Relationship between overall dynamic body acceleration, vectorial dynamic body acceleration and r.m.s. acceleration

Consider the instantaneous dynamic acceleration $\boldsymbol{a}_{\text{d}} = (a_x, a_y, a_z)$ derived from a triaxial accelerometer. The generalized mean or L^p-norm of the components of $\boldsymbol{a}_{\text{d}}$ is defined as

$$||\boldsymbol{a}_{\text{d}}|| = (|a_x|^p + |a_y|^p + |a_z|^p)^{1/p}. \tag{B 1}$$

Therefore, the magnitude of $\boldsymbol{a}_{\text{d}}$ according to VeDBA is $\sqrt{a_x^2 + a_y^2 + a_z^2}$, whereas its magnitude according to ODBA is $|a_x| + |a_y| + |a_z|$. Converting to spherical coordinates (r, θ, ϕ), one has

$$a_x = r\sin\theta\cos\phi, \tag{B 2}$$

$$a_y = r\sin\theta\sin\phi \tag{B 3}$$

and

$$a_z = r\cos\theta. \tag{B 4}$$

The magnitude of $\boldsymbol{a}_{\text{d}}$ using VeDBA is thus

$$\begin{aligned}\sqrt{a_x^2 + a_y^2 + a_z^2} &= (r^2\sin^2\theta\cos^2\phi + r^2\sin^2\theta\sin^2\phi \\ &\quad + r^2\cos^2\theta)^{1/2} \\ &= r. \end{aligned} \tag{B 5}$$

This confirms the standard expectation of Euclidean trigonometry and the Pythagorean theorem. However, the magnitude of $\boldsymbol{a}_{\text{d}}$ in the case of ODBA generally disagrees with this because

$$\left(\frac{\text{ODBA}}{\text{VeDBA}}\right)^2 = \left(\frac{|a_x| + |a_y| + |a_z|}{\sqrt{a_x^2 + a_y^2 + a_z^2}}\right)^2 \tag{B 6}$$

and

$$\left(\frac{\text{ODBA}}{\text{VeDBA}}\right)^2 = 1 + 2\frac{|a_x a_y| + |a_y a_z| + |a_x a_z|}{a_x^2 + a_y^2 + a_z^2}. \tag{B 7}$$

Due to the second term, ODBA will exceed VeDBA unless at least two of the three acceleration components are zero. The two will agree only when there is alignment of the acceleration with one of the three measurement axes. Hence, the response of ODBA varies according to orientation.

To find the maximum error in ODBA, let $a_y = a_x + \alpha$ and $a_z = a_x + \beta$ where, without loss of generality, it can be assumed that neither a_x, a_y nor a_z are negative. Now let $\zeta = (\text{ODBA}^2/\text{VeDBA}^2 - 1)/2$ so that the stationary points of ζ will be identically located to those of ODBA/VeDBA:

$$\zeta = \frac{a_x a_y + a_y a_z + a_x a_z}{a_x^2 + a_y^2 + a_z^2} = \frac{3a_x^2 + 2\alpha a_x + 2\beta a_y + \alpha\beta}{3a_x^2 + 2x(\alpha + \beta) + \alpha^2 + \beta^2}. \tag{B 8}$$

Equating to zero the partial derivatives of ζ with respect to α and β gives

$$(a_x^2 + a_y^2 + a_z^2)(2a_x + \beta) = 2(a_x + \alpha)(a_x a_y + a_y a_z + a_x a_z) \tag{B 9}$$

and

$$(a_x^2 + a_y^2 + a_z^2)(2a_x + \alpha) = 2(a_x + \beta)(a_x a_y + a_y a_z + a_x a_z) \tag{B 10}$$

These expressions reduce to

$$(a_x + \alpha)(2a_x + \alpha) = (a_x + \beta)(2a_x + \beta) \tag{B 11}$$

and

$$(\alpha + \beta)(\alpha - \beta) = -3a_x(\alpha - \beta). \tag{B 12}$$

The first condition is satisfied only if $\alpha = \beta$, which also ensures the second is satisfied. When $\alpha \neq \beta$, the second condition holds if $\alpha + \beta = -3a_x$ which cannot be true given that neither a_y nor a_z are negative, which implies that $\alpha + \beta \geq -2a_x$. This leaves only $\alpha = \beta$ and hence $|a_y| = |a_z|$ after restoring moduli. For $|a_x| \to 0$, one then finds that $(\mathrm{ODBA}/\mathrm{VeDBA})^2$ can be no less than 2. This can be seen by letting $\gamma = |a_y| = |a_z|$ and $|a_x| = \epsilon$ with $\epsilon \ll \gamma$:

$$\left(\frac{\mathrm{ODBA}}{\mathrm{VeDBA}}\right)^2 = 1 + 2\left(\frac{\gamma^2 + 2\epsilon\gamma}{2\gamma^2 + \epsilon^2}\right) \approx 2 + 2\epsilon/\gamma \geq 2. \tag{B 13}$$

However, as $|a_x| \to |a_y| = |a_z|$ one finds that $(\mathrm{ODBA}/\mathrm{VeDBA})^2$ can be no greater than 3. This can be seen by letting $|a_x| = \gamma \pm \epsilon$ where, once again, $\epsilon \ll \gamma$ and $\gamma = |a_y| = |a_z|$:

$$\begin{aligned}\left(\frac{\mathrm{ODBA}}{\mathrm{VeDBA}}\right)^2 &= 1 + 2\left(\frac{3\gamma^2 \pm 2\epsilon\gamma}{3\gamma^2 \pm 2\epsilon\gamma + \epsilon^2}\right)\\ &\approx 1 + \frac{2}{1 + \epsilon^2/3\gamma^2} \leq 3.\end{aligned} \tag{B 14}$$

Hence, ODBA/VeDBA is maximized when the acceleration components on each axis have an identical magnitude. Because the minimum is already known to occur when two of the components are zero, one may conclude that ODBA is confined to the range

$$\mathrm{VeDBA} \;\leq\; \mathrm{ODBA} \;\leq\; \sqrt{3}\,\mathrm{VeDBA}. \tag{B 15}$$

It is interesting to ask whether VeDBA can be recovered from historical records of ODBA. This is possible only in an approximate statistical sense, and best results would be obtained when data have been collected from animals whose orientation in space varies considerably or in situations where the orientation of the accelerometer itself is free to drift. In order to determine the rescaling factor, it is first necessary to calculate the mean exaggeration of ODBA relative to the true acceleration magnitude. Due to symmetry, it is sufficient to consider the solid angle $\Omega = \pi/2$ corresponding to the octant $0 \leq \theta \leq \pi/2$, $0 \leq \phi \leq \pi/2$. Although the mean value of VeDBA is simply the vector length r, the mean value of ODBA is

$$\langle \mathrm{ODBA} \rangle = \frac{2}{\pi}\int_{\Omega} \mathrm{ODBA}\,\mathrm{d}\Omega = \int_{\Omega} (|a_x| + |a_y| + |a_z|)\,\mathrm{d}\Omega, \tag{B 16}$$

$$\begin{aligned} &= \frac{2}{\pi}\int_0^{\pi/2}\int_0^{\pi/2} (r\sin\theta\cos\phi + r\sin\theta\sin\phi\\ &\qquad + r\cos\theta)\sin\theta\,\mathrm{d}\phi\,\mathrm{d}\theta,\end{aligned} \tag{B 17}$$

$$\begin{aligned} &= \frac{2r}{\pi}\int_0^{\pi/2} [\sin^2\theta\sin\phi - \sin^2\theta\cos\phi\\ &\qquad + \phi\sin\theta\cos\theta]_0^{\pi/2}\mathrm{d}\theta,\end{aligned} \tag{B 18}$$

$$= \frac{2r}{\pi}\int_0^{\pi/2}\left(1 - \cos 2\theta + \frac{\pi}{4}\sin 2\theta\right)\mathrm{d}\theta, \tag{B 19}$$

$$\begin{aligned} &= \frac{2r}{\pi}\left[\theta - \frac{\sin 2\theta}{2} - \frac{\pi\cos 2\theta}{8}\right]_0^{\pi/2}\\ &= \frac{2r}{\pi}\left(\frac{\pi}{2} + \frac{\pi}{8} + \frac{\pi}{8}\right) = \frac{3r}{2}.\end{aligned} \tag{B 20}$$

Therefore, on average, ODBA exaggerates the true acceleration magnitude by 50% and so, in some circumstances, ODBA data records can be translated into estimates of VeDBA simply using

$$\mathrm{VeDBA} \approx \tfrac{2}{3}\,\mathrm{ODBA}. \tag{B 21}$$

A highly significant linear relationship between these two measures has already been experimentally observed, with the best fit corresponding to VeDBA $\approx 0.014 + 0.6418$ ODBA for units of g [27]. The slope of this empirical relationship agrees with the theoretical value to within 4%. In the same work, the envelope of figure 2 exhibits a wedge distribution whose upper and lower slopes are approximately unity and $1/\sqrt{3}$, corresponding to the anticipated range in error of ODBA due to changes in orientation.

When evaluating r.m.s. accelerations, there is no explicit requirement to calculate vector lengths, but we stress that the Euclidean formulation, as adopted by VeDBA, is implicit in the present modelling. While VeDBA and r.m.s. acceleration are in agreement here, and one would generally expect to find an excellent correlation between them, their magnitudes are anticipated to differ whenever there is any spread in the distribution of the dynamic acceleration data. For complex or aperiodic acceleration profiles, we recommend the r.m.s. method over VeDBA in all cases, because the ambiguity implies that no single rescaling factor will suffice. However, for sinusoidal motion $\psi = \beta\sin(t)$ along a straight line, a simple rescaling is possible. The time-averaging used by VeDBA follows that of ODBA, namely the L^1-norm or arithmetic mean. However, that of the r.m.s. prescription follows the L^2-norm or quadratic mean which, as found previously in (3.11), yields $\langle\psi_{\mathrm{rms}}\rangle = \beta/\sqrt{2}$. If follows from the properties of the generalized means that $\langle\psi_{\mathrm{VeDBA}}\rangle$ will never be smaller than $\langle\psi_{\mathrm{rms}}\rangle$ and its value is

$$\langle\psi_{\mathrm{VeDBA}}\rangle = \frac{\beta}{\pi}\int_0^{\pi}\sin(t)\mathrm{d}t = \frac{\beta}{\pi}[-\cos(t)]_0^{\pi} = \frac{2\beta}{\pi}. \tag{B 22}$$

For this simplified situation, one finds $2\sqrt{2}\langle\psi_{\mathrm{rms}}\rangle \approx \pi\langle\psi_{\mathrm{VeDBA}}\rangle$ and hence

$$\mathrm{aRMS} \approx \frac{\pi}{\sqrt{8}}\,\mathrm{VeDBA} \approx \frac{\pi}{\sqrt{18}}\,\mathrm{ODBA}. \tag{B 23}$$

In applications where approximate alignment of the accelerometer's z-axis with gravity is attempted, small changes in orientation occurring at frequencies that are not rejected by the sampling window will cause ODBA to increase even in the absence of vibration. Because the magnitudes of a_x and a_y are then much smaller than gravity one finds that

$$\left(\frac{\mathrm{ODBA}}{\mathrm{VeDBA}}\right)^2 = 1 + 2\frac{|a_x| + |a_y|}{|a_z|} \tag{B 24}$$

Hence, the lack of rotational invariance in ODBA (as depicted in figure 10) then causes it to respond linearly to tilting of the accelerometer, tending to accentuate the sensitivity of ODBA to activity. Dependent on the moment of inertia there can be a cost associated with periodic adjustments in attitude, as might occur in animals exercising on a treadmill, and ODBA may be sensitive to it. For arbitrary orientations with respect to gravity, ODBA can both exaggerate and underestimate changes in the acceleration magnitude caused by rotation. Almost any acceleration measure is vulnerable to errors when the rotation of a transducer is not limited to low frequencies because it is then impossible to accurately separate the static and dynamic accelerations without information from a gyroscope.

When significant rotation exists, in the absence of a gyroscope, some measure of the variability of the instantaneous magnitude of the total acceleration vector $\boldsymbol{a}$ could

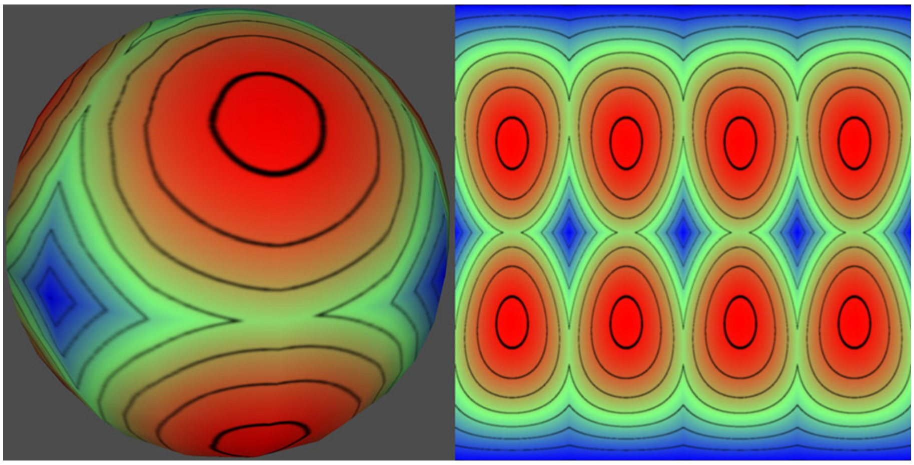

Figure 10. Variation of the error in ODBA with orientation, rising from a minimum of zero (six centres of the square contours) to a maximum of 73.2% (eight centres of the circular contours) with a mean error of 50% (contours at 10% intervals). A single contiguous contour is obtained when ODBA/VeDBA $=\sqrt{2}$. (Online version in colour.)

offer an alternative proxy for biomechanical effort. For instance, one might calculate the standard deviation of $\sqrt{A_x^2+A_y^2+A_z^2}$ for all the raw outputs of the accelerometer falling within some time interval. This could prove informative whenever a significant component of animal activity involves body rotation. Because accelerometers remain sensitive to gravity even within buoyant media, this may be especially useful in the context of aquatic animals as they are not constrained by gravity when swimming underwater. In circumstances where the dynamic acceleration is extremely small, activity can also be estimated by quantifying the rate of body reorientation $\mathrm{d}\phi/\mathrm{d}t$. This can be approximated as $\Delta\phi/\Delta t$ using pairs of static acceleration vectors $\boldsymbol{A}_{s1}=(A_{x1},A_{y1},A_{z1})$ and $\boldsymbol{A}_{s2}=(A_{x2},A_{y2},A_{z2})$ separated by a fixed time interval Δt appropriate to the rotation rates of interest:

$$\Delta\phi=\arcsin\frac{||\boldsymbol{A}_{s1}\times\boldsymbol{A}_{s2}||}{||A_{s1}||\cdot||A_{s2}||} \tag{B 25}$$

and

$$\Delta\phi=\arcsin\sqrt{\frac{(A_{y1}A_{z2}-A_{y2}A_{z1})^2+(A_{x1}A_{z2}-A_{x2}A_{z1})^2+(A_{x1}A_{y2}-A_{x2}A_{y1})^2}{(A_{x1}^2+A_{y1}^2+A_{z1}^2)(A_{x2}^2+A_{y2}^2+A_{z2}^2)}}. \tag{B 26}$$

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Paper III

An implantable instrument for studying the long-term flight biology of migratory birds.

Robin J. Spivey & Charles M. Bishop

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REVIEW OF SCIENTIFIC INSTRUMENTS **85**, 014301 (2014)

An implantable instrument for studying the long-term flight biology of migratory birds

Robin J. Spivey[a] and Charles M. Bishop[a]
Department of Biological Sciences, Bangor University, Gwynedd LL57 2UW, United Kingdom

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The design of an instrument deployed in a project studying the high altitude Himalayan migrations of bar-headed geese (*Anser indicus*) is described. The electronics of this archival datalogger measured $22 \times 14 \times 6.5$ mm, weighed 3 g, was powered by a $\frac{1}{2}$AA-sized battery weighing 10 g and housed in a transparent biocompatible tube sealed with titanium electrodes for electrocardiography (ECG). The combined weight of 32 g represented less than 2% of the typical bodyweight of the geese. The primary tasks of the instrument were to continuously record a digitised ECG signal for heart-rate determination and store 12-bit triaxial accelerations sampled at 100 Hz with 15% coverage over each 2 min period. Measurement of atmospheric pressure provided an indication of altitude and rate of ascent or descent during flight. Geomagnetic field readings allowed for latitude estimation. These parameters were logged twice per minute along with body temperature. Data were stored to a memory card of 8 GB capacity. Instruments were implanted in geese captured on Mongolian lakes during the breeding season when the birds are temporarily flightless due to moulting. The goal was to collect data over a ten month period, covering both southward and northward migrations. This imposed extreme constraints on the design's power consumption. Raw ECG can be post-processed to obtain heart-rate, allowing improved rejection of signal interference due to strenuous activity of locomotory muscles during flight. Accelerometry can be used to monitor wing-beat frequency and body kinematics, and since the geese continued to flap their wings continuously even during rather steep descents, act as a proxy for biomechanical power. The instrument enables detailed investigation of the challenges faced by the geese during these arduous migrations which typically involve flying at extreme altitudes through cold, low density air where oxygen availability is significantly reduced compared to sea level.
[http://dx.doi.org/10.1063/1.4854635]

INTRODUCTION

Obtaining detailed physiological and biomechanical measurements from free-ranging birds has become increasingly feasible in recent years due to advances in electronics and transducer technology.[1–3] Miniaturisation and power reductions have allowed instruments to be implanted into the abdominal cavity of birds, recording heart-rate for many months.[4,5] Real-time QRS detection from the electrocardiogram (ECG) signal is an error-prone process and notoriously challenging when weight, size, and power consumption are prime considerations.[6] The present design successfully implemented an alternative approach which has only very recently become viable for year-long deployments: the storage of raw ECG and subsequent signal post-processing of arbitrary sophistication to obtain robust measures of heart-rate following recapture. Since immense amounts of memory are required, the possibility arises of simultaneously storing additional information from other high data-rate transducers such as accelerometers. For animals whose recapture is not impractical, this archival approach to data collection can collect vast biologically informative datasets, overcoming the data restrictions associated with remote download systems.

Bar-headed geese (*Anser indicus*) are evolutionarily adapted to flight at high altitudes owing to the geologically recent formation of the Himalayas cutting directly across their annual migration routes.[7] Although evolution could have tackled this problem by favouring longer migratory routes to the east of the Qinghai-Tibetan plateau, natural selection has instead conferred on this species an extraordinary ability to tolerate hypoxia. While Brent geese (*Branta bernicla*) apparently struggle to cross the ice-caps of Greenland at 2500 m,[8] bar-headed geese are able to fly comfortably at twice (and possibly even three times) that altitude. Anecdotal eyewitness accounts by mountaineers climbing the treacherous Annapurna massif, which forms a natural 23 km wide barrier to goose migration, have reported bar-headed geese circling overhead at altitudes of 7000–8000 m.[9] However, such events may be relatively infrequent and dependent upon favourable weather conditions. General results and two record altitudes (6540 m and 7290 m) from GPS satellite tags suggest that Himalayan crossings more typically involve maximum altitudes of between 5000 m and 6000 m, with flight tending to follow the valleys.[10]

The detailed study of the complex migrations of birds such as bar-headed geese demands sophisticated, high performance instrumentation. This work describes the design of a compact, ultra-low power miniature archival datalogger for abdominal implantation. The instrument was first deployed during the summer of 2010, the design having been undertaken over the course of the previous 12 months. The system was capable of monitoring body temperature, atmospheric

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[a] Authors to whom correspondence should be addressed. Electronic addresses: r.spivey@bangor.ac.uk and c.bishop@bangor.ac.uk

pressure, the Earth's geomagnetic field, recording ECG continuously, and triaxial accelerometry periodically. Since the flight corridor of the bar-headed geese between Mongolia and the Himalayan crossing into India happens to run parallel to the horizontal projection of the geomagnetic field, magnetometry could permit estimates of latitude, even for an implanted system. In addition, several systems were mounted on neck collars and deployed on Whooper Swans (*Cygnus cygnus*) in a pilot study intended to investigate the practicality of intelligently managing acceleration data collection during flight.

MECHANICAL CONSIDERATIONS

GPS tracking devices communicating results in real-time via satellite telemetry had established by 2009 that bar-headed geese do not all spend the winter in India with a minority content to settle into valleys in southeastern Tibet.[11,12] However, the weight of the GPS backpacks may have contributed to the reluctance of those birds to follow the main flocks into India. Therefore, at the outset of this project, there was a need to attempt to keep the weight and volume of the instrument to a minimum. In order to reliably collect ECG so as to permit heart-rate measurements, the logger had to be implantable. This imposed the additional need for a biocompatible housing. An initial design request for a flashing LED was intended to confirm the continuing functioning of the logger at the time of surgical implantation. To achieve both goals, transparent perfluoroalkoxy (PFA) tubing was chosen (Polyflon, Stone, Staffordshire, UK). Cut to 56 mm lengths, the ends of the tubes were sealed by titanium electrodes providing ECG pick-up. Titanium is a low density metal and PFA is a fluoropolymer similar to polytetrafluoroethylene (PTFE). These materials are highly inert and widely used in medical implants. The design of a sealing mechanism between the PFA tubing and the electrodes was conducted in collaboration with a company that machined the mechanical components for this project (Beaumaris Instruments, Anglesey, UK). A small board incorporating a combined pressure and temperature sensor was mounted on an external recess of one of the electrodes. This allowed the communication of ambient atmospheric density which would not have been possible from within a rigid, sealed housing.

DESIGN OF ELECTRONIC CIRCUITRY

Instrument design centred around a micro SD card for storage and a microcontroller (μC) programmed in C making use of inline coding techniques and assembly language macros to optimise for speed and power consumption. The first step during development was to assess whether to perform ECG beat detection in real-time, as has been the traditional approach in the field study of animals,[6] or whether the continuous logging of raw ECG was feasible. Assembler code was used to program an 8-bit μC (PIC16LF872, Microchip, Chandler, Arizona, USA) to control a SD card over a serial peripheral interface (SPI). This allowed its power requirements to be investigated under a variety of operating conditions. Data could be stored with good energetic efficiency but the standby current of the SD card during inactivity was sufficient to fully drain the preferred battery over the course of a year. Specifications state that around half a second is required for initialisation of an SD card following power-up. Since the initialisation current could be as high as 50 mA, this posed another difficulty. As the internal RAM of most μCs is rather limited, it was decided that an intermediate buffer would be required to hold data, and power would be completely withdrawn from the micro SD card under the control of a P-channel MOSFET when it was not in use. Dynamic RAM offered ample memory capacity but the complexity of the interfacing and the need for refresh cycles was unnecessarily problematic. Serial memory devices were considered but neither static RAM (SRAM) nor ferroelectric RAM was available with sufficient density, and serial Flash and EEPROM drew relatively large currents. A parallel SRAM of 1 MB capacity offered a good overall compromise in terms of performance and power consumption, with a standby current of just 2 μA and operating current of less than 2 mA at 1 MHz (CY62158, Cypress, San Jose, California, USA). However, its control required an 8-bit data bus and a 20-bit address bus, which was not easily driven using a low-end 8-bit μC. Thus, Microchip's 64 pin PIC24FJ128GA106 was selected for its enhanced I/O, superior processing throughput, low power consumption, flexible sleep and standby modes, multiple SPI interfaces, 10-bit A/D conversion capability, 128 KB program memory, and 16 KB of internal RAM. This processor was capable of directly driving the data bus and twelve of the address lines to the SRAM, along with handshaking lines. A commonly available serial-in, parallel-out shift register (74HC164) was used to generate the remaining eight address lines. These were assigned to the uppermost addresses so that they only needed to be changed as 4 KB page boundaries were crossed. ECG and accelerometry data had a high throughput and were asynchronously collected into 4 KB blocks of the internal RAM (one block for ECG and two for accelerometry) and flushed to pages in the external RAM once filled. Due to the responsiveness of the parallel SRAM and the speed of the processor, this could be accomplished without any pause or delay in either the ECG or the accelerometry sampling.

ECG amplifier

Due to the limited bandwidth of the ECG signal (2–64Hz passband), it was possible to use ultra-low power operational amplifiers drawing only 1 μA per op-amp (AD8504, Analog Devices, Norwood, Massachusetts, USA). Given the limited 7 kHz gain-bandwidth product of these devices and the need for a high order filtering cut-off so that the digitisation sample rate could be minimised, a two-stage approach was used for amplification with gain set to 22 on the first stage and 43 on the second stage, resulting in an overall gain approaching 1 V/mV. A single pole high pass filter was implemented in the first stage and a third order low pass filter with a Q-factor of 2.7 was used on the second stage. The input impedance of the ECG amplifier was several MΩ and the output signal was sampled at $32768/182 \approx 180$ s/sec, just above the Nyquist rate required for a 64 Hz signal and to faithfully capture QRS complexes. The ECG amplifier circuit required only about 7 μA when operating which was easily driven by a port of the μC, a RC filter being added as a precaution against system noise.

Accelerometer

A "nano" triaxial accelerometer (LIS331DLH, ST Microelectronics, Geneva, Switzerland) with on-board 12 bit digitiser supporting SPI output update rates as high as 1 kHz and with a range of $\pm 8g$ was chosen. Using capacitive bridges as sensing elements, its current consumption was 250 μA when active and 1 μA in power-down mode. This compared favourably with commercially available alternatives at the time but was expensive to run compared to the ECG circuit, even including the burden on the processor due to regular interrupt driven ECG sampling and data buffering. Continuous activation of the accelerometer would have completely discharged the battery in $3\frac{1}{2}$ months. Though flight activity could have been intelligently detected in firmware, it was felt that data on background activity of the geese was useful to collect. Therefore, the decision was taken to collect data from the accelerometer every 2 min. Given the buffering arrangement with internal RAM, ~18 s of data would fill 8 KB or two pages in external RAM. This resulted in a duty cycle of 15% which would only drain about half the battery.

Pressure and temperature

A barometer was crucial to the study of the trans-Himalayan flights, allowing altimetry and rate of ascent estimation. The transducer selected (MS5540-C, Intersema, Bevaix, Switzerland) was capable of measuring absolute pressure to a resolution of 0.1 mbar and an absolute accuracy of ± 1.6 mbar throughout the range 10–1100 mbar, encompassing all possible experimental changes in atmospheric pressure with altitude. Equipped with a 16 bit ADC, it featured a built-in temperature sensor and calibration registers programmed at the factory prior to shipping. The temperature sensor was needed to refine the calculation of atmospheric pressure and also record the internal body temperature of the goose, providing insights into episodes of intense flight and environmental changes such as sudden changes in wind conditions, as, for instance, might occur due to ridge soaring. The sensing element was supplied coated in a layer of gel claimed to be waterproof to a depth of 100 m which was covered in a layer of protective medical grade silicone. The standby current of the device was less than 0.1 μA. Its serial output was multiplexed with the SPI bus used by the accelerometer since pressure and temperature measurements were only required every 30 s so simultaneous collection of accelerometry with barometry could be avoided. The processor was required to actively generate a 32 kHz square wave for clocking the barometer. This was possible using the built-in output compare module but meant the processor could not enter sleep mode during the 35 ms needed for each temperature or pressure reading. To conserve power, the processor clock was reduced from 8 MHz to 1 MHz at these times.

Magnetometer

The intensity of the Earth's geomagnetic field ranges between 0.25 and 0.65 Gauss. Along the migratory route of the bar-headed geese it varies from 0.43 Gauss in central India to 0.6 Gauss in Mongolia. It is quite possible that the birds are more sensitive to changes in field inclination than intensity. Inclination varies considerably over the same route, between about 20° and 70°. The datalogger was designed to accept a triaxial digital magnetometer (HMC5843, Honeywell, Morristown, New Jersey, USA), however, its performance proved somewhat erratic on some loggers during trials and so only a minority of instruments were fitted with it during manufacture. A ferromagnetic spring within the latching mechanism of the micro SD connector or magnetic fields generated by the logger itself could also have interfered with measurements. Being cylindrical in shape, the dataloggers were free to rotate within the abdominal cavity which may have resulted in some internal movement of the battery wires in the vicinity of the sensor. The combined influence of these factors may have caused the readings obtained to vary according to changes in orientation of the instrument.

Power

A 3.7 V, $\frac{1}{2}$ AA sized Lithium Thionyl Chloride battery (ER14250, Omnicel, Phoenixville, Philadelphia, USA) was used as an energy source. Tests determined its capacity to be somewhere between 800 and 1000 mAh at a typical operating currents. Linear regulators (TPS78228 and TPS78223, Texas Instruments, Dallas, Texas, USA) rated at 150 mA output current and 1 μA quiescent current were used to generate voltage rails of 2.8 V and 2.3 V. The latter provided core power to the μC, avoiding the need to enable the built-in voltage regulator which would either have drawn a high current during sleep or incurred an unacceptably lengthy start-up delay as it was re-enabled on waking up. Provision was made for the processor to monitor the battery voltage. The output current capability of the battery varied according to pulse duration but was capable of sustaining 20 mA until deeply discharged. Mean currents were kept below this level by episodically pausing in sleep mode as contents of external SRAM were being transferred to the micro SD card.

Circuit layout and mechanical assembly

Electronic circuitry was laid out on three printed circuit boards (PCBs). One was a small circular board of diameter 10 mm mounting the pressure/temperature transducer and a decoupling capacitor. This was externally mounted at a right angle to the other boards within a recess inside one of the titanium electrodes and connected via a 6-way, 0.05 in. pitch connector passing through a slot in the electrode to one of the other two boards, see Fig. 1. Once soldered into position, the slot was sealed against ingress using epoxy resin adhesive. The other two boards were of the same rectangular shape and size (22 mm × 14 mm) and were stacked above one another with the micro SD card connector sandwiched in between. A 22 position 0.05 in. pitch connector in a dual-row

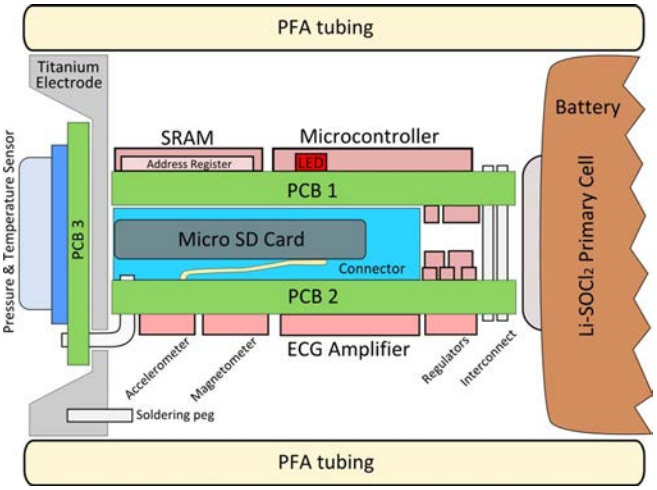

FIG. 1. Mechanical assembly of the logger showing the three PCBs (4 layer boards, FR4 substrate, thickness 0.8 mm), their interconnections, the locations of the sensors and circuit elements, and their physical positions relative to one another. Programming of firmware was achieved via five prominent pins of the primary interconnect using a PicKit3. Internal boards were protected by dipping in wax. Putty was used to prevent the battery from sliding back and forth within the PFA tubing which might otherwise cause spurious impacts to be transmitted to the accelerometer.

FIG. 2. Top left: titanium electrodes and view of the sensor board. Top right: with pressure/temperature sensor attached through the slot in the titanium electrode (magnetometer also fitted). Bottom left: Top view showing the recess of the titanium electrode sealed with silicone. Bottom right: Extraction of the logger from the housing following recapture. Micro SD cards (15 × 11 mm) are intended to provide a sense of scale.

2 × 11 arrangement was used to join the two boards electrically, running width-wise along the edge of the board opposite the end to which the electrode board attached. The width of the assembly was intended to match the diameter of the battery so that all components could fit tightly within a tube to reduce space and weight. The uppermost board was used to mount the 64 pin μC, the 48-pin external SRAM, and the 14-pin address register, components sharing many interconnections. Oscillator-related components were positioned underneath this board. The high density of this PCB required manual tracking on four layers taking several days. An initial solution was found using a slightly enlarged PCB area with the design progressively reduced in size until further space savings became very difficult. This took several weeks and the outcome was used to determine the dimensions of the second board which, like the first board, was populated with components on both sides. On the innermost surface was placed the micro SD card connector, its high-side switching MOSFET, glue logic for the barometer, and some passive components. The ECG circuit, accelerometer, magnetometer, linear regulators, and the majority of the passive components were placed on the underside. This second board was not quite as dense as the first but also required manual tracking on four layers. It was to this board that the barometer was soldered. The titanium electrodes could not be soldered to directly so metal pegs were tapped into drilled holes. This provided a reliable interference fit which required no additional adhesive. Photographs of the physical assembly are provided in Fig. 2.

FIRMWARE DESIGN

The PIC24FJ128GA106 μC contains a wide range of peripheral modules which can be individually enabled and disabled to save power. An in-built RC oscillator runs at ∼8 MHz and allows the execution of code to be resumed rapidly after waking from sleep without needing to wait for a phase-locked-loop (PLL) to settle. In order to achieve extremely low power consumption during ECG sampling, low latency sleep recovery was required. This particular design consideration featured prominently in the selection of this μC. An external 32 kHz crystal oscillator was used to provide accurate timing, generating interrupts at the ECG sampling rate. This oscillator consumed very little power but sometimes required several seconds to stabilise after application of power. A flowchart for the firmware is provided in Fig. 3. Accelerometry was collected when a hardware line signalled the availability of a new sample. Other measurements were synchronised to the ECG sampling with various flags and status registers being used to coordinate background operations.

Once the processor was brought out of reset, pin functions and mappings were configured, peripherals were initialised, and time was allowed for the 32 kHz oscillator to stabilise. The firmware then proceeded to establish communications with the micro SD card by first activating the MOSFET powering the card, allowing time for it to power-up, then engaging in preamble. The SD card was then interrogated via a SPI link to ensure that it was functioning correctly and of the expected type, etc. Initial transactions were carried out at a μC clock rate of 1 MHz but once the SD card was properly initialised, the μC clock rate was raised to 16 MHz using the PLL allowing the SPI data rate to be increased from 256 kb/s to 8 Mb/s. The boot records were then read and the contents of their registers used to determine such things as the number of bytes per sector, sectors per cluster, and number of entries in the root directory. This provided sufficient information to access the file allocation table (FAT), two copies of which are usually present. Errors can easily arise when one copy is being modified and power is interrupted, as might happen due to the card being ejected. This sensible precaution, however, is not true of the root directory, only one copy of which exists.

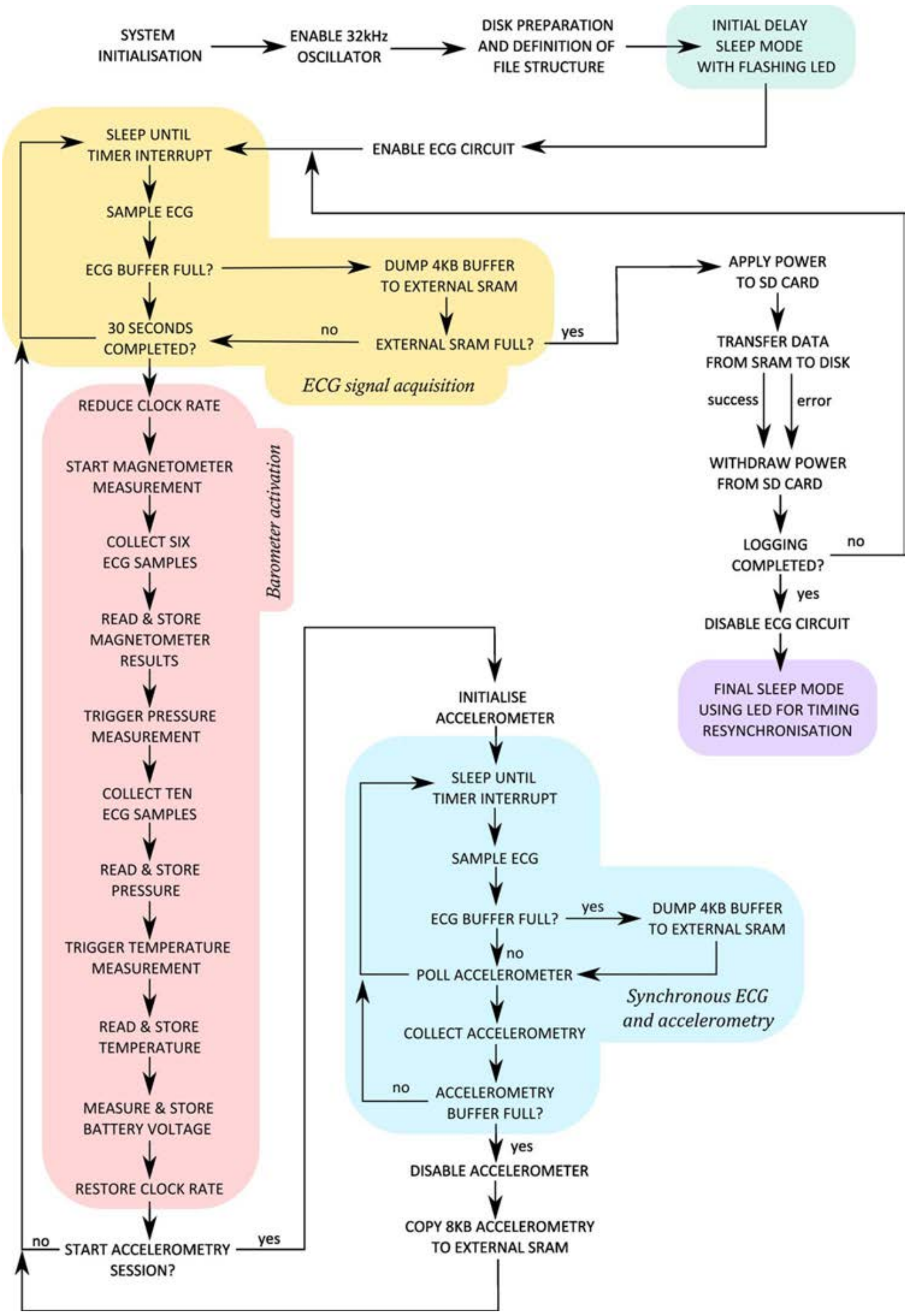

FIG. 3. Flowchart showing the sequence of primary tasks performed by system firmware.

In order to streamline the logging of data, minimise battery drain, and reduce the risk of programming errors, the simplest possible storage arrangement was used involving writing fresh data to consecutive sectors on the SD card starting from the first available data sector. This resulted in a particularly simple FAT structure involving a consecutive sequence of incrementing cluster references until the last cluster of each file was reached. The file organisation in the root directory reflected this simplicity with a distinct file name being assigned to each consecutive gigabyte of logged data and no other files, folders, or directories being present. For a typical 8 GB card (which actually contains 8 billion bytes rather than 8 GB, not all of which is available for data storage), this resulted in seven files of exactly 1 GB and an eighth file of size 388 MB. This reduction in capacity was acceptable as the memory requirement for a full year's data storage was slightly less than 7 GB. In this way, data recovery was extremely straightforward, involving only removal of the SD card from its holder and insertion into a PC which could directly access the data in each of the seven relevant files. Disk preparation typically took 60 s, including deliberately inserted delays to reduce the mean current draw from the battery to an acceptable level. This would only consume ~0.04% of the total battery charge.

After the preparation of the SD card, a sleep mode lasting 25 days was entered where the battery drain was typically reduced to about 6 μA. This allowed time for the instruments to be assembled, shipped to Mongolia, and transported 400 km to a remote lake. Geese were ushered ashore using a flotilla of kayaks, and corralled into a net. After ethylene oxide sterilisation and travelling over rough terrain to the catch site 400 km remote from Ulaanbaatar, instruments whose LEDS were still flashing correctly were implanted into captured geese by a veterinary surgeon. Once the effects of anesthesia had abated, geese were released back to the lake. Implantation reduces adverse effects on animals over the long-term compared to external attachments.[13]

Software was written for the PC to strip out the binary format data logged to the micro SD cards into distinct files, a second program was used to display the data, and a third to extract heart-rate from the raw ECG. Various scripts were then written in R to further process and analyse the data.

A speed-optimised subroutine was used to transfer 4 KB pages of data quickly to external SRAM. This involved briefly increasing the μC clock rate from 8 MHz to 32 MHz and utilising the Parallel Master Port of the μC which automatically performed the data transfer and the strobing of control signals. Whenever the external RAM became full, data were written to the SD card in sector bursts by specifying the address of the first sector and using the *write_multiple_sector* command. Firmware also kept track of the current sector number for the next cycle of writing. In this way there was no need to call on library routines for opening, accessing, and closing files, which have additional overheads, and no need to access the FAT or the root directory again after the initial preparation of the SD card.

Three seconds were typically required to write 1026 KB of data to the SD card, including inserted delays to reduce mean current drawn from the battery. A μC clock rate of 16 MHz was used during data transfer as it offered superior energy efficiency to the alternative of 32 MHz. If any error condition was detected, data transfer was immediately aborted and logging resumed. This provided a safeguard against momentary loss of electrical contact due to the mechanical bounce of the fingers within the SD card and also allowed some data collection to continue when batteries were so discharged as to be incapable of sustaining an output current of 20 mA for very long. The external SRAM buffer would refill in 4231.5 s (70.525 min), collecting 744 KB of ECG digitised at 8 bits/sample along with 280 KB of 12-bit triaxial accelerometry collected at a nominal rate of 100 Hz in 35 blocks of 8 KB spanning $\sim$18 s each. To conserve memory and reduce power, pairs of 12 bit triaxial accelerometry samples were packed into packets of 9 bytes prior to being buffered within internal RAM. Since the sample rate of the accelerometer was not accurately set by the transducer itself, and drifted a little with time and temperature, the duration of each block of accelerometry in ECG samples was appended to the accelerometry in the two spare bytes left over after 910 packets of data had been placed in the 8 KB accelerometry buffer. In this way, the true accelerometer sample rate could be determined to an accuracy of 0.016%. In addition to the data in external SRAM, a 2 KB internal RAM allocation was used to hold raw barometer readings (pressure and temperature) along with magnetometer measurements. These results were collected every 30 s, data being manually clocked out under firmware control. The μC clock rate was dropped to 1 MHz at this time, and fresh measurements took less than 0.1 s to collect. This internal buffer also stored calibration registers for the barometer, a battery reading, and an absolute time stamp in units of ECG sampling interruptions since logging began (these interrupts were always enabled and were assigned a high priority so that they were never skipped, even though the ECG signal was not sampled during disk writes). This internal RAM buffer was written to the SD card immediately after the data from external SRAM had been written. A *write_multiple_end* command then instructed the SD card to transfer its buffer contents to non-volatile memory. Once this was accomplished, power was withdrawn from the card whereupon datalogging was resumed.

DISCUSSION

The earliest trans-Himalayan flight recorded by this instrument occurred in late 2010. This system may well have been the first implantable datalogger design capable of collecting year-round continuous ECG from a flying animal. To the best of our knowledge, the archival recording of ECG for a full year has never been attempted before on any animal, although a system relaying beat intervals telemetrically was capable of operating for several years.[14] The data collected from the present instrument design will allow the long-term study of avian migration in unprecedented detail. Comparisons will be possible between power estimated from heart-rate combined with knowledge of body and/or heart mass[15] and power estimates obtained purely from measurements of bodyweight and RMS vibrations collected from a body-mounted accelerometer.[16] Results and findings are currently being prepared for publication elsewhere.

As oxygen consumption is generally proportional to the square of the heart-rate,[15] and bar-headed geese exhibit a large variation in this physiological variable,[17] see also Fig. 4, their metabolic rate could vary considerably. The pronghorn antelope (*Antilocarpa americana*) is adapted to outrun feline predators such as the now extinct sabre-tooth cat and, to date, has the largest experimentally measured aerobic scope of any animal.[18] Though a cheetah might be capable of catching this species, it is a specialist sprinter and no match for the pronghorn on stamina. However, the bar-headed goose may rival the pronghorn both in terms of its range of metabolic rate and its endurance.

During the first 2009 field trip when GPS systems were first deployed, a preliminary study involved the implantation of a different instrument recording only body temperature and averages of fifty heart-rate intervals. Several of those previous generation units were recovered in 2010. Although their ECG electrodes were of a protruding, silicone-shafted *flying-lead* design (see Ref. 1), allowing insertion closer to the heart, the real-time beat detection algorithm was insufficiently robust to reject occasional interference from motion artefacts and strong electromyographic production during bouts of intense flapping. Performing beat detection "on the fly" required

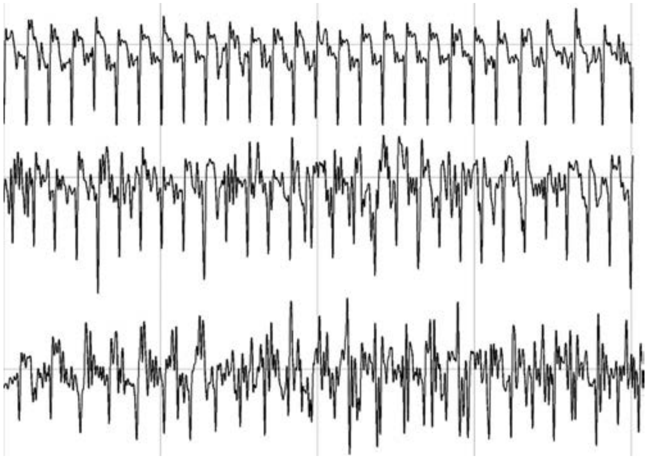

FIG. 4. Examples of ECG traces captured during the migratory flight of a single goose. Signal quality was adequate despite the fact that flying lead electrodes adjacent to the heart were not used. Each trace covers 4 s and ECG has been upsampled by a factor of 8. Top: a clean signal, HR = 420 bpm. Middle: a noisier signal during ascending flight, HR = 440 bpm. Bottom: signal contaminated by motion artefacts close to take-off.

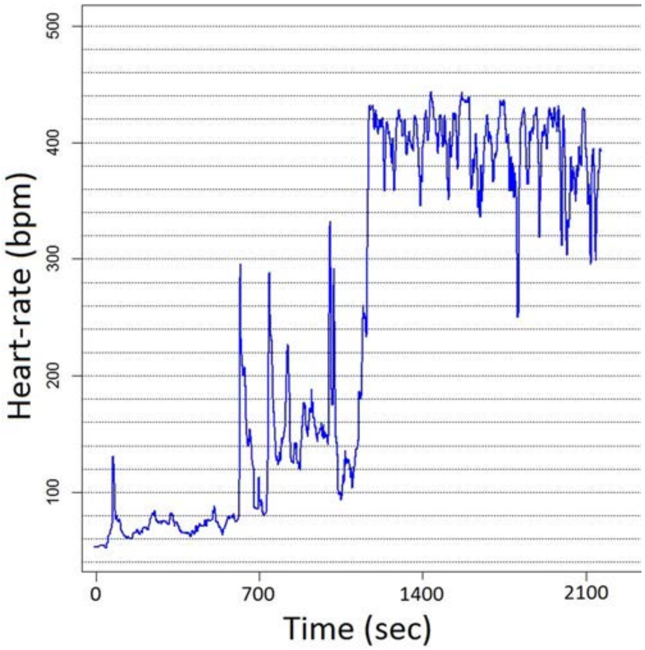

FIG. 5. Heart-rate determined from post-processing of ECG covering the first few minutes of a lengthy flight.

the μC to draw a mean current of 100 μA or less, severely restricting the sophistication of real-time signal processing algorithms. Power limitations also prohibited alternative approaches, such as hybrid processing via some combination of analog and digital circuitry. The recording of raw ECG for extended periods overcomes any uncertainty regarding the reliability of heart-rate estimates, whether beat-by-beat or time-averaged.[19] It can, therefore, enhance the practicality of using heart-rate as the basis for metabolic rate estimation[6] by allowing heart-rate to be confidently determined even during intense and biologically interesting episodes of flight, see Figs. 4 and 5. It also improves opportunities for beat-by-beat heart-rate variability assessment[20] and identification of pathological heart conditions/cardiac arrhythmia.

The original impetus for the design approach described here was the desire to robustly measure heart-rate during migratory flight. Prototyping demonstrated that storage of a digitised ECG signal to a micro SD card using an appropriately selected μC and carefully written firmware would halve the battery drain compared to real-time beat detection and averaging, despite the greatly increased memory requirements. With energy to spare, it was then possible to also incorporate additional sensors. Over the course of a year, the collection of accelerometry at 15% duty cycle and continuous ECG consumed a very similar fraction of the total energy. Accelerometry required 1.8 GB of memory storage compared to 4.9 GB for ECG. The cost of collecting data from other sensors was negligible both in terms of energy and memory. For an implantable system, geolocation via either GPS satellite signals or daylight monitoring is impractical. However, it was possible to confirm that at least one bird had crossed the Himalayas after median filtering of data from a unit equipped with a magnetometer. This was apparent from changes in magnetic field intensity with time during the migration period, see Fig. 6.

A conscious decision was taken early on to monitor the year-round activity of bar-headed geese as opposed to focusing only on episodes of flight. However, the acceleration spectrum of flight and non-flight exhibits a strong dichotomy. In principle, this could have allowed for the intelligent collection of data during flight only. Indeed, the firmware of this instrument has already been modified to do so and successfully deployed on several neck collars for Mongolian Swans in the 2012/2013 season. For strength and UV resistance, a durable opaque thermoplastic was used for the housing, Fig. 7. Power at frequencies associated with the flapping of the wings was estimated using a computationally efficient time-domain technique operating on short bursts of accelerometry spanning several wing-beats. This proved very effective, enabling accelerometry to be collected during flights with an acceptably small latency at the commencement of flight activity. The potential advantages are apparent since, when flight can be efficiently discerned, both memory storage and battery requirements can be reduced by an order of

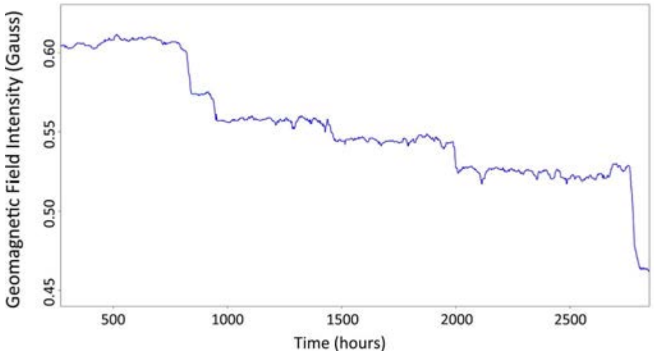

FIG. 6. The geomagnetic field after median filtering. Step changes were confirmed by accelerometry to be associated with episodes of flight. The prominent final flight was a southward trans-Himalayan crossing involving a 0.06 Gauss change in geomagnetic field intensity, a 12° change of latitude, and an estimated distance of 1300 km. The heart-rate plot of Fig. 4 covered the start of this 26 h flight.

FIG. 7. Loggers within rugged housings were strapped and bonded to neck collars, internally lined here with foam strips in an attempt to improve coupling of flight movements from the neck to the accelerometer. These units were deployed on swans to collect accelerometry, temperature, and altitude measurements.

magnitude or more, dependent on the species under study. This offers a very promising approach towards the reduction of size, weight, and power requirements, while collecting high resolution flight data with improved coverage, thus minimising the burden and potential impact to free-ranging birds during long-term experimental work.

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Paper IV

Analysing the intermittent flapping flight of a Manx Shearwater, *Puffinus puffinus*, and its sporadic use of a wave-meandering wing-sailing flight strategy.

R. J. Spivey, S. Stansfield & C. M. Bishop

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Analysing the intermittent flapping flight of a Manx Shearwater, *Puffinus puffinus*, and its sporadic use of a wave-meandering wing-sailing flight strategy

R.J. Spivey [a],*, S. Stansfield [b], C.M. Bishop [a]

[a] Department of Biological Sciences, Bangor University, United Kingdom
[b] Bardsey Bird and Field Observatory, Cristin, Bardsey Island, United Kingdom

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ABSTRACT

Flights of Manx Shearwaters over the Irish Sea were investigated using GPS ($n = 6$) and simultaneous high sample rate triaxial accelerometry ($n = 1$). This pelagic species executes flight through intermittent bursts of flapping flight interspersed with gliding phases while meandering low over the waves. To facilitate the analysis and interpretation of body-mounted accelerometry in these challenging circumstances we introduce a combined time and frequency domain technique allowing accurate separation of flapping from gliding, measurement of wing-beat frequency and determination of flapping duty cycle. Considerable fluctuations in cycle period and time-averaged flapping duty cycle were found. Our approach offered high temporal precision, which was crucial as half the flapping bursts were briefer than 0.8 s and half the cycle times shorter than 2.55 s. Flapping duty cycles exceeding 38% were likeliest for short range flights and ascending flights. At higher duty cycles, cycle time decreased and wing-beat frequency and amplitude was only moderately elevated. Near-continuous flapping was only observed during steep ascents and strong headwinds. During a long-range foraging flight with good GPS coverage duty cycles between 7% and 63% were observed. We posit that flapping was modulated in order to maintain a steady airspeed in somewhat variable wind and wave conditions as part of a complex wave-meandering wing-sailing flight strategy that was often effective in reducing locomotion costs. Periods of very low duty cycle flight appear to have benefited from instantaneous crosswinds exceeding 10 m s^{-1} with an estimated three-fold reduction in biomechanical power. Accelerometry offers a very practical tool for studying flight performance and the methods herein described can be readily adapted to other species that intermittently beat their wings.

Introduction

Manx Shearwaters, *Puffinus puffinus*, are long-lived, ocean-faring procellariidae. Like many birds, particularly those with pointed high-aspect-ratio wings, they intermittently flap and glide (Tobalske, 2001). This behaviour is common in petrels of 0.3-0.7 kg body mass (Sato et al., 2009). Manx Shearwaters, which weigh ~0.4 kg, are typical of this range. Generally regarded as adept fliers (Pennycuick, 1982; Pennycuick, 2002), these seabirds complete complex 12,000 km migrations between the Irish Sea and the Atlantic coast of South America each year (Guilford et al., 2009; Freeman et al., 2013). This species exhibits a wide variation in flapping duty cycle — the fraction of time spent actively beating the wings. These variations are sometimes observed despite little change in flight speed. Hinting that they sporadically harness energy from their environment, this makes them a very interesting study species (Tobalske, 2001).

Shearwaters can potentially take advantage of ground effect, lift from updrafts caused by relative motion of air across the waves, dynamic soaring in the presence of vertical wind shear and eddies that form in the wake of the waves capable of providing temporary respite from winds. Typically flying low over turbulent sea surfaces, shearwaters combine the challenges of efficiently interacting with the wind and having to deftly avoid waves, sea spray and other birds. Frequently banking and turning, their flight is executed very different to continuous periodic flapping along a steady course at a steady speed and altitude; circumstances more amenable to the estimation of flight costs from a body-mounted accelerometer (Spivey and Bishop, 2013). High resolution accelerometry potentially encodes an enormous quantity of information relevant to the study of avian flight dynamics. Thus, even in birds exhibiting

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* Corresponding author. Tel.: +44 1248388813.
E-mail addresses: r.spivey@bangor.ac.uk (R.J. Spivey), warden@bbfo.org.uk (S. Stansfield), c.bishop@bangor.ac.uk (C.M. Bishop).

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complex flight patterns, including tortuous motions and flapping interspersed with gliding, accelerometry could prove very informative and holds much promise with regard to power estimation (Halsey et al., 2009a; Spivey and Bishop, 2013; Duriez et al., 2014).

The primary goals of this work are to (i) introduce a method facilitating the analysis of high sample rate accelerometry collected from birds that intermittently flap and glide (ii) study the variations in the flapping duty cycle of the Manx Shearwater particularly during long-range foraging missions and relate these to airspeed as determined from GPS and prevailing wind conditions and (iii) attempt to glean insights from the results as to the flight manoeuvres employed by shearwaters to reduce their flapping duty cycle, especially on windy days.

Materials and methods

During the summer months of the northern hemisphere, the global population of Manx Shearwaters is concentrated in Britain and Ireland (Lloyd et al., 1991) where their breeding is restricted to a handful of small islands. A significant population is found on the Copeland Islands and there may be 150 thousand breeding pairs on the Pembrokeshire islands Skokholm and Skomer (Smith et al., 2001). This study used fourteen adult birds from Bardsey Island, home to around 32 thousand breeding birds. Shearwaters avoid egg predation (mainly from gulls) using subterranean burrows which they enter and exit only during hours of darkness. This facilitates both their capture and recapture. One parent will usually guard the egg while the other spends several days at sea before duties are exchanged (Brooke, 1990). Stray parents are more likely to return to the burrow during hours of darkness once chicks have hatched.

Similar to a previous GPS-only study that also found no negative effects (Guilford et al., 2008), the loggers deployed here weighed no more than 17 g. They were attached using strips of marine grade TESA tape to avoid the drawbacks associated with harnesses (Phillips et al., 2003). Being some 4% of the typical bodyweight of the birds (426 ± 25 g), this did not represent an unacceptable encumbrance. Manx Shearwaters lay heavy eggs, approximately 15% of their bodyweight.

Bespoke hardware and firmware was used to initialise the GPS modules and subsequently retrieve their data. Modules were configured to log fixes in clusters at 1 Hz for up to 16 s every ten minutes, permitting the determination of bearing and speed. Within subterranean burrows, GPS signal reception ranged from difficult to impossible. However, outside the burrows where reception was far better, 3–4 s was typically sufficient for the first fix and roughly 12 fixes were obtained before returning to sleep mode (overall coverage ~2%). Seven days of predictive satellite ephemeris from an internet database was preloaded into the loggers to improve the 'time to first fix'. Once the ephemeris data expired, the GPS modules periodically activated for periods of ~80 s rather than 16 s in an attempt to reacquire almanac information from the satellites. Although this decreased battery life it also provided higher GPS coverage on some later flights.

In June 2013, the 14 birds selected for this study were equipped with dorsally mounted archival tags under BTO (British Trust for Ornithology) permit number 4337 awarded to Steve Stansfield. Of the eight systems recovered, two (A5 & A10) logged accelerometry only (4.2 V, 250 mAh batteries), five (S1, S3, S6, S7 & S9) logged GPS only (3.7 V, 800 mAh batteries) and one (logger S10) logged both GPS and accelerometry (4.2 V, 250 mAh batteries). Triaxial accelerometry was captured at 400 Hz with 12-bit resolution.

Unfortunately, neither A5 nor A10 recorded any flight activity due to the birds having spent their entire time within a burrow. After a brief excursion south of Bardsey, logger S1 returned to its burrow within 16 h, where it remained on the nest with a newborn chick until recapture some days later. By the time their batteries were exhausted, loggers S3, S6, S7 and S9 had collected a full quota of GPS fixes. Logger S10 had filled ~73% of its 128 kB GPS memory while recording 1.2 GB of triaxial accelerometry data. GPS flight data was therefore obtained for six birds in all, but the most interesting dataset involving combined GPS and accelerometry was only collected for a single bird. Thus, where this work analyses accelerometry obtained during flight, the results pertain solely to the bird equipped with logger S10.

Observed foraging patterns

GPS tracks for each bird are presented in Fig. 1. The main foraging areas to the north of the Irish Sea are reached after several hours of flying. Consistent with previous findings, these coincide with deep water zones frequented by birds nesting on Skomer (Guilford et al., 2008; Dean et al., 2013). In addition, localised foraging can also be observed along the NW coast of the Lleyn peninsula and the SW coast of Anglesey, and some rafting activity is apparent to the south of Bardsey. Animated tracks for each bird are provided in kmz format for Google Earth as supplementary information.

For each section of uninterrupted GPS logging, it was possible to derive distance travelled, bearing and horizontal velocity. The convention is adopted here that bearing is measured in degrees clockwise from true north. Ground speed data, presented in Fig. 2, clearly differed from zero at times when the birds were flying. Inspection of the ground speed histogram (Fig. S1 in supplementary information) for logger S10, the most airborne bird, shows a dearth of speeds in the range 4–6 m s^{-1}. This allowed discrimination between flight and resting on water using a threshold of 5 m s^{-1}. For each flight section involving incremental distances Δs and total straight line distance s_T, the tortuosity λ of the flight path was evaluated using the expression

$$\lambda = \frac{(\Sigma \Delta s) - s_T}{s_T} \tag{1}$$

Since $\Sigma\ \Delta s$ cannot be smaller than s_T, λ cannot be negative, and will only approach zero during highly directed flight. Application of the 5 m s^{-1} threshold also enabled the fraction of time each bird spent airborne to be estimated and the mean flight velocity to be determined (see Table 1).

Pooling data from all flights, tortuosity generally decreased and became less variable with ground speed (Fig. S2), in good agreement with the findings of Guilford et al., 2008. Speeds were intermediate between the estimated minimum power velocity of 7.5 m s^{-1} and the maximum range velocity of 14 m s^{-1} for the Manx Shearwater (Pennycuick, 1969), possibly due to ground effects and energy savings through soaring strategies (Guilford et al., 2008).

GPS fixes have superior horizontal accuracy than vertical accuracy due to triangulation by satellites orbiting at an altitude of approximately π times the Earth's radius. Even in ideal conditions, no more than 95% of altitude fixes are accurate to better than ±23 m. All burrows on Bardsey were located at an elevation of about 75 m above sea level. A histogram of all raw GPS altitude measurements is provided in Fig. S3. Its bimodal distribution is due to time spent at sea and time spent on Bardsey, confirmed by the disappearance of the higher altitude hump when GPS fixes within 400 m of the burrows are eliminated. On days of interest, tidal variations resulted in sea levels that were confined to the range 1–6 m.

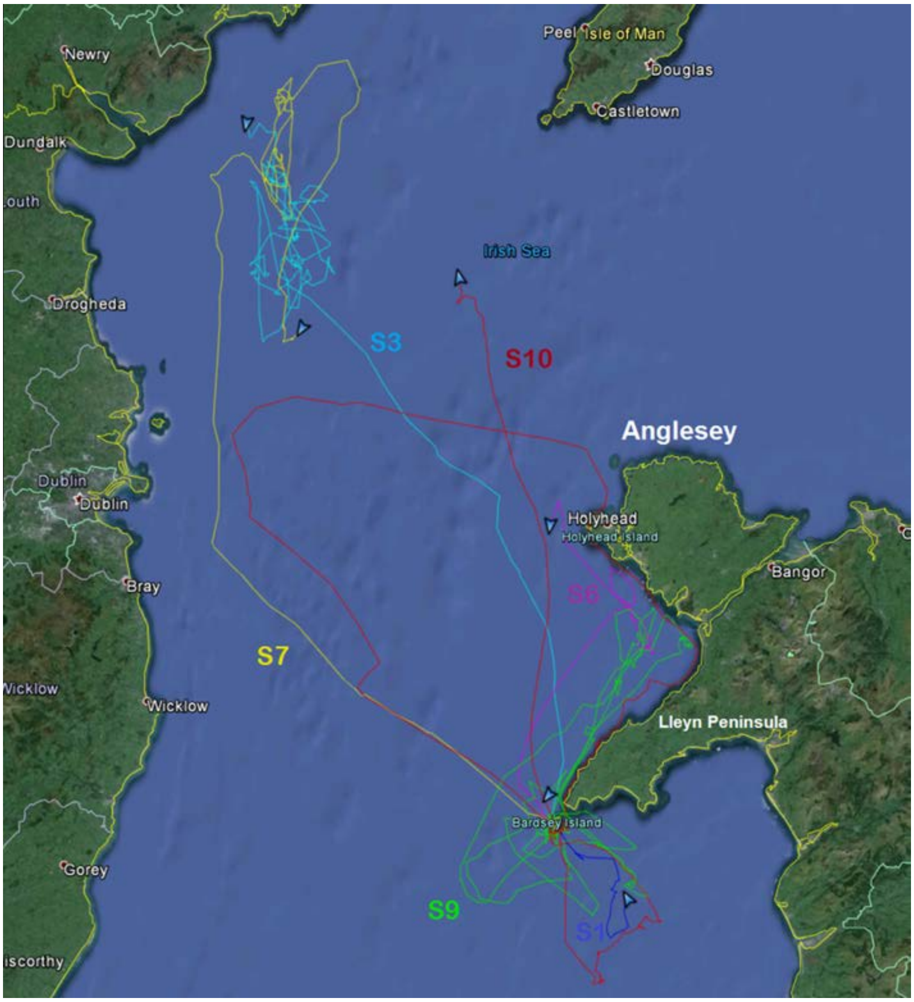

Fig. 1. The GPS tracks obtained from six birds (loggers S1, S3, S6, S7, S9 and S10) as displayed by Google Earth. Long-range foraging excursions to the north of the Irish Sea are apparent.

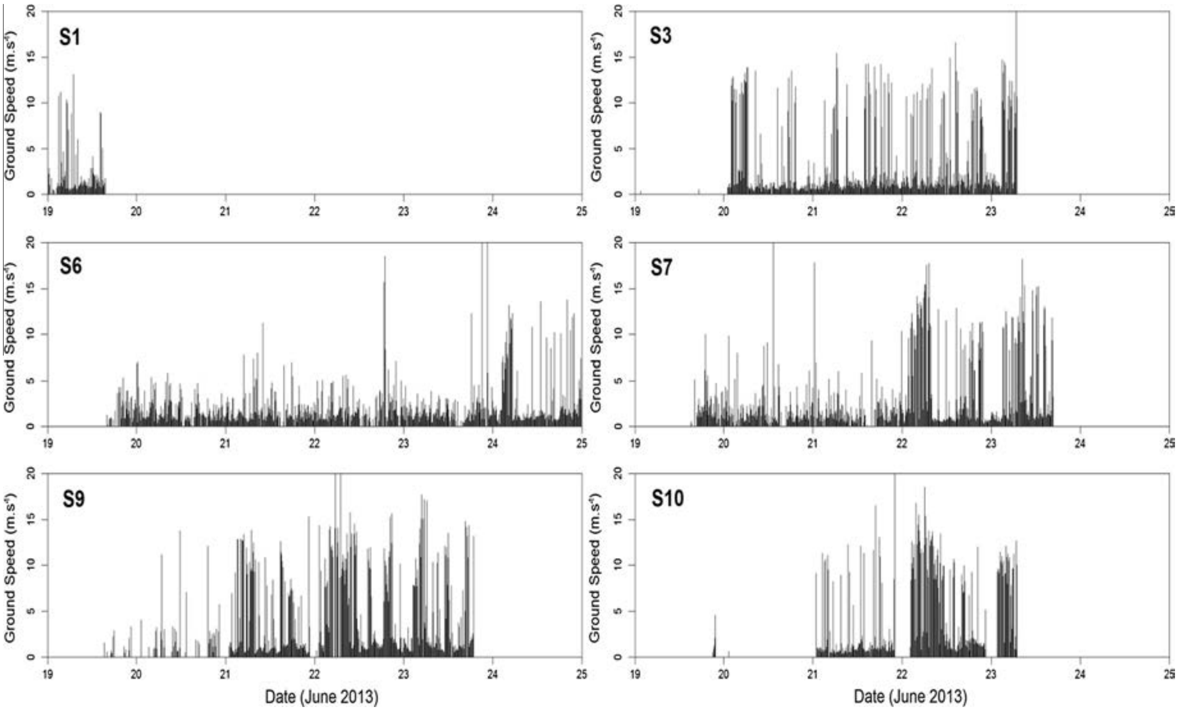

Fig. 2. Ground speeds (in m s^{-1}) as determined from GPS-derived integrated distances for each of the six birds recaptured with GPS loggers. GPS reception was impeded within the burrows.

Table 1
Summary statistics for the GPS modules.

Logger ID	Flight sections	Airborne fraction	$\bar{\lambda}$, Mean tortuosity	Ground speed ± s.d. (m s^{-1})
S1	11	0.126	0.058	9.1 ± 2.4
S3	102	0.221	0.151	10.9 ± 2.4
S6	55	0.077	0.602	8.8 ± 3.7
S7	101	0.191	0.482	10.6 ± 3.4
S9	148	0.345	0.369	10.6 ± 2.9
S10	103	0.364	0.268	10.6 ± 2.6

A technique for analysing accelerometry obtained from a flap-gliding bird

Intermittent flight poses special challenges for the interpretation of accelerometry. It is customary when analysing data from accelerometers to decompose the data into two frequency bands. The static acceleration is obtained by low-pass filtering whereas the dynamic acceleration can either be derived by band-pass or high-pass filtering the raw acceleration or by subtracting the static acceleration from the raw acceleration. For birds that flap their wings in bursts, the dynamic acceleration is not periodic and so disentangling it from the static acceleration is not straightforward. If a bird is negotiating an undulating sea surface the situation is further complicated since the acceleration transducer may be rotating in space. In order to proceed, a simplifying assumption is helpful. Changes in sensor orientation are likely to be limited to frequencies below about half the wing-beat frequency, allowing their rejection. Although there may be occasions where this assumption is violated, they will likely be fleeting events involving sudden and extreme banking or strong gusts of wind. If necessary, it would be possible to assess the frequency and severity of such events by searching for unusually large departures of the raw acceleration away from the sagittal plane where accelerations associated with flapping are normally constrained to lie, even during banking flight.

A threshold could be applied to a time-averaged measure of acceleration such as ODBA (overall dynamic body acceleration), VeDBA (vectorial dynamic body acceleration) or a root-mean-square (RMS) value of the dynamic acceleration, $a_{rms} = \sqrt{\sum_1^N a_{dyn}^2/N}$. This might distinguish flapping from gliding (Halsey et al., 2009b) but there are several drawbacks to beware of. Firstly, these acceleration measures are typically derived from time windows greatly exceeding the duration of a single wing-beat and may therefore ignore shorter bursts of flapping. Secondly, they can introduce unnecessary temporal ambiguity concerning the onset and termination of a flapping burst, limiting the accuracy of duty cycle estimates. Classification of behaviour via ethograms based on wavelet or Fourier transforms similarly involves some sacrifice in temporal resolution (Sakamoto et al., 2009a). Thirdly, such techniques do not readily lend themselves to the accurate extraction of wing-beat frequency either for a burst of flapping or for individual flaps of the wings, yet this is a fundamental parameter descriptive of flight (Pennycuick, 1996). Crude peak and trough detectors have been employed in other contexts (Sato et al., 2003; Watanuki et al., 2005), but incur inaccuracy due to finite sampling rates, the vanishing derivatives at maxima and minima and the inherent inability to pinpoint the start and end times of flapping bursts.

A superior technique is now described. The dorsoventrally-aligned *static* acceleration can be obtained via Fourier methods, each raw acceleration channel being separately low-pass filtered in the frequency domain, retaining sufficient information to track banked flight according to the earlier simplifying assumption. An inverse Fourier transform then yields the vector-valued static acceleration in the time domain. The dorsoventrally-aligned *dynamic* acceleration, a_{dv}, can be calculated by taking the scalar product of the raw triaxial acceleration with a normalised copy of the static acceleration and then band-pass filtering using Fourier methods once more to leave the frequencies associated with beating of the wings.

Following band-pass filtering, the mean value of a_{dv} is guaranteed to be zero. The timings of positive-going zero crossings in a_{dv} can usually be obtained to good accuracy by linear interpolation from the two neighbouring samples. Supposing a_j and a_k ($a_j < 0$and $a_k \geqslant 0$) are two consecutive values of a_{dv} respectively obtained at times t_j and t_k, then the time t_0 at which the zero crossing occurs can be calculated using the expression:

$$t_0 = \frac{a_k t_j - a_j t_k}{a_k - a_j} \tag{2}$$

If accelerometry is collected at a sample rate barely above the Nyquist limit, however, we would advise first interpolating the data to a higher sample rate. This could be achieved through digital convolution $a_{dv} \leftarrow a_{dv} * L$ where L is a Lanczos filtering kernel defined as:

$$L(x) = \frac{b \sin(\pi x)}{\pi^2 x^2} \sin\left(\frac{\pi x}{b}\right) \tag{3}$$

The parameter b determines the breadth of the kernel ($b = 3$ being a popular choice) and x represents the time-offset from each freshly interpolated sample in sample intervals. Note that $L(0) = 1$ and $L(x) = 0$ for $|x| > b$ and the interpolated samples are merely outputs of the convolution process i.e. they are not fed back in as inputs. Once the times of the zero-crossings have been obtained, the RMS value of a_{dv} between adjacent zero crossings can then be calculated and used to distinguish between episodes of flapping and gliding flight. Fig. 3 presents an idealised pictorial representation of the process. Where flapping flight is detected, the wing-beat frequency, f_w, is obtained as the reciprocal of the time-interval between successive detected wing-beats (zero-crossings) demarcating each individual flap.

This approach offers improved accuracy when estimating wing-beat frequency compared to a peak detection method which hunts for local maxima in acceleration samples. This can be confirmed through a simple analysis. Let us assume that an accelerometer produces noise-free samples separated in time by a fixed sampling interval, t_s, and that the system being monitored vibrates at maximum frequencies $f_v < 1/2t_s$, i.e. below the Nyquist frequency. Identification of the largest valued sample during peak detection will result in a maximum timing error, $\Delta t_0^{\max}$, of half the sampling interval, $t_s/2$.

Turning now to the maximum timing error incurred by the zero-crossing linear interpolation method, consider a normalised sine wave of maximal frequency $a(t) = \sin(2\pi f_v t)$ which, having zero phase shift, transitions from negative to positive at $t = 0$. For some variable $0 < \mu \leqslant 1$ the sample preceding the zero crossing occurs at time $t_1 = -\mu t_s$ and the subsequent sample is therefore obtained at $t_2 = t_1 + t_s = (1 - \mu)t_s$. Assuming that f_v is comfortably below the Nyquist frequency, as it must be in practice to avoid aliasing, then the angles $2\pi f_v t_1$ and $2\pi f_v t_2$ will be small and one can employ the approximation $\sin x \approx x - x^3/3!$ when calculating $a(t_1)$ and $a(t_2)$, using the results to evaluate t_0 via (2) as follows:

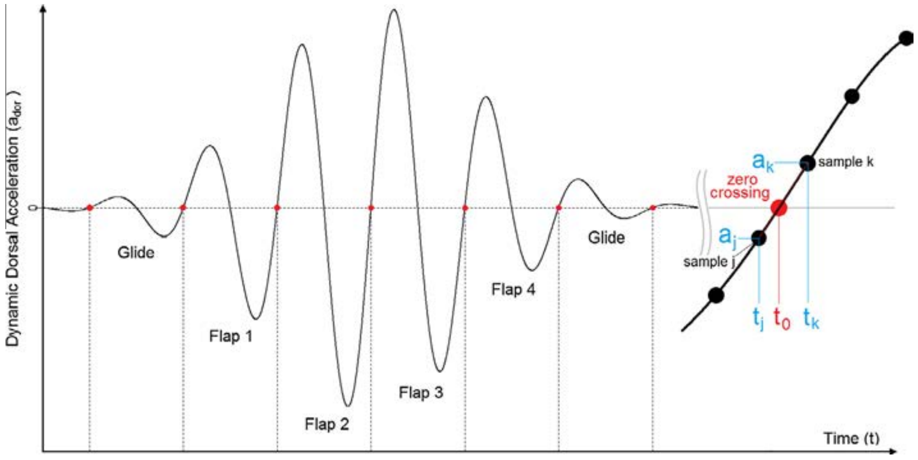

Fig. 3. In this idealised example, the times of positive-going crossings (red dots) in the dynamic dorsoventral acceleration, a_{dv}, were obtained by linear interpolation (using Eq. (2)) of samples either side (magnified example to the right). Flapping flight was detected when the RMS value of a_{dv} evaluated between successive zero-crossings exceeded a predetermined threshold. Wing-beat frequency could then be derived from intervals between the demarcating zero crossings. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$
\begin{aligned}
t_0 &= \frac{t_1 a(t_2) - t_2 a(t_1)}{a(t_2) - a(t_1)} \\
&= \frac{-\mu t_s \sin[2\pi f_v (1-\mu) t_s] - (1-\mu) t_s \sin[-2\pi f_v \mu t_s]}{\sin[2\pi f_v (1-\mu) t_s] - \sin[-2\pi f_v \mu t_s]} \\
t_0 &\approx \frac{-\mu t_s [2\pi f_v (1-\mu) t_s - 8\pi^3 f_v^3 (1-\mu)^3 t_s^3/6] - (1-\mu) t_s [-2\pi f_v \mu t_s + 8\pi^3 f_v^3 \mu^3 t_s^3/6]}{2\pi f_v (1-\mu) t_s + 2\pi f_v \mu t_s} \\
t_0 &\approx 2\pi^2 f_v^2 t_s^3 (2\mu^3 - 3\mu^2 + \mu)/3
\end{aligned}
\tag{4}
$$

The maxima and minima of t_0 are of equal magnitude but opposite sign and are obtained as roots of the Eq. (6) $\mu^2 - 6\mu + 1 = 0$. Since it is known that the sine wave actually crosses zero at time $t = 0$, the root $\mu = 1/2 - 1/\sqrt{12}$, which yields a positive value for t_0, will correspond to the maximum timing error:

$$\Delta t_0^{\max} \approx 0.633 f_v^2 t_s^3 \tag{5}$$

The sampling frequency f_s is simply $1/t_s$ and so the result can be expressed:

$$\frac{\Delta t_0^{\max}}{t_s} \approx 0 \cdot 633 \left(\frac{f_v}{f_s}\right)^2 \tag{6}$$

This can be compared with the result obtained for the peak detection method, which was $\Delta t_0^{\max}/t_s = 1/2$. Therefore, the error obtained by the zero-crossing method is smaller than the error obtained through peak detection by a factor $\beta = 1.266 f_v^2/f_s^2$. Note that since $f_v/f_s < 1/2$, it holds that $\beta < 0.3165$. Even though the peak detector's error in estimating wing-beat frequency can be reduced by increasing the sample rate, doing so increases the relative error compared to the zero-crossing method we advance here. For example, if the wing-beat frequency is 7 Hz and the sampling rate is 400 Hz, as it was in this study, one finds that β is only 0.00039. In this example, the timing error of the peak detector could be as large as 1.25 ms whereas that of the zero-crossing method would be smaller than 0.5 microseconds. For a modest sample rate of 30 Hz, the frequency of a single 7 Hz wing-beat would have been limited in accuracy to about 12% for the peak detection approach whereas for the zero crossing technique the inaccuracy would be 0.8% at most, assuming the data is not first upsampled.

Once the times of the zero crossings have been obtained, for each burst of flapping it is possible to determine the number of detected wing-beats, the mean value of f_w, the duration of the burst, the time spent during the preceding glide phase, the RMS value of the dorsoventral acceleration during flapping, the RMS value of the dorsoventral acceleration during gliding, the mean value of the static acceleration during flapping, the mean value of the static acceleration during the glide phase and the fraction of the time the bird spent flapping its wings.

Application to accelerometry from logger S10

Logger S10 was deployed on a bird weighing 415 g (ring number FB36643) with logging commencing at 20:38:17 UTC on June 19th 2013. This bird spent the first day in its burrow but then left Bardsey on the three following days (June 21–23). Some 178 million triaxial acceleration samples were recorded (64 million during flight) using the internal electronics (weight 3 g) of an implantable instrument originally designed to study the Himalayan migrations of geese (Spivey and Bishop, 2014). The GPS-derived ground speed of Fig. 2 indicates that this bird returned briefly to its burrow each night to feed a chick (ring number FB36646). It spent its first active day mainly sitting on the sea south of Bardsey. The second day involved a more ambitious clockwise northward navigation of the Irish Sea and the third began with a highly directed northward excursion during which the battery expired. Tortuosity and mean flight speed for logger S10 was typical of the other birds.

Accelerometry was logged for 371 s or 6.18 m at a time yielding approximately 148400 triaxial samples at 400 s sec^{-1}. Logging was temporarily suspended for 3 s as data were transferred to long-term memory. The large quantity of accelerometry data collected by logger S10 can be summarised by a spectrogram. Without further subdivision, each 371 s segment of dorsoventrally-aligned accelerometry was Fourier processed. The static acceleration was obtained using a low-pass filter with a cut-off frequency of 3 Hz. Dynamic accelerations were determined by band-pass filtering between 4.5 and 9 Hz. The high sample rate produced very high resolution spectral magnitude information and phase details were discarded. After collating the results in frequency bins, the spectrogram presented in Fig. 4 was obtained. Episodes of flight and overnight returns to the burrow are clearly discernible. It should be noted that spectral intensity reflects the mean duty cycle over each 371 s segment more so than it represents actual changes in effort during flapping.

To discriminate between flapping flight and gliding, an experimentally determined threshold of 3.3 m s^{-2} was applied to the RMS value of a_{dv} between its zero-crossings. Very rarely did this

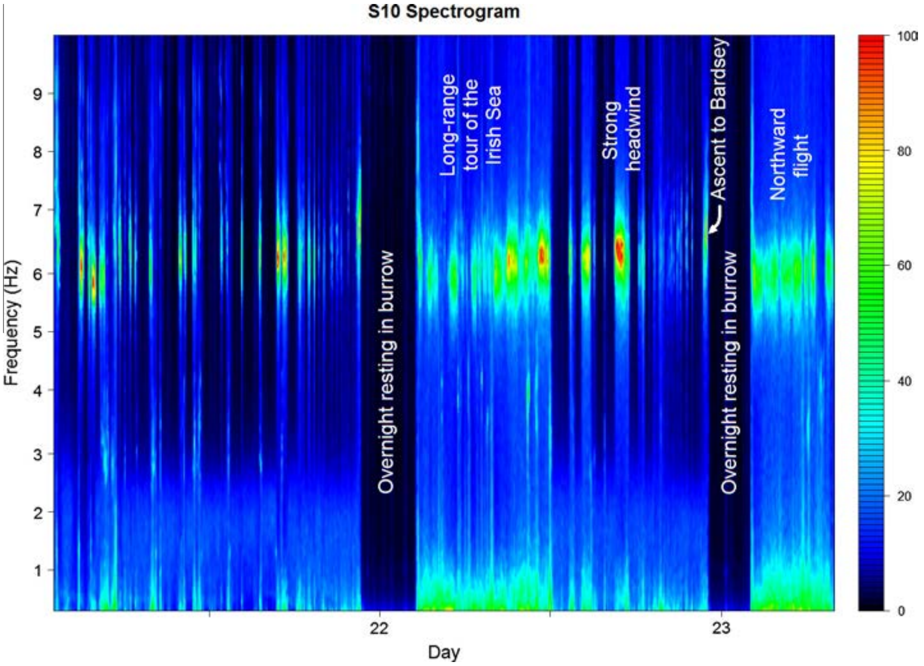

Fig. 4. Spectrogram of the accelerometry for logger S10 covering June 21–23 2013, each vertical spectrum representing the summed results of a 160 K point FFT for each accelerometer axis drawn from data spanning 371 s. Flight corresponds to significant power at frequencies exceeding 5 Hz. Colouring reflects a combination of flapping intensity and duty cycle.

bird beat its wings continuously for longer than five seconds, Fig. 5(a), or glide for longer than ten seconds, Fig. 5(b). There was considerable variability in the overall glide-flap cycle duration, see Fig. 5(c), but the median value was 2.55 s and mode was 2 s.

As is evident from Fig. S4, lengthy glides are primarily associated with brief flapping bursts (and low burst duty cycle, longer range flights) and lengthy flapping bursts are usually preceded by short glides (and high burst duty cycle, shorter range flights). A histogram of the burst duty cycle is presented in Fig. S5. The flights of June 21st were predominantly short-range while subsequent days involved longer foraging missions. Flapping duty cycles of 0.5–0.7 were favoured on short flights (median flap duration was 0.97 s, median glide duration was 1.01 s and median duty cycle was 0.50) and lower flapping duty cycles were obtained during longer range flights (median flap duration was 0.68 s, median glide duration was 1.69 s and median duty cycle was 0.30). Although continuous flapping was occasionally observed, GPS data confirmed it was exclusively associated with sustained ascending flight during return to burrows on Bardsey. Since wing-beat frequency was also elevated at those times, Manx Shearwaters seem quite capable of sustaining continuous flapping – as might be required in strong headwinds.

Wing-beat frequency, which was typically in the range 5.9–6.4 Hz, increased modestly with the flapping duty cycle. Although the relationship was rather loose (Fig. 6) this suggests that the bird tended to adjust its wing-beat frequency slightly in tandem with its duty cycle even though changes in duty cycle were the dominant modulator of flight effort. The trend-line on the plot has a slope of 0.46 ± 0.05 Hz. A plot of wing-beat frequency against flapping burst duration (Fig. S6) suggests that flapping tends to be prolonged at higher wing-beat frequencies until suddenly, above 6.5 Hz, a drop-off occurs. This frequency may represent an upper limit to what this bird found comfortable during sustained long-range flight.

The RMS value of the dynamic dorsoventral acceleration during flapping bursts encodes the vigour or amplitude of the wingbeats. Fig. S7 shows that this measure increases slightly with flapping

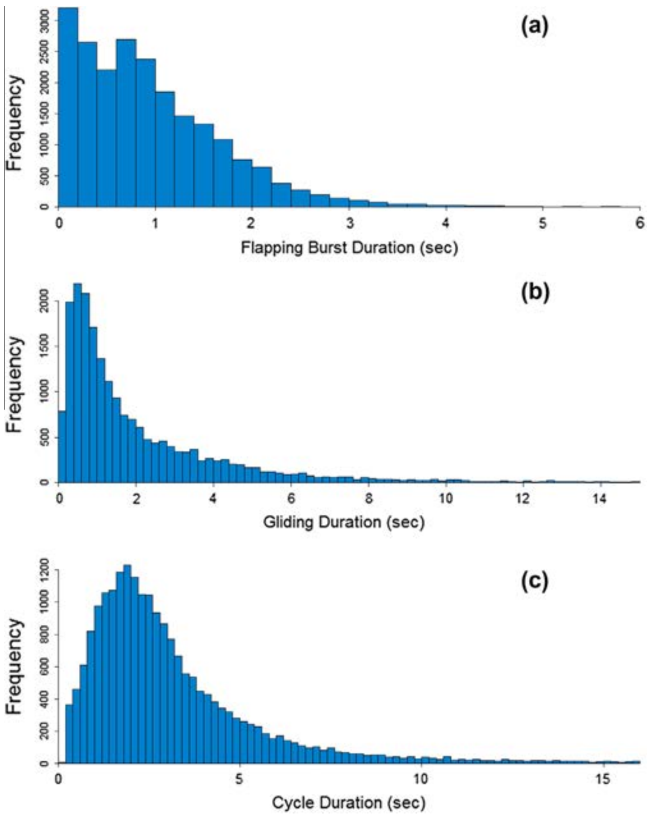

Fig. 5. (a) Histogram of the duration of each burst of flapping. Uninterrupted flapping rarely continued for more than three seconds. Median flapping burst duration was 0.80 s (mode 0.40 s) with a median of 5 flaps per burst (mode 2 flaps per burst). (b) Histogram of the duration of each gliding phase. Gliding between flapping bursts rarely lasted longer than ten seconds (median glide duration 1.32 s, mode 0.68 s). (c) Histogram of flap-glide cycle duration (median 2.55 s, mode 1.96 s).

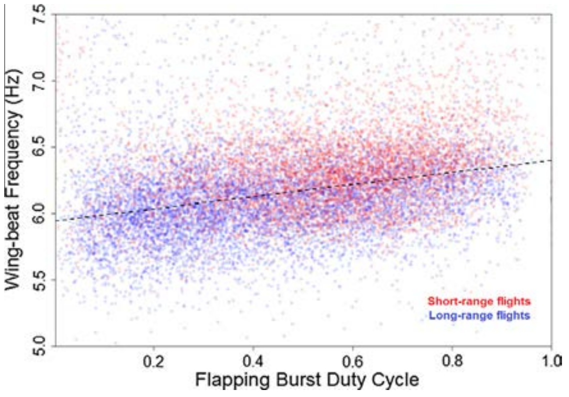

Fig. 6. Wing-beat frequency versus flapping duty cycle for bursts of more than two flaps. Results for short-range flights are marked in red and those of long-range flights in blue. Wing-beat frequency increases gently with duty flapping burst cycle, with regression finding that the frequency increases by 0.46 Hz as the duty cycle increases from zero to one. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

duty cycle. Furthermore, during strenuous flight at least, this measure is also positively correlated with wing-beat frequency – see Fig. S8. Since biomechanical flight power increases with both RMS dynamic acceleration and wing-beat frequency (Spivey and Bishop, 2013), the cost of flight must increase at least linearly with flapping duty cycle for this shearwater.

Analysis of GPS-augmented accelerometry from logger S10 for the northward flight

Starting at 01:40 UTC on June 23rd, S10 began an uninterrupted northward flight lasting 102 minutes. The GPS module was at this time seeking almanac data from overhead satellites, which boosted GPS coverage from 2–13%. Ten clusters of 1 Hz GPS fixes each lasting about 82 s were obtained every ~670 s. This section of flight is highlighted in Fig. 7 along with movements, colour coded for each day, and the estimated prevailing winds according to hourly meteorological measurements taken at Dublin Airport. Because moderate winds had been sustained for 16 h by the time of this northward flight, the height, speed and direction of the sea waves could be estimated. Furthermore, the wind measurements at Dublin were very consistent with readings obtained by a London weather station if a time allowance was made for the passage of air between the two locations. Wind velocities were processed using local regression filtering to obtain estimates concurrent with GPS fixes (see Fig. S10). The bird's airspeed was deduced by subtracting the wind velocity from the ground velocity, ignoring possible short-term changes in the wind speed and direction which we lack information on and might also be exacerbated by interactions of the atmosphere with the turbulent sea surface.

A marked change in the wind speeds on the mornings of the 22nd and 23rd, is apparent from the obvious differences in the ground-speed/bearing relationship for S10 on these two days (see Fig. S11). Cory's Shearwaters have been observed to adjust their foraging excursions so as to profit from crosswinds (Paiva et al., 2010) and a strong preference for crosswinds has been found in diving shearwaters, gadfly petrels and storm petrels (Spear and Ainley, 1997a). The same may hold here as there was a 10–11 m s^{-1} crosswind blowing from the west during the northward flight of June 23rd.

The time-averaged flapping duty cycle, μ_F, was estimated using a sliding 60 s window. Its variation during the northward flight is presented in Fig. S12, with data corresponding to GPS fix clusters in red. Despite steady progress to the north, large fluctuations in μ_F can be clearly observed. For the temporal variation of wing-beat frequency and RMS dorsal acceleration during flapping bursts see Figs. S13 and S14.

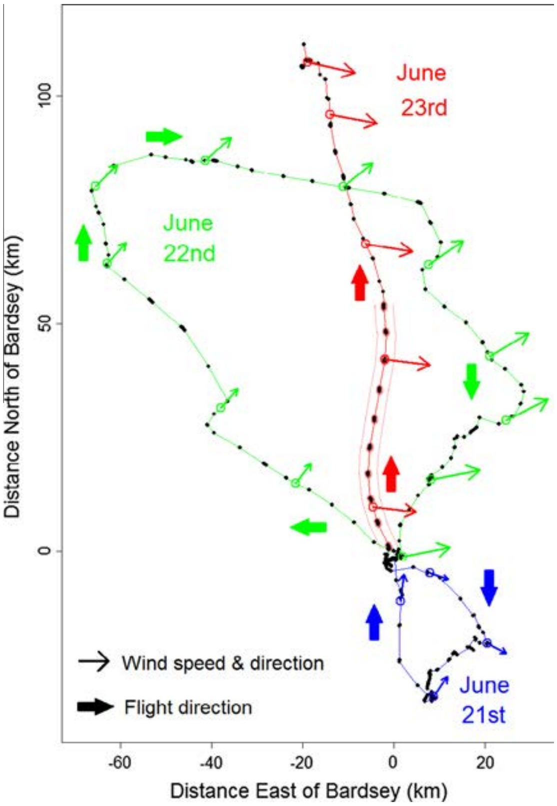

Fig. 7. The path followed by S10 on the 21st (blue, clockwise), 22nd (green, clockwise) and 23rd (red, northward) covered approximately 470 km in all. There was a relatively constant northward bearing during an uninterrupted 6112 second episode of flight (section marked with adjacent red lines) starting at 01:40 on the 23rd where, due to loss of satellite ephemeris, enhanced GPS coverage was available; the prevailing wind at the time was westerly with a speed of 10–11 m s^{-1}. Arrows represent hourly wind measurements from Dublin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Mean values for all variables were obtained for each cluster of GPS fixes allowing accelerometry-derived and GPS-derived measures to be directly compared and correlations sought. The results are presented in Fig. 8. It can be seen that airspeed increased slightly with flapping duty cycle μ_F whereas cycle time declined dramatically with μ_F. As one would expect, μ_F was sensitive to small changes in the bird's heading, increasing the more the bird flew into the wind. The highest RMS dorsoventral accelerations were clearly associated with the highest flapping duty cycles. The bird's airspeed was apparently highest when combating headwinds but this may have been due to the bird taking advantage of lulls in the wind which our airspeed calculations were unable to take into account. There was a modest increase in airspeed with flapping duty cycle. Perhaps most surprisingly there was almost no correlation at all between airspeed and wing-beat frequency.

As heavy averaging can conceal subtleties in the data distribution we provide a second set of plots in Fig. S15 using kernel density estimation. Data drawn from the ten GPS clusters are plotted in red. Where available, data for all flights are plotted in black, and are in good general agreement with the northward flight. Table 2 compares some of the statistics of the northward flight with the statistics obtained from the same bird on all its flights.

The pronounced variations in flapping duty cycle μ_F are particularly interesting. We therefore present three further plots in Fig. S16, looking at how wing-beat frequency mildly increases,

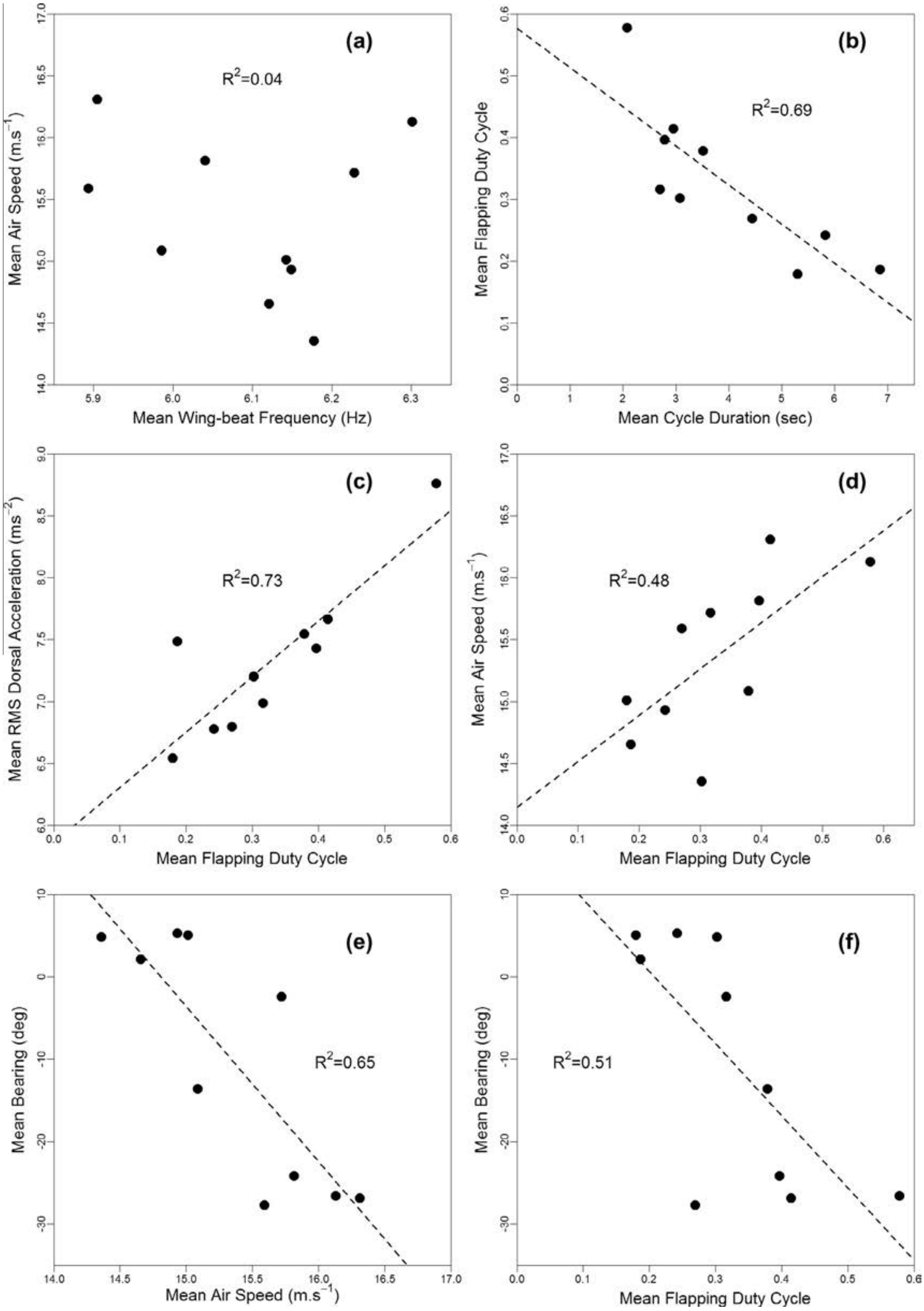

Fig. 8. Using least-squares regression, correlations were found between mean values of various parameters derived from each of the ten high resolution GPS sections of the northward flight of S10 on June 23rd. There was little correlation between mean airspeed and mean wing-beat frequency. Bearing was measured in degrees clockwise from true north.

the dynamic RMS acceleration during gliding decreases and the RMS dorsoventral acceleration during flapping modestly increases with μ_F for this flight. Since the biomechanical costs of flight are expected to rise with flapping RMS acceleration and wing-beat frequency, which only gently increased with μ_F, when one factors in the relatively small cost of gliding it is apparent that the total biomechanical costs of flight will, to a first approximation, be linearly related to μ_F. Thus, the bird modulated its flight power primarily through flapping duty cycle as opposed to adjusting its wing kinematics or its wing-beat frequency.

Table 2
Flight characteristics for logger S10.

Variable (±standard dev.)	Northward flight	All data	Mode
Airspeed (m s^{-1})	15.5 ± 0.7	11.1 ± 4.6	13.2
Ground speed (m s^{-1})	9.9 ± 0.7	9.9 ± 3.6	10.0
Wing-beat frequency (Hz)	6.1 ± 0.14	6.32 ± 0.48	6.18
Duty cycle, μ_F	0.26 ± 0.13	0.32 ± 0.18	0.27
Cycle time (s)	3.95 ± 1.58	5.6 ± 19.5	1.96
Flapping RMS accel. (m s^{-2})	7.3 ± 0.63	7.6 ± 2.1	8.2
Gliding RMS accel. (m s^{-2})	2.35 ± 0.38	2.2 ± 1.7	1.9

The weak correlation between wing-beat frequency and airspeed (Figs. 8a and S15a) and the modest variations of wing-beat frequency with duty cycle (Figs. 6 and S16a) implies that changes in duty cycle are unlikely to have a strong influence on airspeeds. This expectation is largely upheld in Fig. S17, which presents instantaneous airspeed estimates taking full account of instantaneous bearing, integrated path lengths and prevailing winds obtained for each detected burst of flapping for each of the ten GPS clusters (numbered in the plot) during the northward flight. All airspeeds can be seen to lie within the range 14–17 m s^{-1} (mean 15.5 m s^{-1}), which is remarkable given that the μ_F values range here between 0.07 and 0.63 (mean 0.292 ± 0.123).

Since this northward flight lasted less than two hours, during which the wind measurements in Dublin varied little, and the flight followed a steady northward bearing, the bird may either have been regulating its airspeed or its ground speed. However, as accelerometry was continuously logged during every flight for S10 and shorter (typically 12 s) clusters of GPS fixes provided sufficient data to estimate course, ground speed and airspeed, it was possible to include in this analysis the other flights of this bird. Although the wind direction and intensity did vary considerably between flights, it was not possible to discern any striking pattern here either between airspeed and μ_F. This resolves the potential ambiguity and confirms our suspicion that the bird modulated its flapping duty cycle to regulate its airspeed rather than its ground speed.

During long-range flight, the path of the bird often meandered across the sea while the same general bearing was being maintained. The static acceleration was more variable during flapping bursts for long-range flights (s.d. 3.08 m s^{-2}) than for short-range flight (s.d. 1.96 m s^{-2}). Much greater variation of the mean static acceleration occurred during flapping at duty cycles below 0.38 (Fig. S9). This is consistent with an increasing reliance on turns and banking manoeuvres when environmental conditions are more favourable to gliding flight. It may also be evidence that long-range flight is more likely to be attempted in such conditions. Meandering flight was frequently observed during the northward flight, though it was also interspersed with more directed flight.

An example of meandering flight is provided in Fig. 9. This was obtained from an 80 s burst of high resolution GPS during the northward flight and shows how the meandering strategy operates, becoming more successful in the latter half as the flapping duty cycle is suddenly reduced. Changes in absolute height of amplitude 5–7 m per cycle can be discerned. If gravitational and kinetic energy is being repeatedly exchanged, this predicts changes in airspeed of about 6 m s^{-1}. Indeed, this expectation is upheld, being visible in the variations in the ground speed trace. Periods when the bird was flapping its wings have been superimposed on the plot. What may seem curious at first is that the ground speed fluctuates most during the latter half of this flight section, when relatively little flapping occurred. This strongly implies the input of energy from some source other than the wings. Since the bird is not in contact with the water, this energy can only have come from the wind. The traces suggest this energy is delivered rather abruptly as the bird changes course to fly north-west, into the wind.

Discussion

The technique presented here for assessing accelerometry captured from a flap-gliding bird used linear interpolation to obtain the times of zero-crossings in the dynamic dorsoventral acceleration. This has allowed detailed analysis of a Manx Shearwater's flight dynamics and wing kinematics in unprecedented detail. Although the data was obtained from a single bird, this method has yielded a wealth of fascinating and informative data. Our approach can be readily adapted to other species employing intermittent flapping during flight.

The cost of flapping flight for a Manx Shearwater is likely to be similar to that of a laughing gull, 66 W kg^{-1} (Tucker, 1972), and the

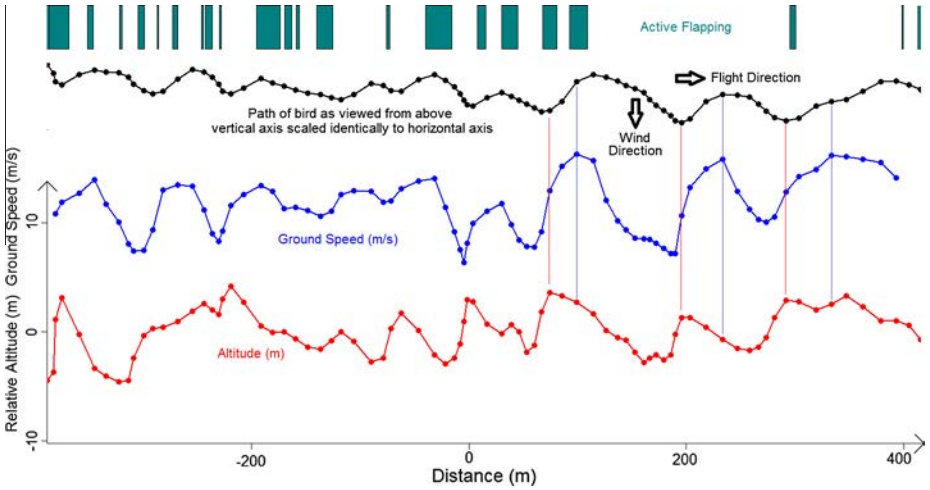

Fig. 9. An 82-second section of northward flight between 04:32 and 04:34 on June 23rd. Vertically aligned points are synchronised in time. Episodes of active flapping inferred from accelerometry are shown as solid coloured bars along the top. Uppermost trace (black): path of the shearwater across the sea (vertical scaling matches the horizontal scaling). Central trace (blue): ground speed calculated using the four nearest positional fixes. Lowermost trace (red): GPS-derived altitude after bandpass filtering (0.04–0.18 Hz) to reduce noise and drift. Sudden gains in total energy (height and speed) are apparent as the shelter of a wave is abandoned (vertical red lines) and speeds continue to build as height is traded in order to reach the next wave (vertical blue lines). Note: although the blue and red traces share the same vertical axis their units differ. The mean altitude is zero as a consequence of the bandpass filtering. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

basal metabolic rate is about 7.2 W kg^{-1} (Bryant and Furness 1995). The pectoralis is active during intermittent glides (Meyers, 1993; Tobalske and Dial, 1994) but it is thought that the costs of gliding are only about twice the basal metabolic rate (Bevan et al., 1995). Although metabolic rate following exercise can remain elevated in mammals (Baker and Gleeson, 1999) and heart-rate does not decline immediately when gannets glide after flapping their wings (Ropert-Coudert et al., 2006), for the purposes of this discussion it will be assumed that short-duration gliding requires similar power to long-duration glides. Offsetting this would be the moderate increases in wing-beat frequency observed at higher duty cycles. We therefore estimate that mean flight power can be approximated as $51.6\mu_F + 14.4$ W kg^{-1} for a Manx Shearwater. From the duty cycle histogram (Fig. S18) it would appear that any value in the range $0 < \mu_F < 0.6$ was quite likely on these days. There is a steep fall-off above 0.6, and we suggest a duty cycle of around 0.56 corresponds to weight support during horizontal flight in still air, including any ground-effect assistance. Hence, any distinction between flap-gliding and glide-flapping (Spear and Ainley, 1997b) may be wind-dependent. Duty cycles in the range $0 < \mu_F < 0.56$ span metabolic rates of 14.4–43.3 W kg^{-1}, a three-fold variation.

To illustrate the striking variability in the flapping duty cycle of S10 (and hence its flight power), each GPS fix has been colour-coded according to duty cycle and annotated with the prevailing winds in Fig. 10 (see also “S10 Duty Cycle.kmz” in supplementary information). It is particularly noticeable that flight into an unavoidable headwind along the northern coast of the Lleyn peninsula late on June 22nd was responsible for the intense effort apparent in the spectrogram of Fig. 4. This might otherwise have been attributed to a substantial gain in bodyweight from a successful day’s foraging. The late night return to Bardsey, brief but also perceptible in the spectrogram, is yet more intense and at a significantly higher wing-beat frequency – but readily understood as rapidly ascending flight.

It is illuminating to consider the energetics of the observed meandering sections of the northward flight. Due to the sustained winds, the largest sea waves would have had a phase velocity of 6 m s^{-1}, a wavelength of some 20 m and a period of around 4 s. Meandering flight, where present, had a period in the range 12–16 s and thus 3–4 waves would have been traversed during each cycle. As the latter half of Fig. 9 shows, from a low initial ground speed, sharp increases in altitude are quickly followed by rises in ground speed. This injection of energy occurs as the bird turns to obliquely face the wind, presumably as it abandons the shelter of a wave it has been flying below and parallel to. This can be understood on two counts. Firstly, by banking to fly into the wind the bird can experience a sudden increase in airspeed and therefore kinetic energy, which is defined with respect to airspeed rather than ground speed. Secondly, orographic lift is possible due to the updraft of air encountered on crossing the crest of a wave. Since a high airspeed incurs high drag and energy losses, it is preferable to convert kinetic energy into gravitational energy. This is consistent with the bird’s swift gain in height on departing a wave which then powers a lengthier windward descent during which the bird gains momentum. Maximum speed is obtained just as a convenient destination wave is reached. This can be contrasted with dynamic soaring strategies in which sections of windward flight involve gradual ascent and gradual loss of forward momentum, culminating in maximum height and minimum speed (Rayleigh 1883; Sachs et al 2012 – see Text S2).

Once the shearwater arrives at the destination wave it banks to follow its lee. If the bird has sufficient speed at this point it can simply glide until the time comes for another course adjustment whereupon the cycle repeats. The defence of a wave against cross-winds not only reduces drag through decreased airspeed but also ensures that the effective aerodynamic profile of the bird is lessened as the direction of its airspeed then coincides with its direction of travel. These considerations facilitate gliding. It may also be that shearwaters are able to take advantage of eddies that form downwind of waves to prolong their glides. In favourable winds, the possibility exists that the birds need not flap their wings at all in order to continue flying.

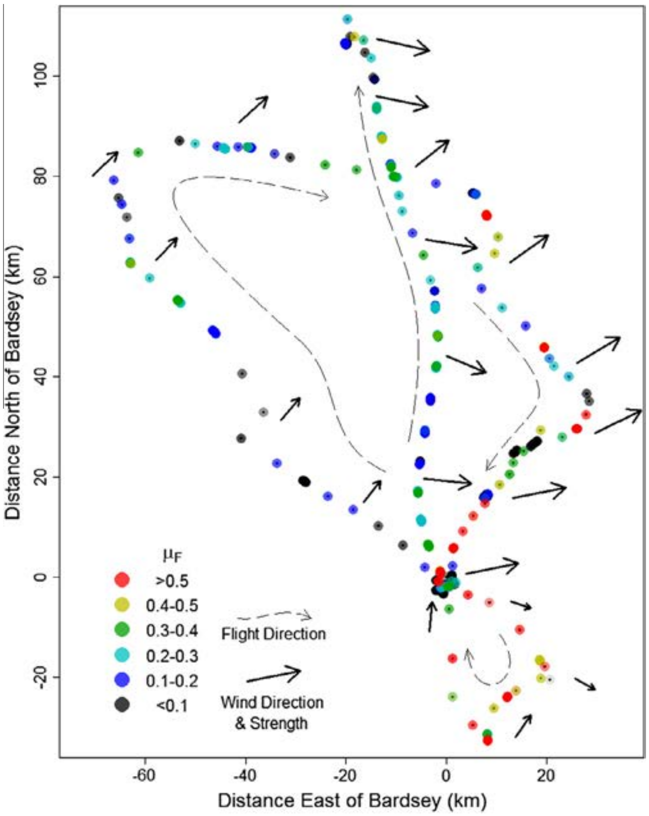

Fig. 10. Variation of flapping duty cycle according to location with black arrows indicating the prevailing winds. It is evident that much of the flight was undertaken at 90° to the wind and that the duty cycle increased when returning to Bardsey Island along the north coast of the Lleyn peninsula as unavoidable headwinds were being negotiated.

This strategy of exploiting energy from crosswinds and periodically sheltering behind waves can explain why the shearwater flies so much lower over the water than the albatross, a species which is entirely reliant on a dynamic soaring flight strategy (Rayleigh, 1883; Weimerskirch et al., 2000; Sachs et al., 2012; Sachs et al., 2013). The wingspan of a Manx Shearwater is a quarter that of a Great Albatross and there is a 25-fold disparity in body mass. Although allometric factors may call for different flight strategies, a moderately strong prevailing wind could be extremely useful to both species. Winds of the Roaring Forties, latitudes where albatrosses are commonly found, are thought to average 8–9 m s^{-1}. This is somewhat less than experienced by the bird studied here on June 23rd. The mean wave height of the southern oceans is some 3 m, trough to crest (see Fig. S19). During the northward flight, the sustained strong breeze over the Irish Sea would also have resulted in waves approaching the same size.

The intriguing variations observed in the flapping duty cycle imply that this shearwater benefited sporadically from environmental assistance. These variations may have been caused either by fluctuations in the wind, the availability of large waves, or both. The median duty cycle for the northward flight was 0.278 but it had a bimodal distribution resembling the duty cycle histogram for all

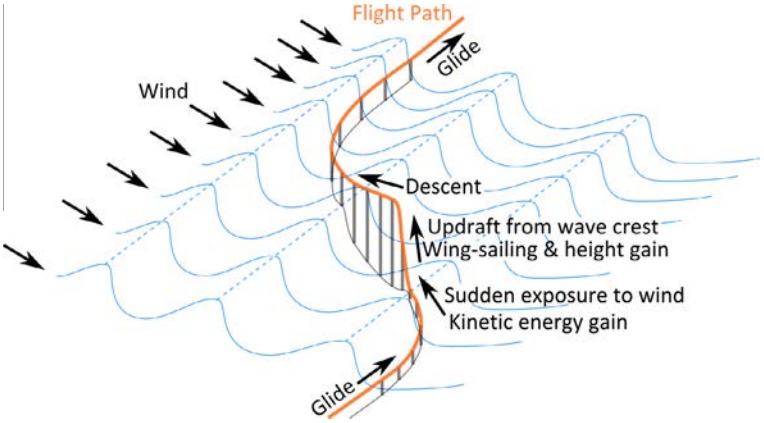

Fig. 11. An idealised 3-D representation of a single cycle of the wave-meandering wing-sailing flight strategy which was observed in the presence of a moderate wind. In this example, a single wave front is skipped as one wave is abandoned for another. Turning to face the wind and crossing the crest of a wave provides an injection of kinetic energy that is partially converted to height and used to power the next meandering cycle which involves gliding along the lee of a wave. Note that the bird is on average flying at 90° to the wind since the waves are moving in the same direction as the wind, albeit at a more sedate speed.

flights (Fig. S18). This hit-or-miss aspect of the bird's flight strategy seems especially consistent with volatile wind conditions since the power present in the wind is proportional to the cube of its speed whereas wave heights are determined by the mean power in the wind averaged over several hours. With the mean duty cycle of the northward flight (0.26) being roughly half that observed in less favourable circumstances, we estimate the threshold wind speed (as reported by a local weather station) at which a significant reduction in duty cycle is possible lies in the vicinity of 10–11 m s^{-1}, the mean wind speed at the time at heights of at least ten metres above the waves. In theory, the effective wind speed is sensitive to height above sea level (Pennycuick, 1982), and possible profiles are provided in Fig. S20 for a mean wind speed of 11 m s^{-1} ten metres above sea level. A reduction in wind from 11 m s^{-1} to 7.5–10 m s^{-1} would have a modest impact on the mean airspeed of 15.5 m s^{-1} reported earlier, reducing it to the range 13.3–14.9 m s^{-1}. Nevertheless, these results are all consistent with airspeeds of 14.4 ± 1.1 m s^{-1} reported elsewhere for this species (Spear and Ainley, 1997b).

The possibility that petrels might employ a gust-soaring strategy has been previously aired (Pennycuick, 2002; Richardson, 2011). By swooping upwards as they fly parallel to a defensive wave, birds are suddenly subjected to a crosswind. By turning into the wind they can avoid being blown sideways, reduce their aerodynamic cross-section and experience a sudden increase in airspeed. In the bird's frame of reference an increased airspeed is equivalent to a rise in kinetic energy. This extra energy can be obtained without any change in altitude and can, for instance, be converted into height gain. We therefore stress that a sufficiently strong steady wind suffices and that at such times the birds need not wait for gusts. We also point out that the main goal of the Manx Shearwater in suitable conditions could be to further profit from an updraft caused by a strong wind passing over the wave it is traversing. Doing so would entail remaining very low above the water as it crosses the crest of a wave at a relatively high airspeed.

We therefore suggest that Manx Shearwaters can achieve flight at very low duty cycles through a '*wave-meandering wing-sailing*' strategy reliant on the presence of sufficiently strong winds and sufficiently large waves. A three-dimensional depiction of this behaviour is given in Fig. 11. During each wave-meandering cycle, the bird receives a sudden spurt of energy on departing each wave which results in a rapid increase in both height and speed. On leaving the protection of a wave trough and crossing a separation layer the bird can further increase its airspeed by adjusting its heading, turning into the crosswind. Flying swiftly over the crest of the wave while making no attempt to first convert its elevated airspeed to height, it then encounters a powerful updraft due to wind rising up the trailing edge of the wave beneath it. The bird can use this to launch itself well above the water with little or no sacrifice in airspeed. During this rapid manoeuvre the energy gained would be maximised by leaving the wings outstretched. In effect, the wings would be used at such times for sailing as opposed to gliding, in analogy with the way a sailboat harnesses wind energy or how a kite can be sent skyward by pulling hard on its strings. The term '*wing-sailing*' encapsulates the dynamics of these somewhat violent wave-crossing events. In suitable conditions, the energy thus harvested may potentially sustain the remainder of a wave-meandering cycle with no need for flapping. After the injection of energy gained by from wing-sailing, the bird would gradually glide windward towards the trough of a new wave. As height is slowly lost, ground speed could increase especially on entering slower-moving air near the surface of the sea. Once the desired wave trough is reached, the bird could bank again to fly parallel to another wave until the next meandering cycle commences.

Independent confirmation of the flight strategy suggested by our GPS data, and our inference that in windy conditions Manx Shearwaters follow the troughs of the waves, could be obtained by deploying video cameras. Still images have already been collected during flight from albatrosses (Sakamoto et al., 2009b) and continuing advances in miniaturisation are now making it feasible to collect even video from smaller birds.

In squally winds, an ability to sense and respond to fleeting gusts may be advantageous. It has been conjectured that the prominent tubular nostrils of Procellariiformes might serve as pitot tubes, the internal pressure reflecting the airspeed of the bird (Pennycuick, 2002). However, the pitot tubes employed in the aviation industry are designed to operate at far greater airspeeds. At modest speeds relevant to bird flight, exquisite sensitivity to tiny pressure changes would be required. We therefore propose an alternative in which crosswinds of an appropriate strength passing transversely across the forward pointing nasal orifices induce resonance within the tubular nostril cavities. The resulting pressure oscillations, which the geometry suggests should occur at fundamental frequencies of several kHz, are within the acoustic range. Therefore, the presence of favourable wind conditions might be very quickly sensed by shearwaters as a whistling sound. It would be possible to further investigate this by attaching microphones to the beaks of petrels as they fly in windy weather and recording the sounds picked up.

On sufficiently windy days on islands far out at sea, we would expect shearwaters to choose a bearing that ensures a perpendicular crosswind on both the outward and return leg of a foraging mission. By this strategy, wind assistance would always be available and net headwinds could be avoided on both legs. This would allow commuting to more distant foraging areas where, due to less regular predation and deeper waters, food may be more plentiful.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.pocean.2014.04.005. These data include files for viewing in Google Earth.

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Analysis of intermittent flapping flight.

Supplementary Figures

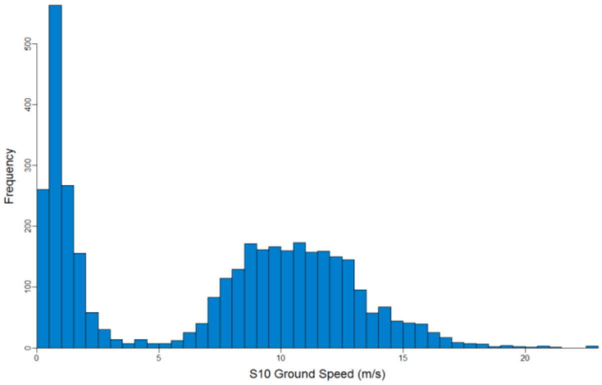

Figure S1. A histogram of the calculated ground speeds for logger S10 exhibits a pronounced dip at around 5 m/s which enabled flight to be simply delineated from other activities.

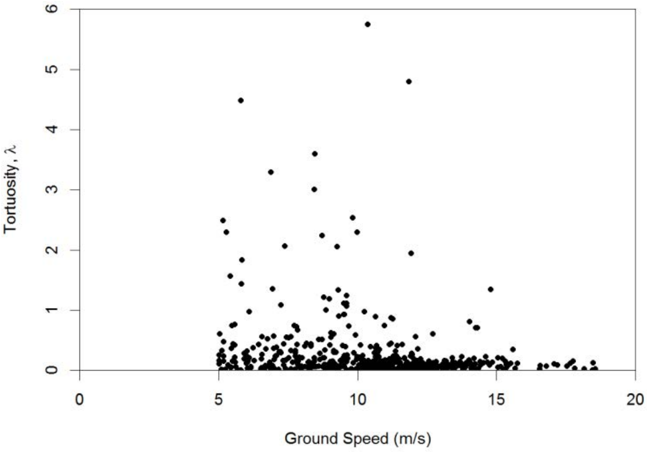

Figure S2. Relationship between flight path tortuosity and ground speed. The most directed flight is associated with higher ground speeds, consistent with the avoidance of banking at high g-forces. Tortuosity was only calculated during flight using the threshold of 5 m/s suggested by Fig. S1.

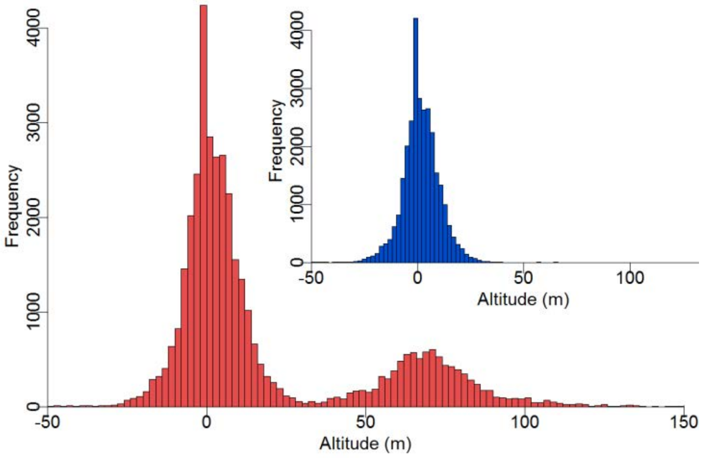

Figure S3. A histogram of raw altitude measurements pooled from all GPS loggers. The striking bimodality is due to birds spending time either at sea or on Bardsey Island, as is apparent when GPS fixes within 400m of the burrows are excluded - see blue histogram inset.

Analysis of intermittent flapping flight.

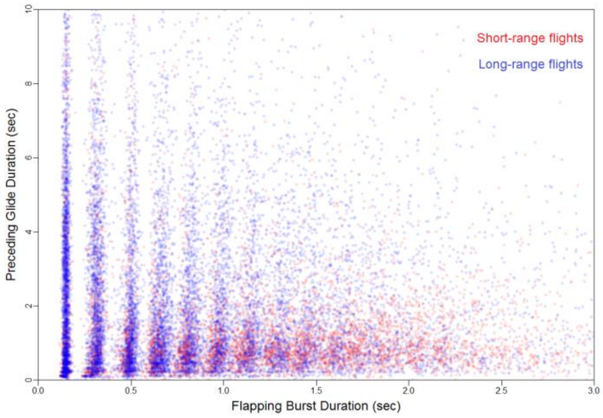

Figure S4. Duration of flapping bursts versus duration of preceding glide phases. Results for short range flights are plotted in red and longer range flights in blue. Vertical banding arises due to an integer number of wing-beats in each burst of flapping and little variation in wing-beat frequency.

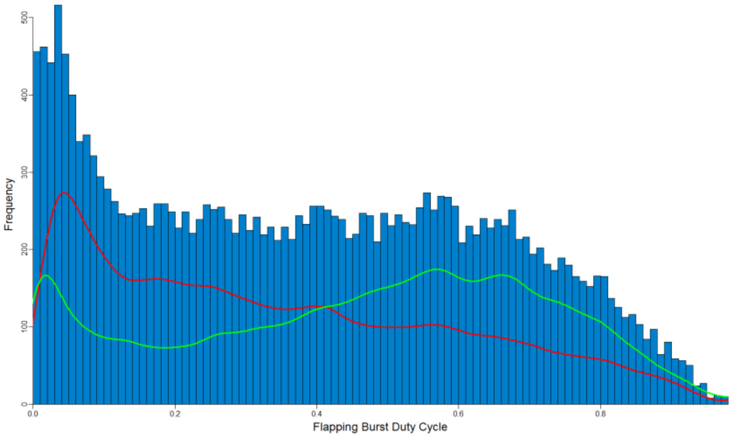

Figure S5. Histogram of the flapping duty cycle (blue). A disparity in the histograms is obtained when flights are partitioned according to range, with short range flight (green) predominantly utilising duty cycles of 0.5 to 0.7 and long range flight (red) favouring much lower duty cycles. A smoothing bandwidth of 0.02 was employed for the density traces.

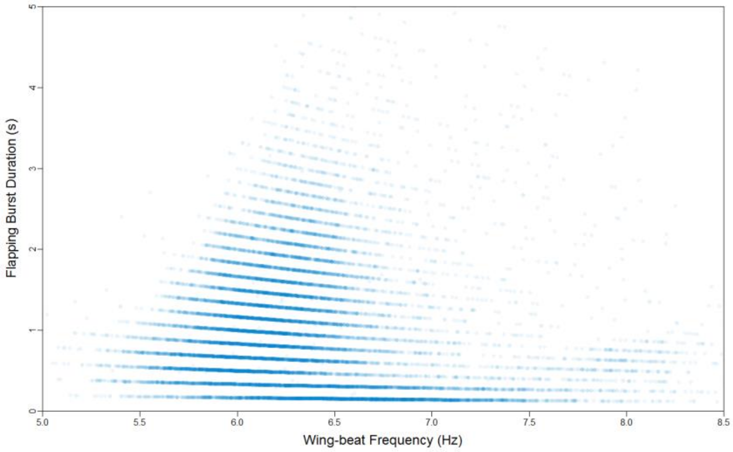

Figure S6. Relationship between the duration of flapping bursts and wing-beat frequency. Something of a wall can be discerned at 6.5 Hz, above which flight is less likely to occur.

Analysis of intermittent flapping flight.

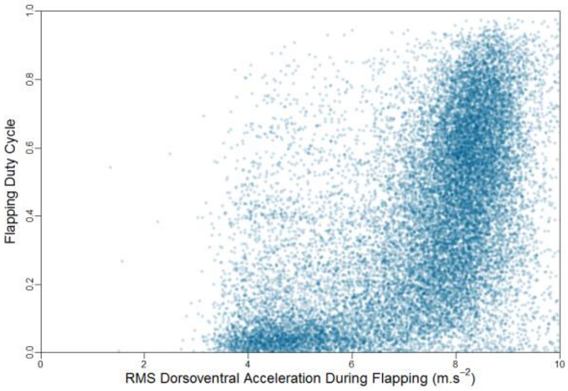

Figure S7. The dynamic dorsoventral acceleration during flapping bursts tend to be gentle at lower duty cycles and increases somewhat with duty cycle when the wind provides less assistance.

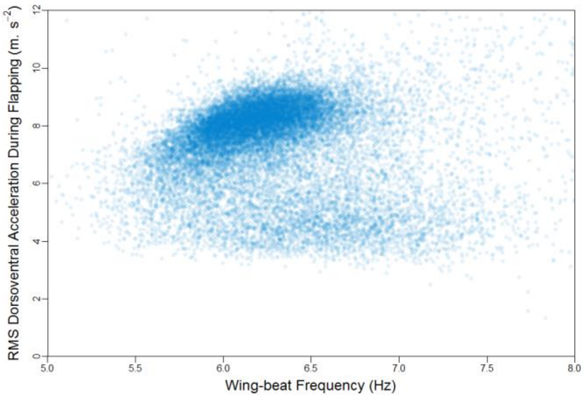

Figure S8. The relationship between the RMS dorsoventral dynamic acceleration and wing-beat frequency. The nature of the apparent wall at 6.5 Hz in Fig. S6 is elucidated as being effort-related. Low effort flapping was more likely during short-range flights.

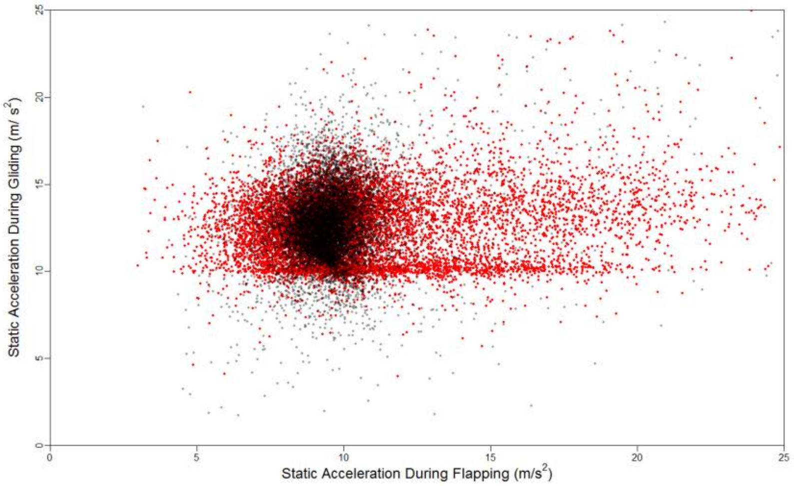

Figure S9. Comparison of mean static acceleration (low-pass filtered acceleration) during flapping and during gliding thresholded according to flapping duty cycle. Red points are mainly associated with long-range flights whereas grey points are mainly associated with short-range flights, the two sets being of equal size according to duty cycle with a threshold of 0.38. Values of the static acceleration during gliding lying close to 1-g occur primarily for lengthier episodes of gliding and are primarily associated with duty cycles below 0.02.

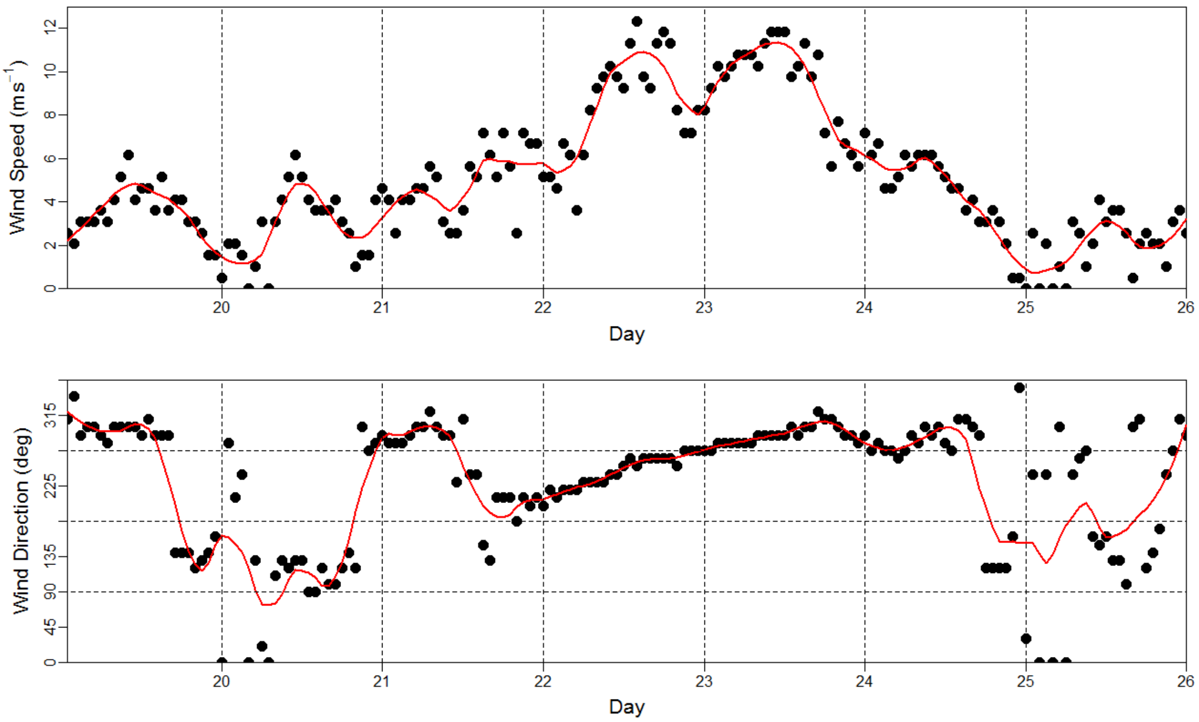

Figure S10. Wind Speed and Direction for Dublin Airport as reported by the Irish Meteorological Service on the June dates of interest showing a 10 m·s^{-1} westerly cross-wind on the morning of the 23rd and a 6 m·s^{-1} south-westerly tailwind on the morning of the 22nd. Local regression (LOESS) fits(red traces) were used to estimate wind strength and direction at intermediate times.

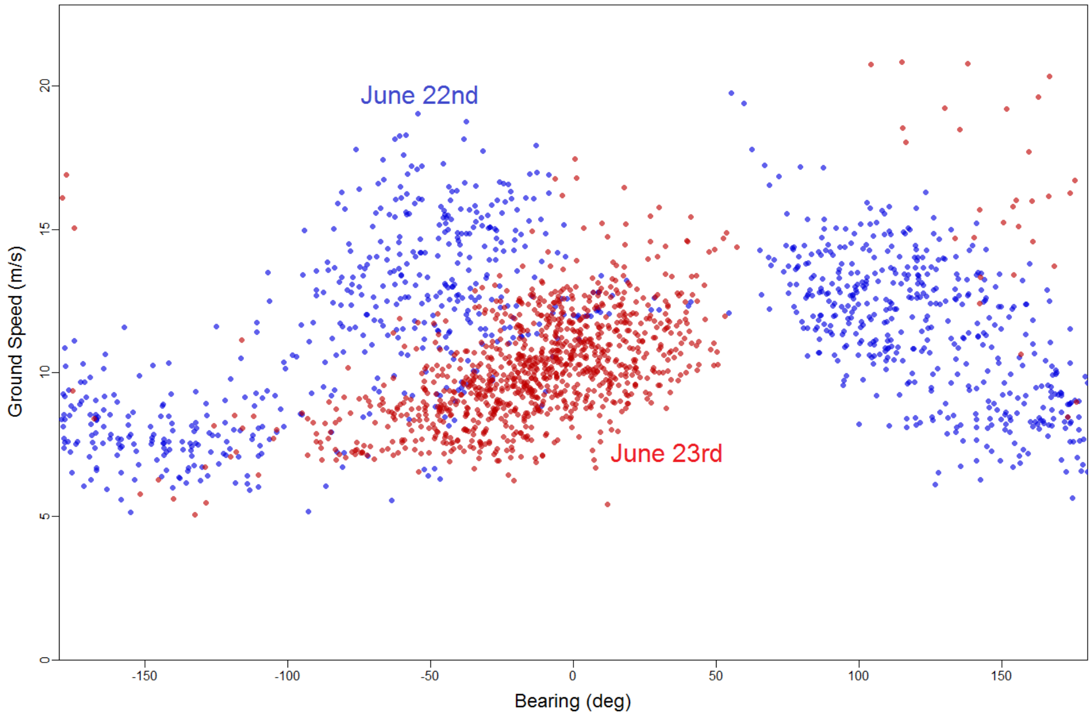

Figure S11. Ground speed and bearing during flight for logger S10 on June 22 (blue) and June 23 (red). Bearings are reported in degrees clockwise from true north. Differences may be entirely attributable to changes in the prevailing wind speeds and wind directions.

Analysis of intermittent flapping flight.

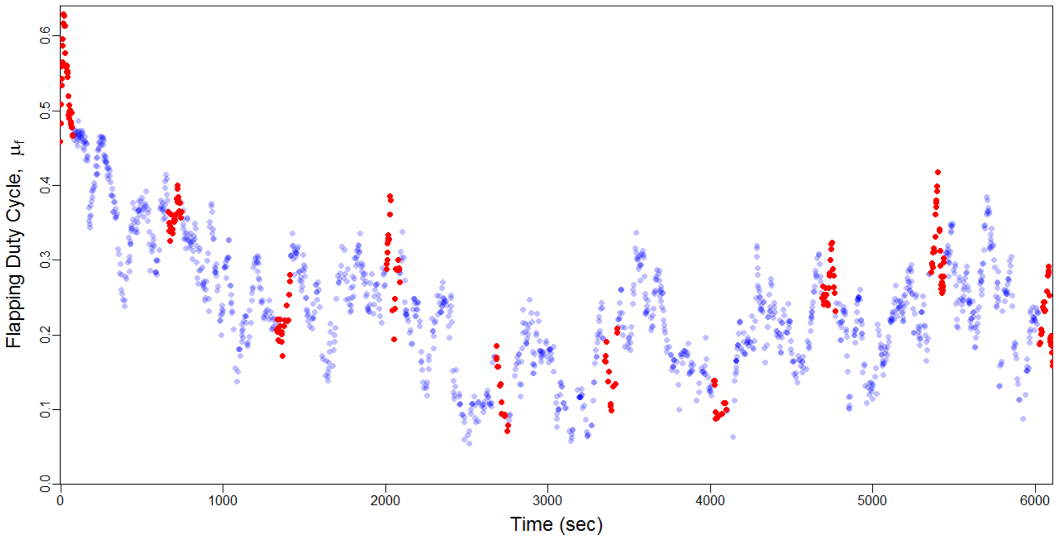

Figure S12. The time-averaged flapping duty cycle for the northward flight varied considerably despite the fact that the general rate of progress towards the north varied very little (see fig.8). GPS data are available for the red points and all times are relative to 01:40 UTC on June 23rd: this applies also to the following two plots (figures S13 and S14).

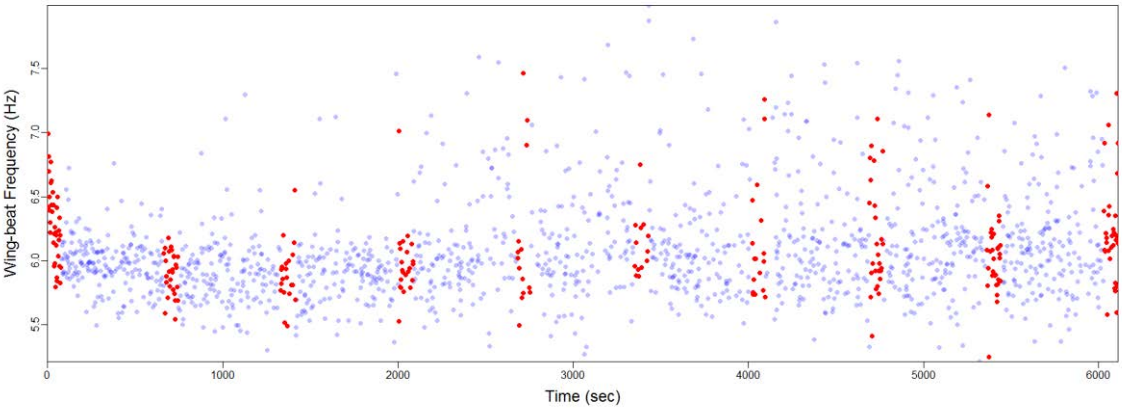

Figure S13. Wing-beat frequency during flapping bursts for the northward flight with times. Wing-beat frequencies are generally more consistent at higher duty cycles.

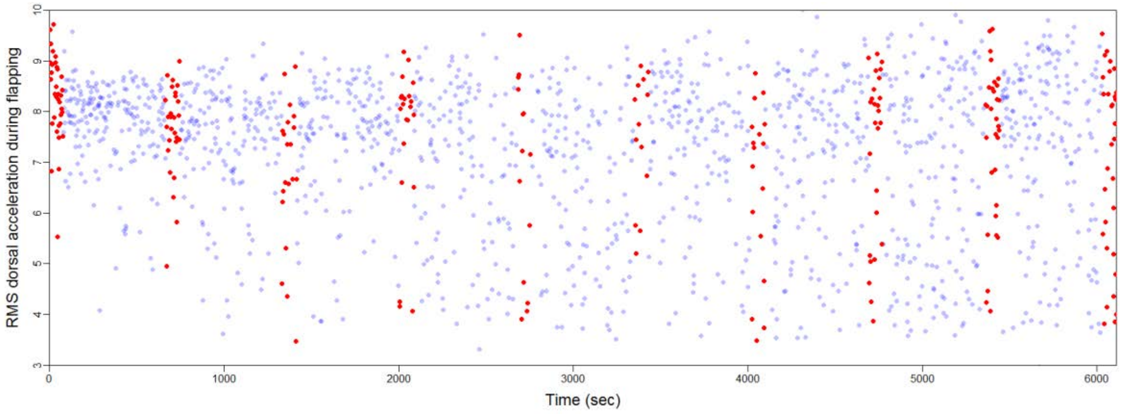

Figure S14. The RMS acceleration (in m.s^{-2}) during flapping bursts for the northward flight. It is apparent that effort levels declined, often dramatically, when flapping at lower duty cycles.

Analysis of intermittent flapping flight.

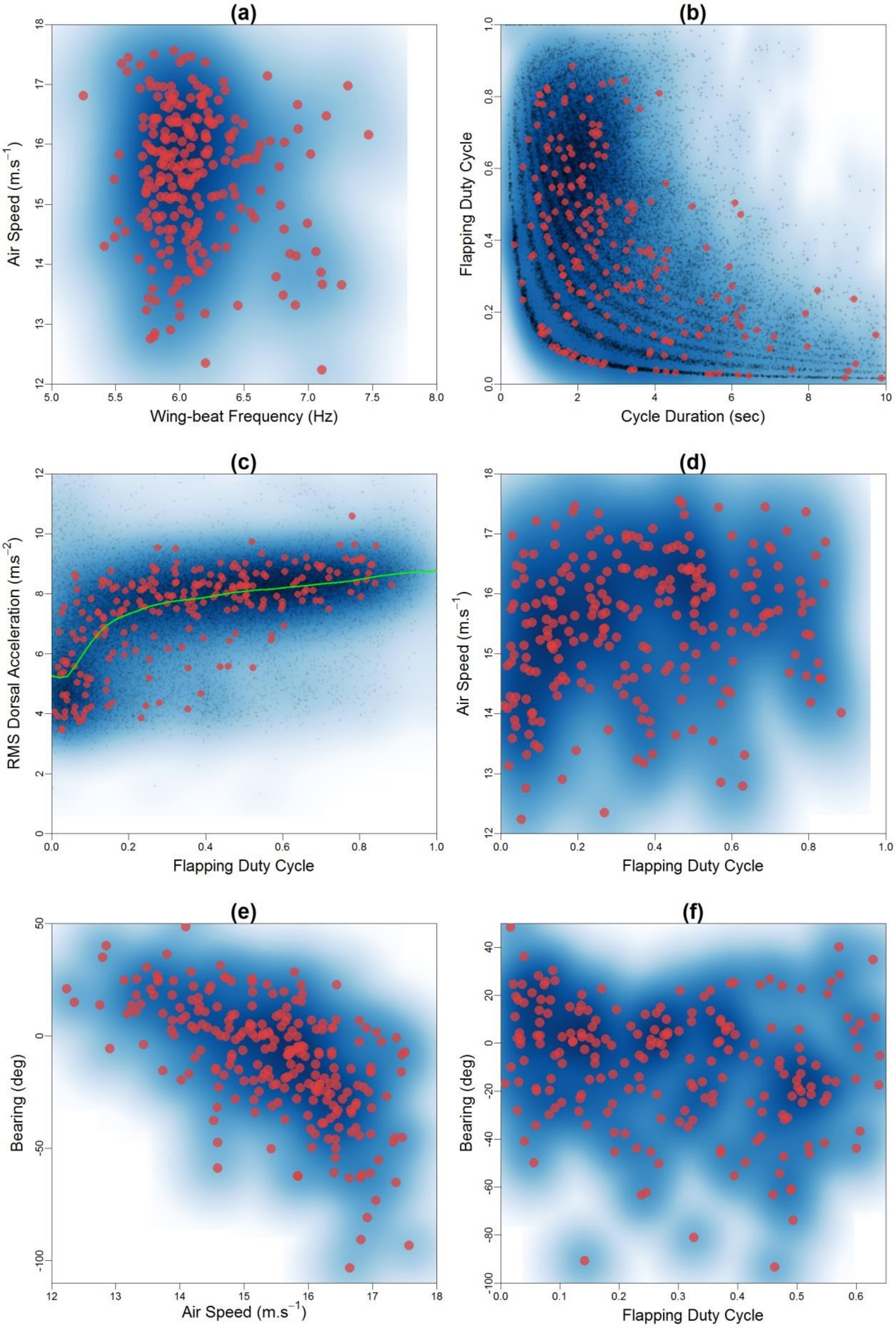

Figure S15. Plots showing data for the June 23rd northward flight section of bird S10 in red and, where available, all flight data in black. Two dimensional kernel density estimation, operating on all available data for this bird, was used to provide the background shading in blue.

Analysis of intermittent flapping flight.

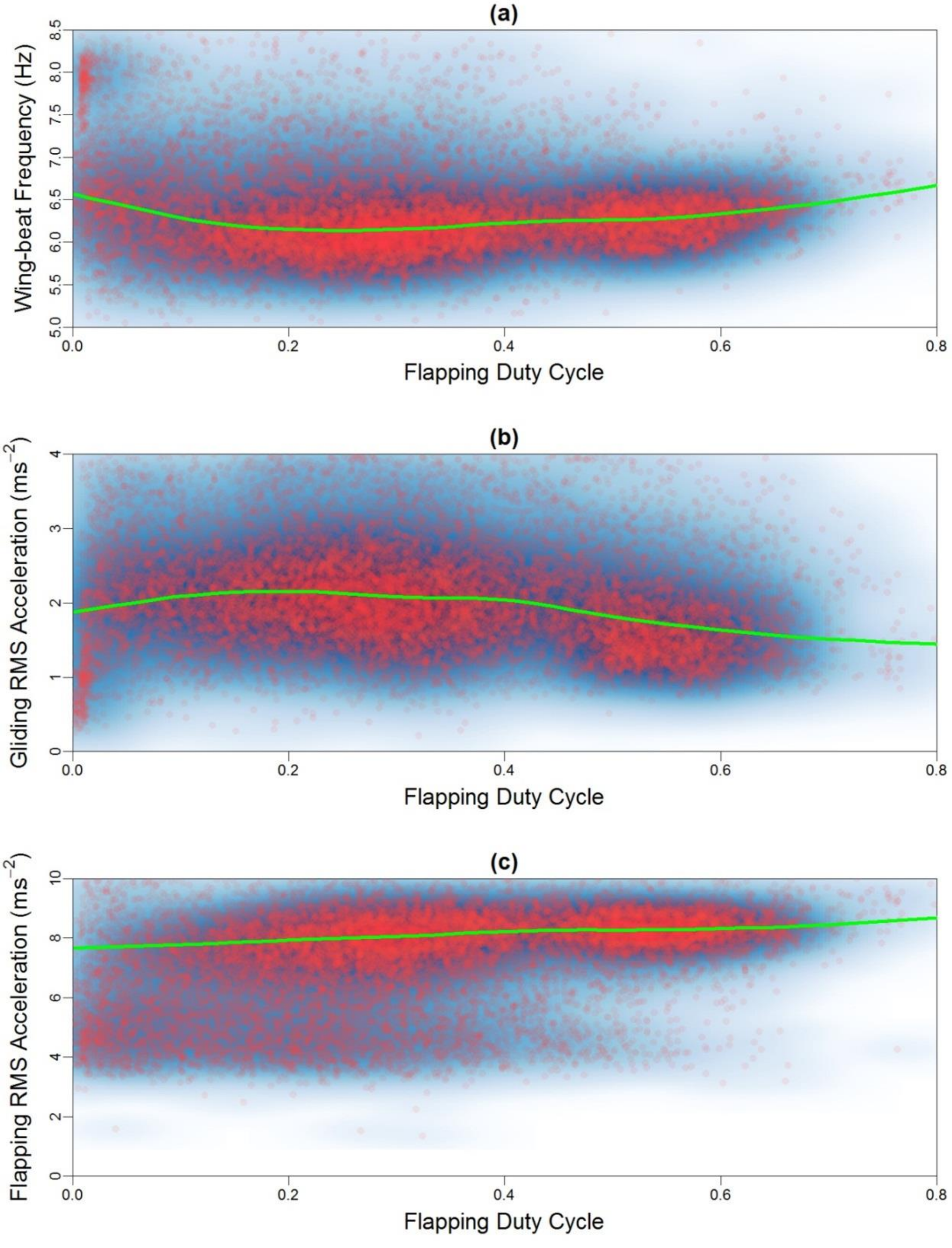

Figure S16. (a) An upward trend in wing-beat frequency with duty cycle is apparent, consistent with increasing effort at higher duty cycles. (b) The dynamic acceleration during gliding episodes was stronger at lower duty cycles, implying greater use of dynamic soaring. (c) Flapping flight tended to occur at dynamic accelerations around 8 m·s^{-2} *but with a modest increase at higher duty cycles. Trend lines were obtained using LOESS local regression with a smoothing bandwidth of 0.3 and accelerations below 6.8 m·s*$^{-2}$*were ignored in the fit shown in (c).*

Analysis of intermittent flapping flight.

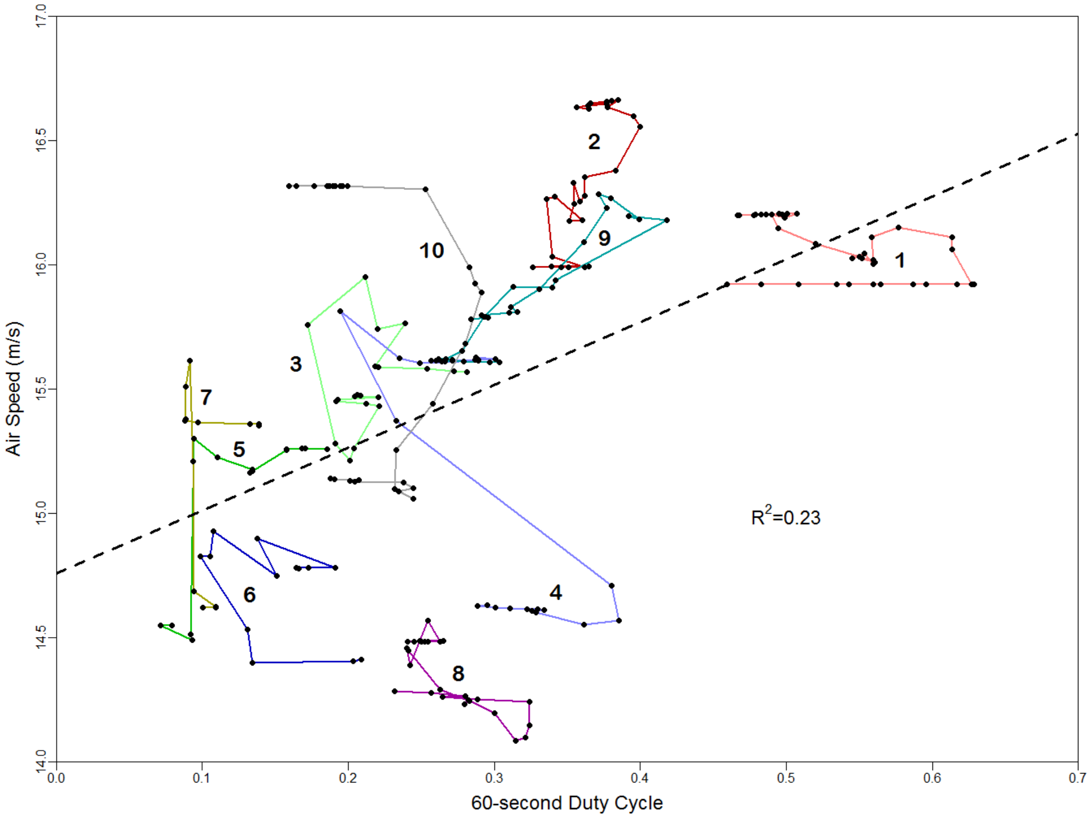

Figure S17. Airspeed varied little on the northward flight. Flapping bursts from the same contiguous section of GPS are connected by coloured lines and consecutively numbered. The dashed line was obtained by least squares regression and exhibits a weak correlation of just 0.23.

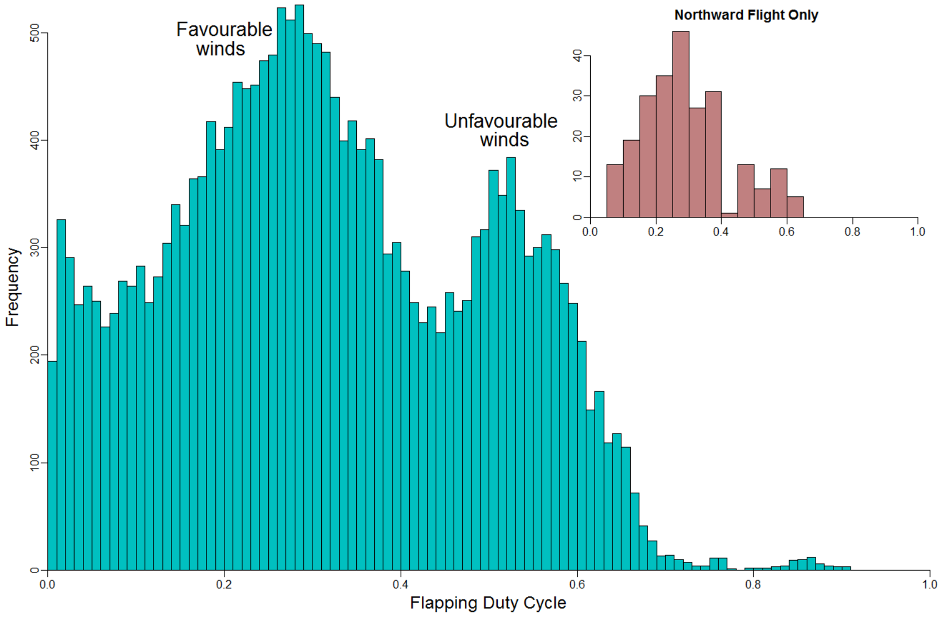

Figure S18. The duty cycle histogram derived from all flights for bird S10 has a bimodal distribution (also apparent in the northward flight: see inset). This bimodality may be associated with favourable and unfavourable wind conditions. We associate the hump whose median duty cycle is 0.26 with strong crosswinds and the hump whose median duty cycle is 0.54 with lighter winds, headwinds and possibly also tailwinds.

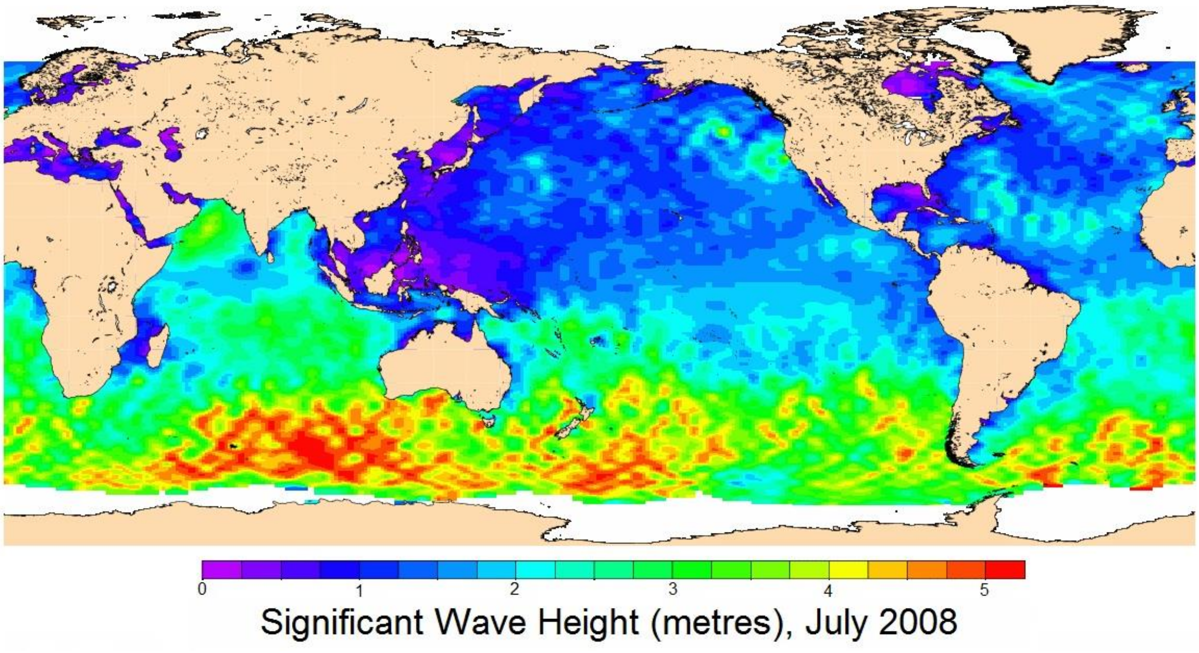

Figure S19. Wave heights are generally higher in the southern hemisphere than the northern hemisphere. Since wave heights are strongly correlated with wind speeds, conditions in the Irish Sea on June 23rd resembled those of the Roaring Forties. Image courtesy of NASA.

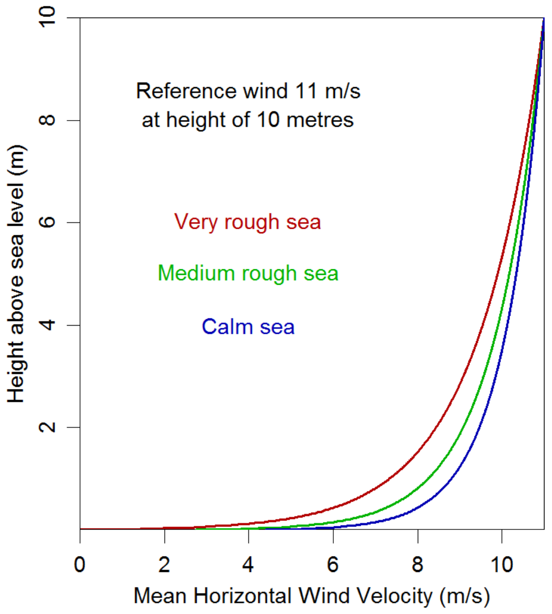

Figure S20. Wind profiles for various sea conditions in nominal winds of 11 m/s at a reference height of ten metres above sea level according to the classic equation $\frac{v_2}{v_1} = \frac{\ln(h_2/h_0)}{\ln(h_1/h_0)}$ *in which the height scale* h_0 *ranges between 0.1 and 10 mm according to the roughness of the sea.*

Paper V

The roller coaster flight strategy of bar-headed geese migrating across the Tibetan Plateau and the Himalayas.

C. M. Bishop*, R. J. Spivey*, L. A. Hawkes, N. Batbayar, B. Chua, P. B. Frapell, W. K. Milsom T. Natsagdorj, S. H., Newman, G. R. Scott, J. Y. Takekawa, M. Wikelski, P. J. Butler

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essential crop repertoire, buffered against temperature change with the significant addition of cold-hardy barley. That same combination of crops additionally enabled the establishment of farms at altitudes hitherto uncultivated, taking farming in some places to elevations above 4000 masl.

Several features of this high-altitude farming prompt further questions about adaptive response. As indicated at the outset, these may include genetic resistance in humans to altitude sickness (*27*); genetic response in crop plants that is observable in the genetics of barley, in relation to such attributes as grain vernalization, flowering time response, and ultraviolet radiation tolerance (*28*); and the identity, genetic and ethnic, of the human communities themselves (*1*, *29*). Such genetic outcomes are all consequent upon the ecological trajectories of cross-continental crop movement. Elsewhere in Europe, Asia, and Africa, that movement has been seen to have a wide variety of outcomes. In the NETP, the data presented here document its facilitation of cultivating the “roof of the world.”

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/347/6219/248/suppl/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S6
Tables S1 to S3
References (*30*–*44*)

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ANIMAL PHYSIOLOGY

The roller coaster flight strategy of bar-headed geese conserves energy during Himalayan migrations

C. M. Bishop,[1]*‡ R. J. Spivey,[1]* L. A. Hawkes,[1]†‡ N. Batbayar,[2] B. Chua,[3] P. B. Frappell,[4] W. K. Milsom,[3] T. Natsagdorj,[5] S. H. Newman,[6] G. R. Scott,[7] J. Y. Takekawa,[8] M. Wikelski,[9,10] P. J. Butler[11]

The physiological and biomechanical requirements of flight at high altitude have been the subject of much interest. Here, we uncover a steep relation between heart rate and wingbeat frequency (raised to the exponent 3.5) and estimated metabolic power and wingbeat frequency (exponent 7) of migratory bar-headed geese. Flight costs increase more rapidly than anticipated as air density declines, which overturns prevailing expectations that this species should maintain high-altitude flight when traversing the Himalayas. Instead, a “roller coaster” strategy, of tracking the underlying terrain and discarding large altitude gains only to recoup them later in the flight with occasional benefits from orographic lift, is shown to be energetically advantageous for flights over the Himalayas.

Migrating birds must overcome many challenging environmental obstacles, such as arid deserts (*1*, *2*) and featureless oceans (*3*–*5*), but few are capable of negotiating the formidably high mountains separating the Indian subcontinent from central Asia. Famously, one species that manages this feat is the bar-headed goose (*Anser indicus*), which biannually traverses the high passes of the Tibetan massif and snow-capped Himalayan mountains (*6*–*8*). Over the years, there has been much debate as to how high these birds might fly and what physiological mechanisms could be involved at the highest altitudes (*8*–*12*), but, although one goose has been directly tracked as high as 7290 m for a brief period (*12*), no measurements of their physiological or biomechanical flight performance have been made in the wild.

To investigate the flight dynamics and energetics of migratory bar-headed geese, we used custom-designed implantable instruments (*13*) to measure abdominal temperature and pressure (every 30 s), tri-axial acceleration (100 Hz in 18-s bursts every 2 min), and electrocardiography (180 Hz in the same 18-s period) from seven birds, collecting data totaling 391 hours of migratory flight (Fig. 1). The data loggers weighed 32 g and were housed in biocompatible tubing (dimensions 7 × 2 cm) capped by titanium electrodes.

Abdominal body temperature during flight (40.2°C ± 1.2 SD) tended to increase in tandem with flight activity, especially during times of

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[1]School of Biological Sciences, Bangor University, Bangor, Gwynedd, UK. [2]Wildlife Science and Conservation Center of Mongolia, Ulaanbataar, Mongolia. [3]Department of Zoology, University of British Columbia, Vancouver, British Columbia, Canada. [4]Office of the Dean of Graduate Research, University of Tasmania, Tasmania, Australia. [5]Mongolian Academy of Sciences, Ulaanbataar, Mongolia. [6]Emergency Prevention System (EMPRES) Wildlife and Ecology Unit, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. [7]Department of Biology, McMaster University, Ontario, Ontario, Canada. [8]San Francisco Bay Estuary Field Station, Western Ecological Research Center, U.S. Geological Survey, Vallejo, CA 94592 USA. [9]Max Planck Institüt für Ornithologie, Radolfzell, Germany. [10]Department of Biology, University of Konstanz, Konstanz, Germany. [11]School of Biosciences, University of Birmingham, Birmingham, UK.
*These authors contributed equally to this work. †Present address: Centre for Ecology and Conservation, University of Exeter, Cornwall Campus, UK. **‡Corresponding author. E-mail: c.bishop@bangor.ac.uk (C.M.B.); l.hawkes@exeter.ac.uk (L.A.H.)**

intense effort (Fig. 1) but was generally insensitive to changes in altitude (fig. S1). The frequency distribution of all pressure-determined altitude measurements recorded during the migratory flights is shown in Fig. 2A. The median altitude while traversing the Tibetan plateau was 4707 m (maximum 6443 m, 90% of observations <5600 m). Thus, pressure-derived altitudes do not provide evidence for a general paradigm of extreme high-altitude (>8000 m) migratory flight in this species (*12*).

In order to estimate rate of oxygen consumption ($\dot{V}_{O_2}$, ml min^{-1}) during flight from measures of heart rate (f_h, beats min^{-1}) (*14–17*), we apply an allometric proportionality derived for 12 species of birds during flight (*14*) to data obtained from bar-headed geese flying in a wind tunnel (*17*) (fig. S2), and obtain the calibration relationship:

$$\dot{V}_{O_2} = 0.07 \pm 0.002\, M_b^{0.24 \pm 0.01} M_h f_h^2 \qquad (1)$$

For wild migratory geese, we substitute values for body mass (M_b) of 2.8 kg and heart mass (M_h) of 1% of body mass (*18*). We then converted estimates of $\dot{V}_{O_2}$ to estimates of metabolic flight power (P_m, W kg^{-1}) by assuming 1 ml O$_2$ ≅ 20.9 J. Additionally, we estimate biomechanical body power (P_b, W kg^{-1}) during flight, using measures of dynamic body acceleration (*19–22*). Here, we show that a single P_b component is dominant when empirically correlating several theoretical terms (*22*) for P_b against our estimates of P_m, which determines that time-averaged body power during the flapping flight of geese could be predicted by

$$P_b = \frac{\ddot{Z}^2_{rms}}{2p^2 f_w} \qquad (2)$$

where $\ddot{Z}^2_{rms}$ is root-mean-square dorsoventral acceleration (*z* axis) and f_w is wingbeat frequency.

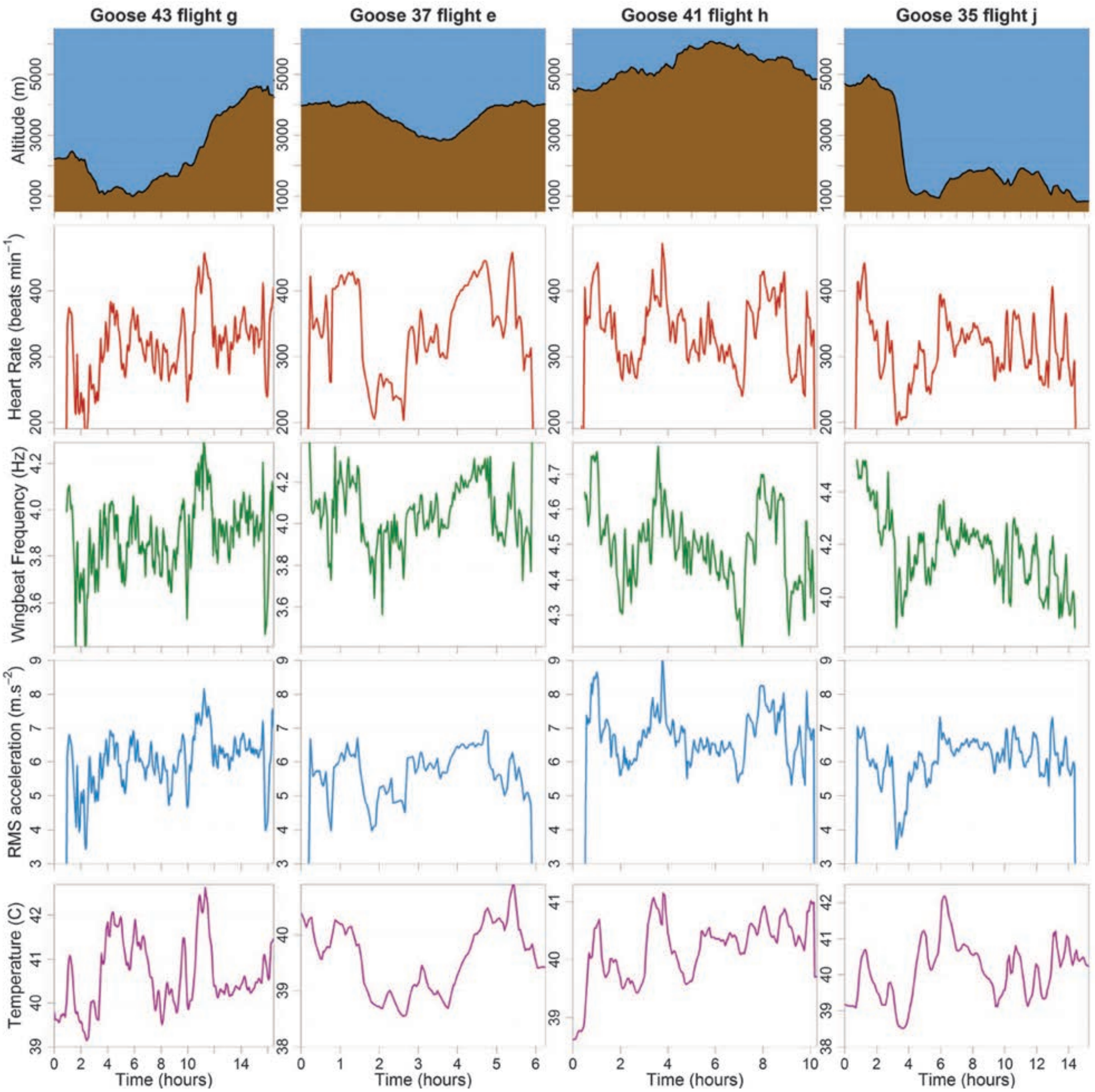

Fig. 1. Examples of autumn migratory flights. Bar-headed goose (*Anser indicus*) P43 travelled South from Mongolia and ascended onto the Tibetan Plateau (column 1); goose P37 (column 2) and goose P41 (column 3) were traversing the Tibetan Plateau; goose P35 (column 4) crossed the Himalayas and descended into India. Pressure altitude (row 1), f_h (row 2), f_w (row 3), $\ddot{Z}^2_{rms}$ (row 4), abdominal body temperature (row 5).

This simple term maximized correlations between the independently derived biomechanical P_b and metabolic P_m (mean $r^2 = 0.91 \pm 0.05$ SD) (Fig. 2B).

During flight, heart rate and wingbeat frequency were significantly correlated (mean $r^2 > 0.86 \pm 0.11$ SD) (Fig. 2, C and D, and fig. S3A), as well as heart rate and $\ddot{Z}^2_{\mathrm{rms}}$ (mean $r^2 = 0.91 \pm 0.05$ SD) (Fig. 2C and fig. S3B) and wingbeat frequency and $\ddot{Z}^2_{\mathrm{rms}}$ (mean $r^2 = 0.89 \pm 0.09$ SD) (fig. S3C). Median wingbeat frequency increased with pressure-derived altitude as air density declined (median f_w = 3.94 Hz at altitude < 2300 m; f_w = 4.35 Hz at altitude >4800 m) (Fig. 2E). Similarly, median heart rate during flight increased with altitude and was generally higher on the Tibetan plateau (f_h = 364 beats min^{-1} at altitude >4800 m) (Fig. 2F) than at lower altitudes (f_h = 300 beats min^{-1} at altitude <2300 m). Although the partial pressure of oxygen decreases with increasing altitude, up to around 5000 m, any potential desaturation of oxygen-bound hemoglobin in the blood of bar-headed geese should still be relatively small, at around 10% (*18*, *23*). Indeed, captive bar-headed geese are able to run for 15 min at similar maximum speeds, whether exposed to atmospheres of 21, 10.5, or 7% oxygen, the last-mentioned condition resulting in a desaturation of between 20 and 23% (*18*).

Our data show that median heart rate during flight scales with air density (ρ) as $f_h \propto \rho^{-0.64}$ (Fig. 2G) and, therefore, that estimated P_m should scale approximately as $P_m \propto \rho^{-0.91}$ (if one assumes that $P_m \propto f_h^2$ but allowing for a 10% additional increase of f_h for a given value of $\dot{V}_{O_2}$ at 5500 m due to a hemoglobin desaturation of 10%). Thus, the relative metabolic flight power of the geese at 5000 m compared with that at sea level is estimated to be around 1.7-fold. This is higher than the anticipated sensitivity of flight power to air density of $P_m \propto \rho^{-0.54}$ predicted by aerodynamic theory (*24*). Similarly, flight theory predicts that wingbeat frequency should be $\propto \rho^{-0.38}$, whereas the present results for bar-headed geese show median $f_w \propto \rho^{-0.23}$ (Fig. 2H). This is at the lower end of the predicted range but in keeping with the observations of large Ciconiiformes (herons, spoonbill, ibis) migrating high above the Negev Desert in Israel (*25*).

Bar-headed geese exhibit an extreme sensitivity of heart rate and, therefore, metabolic flight power to small changes in wingbeat frequency, when a precise method is used for extracting values of f_w (*26*). For example, a 5% increase in f_w from 4.0 to 4.2 Hz equates to a 19% increase in f_h and, therefore, a 41% increase in estimated P_m. Across all migratory flights, f_h correlated in the range of $f_h \propto f_w^{1.95 \text{ to } 6.65}$ and estimated P_m as $P_m \propto f_w^{3.9 \text{ to } 13.3}$, the latter exponent exceeding 3 in every case (median exponent 6.96) (Fig. 2I). For steady horizontal flight, the inertial

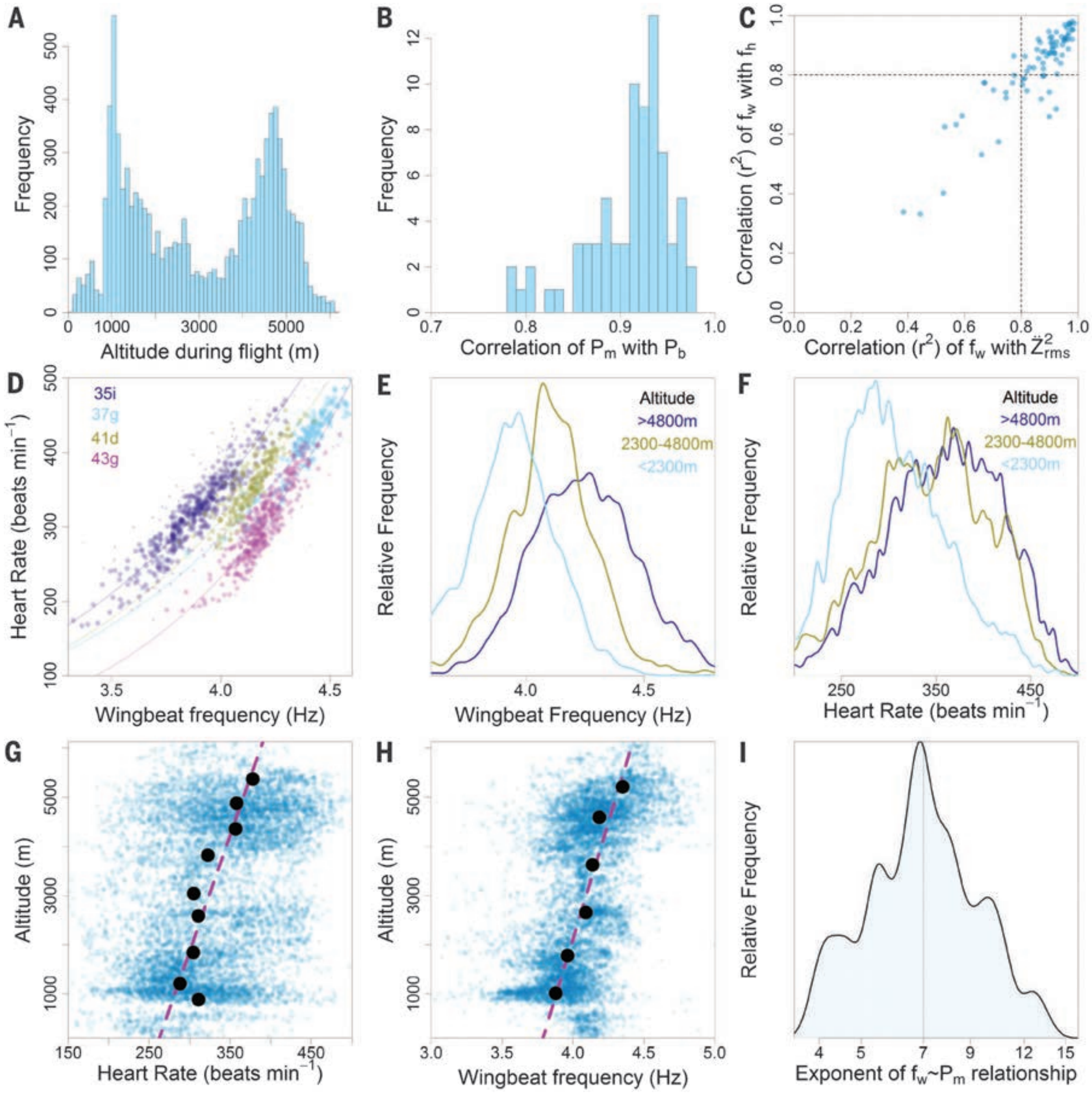

Fig. 2. Descriptive flight statistics. Frequency histograms of (**A**) altitude reported during migratory flights of bar-headed geese (*Anser indicus*) and (**B**) correlation of estimated P_m versus estimated P_b. (**C**) Correlation of f_h versus f_w plotted against correlation of $\ddot{Z}^2_{\mathrm{rms}}$ versus f_w. (**D**) Examples of f_h against f_w for four individual flights. Frequency distribution of (**E**) f_w and (**F**) f_h within three altitude zones. Scatter plots of (**G**) f_h and (**H**) f_w plotted against altitude. (**I**) Frequency distribution of power exponents for f_w against estimated P_m.

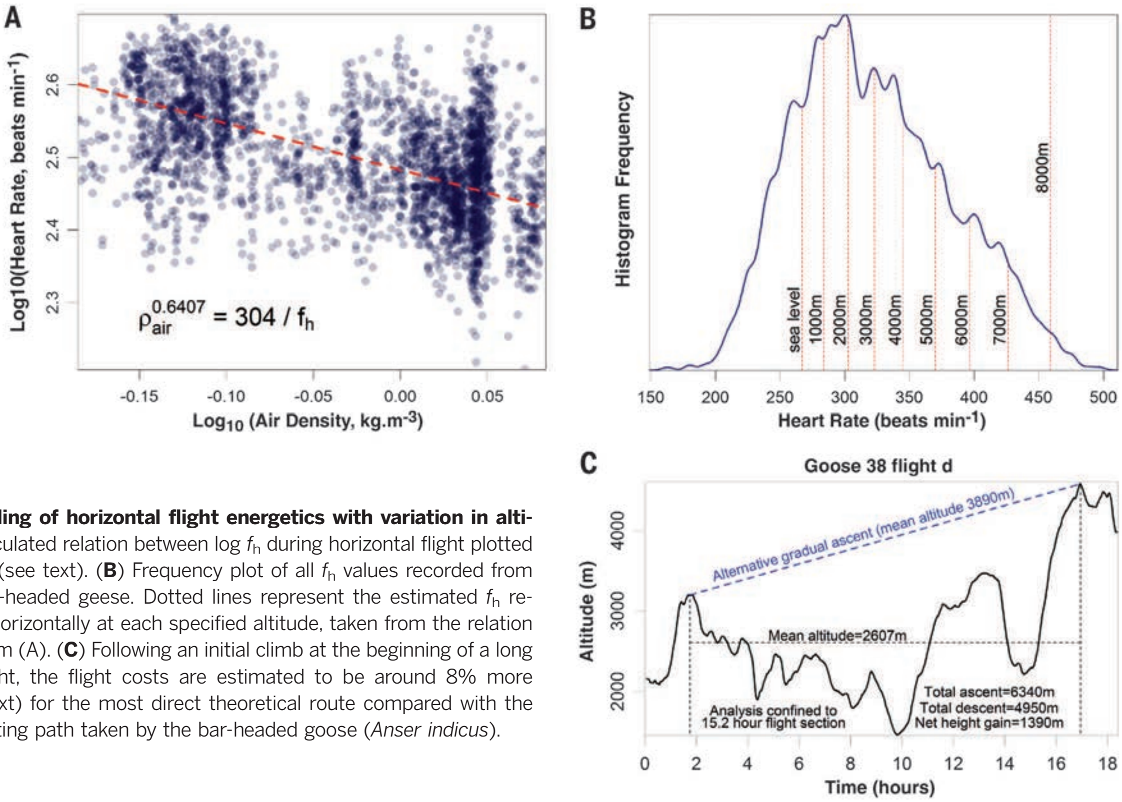

Fig. 3. Modeling of horizontal flight energetics with variation in altitude. (**A**) Calculated relation between log f_h during horizontal flight plotted against log ρ (see text). (**B**) Frequency plot of all f_h values recorded from the same bar-headed geese. Dotted lines represent the estimated f_h required to fly horizontally at each specified altitude, taken from the relation calculated from (A). (**C**) Following an initial climb at the beginning of a long migratory flight, the flight costs are estimated to be around 8% more costly (see text) for the most direct theoretical route compared with the actual undulating path taken by the bar-headed goose (*Anser indicus*).

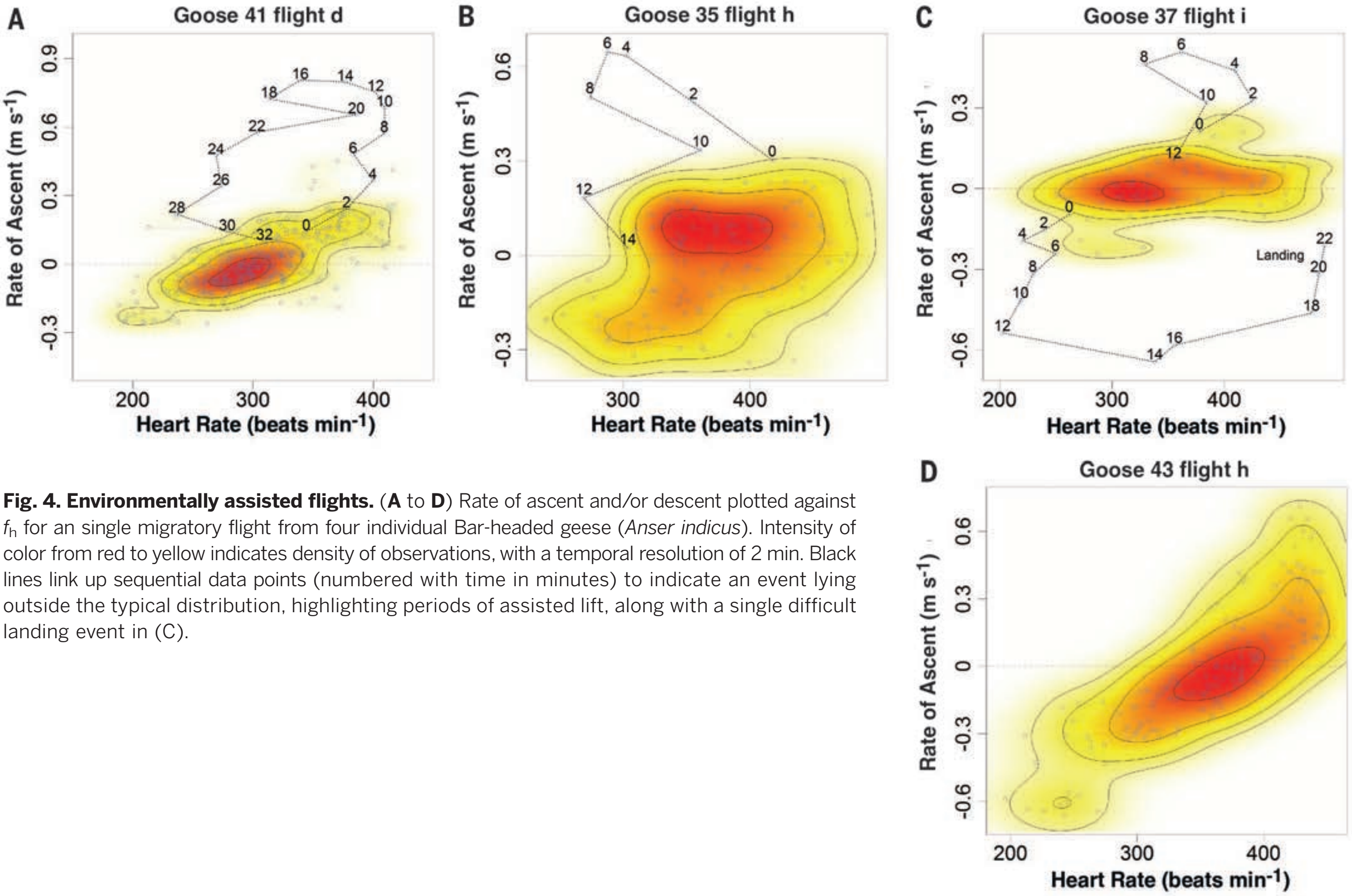

Fig. 4. Environmentally assisted flights. (**A** to **D**) Rate of ascent and/or descent plotted against f_h for an single migratory flight from four individual Bar-headed geese (*Anser indicus*). Intensity of color from red to yellow indicates density of observations, with a temporal resolution of 2 min. Black lines link up sequential data points (numbered with time in minutes) to indicate an event lying outside the typical distribution, highlighting periods of assisted lift, along with a single difficult landing event in (C).

costs of flapping the wings should be proportional to the product of wingbeat frequency cubed and the wing amplitude squared. If the body of the bird undergoes sinusoidal amplitude displacements on the vertical axis (B) then $\ddot{Z}^2_{\mathrm{rms}} = 2\ \sqrt{2}\pi^2\ B\ f_{\mathrm{w}}^2$ (*22*) and so Eq. 2 can be rewritten

$$P_{\mathrm{b}} = 4\pi^2\ B^2\ f_{\mathrm{w}}^3\ (3). \qquad (3)$$

Because B should be positively correlated with wingbeat amplitude, the implication of our experimental data, showing that $P_{\mathrm{m}} \propto f_{\mathrm{w}}^{6.96}$, is that the angular travel of the wing increases with higher f_{w}. Thus, the exquisite sensitivity of P_{m} to f_{w} in geese stems from wingbeat amplitude that is positively correlated with changes in wingbeat frequency.

In the present study, there was no evidence of gliding behavior in bar-headed geese, even when descending rapidly from the Himalayas into India (fig. S4). During the steepest descent phases, f_{w} remained above 3.6 Hz for 98% of observations, whereas f_{h} decreased to between 150 and 200 beats min^{-1}. Indeed, f_{h} was surprisingly low in general throughout the entire migration (overall mean f_{h} = 328 ± 64 beats min^{-1}) (Fig. 2F), with geese only spending 2.3% of their flight time at altitudes above 4800 m with a f_{h} greater than 455 beats min^{-1} (and 0.37% of their flight time when below 2300 m altitude). A simple extrapolation of the relations between heart rate and air density (Fig. 3A), with data filtered so that only rates of ascent or descent lying between ±0.1 m s^{-1} are included (an approximation of horizontal flight), demonstrates that a minimum heart rate of around 460 beats min^{-1} might just suffice at around 8000 m in still air conditions (Fig. 3B). However, even this assessment might seem unduly optimistic, given that it ignores the energetics and time required to make the climb itself and the steepness of the relation for hemoglobin desaturation once the partial pressures of oxygen fall below a critical value (*18*, *23*). Thus, unaided horizontal flights over 8000 m are likely to be approaching the limit for sustained aerobic capacity in this species.

Previous low temporal-resolution global positioning system altitude data (*12*) indicated that bar-headed geese tend to fly closest to the ground when traversing the Tibetan massif, with a median height of only 62 m. This is consistent with the high-resolution pressure altitude results of the present study, which imply that geese opt repeatedly to shed hard-won altitude only subsequently to regain height later in the same flight. An example of this tactic can be seen in a 15.2-hour section of a 17-hour flight (Fig. 3C) in which, after an initial climb to 3200 m, the goose followed an undulating profile involving a total ascent of 6340 m with a total descent of 4950 m for a net altitude gain of only 1390 m. Revealingly, calculations show that steadily ascending in a straight line would have increased the journey cost by around 8%. As even horizontal flapping flight is relatively expensive, the increase in energy consumption due to occasional climbs is not as important as the effect of reducing the general costs of flying by seeking higher-density air at lower altitudes.

Rates of ascent and descent during four migratory flights are plotted against f_{h} (Fig. 4) and against f_{w} (fig. S5), with maximum ascent rates of up to at least 0.8 m s^{-1}, lasting for several minutes. However, such extreme ascent rates were generally not associated with increases in f_{h} and f_{w}. A particularly clear example of such an episode that occurred during a 13-hour migratory flight is shown in Fig. 4A. The central cluster of Fig. 4A exhibits a sloping relation between f_{h} and rate of ascent (typical of a number of flights), but there was a dramatic departure from this pattern lasting ~30 min involving unusually high rates of ascent despite "normal" values of heart rate. Although the degree of central clustering varied between flights, presumably according to the prevailing wind conditions and underlying terrain, similar unusually high ascent rates occurred on other flights (Fig. 4, B to D). These unique results are interpreted as evidence of sustained assistance from updrafts due to orographic lift (*27*, *28*), presumably indicative of geese flying along the windward side of a ridge. Thus, it is logical to conclude that weaker vertical updrafts could also provide more gentle assistance during other phases of the migratory flights, perhaps comparable in magnitude to the assistance geese might at times receive from V-formation flight (*29*, *30*).

When traversing mountainous areas, a terrain-tracking strategy or flying in the cool of the night (*12*) can reduce the cost of flight in bar-headed geese through exposure to higher air density. Ground-hugging flight may also confer additional advantages including maximizing the potential of any available updrafts of air, reduced exposure to crosswinds and headwinds, greater safety through improved ground visibility, and increased landing opportunities. The atmospheric challenges encountered at the very highest altitudes, coupled with the need for near-maximal physical performance in such conditions, likely explains why bar-headed geese rarely fly close to their altitude ceiling, typically remaining below 6000 m. Given that aerodynamic mass-specific flight costs are thought to increase with body mass and that bar-headed geese are heavier than 98% of avian species, it is particularly impressive that these birds are able to migrate across the world's highest land massif while remaining comfortably within their physiological capabilities.

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SUPPLEMENTARY MATERIALS

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Supplementary Text
Figs. S1 to S5
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Supplementary Materials for

The roller coaster flight strategy of bar-headed geese conserves energy during Himalayan migrations

C. M. Bishop,* R. J. Spivey, L. A. Hawkes,* N. Batbayar, B. Chua, P. B. Frappell,
W. K. Milsom, T. Natsagdorj, S. H. Newman, G. R. Scott, J. Y. Takekawa,
M. Wikelski, P. J. Butler

*Corresponding author. E-mail: c.bishop@bangor.ac.uk (C.M.B.); l.hawkes@exeter.ac.uk (L.A.H.)

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Materials and Methods
Figs. S1 to S5
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Supplementary Materials

Materials and Methods

Fieldwork and instrumentation

All fieldwork and use and care of animals were conducted following approval of the Animal Ethics Committee at Bangor University. During their summer moult (1st to the 20th July 2011), flightless geese were captured from Terkhiin Tsagaan Lake, Mongolia (Lat 48.147 ºN, Lon 99.576 ºE). Thirty custom-designed data logging instruments (32 g) were implanted into anaesthetised adult geese of mean body mass 2.35 kg (range 2 - 2.57 kg), by a veterinarian (B.C.) and the birds released to the wild following recovery from surgery. Geese were fitted with numbered neck collars and 17 geese were recaptured in 2012 and 2013. No detrimental effects were observed in these geese prior to release, or on recapture, and re-sightings of implanted animals were comparable to those for birds marked with neck collars. This is consistent with a recent meta-analysis, indicating that the negative effects of internal tag implantations have been generally preferable to those of externally attached devices (*30*). The data loggers recorded abdominal temperature and pressure (every 30 seconds), tri-axial acceleration (100 Hz in 18 s bursts every two minutes, i.e. 15% coverage) and ECG (180 Hz in the same 18 s period). Seven of the loggers collectively recorded data on 77 flights of between one and twenty hours duration, totalling 391 hours of flying. Four loggers had a full suite of working sensors and recorded the complete autumn migration of the geese (range 148 - 215 days, total 2,574 hours accelerometry), flight data from which are presented in Fig. 1. Three additional loggers did not function long enough to record the entire migration but provided data between the first 66 - 107 days, while an additional logger completed the migration without recording ECG but did collect data from the other sensors for 148 days. These latter three birds provided some additional flight information (total 1,864 hours of raw accelerometry). Recordings of acceleration were converted into root mean squared dorsoventral-aligned dynamic acceleration (hereafter referred to as $\ddot{Z}_{rms}$, m s^{-2}) and wingbeat frequency (f_w, flaps s^{-1} or Hz). ECG data was post-processed to obtain heart rate (f_h, beats min^{-1}) using a custom QRS-complex detection algorithm. Altitudes were estimated from a factory calibrated pressure transducer (range 1-110 kPa, resolution 10 Pa), converted to pressure altitudes = $44331 (1 - 0.2695 P^{0.1902})$ and subsampled to 2 min mean values. Rates of ascent were calculated by taking the median of four altitude shifts measured over 150 s periods spanning a 2 min altitude measurement. Rate of ascent data were then further filtered by convolution with a Bartlett function so as to obtain estimated rates of ascent sustained over 5 minute periods, considered comparable to the definition of sustained climbing flight as used by Hedenstrom & Alerstam 1992.

Triaxial accelerometry (100 Hz, 12 bit resolution, range ± 8 *g*) was monitored in 18s bursts every two minutes (i.e. 15% coverage), recording 5.56 MB of data each day. Electrocardiography (ECG, 180 Hz, 8 bit resolution) was also monitored in the same 18s period every 2 min and recorded 14.84 MB of data each day. ECG data was processed using bespoke software to derive inter-beat intervals, t_b, and the mean heart rate ($f_h \sim \Delta t_b^{-1}$) calculated (individually weighted as Δt_b^{-2} due to the $P_m \propto f_h^2$ relationship) using only inter-beat intervals lying within ±20% of median t_b. ECG quality could occasionally suffer from EMG interference, so it was important to have a robust method of obtaining representative mean ECG over the 18 s window to allow for accurate automation by the software. Similarly, wing-beat frequency measurements were confined to the range 2.8—5.6 Hz as values less than 2.8 Hz were not seen and it was necessary to define non-flight periods to allow efficient automation of the software. Static accelerations $\boldsymbol{s}(s_1, s_2, s_3)$ were obtained by low-pass filtering the raw accelerations $\boldsymbol{a}(a_1, a_2, a_3)$ with a corner frequency of 0.56 Hz via fast Fourier Transforms (FFT) operating on 7 x 2^8 = 1792 samples at a time, discarding the first few accelerometer samples of each burst as the circuitry settled during recovery from sleep. The magnitude of the dorsoventral component of the acceleration ($\boldsymbol{a}_{\mathrm{dv}}$) was then obtained using

$$a_{dv} = \frac{a_1s_1 + a_2s_2 + a_3s_3}{(s_1^2 + s_2^2 + s_3^2)^{\frac{1}{2}}} \tag{M1}$$

Unit vectors in the coronal plane perpendicular to the dorsoventral axis were calculated by taking the vector product of $\boldsymbol{a}_{\mathrm{dv}}$ with a copy of itself arbitrarily shifted on one of the three component axes, then taking the vector product of that vector with $\boldsymbol{a}_{\mathrm{dv}}$ and normalising both the vectors obtained. The scalar products of these unit vectors with $\boldsymbol{a}$ were then used to project the raw accelerations onto the coronal plane.

Wingbeat Frequency, root mean acceleration and heart rate

A reorientation technique capable of deriving forward and transverse accelerations from the 2-D coronal plane accelerations in flying birds has been described elsewhere and involves construction of an angular histogram and the use of phase information (*20*). The reoriented accelerations were bandpass filtered between 2.8 and 5.6 Hz (to capture the fundamental wing-beat frequency but reject the static accelerations and the harmonics) using FFT methods to obtain the three components of the dynamic acceleration $\boldsymbol{a}_{\mathrm{dyn}}$ (x, y, z) which can be loosely described as lateral ($\ddot{X}_{rms}$), forward ($\ddot{Y}_{rms}$) and upward ($\ddot{Z}_{rms}$). Root-mean-squared measures were obtained for each 18-s window. If $\ddot{Z}^2_{rms}$ exceeded a threshold of 2 m s^{-2} then an attempt was made to quantify the wingbeat frequency. For this, linear interpolation of consecutive samples spanning positive-going zero-crossings in z was used to accurately determine the start and end time of each wingbeat (*25*). Wingbeat frequency measurements involved taking the harmonic mean of the wing-beat intervals present in each 18s time window. Body power was then estimated using the expression $\ddot{Z}^2_{rms} / 2\pi^2 f_{\mathrm{w}}$ (W kg^{-1} or m^2 s^{-3} kg^{-1}).

For each of the flights lasting for more than an hour, for which $\ddot{Z}_{rms}$, f_{w}, and f_{h} data were all available, data were logarithmically transformed and scaled in such a way as to equalise the span on each axis. Principal component analysis was then used to obtain a straight line through the points in three dimensions, which minimised the squared error terms. A straight line in three dimensions can be represented by

$$\frac{x - x_0}{k_x} = \frac{y = y_0}{k_y} = \frac{z - z_0}{k_z} \tag{M2}$$

where k_{x}, k_{y}, k_{z} are the direction numbers of the line and x_0, y_0, z_0 is some point along it. This can alternatively be expressed by the three equations

$$x = x_0 + r_{\mathrm{xy}} (y - y_0) \tag{M3}$$

$$y = y_0 + r_{\mathrm{yz}} (z - z_0) \tag{M4}$$

$$x = x_0 + r_{xz}(z - z_0) \tag{M5}$$

where $r_{xy} = k_x/k_y$, $r_{yz} = k_y/k_z$ and $r_{xz} = k_x/k_y$. This was repeated for each flight, with the poorest fitting point being discarded on each iteration until 10% of the original points had been rejected. Results for individual geese are summarised below:

BIRD	r_{xy}	r_{yz}	r_{xz}	X_0	Y_0	Z_0
P35	4.292	0.206	0.954	0.787	0.615	2.559
P37	3.877	0.174	0.627	0.758	0.597	2.511
P41	3.608	0.248	0.793	0.827	0.630	2.523
P43	3.164	0.274	0.843	0.774	0.594	2.539
Means	3.735	0.226	0.804	0.787	0.609	2.533
± SD	±0.473	±0.044	±0.136	±0.029	±0.017	±0.021

Using these results and transforming backwards from the logarithmic domain the global best fit obtained yielded the following power laws between the three variables:

$$\ddot{Z}_{rms} = 0.03603\, f_w^{3.640\pm0.413}; \quad f_w = 2.4925\, \ddot{Z}_{rms}^{\;0.275\pm0.032} \tag{M6}$$

$$f_w = 1.0024\, f_h^{0.242\pm0.047}; \quad f_h = 0.9909\, f_w^{4.137\pm0.834} \tag{M7}$$

$$\ddot{Z}_{rms} = 0.04816\, f_h^{0.832\pm0.119}; \quad f_h = 38.381\, \ddot{Z}_{rms}^{\;1.202\pm0.176} \tag{M8}$$

If flight power (P_f) is estimated from heart rate using $P_f \propto f_h^2$ then $P_f \propto f_w^{8.274\pm1.668}$. If, alternatively, P_f is estimated from accelerometry using $P_f \propto \ddot{Z}_{rms}^2 / f_w$ then this yields the power law $P_f \propto f_w^{7.038\pm0.873}$. Reasonable agreement is achieved between the two theoretical approaches for exponents of f_w between 6.606 and 7.911. If neither theoretical model is in error then, to one standard deviation, the sensitivity of flight power to wing-beat frequency can be summarised as

$$P_f \propto f_w^{7.26\pm0.65} \tag{M9}$$

Estimation of cost of Transport during Roller Coaster flight

Cost of Transport Modelling the total transport costs for the 15.2-hour section of the 17-hour flight of shown in Fig. 4c, involved integrating the estimated changes in Pm due to alteration in altitude, based on the relationship that metabolic power was $\alpha \sim \rho^{-0.91}$. The biomechanical cost of horizontal flight of a 2.8 kg goose was taken to be 15 W kg^{-1} during horizontal flight at the starting altitude of 3200 m, and then costs determined for the journey by integrating along the route, taking into account the effect of air density according to the International Standard Atmosphere. The additional energy required to climb was taken to be the product of mass, gravity and the vertical height gain. This calculation already indicated a potential saving resulting from taking the lower altitude path, even without taking in to account savings due to descending flight. A simple way to approximate the savings due to descent was to reduce the time calculated for the flight by the time it would take to descend at the very fast rate of minus 1.5 m s^{-1} and to assume that this was at zero cost. Descent rates of half this angle would then have costs of around half those for horizontal flight, which are actually likely to be an overestimate given that heart rates are often as low as 200 to 250 beats min^{-1}. Flight velocity was also taken into account by adjusting flight speeds from the reference point of 15 m s^{-1} at sea level, according to velocity $\sim\rho^{-0.25}$, which is estimated from GPS ground speed data (*12*).

Supplementary Figures

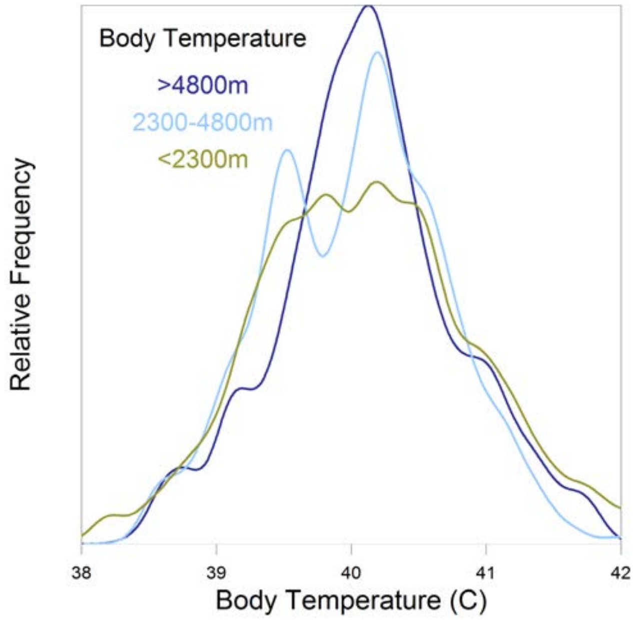

Fig. S1. Frequency plot of body temperature during flight. Distribution of body temperature recorded during flight plotted against altitude.

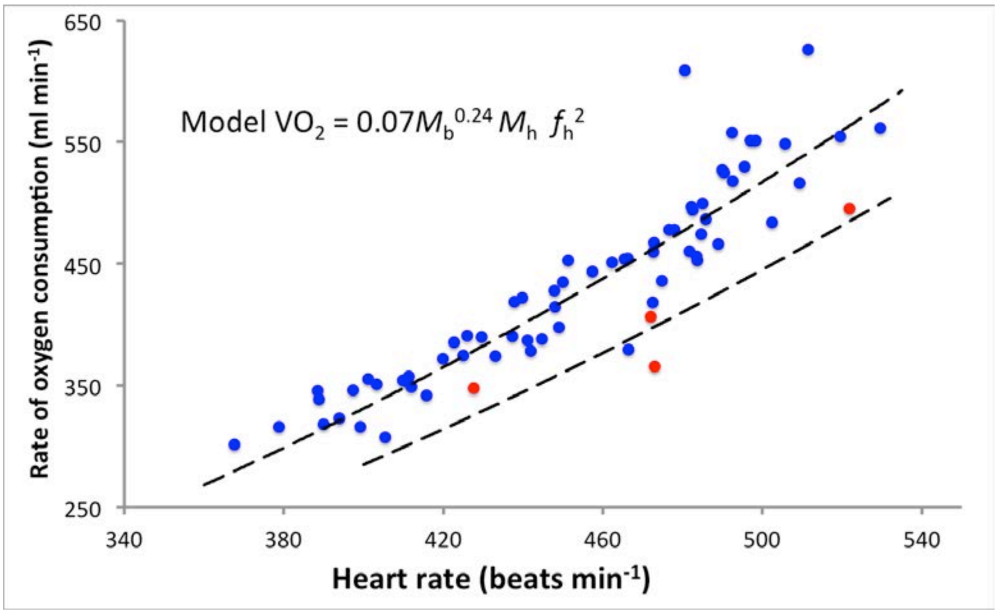

Fig. S2. Calibration of rate of oxygen consumption against heart rate. Data shown for 11 flights (blue dots) and 1 flight (red dot) from two juvenile bar-headed geese, respectively, on 7 different days (*17*). Body mass 2.83 kg and heart mass 0.023kg (blue dots) and body mass 2.35 kg and heart mass 0.0207 kg (red dots). Each point is the average of 2 minutes of flying. The modelled line fits are generated from the proportionality $\dot{V}o_2 \propto M_b^{0.241} M_h \; f_h^{2}$ from reference (appendix D in (*14*)), for 12 species of birds, and passing through the mean value for the variables of the 11 flights (blue dots).

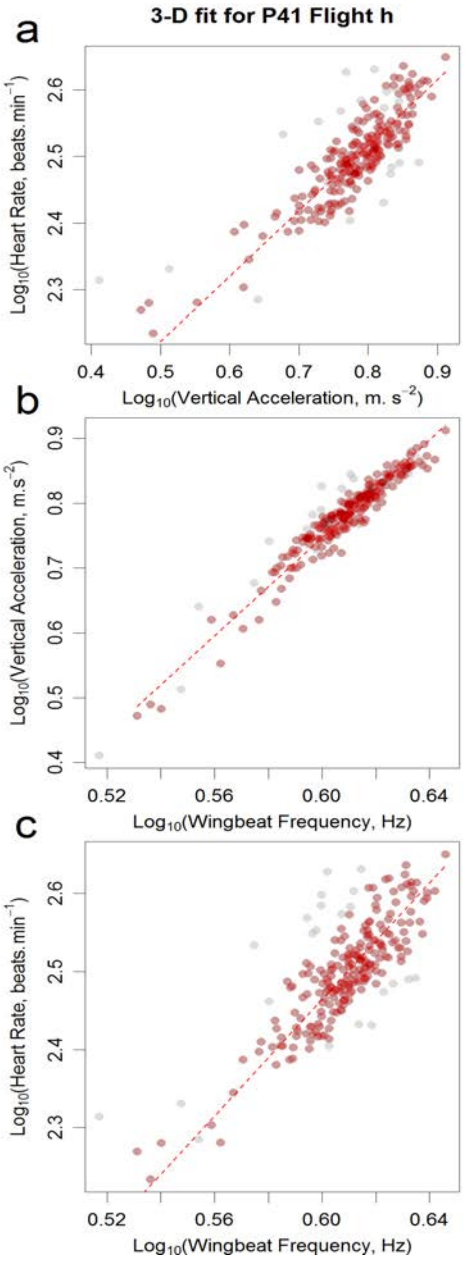

Fig. S3. Correlation analysis for a single 10 h migratory flight of goose P41 (flight h). a, log of heart rate plotted against log of zRMS acceleration ($r^2 = 0.896$). **b**, log of zRMS acceleration plotted against log of wingbeat frequency ($r^2 = 0.967$). **c,** log of heart rate plotted against log wingbeat frequency ($r^2 = 0.889$). Each point represents the mean of 18 s of data, repeated every 2 minutes. ‘Greyed out’ points are the 10% of data removed by repeated iteration during 3D principal component analysis.

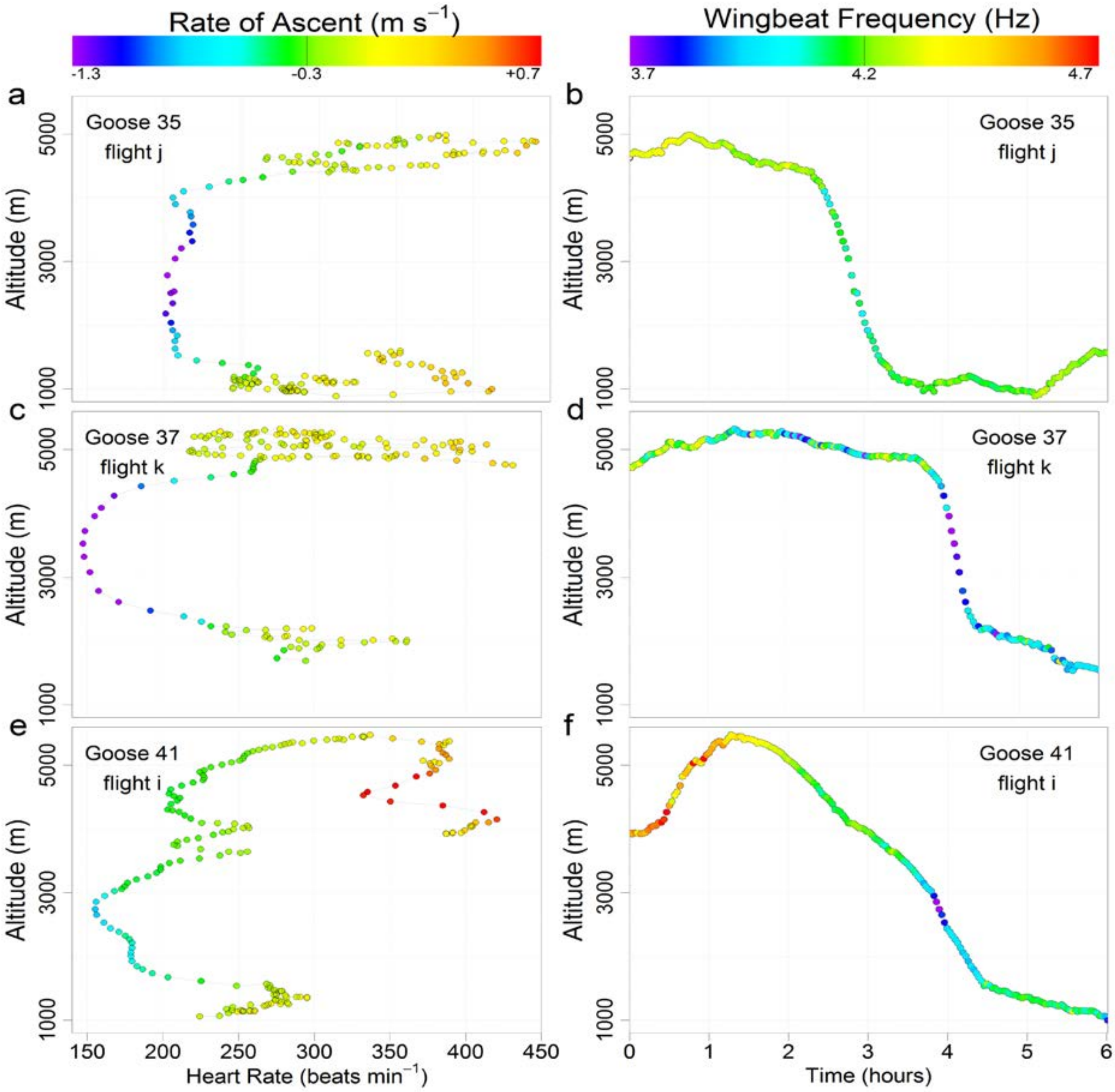

Fig. S4. Descending flights into India. a-c, show altitude plotted against f_h, for the three geese which migrated from the Himalaya down into India. Each trace is colour coded to indicate the rate of ascent/descent ranging from +0.7 m s^{-1} (red) to -1.3 m s^{-1} (purple), with a temporal resolution of 2 minutes. **d-f,** shows the same altitude data but plotted against time and colour coded for f_w ranging from 4.7 flaps s^{-1} (red) to 3.7 flaps s^{-1} (purple). Geese continued to flap even during steep descents but with minimal power outputs.

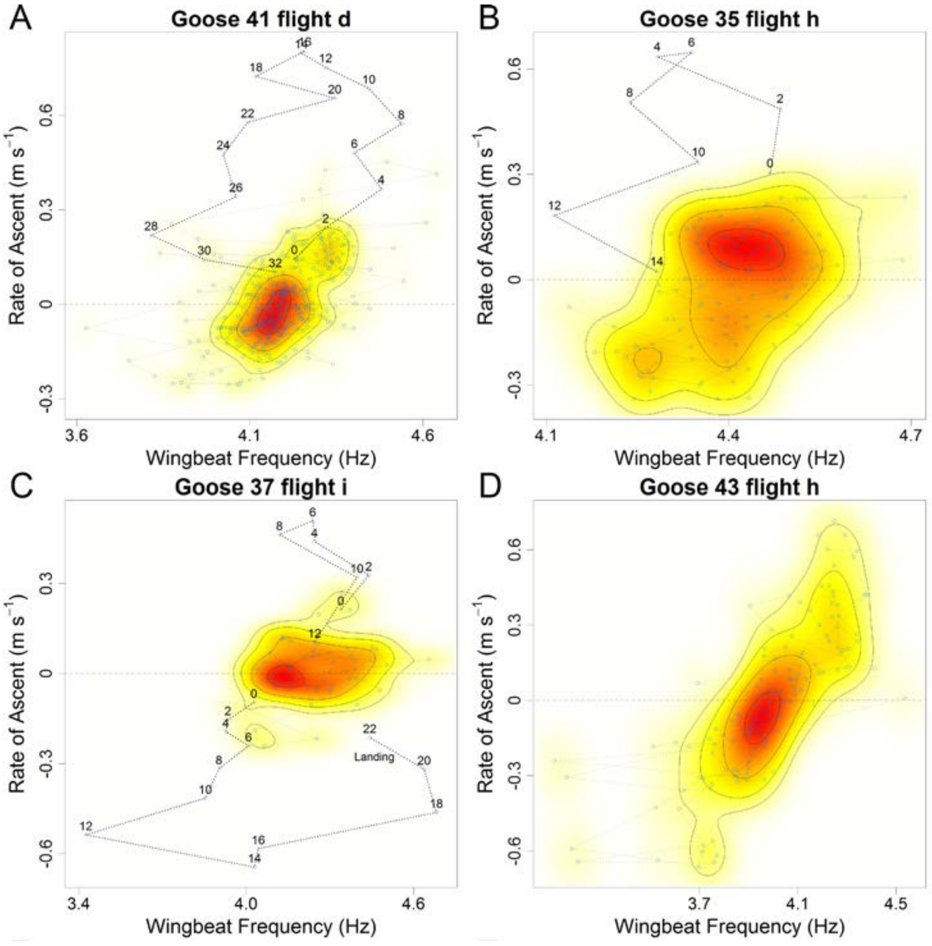

Fig. S5. Environmentally assisted flights. (A to D), Rate of ascent/descent plotted against wingbeat frequency (rather than heart rate as in Fig. 3, main text) for migratory flights (2.7 to 13 hours), each from a different goose. Intensity of colour from red to yellow indicates density of observations, with a temporal resolution of 2 minutes. Black lines link up sequential data points (numbered with time in minutes), indicate an event lying outside the typical distribution and highlighting a period of assisted lift, or a difficult landing event.

Paper VI

A cosmological hypothesis potentially resolving the mystery of extraterrestrial silence with falsifiable implications for neutrinos.

Robin James Spivey

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A cosmological hypothesis potentially resolving the mystery of extraterrestrial silence with falsifiable implications for neutrinos

Robin J. Spivey
School of Biological Sciences, Bangor University, Brambell, Deiniol Road, Bangor, Gwynedd. LL57 2UW. U.K.
Email address: y.gofod@gmail.com

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Abstract: Should dark energy decay predominantly into active neutrinos in ~60 Gyr, their mutual annihilation within iron-cored oceanic planets might give rise to attractive habitats for aquatic life persisting upwards of 10^{25} years. Neutrino haloes of density exceeding ~1 picogram·km^{-3} could efficiently maintain liquid oceans beneath thermally insulating layers of floating ice. Iron's hcp→fcc phase transition constitutes a mechanism for regulating neutrino annihilation, capable of achieving a remarkably consistent heat flux through the oceans almost irrespective of planet size. Heavier sterile neutrinos may presently account for a good share of dark matter and could catalyse planetary heating as active haloes become depleted. Given the impressive energetic efficiency of the arrangement, if extraterrestrial civilisations are acquainted with this knowledge they may possess a universal outlook distinctly different to ours involving a harmony between the physical and life sciences. Three resolutions of the Fermi Paradox then emerge, novel explanations for extraterrestrial silence yielding falsifiable predictions concerning particle physics. It is conceivable that improved knowledge of the properties of active and sterile neutrinos might soon herald a new dawn in cosmology. © 2015 Physics Essays Publication.

Résumé: Si l'on suppose que l'énergie sombre se désintègre en neutrinos actifs en ~60 Gyr, leur annihilation mutuelle à l'intérieur de planètes océaniques à noyau ferreux pourrait créer des habitats attrayants pour la vie aquatique subsistant plus de 10^{25} ans. Des halos de neutrinos d'une densité supérieur à ~1 picogramme·km^{-3} pourraient conserver efficacement des océans liquides sous des couches de glace flottante assurant une isolation thermique. La transition de phase hcp→fcc du fer constitue un mécanisme de régulation de l'annihilation des neutrinos qui est capable de produire un flux de chaleur remarquablement reproductible à travers les océans et presque indépendant de la taille de la planète. Les neutrinos stériles lourds, susceptibles de représenter une proportion importante de la matière sombre à l'heure actuelle, pourraient catalyser le chauffage planétaire à mesure que les halos actifs s'amenuiseraient. Étant donnée l'impressionnante efficacité énergétique de cette configuration, si des civilisations extraterrestres possédaient ces connaissances, elles pourraient avoir une perspective universelle sensiblement différente de la nôtre et qui mettrait en jeu une harmonie entre la physique et les sciences de la vie. Trois résolutions du paradoxe de Fermi émergent alors avec des explications nouvelles du silence extraterrestre fournissant des prédictions réfutables au sujet de la physique des particules. Il est envisageable qu'une meilleure connaissance des propriétés des neutrinos actifs et stériles pourrait bientôt annoncer une nouvelle ère en cosmologie.

Key words: Extraterrestrial silence, Fermi paradox, active & sterile neutrinos, dark matter, dark energy, cosmology.

I. INTRODUCTION

Microbial life emerged quite promptly once the primordial Earth had cooled. The same may have occurred on other planets where water exists in the liquid state, with natural selection subsequently breeding increasingly complex multicellular organisms with central nervous systems and cognitive abilities. Our own existence implies that a fraction of these worlds would have spawned species with some technological aptitude and a curiosity concerning their cosmic habitat. Thus, the continuing failure of SETI to detect incoming radio signals[1] lies in stark contrast with the age and scale of the Milky Way, the abundance of extrasolar planets and the feasibility of interstellar travel given millions of years of preparation. The difficulty of formulating plausible hypotheses to explain this bewildering fact, especially ones that abide by the scientific method, has led to the mystery becoming colloquially referred to as the Fermi Paradox. This disquieting state of affairs may indicate that our present understanding of nature is fundamentally incomplete.

Olbers' paradox pointed to a universe of finite age and Fermi's paradox implies the same. Hence, our apparent solitude may insinuate that this is an infant universe, still evolving towards a long-term configuration. The term astrobiology conveys the impression that life everywhere is reliant, whether directly or indirectly, upon the energy liberated by stellar fusion. Once stellar activity ceases, when the current phase of accelerating cosmic expansion may have ended, circumstances could be radically altered. Stars are a relatively inefficient source of energy but nuclear fusion is essential if the elements necessary for life and habitable planets are to be forged.

Even prior to our comprehension of how the Sun could have remained active for several billion years, fossils offered evidence that the Earth's biosphere has a vivid and lengthy history. At a time before carbon dating and DNA sequencing technology, most scientists realised that humans shared a common ancestry with other animals. Similarly, some have already sensed that the universe is inordinately favourable towards life[2]. This view was recently reinforced when it was shown that active neutrinos, perhaps with assistance from sterile species, might very efficiently fuel aquatic life on galactic scales[3]. The cosmological abundance of active neutrinos would first need to be augmented. The decay of dark energy which currently drives the accelerating expansion of the cosmos[4,5] into neutrinos could satisfy this demand[3]. Unrelated to human evolution, the presence in nature of particles with a propensity for internally heating and thermally regulating oceanic planets lacks any credible anthropic explanation, opening new avenues for cosmological research. Expanding upon previously described physics[3], the goal here is to explain why accurate determination of the characteristics of neutrinos could offer sufficiently profound insights as to elucidate the hitherto bizarre lack of evidence for extraterrestrial life.

II. EFFICIENT PLANETARY HEATING

A. IRON-MEDIATED NEUTRINO ANNIHILATION

Neutrinos possess mass[6] and are capable of congregating under the action of gravity. As fermionic particles, they abide by Pauli's exclusion principle which, under spatial confinement, gives rise to degeneracy pressure. Thereby, neutrinos can form galaxy-engulfing haloes, stable against collapse, of a mass greatly exceeding that of any galaxy, galaxy group or galaxy cluster. Since neutrinos only interact with other particles through the short-range weak force, they rarely scatter off other particles, reducing the orbital decay of planets orbiting within their haloes.

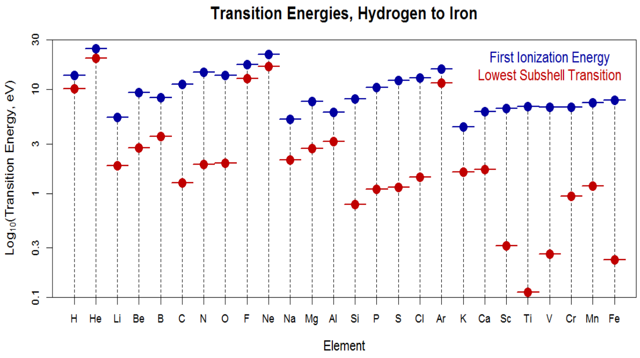

FIG.1: Neutrino annihilation would typically impart energies of less than 0.01 eV to receptive electrons, far smaller than the transitions accessible from the ground state of most common elements. Of the period 4 transition elements, iron is by far the most abundant in nature. Pressures and temperatures encountered within planets tend to reduce the energy gap between its 3d and 4s orbitals, in some cases to the point that all 4s electrons transfer to the 3d subshell. Data obtained from the *NIST Atomic Spectra Database* [redacted]

Neutrino annihilation differs qualitatively from scattering interactions because the annihilation path length sensitively depends upon the ambient neutrino concentration whereas the scattering path length is independent of it. In sufficiently dense haloes, neutrinos can undergo mutual annihilation far more frequently than they undergo scattering. Their annihilation requires the presence of certain forms of matter, primarily planetary interiors where iron atoms possess 4*s* electrons[3]. Transition elements generally allow lower energy excitations of ground state electrons than other common elements, as can be seen in fig.1. Being dense, these elements tend to occupy planetary cores.

At pressures encountered within planets, iron exists in one of two structural phases[7] — hexagonally close-packed (hcp) and face-centered cubic (fcc). As temperature increases a transition occurs from hcp to fcc iron. This phase transition coincides with the energies of the 4*s* and 3*d* orbitals becoming equal[7]. Planetary heating is strongly inhibited in fcc iron due to the lack of 4*s* electrons following 4*s* to 3*d* electron transfer. Thus, the hcp/fcc boundary (see fig.2) prohibits overheating, which essentially constitutes a mechanism capable of regulating planetary core temperatures. Moreover, the boundary has a favourable gradient, allowing internal temperature to scale with planet mass so that quite consistent heat fluxes can be achieved through subglacial surface oceans[3].

Before the discovery that extrasolar planets orbit an appreciable fraction of stars[8], oceanic planets were already garnering some attention[9-12]. Thought to be common already[13], their abundance will steadily increase throughout the stelliferous era due to planetary bombardment by watery comets and type Ia supernova activity[14]. Various clues hint that electron neutrinos have a mass in the vicinity of 50 meV [3], compatible with cosmological limits, $\Sigma\, m_\nu < 170$ meV [13-15]. Aquatic life can potentially be sustained by neutrino annihilation for an electron neutrino mass range $6 < m_\nu < 100$ meV, delivering a planetary power of [3]

$$Q_p \approx \frac{2\pi^2 c^2 \rho_\nu n_e v_{rel} \lambda_w^2 R_c^3}{25} \tanh\left(\frac{2c^2 \lambda_w m_w}{5\hbar g_w v_{rel}}\right) \quad (1)$$

where ρ_ν is the neutrino density (kg.m^{-3}), n_e is the number density of 4*s* electrons in hcp iron (~$5\cdot10^{28}$ m^{-3}), R_c is the radius of the iron core, m_w is the mass of the W boson (~$1.4\cdot10^{-25}$ kg) and $\lambda_w = \hbar / c m_w$ is the reduced Compton wavelength of the W boson. For m_ν=50 meV, the relative velocity, v_{rel}, between neutrinos and 4*s* electrons in a habitable halo can be as low as 0.14c [3]. The hyperbolic tangent term simplifies to $\tanh(3c/5v_{rel})$ and remains within 10% of unity for $v_{rel} < 0.4$c. For depleted haloes, the volumetric neutrino annihilation power, $Q_\nu = 3Q_p/4\pi R_c^3$, within hcp iron can therefore be approximated by

$$Q_\nu \sim \pi c \rho_\nu n_e (\hbar / 11 m_w)^2 \approx 2\times10^{17} \rho_\nu \ \text{W}\cdot\text{m}^{-3}. \quad (2)$$

Habitable liquid oceans are possible if $Q_\nu > 0.1\mu\text{W}\cdot\text{m}^{-3}$, a condition that can be met if $\rho_\nu > 7.4\cdot10^{-25}$ kg·m^{-3}. Hence, aquatic life can continue even when the ambient neutrino density falls below one picogram per cubic km. Densities several orders of magnitude higher are achievable for m_ν=50meV.

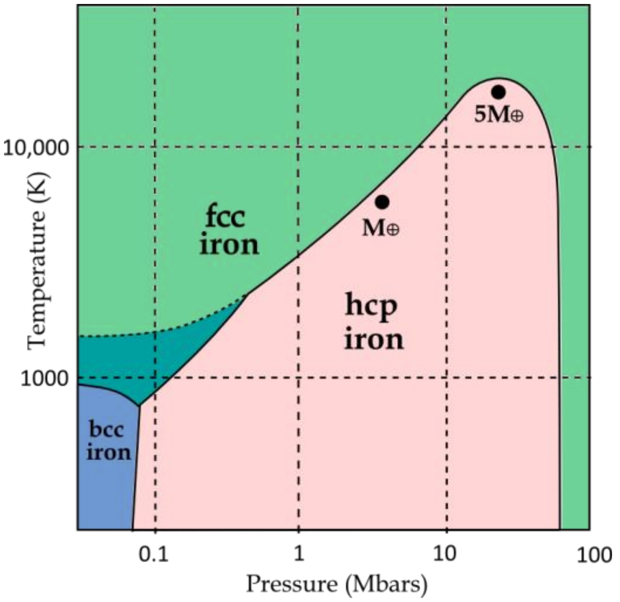

FIG.2: The hcp phase of iron is receptive to neutrino annihilation close to the hcp/fcc boundary where tiny energies suffice to promote 4s electrons to vacant 3d orbitals. This zone widens due to pressure-broadening, allowing heating to proceed even at low temperatures in larger planets. This diagram is based on results obtained using first-principles calculations performed by Lars Stixrude encompassing temperatures and pressures as high as 40,000 K and 1 Gbar[7].

B. PATHWAYS TO INVESTIGATING NEUTRINO ANNIHILATION.

Several lines of inductive reasoning can lead to a suspicion that neutrino annihilation might sustain aquatic life, which may have allowed extraterrestrial civilisations (ETCs) to converge on a common perspective concerning the cosmos. One chain of thought is prompted by the various examples of how the universe is more conducive to life than our own presence can explain, their synthesis hinting that nature may not be altogether devoid of purpose.

For instance, whilst elements other than hydrogen and helium were scarce following the big bang, supernovae have successfully manufactured the heavier elements necessary for terrestrial planet formation, chemistry and life. The weak anthropic principle reminds us that we could not exist in a chemically barren universe but is more consistent with a universe in which only a single supernova mechanism ever generates heavier elements, does so inefficiently and struggles to disperse them into space. Instead, this universe exhibits several supernova mechanisms (e.g. electron capture, pair instability, iron core collapse and accretion-triggered reignition of fusion in carbon-oxygen white dwarves), all of which are remarkably effective at forging heavy elements and scattering their ejecta. Furthermore, neutron degeneracy pressure offers stiff resistance to black hole formation during the gravitational implosion of heavier stars: the circumference of a neutron star is barely any larger than that of a black hole of the same mass.

Iron, cobalt and nickel are the final three elements produced by exothermic nucleosynthesis. All three happen to be ferromagnetic with relatively high Curie temperatures. Electromagnetism and gravity are the only two long-range forces in nature, both following inverse square law relationships, but gravity is intrinsically far weaker than electromagnetism. The ensuing mutual attraction between the atoms of ferromagnetic elements expelled by supernovae can lead to clumping on various scales. Heat accumulates through agglomeration and, once the Curie temperature is exceeded, time is needed before ferromagnetism can be restored via cooling. Radioactive decay of ^{56}Ni through ^{56}Co to ^{56}Fe also releases heat, delaying the cooling of larger iron-rich protoplanets. These processes collectively conspire to assemble quite consistently sized terrestrial planets whose surface gravities are strong enough to retain breathable atmospheres yet not so strong as to prohibit the evolution of large-brained terrestrial fauna.

All animals are primarily composed of water, a substance with many anomalous properties. The ice Ih phase of H_2O is less dense than liquid water and so bodies of water freeze from the top down, safeguarding the habitats of aquatic lifeforms. However, this can deprive land animals such as ourselves of drinking water, without which we perish in days. Water is the only known compound that expands as it freezes, hence providing life-preserving thermal insulation for lakes and seas during episodes of cold weather. Though advantageous to many forms of life, this would have undoubtedly inconvenienced our most immediate ancestors.

Countering such examples is the fact that, although energy is a fundamental currency of life, a paltry fraction of the Sun's output is biologically harnessed. Including photosynthetic autotrophs, only 0.1% of the radiation incident on the Earth is utilised by life. Any planet orbiting within the habitable zone of a life-cultivating (class F, G or K) star intercepts roughly one billionth of the stellar radiation. Nuclear fusion cannot liberate more than 1% of a star's rest mass energy and life-cultivating stars only burn ~10% of their hydrogen. Although stars can only inefficiently deliver power to planetary lifeforms they represent the only natural means of generating and scattering the heavier elements of which planetary habitats and biomolecules are made. It may therefore be appropriate to regard stars as, above all else, crucibles where the heavy elements needed by oceanic planets are presently being efficiently forged.

Dark matter's distribution roughly traces that of visible matter. Despite the uncertain origin of the life-favouring baryon asymmetry, most dark matter candidates are an even admixture of matter and antimatter particles. Their mutual annihilation could, in principle, efficiently convert mass into energy. Of the various dark matter particles proposed to date, only neutrinos are known to actually exist. Dark matter has now been eclipsed by dark energy[4,5], a yet more enigmatic substance. Since the energy density of dark energy is not thought to change appreciably over time, it increasingly dominates the total energy of the universe. This is reminiscent of how the inflationary field may have dominated the early universe prior to its decay. However, the spatial energy density of the vacuum is now tiny compared to its value during inflation – this could well restrict the possibilities for dark energy decay to particles of relatively small mass. By some considerable margin, neutrinos are the lightest fermions. Thus, the decay of dark energy almost exclusively into neutrinos warrants serious attention. This in turn prompts the question of whether high neutrino concentrations could potentially have some biological significance.

The fundamental particles and forces allow a more direct assault. ETCs may have scrutinised nature’s inventory of particles and forces to see whether they could perceive some coherent arrangement. First generation particles of the standard model are more stable than those of other generations (fig. 3). These comprise the up and down quarks, which make up the protons and neutrons of atomic nuclei, and the electrons which orbit those nuclei. Only the electron neutrinos remain, highly inert particles incapable of binding with any others. The importance of atoms to planetary habitats and biochemistry is immediately apparent, but what of the electron neutrinos?

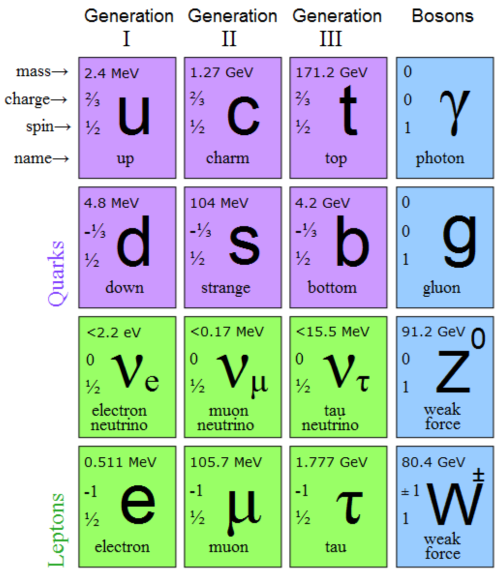

FIG.3: Everyday atoms consist of three of the four first generation fermions. The remaining particles, electron neutrinos, interact only via the weak force, which is mediated by W and Z bosons.

As for the forces of nature, there are only four to consider. Gravity allows planets to occupy habitable orbits around stars. Electromagnetism enables positively charged nuclei to attract and retain negatively charged electrons within atoms. The strong interaction overcomes the electrostatic repulsion between protons, necessary for the stability of atomic nuclei in elements beyond hydrogen. The weak interaction plays a part in the proton-proton chain reaction used by the Sun to convert helium-2 nuclei into deuterium nuclei. However, if the abundance of primordial deuterium were increased, the evolution of complex life would still have been possible even without the weak force [15].

Thus, from a biological perspective, physics apparently has two major deficiencies. Ghostly neutrinos seem to lack any biochemical significance and the weak interaction underlies the biologically hazardous process of radioactive decay. However, neutrinos can only interact with other particles via the weak force. With the expansion of the universe accelerating, life-cultivating stars being relatively short-lived (~70 Gyr or less) and oceanic planets becoming more abundant with time due to type Ia supernovae, one expects ETCs with an interest in their cosmic habitat to eventually consider whether neutrinos may have some impact on the future habitability of the universe.

A third approach might involve surveying the various structures encountered in nature. Everyday objects are made of condensed matter, solids or liquids of a density loosely comparable to water. This can also be said of the planets of the solar system and the Sun itself. When stars die they collapse to far denser objects: white dwarves, neutron stars and black holes. The ‘mean density’ of a Schwarzschild black hole, $\rho_\bullet$, can be obtained as its mass,

$M_\bullet$, divided by $(4\pi/3)R_s^3$ where $R_s = 2GM_\bullet/c^2$. Thus, $\rho_\bullet$ declines quadratically with mass[16]:

$$\rho_\bullet = \frac{3c^6}{32\pi G^3 M_\bullet^2}. \tag{3}$$

If $M_\bullet=10^8 M_\odot$, the value of $\rho_\bullet$ resembles the density of water. Gravitationally bound structures of the universe such as nebulae, galaxies and the Solar System have much lower densities. A partitioning is discernible when these are plotted (fig. 4). If mass is gradually added to an object composed of condensed matter, it will first transform into degenerate matter rather than collapse immediately to form a black hole. However, large gravitationally bound systems can directly implode to black holes. This threat could be greatly enhanced following dark energy decay.

Galaxy clusters represent the largest bound structures of the universe. Could a dense energy reservoir comparable in size to a galaxy cluster support its own weight? Extrapolation towards the black hole boundary suggests that structures some 5–6 orders of magnitude more massive and 2–3 orders of magnitude less dense than galaxy clusters should be considered. A self-supporting cloud of degenerate fermions could constitute such a formation. If the cloud has mean density ρ_c and total mass M_c, the individual fermion mass, m_f, can be estimated using[17]:

$$m_f^8 = \frac{23\pi\rho_c\hbar^6}{12G^3M_c^2}. \tag{4}$$

With $M_c \approx 10^{20}\ M_\odot$ and $\rho_c \approx 10^{-24}$ kg·m^{-3}, the value obtained is 40 meV, reassuringly consistent with our present knowledge of the neutrino mass scale. A halo of neutrino dark matter matching this description is plotted in fig. 4. In comparison, the characteristics of a galaxy cluster ($M_c \approx 10^{15}\ M_\odot$ and $\rho_c \approx 10^{-26}$ kg·m^{-3}) would yield an estimate of the fermion mass one order of magnitude larger, the possible relevance of which shall be returned to shortly. This line of thinking may also stimulate ETCs to examine the possibility that dense neutrino haloes, such as might form following the decay of dark energy, could have biological repercussions.

All known living organisms contain liquid water, a compound which has understandably been dubbed the "matrix of life". One therefore expects habitats to provide steady temperatures in the region of 300 K. ETCs might have appreciated that, due to the equivalence of mass and energy, the mutual annihilation of sub-relativistic particles can serve as an efficient means of power delivery, with each decay event imparting a well-defined energy. Whereas mass can be translated into energy via $E=mc^2$, temperature and energy are related by $E=kT$. Thus, annihilation of nonrelativistic particles of rest mass m_χ simultaneously define an energy and temperature scale, from which

$$m_\chi \approx \frac{kT}{2c^2} \approx 0.043\,T \ \text{meV}. \tag{5}$$

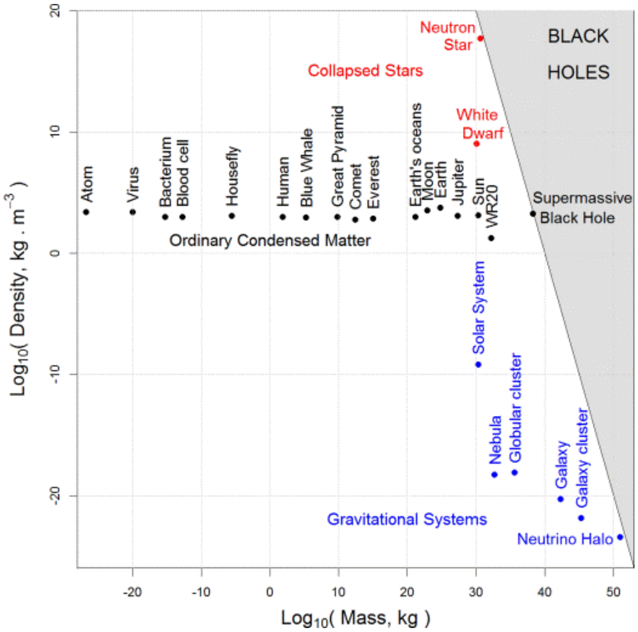

FIG.4: Excepting black holes and degenerate stars, objects and structures of the universe separate into two clearly distinct sets when viewed in terms of their mean density: objects which consist of condensed matter and gravitationally bound systems.

Therefore, if nature uses mutually annihilating nonrelativistic particles to efficiently deliver energy in a thermally regulated manner, sustaining liquid water habitats, their mass should exceed ~12 meV. However, much larger masses equate to temperatures at which atoms become ionised. This simple argument uniquely singles out neutrinos. Thus, ETCs could have been led to evaluate the possibility of neutrino-powered oceans sustaining aquatic life well beyond the stelliferous era by following a variety of logical inferences.

C. COUNTERACTING HALO DEPLETION

Although neutrino annihilation has the potential to heat planets with an efficiency exceeding 90%, as a neutrino halo becomes heavily depleted, planetary oceans will freeze before the neutrinos are fully exhausted. In terms of the halo mass, the dynamic range cannot be more than 42-fold for 50 meV neutrinos[3]. This makes no allowance for a safety margin guarding against gravitational implosion of the initial halo. A pertinent question once posed by J. B. S. Haldane arises: "why was it not created better?". Haloes consisting of 50 meV active neutrinos would easily envelop a supergiant galaxy, providing latitude to increase their local concentration through gravitational loading – much as the Earth's atmosphere is concentrated near its surface. A compact secondary halo of roughly twice the radius of the contained galaxy would suffice. Ideally, its constituent particles would only interact with matter via gravity.

A curious feature of the weak interaction is that it maximally violates parity so that only left-handed particles and right-handed antiparticles are susceptible to it. Hence, right-handed neutrinos and left-handed antineutrinos, i.e. *sterile neutrinos*, would only interact gravitationally. Active and sterile neutrinos are expected to have different masses. A sterile neutrino mass in the 1~2 eV range could very effectively boost the local concentration of active neutrinos within large galaxies for negligible energetic expenditure[3].

The possibility that neutrinos might account for the dark matter of galaxy clusters was proposed four decades ago[18]. More recently, modelling of the distribution of dark matter reconstructed from gravitational lensing data for the Abell 1689 galaxy cluster has inferred that 1.5 eV fermions may be responsible[19,20]. Anomalies in short baseline neutrino oscillation studies hint at the existence of eV-scale sterile neutrinos[21-23]. Since low energy particles will naturally condense on galaxy clusters[24], 1.5 eV sterile neutrinos could be an important component of dark matter[3]. Cosmology can easily accommodate extra radiation from sterile neutrinos of this mass[25] and their existence would not preclude MACHOs or WIMPs as galactic dark matter within the Milky Way. However, evidence of cold dark matter particles has not been forthcoming either from particle colliders or nuclear recoil experiments[26].

The influence of a sterile halo whose total mass is ~30% that of the implosion limit is presented in fig. 5 for a range of active neutrino and halo masses. Overall halo efficiencies exceeding 99% are realistically attainable. The gravitational potential of the sterile halo would dominate the orbital dynamics within the galaxy it contains, regularising the angular speeds of circular orbits and inhibiting relaxation from a triaxial galactic morphology to a planar configuration. This has distinct advantages over the long-term, reducing the risk of collisions/violent encounters and orbital decay through gravitational radiation.

The evolution of complex lifeforms, such as ourselves, on planets orbiting life-cultivating stars is not reliant on the properties of either active or sterile neutrinos. Nor is it reliant on iron's favourable hcp-fcc phase transition boundary, ice Ih being less dense than liquid water, a multitude of efficient supernova mechanisms nor the presence of ferromagnetism in the final three elements of nuclear fusion. The low temperature phenomenon of ferroelectricity in ice XI assists comet formation through electrostatic attraction of ice fragments, providing long-term segregation of water from iron which in turn permits the gradual delivery of water to stratified planets. In this way, oceanic planets become abundant over time. Traditional reservations concerning the inefficiency of stars in powering planetary life are no longer relevant. In order to pursue these investigations further, especially with a view to comprehending extraterrestrial silence, it is imperative to set aside the common preconception that the universe is purposeless[27-29].

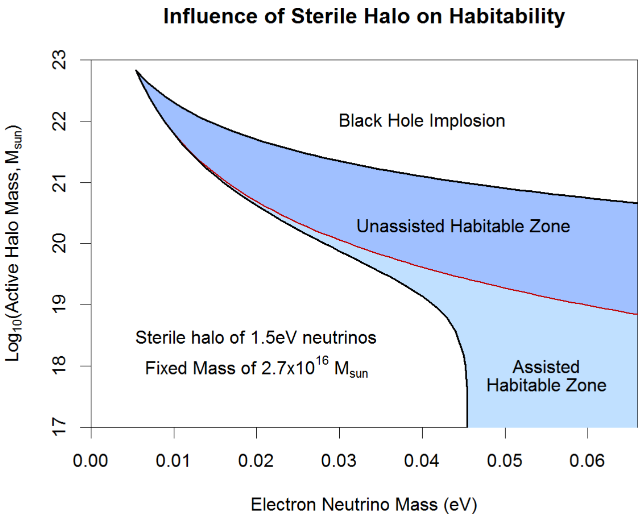

FIG.5: An example illustrating how a halo of 1.5 eV sterile neutrinos of total mass $2.7\cdot10^{16}\ M_\odot$ (approximately 30% of the limiting mass at which gravitational implosion of the sterile halo occurs) can boost the habitability of an active halo so that planetary heating remains adequate throughout the central region of the sterile halo , which is large enough to accommodate a large galaxy.

III. HOW MIGHT THE COSMOS BE ETHICALLY POPULATED?

The decay of dark energy into neutrinos in some 50~60 Gyr would be opportune. A minority of life-cultivating stars are able to remain active throughout the intervening period. If liquid oceans will subsequently be maintained for $\sim10^{25}$ years[3] a key goal of the universe could be to efficiently sustain aquatic life over the long-term. It may be that finer subtleties to an underlying cosmic strategy are discernible to civilisations everywhere.

It is therefore interesting to consider the various factors that are likely to influence the appearance, development, containment, expansion and long-term opportunities for life. Can we couple our theoretical knowledge of the universe with our grasp of bioethical issues to perceive any further salient features of a cosmic strategy for life? If we could configure a life-hosting universe, what precautions would it be desirable to implement?

Active neutrinos are most likely to condense on galaxy clusters[24]. As the brightest cluster galaxies already demonstrate, galactic mergers have produced giant elliptical galaxies serving as the focus for continuing mergers. Computer simulations suggest this process will eventually terminate once the universe is 2-4 times its present age[30]. Thus, galactic mergers may stimulate competition and collaboration prior to the decay of dark energy.

Approximately 90% of the baryonic matter in galaxy clusters is currently accounted for by the plasma of the intracluster medium (ICM) consisting of protons, electrons and ionized helium at high temperatures ($10^7\sim10^8$ Kelvin).

Since free neutrons decay with a half-life of ten minutes, the ICM is a rarefied soup of electrically charged particles. Using lossless superconductors to generate magnetic fields, spacecraft could deflect and scatter these particles, providing a means of passive deceleration requiring no fuel. This overcomes a perennial problem with long-range spaceflight that the need for active deceleration very substantially increases the journey time. Likewise, the plasma of the ICM could assist the widespread colonisation of oceanic planets following the decay of dark energy by dispensing with the need for active deceleration during intragalactic as well as intergalactic missions.

The design of subglacial aquatic ecosystems is not without its challenges. The Earth's more complex, potentially sentient, aquatic lifeforms would not thrive within a dark, oxygen-starved ocean. Similar environments exist on Earth in rocks deep underground, but are home only to simple unicellular bacteria. Jupiter's moon Europa is thought to possess a subglacial ocean which might host chemosynthetic forms of life. Extremophiles in hydrothermal vents here suggest this may be possible. However, if neutrino heated oceanic planets are ever to host larger, intelligent aquatic lifeforms, some degree of genetic engineering will presumably be called for.

Proficiency in genetics also offers a means by which civilisations can tackle the deleterious random mutations that plague haphazard reproductive processes. This might represent the only robust way in which civilisations might assure their own long-term survival. Failure to explore this possibility could act as a filtering mechanism.

It has been argued that a Principle of Procreative Beneficence[31] should be observed whenever reproduction can profit from genetically informed choices. It asserts that genes affording the best prospects for the well-being of offspring should ideally be selected. Once bioscience is sufficiently advanced, safe, affordable and accessible, adherence to this principle might inevitably lead in time to the abandonment of hereditary genetics.

Amongst the myriad possible consequences could be adjustments to dietary preferences. Since the Cambrian explosion, predation has been a vicious fact of life within the animal kingdom. One of the challenges facing the Earth at present is that the farming of livestock is relatively costly, exacerbates global warming and takes up much land which could be used for growing crops capable of feeding a larger population. Thus, there are economic, environmental and ethical arguments for eliminating the innate desire to consume meat. The manufacture of in-vitro meat is currently at the research stage and prohibitively expensive for consumers. However, it is anticipated that so-called 'victimless' or artificially grown meat will eventually become affordable. Consumption of animal flesh might subsequently be outlawed on ethical grounds.

Cannibalism, carnivorism and the predation of sentient lifeforms are therefore practices that a cosmic strategy might seek to restrict. This may explain why life-cultivating stars, without exception, expand to become bloated red giants as they end their lives, presaging their collapse to white dwarves. Luminous and destructive, red giants are capable of immolating or completely absorbing formerly habitable planets in orbit around them, purging them of all vestiges of life – including even microbial forms. It is thought that the Sun may eventually engulf the Earth during its time on the red giant branch. As a similar fate awaits all habitable planets, lifeforms lacking interstellar travel capability are unlikely to outlive their host stars.

Bearing in mind technological projections, ethical considerations, relocation pressures and potential guidance from cosmology, virtually all ETCs that successfully overcome the existential/self-destruction obstacle may be post-evolutionary. Admittedly, this may seem a radical idea to us at present, but it is only during the most recent generations that we have discovered the structure of DNA and started to sequence genomes. Nevertheless, tentative steps in this direction have already been taken, such as the UK's legalisation of three-parent babies in 2015. The Principle of Procreative Beneficence is a manifestly responsible ethical code of conduct so the assumption shall be adopted here that very few ETCs have failed to wrest command of their own genetics from evolution.

Having had considerable time to ponder the cosmos, ETCs may realise that galactic mergers, like red giants, can safeguard against the spread of less advanced civilisations – even those harbouring colonisation ambitions that possess spaceflight capability. Viewing themselves as responsible colonists within galaxies generating perhaps 10^{15}~10^{16} oceanic planets, ETCs might regard lifeforms still reliant on hereditary genetics as undesirable partners in space colonisation. Should opposition arise, their mastery of genetics and virology might be utilised to keep less advanced civilisations in check. To avoid inflicting suffering via biological warfare, they might favour the deployment of agents capable of locally obstructing reproduction. Hence, the outcome of numerous galactic mergers may be essentially predictable: a sophisticated network of advanced cooperating civilisations awaiting dark energy's decay. Following this, aquatic habitats could be competently populated by a trustworthy consortium of post-evolutionary civilisations with a wealth of expertise in both genome and ecosystem design.

Despite its simplicity, this brief overview at least provides possible insights into the organisation of the universe. The current accelerating expansion may usefully postpone the delivery of neutrinos to the cosmos, limiting its habitability until ethically responsible civilisations possessing virtuosity in genetics have arisen and prepared themselves for full-scale colonisation. This in turn may explain why the longest lived life-cultivating stars have relatively brief lifespans and why all life-cultivating stars ultimately transform themselves into lethally incandescent red giants. In this way, predation and carnivorism can be reliably brought to a close with little risk of even ancient, long-extinct microbial life being revived during the aquatic era following several billion years of suspended animation. With the assistance also of galactic mergers in galaxy clusters, the long-term welfare of lifeforms could be quite robustly assured, with post-evolutionary lifeforms dominating the time-integrated entropy increasing processes of the cosmos. It may be no coincidence that our evolution has required a timescale comparable to the Sun's total lifespan.

IV. NOVEL EXPLANATIONS FOR EXTRATERRESTRIAL SILENCE

Previously proposed motives for contact avoidance have invariably suffered from a lack of universality[32]. According to the present hypothesis, almost all ETCs would have independently arrived at a virtually identical view of the cosmos based on scientific evidence. This establishes a new class of cosmological explanations for extraterrestrial silence, distinct from the familiar sociological explanations[32]. Three novel resolutions of the Fermi paradox falling under this new umbrella are now described, all reliant upon the perceived or actual future decay of dark energy into active neutrinos. The first relates to the anticipated distribution of neutrinos following dark energy decay, the second requires that ETCs are convinced that the universe will in time provide efficient habitats for aquatic life and the third rests upon the universe actually having been specifically configured for life.

A. RELOCATION

Only some 15% of galaxies currently belong to galaxy clusters[33]. This fraction is still increasing but will ultimately plateau, probably at a level below 50%. ETCs that originate externally to clusters will be eager to relocate. Unfortunately, neither the Milky Way nor the Local Group belongs to a galaxy cluster. Accelerating cosmic expansion has already ejected us from the Virgo cluster, which is currently 50 million light years distant[34]. While the interstellar medium within the Milky Way is perilous to high speed spaceflight, intergalactic space is not and the ICM of the Virgo cluster allows safe magnetic breaking even from relativistic arrival velocities.

Antimatter propulsion could achieve a relativistic cruising velocity after just one year of acceleration at 1-g. Following a 50 million light year journey, gentle deceleration at Virgo taking several million years would seem acceptable. The artificial conception and generation of crew upon arrival could be used to circumvent the tedium of a long voyage and the need for provisions. Many stars are observed drifting between galaxies within galaxy clusters. Some proportion of these will be orbited by habitable planets, thereby assuring refuge for incipient civilisations.

Negotiation of the relocation bottleneck remains incomplete so long as the original civilisation maintains some presence within its natal galaxy. This suggests that any legacy civilisation will abstain from the colonisation of its own future-starved field galaxy and implies an eventual cessation of reproduction due to respect for the welfare of future generations. This can be compared to prospective parents delaying attempts to conceive until recovering from congenitally transmissible diseases. Those who find themselves born in the wrong place and time, avoidably deprived of an opportunity to engage in colonisation efforts, would have cause to question their existence. Thus, if the Milky Way has already spawned advanced civilisations, on appreciating that long-term survival prospects are much improved within the Virgo Cluster, they may have vacated the galaxy following timely relocation.

B. DEFERENCE TO THE COSMIC ARRANGEMENT

A second explanation for extraterrestrial silence pertains to all civilisations of comparable advancement still confined to their natal star systems, irrespective of their host galaxy's location. After deciphering the architecture of the universe, ETCs may regard biological evolution as a stepping stone – a means of cultivating lifeforms with the potential to blossom into skilled colonists. Evolution may seem to them a harrowing but vitally important sacrifice sanctioned by a shrewd cosmic strategy. If its probability of success has been precisely factored into nature's tapestry, ETCs may believe it would be as reckless to meddle with evolution as to tamper with the physical constants.

According to this perspective, ETCs would meticulously avoid planets where evolution is underway. Communication, radio or otherwise, with rudimentary technological civilisations could unfairly assist, or even inadvertently hinder, their prospects of attaining colonist status. Thus, even if the Milky Way has previously been host to ETCs, there would be little prospect of our discovering Bracewell probes[35] or fragments of matter inscribed with messages[36]. Without collusion or conspiracy, ETCs would unilaterally refrain from advertising their presence and passing on knowledge, acts that might potentially compromise the calibre of future colonists. Universality would be upheld, ETCs deferring to an overarching cosmic strategy in which red giants impose sensible time-limits to evolution – absolving colonists of otherwise onerous responsibilities towards rudimentary life on other planets.

C. THE RARITY OF LIFE

A common if rather empty explanation for extraterrestrial silence is that ours is the only civilisation within the Milky Way[32]. This skirts around a hitherto reasonable expectation, indeed one that is fundamentally integral to the Fermi Paradox, that intelligent life is unlikely to be rare on galactic scales. It is by now generally acknowledged that ample time has elapsed for galactic colonisation. So why was the optimism at the dawn of SETI misplaced? The possibility that the universe has been expressly designed for life is, at least superficially, at odds with our perceived seclusion. However, a need for post-evolutionary colonists suggests that more primitive forms of life may only arise sporadically during the early universe. Opportunities for carnivorism and predation might thereby be minimised.

Although ETCs would currently refrain from extensively colonising their host galaxies, the establishment of several outposts would be a sensible safeguard against devastating wars, pandemics and natural calamities such as nearby supernovae, gamma-ray bursters or direct asteroid impacts. When galactic mergers are imminent, some staking of territory would also be understandable. A viable colonisation strategy would involve each galaxy cultivating a biotechnological civilisation in advance of mergers where productive collaborations might be forged. However, as evolutionary species might find ways of expanding across space before encountering opposition, mergers could also on occasion introduce more advanced civilisations so that colonists could regain control of galaxies where evolution has ‘run amok’, as it were. Less advanced civilisations might then be politely invited to halt their colonisation activities and retreat to their natal star system while they reconsider their aspirations.

To estimate the probability of a typical galaxy recruiting a worthy colonising civilisation, a simple mathematical model of galactic mergers within clusters is now considered. Galaxies host only to evolutionary lifeforms shall be treated identically to galaxies where no life flourishes. Colonists are taken to be exclusively post-evolutionary. It shall be assumed that rudimentary civilisations have little choice but to cede control to post-evolutionary civilisations. A compromise shall be sought between minimising opportunities for evolution and rigorously assuring that colonisation is competently discharged during the aquatic era.

A dimensionless quantity, Ψ, shall represent the galactic merger fraction within clusters. Increasing from zero at the big bang, t=0, to unity at late times, $t\to\infty$, its derivative with respect to time, dΨ/dt, represents the normalised galactic merger rate, modelled here by the function

$$\frac{d\Psi}{dt}=\frac{(t/Gyr)^4}{24576\exp(t/4Gyr)}. \tag{6}$$

The factor 24576 has units of Gyr making Ψ dimensionless. Since the integral of $t^4\exp(-t/4)$ from t=0 to $t\to\infty$ is $4\times4!\times4^4$, the merger fraction at late times is unity, $\Psi\ (t\to\infty)=1$, as required. The merger rate attains a maximum value $8/3e^4$ after 16 Gyr and negligible mergers occur following dark energy's decay at $t\approx75$ Gyr.

The colonist recruitment rate, dΘ/dt, is taken to commence at t =5 Gyr. This allows time for supernovae to forge the heavy elements needed for planet formation and biochemistry, and opportunities for life to subsequently emerge and evolve via natural selection. The recruitment process is modelled using

$$\frac{d\Theta}{dt}=\frac{\beta\times(t/Gyr-5)H(t/Gyr-5)}{64\exp[(t/Gyr-5)/8]}. \tag{7}$$

This expression involves the Heaviside step function, $H(z)=1$ for $z\geq0$ and $H(z)=0$ otherwise. Therefore, dΘ/dt =0 for $t<5$ Gyr and the colonist recruitment rate peaks at β/8e when t = 13 Gyr, assuring compatibility with the principle of mediocrity. The factor 64 has units of Gyr whereas β is dimensionless and confined to the range $0<\beta<1$. Negligible recruitment occurs either after dark energy decays or after life-cultivating stars die out. In the remainder of this analysis, t is normalised with respect to 1 Gyr. Integration of dΘ/dt from t=0 to $t=t_*$ now gives

$$\Theta(t_*)=\beta-\frac{\beta(t_*+3)}{8\exp[(t_*-5)/8]}. \tag{8}$$

Hence, as $t_*\to\infty$ one has $\Theta(t_*)\to\beta$. Indeed, $\Theta(t_*)\approx\beta$ after about 60 Gyr. The quantity β therefore represents the (dimensionless) probability of a typical galaxy recruiting colonists prior to the decay of dark energy and the commencement of the aquatic era. The aim here is to estimate the value of β.

If there are N_m galaxy mergers per cluster then the time, t_j, of the j-th merger can be obtained from the time at which $\Psi=(j\text{-}1/2)N_m$. Mergers are taken to be sequential so that the central galaxy is always involved. The probability, P_k, that the central galaxy lacks colonists after k mergers thus comes to

$$P_k=\prod_{l=1}^{k}\{1-\frac{\beta}{64}\int_5^{t_l}\frac{(t-5)dt}{\exp[(t-5)/8]}\} \tag{9}$$

The galactic merger rate, merger fraction, colonist recruitment rate, colonist presence and P_k are plotted against time in fig. 6 for N_m = 250, 500 and 1000 galaxy mergers and selected values of β. Results are acceptable for $\beta\approx1/2$, even for clusters containing relatively few galaxies. Hence, the strategy functions well even if the majority of galaxies never recruit more than one colonising civilisation. Accordingly, intelligent life would be rare on galactic scales at the present time, offering a third resolution of the Fermi paradox. This is compatible with a cosmic arrangement judiciously harnessing natural selection to ensure the welfare of the vastly more abundant aquatic lifeforms of the future universe. Minimising the probability of a galaxy cluster’s remnant galaxy being improperly colonised is a potentially far more critical concern than the risk of an entire galaxy cluster remaining forever uncolonised.

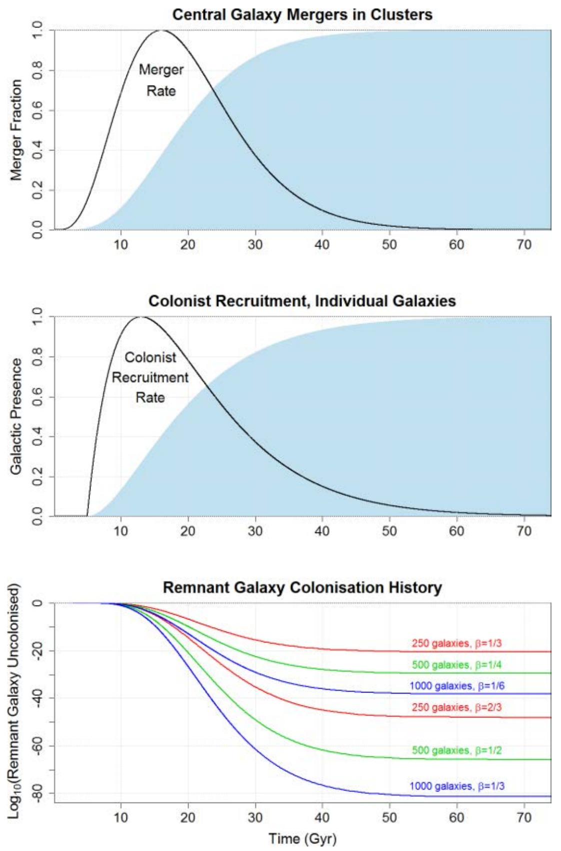

FIG.6: Upper panel: the fraction of galaxies merged with the central galaxy (shaded) and its derivative, the merger rate $d\Psi/dt$ (black trace, not drawn to scale). Middle panel: the probability of colonists being present within a galaxy (shaded) and its derivative, the colonist recruitment rate $d\Theta/dt$ (black trace, not drawn to scale). Lower panel: results for clusters with 250 (β =1/3,2/3), 500 (β =1/4,1/2) and 1000 (β =1/6,1/3) mergers.

V. DISCUSSION

Previous proposals for explaining extraterrestrial silence have not yielded physically testable predictions. Their adherence to the scientific method has hence been rather tenuous, relying either on the future interception of incoming messages or brute force space exploration for falsification or verification. However, the present model suggests that a familiar standard model particle may be superlatively well-suited to sustaining aquatic life, and that an inert counterpart may expedite planetary heating at late times. These expectations can be readily investigated today without undue effort or investment.

The analysis presented here dismisses the possibility that our apparent solitude is due to a complete absence of ETCs within the universe, hinting instead that neighbouring ETCs are typically separated by intergalactic distances at the present time, making communication prohibitively difficult. Nevertheless, well before the extinction of the Neanderthals, the dinosaurs, or perhaps even prior to the formation of the Solar System, most ETCs currently resident within the universe may have independently realised that cosmology is not a purely physical science. Even so, it remains unclear whether such knowledge and a vast head-start would be adequate to tackle some of the more difficult questions this new vantage prompts. By what mechanism might dark energy decay to yield neutrino haloes? Do smaller or larger galaxy clusters offer the best long-term habitation prospects? How might the scavenging of neutrinos by supermassive black holes be avoided? Could a vacuum transition erase black holes from the cosmos? Are the strong time dilation effects in the vicinity of gravitationally collapsed objects in some way connected to the formation of dense haloes of nonrelativistic neutrinos? How could the physical constants have been manipulated?

The cosmic design scenario as proposed here can be falsified in several ways. Firstly, since the de Broglie wavelength of a particle is inversely related to its momentum, and hence its mass, the dynamic range of a habitable halo declines rather sharply as the neutrino mass scale is reduced, vanishing completely if $m_\nu < 6$ meV [3]. From (5) one expects $m_\nu > 12$ meV, if not more due to the need to suppress vacuum annihilation to three photons, the cross-section growing rapidly for smaller neutrino masses[3]. It is therefore encouraging that $|\Delta m_{32}|=2.43\pm0.13\times10^{-3}$ eV^2. For a non-degenerate mass hierarchy, this implies differences between two mass eigenstates of ~50 meV. Secondly, a large neutrino mass scale would also be problematic. Apart from curtailing the aquatic era, and hence diminishing the dilution of evolutionary life, extraneous neutrino heating might then occur in forms of matter other than hcp iron. The risk would be particularly high in haloes close to the threshold of gravitational implosion in which the neutrinos become moderately relativistic. The fraction of the annihilation energy received by the final electron could then rise from 5% to ~25% [3]. However, the possibility of exciting ground state electrons in other forms of matter seems unlikely if $m_\nu < 100$ meV. Larger values of m_ν would require a degenerate neutrino mass hierarchy, which is already somewhat disfavoured by cosmological data[37-39]. Thirdly, sterile neutrinos may not exist or have a mass that is completely inappropriate for concentrating active neutrinos on galactic scales. A 2:1 variation in the sterile neutrino mass, m_s, approximately translates to a 4:1 change in the sterile halo radius since $R_h \propto m_s^{-2}$ [3]. Thus, this model yields a rather tight prediction for the effective mass of a sterile neutrino spanning barely one octave. This mass scale happens to be many orders of magnitude smaller than historically anticipated by astronomers seeking candidates for warm or cold dark matter[40] or theoreticians seeking to understand why the active neutrino mass scale is so small by invoking, for instance, a 'seesaw mechanism'[41].

These resolutions of the Fermi Paradox are not only able to furnish predictions, they can draw on existing experimental support. Flavour oscillations demonstrate that neutrinos carry mass[6], which remains the only known departure from Standard Model physics. Existing empirical data argues that electron neutrinos have an effective mass in the range 45—66 meV, very much in keeping with efficient planetary heating[3]. Hints of the existence of eV-scale sterile neutrinos have already been obtained from short baseline neutrino oscillation experiments[21-23] and further clues suggest they may have a mass of 1.5 eV and be responsible for the dark matter of galaxy clusters[19,20,3]. The hexagonally close-packed phase of iron present within planetary cores possesses 4*s* electrons that may be uniquely receptive to excitation by neutrino annihilation and the hcp/fcc phase transition boundary is compatible with internal temperature regulation so as to provide remarkably consistent conditions for aquatic life over a range of planetary masses[7,3]. The accelerating expansion of the universe [4,5] not only implies that the total energy of the cosmos is increasing but also that its gestation may be incomplete. If one generalises to lifeforms everywhere, these facts lend credence to Freeman Dyson's maxim “the more I examine the universe and study the details of its architecture, the more evidence I find that the universe in some sense must have known we were coming”[42].

Despite stunning technological advances, our civilisation still faces many challenges. However, there is now the tantalising prospect that we may be on the cusp of elucidating our place within the wider universe. In coming years, improved knowledge of both active and sterile neutrinos and the interactions of these elusive particles may lead to a more cohesive scientific view of nature with the potential to inform the political and cultural objectives of our species. Ironically, our hitherto perplexing solitude in a vast and ancient galaxy may currently be the strongest evidence that we inhabit a universe that is, and always has been, adeptly configured for life.

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The status of our bird populations: the fifth Birds of Conservation Concern in the United Kingdom, Channel Islands and Isle of Man and second IUCN Red List assessment of extinction risk for Great Britain

Andrew Stanbury, Mark Eaton, Nicholas Aebischer, Dawn Balmer, Andy Brown, Andy Douse, Patrick Lindley, Neil McCulloch, David Noble and Ilka Win

Alan Harris

Common Swifts *Apus apus*

Abstract The fifth review of *Birds of Conservation Concern* (*BoCC5*) in the UK, Channel Islands and Isle of Man assessed and assigned 245 species to updated Red, Amber and Green lists of conservation concern and showed a continuing decline in the status of our bird populations. In total, 70 species (29% of those assessed) are now on the Red list, up from 36 species in the first review in 1996. Since the last review, in 2015, Golden Oriole *Oriolus oriolus* has been lost as a breeding species. Eleven species have been moved to the Red list, while only six species moved from Red to Amber. Newly Red-listed species include Common Swift *Apus apus*, House Martin *Delichon urbicum*, Greenfinch *Chloris chloris* and the globally threatened Leach's Storm-petrel *Oceanodroma leucorhoa*. There has been no improvement in the overall status of species associated with farmland and upland, or Afro-Palearctic migrants; indeed, more such species have been Red-listed. Concerns over the status of our wintering wildfowl and wader populations have also increased. As a direct result of targeted conservation action, White-tailed Eagle *Haliaeetus albicilla* has been moved from Red to Amber.

We also present the separate, and distinct, second IUCN Regional Red List assessment of extinction risk for Great Britain, which shows that 46% of 235 regularly occurring species, and 43% of 285 separate breeding and non-breeding populations, are assessed as being threatened with extinction from Great Britain.

Introduction

Regular assessments of status are crucial aids in identifying species and habitat conservation priorities, enabling us to target finite resources most effectively. The first formal assessment for UK birds listed 117 species (*Red Data Birds in Britain*, Batten *et al.* 1990). Since then, a process for identifying priority species has become well established: *Birds of Conservation Concern* (*BoCC*), which uses quantitative assessments against standardised criteria to allocate species to Red, Amber or Green lists depending on their level of conservation concern. Gibbons *et al.* (1996a; *BoCC1*) were the first to adopt this traffic-light system. Since then, the *BoCC* process has been repeated at regular intervals, by Gregory *et al.* (2002; *BoCC2*), Eaton *et al.* (2009; *BoCC3*) and Eaton *et al.* (2015; *BoCC4*). All of these reviews have used the same approach to establish priorities, although there have been some changes in the details of methodology to reflect growing experience and changes in data availability.

These reviews have documented the declining status of UK bird populations, with a progressive lengthening of the Red list, from 36 species in *BoCC1* to 67 in *BoCC4*. *BoCC1* raised the profile of the widespread decline of farmland birds, while subsequent reviews have highlighted other topics of concern, such as the plight of woodland birds in *BoCC2*, Afro-Palearctic migrants in *BoCC3* and upland birds in *BoCC4*. The reviews have also showcased conservation success stories, such as the recovery, or partial recovery, of some raptor species and Eurasian Bittern *Botaurus stellaris*.

We are extremely fortunate in the UK to have many thousands of dedicated volunteer birdwatchers, coordinated by professional research and conservation organisations, collecting information on our bird populations. As a result, an impressive repository of robust data, including regularly updated species' trends, population estimates and range maps, allow us to undertake detailed assessments such as *BoCC*. This level of information is rarely available for birds elsewhere, or for other taxonomic groups in the UK or beyond. Although similar exercises are carried out in Ireland (Gilbert *et al.* 2021), Wales (Johnstone & Bladwell 2016) and the Isle of Man (Morris & Sharpe 2021), the *BoCC* concept is not widely used elsewhere, so our reviews can rarely be viewed in a quantitative context beyond birds in the UK.

A more recently developed but now well-established approach, with many parallels to our own, is the International Union for Conservation of Nature (IUCN) Red List process. In contrast to *BoCC*, which concerns conservation in a broad sense, the IUCN assessment solely concerns extinction risk, using standardised criteria that can be applied to assess any plant or animal taxon. IUCN Red Lists are used to assess the global status of species (IUCN 2019; www.iucnredlist.org), but can also be applied at regional, national or local scales (IUCN 2012), including the *European Red List of Birds* (BirdLife International 2021). The IUCN approach is used to assess the status of a broad suite of our native wildlife and, to date, c. 12,000 species from around 40 taxonomic groups have been assessed Britain-wide, providing an increasingly detailed context within which to view the changing status of our birds. Recognising this, we conducted the first IUCN assessment of bird populations in Britain in 2017 (*IUCN1*, Stanbury *et al.* 2017).

BoCC thus embraces factors such as change over longer periods than IUCN (notably including a historical context) and the international importance of UK bird populations. On the other hand, the IUCN approach allows different taxonomic groups to be assessed on a more level playing field, using the same well-established, internationally recognised criteria. This allows changes in status to be tracked and the potential creation of multi-taxa indicators (e.g. *Red List Index*, Butchart *et al.* 2005).


Luke Seitz

461. Leach's Storm-petrel *Oceanodroma leucorhoa*, Massachusetts, USA, August 2015. The St Kilda archipelago, off the coast of northwest Scotland, holds the vast majority of the UK breeding population of Leach's Storm-petrel. Recent surveys here have highlighted a decline of 68% between 2000 and 2019, likely in part due to predation by Great Skuas *Stercorarius skua*. This, along with Leach's Storm-petrel being classed as Vulnerable globally, has resulted in the species being added to the Red list and qualifying as Critically Endangered in Great Britain.

Here, we present the fifth *Birds of Conservation Concern* review for the UK, Channel Islands and Isle of Man (*BoCC5*), alongside the second IUCN Regional Red List assessment of extinction risk for Great Britain (*IUCN2*), thereby harmonising the timings of these two assessments. Our focus is on the current status of species (up to 2019 or winter 2019/20). The factors that are driving change in species' status are covered in detail elsewhere, such as in the *State of Nature* reports (e.g. Hayhow *et al.* 2019).

We had hoped to incorporate the results from the latest seabird census, *Seabirds Count*, in this review but, owing to delays to fieldwork caused by Covid-19, this has not been possible. As there are currently uncertainties around the status of some of our seabirds, we decided against the inclusion of most of these species and we shall publish an addendum after the census results become available. Thus, the assessment for breeding seabirds from previous reviews (Eaton *et al.* 2015; Stanbury *et al.* 2017) are transcribed here. The exception to this is Leach's Storm-petrel *Oceanodroma leucorhoa,* as most of the relevant data for this species are already available (Deakin *et al.* in press).

Methods

The *BoCC* assessment process

The *BoCC5* process followed those of previous reviews, whereby each bird species was assessed against a set of standardised Red- and Amber-list criteria, which remained unchanged since *BoCC4* (see below). Species were placed on the highest priority list for which they satisfied any criteria. If they met none of these criteria, they were placed on the Green list. Breeding species were placed on the list of 'former breeders' if they had not bred in any of the five most recent years for which data were available.

Red- and Amber-list criteria – colours denote which list the criterion is applicable to.

IUCN: Global IUCN Red List status. Species that are globally threatened (Critically Endangered, Endangered and Vulnerable, but not Near Threatened) under IUCN guidelines, as assessed by BirdLife International, the IUCN Red List Authority for birds in 2021 (www.iucnredlist.org).

ERLOB: European Red List status. Species that are threatened (Critically Endangered, Endangered and Vulnerable, but not Near Threatened) in Europe under IUCN guidelines, as assessed by BirdLife International, the IUCN Red List Authority for birds, in 2021 (BirdLife International 2021).

HD: Historical decline in breeding populations. Species judged to have declined severely between 1800 and 1995, from an assessment conducted by Gibbons *et al.* (1996b), and which have not recovered subsequently. Species that are deemed to have recovered partially are Amber-listed (see below), or Green-listed if they have recovered completely.

HDrec: Historical decline – recovery. Species previously Red-listed for historical decline, followed by an increase of at least 100% over 25 years or the longer-term period. If, following a move to HDrec, a species increases by at least 167% from its HDrec level, it no longer qualifies as HDrec (e.g. would move to Green if not qualifying under other criteria). Further explanation of this process is given in Eaton *et al.* (2015).

BDp/**BDMp**: Breeding population decline. Defined as a severe decline of >50% (**BDp**), or moderate decline (>25% but <50% **BDMp**) in the UK breeding population size over either of two assessment periods: 25 years (**BDp**^{1}/**BDMp**^{1}) or the longer term (**BDp**^{2}/**BDMp**^{2}). The latter is defined as the entire period used for assessments starting in 1969.

WDp/**WDMp**: Non-breeding population decline. Defined as a severe decline of >50% (**WDp**), or moderate decline (>25% but <50% **WDMp**) in the UK population size over either of two assessment periods: 25 years (**WDp**^{1}/**WDMp**^{1}) or the longer term (**WDp**^{2}/**WDMp**^{2}). Non-breeding trends were assessed only if a species has substantially independent breeding and non-breeding populations, otherwise only the breeding population was assessed. The same was true for other criteria which could be applied to both breeding and non-breeding populations.

BDr/**BDMr**: Breeding range decline. Defined as a severe decline in UK range of >50% (**BDr**) or moderate decline (>25% but <50% **BDMr**) between the breeding bird atlases in 1988–91 and 2007–11 (**BDr**^{1}/**BDMr**^{1}) or 1968–71 and 2007–11 (**BDr**^{2}/**BDMr**^{2}), as measured by the calculated change in the number of occupied 10-km squares.

WDr/**WDMr**: Non-breeding range decline. Defined as a severe decline in UK range of >50% (**WDr**^{1}) or moderate decline (>25% but <50% **WDMr**^{1}) between the wintering bird atlases 1981–84 and 2007–11, as measured by the calculated change in the number of occupied 10-km squares. Since there are only two wintering bird atlases, it was not possible to measure range change over a longer time period.

BR & **WR**: Breeding and non-breeding rarity. Species qualified as rare breeders (BR) if the UK breeding population was <300 pairs, and as rare non-breeders (WR) if the UK non-breeding population was <900 individuals.

BL & **WL**: Breeding and non-breeding localisation. Species were considered localised if more than 50% of the UK population was found at ten or fewer sites in either the breeding (BL) or the non-breeding (WL) season. Sites were defined as either Special Protection Areas (SPAs; Stroud *et al.* 2016) or Important Bird Areas (IBAs; Heath & Evans 2000). Rare breeders or rare non-breeders (see above) were not assessed against this criterion, as their small population sizes predispose them to be restricted to a small number of sites.

BI & **WI**: Breeding and non-breeding international importance. Species were considered of international importance if the UK holds at least 20% of the European population in either the breeding (BI) or the non-breeding (WI) season. European estimates were derived from data collated as part of the ERLOB assessments, but for non-breeding waterbirds we used estimates for the flyway populations for northwest Europe (wildfowl) or East Atlantic (waders) (CSR8; Wetlands International 2021).

The IUCN Regional Red List assessment process

We followed the IUCN's guidelines for the application of Red List criteria at regional and national levels. This regional process comprises three stages: 1) identify the taxa to be assessed; 2) assess the extinction risk faced by regional populations of each taxon as if in isolation using the global Red List criteria (IUCN 2019); and 3) consider the influence of potential interactions with populations outside the region. It is worth noting that the time periods used for the assessments differ between *BoCC* and IUCN. The IUCN assessments are based around the generation length, mainly multiplied by three, of each individual species, while those of *BoCC*, for all species, are based on the last 25 years and a longer time period (which is determined by data availability). Generation lengths for species were obtained directly from BirdLife International (Ian Burfield pers. comm.). These were recently reassessed by BirdLife International (e.g. Bird *et al.* 2020), so our assessment differs in this respect from *IUCN1*.

IUCN Red List criteria

Each species was assessed against the five standard IUCN Red List criteria (summarised below). See IUCN (2019) for full details.

- Criterion A: Reduction in the size (either abundance or range) of the population, measured over ten years or three generations, whichever is longer.
- Criterion B: Restricted geographical range in conjunction with fragmentation, continuing decline, or extreme population fluctuations.
- Criterion C: Small population size and continuing decline.
- Criterion D: Very small population or very restricted distribution.
- Criterion E: Quantitative analysis of extinction risk.

Each species was assessed against thresholds for each criterion and its subcriteria, which, if met or exceeded, qualified it for one of the standard IUCN Red List threat categories: Extinct, Regionally Extinct, Critically Endangered, Endangered, Vulnerable, Near Threatened and Least Concern. Data Deficient was used to indicate that a species was evaluated using available data but this was found to be insufficient to place the species into a category. For the Near Threatened category, which identifies species not considered formally threatened with extinction but sufficiently close to be likely to become so in the near future, we followed the examples in the guidelines (IUCN 2019; see Supplementary Online Material (SOM) https://doi.org/10.5061/dryad.cc2fqz672).

For species that have substantial and at least partially distinct breeding and non-breeding populations in Britain (defined as having a population in the non-breeding season that is more than twice the size of the breeding population), notably waterbirds, we assessed breeding and wintering populations separately.

The final stage of the Regional IUCN Red List process examines the extent to which neighbouring populations of the same species, outside the region, may affect extinction risk within the region by, for example, providing a 'rescue effect'. Under favourable conditions, such as a continuing or even increasing flow of immigrants into the region, it might be appropriate to downlist the threat category.

Populations qualifying as Critically Endangered, Endangered or Vulnerable after this final stage were collectively termed as 'threatened with extinction'. Where both breeding and non-breeding assessments were carried out, we followed the first *European Red List of Birds* (BirdLife International 2015) and the previous Great Britain assessments (Stanbury *et al.* 2017) and assigned the highest threat status from either population assessment to the species. Further details of the IUCN assessments are given in the SOM.

Species list

As in previous *BoCC* reviews (see Eaton *et al.* 2015), we considered only naturally occurring species with self-sustaining populations, with filters to exclude vagrants, defined as species assessed by the British Birds Rarities Committee (www.bbrc.org.uk), or species occurring only as scarce migrants (see e.g. White & Kehoe 2020a,b). Breeding species were considered only if they had been proven (or strongly suspected) to have bred for a period of at least five consecutive years within the most recent 25 years for which data are available. Updating the list on the basis of these criteria resulted in the addition of Little Bittern *Ixobrychus minutus*, Cattle Egret *Bubulcus ibis*, Great White Egret *Ardea alba* and Black-winged Stilt *Himantopus himantopus* (all appear to have become, or are in the process of becoming, established regular breeders), and Yellow-browed Warbler *Phylloscopus inornatus* (no longer considered a scarce migrant). Unlike *BoCC4*, we did not include globally threatened species (www.iucnredlist.org) that have occurred in the UK in each of the last 25 years, regardless of scarcity in the UK, resulting in the removal of Aquatic Warbler *Acrocephalus paludicola* (assessed in *BoCC1* to *BoCC4*).

Note that some species were excluded from assessment as breeding species, but were assessed because they have larger or better-established non-breeding populations (e.g. Red-necked Grebe *Podiceps grisegena*).

The selection criteria used for *IUCN2* were similar to those for *BoCC5*, but differed in the following respects: i) we followed the Regional Red List recommendation (IUCN 2012) to exclude colonising species unless they have bred for ten consecutive years; ii) as with *IUCN1*, we applied an optional filter to exclude species that appear only on passage; iii) spatial differences between the UK and Great Britain. As a result, ten species assessed for *BoCC5* were excluded from the *IUCN2* assessment: Sooty Shearwater *Ardenna grisea*, Great Shearwater *A. gravis*, Black-winged Stilt, Curlew Sandpiper *Calidris ferruginea*, Little Stint *C. minuta*, Little Gull *Hydrocoloeus minutus*, Long-tailed Skua *Stercorarius longicaudus*, Pomarine Skua *S. pomarinus*, Snowy Owl *Bubo scandiacus* and Short-toed Treecreeper *Certhia brachydactyla*.

As with *BoCC3* and *4*, we conducted a parallel assessment of the *BoCC* status of regularly occurring races of birds in the UK. The process was as described in Eaton *et al.* (2009 & 2015) and mirrored the species-level assessment. As before, the lack of some data sources at a subspecific level (e.g. Global and European IUCN assessments, and monitoring data at the race level) required us to create new estimates of populations, trends and status outside the UK as best we could with existing data sources. For the first time, we carried out IUCN assessments for all of the relevant *BoCC* races.

Taxonomy in *BoCC5* follows HBW & BirdLife International (2020). Thus, Taiga Bean *Anser fabalis* and Tundra Bean Geese *A. serrirostris*, Carrion *Corvus corone* and Hooded Crows *C. cornix* and Common *Acanthis flammea* and Lesser Redpolls *A. cabaret* are treated as single species, with races assessed separately. For the crows and redpolls, this represents a change in status since their assessment in *BoCC4*. Further details and results of race assessments in *BoCC5* are given in the SOM.

Data sources

The principal sources of data were the same as for previous assessments and described in Eaton *et al.* (2009 & 2015), Stanbury *et al.* (2017), and in further detail in the SOM. Trend data was used up to summer 2019, winter 2019/20, or the most recently available year before then. The main data sources accessed were:

- The BTO/JNCC Common Birds Census (CBC) and BTO/JNCC/RSPB Breeding Bird Survey (BBS) (to 2019).
- The BTO Waterways Bird Survey (WBS) and BTO/JNCC/RSPB Waterways Breeding Bird Survey (WBBS) (to 2019).
- BTO/RSPB/JNCC Wetland Bird Survey (WeBS) and WWT/JNCC/NatureScot Goose and Swan Monitoring Programme (to 2019/20).
- The Rare Breeding Birds Panel database (to 2018).
- Periodic species surveys run under the Statutory Conservation Agency and RSPB Annual Breeding Birds Scheme (SCARABBS), BTO species surveys and the GWCT/BTO Woodcock survey.
- The three breeding bird atlases (Sharrock 1976; Gibbons *et al.* 1993; Balmer *et al.* 2013) and two wintering bird atlases (Lack 1986; Balmer *et al.* 2013).
- Two sources for seabird monitoring: the three complete censuses conducted in 1969–70 (Cramp *et al.* 1974), 1985–88 (Lloyd *et al.* 1991) and 1998–2001 (Mitchell *et al.* 2004), and the Seabird Monitoring Programme that has monitored a UK-wide sample of colonies since 1986. These data remained unchanged from *BoCC4* for most of the breeding seabirds.

- Population estimates from the Avian Population Estimates Panel (Woodward *et al.* 2020a).
- GWCT's National Gamebag Census (Aebischer 2019).

The process adopted the voluntary application of the National Statistics Code of Practice (https://code.statisticsauthority.gov.uk/voluntary-application). A statement of compliance is shown in the SOM.

Results

BoCC5

Former breeders

The two preceding *BoCC* reviews (Eaton *et al.* 2009, 2015) presented a list of former regularly breeding species in the UK. All eight species identified as such in *BoCC4* remain as former breeders in *BoCC5* (table 1). In addition, Golden Oriole *Oriolus oriolus* is now added to this list, as there have been no confirmed breeding records since 2009. All but one of the former breeders were not considered further and removed from the Red, Amber and Green list process. Black Tern *Chlidonias niger* remained as it was assessed for its passage population.

James Kennerley

462. Golden Oriole *Oriolus oriolus*, Uzbekistan, April 2018. With the last confirmed breeding in 2009, Golden Oriole moves to the list of former breeding species in *BoCC5*.

The updated Red, Amber and Green species lists

We assessed 245 species for the Red, Amber and Green lists in *BoCC5*. We placed 70 (29%) species on the Red list, 103 (42%) on the Amber list and 72 (29%) on the Green list (table 2).

A total of 29 species (12%) have moved lists since *BoCC4*: 11 species joined the Red list, with Ptarmigan *Lagopus muta* and Greenfinch *Chloris chloris* moving straight from Green to Red, and Bewick's Swan *Cygnus columbianus*, Common Goldeneye *Bucephala clangula*, Smew *Mergellus albellus*, Common Swift *Apus apus*, Dunlin *Calidris alpina*, Purple Sandpiper *C. maritima*, Leach's Storm-petrel, Montagu's Harrier *Circus pygargus* and House Martin *Delichon urbicum* moving from Amber to Red.

Table 1. Former regularly breeding species in the UK, with status from previous *BoCC* reviews. Species are placed on the Red (**R**) or Amber (**A**) lists, or identified as a former breeder (FB).

	Previous *BoCC* reviews				Last confirmed
	1 (1996)	2 (2002)	3 (2009)	4 (2015)	breeding attempt
Great Bustard *Otis tarda**	FB	FB	FB	FB	c.1833
Kentish Plover *Charadrius alexandrinus*	FB	FB	FB	FB	1979
Temminck's Stint *Calidris temminckii*	**A**	**A**	**R**	FB	1993
Black Tern *Chlidonias niger*	FB	FB	FB	FB	1975
Great Auk *Pinguinus impennis*	FB	FB	FB	FB	c.1812
Snowy Owl *Bubo scandiacus*	FB	FB	FB	FB	1975
Wryneck *Jynx torquilla*	**R**	**R**	**R**	FB	2002
Golden Oriole *Oriolus oriolus*	**A**	**A**	**R**	**R**	2009
European Serin *Serinus serinus*	**A**	**A**	**A**	FB	2006

* Although a Great Bustard reintroduction project has been under way since 2004, the population is not yet considered self-sustaining (BOU 2017) and was therefore not assessed for *BoCC5*.

Ptarmigan

BOX 1

In Britain, the Ptarmigan is restricted to the arctic-alpine heaths of the Scottish Highlands, with a population estimated at 2,000–15,000 pairs. The wide range in the estimate reflects cyclical fluctuations and a lack of formal surveys. As a quarry species, it may be hunted between 12th August and 10th December. The numbers shot and reported by Highland estates to GWCT's National Gamebag Census represent the only source of continuous long-term data on Ptarmigan in Scotland. Analysed in a similar way to standard avian monitoring data (Aebischer 2019), shooting returns ('bags') can be converted into annual indices to reveal the trend over time from 1961 to 2019 (fig. 1). The indices fluctuate considerably from year to year but show an overall decline from start to end (58 years) of 81% (95% confidence limits 39–94% decline). Interpreting trends in bag data is complicated because they reflect the effects of both abundance and shooting effort. Bags have, however, been found to be a good surrogate for abundance of Red Grouse *Lagopus lagopus* (Cattadori *et al.* 2003) and have been used to infer population fluctuations in Ptarmigan elsewhere (Nielsen & Pétursson 1995). The decline is consistent with the likely sensitivity of Ptarmigan to a northwards and upwards contraction of montane habitat caused by climate change (Moss 1998); the species has already been lost from lower marginal areas, especially in the southwest (Balmer *et al.* 2013), and 75% of estates reported declines across its southern range (Fletcher *et al.* 2013). Dedicated surveys of abundance, distribution and habitat are urgently needed to corroborate the trends in bags and monitor future change.

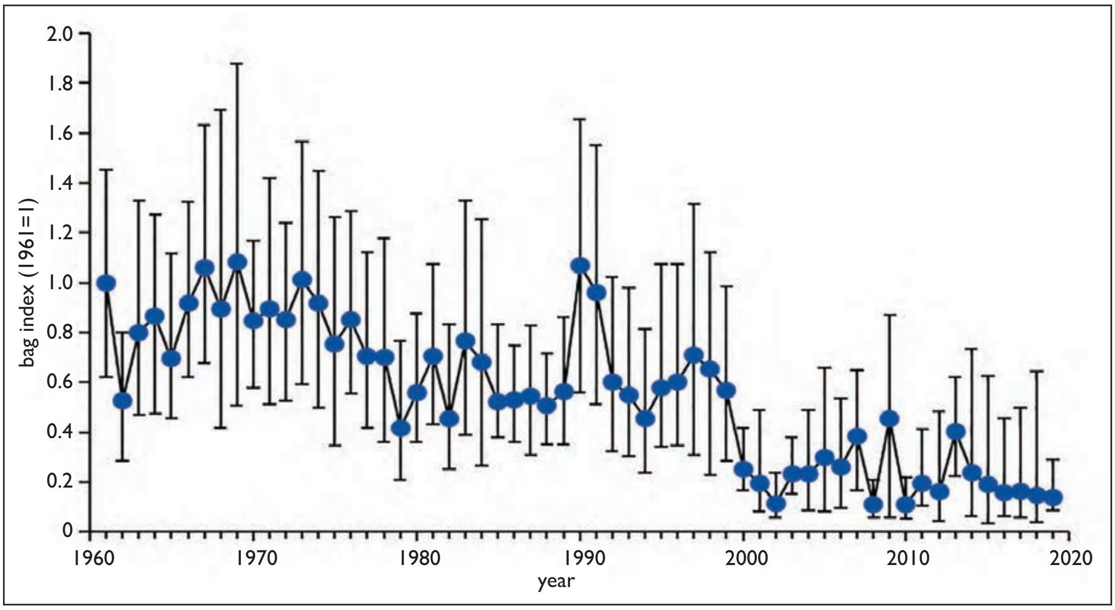


Fig. 1. Annual bag index (± 95% confidence limits) for Ptarmigan *Lagopus muta* in Scotland, 1961–2019, from GWCT's National Gamebag Census.

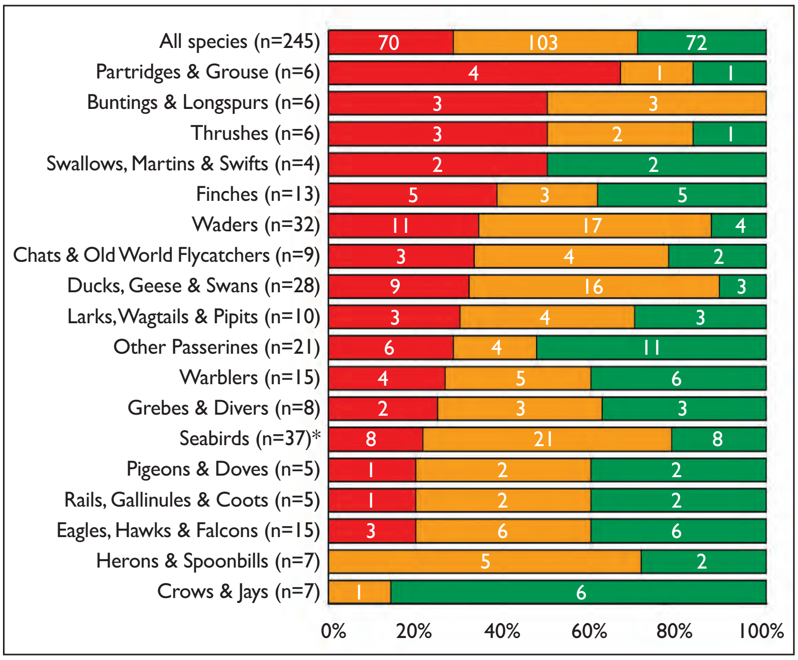
Six species moved from Green to Amber owing to increasing rates of decline in breeding or non-breeding populations: Red-breasted Merganser *Mergus serrator*, Moorhen *Gallinula chloropus,* Eurasian Sparrowhawk *Accipiter nisus*, Sedge Warbler *Acrocephalus schoenobaenus*, Common Whitethroat *Curruca communis* and Northern Wheatear *Oenanthe oenanthe*. A further three species moved from Green to Amber owing to other criteria: Rook *Corvus frugilegus* is now classed as Vulnerable at a European scale; and, in recognition of the significance of the UK population in a European context (now >20% of the breeding population), Wood Pigeon *Columba palumbus* and Wren *Troglodytes troglodytes* also move up to Amber.

The status of nine species has improved. Five species moved from Red to Amber owing to less severe declines: Song Thrush *Turdus philomelos*, Redwing *T. iliacus*, Pied Flycatcher *Ficedula hypoleuca*, Black Redstart *Phoenicurus*

Fig. 2. Proportion of species allocated to the Red, Amber and Green lists in *BoCC5*, overall and split into different groupings. Groupings largely based around HBW & BirdLife International (2020) families.

n = number of species.

* Breeding seabird assessments were the same as in *BoCC4*.



ochruros and Grey Wagtail *Motacilla cinerea*. White-tailed Eagle *Haliaeetus albicilla* moved from Red to Amber as it no longer qualifies for Historical Decline (now HD recovering; see also box 5). Red Grouse *Lagopus lagopus*, Mute Swan *Cygnus olor* and Common Kingfisher *Alcedo atthis* moved from the Amber to the Green list.

Native partridges and grouse had the highest proportion of Red-listed species in *BoCC5* (fig. 2), followed by: buntings; thrushes; swallows, martins and swifts; finches; waders; chats and flycatchers; and wildfowl. No herons and spoonbills or crows and jays were Red-listed. Further details of the *BoCC* assessments, along with race-level results, can be found in the SOM.

IUCN2 overview

The second IUCN Regional Red List review of extinction risk for Great Britain assessed 243 species, making 293 individual assessments (210 breeding, 83 non-breeding). Fifty species were assessed for both breeding and non-breeding populations. One species (Great Auk *Pinguinus impennis*) qualified as Extinct and seven as Regionally Extinct (all the former breeding species shown in table 1, with the exception of Snowy Owl, which was not evaluated as the species had never bred for ten consecutive years and therefore never qualified as a colonising species under the IUCN guidelines (IUCN 2012)). Golden Oriole was assessed as Regionally Extinct, having been classed as Critically Endangered (Possibly Extinct) in the previous review (Stanbury *et al.* 2017).

The final assessments for the 235 regularly occurring, or extant, species is presented in table 2. Of these 235 species, 108 (46%) had at least one population (breeding and/or non-breeding) that qualified as threatened with extinction (21 Critically Endangered, 41 Endangered, 46 Vulnerable).

Of the 285 separate assessments of breeding and non-breeding populations, 21 qualified as Critically Endangered, 43 as Endangered, 58 as Vulnerable, 33 as Near Threatened, 127 as of Least Concern and three as Data Deficient. Hence, an estimated 43% of currently occurring populations qualified as threatened with extinction. The corresponding figure was greater for non-breeding assessments (50%) than breeding assessments (41%).

The recent reassessment of generation lengths by BirdLife International (Bird *et al.* 2020) resulted in the time window examined for the assessments changing for 225 of the 243 species when compared with those used for *IUCN1*. On this basis, coupled with it being only four years since Stanbury *et al.* (2017), we do not present a detailed assessment of change. However, there were some notable differences between the assessments. Both Spotted Crake *Porzana porzana* and Leach's Storm-petrel move to Critically Endangered, from Endangered and Least Concern respectively. Ten other populations, all previously assessed as Near Threatened or of Least Concern, move to a higher threat status by at least two categories. Breeding

Table 2. Species assessments from the UK *BoCC5*[a] and *IUCN2*[b], with qualifying criteria. Species order follows HBW & BirdLife International (2020)[e]. In *BoCC*, species were placed on the Red (R), Amber (A) or Green (G) lists. Previous versions shown for context (n = not assessed). IUCN threat status categories: Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC), Data Deficient (DD) and Not Evaluated (NE).

Species	Previous *BoCC* reviews				*BoCC5* species assessment	*BoCC5* Red- & Amber-list qualifying criteria[a]	*IUCN2* species assessment	*IUCN2* population assessment with qualifying criteria[b] (br = breeding; n-br = non-breeding)
	1 (1996)	2 (2002)	3 (2009)	4 (2015)				
Common Quail *Coturnix coturnix*	R	R	A	A	Amber	HDrec, BDMp$^{1/2}$	EN	EN C1+2a(ii) (br)
Grey Partridge *Perdix perdix*	R	R	R	R	Red	BDp$^{1/2}$; BDMr^{2}	VU	VU A2b+3b+4b (br)
Red Grouse *Lagopus lagopus*	G	A	A	A	Green		LC	LC (br)
Ptarmigan *Lagopus muta*	G	G	G	G	Red	BDp$^{1/2}$	VU	VU C1+2a(ii) (br)
Capercaillie *Tetrao urogallus*	R	R	R	R	Red	BDp^{2}, BDr^{2}, WDr^{1}; BDMp^{1}	EN	EN C1 (br)
Black Grouse *Lyrurus tetrix*	R	R	R	R	Red	HD, BDp^{2}; BDMp^{1}, BDMr^{2}	VU	VU C1 (br)
Mute Swan *Cygnus olor*	G	A	G	A	Green		LC	LC (br); LC (n-br)
Whooper Swan *Cygnus cygnus*	A	A	A	A	Amber	BR, WL	EN	EN[o] D (br); LC (n-br)
Bewick's Swan *Cygnus columbianus*	A	A	A	A	Red	WDp^{1}; ERLOB, WDMp^{2}, WL, WI	CR	CR A2b+3b+4b (n-br)
Brent Goose *Branta bernicla*	A	A	A	A	Amber	WL, WI	LC	LC (n-br)
Barnacle Goose *Branta leucopsis*	A	A	A	A	Amber	WL	LC	LC (n-br)
Greylag Goose *Anser anser*	A	A	A	A	Amber	WL, WI	LC	LC (br); LC (n-br)
'Bean Goose' *Anser fabalis*[c]	A	A	A	A	Amber	WDMp^{1}, WR	EN	EN A4b+C1 (n-br)
Pink-footed Goose *Anser brachyrhynchus*	A	A	A	A	Amber	WL, WI	LC	LC (n-br)
White-fronted Goose *Anser albifrons*	A	A	G	R	Red	WDp$^{1/2}$	EN	EN A2b+3b+4b (n-br)
Long-tailed Duck *Clangula hyemalis*	G	A	G	R	Red	IUCN	NT	NT C1+2a(ii) (n-br)
Common Eider *Somateria mollissima*	A	A	A	A	Amber	ERLOB, WDMp$^{1/2}$	EN	EN A4b (n-br)
Velvet Scoter *Melanitta fusca*	A	A	A	R	Red	IUCN; ERLOB, WL	VU	VU C1+2a(ii) (n-br)
Common Scoter *Melanitta nigra*	R	R	R	R	Red	BDp^{2}, BDr$^{1/2}$; BDMp^{1}, BR, WL	CR	CR C2a(ii) (br); LC (n-br)
Common Goldeneye *Bucephala clangula*	A	A	A	A	Red	WDp^{1}; BR	VU	VU D1 (br); VU A2b+3b+4b (n-br)
Smew *Mergellus albellus*	G	G	A	A	Red	WDp^{1}; WDMp^{2}, WR	CR	CR A4b+C1+2a(ii) (n-br)
Goosander *Mergus merganser*	G	G	G	G	Green		LC	LC (n-br)
Red-breasted Merganser *Mergus serrator*	G	G	G	G	Amber	WDMp^{1}	VU	NT A2c+3c+4c (br); VU A2b+3b+4b (n-br)
Common Shelduck *Tadorna tadorna*	A	A	A	A	Amber	BDMp^{1}, WDMp^{1}, WL	EN	EN A4b (br); VU A2b+3b+4b (n-br)
Common Pochard *Aythya ferina*	A	A	A	R	Red	IUCN, WDp^{1}; ERLOB, WDMp^{2}, BDMr$^{1/2}$	EN	VU A2c+3c+4c (br); EN A2b+3b+4b (n-br)

Table 2. *cont.*

Tufted Duck *Aythya fuligula*	G	G	A	G	Green		VU	VU A4b (br); LC (n-br)
Greater Scaup *Aythya marila*	A	A	R	R	Red	WDp^{2}; WDMp^{1}, WL	EN	EN A2b+3b+4b (n-br)
Garganey *Spatula querquedula*	A	A	A	A	Amber	BR	EN	EN D (br)
Shoveler *Spatula clypeata*	A	A	A	A	Amber	WI	LC	LC (br); LC (n-br)
Gadwall *Mareca strepera*	A	A	A	A	Amber	WI	LC	LC (br); LC (n-br)
Eurasian Wigeon *Mareca penelope*	A	A	A	A	Amber	WL, WI	VU	VU D1 (br); NT A4b (n-br)
Mallard *Anas platyrhynchos*	G	G	A	A	Amber	WDMp$^{1/2}$	VU	LC (br); VU A4b (n-br)
Pintail *Anas acuta*	A	A	A	A	Amber	ERLOB, BDMp^{1}, BDMr$^{1/2}$, BR, WL, WI	CR	CR C2a(ii) (br); VU A2b+3b+4b (n-br)
Eurasian Teal *Anas crecca*	A	A	A	A	Amber	WI	LC	LC (br); LC (n-br)
Little Grebe *Tachybaptus ruficollis*	G	G	A	G	Green		LC	LC (br); LC (n-br)
Red-necked Grebe *Podiceps grisegena*	A	A	A	R	Red	WDp^{1}; ERLOB, WR	CR	CR C2a(ii) (n-br)
Great Crested Grebe *Podiceps cristatus*	G	G	G	G	Green		LC	LC (br); LC (n-br)
Slavonian Grebe *Podiceps auritus*	A	A	A	R	Red	IUCN, BDp$^{1/2}$; BDMr^{1}, BR, WI	CR	CR C2a(ii) (br); VU D1 (n-br)
Black-necked Grebe *Podiceps nigricollis*	A	A	A	A	Amber	ERLOB, BR, WR	EN	EN D (br); EN D (n-br)
Rock Dove/Feral Pigeon *Columba livia*	G	G	G	G	Green		NT	NT A2b+3b+4b (br)
Stock Dove *Columba oenas*	A	A	A	A	Amber	BI	LC	LC (br)
Wood Pigeon *Columba palumbus*	G	G	G	G	Amber	BI	LC	LC (br)
Turtle Dove *Streptopelia turtur*	R	R	R	R	Red	IUCN, BDp$^{1/2}$, BDr^{2}; ERLOB, BDMr^{1}	CR	CR A2b+3b+4b (br)
Collared Dove *Streptopelia decaocto*	G	G	G	G	Green		NT	NT° A4b (br)
European Nightjar *Caprimulgus europaeus*	R	R	R	A	Amber	BDMr^{2}	LC	LC (br)
Common Swift *Apus apus*	G	G	A	A	Red	BDp^{1}	EN	EN A2b+3b+4b (br)
Common Cuckoo *Cuculus canorus*	G	A	R	R	Red	BDp^{2}; BDMp^{1}	LC	LC (br)
Water Rail *Rallus aquaticus*	A	A	G	G	Green		LC	LC (br)
Corn Crake *Crex crex*	R	R	R	R	Red	BDp^{2}, BDr^{2}; HDrec	LC	LC (br)
Spotted Crake *Porzana porzana*	A	A	A	A	Amber	BR	CR	CR C2a(ii) (br)
Moorhen *Gallinula chloropus*	G	G	G	G	Amber	BDMp^{2}	VU	VU A4b (br)
Common Coot *Fulica atra*	G	G	G	G	Green		VU	VU A4b (br); VU A4b (n-br)
Common Crane *Grus grus*	A	A	A	A	Amber	BR, WR	VU	VU° D (br)
Red-throated Diver *Gavia stellata*	A	A	A	G	Green		NT	NT A2c+3c+4c (br); LC (n-br)
Black-throated Diver *Gavia arctica*	A	A	A	A	Amber	BR, WR	VU	VU D1 (br)
Great Northern Diver *Gavia immer*	A	A	A	A	Amber	WI	LC	LC (n-br)
European Storm-petrel *Hydrobates pelagicus**	A	A	A	A	Amber	BL	LC	LC (br)
Leach's Storm-petrel *Oceanodroma leucorhoa*^{e}	A	A	A	A	Red	IUCN, BDp^{1}; BL, BI	CR	CR A4b (br)
Fulmar *Fulmarus glacialis**	G	A	A	A	Amber	ERLOB, BL	LC	LC (br)

Table 2. *cont.*

Sooty Shearwater *Ardenna grisea*	G	G	A	G	Green		NE	NE
Great Shearwater *Ardenna gravis*	G	G	G	G	Green		NE	NE
Manx Shearwater *Puffinus puffinus**	A	A	A	A	Amber	BDMr^{2}, BL, BI	LC	LC (br)
Balearic Shearwater *Puffinus mauretanicus*	n	n	R	R	Red	IUCN; ERLOB, WI	VU	VU D1 (n-br)
Eurasian Spoonbill *Platalea leucorodia*	n	A	A	A	Amber	BR, WR	VU	VU° D (br); VU° D (n-br)
Eurasian Bittern *Botaurus stellaris*	R	R	R	A	Amber	HDrec, BR, WR	VU	VU D1 (br); NT° D1 (n-br)
Little Bittern *Ixobrychus minutus*	n	n	n	n	Amber	BR	CR	CR D (br)
Cattle Egret *Bubulcus ibis*	n	n	n	n	Amber	BR	VU	VU° D (n-br)
Grey Heron *Ardea cinerea*	G	G	G	G	Green		VU	VU A4b (br); LC (n-br)
Great White Egret *Ardea alba*	n	n	n	n	Amber	BR, WR	EN	EN° D (br); VU° D (n-br)
Little Egret *Egretta garzetta*	n	A	A	G	Green		LC	LC (br); LC (n-br)
Northern Gannet *Morus bassanus**	A	A	A	A	Amber	BL, BI	LC	LC (br)
Shag *Phalacrocorax aristotelis*^{e}*	A	A	A	R	Red	BDp^{1}; BDMp^{2}, BI	EN	EN A2b+3b+4b (br)
Great Cormorant *Phalacrocorax carbo**	G	A	G	G	Green		NT	NT° A4b (br); LC (n-br)
Stone-curlew *Burhinus oedicnemus*	R	R	A	A	Amber	BDMr^{2}, BL	VU	VU A2c+3c+4c+D1 (br)
Oystercatcher *Haematopus ostralegus*	A	A	A	A	Amber	ERLOB, WL, WI, BI	VU	VU A4b (br)
Avocet *Recurvirostra avosetta*	A	A	A	A	Amber	BL, WL	LC	LC (br); LC (n-br)
Black-winged Stilt *Himantopus himantopus*	A	n	n	n	Amber	BR	NE	NE
Grey Plover *Pluvialis squatarola*	A	A	A	A	Amber	WDMp^{1}, WL	VU	VU A2b+3b+4b (n-br)
European Golden Plover *Pluvialis apricaria*	A	G	A	G	Green		LC	LC (br); LC (n-br)
Dotterel *Charadrius morinellus*^{e}	A	A	A	R	Red	BDp^{1}	VU	VU A2b+3b+4b+C1+2a(ii)+D1 (br)
Ringed Plover *Charadrius hiaticula*	A	A	A	R	Red	WDp^{1}; BDMp^{1}, WDMp^{2}, WI	VU	NT A2b+3b+4b+C1+2a(ii) (br); VU A2b+3b+4b (n-br)
Little Ringed Plover *Charadrius dubius*	G	G	G	G	Green		LC	LC (br)
Northern Lapwing *Vanellus vanellus*	A	A	R	R	Red	BDp^{2}; ERLOB, BDMp^{1}, WDMp^{1}	VU	VU A2b+3b+4b (br); VU A2b+3b+4b (n-br)
Whimbrel *Numenius phaeopus*	A	A	R	R	Red	BDp^{1}, BDr^{1}; BDMr^{2}, WR	EN	EN A2bc+3bc+4bc+C1+2a(ii) (br)
Eurasian Curlew *Numenius arquata*	A	A	A	R	Red	BDp^{2}; BDMp^{1}, WDMp^{1}, BI	EN	EN A4b (br)
Bar-tailed Godwit *Limosa lapponica*	A	A	A	A	Amber	WL, WI	VU	VU A4b (n-br)
Black-tailed Godwit *Limosa limosa*	R	R	R	R	Red	HD; BDMr^{1}, BR, WL	EN	EN C2a(i)+D (br); LC (n-br)
Turnstone *Arenaria interpres*	A	A	A	A	Amber	WDMp^{1}	VU	VU A4b (n-br)
Red Knot *Calidris canutus*	A	A	A	A	Amber	WL, WI	LC	LC (n-br)
Ruff *Calidris pugnax*	A	A	R	R	Red	BDr^{1}; BDMp$^{1/2}$, BR	CR	CR D (br); EN A4b+C2a(ii) (n-br)
Curlew Sandpiper *Calidris ferruginea*	G	G	G	A	Amber	ERLOB	NE	NE
Sanderling *Calidris alba*	G	G	G	A	Amber	WL	LC	LC (n-br)

Table 2. *cont.*

Dunlin *Calidris alpina*	A	A	R	A	Red	WDp^{2}; WDMp^{1}, BDMr^{1}, BL, WL	VU	VU A2c+3c+4c (br); VU A2b+3b+4b (n-br)
Purple Sandpiper *Calidris maritima*	A	A	A	A	Red	BDp^{1}; WDMp^{1}, BDMr^{1}, BR	CR	CR B2ab(ii,iv,v)+C2a(i,ii)+D (br); VU A2b+3b+4b+C1+2a(ii) (n-br)
Little Stint *Calidris minuta*	G	G	G	G	Green		NE	NE
Woodcock *Scolopax rusticola*	A	A	A	R	Red	BDr^{2}; BDMr^{1}	VU	VU A2c+3c+4c (br); NT A2b+3b+4b (n-br)
Common Snipe *Gallinago gallinago*	A	A	A	A	Amber	ERLOB, WDMp^{1}, BDMr^{2}	VU	LC (br); VU A4b (n-br)
Jack Snipe *Lymnocryptes minimus*	A	G	A	G	Green		LC	LC (n-br)
Red-necked Phalarope *Phalaropus lobatus*	R	R	R	R	Red	HD; BR	EN	EN D (br)
Common Sandpiper *Actitis hypoleucos*	G	G	A	A	Amber	BDMp$^{1/2}$, WR	NT	NT A2b+3b+4b (br)
Green Sandpiper *Tringa ochropus*	G	A	A	A	Amber	BDMr^{1}, BR, WR	CR	CR C1+D (br); VU D1 (n-br)
Spotted Redshank *Tringa erythropus*	G	A	A	A	Amber	WR	EN	EN D (n-br)
Greenshank *Tringa nebularia*	A	G	G	A	Amber	BL	LC	LC (br)
Common Redshank *Tringa totanus*	A	A	A	A	Amber	ERLOB, BDMp^{1}, BDMr$^{1/2}$, WI	VU	VU A2bc+3bc+4bc (br); NT A2b+3b+4b (n-br)
Wood Sandpiper *Tringa glareola*	A	A	A	A	Amber	BR, WR	EN	EN D (br)
Little Gull *Hydrocoloeus minutus*	A	G	A	G	Green		NE	NE
Kittiwake *Rissa tridactyla**	G	A	A	R	Red	BDp$^{1/2}$; ERLOB	CR	CR A4b (br)
Black-headed Gull *Chroicocephalus ridibundus*^{e}*	G	A	A	A	Amber	WDMp^{1}, WI	VU	LC (br); VU A2b+3b+4b (n-br)
Mediterranean Gull *Ichthyaetus melanocephalus*^{e}*	A	A	A	A	Amber	BL	LC	LC (br)
Common Gull *Larus canus**	A	A	A	A	Amber	WI	LC	LC (br); LC (n-br)
Lesser Black-backed Gull *Larus fuscus**	A	A	A	A	Amber	BL, BI	DD	DD (br)
Herring Gull *Larus argentatus**	A	A	R	R	Red	BDp^{2}, WDp^{1}; BI, WI	EN	DD (br); EN A2b+3b+4b (n-br)
Yellow-legged Gull *Larus michahellis**	n	n	A	A	Amber	BR	EN	EN^{o} D (br); LC^{o} (n-br)
Caspian Gull *Larus cachinnans*	n	n	n	A	Amber	WR	VU	VU^{o} D (n-br)
Iceland Gull *Larus glaucoides*	G	G	A	A	Amber	WR	NT	NT^{o} D1 (n-br)
Glaucous Gull *Larus hyperboreus*	G	G	A	A	Amber	WR	VU	VU^{o} D (n-br)
Great Black-backed Gull *Larus marinus**	G	G	A	A	Amber	BDMp^{2}, WDMp^{1}	EN	LC (br); EN A2b+3b+4b (n-br)
Little Tern *Sternula albifrons**	A	A	A	A	Amber	BDMr^{2}, BL	VU	VU A2c+3c+4c (br)
Black Tern *Chlidonias niger (passage only)*	G	G	A	G	Green		NE	
Roseate Tern *Sterna dougallii**	R	R	R	R	Red	BDp$^{1/2}$, BDr^{2}; BDMr^{1}, BR	EN	EN^{o} A2b+C2a(ii) (br)
Common Tern *Sterna hirundo**	G	G	A	A	Amber	BL	NT	NT A2b+3b+4b (br)
Arctic Tern *Sterna paradisaea**	A	A	A	A	Amber	BDMp^{1}, BDMr^{1}	VU	VU A2c+3c+4c (br)
Sandwich Tern *Thalasseus sandvicensis**	A	A	A	A	Amber	BDMp^{1}, BL	LC	LC (br)
Long-tailed Skua *Stercorarius longicaudus*	G	G	G	G	Green		NE	NE
Arctic Skua *Stercorarius parasiticus**	G	G	R	R	Red	BDp^{1}; BDMp^{2}	CR	CR A4b (br)

Table 2. *cont.*

Pomarine Skua *Stercorarius pomarinus*	G	G	G	G	Green		NE	NE
Great Skua *Stercorarius skua*[e]*	A	A	A	A	Amber	BI, BL	LC	LC (br)
Puffin *Fratercula arctica**	A	A	A	R	Red	IUCN; ERLOB, BDMr[2], BL	LC	LC (br)
Black Guillemot *Cepphus grylle*[e]*	A	A	A	A	Amber	BDMr[1]	LC	LC (br)
Razorbill *Alca torda**	A	A	A	A	Amber	BL, BI	LC	LC (br)
Little Auk *Alle alle*	G	G	G	G	Green		DD	DD (n-br)
Common Guillemot *Uria aalge**	A	A	A	A	Amber	BL, BI	LC	LC (br)
Barn Owl *Tyto alba*	A	A	A	G	Green		LC	LC (br)
Long-eared Owl *Asio otus*	G	G	G	G	Green		LC	LC (br)
Short-eared Owl *Asio flammeus*	A	A	A	A	Amber	BDMr[1/2]	EN	EN A2c+3c+4c (br)
Tawny Owl *Strix aluco*	G	G	G	A	Amber	BDMp[1/2]	NT	NT A2b+3b+4b (br)
Osprey *Pandion haliaetus*	R	A	A	A	Amber	HDrec, BR	NT	NT[o] D1 (br)
Honey-buzzard *Pernis apivorus*	A	A	A	A	Amber	BR	EN	EN D (br)
Golden Eagle *Aquila chrysaetos*	A	A	A	G	Green		NT	NT D1 (br)
Marsh Harrier *Circus aeruginosus*	R	A	A	A	Amber	BL	LC	LC[o] (br)
Hen Harrier *Circus cyaneus*	R	R	R	R	Red	HD; BDMp[1]	EN	EN C1 (br)
Montagu's Harrier *Circus pygargus*	A	A	A	A	Red	BDp[1]; BDMr[2], BR	CR	CR A4b+C1+2a(ii)+D (br)
Eurasian Sparrowhawk *Accipiter nisus*	G	G	G	G	Amber	BDMp[1]	VU	VU A4b (br)
Northern Goshawk *Accipiter gentilis*	G	G	G	G	Green		NT	NT D1 (br)
White-tailed Eagle *Haliaeetus albicilla*	R	R	R	R	Amber	HDrec, BR	EN	EN D (br)
Red Kite *Milvus milvus*	R	A	A	G	Green		LC	LC (br)
Common Buzzard *Buteo buteo*	G	G	G	G	Green		LC	LC (br)
Common Kingfisher *Alcedo atthis*	A	A	A	A	Green		VU	VU C1+2a(ii) (br)
Green Woodpecker *Picus viridis*	A	A	A	G	Green		NT	NT A2b+3b+4b (br)
Lesser Spotted Woodpecker *Dryobates minor*	G	R	R	R	Red	BDp[1/2]; BDMr[1/2]	EN	EN A2b+3b+4b+C1+2a(ii) (br)
Great Spotted Woodpecker *Dendrocopos major*	G	G	G	G	Green		LC	LC (br)
Common Kestrel *Falco tinnunculus*	A	A	A	A	Amber	BDMp[1/2]	VU	VU A4b (br)
Merlin *Falco columbarius*	R	A	A	R	Red	HD; ERLOB	EN	EN C2a(ii) (br)
Hobby *Falco subbuteo*	G	G	G	G	Green		NT	NT A4b (br)
Peregrine Falcon *Falco peregrinus*	A	A	G	G	Green		LC	LC (br)
Red-backed Shrike *Lanius collurio*	R	R	R	R	Red	HD, BDp[1/2], BDr[2]; BR	CR	CR D (br)
Red-billed Chough *Pyrrhocorax pyrrhocorax*	A	A	A	G	Green		VU	VU D1 (br)
Eurasian Jay *Garrulus glandarius*	G	G	G	G	Green		LC	LC (br)
Magpie *Pica pica*	G	G	G	G	Green		LC	LC (br)

Table 2. *cont.*

Jackdaw *Coloeus monedula*[e]	G	G	G	G	Green		LC	LC (br)
Rook *Corvus frugilegus*	G	G	G	G	Amber	ERLOB	NT	NT A2b+3b+4b (br)
Common Raven *Corvus corax*	G	G	G	G	Green		LC	LC (br)
'Carrion/Hooded Crow' *Corvus corone*[c,d]	G	G	G	G	Green		LC	LC (br)
Coal Tit *Periparus ater*	G	G	G	G	Green		LC	LC (br)
Crested Tit *Lophophanes cristatus*	A	G	A	G	Green		LC	LC (br)
Marsh Tit *Poecile palustris*	A	R	R	R	Red	BDp^{2}; BDMp^{1}	NT	NT A2b+3b+4b (br)
Willow Tit *Poecile montanus*	A	R	R	R	Red	BDp$^{1/2}$, BDr^{2}; BDMr^{1}, WDMr^{1}	EN	EN A2c+3c+4c (br)
Blue Tit *Cyanistes caeruleus*	G	G	G	G	Green		LC	LC (br)
Great Tit *Parus major*	G	G	G	G	Green		LC	LC (br)
Shore Lark *Eremophila alpestris*	n	n	A	A	Amber	WR	EN	EN D (n-br)
Woodlark *Lullula arborea*	R	R	A	G	Green		LC	LC (br)
Skylark *Alauda arvensis*	R	R	R	R	Red	BDp^{2}	LC	LC (br); LC (n-br)
Bearded Tit *Panurus biarmicus*	A	A	A	G	Green		LC	LC (br)
Sedge Warbler *Acrocephalus schoenobaenus*	G	G	G	G	Amber	BDMp^{2}	NT	NT A4b (br)
Marsh Warbler *Acrocephalus palustris*	R	R	R	R	Red	BDp$^{1/2}$; BR	CR	D (br)
Reed Warbler *Acrocephalus scirpaceus*	G	G	G	G	Green		LC	LC (br)
Savi's Warbler *Locustella luscinioides*	A	R	R	R	Red	BDp$^{1/2}$; BDMr^{1}, BR	CR	CR D (br)
Grasshopper Warbler *Locustella naevia*	A	R	R	R	Red	BDp^{2}	LC	LC (br)
House Martin *Delichon urbicum*	G	A	A	A	Red	BDp^{2}	NT	NT A2b+3b+4b (br)
Barn Swallow *Hirundo rustica*	A	A	A	G	Green		VU	VU A2b+3b+4b (br)
Sand Martin *Riparia riparia*	A	A	A	G	Green		LC	LC (br)
Wood Warbler *Phylloscopus sibilatrix*	G	A	R	R	Red	BDp^{1}; BDMr$^{1/2}$	VU	VU A2c+3c+4bc (br)
Yellow-browed Warbler *Phylloscopus inornatus*	n	n	n	n	Amber	WR	EN	EN[o] D (n-br)
Willow Warbler *Phylloscopus trochilus*	G	A	A	A	Amber	BDMp^{2}	LC	LC (br)
Common Chiffchaff *Phylloscopus collybita*	G	G	G	G	Green		LC	LC (br)
Cetti's Warbler *Cettia cetti*	A	G	G	G	Green		LC	LC (br)
Long-tailed Tit *Aegithalos caudatus*	G	G	G	G	Green		LC	LC (br)
Blackcap *Sylvia atricapilla*	G	G	G	G	Green		LC	LC (br)
Garden Warbler *Sylvia borin*	G	G	G	G	Green		LC	LC (br)
Lesser Whitethroat *Curruca curruca*[e]	G	G	G	G	Green		LC	LC (br)
Common Whitethroat *Curruca communis*[e]	G	G	A	G	Amber	BDMp^{2}	LC	LC (br)
Dartford Warbler *Curruca undata*[e]	R	A	A	A	Amber	HDrec, BL	LC	LC (br)
Short-toed Treecreeper *Certhia brachydactyla*	G	G	A	A	Amber	BR	NE	NE

Table 2. *cont.*

Eurasian Treecreeper *Certhia familiaris*	G	G	G	G	Green		LC	LC (br)
Eurasian Nuthatch *Sitta europaea*	G	G	G	G	Green		LC	LC (br)
Wren *Troglodytes troglodytes*	G	G	G	G	Amber	BI	LC	LC (br)
Dipper *Cinclus cinclus*	G	G	G	A	Amber	BDMp^{2}	LC	LC (br)
Common Starling *Sturnus vulgaris*	A	R	R	R	Red	BDp$^{1/2}$	VU	VU A2b+3b+4b (br); LC (n-br)
Mistle Thrush *Turdus viscivorus*	G	A	A	R	Red	BDp^{2}; BDMp^{1}	NT	NT A2b+3b+4b (br)
Song Thrush *Turdus philomelos*	R	R	R	R	Amber	BDMp^{2}	LC	LC (br)
Redwing *Turdus iliacus*	A	A	R	R	Amber	BDMr$^{1/2}$, BR	CR	CR D (br); LC (n-br)
Blackbird *Turdus merula*	A	G	G	G	Green		LC	LC (br)
Fieldfare *Turdus pilaris*	A	A	R	R	Red	BDp$^{1/2}$, BDr^{1}; BDMr^{2}, BR	CR	CR A2c+3c+4c+C2a(i,ii)+D (br); LC (n-br)
Ring Ouzel *Turdus torquatus*	A	R	R	R	Red	BDp^{2}; BDMr^{2}	NT	NT A2c+3c+4c (br)
Spotted Flycatcher *Muscicapa striata*	R	R	R	R	Red	BDp$^{1/2}$	NT	NT A4b (br)
Robin *Erithacus rubecula*	G	G	G	G	Green		LC	LC (br)
Common Nightingale *Luscinia megarhynchos*	A	A	A	R	Red	BDp$^{1/2}$; BDMr^{2}	VU	VU A4b (br)
Pied Flycatcher *Ficedula hypoleuca*	G	G	A	R	Amber	BDMp^{1}, BDMr^{1}	NT	NT A2c+3c+4c (br)
Black Redstart *Phoenicurus ochruros*	A	A	A	R	Amber	BR, WR	VU	VU° D (br); NT° D1 (n-br)
Common Redstart *Phoenicurus phoenicurus*	A	A	A	A	Amber	BDMr^{2}	LC	LC (br)
Whinchat *Saxicola rubetra*	G	G	A	R	Red	BDp^{1}; BDMr$^{1/2}$	NT	NT A2c+3c+4bc (br)
European Stonechat *Saxicola rubicola*	A	A	G	G	Green		LC	LC (br)
Northern Wheatear *Oenanthe oenanthe*	G	G	A	G	Amber	BDMp^{1}	EN	EN A4b (br)
Goldcrest *Regulus regulus*	G	A	G	G	Green		LC	LC (br)
Firecrest *Regulus ignicapilla*	A	A	A	G	Green		LC	LC (br)
Waxwing *Bombycilla garrulus*	G	G	G	G	Green		LC	LC (n-br)
Dunnock *Prunella modularis*	A	A	A	A	Amber	BDMp^{2}	LC	LC (br)
House Sparrow *Passer domesticus*	G	R	R	R	Red	BDp^{2}	LC	LC (br)
Tree Sparrow *Passer montanus*	R	R	R	R	Red	BDp^{2}; BDMr^{2}	VU	VU A2c+3c+4c (br)
Tree Pipit *Anthus trivialis*	G	A	R	R	Red	BDp^{2}; BDMr^{2}	LC	LC (br)
Meadow Pipit *Anthus pratensis*	G	A	A	A	Amber	BDMp^{2}	LC	LC (br)
Water Pipit *Anthus spinoletta*	G	G	A	A	Amber	WR	EN	EN D (n-br)
Rock Pipit *Anthus petrosus*	G	G	G	G	Green		LC	LC (br)
Yellow Wagtail *Motacilla flava*	G	A	R	R	Red	BDp^{2}; BDMp^{1}, BDMr$^{1/2}$	NT	NT A2c+3c+4c (br)
Grey Wagtail *Motacilla cinerea*	G	A	A	R	Amber	BDMp^{2}	NT	NT A2b+3b+4b (br)
White/Pied Wagtail *Motacilla alba*	G	G	G	G	Green		LC	LC (br)
Common Chaffinch *Fringilla coelebs*	G	G	G	G	Green		EN	EN A4b (br)

Table 2. *cont.*

Brambling *Fringilla montifringilla*	A	G	G	G	Green		LC	LC (n-br)
Hawfinch *Coccothraustes coccothraustes*	A	A	R	R	Red	BDp^{1}, BDr$^{1/2}$	EN	EN A2bc+3bc+4bc+C1+2a(ii) (br)
Bullfinch *Pyrrhula pyrrhula*	R	R	A	A	Amber	BDMp^{2}	LC	LC (br)
Greenfinch *Chloris chloris*	G	G	G	G	Red	BDp$^{1/2}$	EN	EN A2b+3b+4b (br)
Twite *Linaria flavirostris*	R	R	R	R	Red	HD, BDp^{1}	EN	EN A2b+3b+4b (br)
Linnet *Linaria cannabina*	R	R	R	R	Red	BDp^{2}	LC	LC (br)
‘Redpoll’ *Acanthis flammea*[c,d]	G	A	R	R	Red	BDp^{2}	LC	LC (br)
Parrot Crossbill *Loxia pytyopsittacus*	A	A	A	A	Amber	BR	EN	EN D (br)
Scottish Crossbill *Loxia scotica*	R	R	A	A	Amber	BI	LC	LC (br)
Common Crossbill *Loxia curvirostra*	G	G	G	G	Green		LC	LC (br)
Goldfinch *Carduelis carduelis*	A	G	G	G	Green		LC	LC (br)
Siskin *Spinus spinus*	G	G	G	G	Green		LC	LC (br)
Lapland Bunting *Calcarius lapponicus*	G	G	A	A	Amber	WR	VU	VU D1 (n-br)
Snow Bunting *Plectrophenax nivalis*	A	A	A	A	Amber	BR	EN	EN D (br); LC (n-br)
Corn Bunting *Emberiza calandra*	R	R	R	R	Red	HD, BDp^{2}, BDr^{2}; BDMp^{1}, BDMr^{1}, WDMr^{1}	NT	NT A2c+3c+4c (br)
Cirl Bunting *Emberiza cirlus*	R	R	R	R	Red	BDr^{2}	LC	LC (br)
Yellowhammer *Emberiza citrinella*	G	R	R	R	Red	BDp^{2}; BDMp^{1}	LC	LC (br)
Reed Bunting *Emberiza schoeniclus*	R	R	A	A	Amber	BDMp^{2}	LC	LC (br)

[a] ***BoCC* Red-list criteria** IUCN: Globally threatened; HD: historical decline in the breeding population; BDp$^{1/2}$: severe breeding population decline over 25 years/longer term; WDp$^{1/2}$: severe non-breeding population decline over 25 years/longer term; BDr$^{1/2}$: severe breeding range decline over 25 years/longer term; WDr^{1}: severe non-breeding range decline over 25 years. ***BoCC* Amber-list criteria** ERLOB: Threatened in Europe; HDrec: historical decline – recovery; BDMp$^{1/2}$: moderate breeding population decline over 25 years/longer term; WDMp$^{1/2}$: moderate non-breeding population decline over 25 years/longer term; BDMr$^{1/2}$: moderate breeding range decline over 25 years/longer term; WDMr^{1}: moderate non-breeding range decline over 25 years; BR/WR: breeding/non-breeding rarity; BL/WL: breeding/non-breeding localisation; BI/WI: breeding/non-breeding international importance.

[b] **IUCN main criteria** A = population size reduction; B = restricted geographic range; C = small population size and decline; D = very small or restricted population. Details on subcriteria can be found at www.iucnredlist.org. ^{o} denotes that the taxa was downlisted during the regional stage of the IUCN process owing to potential rescue effects.

[c] The assessments follow HBW & BirdLife International (2020) taxonomy. The following six taxa, recognised as species by Gill *et al.* (2020) but as races by HBW & BirdLife International, were assessed at race level (with *BoCC5* and *IUCN2* assessments in parentheses): Taiga Bean Goose *Anser f. fabalis* (Red, CR); Tundra Bean Goose *A. f. rossicus* (Amber, VU); Carrion Crow *Corvus c. corone* (Green, LC); Hooded Crow *C. c. cornix* (Green, EN); Common Redpoll *Acanthis f. flammea* (Amber, EN); Lesser Redpoll *A. f. cabaret* (Red, LC).

[d] Species-level taxonomic changes since *BoCC4*/*IUCN1*.

[e] Scientific names in HBW & BirdLife International (2020) differ from those used here. The HBW & BirdLife International scientific names are as follows: Leach’s Storm-petrel *Hydrobates leucorhous*; Shag *Gulosus aristotelis*; Dotterel *Eudromias morinellus*; Black-headed Gull *Larus ridibundus*; Mediterranean Gull *L. melanocephalus*; Great Skua *Catharacta skua*; Jackdaw *Corvus monedula*; Lesser Whitethroat *Sylvia curruca*; Common Whitethroat *S. communis*; Dartford Warbler *S. undata*.

[*] Seabird assessments based on those from Eaton *et al.* (2015) and Stanbury *et al.* (2017).

Common Quail *Coturnix coturnix*, Northern Wheatear, Common Chaffinch *Fringilla coelebs* and Twite *Linaria flavirostris* move to Endangered, while breeding Ptarmigan, Tufted Duck *Aythya fuligula*, Oystercatcher *Haematopus ostralegus*, Common Kingfisher, Barn Swallow *Hirundo rustica* and non-breeding Bar-tailed Godwit *Limosa lapponica* move to Vulnerable. Conversely, breeding populations of Great Crested Grebe *Podiceps cristatus*, Woodlark *Lullula arborea* and Dartford Warbler *Curruca undata* move from Vulnerable in *IUCN1* to being of Least Concern. Further details of the IUCN assessments, along with race-level results, can be found in the SOM.

Discussion

The continued long-term decline in the status of UK bird populations

All previous *BoCC* assessments have highlighted a continuing decline in the status of UK bird populations, with an ever-growing Red list. Unfortunately, this trend continues with the results from *BoCC5*. We have now placed 70 species (28.6% of those assessed) on the Red list, and the length of the Red list has grown by three species since *BoCC4*, with 11 species moving on and six moving off to Amber. Two other species were not assessed for the Red, Amber and Green lists in *BoCC5*: Golden Oriole, a species that never had more than a toehold in the UK, has now been lost as a regular breeding species and joins the list of former breeders, while Aquatic Warbler (Red-listed in *BoCC1* to *BoCC4*) was removed in *BoCC5* owing to change in species selection criteria. Newly Red-listed species include some of our more familiar birds, such as Common Swift, House Martin and Greenfinch. Two rare breeders, Montagu's Harrier and Purple Sandpiper, are close to being lost from the UK, with just two and one breeding pair, respectively, reported in 2019 (Eaton *et al.* 2021). The length of the Amber list has also grown, by seven species. It is important to note that there were no changes in assessment criteria between *BoCC4* and *BoCC5*, and any movements between lists were as a direct result of changes in species status.

BoCC4 saw the addition of 20 species to the Red list with only three species moving off to Amber. The magnitude of the changes reported here in *BoCC5* is less, but overall more species still qualified for the Red list than ever before (fig. 3). Since *BoCC1* (25 years ago), and notwithstanding some minor changes to taxonomy and the details of some of our criteria, the number of former

The declining status of swifts and hirundines

BOX 2

Many of our aerial insectivores are in trouble. Both Common Swift and House Martin move from the Amber to Red list in *BoCC5* owing to severe population declines of 58% (1995 to 2018) and 57% (1969 to 2018) respectively. The former is IUCN Endangered, the latter Near Threatened. The causes of Common Swift decline are unclear and more robust evidence is needed, but the loss of traditional nest sites is likely to be a contributory factor. Conservation action has so far focused on protecting existing sites and providing artificial nest sites, by erecting nestboxes and promoting the installation of Swift bricks within new housing developments. Similarly, House Martins prefer to use existing nests remaining from the previous year, and house owners are encouraged to leave them in place. The causes of the House Martin decline also remain unclear, but several factors on their breeding grounds and in Africa have been suggested, including climate and land-use changes (Woodward *et al.* 2020b; Kettel *et al.* 2021). Another aerial insectivore to show recent declines is the Barn Swallow, with a 31% decrease between 2008 and 2018 (Harris *et al.* 2020). Although it does not currently exceed a *BoCC* threshold over either assessment period, the recent decline led to Barn Swallow being classified as Vulnerable to extinction within the *IUCN2* assessment. All three species spend the non-breeding season in the sub-Saharan humid and southern zones (Vickery *et al.* 2014). This is in contrast to Sand Martin *Riparia riparia*, which is currently Green-listed, winters farther north in the arid zone, and shows a 28% increase over the last 25 years (Harris *et al.* 2020).

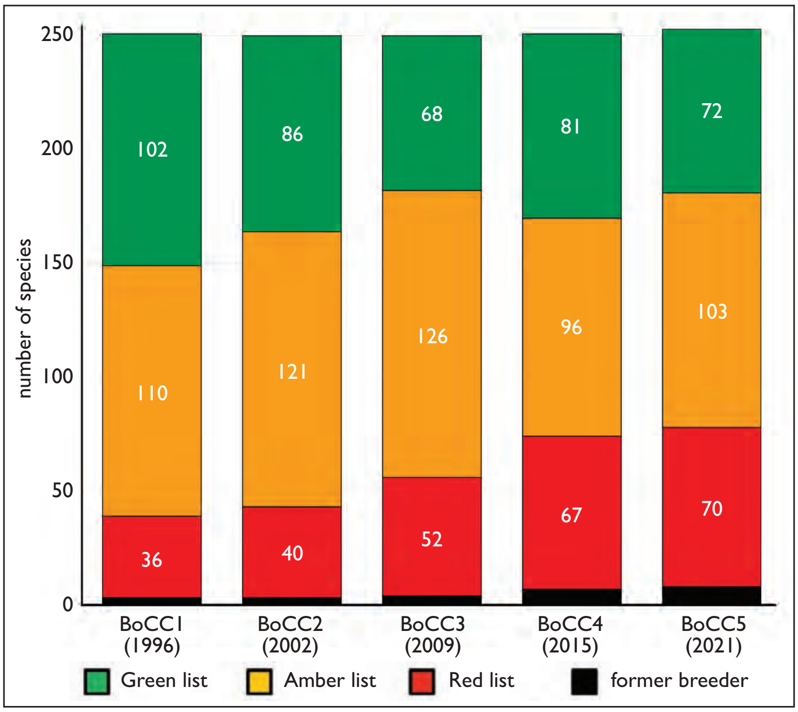


Fig. 3. Length of the Red, Amber and Green lists across all five *BoCC* reviews. Note that the assessment process has developed over time and this figure does not take account of changes to criteria, taxonomy or species joining or being omitted. Some changes in Red-, Amber- and Green-list lengths have been as a consequence of these changes. For example, the move from using the Species of European Conservation Concern (SPEC) assessments to the European Red List of Birds to determine the wider regional concern for a species in *BoCC4* resulted in a reduction in the length of the Amber list.

breeders has increased by four and the number of Red-listed species has nearly doubled (36 to 70), while the number of species on the Green list has decreased by almost a third, from 102 to 72.

Criteria affecting the length of the lists

Much of the increase in the length of the Red and Amber lists arises because more species qualify by virtue of more severe declines in their breeding population. In *BoCC5*, 77 species showed breeding-abundance declines that exceeded at least the Amber-list threshold (54 for 25-year decline and 57 for longer-term decline), up from 29 in *BoCC1* (25-year decline only).

No species qualified for the Red or Amber list through non-breeding population declines in *BoCC1* but 23 species, primarily wildfowl and waders, exceeded at least the Amber list threshold in this review. The publication of the most recent atlas (Balmer *et al.* 2013) saw the number of species qualifying for the breeding range criteria (BDr$^{1/2}$/BDMr$^{1/2}$) more than double, from 21 in *BoCC1* to 46 in *BoCC4* (these data remained unchanged in *BoCC5*). The number of species qualifying for the Historical Decline (HD), localisation (BL/WL) and international importance (BI/WI) criteria shows a small reduction over time, with eight, 38 and 34 species qualifying in *BoCC5*, respectively.

There has been a worrying trend towards more of the UK's regularly occurring species being classed as threatened with global extinction by the IUCN (www.iucnredlist.org); with the addition of Leach's Storm-petrel and Kittiwake *Rissa tridactyla*, there are now nine.

Existing and emerging themes

Previous *BoCC* reviews have highlighted the plight of bird communities breeding in farmland, the uplands and woodland. In *BoCC5*, we found no improvement in the overall status of the first two of these groupings (as defined by Gibbons *et al.* 1993 and Eaton *et al.* 2015); indeed, more species have been Red-listed. Since *BoCC4*, the number of Red-listed farmland species increased from 12 to 14, with the addition of Montagu's Harrier and Greenfinch, while Common Whitethroat moved from Green to Amber. It is a similar story among species associated with uplands, where the number of Red-listed species increased from 12 to 14, with the addition of Ptarmigan (see also box 1), Purple Sandpiper and Dunlin, while Grey Wagtail showed a positive move back to Amber. Furthermore, Northern Wheatear and Red-breasted Merganser moved from Green to Amber. Note, however, that both Dunlin and Red-breasted Merganser moved lists owing to declines in non-breeding population; we do not have robust breeding

David Tipling

463. Greenfinch *Chloris chloris*, Norfolk, November 2008. In *BoCC5*, the Greenfinch has moved directly from the Green to the Red list due to a dramatic population crash caused by a severe outbreak of trichomonosis. As of 2019, the decline shows no sign of abating.

Afro-Palearctic long-distance migrants

BOX 3

The populations of many species of long-distance, European-breeding Afro-Palearctic migrants are in sharp decline. Potential causes are diverse and occur across widely separated breeding, migration and wintering sites. Degradation of breeding habitat as well as the interactions between habitat degradation and climatic factors in their non-breeding areas, such as Sahel zone droughts, are believed to be key factors (Vickery *et al.* 2014).

The worrying plight of our Afro-Palearctic migrants in the UK was raised in *BoCC3* when Common Cuckoo, Whimbrel *Numenius phaeopus*, Golden Oriole, Wood Warbler *Phylloscopus sibilatrix* and Tree Pipit *Anthus trivialis* were all added to the Red list. These were joined by Common Nightingale *Luscinia megarhynchos*, Pied Flycatcher and Whinchat *Saxicola rubetra* in *BoCC4*. The status of these long-distance migrants continues to decline, with Common Swift and House Martin moving to the Red list, and Sedge Warbler, Common Whitethroat and Northern Wheatear going from the Green to Amber list in this review. Hewson & Noble (2009) were the first to note differing trends between those that spend the non-breeding season in the arid northern zone and those that spend it in the humid southern areas. Although the status of the arid-zone species continues to decline (fig. 4a), it is the species that winter farther south that are of higher conservation concern (fig. 4b). Only Pied Flycatcher shows a positive move from the Red list back to Amber, but the trend for this species remains close to the Red-list threshold. Wryneck *Jynx torquilla* and Golden Oriole joined the list of former breeders in *BoCC4* and *BoCC5* respectively.

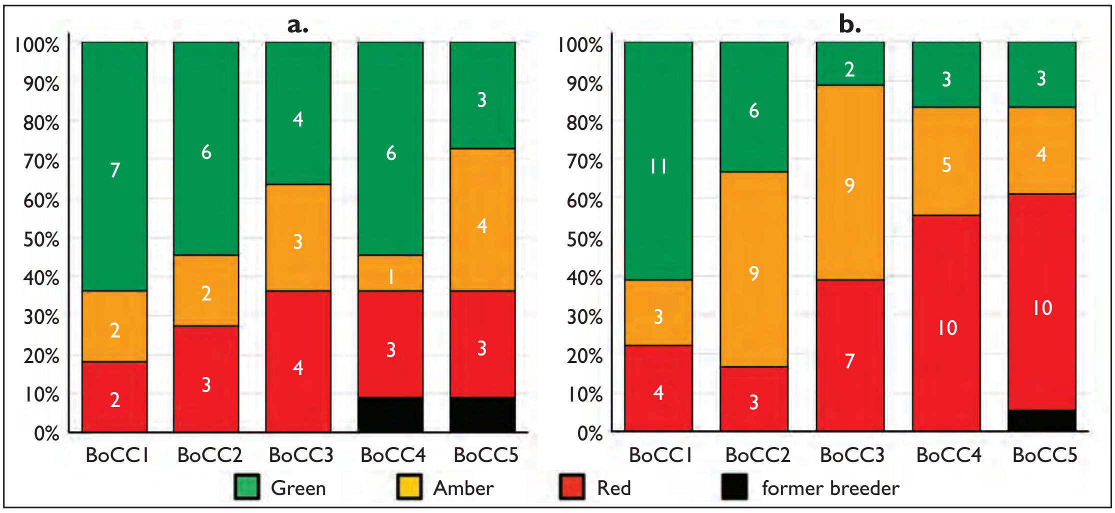


Fig. 4. The changing status between *BoCC1* and *BoCC5* of long-distance Afro-Palearctic migrants that spend the non-breeding season in the (a) arid zone (11 species) and (b) humid and southern zone (18 species). Species groups and wintering zones defined by Vickery *et al.* (2014).

Wintering waterbirds in decline

BOX 4

In this *BoCC* review, we highlight the declining status of non-breeding waterbird populations. The UK holds internationally important assemblages of wintering wildfowl and waders, as demonstrated by 20 species meeting our Amber-list non-breeding international importance criterion. No wintering trends exceeded Red-list thresholds in *BoCC1* and *BoCC2* (fig. 5), but this has changed. *BoCC3* and *BoCC4* highlighted the plight of White-fronted Goose *Anser albifrons*, Greater Scaup *Aythya marila*, Common Pochard *A. ferina* and Ringed Plover *Charadrius hiaticula*. A further four species have now joined the Red list owing to declines in non-breeding populations: Bewick's Swan, Common Goldeneye, Dunlin and Smew, while Red-breasted Merganser moved from Green to Amber. Pressures are wide-ranging, from threats on migration, illegal hunting, ingestion of lead ammunition to the impacts of climate change. Assessing drivers is further complicated by the fact that many wintering waterbird populations in the UK have been affected by 'short-stopping', whereby species have shifted their wintering grounds northeastwards in response to increased temperatures.

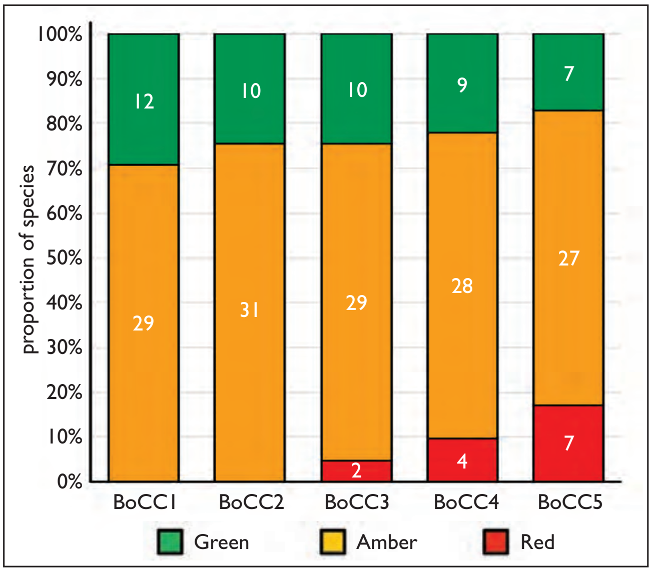


Fig. 5. The changing status of the 41 species within the UK wintering waterbird indicator (JNCC 2020). Number of species qualifying for the Red, Amber and Green list for either international status (IUCN, ERLOB) or criteria relating to non-breeding populations in the UK (WDP, WDMP, WDR, WDMR, WR, WL, WI). Within the IUCN assessment, 49% of these waterbird populations were classed as threatened. Note, Smew joined the Red list in *BoCC5* but is not included within the indicator.

trends for either species.

It is a mixed picture in woodlands. Three species – Pied Flycatcher, Song Thrush and Redwing – moved off the Red list to Amber; but we have lost Golden Oriole as a regular breeder and Eurasian Sparrowhawk moved from Green to Amber. It is also worth noting that some of the movements between lists documented in this review have been due to small variations in trend, rather than species showing dramatic changes in fortune. For example, Song Thrush and Pied Flycatcher, which moved from Red to Amber owing to trends of -49.9% and -43.4% respectively, remain (very) close to the -50% Red-list threshold.

The plight of Afro-Palearctic migrants was first highlighted in *BoCC3*, with further declines noted in *BoCC4* (see also box 3; fig. 4). The *BoCC5* review has identified continued declines in the status of this group, with two migrant aerial insectivores joining the Red list – Common Swift and House Martin – and others moving up to the Amber list (see also box 2). *BoCC4* highlighted declines in several wintering wildfowl and wader species and *BoCC5* gives us little cause for new optimism (see also box 4; fig. 5).

We need to wait for results of the current census to robustly assess the status of our seabird populations; however, Leach's Storm-petrel moved from Amber to Red based on the change in its global status – now globally Vulnerable – and the dramatic declines noted by recent surveys on St Kilda (Deakin *et al.* in press).

It is important to recognise and celebrate the few positive stories to come out of *BoCC5*. Following extensive conservation action, White-tailed Eagle has now moved from Red

White-tailed Eagle reintroduction

BOX 5

White-tailed Eagle moves from the Red to Amber list in *BoCC5*, as the species no longer qualifies for the Historical Decline criterion and is now classed as HD recovering. Its population remains small, however, and it is considered to be IUCN Endangered. The species' reintroduction into Scotland is a conservation success story. After the failure of two early attempts in 1959 and 1968, the release of 82 birds on Rum between 1975 and 1985, 58 birds in northwest Scotland between 1993 and 1998 and 86 birds in east Scotland from 2007 to 2012 brought a change in fortune, with successful breeding in Scotland recommencing in 1985. By 2002, a total of 25 territories were known, increasing to 52 in 2010, 100 in 2015, and 123 in 2019. The White-tailed Eagle's range has also expanded to the extent that birds are now breeding as far north as Orkney, south to southern Argyll and eastwards into much of eastern Scotland north of the Central Belt. The population has now reached a level at which monitoring is becoming increasingly challenging, and it is estimated that about ten new territories are being established annually, though this may be an under-estimate. A reintroduction project has now started in England in the Isle of Wight.

to Amber, as the species no longer qualifies for the Historical Decline criterion. In addition, the ongoing increase in the Marsh Harrier *Circus aeruginosus* population means that this species is now considered to have fully recovered from its historical decline, although it still qualifies for the Amber list through being a localised breeder. Other species that have increased sufficiently to move off the Red list are two rare breeders, Black Redstart and Redwing. These changes are as a direct consequence of recent population increases.

The UK has seen continued colonisation, particularly by waterbirds, and we added five new species to this review: breeding Great White Egret, Cattle Egret, Little Bittern and Black-winged Stilt, and non-breeding Yellow-browed Warbler. While we welcome these additions to our avifauna, we should simultaneously recognise that the arrival of new species here owes much to man-induced climate change, which may have an adverse effect elsewhere in their ranges.

The updated assessment of extinction risk in Great Britain

The benefit of undertaking the internationally recognised standardised IUCN Regional Red List process, in addition to *BoCC*, is that we can compare the status of our bird populations with other geographical areas as well as with other taxonomic groups in Great Britain, plus it allows birds to be incorporated into multi-taxa assessments and higher-level biodiversity indicators. *IUCN2* found that 46% of regularly occurring species and 43% of populations were assessed as being threatened with extinction from Great Britain. This is high compared with the equivalent figure for birds in Europe (13%, BirdLife International 2021) and most other taxonomic groups in Great Britain. The State of Nature report (Hayhow *et al.* 2019) showed that 15% of 8,431 species across 11 taxonomic groups in Great Britain were classified as threatened. Other groups showing relatively high proportions of threatened species are terrestrial mammals (26%, Mathews & Harrower 2020), vascular plants (22%, Cheffings & Farrell 2005) and butterflies (33%, Fox *et al.* 2010).

As noted by Stanbury *et al.* (2017), we believe there are good reasons why the proportion of threatened populations in birds in Great Britain is high. First, the risk of extinction tends to increase as the geographical area considered becomes smaller. Secondly, there are fundamental biological differences between taxonomic groups which have relevance to the IUCN criteria. Even scarce invertebrates or plants can still have populations in the thousands of individuals, and thus do not approach the IUCN's qualifying thresholds for small population size. Thirdly, data availability for birds far exceeds that of many other taxonomic groups thanks to the effort of volunteers, so species can be tested robustly against more criteria. We believe that, if similar data were available for other, similar-sized areas and for other taxonomic groups, levels of assessed extinction risk would be considerably higher than is estimated currently. Therefore, although the IUCN Red-listing process is scalable between regions and taxa, it is not perfect, and, on this basis, it is fair to assume there are limits to our ability to make comparisons.

There is much commonality between the results of *IUCN2* and *BoCC5* (table 3). Of the 108 species to have a population qualifying as threatened (CR, EN, VU) through the IUCN process, all but seven are on the *BoCC* Red or Amber lists (50 on the Red list, 51 on the Amber list). Since the IUCN Regional Red List process focuses on extinction risk, assessments tend to identify species with extremely low numbers, restricted ranges and/or rapid recent declines; justifiably so, since these are the species most likely to become extinct. Similar criteria exist in the *BoCC* process, albeit with different thresholds and over different time periods. Of the seven exceptions (IUCN threatened species on the Green list), one qualified for criterion D (very small population size), one for criterion C (small population and decline) and five by virtue of criterion A4 (a projected future decline). The last highlights an important difference between the two processes: *BoCC* focuses on the current and past status, while IUCN focuses on current and likely future trends (for species where reliable data indicate that a trend is likely to continue), providing an early warning signal of trouble ahead. Both Common Chaffinch and Barn Swallow qualified under criterion A4, show recent changes in fortune (Woodward *et al.* 2020b) and may be worthy of additional conservation attention.

Unlike *BoCC*, the IUCN process does not consider the international significance of our populations or species showing severe declines prior to the three-generation-length assessment window; therefore, there is less commonality between *IUCN2* and *BoCC5* results than the other way around. Indeed, 49 Red- and Amber-listed species are assessed as of Least Concern. Examples of *BoCC* species whose past decline is of concern, but that are not IUCN threatened (because they are not currently declining to the extent they are threatened with extinction) include Common Cuckoo *Cuculus canorus*, Corn Crake *Crex crex* and Skylark *Alauda arvensis*, while some of our internationally significant (and hence *BoCC*-listed) seabird populations are not threatened with extinction.

Data gaps

We are extremely fortunate in the UK to have a large number of dedicated volunteers contributing data towards established biodiversity-monitoring schemes, such as BBS and WeBS. Without these data, our prioritisation and status assessments would not be possible. Notwithstanding the existence of these rich datasets, gaps in our knowledge do exist. Eaton *et al.* (2015) documented these in detail and many remain relevant: for example, we lacked robust trends for 20 breeding species including Short-eared Owl *Asio flammeus* and Scottish Crossbill *Loxia scotica*. The publication of results from the current seabird census will make a major contribution to our understanding of the status of this group and fill a large knowledge gap. It is the case though that, owing to less species/group-specific monitoring being undertaken (because of lower investment), we are increasingly reliant on ageing information. For example, the last national breeding survey of European Nightjar *Caprimulgus europaeus* was in 2004, of Red-

Table 3. Matrix showing the commonalities and differences between the *BoCC5* and *IUCN2* results. It excludes former breeding, Regionally Extinct and Extinct species. IUCN threat status categories: Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC), Data Deficient (DD), Not Evaluated (NE). The highest threat status has been used when two different seasons were assessed for the same species.

		IUCN2 assessment							
		CR	EN	VU	NT	LC	DD	NE	Total
BoCC5 assessment	**Red**	16	19	15	9	11	0	0	70
	Amber	5	21	25	9	39	1	3	103
	Green	0	1	6	8	49	1	7	72
	Total	21	41	46	26	99	2	10	245

throated *Gavia stellata* and Black-throated Divers *G. arctica* in 2006, Ringed and Little Ringed Plovers *Charadrius dubius* in 2007, and Merlin *Falco columbarius* in 2008, while the most recent Winter Gull Roost Survey (WinGS) was undertaken during the winters of 2003/04 and 2005/06. We recommend that increased resources are made available to ensure timely monitoring of these and other species that may otherwise not receive the conservation attention they deserve.

Conclusion

The *BoCC* and IUCN processes provide a robust framework for targeting conservation actions for birds. Both allow us to track the effectiveness of our interventions for birds and the IUCN assessments offer the prospect of including birds in high-level, cross-taxa Red List-type biodiversity indicators which can help us measure overall conservation effectiveness and thus progress towards national and global targets to halt and reverse biodiversity loss.

These latest reviews, *BoCC5* and *IUCN2*, add to the already extensive weight of evidence that many of our bird populations are in trouble. Our findings reinforce previous reviews and are supported elsewhere. For example, the UK Government's own Biodiversity Indicators show long-term declines in farmland birds and more recent declines in wintering waterbirds (JNCC 2020). We highlight new species that should now be considered of high conservation concern, such as Leach's Storm-petrel, Common Swift, House Martin and Greenfinch, but we must not forget the 59 species already on the Red list. With nearly 30% of UK species now Red-listed, further prioritisation may be necessary unless nature conservation action becomes bolder, takes place over a greater scale and is much better resourced. Whilst the need for conservation action is obvious if we are to address the current biodiversity crisis, it is vital that we continue to monitor our bird populations and to make regular, periodic updates to our *BoCC* and IUCN assessments – we recommend a continuation of the six-year interval – so that we can measure progress towards relevant biodiversity targets and refresh our priorities.

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Andrew J. Stanbury, RSPB Centre for Conservation Science, The Lodge, Sandy, Bedfordshire SG19 2DL; e-mail andrew.stanbury@rspb.org.uk

Mark A. Eaton, 21 Chapel Lands, Alnwick, Northumberland NE66 1EL

Nicholas J. Aebischer, Game & Wildlife Conservation Trust, Fordingbridge, Hampshire SP6 1EF

Dawn Balmer and David G. Noble, BTO, The Nunnery, Thetford, Norfolk IP24 2PU

Andy Brown, Natural England, Unex House, Peterborough PE1 1NG

Andy Douse, NatureScot, Great Glen House, Leachkin Road, Inverness IV3 8NW

Patrick Lindley, Natural Resources Wales, Maes y Ffynnon, Penrhosgarnedd, Bangor LL57 2DW

Neil McCulloch, Northern Ireland Environment Agency, Cromac Avenue, Gasworks Business Park, Lower Ormeau Road, Belfast BT7 2JA

Ilka Win, JNCC, Inverdee House, Baxter Street, Aberdeen AB11 9QA

CHAPTER 3

BELGIAN SEABIRD DISPLACEMENT MONITORING PROGRAM

MACRO-AVOIDANCE OF GPS-TAGGED LESSER BLACK-BACKED GULLS & POTENTIAL HABITUATION OF AUKS AND GANNETS

VANERMEN Nicolas *, COURTENS Wouter, VAN DE WALLE Marc,
VERSTRAETE Hilbran & STIENEN Eric

Research Institute for Nature and Forest, Havenlaan 88, bus 73, 1000 Brussels, Belgium.

*Corresponding author: nicolas.vanermen@inbo.be

Abstract

This study illustrates macro-avoidance by GPS-tagged lesser black-backed gulls at the Norther wind farm, by comparing the presence of tagged birds before and after construction and comparing the observed trend with the trend in two nearby control areas. The results mirror those obtained at the Thornton Bank wind farm just north of the study site (Vanermen *et al*. 2019a). Collision risk models should thus always take into account post-construction avoidance to reliably estimate the number of expected collision fatalities in lesser black-backed gull, a species highlighted to potentially suffer population impact following current wind farm development plans in the North Sea. The second part of this chapter reports the results of the first two-day monitoring survey of the full Belgian wind farm concession zone, performed in February 2021. Though much too soon to draw any conclusions, the findings are quite remarkable as we encountered good numbers of northern gannet *Morus bassanus*, common guillemot *Uria aalge* and razorbill *Alca torda* inside the concession zone, all species generally perceived to actively avoid offshore wind farms across European waters (Vanermen & Stienen 2019). Coming surveys should tell whether these first results were anecdotic, or alternatively fit into a trend of actual habituation of seabirds to the presence of offshore wind farms.

1. Introduction

In this chapter we will elaborate on the progress of two (sub)studies following the feasibility study (Vanermen *et al*. 2020) on targeted monitoring of seabirds at offshore wind farms (OWFs) in the Belgian Part of the North Sea (BPNS). One of the proposals was to take advantage of the momentum of the construction of the Norther wind farm in 2018–2019, coinciding with the availability of GPS data of lesser black-backed gulls *Larus fuscus*, tagged in the nearby colonies of Ostend, Zeebrugge and Vlissingen in the period 2013–2020 (Stienen *et al*. 2016). As such we have data on the habitat use of the wind farm area from before the wind farm construction up to one year after installation, allowing to perform a BACI analysis (§2).

Secondly, Vanermen *et al.* (2020) proposed a new strategy for the monitoring of OWF-induced seabird displacement. This strategy includes a full coverage of the entire concession zone alongside a wide reference area, thus stepping away from the earlier adopted farm-by-farm approach. The intense coverage of the study area will allow state of the art spatial analyses once enough data are collected. As such we aim to gain insight in the effect of turbine density on seabird displacement rates and the use of corridors between individual farms for local or migration movements. In February 2021 we sailed the proposed two-day monitoring route for the first time and in §3 we discuss the numbers and distribution of six key seabird species encountered during this trip.

2. Lesser black-backed gull presence in the Norther wind farm: a BACI analysis of GPS data

2.1. Methods

2.1.1. BACI set-up

The recent installation of the Norther wind farm in the most south-east part of the Belgian wind farm concession zone offered the opportunity to compare the distribution of tracked lesser black-backed gulls in and around this particular OWF site before, during and after construction of the turbines by applying a classic BACI set-up. To this end, one impact and two equally-sized control areas were delineated as illustrated in Fig. 1.

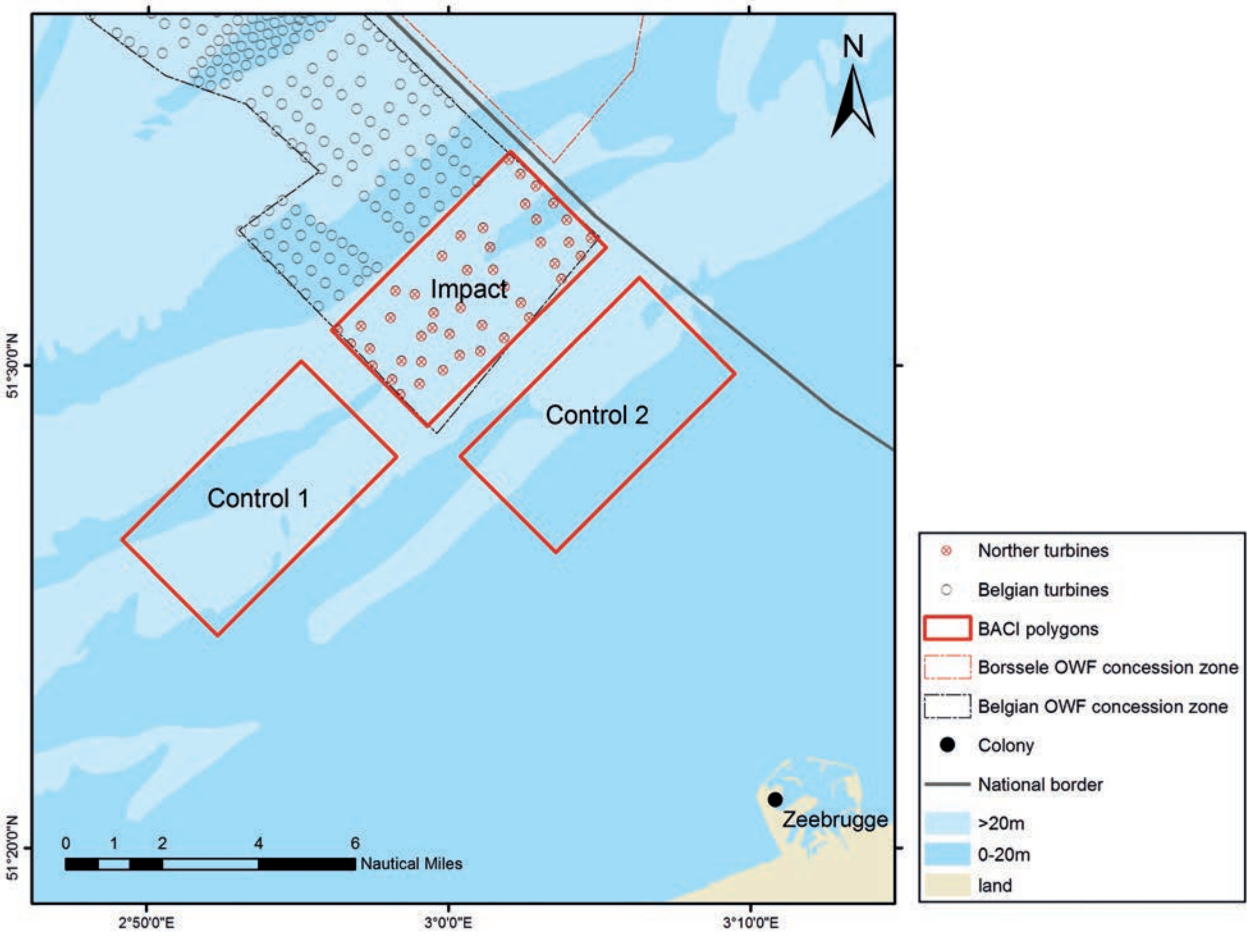

Figure 1. BACI setup to study the impact of the construction of the Norther OWF on the habitat use of lesser black-backed gulls.

Based on the project timeline (https://www.norther.be/#timings), we defined the different periods for application in the BACI analysis as follows:

- Pre-construction period: 01/01/2017 – 30/06/2018
- Construction period: 01/07/2018 – 31/08/2019
- Impact period: 01/09/2019 – present

2.1.2. GPS data

Between 2013 and 2020, 156 lesser black-backed gulls breeding in Zeebrugge (n = 83), Ostend (n = 6) and Vlissingen (n = 67) were equipped with a UvA-BiTS tracker generating three-dimensional GPS fixes (Bouten *et al*. 2013, Stienen *et al*. 2016). The deployment of the trackers was authorized by the ethical committee for animal experiments (license number CDE2013–73) and conducted in accordance with Flemish and Belgian legislation. To fit the GPS trackers, all individuals were caught on their nests during incubation using walk-in traps or clap nets. Trackers were attached using a wing harness of Teflon ribbon threaded with a nylon string (Stienen *et al*. 2016). The collected data were remotely transmitted to a base station located inside each colony. Tagging effort strongly decreased after 2018, with only 6 more birds tagged in 2019 and 2020 (Fig. 2). Since the trackers generate data for an average period of about one year and a half (due to loss of the tracker, tracker malfunctioning or birds moving to other colonies), this implies an overall decrease in the number of records in the study area over time.

In the raw database, the sampling rate of GPS fixes varied strongly from 10 to 3600 seconds resulting from the different needs and priorities of the data end-users. In order to obtain an unbiased dataset and meanwhile avoid temporal correlation between records (Ross-Smith *et al*. 2016; Shamoun-Baranes *et al*. 2017), data were subsampled to a minimum frequency of 1100 seconds, after which tracks with a frequency of more than 1500 seconds were omitted as well. This way the sampling frequency of the resulting dataset is in line with the principal frequency of 20 minutes (Fig. 3).

2.1.3. Model

We estimated the effect of the installation of the Norther OWF on the area use of lesser black-backed gull by modelling the number of GPS records in the study area (Fig. 1). The response variable in our model was the number

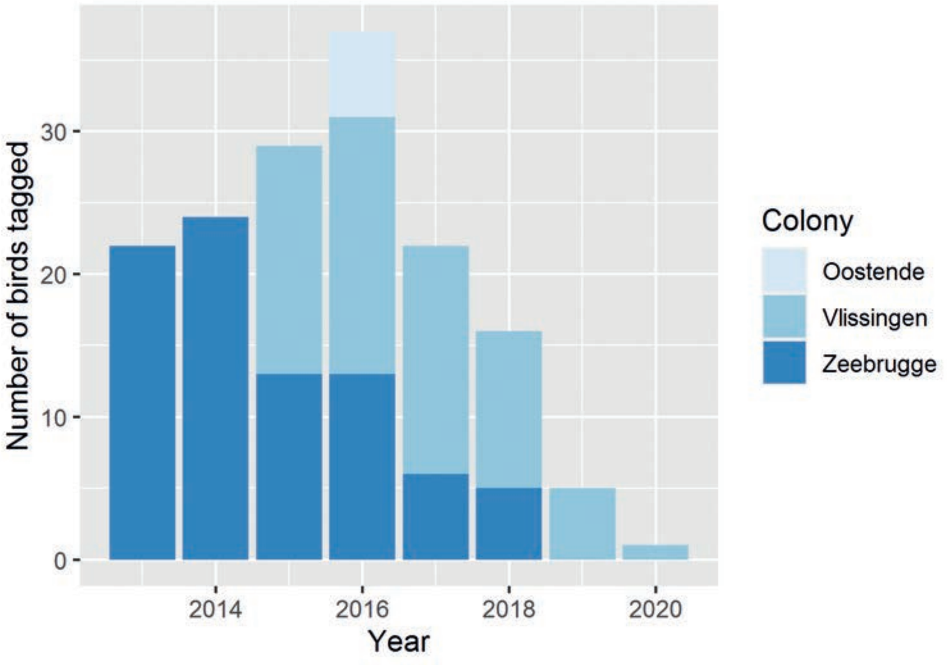

Figure 2. Tagging effort of lesser black-backed gulls per year and per colony.

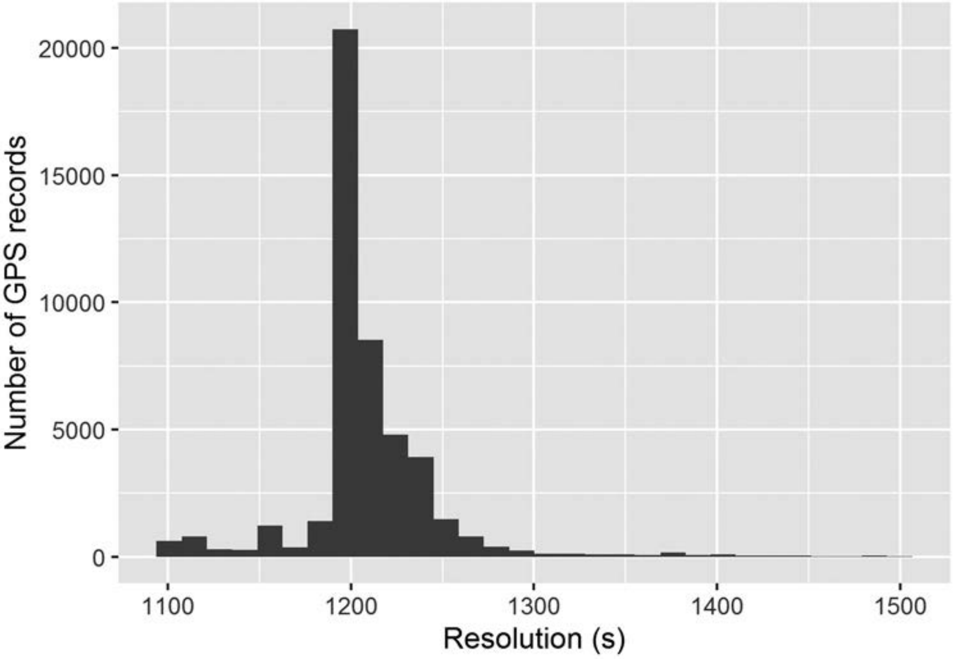

Figure 3. Sampling frequency of the GPS records after subsampling.

of records per day per area, and as covariates we chose month, area (impact area and two reference areas) and period (pre-construction, construction and post-construction), allowing interaction between the two latter. We only considered days between the 1st of March and the 31st of August, as the species is largely absent outside this period. With 306, 246 and 184 days of sampling, respectively in the pre-construction, construction and impact period, and three areas considered, the database holds 2208 unique day-area combinations. The estimated coefficients of the interaction between the impact area factor level on the one hand and the construction / impact period levels on the other hand are thus a measure of the (indirect) effect of the OWF construction / presence. We tested 4 distributions, *i.e.* Poisson, negative binomial, zero-inflated Poisson and zero-inflated negative binomial, and chose the best fitting distribution based on the resulting AIC value (Akaike 1974).

2.2. Results

2.2.1. Maps

Though difficult to interpret visually due to an overall decreasing number of records over time, related to the decreased tagging effort after 2016 (Fig. 2), Figs 4 to 6 illustrate a clear change in the spatial distribution of lesser black-backed gull presence following the construction of the Norther OWF. The northern part of the wind farm in particular seems to be largely avoided by the gulls during the operational impact period (Fig. 6).

2.2.2. Model results

The best model fit was obtained through a negative binomial distribution based on the corresponding AIC, and the model summary is shown in Table 1. The factors ‘periodConstruction’ and ‘periodAfter’ were significantly (and progressively) negative, which reflects the overall decrease in the number of tagged birds since 2016 (see Fig. 2). The factor ‘areaControl2’ was significantly positive, implying a consistently higher number of records inside Control area 2 compared to Control area 1. Importantly, the interactions ‘periodAfter:areaControl2’ and ‘periodConstruction:areaControl2’ were not significant, in line with the assumption that the trend in the number of records in Control area 2 should not be any different from that in Control area 1.

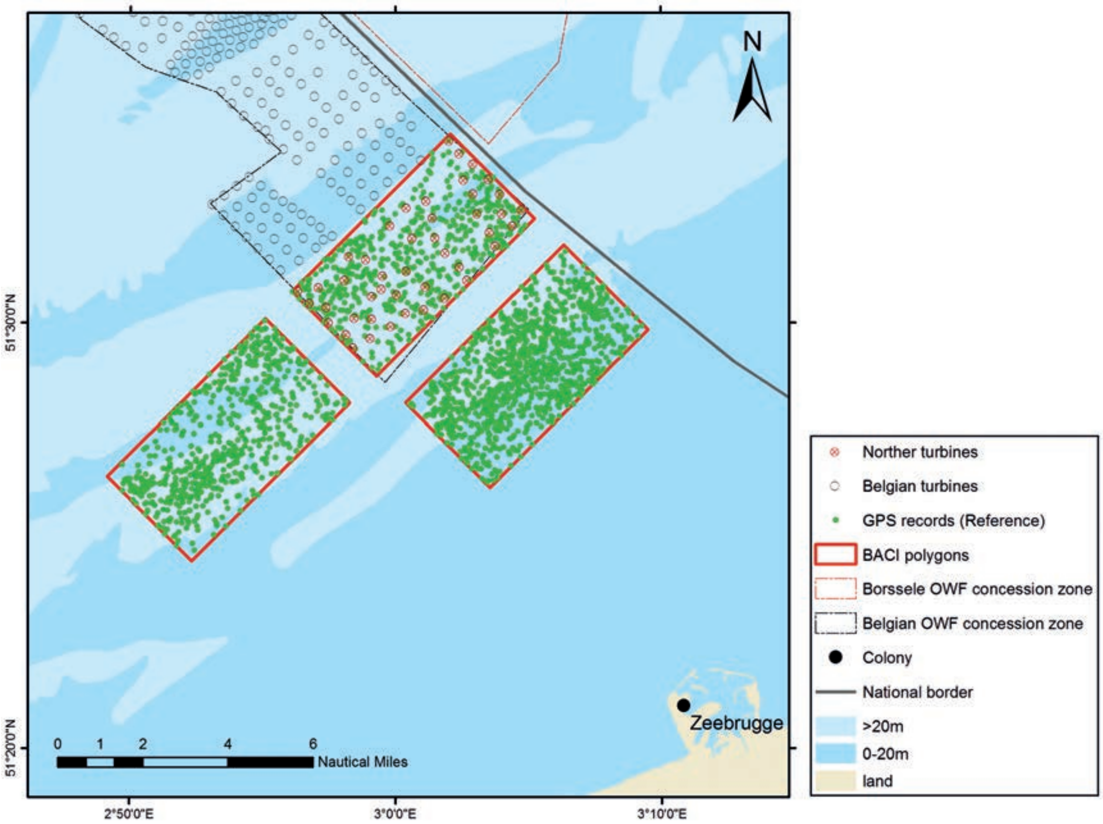

Figure 4. GPS records inside the BACI polygons during the pre-construction period (01/01/2017 – 30/06/2018; N = 2174).

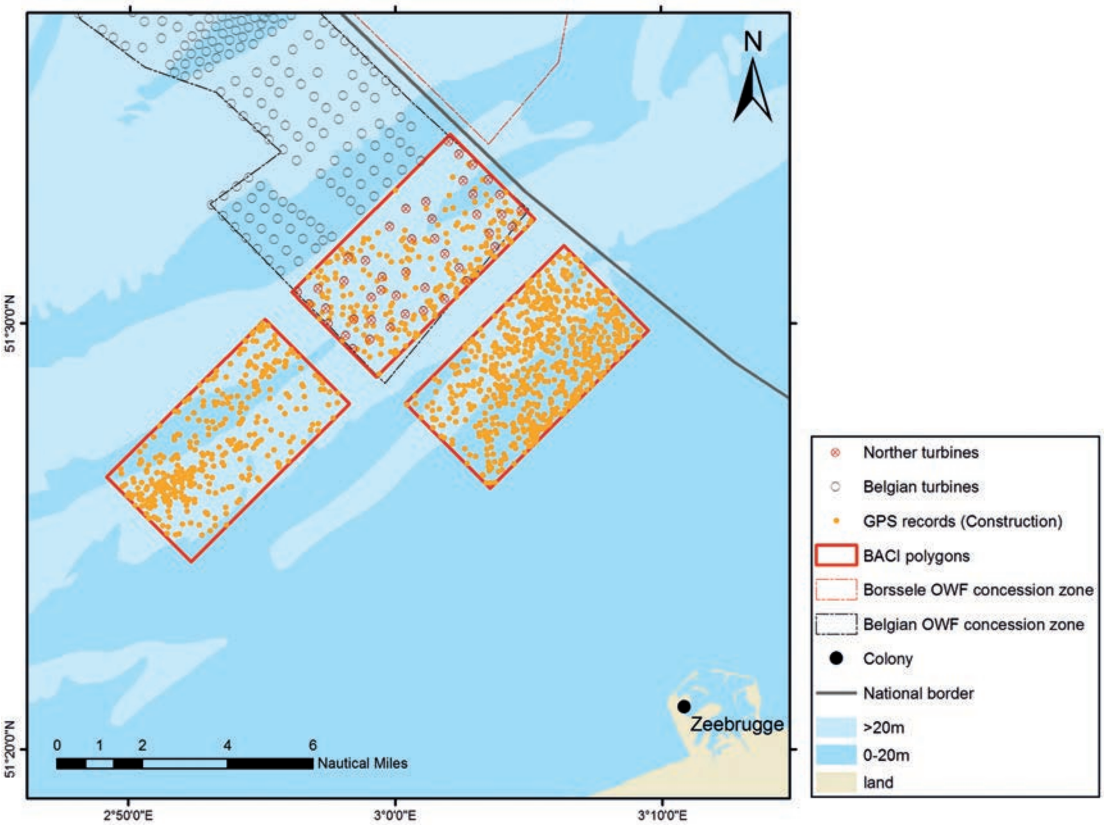

Figure 5. GPS records inside the BACI polygons during the construction period (01/07/2018 – 31/08/2019; N = 1274).

Table 1. BACI model summary results (P < 0.1., P < 0.05*, P < 0.01**, P < 0.001***; the coefficient of the estimated wind farm impact is indicated in red).

	Estimate	Std. Error	Z-value	P-value
(Intercept)	-0.156	0.180	-0.866	0.387
as.factor(month)4	1.078	0.183	5.886	0.000***
as.factor(month)5	1.059	0.182	5.824	0.000***
as.factor(month)6	0.812	0.184	4.402	0.000***
as.factor(month)7	1.278	0.184	6.930	0.000***
as.factor(month)8	0.398	0.190	2.097	0.036*
periodConstruction	-0.375	0.207	-1.814	0.070.
periodAfter	-0.943	0.231	-4.086	0.000***
areaControl2	0.524	0.188	2.784	0.005**
areaImpact	0.010	0.190	0.053	0.958
periodConstruction:areaControl2	0.109	0.284	0.383	0.701
periodAfter:areaControl2	-0.178	0.321	-0.554	0.579
periodConstruction:areaImpact	-0.363	0.291	-1.250	0.211
periodAfter:areaImpact	-1.252	0.352	-3.553	0.000***

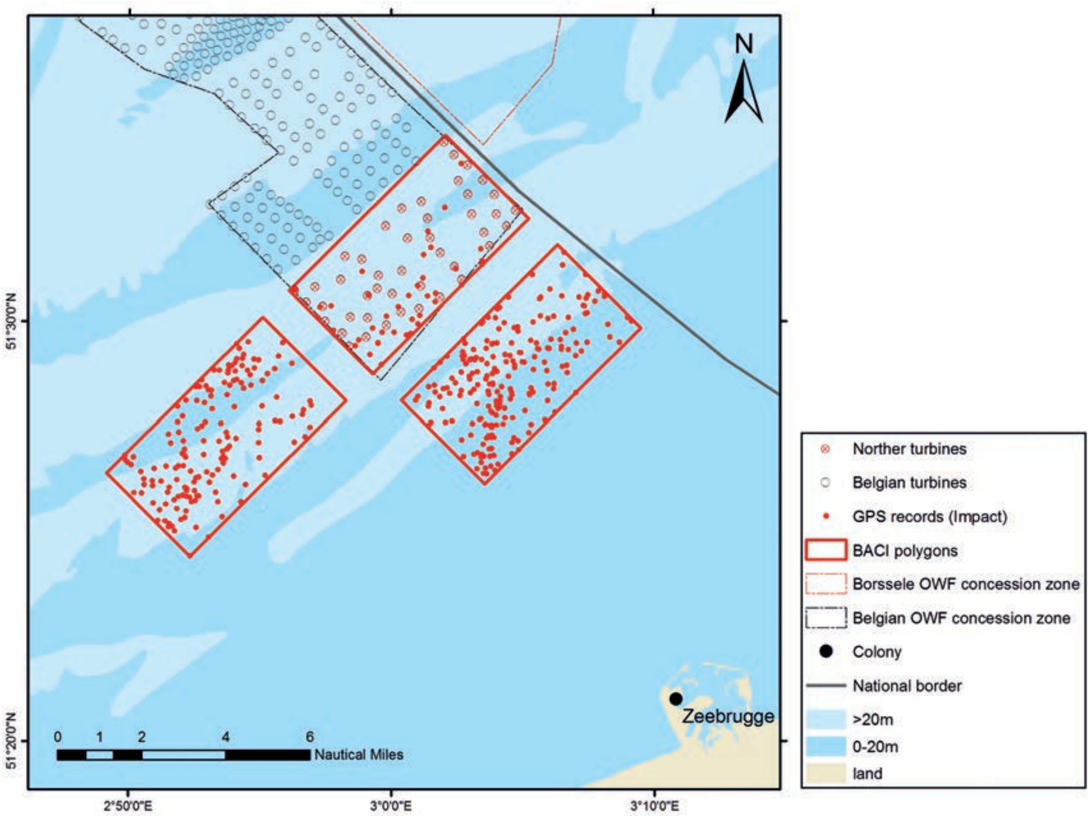

Figure 6. GPS records inside the BACI polygons during the impact period (01/09/2019 – present; N = 412).

Lastly, though negative, the interaction between 'periodConstruction' and 'areaImpact' was not significant, implying that the construction activities did not affect the distribution of tagged lesser black-backed gulls to a statistically discernible extent. The interaction between 'periodAfter' and 'areaImpact' on the other hand was significant, confirming our earlier visual interpretation of Figs 4 to 6 and the effect of the presence of the Norther turbines on the distribution of lesser black-backed gulls in the study area. The coefficient of -1.252 stands for a decrease in lesser black-backed gull occurrence by 71% compared to the pre-construction period and taking account of the trend in the control areas.

2.3. Discussion BACI analysis GPS data

For the Thornton Bank wind farm, Vanermen *et al*. (2019a) already showed how lesser black-backed gulls avoided the wind farm interior, but were attracted to the outer edge turbines for roosting. This study again illustrates the general avoidance of OWFs by tagged lesser black-backed gulls, at yet another location just south-east of the earlier mentioned Thornton Bank. Interestingly, the results obtained through GPS studies counter earlier reported results from designated ship-based surveys, pointing towards attraction of lesser black-backed gulls to the Bligh Bank OWF (Vanermen *et al*. 2019b). Part of the explanation could be that the Bligh Bank is located outside the foraging range of the (adult) birds breeding in the study colonies, and that the perceived attraction effect thus involves birds on migration, immature birds and/or birds with another provenance.

As tagging effort in the colonies of Zeebrugge, Ostend and Vlissingen has decreased over the last few years, a general decrease in the number of GPS records has occurred in the study area. Though easily accounted for by the model, it would be interesting to be able to include more post-construction records to build an even stronger case. In this respect, about ten more birds will be tagged in Zeebrugge in the breeding season of 2021. We may further opt to include GPS data from individuals tagged in the Dutch colony of Neeltje Jans, the foraging range of which is expected to overlap with the study area.

Another step forward would be the analysis of the accelerometer data, that allows to classify GPS records in behavioural categories, most interesting of which is the category 'pecking', indicating foraging behaviour. Analysing the (change in) behaviour in the impact area may give further insight in the habitat use of OWFs by lesser black-backed gulls.

As argued before, the prohibition for trawlers to fish between the turbines is likely to be at least a co-driving force behind the observed decrease in records of lesser black-backed gulls in the impact area. The offshore density of GPS records is indeed closely related to fishery activities. Within Control area 1 for example, the density of GPS records is highest both north and south of the Gootebank (Figs 4 to 6), which relates to less intense fishery activity on sandbank ridges across the BPNS (data download from https://globalfishingwatch.org/). Whether wind farm avoidance is due to a disturbance effect induced by the turbines, the absence of fisheries or a combination of both, however, is hard to assess. To stay close to the set-up of this study, one would actually need to include an additional control area from which all fishery activity can be excluded, in order to 'isolate' its particular effect. Regardless of what actually induces the wind farm avoidance, we should note that the main concern regarding lesser black-backed gulls and OWFs is still the potential population level impact due to increased (collision) mortality, rather than the impact of habitat loss. Importantly, collision risk studies often use pre-construction bird densities to feed the collision models, yet this strategy is expected to result in an overestimation of the number of expected victims by not taking account of post-construction avoidance.

3. Ship-based monitoring of seabird displacement in the Belgian OWF concession zone

3.1. Methods

Since the end of 2020, the Belgian OWF concession zone is fully operational. This new context allows seabird monitoring across the concession zone without any access restrictions due to construction works. In the feasibility study of last year (Vanermen *et al*. 2020), a new monitoring strategy was therefore outlined (Fig. 7), aiming to continue assessing species-specific displacement rates by means of ship-based counts and meanwhile looking for correlations with wind farm configuration characteristics.

Ship-based seabird counts are conducted according to a standardised and internationally applied method, combining a 'transect count' for birds in contact with the water and repeated 'snapshot counts' for flying birds (Tasker *et al*. 1984). For the 'transect count', the focus is on a 300 m wide transect along one side of the ship's track, and while steaming at a speed of about 10 knots, all birds in touch with the water (swimming, dipping, diving) within this transect are counted. The distance to each observed bird (group) is estimated, allowing to correct for decreasing detectability with increasing distance afterwards. The transect is thus divided in four distance categories (A=0-50 m; B=50-100 m; C=100-200 m; D=200-300 m). Counting all flying birds inside the transect, however, would cause an overestimation and would be a measure of bird flux rather than bird density (Tasker *et al*. 1984). The density of flying birds is therefore assessed through one-minute interval counts of birds flying within a quadrant of 300 by 300 m inside the transect (the so-called 'snapshot counts'). As the ship covers a distance of approximately 300 m per minute when sailing the prescribed speed of 10 knots, the full transect is covered by means of these subsequent 'snapshots'.

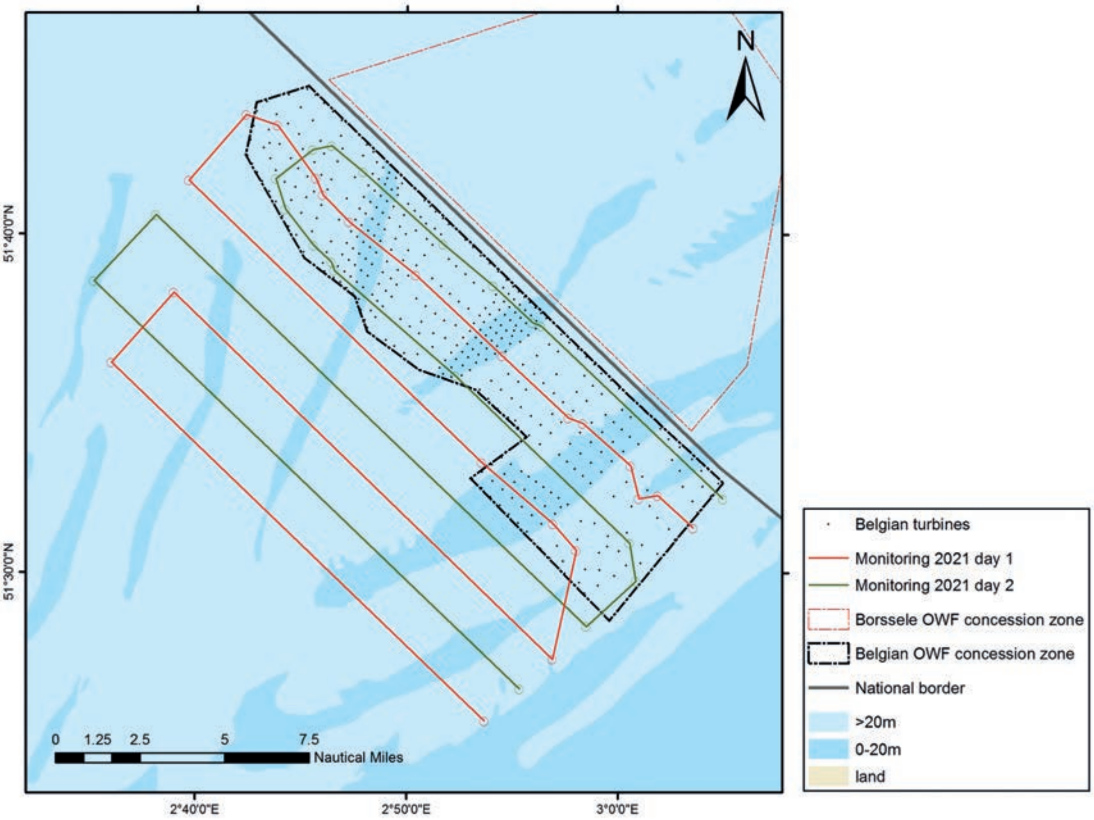

Figure 7. The new seabird displacement monitoring route, which can be covered in the course of two (preferably consecutive) days and is planned to be sailed five times per year.

3.2. Results

The newly proposed monitoring route was sailed for the first time on the 23rd and 24th of February 2021, two days with favourable conditions (wind force of at most 5 Beaufort and significant wave heights below 1 m). Below, the count results for six key seabird species will be discussed by showing distribution maps and comparing the densities encountered inside versus outside the concession zone.

3.2.1. Northern gannet

No less than 84 northern gannets (*Morus bassanus*) were observed between the turbines of the Belgian OWF concession zone (Fig. 8). Most were observed in the south-east part of the wind farm zone, coinciding with increased razorbill densities. Outside the concession zone, northern gannets were most common in the north-western part of the study area, near active fishery activity. Likely due to the latter, densities of northern gannet were eventually much higher outside compared to inside the wind farms (0.8 versus 0.3 birds / km², respectively, see Table 2).

3.2.2. Large gulls

The numbers of large gulls were generally low inside the wind farm concession zone (Figs 9 to 11), with lesser black-backed gull being the most numerous species (0.4 birds/ km²). In contrast, gull densities were particularly high in the north-western part of the study area, near active beam trawlers. Overall, lesser black-backed gull reached a density of 14.3 birds / km² outside the OWF concession zone. For herring and great black-backed gull (*Larus argentatus* and *marinus*) as well, densities were clearly higher outside compared to inside the wind farms (Table 2).

3.2.3. Auks

The south-east edge of the Thornton Bank held particularly high densities of razorbill (*Alca torda*), both in- and outside the OWF concession zone (Fig. 13). Overall, densities inside the concession zone appeared about twice as high compared to densities outside (4.59 versus 2.36 birds / km² respectively, see Table 2). Common guillemot (*Uria aalge*) occurred more homogenously spread across the study area (Fig. 12), with comparable densities inside and outside the concession zone (1.2 and 1.0 birds / km² respectively).

3.2.4. Summarising table

All species known to aggregate near fishing vessels showed clearly increased densities outside the wind farm concession zone. During our campaign, seven fishing vessels were active near our monitoring route (see Figs 8 to 11), with high numbers of associated gulls and gannets near some of them. Inside the wind farms, gulls occurred much more dispersed, while northern gannets concentrated in the south-east part of the concession zone, alongside feeding flocks of razorbill. Worth mentioning also is the relatively large number of yellow-legged gulls (*Larus michahellis*) encountered in the

Table 2. Densities (n / km²) of six key seabird species inside and outside the wind farm concession zone; bold figures indicate where the species reaches its highest density.

	Inside	**Outside**
Northern gannet	0.29	**0.80**
Lesser black-backed gull	0.43	**14.27**
Herring gull	0.10	**0.37**
Great black-backed gull	0.00	**0.11**
Common guillemot	**1.18**	1.03
Razorbill	**4.59**	2.36

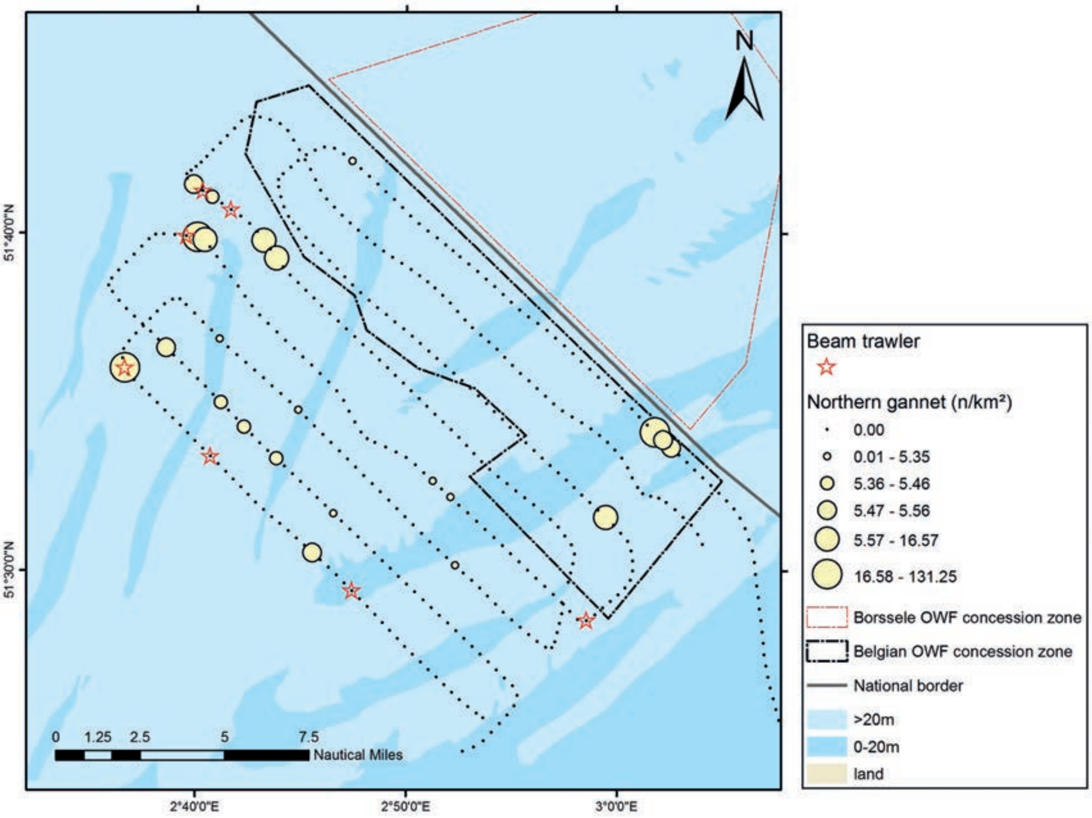

Figure 8. Northern gannet densities encountered during the two-day seabird displacement monitoring on 23 & 24/02/2021.

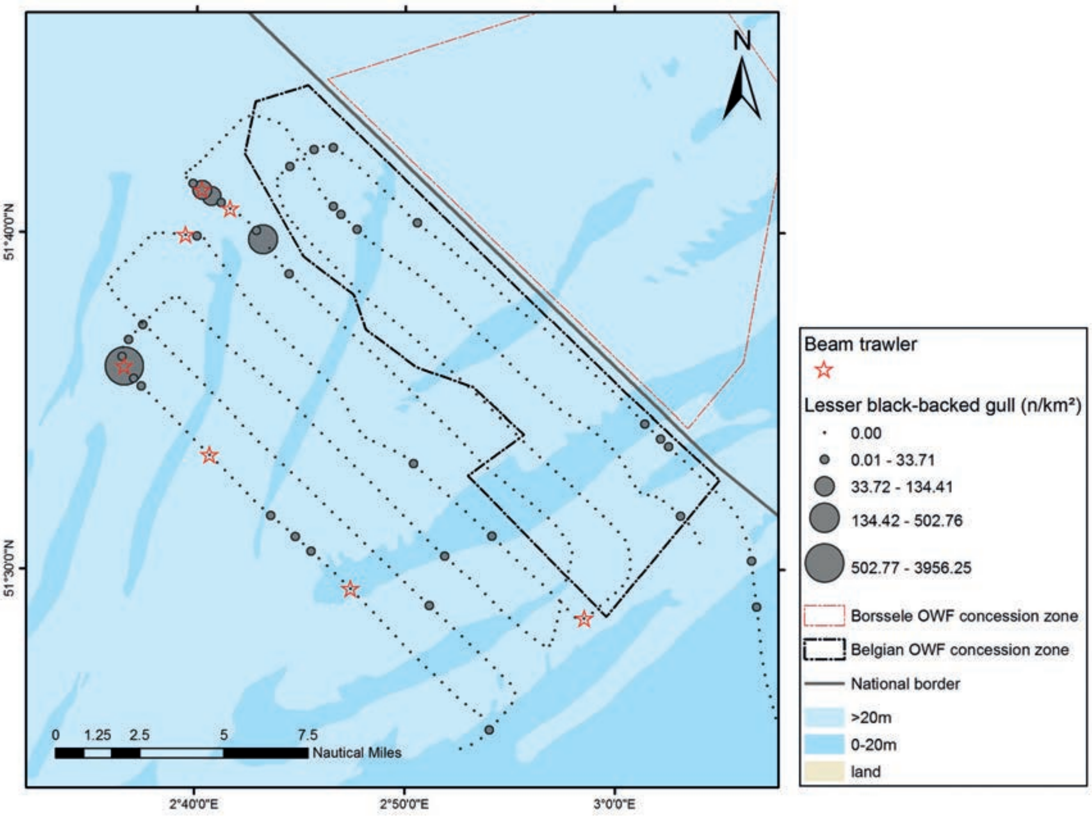

Figure 9. Lesser black-backed gull densities encountered during the two-day seabird displacement monitoring on 23 & 24/02/2021.

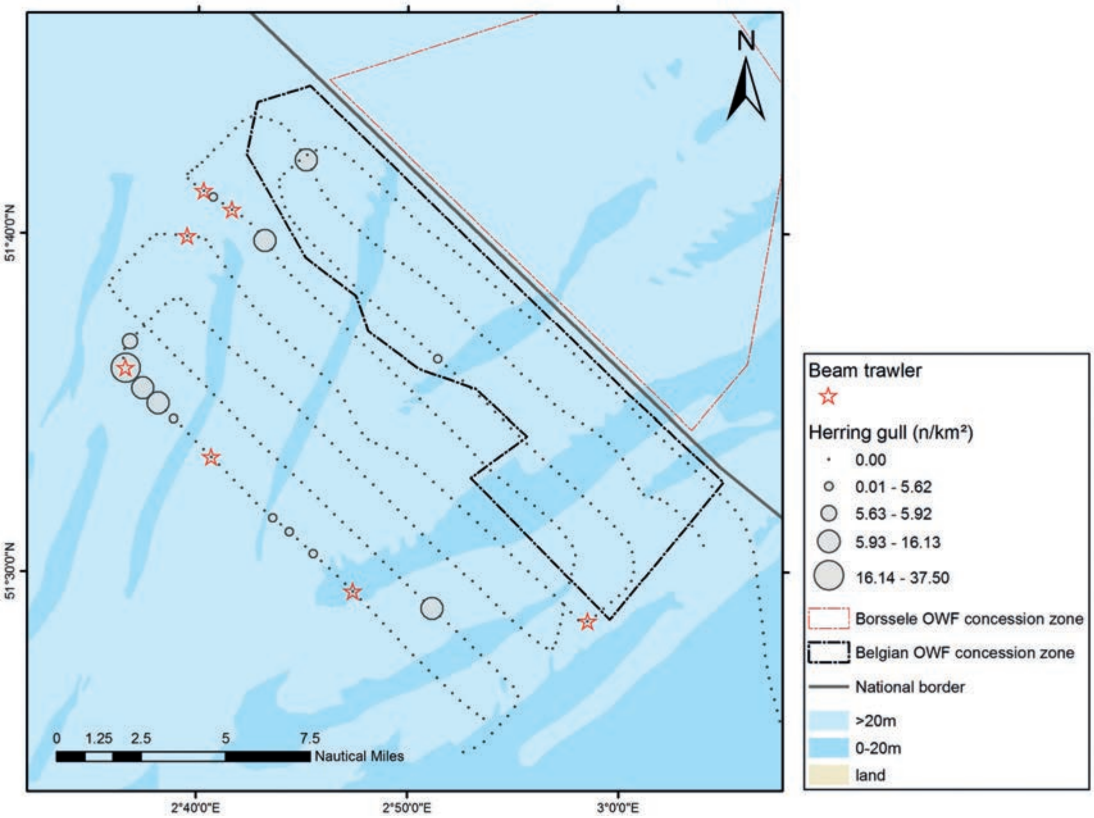

Figure 10. Herring gull densities encountered during the two-day seabird displacement monitoring on 23 & 24/02/2021.

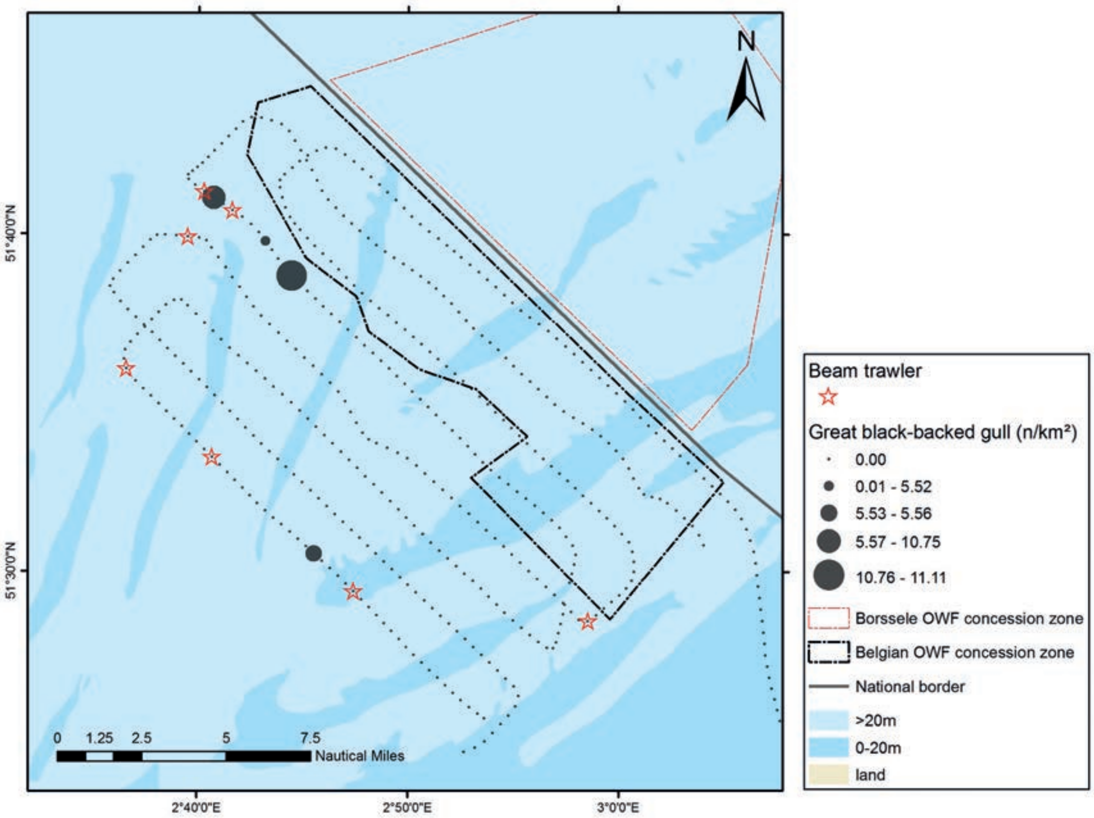

Figure 11. Great black-backed gull densities encountered during the two-day seabird displacement monitoring on 23 & 24/02/2021.

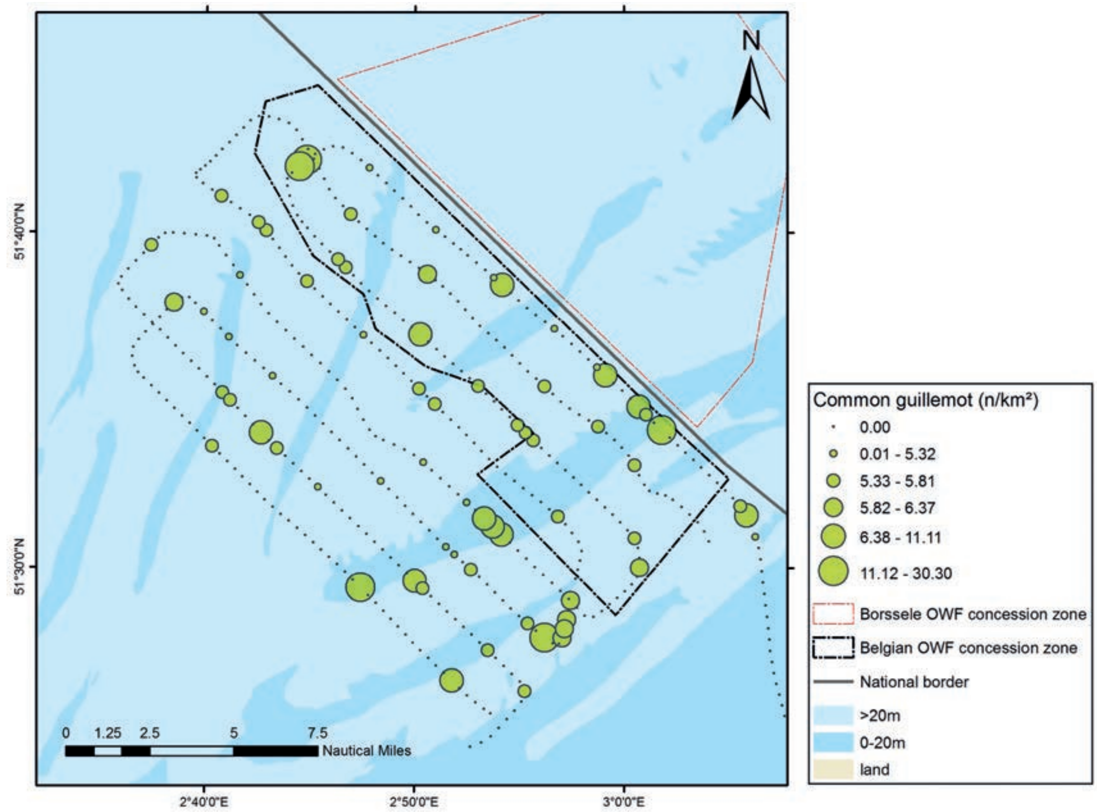

Figure 12. Common guillemot densities encountered during the two-day seabird displacement monitoring on 23 & 24/02/2021.

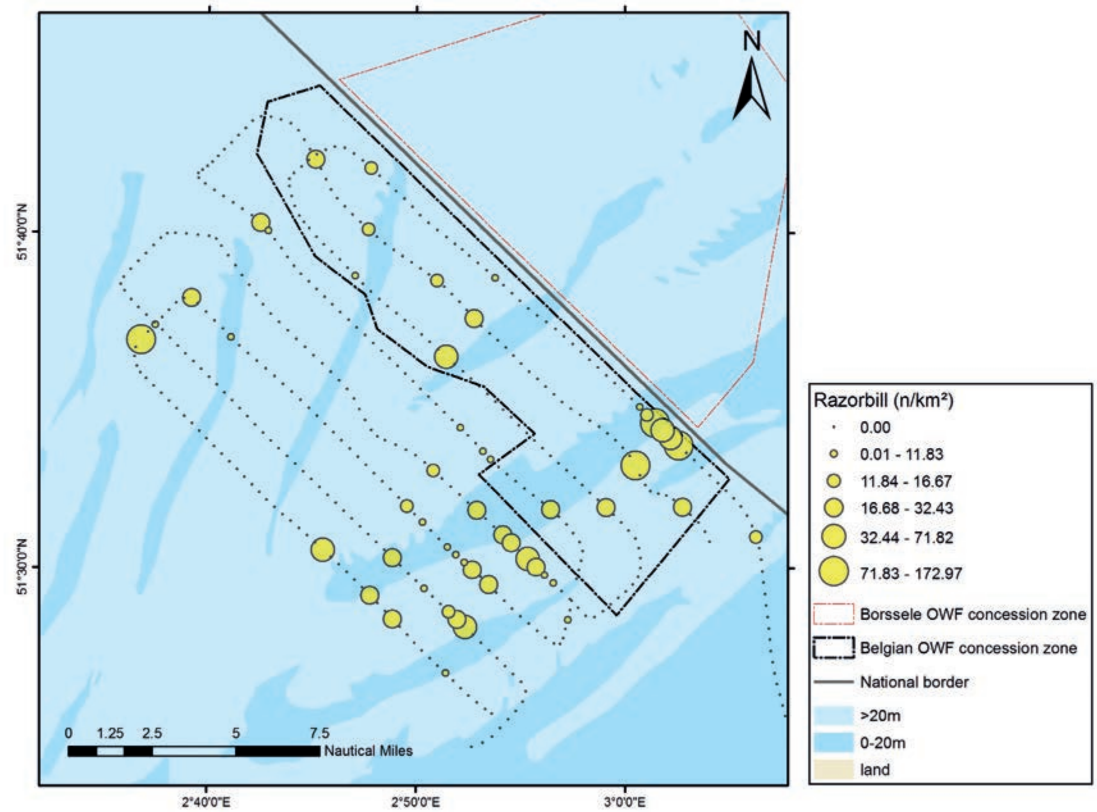

Figure 13. Razorbill densities encountered during the two-day seabird displacement monitoring on 23 & 24/02/2021.

course of the two monitoring days, totalling 31 individuals (14 inside compared to 17 outside the concession zone).

No less than 396 auks were observed between the turbines. When transforming the counted numbers to densities, the density of razorbill was almost twice as high inside compared to outside the wind farms. For common guillemot, densities inside and outside are comparable, yet slightly higher between the turbines (see Table 2).

3.3. Discussion ship-based seabird displacement monitoring

Clearly, the results from one monitoring survey are insufficient to perform statistical analyses, nor to draw any firm conclusions. On the other hand, the first findings are quite remarkable considering the relatively large numbers of auks and gannets observed in the concession zone (razorbill in particular), species generally perceived to actively avoid OWFs across European waters (reviewed in Vanermen & Stienen 2019). This could be a sign of habituation, whether or not in combination with a scale effect. One can indeed imagine how the same birds tending to avoid single wind farms might find it harder to avoid wind farm areas as extensive as the Belgian OWF concession zone. Birds that are now ‘forced’ into the wind farms in turn can be expected to increasingly habituate to their presence. For low-flying species such as common guillemot and razorbill, this can be regarded as good news as it might cancel out the potential impact of habitat loss, while the increased densities are not expected to lead to more collision victims. This, however, is not the case for northern gannet, a much more airborne species. About 7% of gannet flight movements are known to occur at collision risk height (Johnston *et al*. 2014), implying that habituation and increased presence between wind turbines might lead to a higher collision mortality. It will be very interesting to see whether coming surveys can confirm these first findings, and to perform spatial analyses on the resulting data. These analyses should further take in account the effect of active beam trawling on bird distribution in the area, which is now somehow blurring the raw results.

Acknowledgements

First of all, we want to thank all offshore wind farm concession holders for financing the environmental monitoring program, as well as the Management Unit of the North Sea Mathematical Models (MUMM) for assigning the seabird displacement study to INBO. A special word of gratitude goes out to the Belgian Science Policy (BELSPO) for providing ship time on RV Belgica. We wish to thank all crew members of the RV Belgica as well as Robin Brabant, Steven Degraer and Lieven Naudts for their logistic support and cooperation.

The bird tracking network was funded by LifeWatch and was realised in close cooperation with Ghent University (Luc Lens and Hans Matheve), University of Antwerp (Wendt Müller), VLIZ (Francisco Hernandez) and the OSCIBIO team at INBO (Peter Desmet).

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EC Directive 2009/147/EC on the Conservation of Wild Birds

Special Protection Area (SPA)

Name: *Liverpool Bay / Bae Lerpwl Special Protection Area*

Counties/Unitary Authorities:

The SPA lies almost entirely in UK territorial waters adjacent to the following counties / unitary authorities: Lancashire, Blackpool, Merseyside, Sir y Fflint / Flintshire, Conwy, Gwynedd, Ynys Môn / Isle of Anglesey and a small portion sits within Sir Ddinbych / Denbighshire unitary authority.

Boundary of the SPA:

The SPA extends out from Morecambe Bay beyond 12 nautical miles at the northwest point and offshore of the mouth of the Dee Estuary. The western boundary of the SPA extends into Welsh waters to Point Lynas on Anglesey.

The landward boundary of the SPA generally follows the mean low water mark or the boundaries of existing SPAs, whichever is the furthest seaward apart from at Prestatyn and in the river Mersey where it follows mean high water or the boundaries of existing SPAs.

Size of SPA: The SPA covers an area of 252,757.73 ha.

Site description:

Liverpool Bay is located in the south-eastern region of the northern part of the Irish Sea, bordering north-west England and north Wales. The SPA is a broad arc from approximately Morecambe Bay to the east coast of Anglesey. The seabed of the SPA consists of a wide range of mobile sediments. Large areas of muddy sand stretch from Rossall Point to the Ribble Estuary, and sand predominates in the remaining areas, with a concentrated area of gravelly sand off the Mersey Estuary and a number of prominent sandbanks off the English and Welsh coasts. The tidal currents throughout the SPA are generally weak, which combined with a relatively large tidal range facilitates the deposition of sediments.

Qualifying species:

The site qualifies under **Article 4.1** of the Birds Directive (2009/147/EC) as it is used regularly by 1% or more of the Great Britain populations of the following species listed in Annex I in any season:

Species	**Season**	**Count (Period)**	**% of population**
Red-throated diver *Gavia stellata*	Non-breeding	1,171 individuals (2004/05 – 2010/11)	6.89% of GB population
Little gull *Hydrocoloeus minutus*	Non-breeding	319 individuals (2004/05 – 2010/11)	N/A – selected under stage 1.4 guideline
Little tern *Sternula albifrons*	Breeding	260 individuals (2010 - 2014)*	6.84% of GB population
Common tern *Sterna hirundo*	Breeding	360 individuals** (2011 – 2015)	1.80% of GB population

*130 pairs (Apparently Occupied Nests) at Gronant Beach from Seabird Monitoring Programme database. These figures represent the current population at the site (SMP, *pers. comm.*). The ‘at classification’ population for little tern in The Dee Estuary SPA is 138 individuals (1995-1999).
** 180 pairs (Apparently Occupied Nests) at Seaforth Nature Reserve from Seabird Monitoring Programme database.

The site qualifies under **Article 4.2** of the Directive (79/409/EEC) as it is used regularly by 1% or more of the biogeographical populations of the following regularly occurring migratory species (other than those listed in Annex I) in any season:

Species	**Season**	**Count (Period)**	**% of population**
Common scoter *Melanitta nigra*	Non-breeding	56,679 (2004/05 – 2010/11)	10.31% of biogeographic population

Assemblage qualification:

The site qualifies under SPA selection stage 1.3 as it is used regularly by over 20,000 waterbirds (waterbirds as defined by the Ramsar Convention) in any season:

In the non-breeding season, the site regularly supports at least 69,687 (2004/05 – 2010/11) individual waterbirds.

The main components of the assemblage include all of the non-breeding qualifying features listed above, as well as an additional two species present in numbers exceeding 1% of the GB total: red-breasted merganser *Mergus serrator* and great cormorant *Phalacrocorax carbo*.

Principal bird data sources:

Lawson, J., Kober, K., Win, I., Allcock, Z., Black, J. Reid, J.B., Way, L. & O'Brien, S.H. 2015. An assessment of the numbers and distribution of wintering waterbirds and seabirds in Liverpool Bay / Bae Lerpwl area of search. JNCC Report No 576. JNCC, Peterborough.

Tern colony count data from the national Seabird Monitoring Programme database.

This citation relates to a site entered in the Register of European Sites for Great Britain.
Register reference number: UK9020294
Date of registration: 31st October 2017
Signed:
[redacted]

On behalf of the Secretary of State for Environment, Food and Rural Affairs

European Site Conservation Objectives for Liverpool Bay / Bae Lerpwl Special Protection Area
Site Code: UK9020294

With regard to the SPA and the individual species and/or assemblage of species for which the site has been classified (the ‘Qualifying Features’ listed below), and subject to natural change;

Ensure that the integrity of the site is maintained or restored as appropriate, and ensure that the site contributes to achieving the aims of the Wild Birds Directive, by maintaining or restoring;

- **The extent and distribution of the habitats of the qualifying features**
- **The structure and function of the habitats of the qualifying features**
- **The supporting processes on which the habitats of the qualifying features rely**
- **The population of each of the qualifying features, and,**
- **The distribution of the qualifying features within the site.**

This document should be read in conjunction with the accompanying Conservation Advice document (where available), which provides more detailed advice and information to enable the application and achievement of the Objectives set out above.

Qualifying Features:

A001 *Gavia stellata;* Red-throated diver (Non-breeding)

A065 *Melanitta nigra;* Common scoter (Non-breeding)

A177 *Hydrocoloeus minutus*; Little gull (Non-breeding)
A193 *Sterna hirundo*; Common tern (Breeding)
A195 *Sternula albifrons*; Little tern (Breeding)
Waterbird assemblage

Explanatory Notes: European Site Conservation Objectives

These Conservation Objectives are those referred to in the Conservation of Habitats and Species Regulations 2017 (as amended) ('the Habitats Regulations'). They must be considered when a competent authority is required to make a 'Habitats Regulations Assessment' including an Appropriate Assessment, under the relevant parts of this legislation.

These Conservation Objectives, and the accompanying Supplementary Advice (where this is available), will also provide a framework to inform the management of the European Site and the prevention of deterioration of habitats and significant disturbance of its qualifying features

These Conservation Objectives are set for each bird feature for a Special Protection Area (SPA).

Where these objectives are being met, the site will be considered to exhibit a high degree of integrity and to be contributing to achieving the aims of the Wild Birds Directive.

This is a cross border site

This site crosses the border between England and Wales. The advice of Natural Resources Wales should therefore be sought separately.

This is a European Marine Site

This SPA is a part of the Liverpool Bay / Bae Lerpwl European Marine Site (EMS). These Conservation Objectives should be used in conjunction with the Conservation Advice document for the EMS.

Natural England's formal Conservation Advice for European Marine Sites can be found via GOV.UK.

Publication date: 21 February 2019 (version 5). This document updates and replaces an earlier version dated 20 December 2017 to reflect the consolidation of the Habitats Regulations in 2017.

Register entry UK9020291 under regulation 10 of The Conservation (Natural Habitats, etc.) Regulations (Northern Ireland) 1995 as amended by The Conservation (Natural Habitats, etc.) (Amendment) Regulations (Northern Ireland) 2004.

This is the register entry for the European site known as Copeland Islands Special Protection Area. The site has been classified by the Department of the Environment pursuant to Article 4(1) and/or 4(2) of Council Directive 79/409/EEC on the conservation of wild birds as a Special Protection Area.

The register reference number for this European site is UK9020291 and a folder, kept under this reference as part of the register, contains a map of the European site and a citation giving the reasons for the classification for the site as a Special Protection Area. The map and citation are identified by the register reference number and signed by me on the date of registration.

Other details of the European site are as follows:

Date of Classification: 29 September 2009

Site centre location (1):

Longitude:	05° 31' 03" W
Latitude:	54° 41' 17" N

Area: 201.52 hectares

Priority status (2): N/A

Date of Registration: 8 January 2010

The Official Seal of the Department of the Environment hereunto affixed is authenticated by

[redacted]

On behalf of the Department of the Environment

1. This indicates the approximate centre of the site. Where the European site consists of several distinct areas, the co-ordinates of the most important sub-area are entered.

2. Indicates if the site has been identified under Article 4.2 of Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora as hosting one or more priority natural habitat or priority species.

The Register of European Sites in Northern Ireland

Register reference number: UK9020291

Date of Registration: 8 Ja 2010

Signed [redacted]

on behal

EC Directive 79/409 on the Conservation of Wild Birds: Citation for Special Protection Area (SPA)

Name: Copeland Islands Special Protection Area

Unitary Authority/County: Ards Borough Council
County Down

Consultation proposal: Copeland Islands Area of Special Scientific Interest has been selected for classification as a Special Protection Area because of its important breeding and wintering populations of seabirds and waterfowl.

Site description: The Copeland Islands site comprises three islands (Copeland Island, referred to as Big Copeland, together with Light House Island and Mew Island), together with associated islets, off the north-east Co. Down coast and close to the entrance to Belfast Lough. The site encompasses the islands down to the low water mark, excluding buildings and associated structures. It includes rocky shores together with limited areas of sand/mud and cobble/boulder beaches. Terrestrial habitats include saltmarsh, freshwater marsh, maritime grassland, limited extent of inland cliff and semi-improved agricultural grassland. The principal interests are the breeding colonies of Manx Shearwater and Arctic Tern. The boundary of the Special Protection Area site is entirely coincident with the Copeland Islands Area of Special Scientific Interest.

Size of SPA: The SPA covers an area of 201.52 ha.

Qualifying species:
The site qualifies under **Article 4.1** of the Directive (79/409/EEC) by supporting nationally important populations of the following species:

Annex 1 species	**Count and Season**	**Period**	**% population GB**
Arctic Tern *Sterna paradisaea*	566 pairs – breeding	5 year mean (1998 - 2002)	22.6 % Irish population

Bird figures from: Seabird 2000 census and annual counts co-ordinated by Copeland Bird Observatory

The site also qualifies under **Article 4.2** of the Directive (79/409/EEC) by supporting internationally important populations of the following species:

Species	**Count and Season**	**Period**	**% of population**
Manx Shearwater *Puffinus puffinus*	4800 pairs – breeding	Total survey (2000 – 2002)	1.7% world population

Bird figures from: Seabird 2000 census WeBS database

Non-qualifying species of interest
The islands host a nationally important breeding population of Eider Duck *S. mollissima* with some 140 pairs representing 14% of the Irish population.

The breeding birds contribute to the non-breeding flock of Eider *S. mollissima* that form part of the nationally important population that occurs along the Outer Ards SPA and Belfast Lough SPA. Counts of more than 200 duck are regular on Big Copeland especially, being some 10% of the Irish population.

Big Copeland supports Northern Ireland's first confirmed breeding pair of Mediterranean Gull *L. melanocephalus*. Breeding pairs were present in 2002 and again in 2003. Copeland Islands have held between 50% and 100% of the Irish breeding population.

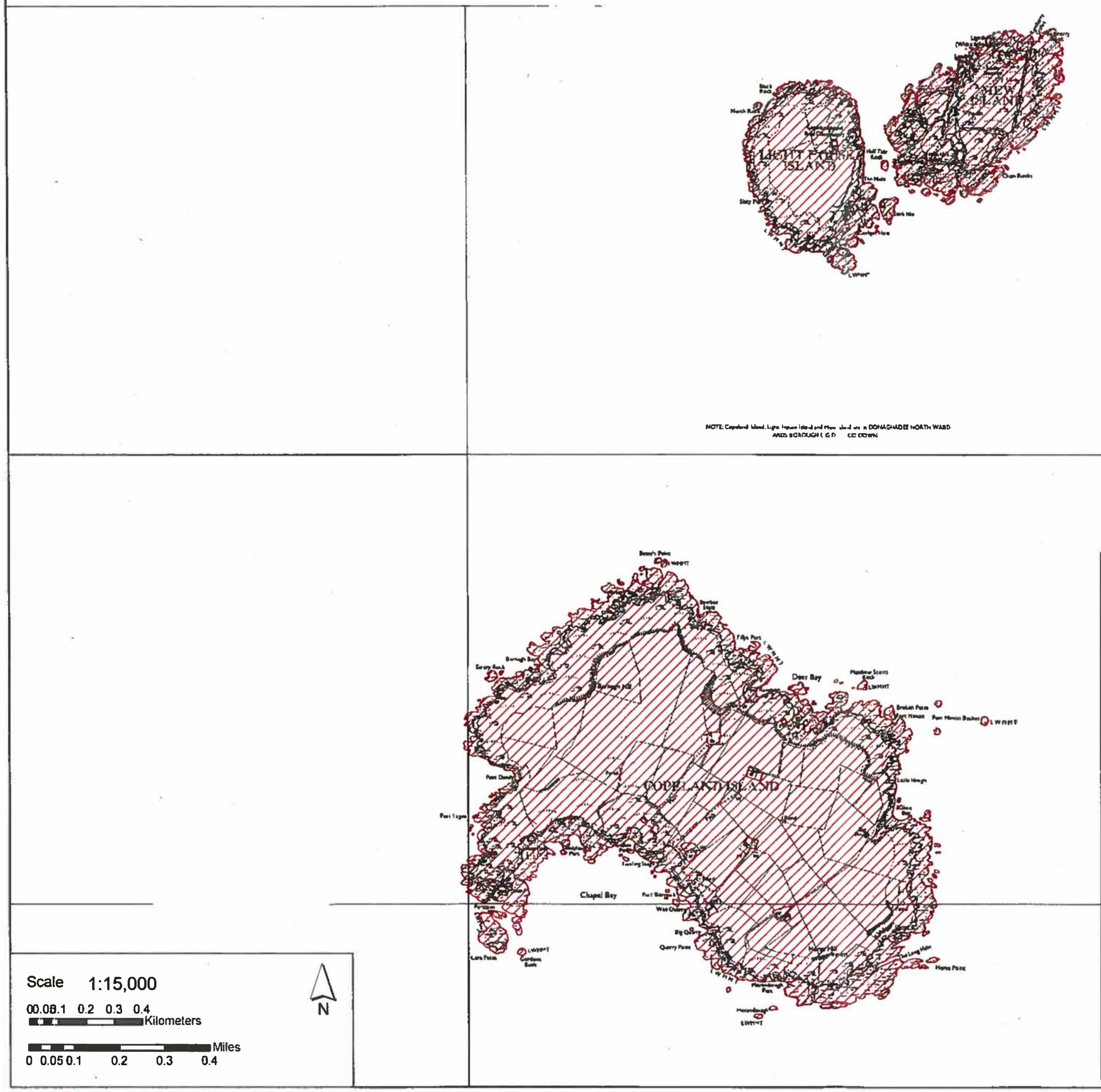
The Islands also support a nationally important population of Common Gull *L. canus* with some 250 pairs present, being some 7% of the Irish population. The site is the most important breeding location for this species in Northern Ireland.

Status of SPA
Copeland Islands Special Protection Area was classified as a Special Protection Area on 29 September 2009.

Special Protection Area
Directive 79/409/EEC

Classified by the Minister for the Department of the Environment

Date: 29 September 2009



The Register of European Sites in Northern Ireland
Register reference number: UK9020291

Date of Registration: 8 January 2010

Signed: G. Rdeymor.

on behalf of the Department of the Environment

COPELAND ISLANDS SPA

EC Site Code: UK9020291

Special Protection Area (SPA) shown thus: ▨

The SPA includes all marine areas contained within the solid red line.

Longitude: 05° 31' 03" W

Latitude: 54° 41' 17" N

Area of SPA: 201.52 ha.

Map 1 of 1

Version number: 1 (24/11/05)

Projection: Irish National Grid

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COPELAND ISLANDS
SPECIAL PROTECTION AREA (SPA)

UK9020291

CONSERVATION OBJECTIVES

Document Details

Title	Copeland Islands SPA Conservation Objectives
Prepared By	*Ian Enlander*
Approved By	*Mark Wright*
Date Effective From	*01/04/2015*
Version Number	*V2*
Next Review Date	January 2020
Contact	cdp@doeni.gov.uk

Revision History:

Version	Date	Summary of Changes	Initials	Changes Marked
V1	29/09/2009	Internal working document	IE	
V1.1	August 2013	Review	IE	
V2.0	February 2015	Draft	IE	Complete review

Site relationship

To fully understand the site conservation requirements for this site it may be necessary to also refer to other site Conservation Objectives

This SPA is in close proximity to Belfast Lough SPA, Belfast Lough Open Water SPA and Outer Ards SPA. It adjoins the proposed East Coast Marine SPA.

See also Boundary Rationale

1. INTRODUCTION

EU Member States have a clear responsibility under the Habitats and Birds Directives[1] to ensure that all habitats and species of Community Interest are maintained or restored to Favourable Conservation Status (FCS). Natura 2000 sites have a crucial role to play in achieving this overall objective since they are the most important core sites for these species and habitats. Each site must therefore be managed in a way that ensures it contributes as effectively as possible to helping the species and habitats for which it has been designated reach a favourable conservation status within the EU.

To ensure that each Natura 2000 site contributes fully to reaching this overall target of FCS, it is important to set clear conservation objectives for each individual site. These should define the desired state, within that particular site, of each of the species and habitat types for which the site was designated.

Once a site has been included in the Natura 2000 network, Member States are required to implement, on each site, the necessary conservation measures which correspond to the ecological requirements of the protected habitat types and species of Community Interest present, according to Article 6.1 of the Habitats Directive. They must also prevent any damaging activities that could significantly disturb those species and habitats (Article 6.2) and to protect the site from new potentially damaging plans and projects likely to have a significant effect on a Natura 2000 site (Article 6.3, 6.4).

Conservation measures can include both site-specific measures (i.e. management actions and/or management restrictions) and horizontal measures that apply to many Natura 2000 sites over a larger area (e.g. measures to reduce nitrate pollution or to regulate hunting or resource use).

In Northern Ireland, terrestrial/inter-tidal Natura 2000 sites are usually underpinned by the designation of an Area of Special Scientific Interest (ASSI) under the Environment (NI) Order 2002 (as amended).

2. ROLE OF CONSERVATION OBJECTIVES

Conservation Objectives have a role in

- Conservation Planning and Management – guide management of sites, to maintain or restore the habitats and species in favourable condition

- Assessing Plans and Projects, as required under Article 6(3) of the Habitats Directive - Habitats Regulations Assessments (HRA) are required to assess proposed plans and projects in light of the site’s conservation objectives.

- Monitoring and Reporting – Provide the basis for assessing the condition of a feature, the factors that affect it and the actions required.

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[1] 92/43/EEC and 2009/147/EC (codified version of Directive 79/409/EEC as amended)

3. DEFINITION OF FAVOURABLE CONSERVATION STATUS

Favourable Conservation Status is defined in Articles 1(e) and 1(i) of the Habitats Directive:

The conservation status of a natural habitat is the sum of the influences acting on it and its typical species that may affect its long-term natural distribution, structure and functions as well as the long term survival of its typical species. The conservation status of a natural habitat will be taken as favourable when:

- Its natural range and areas it covers within that range are stable or increasing, and
- The specific structure and functions which are necessary for its long-term maintenance exist and are likely to continue to exist for the foreseeable future, and
- The conservation status of its typical species is favourable as defined in Article 1(i).

For species, favourable conservation status is defined in Article 1(i) as when:

- population dynamics data on the species concerned indicate that it is maintaining itself on a long-term basis as a viable component of its natural habitats, and;
- the natural range of the species is neither being reduced nor is likely to be reduced for the foreseeable future, and;
- there is, and will probably continue to be, a sufficiently large habitat to maintain its population on a long term basis.

3.1 DEFINITION OF FAVOURABLE CONDITION

Favourable Condition is defined as "**the target condition for an interest feature in terms of the abundance, distribution and/or quality of that feature within the site"**.

The standards for favourable condition (Common Standards) have been developed by JNCC and are applied throughout the UK. Achieving Favourable Condition on individual sites will make an important contribution to achieving Favourable Conservation Status across the Natura 2000 network.

4 GENERAL INFORMATION

COUNTY: Down

Copeland Islands ASSI:		AREA: 201.15ha
Big Copeland	G.R. J593 835	
Light House Island	G.R. J596 858	
Mew Island	G.R. J602 860	
Copeland Islands SPA	G.R. J600 850	AREA: 201.20ha

NB – UK MARINE SPA PROGRAMME HAS IDENTIFIED THE NEED FOR A MARINE EXTENSION TO THE COPELAND ISLANDS SPA TO REFLECT USAGE OF THE MARINE AREA BY RAFTING MANX SHEARWATER.

THE EXTENT OF THE MARINE AREA MANX SHEARWATER RAFTING IS AVAILABLE FROM NIEA.

THIS BOUNDARY WILL BE FURTHER REVISED ONCE JNCC REPORT ON MARINE USAGE BY TERN SPECIES FROM EXISTING SPA'S DESIGNATED FOR BREEDING TERNS IS PUBLISHED.

CONSERVATION OBJECTIVES WILL BE REVISED AS THESE ISSUE PROGRESS

5 SUMMARY SITE DESCRIPTION

The site is composed of three islands, Big Copeland, Light House Island and Mew Island, which collectively make up the Copeland Islands ASSI, lying off the north-east coast of the Outer Ards SPA. The islands are sites for breeding seabirds, with Big Copeland and Lighthouse Island being home to the main colonies. Important breeding and wintering populations of Eider Duck occur. Notable breeding populations of wader species also occur on Big Copeland.

5.1 BOUNDARY RATIONALE

The ASSI/SPA includes all land areas, excluding those with buildings and adjoining gardens, as the Manx Shearwater population especially use both inland and coastal areas for breeding purposes. The inland breeding gull and wader populations also support inclusion of the core of Big Copeland. Sea areas adjoining the Copeland Islands have also been included in the SPA (used by breeding tern and Manx Shearwater). Such areas adjoining colonies are of particular importance for courtship, preening and loafing behaviours, and also feeding.

6 SPA SELECTION FEATURES

Feature Type	**Feature**	**Population**	**Population at time of designation (ASSI)**	**Population at time of designation (SPA)**	**SPA Review population**
Species	Manx Shearwater breeding population [a]	Total 4800 pairs Lighthouse Island (surveyed 2000) and Big Copeland – (surveyed 2002 and 2003)	Total 4800 pairs Lighthouse Island (surveyed 2000) and Big Copeland – (surveyed 2002 and 2003)	Total 4800 pairs Lighthouse Island (surveyed 2000) and Big Copeland – (surveyed 2002 and 2003)	New feature
Species	Arctic Tern breeding population [a]	1998 to 2002 - 5 year average of 566	1998 to 2002 - 5 year average of 566	1998 to 2002 - 5 year average of 566	New feature
Habitat[1]	Habitat extent				

Table 1. List of SPA selection features.

[1] Habitat is not a selection feature but is a factor and is more easily treated as if it were a feature. Habitat extent is also used for breeding birds reported as an area.

Notes on SPA features – may not be applicable to all SPAs
The above table lists all relevant qualifying species for this site. As the identification of SPA features has and continues to evolve, species may have different status but all should be considered in the context of any HRA process. Ultimately all SPAs will be renotified to formalise species features.
[a] – species cited in current SPA citation and listed on current N2K dataform
[b] – species selected post SPA designation through UK SPA Review 2001
[c] – species highlighted as additional qualifying features through the UK SPA Review 2015 or the UK marine SPA programmes.

6.1. ADDITIONAL ASSI SELECTION FEATURES

Feature Type (i.e. habitat, species or earth science)	Feature	Size/ extent/ pop	Population at time of designation (ASSI)	Common Standards Monitoring baseline
Species	Common Gull	**250 pr**	250 pr	250 pr
Species	Eider (breeding)	**140 pr**	140 pr	140 pr
Species	Eider (non-breeding)	**200**	200	458

Table 2. List of ASSI features, additional to those that form all or part of SPA selection features. These will be referred to in ANNEX II.

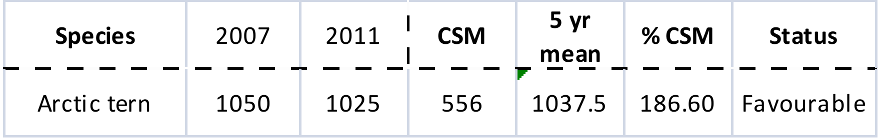
7. CONSERVATION OBJECTIVES

The Conservation Objectives for this site are:

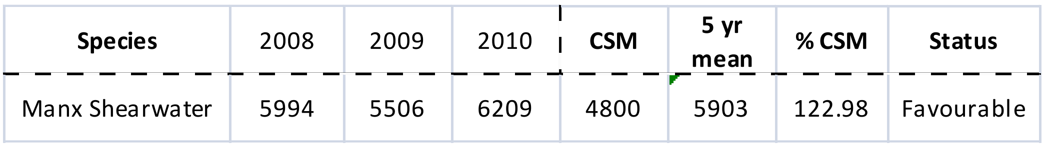
***To maintain each feature in favourable condition*.**

For each feature there are a number of component objectives which are outlined in the tables below. Component objectives for Additional ASSI Selection Features are not yet complete. For each feature there are a series of attributes and measures which form the basis of *Condition Assessment*. The results of this will determine whether a feature is in favourable condition, or not. The feature attributes and measures are found in the attached annexes. Those for Additional ASSI Selection Features (Annex II) are not yet completed.

8. COPELAND ISLANDS SPA CONDITION ASSESSMENT 2014



Species	2007	2011	CSM	5 yr mean	% CSM	Status
Arctic tern	1050	1025	556	1037.5	186.60	Favourable



Species	2008	2009	2010	CSM	5 yr mean	% CSM	Status
Manx Shearwater	5994	5506	6209	4800	5903	122.98	Favourable

9 SPA SELECTION FEATURE OBJECTIVES

To maintain or enhance the population of the qualifying species
Fledging success sufficient to maintain or enhance population
To maintain or enhance the range of habitats utilised by the qualifying species
To ensure that the integrity of the site is maintained;
To ensure there is no significant disturbance of the species and
To ensure that the following are maintained in the long term:

- Population of the species as a viable component of the site
- Distribution of the species within site
- Distribution and extent of habitats supporting the species
- Structure, function and supporting processes of habitats supporting the species

Feature	**Component Objective**
Manx Shearwater breeding population	No significant decrease in population against national trends
Manx Shearwater breeding population	Fledging success sufficient to maintain or enhance population
Arctic Tern breeding population	No significant decrease in population against national trends
Arctic Tern breeding population	Fledging success sufficient to maintain or enhance population
Habitat extent	To maintain or enhance the area of natural and semi-natural habitats used or potentially usable by Feature bird species, (breeding areas 201.20ha) subject to natural processes
Habitat extent	Maintain the extent of main habitat components subject to natural processes

Table 3. List of SPA Selection Feature Component Objectives

Tern nesting localities current and historical (TO BE FINALISED)

Big Copeland
Lighthouse Island
Mew Island

Table 4. Tern nesting locations within the SPA

9.1 ADDITONAL ASSI SELECTION FEATURE OBJECTIVES

Feature Type (i.e. habitat, species or earth science)	**Feature**
Species	Common Gull
Species	Eider (breeding)
Species	Eider (non-breeding)

10. MANAGEMENT CONSIDERATIONS

See also Views About Management for relevant ASSI

***Owner/Occupier's* –** (to be used to identify any key management considerations arising from ownership e.g. owners/organisations having an obvious bearing on conservation matters or from management agreements).

Approximately x individuals/organisations own land within the SPA. Major landowners and leasees within the SPA, relevant to the site management include, Crown Estate Commissioners, National Trust, Commissioner of Irish Lights, the Copeland Bird Observatory and Private Individuals. There may be conflicts of interest between the requirements of individual/organisations, both within and adjacent to the SPA, and the site management needs.

A managed shoot is established on Big Copeland. This is not thought to have an adverse impact on the breeding seabirds (Arctic Tern numbers have increased during the period during which the shoot has been managed while no aspect of the shoot would have a specific impact on the Manx Shearwater). Provision of feeding points for game birds supports the local population of Stock Dove, together with many passerine species.

Activities of the Copeland Bird Observatory are positively directed towards both the Arctic Tern and Manx Shearwater populations. In addition they undertake population monitoring actions and habitat enhancement schemes.

The proposed new sewage treatment works for the greater Bangor area at Donaghadee and associated infrastructure may impact upon the SPA.

There are no management agreements within the SPA.

11. MAIN THREATS, PRESSURES, ACTIVITES WITH IMPACTS ON THE SITE OR SITE FEATURES

***Notifiable Operations* -** Carrying out <u>any</u> of the Notifiable Operations listed in the schedule could affect the site. The list below is not exhaustive, but deals with the most <u>likely</u> factors that are either affecting Outer Ards SPA, or could affect it in the future. Although, features 1, 2, 3, 4 etc, are the qualifying SPA features, factors affecting ASSI features are also considered.

<u>Generic site/feature issues</u>

No	Issue	Threat/comments	Local considerations	Action
1	Boating activity – commercial	Disturbance and potential for impact from high-speed liners.	Fishing boat activity is widespread, centred on the main harbours. Shipping within the Irish Sea may have a bearing with regard to the potential for pollution incidents. No immediate issues evident.	Formal consultation likely relating to new schemes. Consider the collective impact.
2	Boating activity – recreational	Disturbance and potential for impact. Generally relevant to particularly sensitive areas within site.	Main boating centres are at Bangor and Donaghadee. Most activity is likely to be	Liaise with appropriate authority with codes of good practice, zoning and use of by-laws as necessary.

			in the summer period. Implications for seabird nesting sites.	Consider the collective impact.
3	Cull of fledglings/ young	Licensed selective culling of species impacting on ‘more desirable’ species. Licensed by NIEA.	Potentially an issue at tern colonies but numbers of breeding large gulls has declined considerably in recent years.	NIEA to review all licenses. Consider the collective impact.
4	Enhanced bird competition	Activities onsite or offsite that influences or results in a shift in balance of species utilising a site.	Future of landfill operations especially in the wider area could impact on breeding seabirds	Liaise with Planning Service. Review wider countryside changes.
5	Fishing – commercial or recreational	Minimal disturbance consideration but may represent ‘competition’ for piscivorous birds. Represents a net loss to the system in terms of biomass.	Scallop dredging and other trawling is ongoing.	Liaise with DARD and fishing authority as required. Liaise with angling clubs as required.
6	Habitat quality – open water	Alteration of habitat quality through diminution of water quality or invasive species.	Not a significant issue given the sites position in open coastal waters. Impacts are localised.	Assess planning applications. Deal with invasive alien species by preventing their spread or reducing their impact. Liaise with Environmental Protection. Consider the collective impact.
7	Habitat extent and quality- breeding	Alteration of habitat area or quality through inappropriate use or absence of site management.	Habitat management is main issue in context of seabirds. Manx Shearwater on Lighthouse Island are positively managed. This is not the case for Terns and Shearwaters on Big Copeland.	Assess needs of breeding species. Liaise with owner or appropriate authority to adjust or introduce site management.
8	Introduced species	Range of threats from loss of habitat, feeding competition, disease, hosting species presenting a threat outside of the site.	Significant problem on Lighthouse Island.	Liaise with appropriate authority. Consider feasibility of elimination. Participate in national/ international initiatives.
9	Predation.	Mainly of concern on bird breeding sites.	Extent unknown. Introduction of ground predators eg rats, is a major risk to Shearwaters especially.	Must be dealt with as part of wider countryside management considerations.
10	Recreational activities	Disturbance is the main consideration. Breeding birds, especially seabirds, are vulnerable to disturbance as absence of adults can often result in predation or chilling of young with a reduction/loss in fledging success.	Widespread in summer with main concerns being access to Copeland Island (Lighthouse and Mew Islands have greater control on access).	Liaise with local authorities and other managing parties. Signage at vulnerable sites should be reviewed.

11	Game Bird Management	Habitat management.	Potential conflict of habitat management. NB: The game bird rearing on Big Copeland is helping to support the Stock Dove population but may result in competition with waders for some invertebrate prey during the breeding season.	Liaise with holder of sporting rights.
12	Grazing regime	Stock levels must represent a balance between the need to keep a low sward and minimise soil erosion. Grazing/cutting needs also to be assessed in the context of the fluctuating rabbit populations.	On Lighthouse Island an artificial mowing regime is maintained, and on some areas of Big Copeland livestock grazing is maintained. On Mew Island the introduction of a grazing regime would be attractive.	For all islands, depending on rabbit activities, to seek measures to get rid of extra amounts of herbage
13	Field boundaries on Big Copeland	Some Manx Shearwater use the stone walls and dry turf banks.	The stone walls and turf banks need to be managed and maintained appropriately.	Liaise with local landowners.
14	Alien species	Himalayan Balsam invasion.	Eradication.	To contain or reduce extent of ground cover
15	Research activities	Census and ringing activities especially have the potential to impact on bird populations, particularly at breeding sites.	Breeding seabirds are surveyed annually.	Census and ringing activities to be undertaken by competent individuals, appropriately trained. In case of ringers, appropriate license must be held.

Table 5. List of site/feature management issues

12. MONITORING

Monitoring of our Special Protection Areas takes place at a number of levels, using a variety of methods. Methods for both Site Integrity Monitoring and Condition Assessment can be found in the Monitoring Handbook (To be written).

Maintain the integrity of the site. Undertake Site Integrity Monitoring (SIM) at least annually to ensure compliance with the SPA/ASSI schedule. The most likely processes of change (e.g. dumping, infilling, gross pollution) will either be picked up by Site Integrity Monitoring, or will be comparatively slow (e.g. change in habitat such as growth of mussel beds). More detailed monitoring of site features should therefore be carried out by Site Condition Assessment on a less frequent basis (every 6 years initially to pick up long-term or more subtle changes). A baseline survey will be necessary to establish the full extent of the communities present together with the current condition of the features, against which all further condition assessments will be compared.

In addition, detailed quality monitoring or verification monitoring may be carried out from time to time to check whether condition assessment is adequate to detect long-term changes that could affect the site. This type of quality monitoring may involve assessment of aerial photographs to determine site morphological changes. Methodology for this is being developed.

12.1 MONITORING SUMMARY

1. Monitor the integrity of the site (Site Integrity Monitoring or SIM) – Complete boundary survey to ensure integrity of site and that any fencing is still intact. Ensure that no sand extraction or dumping has been carried out within the SAC boundary. This SIM should be carried out once a year.

2. Monitor the condition of the site (Condition Assessment) - Monitor the key attributes for each selection feature (dune, saltmarsh, species). This will detect if the features are in favourable condition or not. See Annexes I and II for SAC and Additional ASSI Features respectively.

The favourable condition table provided in Annex 1 is intended to supplement the conservation objectives only in relation to management of established and ongoing activities and future reporting requirements on monitoring condition of the site and its features. It does not by itself provide a comprehensive basis on which to assess plans and projects, but it does provide a basis to inform the scope and nature of any appropriate assessment that may be needed. It should be noted that appropriate assessments are a separate activity to condition monitoring, requiring consideration of issues specific to individual plans or projects.

12.2. ADDITIONAL MONITORING ACTIONS UNDERTAKEN FOR SITES IN UNFAVOURABLE CONDITION

Monitoring actions set out in section 6 and Annex 1 will use, amongst other attributes, bird population data to determine site condition. In the event of a significant population decline being detected, a series of subsequent actions will be initiated. The following list is not exhaustive, actions will be site dependant, but the order of these points IS hierarchical i.e. consider point 1, then 2, etc.

1. Assess the site population in a wider geographical context – Northern Ireland, Ireland, UK, world. Refer to BTO ALERT limits etc. Liaise with other competent bodies to meaningfully assess wider pattern. No site action if site decline mirrors regional pattern the cause of which is not related to the site. Action may be required at regional or larger scale. If the cause of the regional population decline (e.g. eutrophication) is found at the site then action may be necessary, but this may need to form part of a network of strategic species action. Further research may be required.
2. Assess the site population in a wider geographical context – Northern Ireland, Ireland, UK, Europe, world. Determine if site losses are balanced by gains elsewhere e.g. breeding terns. Review site condition to determine if losses are due to site deterioration. Determine if possible whether population has

relocated within SPA series (national, biogeographical, European). Note that the reasons for such locational changes may not be readily identifiable. Further research may be required.

3. For passage/wintering species assess breeding information. No site action if site decline is due to breeding ground failure, unless breeding ground failure is related to poor adult condition resulting from factors affecting wintering / passage birds.
4. Determine whether a major incident has affected the site e.g. toxic impact on prey items, predation event or geographical shift in available prey. Ability to respond to impacts may be limited.
5. Assess condition of principal site habitats e.g. vegetational composition and structure, change in habitat balance e.g. mudflats reduced by encroaching mussel beds.
6. Assess prey availability. Issues to consider are both within site e.g. water quality, broad site management, and without site e.g. climatically driven factors.
7. Assess whether there have been any changes in any other site features or management practices (see Table 3) that may have affected populations of site selection features.
8. Long-term site value must be considered even when it is found to be in unfavourable condition for a number of reporting cycles. This is particularly important for breeding seabird and wader sites where ongoing appropriate management may ultimately encourage re-establishment of a favourable population.

13. SELECTION FEATURE POPULATION TRENDS

Site trends are reported using running 5 year means of annual maximum count (WeBS data). Long term trends in index values have been used to assess changes in overall wintering populations for Northern Ireland and UK (WeBS data). Caution is always necessary in the interpretation and application of waterbird counts given the limitations of these data. The reduced number of both sites and birds in Northern Ireland, result in a greater degree of fluctuation. Trends for Ireland are based on five years of data 1994-1999 (I-WeBS data). Consequently short-term fluctuations apparent in the data series may reflect changes in between year productivity, or other short term phenomena, rather than being indicative of a real change in a population.

SPECIES	SITE TREND	NI TREND	ROI TREND	UK TREND	COMMENTS
Arctic Tern	-	-	-	-	Not known, to be compiled.
Manx Shearwater	-	-	-	-	Not known, to be compiled.

ANNEX I

Feature (SPA) – Breeding Seabirds

* = primary attribute. One failure among primary attribute = unfavourable condition
# = optional factors. These can be in unfavourable condition without the site being in unfavourable condition

Attribute	**Measure**	**Targets**	**Comments**
* Arctic Tern breeding population	Apparently occupied nests	No significant decrease in Arctic Tern breeding population against national trends	Requirement that annual data is collected, apply 5 year mean criteria. Ideally the population will be maintained above 1% of the national population.
# Arctic Tern fledging success	Annual survey (as per Gilbert *et al*. 1998). Determine number of fledglings raised and add to total number of fledglings raised over previous four years and divide by five to obtain average. This should remove variation from season to season, e.g. in response to bad weather.	>1 fledgling per pair successfully raised per year over five year period.	Appropriate level of fledgling survival to be determined.
* Manx Shearwater breeding population	Occupied nests	No significant decrease in Manx Shearwater breeding population against national trends.	Requirement that data is collected once every reporting cycle. Ideally the population will be maintained above 1% of the national population.
# Manx Shearwater fledging success	Fledging success	>1 fledgling per pair successfully raised over five year period.	Appropriate level of fledgling survival to be determined.

Non-Avian Factors – habitat

Attribute	Measure	Targets	Comments
* Habitat extent	Area of natural and semi-natural habitat	To maintain or enhance the area of natural and semi-natural habitats potentially usable by Feature bird species, (breeding areas 201.20ha) subject to natural processes.	Monitor once every reporting cycle by aerial photography.
# Extent of different habitats	Extent of different habitats	Maintain the extent of main habitat components subject to natural processes.	Evaluate habitat quality should bird populations decline due to on site factors. Map any changes in area. This may include mapping areas with different vegetation structures or breeding sites, where this would lead to different usage by notified species.

Irish Sea Front

Potential Special Protection Area

Draft Conservation Objectives and Advice on Operations

July 2016

Advice under Regulation 18 of The Offshore Marine Conservation (Natural Habitats, &c.) Regulations 2007 (as amended)

Version 4.0

Summary

The Conservation Objectives and Advice on Operations for Irish Sea potential Special Protection Area (pSPA) provided in this document are based on information in the [redacted] The site occurs entirely within UK offshore waters (beyond 12 nautical miles of coast) and thus the Joint Nature Conservation Committee (JNCC) has advisory responsibilities under The Offshore Marine Conservation (Natural Habitats, &c.) Regulations 2007 (as amended). The advice is site- and feature-specific, and has been developed using the best-available scientific information and expert interpretation as at March 2015. The advice provided here will be subject to change as our knowledge about the site, its features and the impacts of human activities develops over time. The Advice on Operations has been generated through a broad grading of sensitivity of features of interest ('interest features') and their supporting habitats to physical, chemical and biological pressures associated with human activity.

Management actions should enable the regularly occurring migratory species Manx shearwater (*Puffinus puffinus*) in the Irish Sea Front pSPA**,** to maintain its local population (subject to natural change). Detailed conservation objectives (with attributes) are provided in the document.

To fulfil the Conservation Objectives for the features and their supporting habitat for this pSPA, relevant[1] and competent[2] authorities should consider whether any human activities whose control is within their remit might affect the site and the Conservation Objectives of the site as described. Any human activities likely to have an adverse impact on the listed features within the site, including activities likely to affect processes on which the population is dependent as outlined in the conservation objectives in section 2 of this document, should be assessed against the conservation objectives and may require management measures to enable the features to meet their conservation objectives.

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[1] Relevant authorities are those who are already involved in some form of relevant marine regulatory function and would therefore be directly involved in the management of a marine site.

[2] A competent authority is any Minister, government department, public or statutory undertaker, public body of any description or person holding a public office.

Contents

1 Introduction

1.1 Background

The Irish Sea potential Special Protection Area (pSPA) is being proposed by the UK Government under the Birds Directive (2009/147/EC). If classified, the Irish Sea Front pSPA would be subject to full protection under the Birds Directive (which along with the Habitats Directive comprises the 'Nature Directives').

This document presents JNCC's advice as required under Regulation 18[3] of The Offshore Marine Conservation (Natural Habitats & c.) Regulations 2007 (as amended), hereafter referred to as the 'Offshore Regulations', for the Irish Sea Front pSPA. Supporting information is also provided for transparency and to aid interpretation. The Offshore Regulations transpose the Nature Directives into law for UK offshore waters (from 12-200 nautical miles from the coast or to the limits of the UK Continental Shelf). For more information on JNCC's responsibilities under the Offshore Regulations, see Regulation 18.

This document fulfils requirements of Regulation 18 of the Offshore Regulations.

1.2 Responsibilities under other conservation designations

There are no other designations within or immediately adjacent to the Irish Sea Front pSPA.

The closest other designation is the Croker Carbonate Slabs SAC.

The obligations of relevant[4], and other competent[5] authorities and organisations under such designations and legislation are not affected by the advice contained in this document.

1.3 The role of Conservation Objectives

Conservation Objectives (as set out in Section 2) are the starting point from which management actions and monitoring programmes may be developed and inform the scope of appropriate assessments.

The Conservation Objectives set out what needs to be achieved for the site to make the appropriate contribution to the conservation status of the features for which the site is designated and thus deliver the aims of the Birds Directive.

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[3] Regulation 18 requires that JNCC establish Conservation Objectives for a European offshore marine site (SACs and SPAs) and notify those objectives to the appropriate competent authorities; and advise such competent authorities of any operations which may adversely affect the integrity of the site.

[4] Relevant authorities are those who are already involved in some form of relevant marine regulatory function and would therefore be directly involved in the management of a marine site.

[5] A competent authority is any Minister, government department, public or statutory undertaker, public body of any description or person holding a public office.

‘Competent Authorities’ can use the Conservation Objectives to meet their obligations to ensure integrity of the site (more information on obligations of competent authorities is described in Regulation 18).

The Conservation Objectives for features on the site may inform the scope and nature of any ‘appropriate assessment’ under the Habitats Regulations of any plan or project that may affect the features of the pSPA. An appropriate assessment will also require consideration of issues specific to the individual plan or project. The scope and content of an appropriate assessment will depend upon the location, size and significance of the proposed project. JNCC will advise on a case-by-case basis.

Following an appropriate assessment, competent authorities are required to ascertain the effect of the plan or project on the integrity of the site. The integrity of the site is defined as the coherence of its ecological structure and function, across its whole area that enables it to sustain the habitat, complex of habitats and/or the levels of populations of the species for which it was classified (ODPM Circular 06/2005 Paragraph 20).

1.4 Advice on Operations

JNCC’s advice identifies those operations (human activities) that may cause damage or deterioration of the qualifying species for which the site has been classified, or of their supporting habitats. Our advice is divided into two sections. The first section - advice on potential operations - lists activities that might adversely impact the features of the pSPA because the best-available evidence indicates they are moderately, or highly, sensitive to associated pressures. This advice includes operations that may not currently be occurring in the Irish Sea Front pSPA. The second section - advice on existing operations - lists only operations that the best-available evidence indicates are currently occurring in the Irish Sea Front pSPA and to which features are moderately or highly sensitive.

The list provides a basis for discussion about the nature and extent of the operations taking place that may have an impact on its interest features. The advice should also be used to help identify the extent to which existing measures of control, management and forms of use are, or can be made, consistent with the Conservation Objectives, and thereby focus the attention of relevant authorities and surveillance to areas that may need management measures.

JNCC’s Advice on Operations may need to be supplemented through further discussions with the relevant authorities and any advisory groups formed for the site.

The Habitats Regulations require that where an authority concludes that a development proposal is unconnected with the nature conservation management of a Natura site and is likely to have a significant effect on that site, it must undertake an appropriate assessment of the implications for the qualifying interests for which the area has been designated.

Competent authorities are required by the Habitats Regulations to undertake a review of all consents and permissions for activities affecting the site as soon as reasonably practicable after it becomes a European Natura site.

2 Conservation Objectives for the Irish Sea Front pSPA

2.1 Background to Conservation Objectives

JNCC have developed the Conservation Objectives for the Irish Sea Front pSPA, which are described in the current section. The Conservation Objectives are designed to ensure that the obligations of the Birds and Habitats Directives can be met; that is, deterioration or significant disturbance of the qualifying features or to the habitat upon which they rely should be avoided. Meeting such obligations will ensure that the site contributes to achieving the aims of the Wild Birds Directive (2009/147/EC).

The Conservation Objectives include both a general statement in section 2.2 setting out the overall objective supplemented with advice on specific attributes which are important to ensure the site contributes appropriately to the status of the wider populations of the bird features. Table 1 lists these attributes.

2.2 Irish Sea Front pSPA Conservation Objectives

The qualifying feature of the Irish Sea Front pSPA is:

- Manx shearwater *Puffinus puffinus* (breeding)

Figure 1 shows the site boundary (details on how this was identified are set out in the Departmental Brief Irish Sea Front pSPA [LINK])

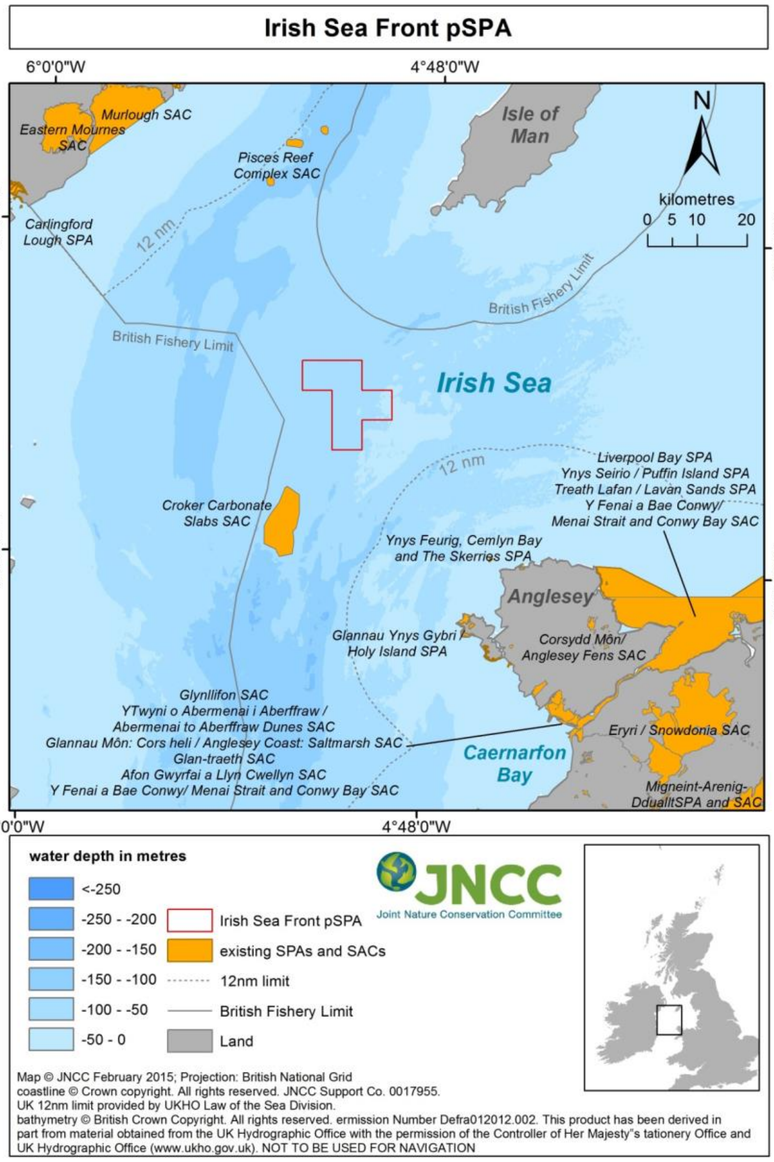

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Figure 1. Boundary of Irish Sea Front pSPA.

The Conservation Objectives for the Irish Sea Front pSPA are:

Site conservation objective:

To avoid significant deterioration of the habitats of the qualifying species or significant disturbance to the qualifying species, subject to natural change, thus ensuring that the integrity of the site is maintained in the long term and makes an appropriate contribution to achieving the aims of the Birds Directive for each of the qualifying species.

This contribution would be achieved through delivering the following objectives for each of the sites qualifying features:

A. Avoid significant mortality, injury and disturbance of the qualifying features, so that the distribution of the species and ability to use the site are maintained in the long-term;
B. Maintain the habitats and food resources of the qualifying features in favourable condition.
C. Ensure access to the site from linked breeding colonies

Explanatory notes are provided below. Supplementary advice on the conservation objectives for Irish Sea Front pSPA provides more site-specific detail and endeavour to comply with the EU Commission's 2012 Note on setting conservation objectives.

Explanatory notes:

General

Marine bird species are exposed to a range of wider drivers of change. Some of these are natural (e.g. population fluctuations/ shifts or habitat changes resulting from natural processes) and are not a direct result of human influences. Such changes in the qualifying species' distribution and use of the site which are brought about by entirely natural drivers, directly or indirectly, are considered compatible with the site's conservation objectives.

There may also be wider ranging anthropogenic impacts driving change within the site, such as climate change or in some cases fisheries stock management, which cannot be managed effectively at site level.

A) Avoid significant mortality, injury and disturbance of the qualifying features, so that the distribution of the species and ability to use the site are maintained in the long-term.

The purpose of this objective is to avoid significant mortality, injury or disturbance of qualifying species that negatively affect the site on a long-term basis. This site has been selected because evidence indicates it is a hotspot for the qualifying features and important for supporting the wider populations of these species. Such an impact would also have a detrimental effect on the contribution that this site makes to the maintenance of qualifying features wider population and therefore should be avoided.

For this site "significant" is taken to mean anthropogenic mortality, injury or disturbance that affect the qualifying species distribution and use within the site such that recovery cannot be expected or effects can be considered lasting.

All birds require energy which they obtain from food, to survive and to breed. Significant disturbance can include displacement and barrier effects on the species. Where such disturbance is brought about by human activities which affect the qualifying species' distribution and use of the site, such that their ability to survive and/or breed is compromised in the longer term, it is considered significant.

For each qualifying species, the ability to use the site should be maintained.

B) To maintain the habitats and food resources of the qualifying features in favourable condition.

The qualifying features using the site require sufficient food resource to be available. The qualifying species can eat a variety of pelagic or benthic prey and these should be maintained at a level able to support species populations. Some of these prey species have particular habitat requirements and where this is the case, the site needs to be managed to ensure the extent and quality of the habitats are sufficient to ensure the site is able to maintain these prey species in the longer term.

C) Ensure access to the site from the linked breeding areas

In order for the qualifying species to be able to continue using the site as delineated, it is important that their movements between the site and linked, but spatially disjointed, breeding colonies are unimpeded during the breeding season.

For the purposes of Habitats Regulations Appraisal (HRA) consideration of the conservation objectives may be required for plans/projects inside and outside the site.

Table 1. Supplementary advice on the conservation objective for qualifying species Irish Sea Front pSPA during the breeding season.

Objective	Additional evidence (site and species specific where possible)
A. Avoidance of significant mortality, injury and disturbance	An area as outlined in Figure 1 has been identified as an aggregation hotspot for Manx shearwater, see Kober *et al.* 2010 and 2012.
B. Maintain the habitats and food resources	The western Irish Sea Front (ISF) encompasses the pSPA. The ISF is a highly productive shallow sea tidal mixing front that forms seasonally from May to September. The pSPA as delineated is thought to be used by Manx Shearwater for foraging during the breeding season (which overlaps in time with the formation of the ISF). The high productivity within the ISF can affect availability of prey to seabirds such as shearwaters, and as such is likely to provide important and predictable foraging habitat. Manx shearwaters have been observed to forage mainly on small shoaling fish such as sandeels, sprat and herring and cephalopod species such as squid (Thompson 1987).There

	is some evidence that Manx Shearwaters from Welsh breeding colonies feed heavily on fish of the clupeid family [herrings, shads, sardines] (Brooke 1990). All these prey species are likely to contribute to Manx shearwater diet in this area. The Irish Sea Front pSPA overlaps low intensity spawning grounds for sandeel (*Ammodytidae* species) (Ellis *et al*. 2012). Sandeels are reliant on favourable sandy benthic habitats. Sandeels have been shown to prefer sandy seabeds with high proportion of coarse and medium sand particles (Greenstreet *et al.* 2010, Holland *et al.* 2005). Sandeels are highly resident and non-migratory, with large-scale dispersal only possible during larval phase and this is generally to a limited extent (Proctor *et al.* 1998; Christensen *et al.* 2008; Christensen *et al*. 2009, van Deurs 2010). Therefore sandeel seabed habitats in or linked to the Irish Sea Front pSPA should be conserved.
C. Ensure access to the site	Manx shearwaters have large foraging ranges, with a mean maximum foraging range from the colony of 330km (Thaxter *et al.* 2012). There are therefore several Manx shearwater colonies within foraging range of the Irish Sea Front pSPA (see Appendix I for more information). Although the Manx shearwaters from existing SPA colonies receive some level of protection, via the current HRA process, whilst at sea, this objective should seek to ensure that Manx shearwater can continue to access the site without being subject to significant additional energetic costs whilst commuting to/from the site from linked colonies.

3 Advice on Operations

3.1 Advice on potential operations

JNCC’s advice covers a range of different human activities and infrastructural developments that could occur in the marine environment, but is not exhaustive. By stating those activities and their associated pressures to which the features are considered to be sensitive, our advice focuses on where we consider there could be a risk of features not achieving their Conservation Objectives for the site should these activities occur in or near the pSPA. This current section does not attempt to cover all possible future activities or eventualities (e.g. as a result of accidents), and does not consider likely cumulative effects that could result from different types of activities being carried out simultaneously within or out with the SPA. This advice is not a prohibition, but rather indicates that some form of management measure(s) may be required or further measures where actions are already in force. It is indicative and does not remove the need for formal consultation on individual plans and projects.

An assessment of sensitivity[6] of bird features to various pressures and activities has been undertaken (Pérez-Domínguez *et al*. 2016) and used to inform this document. The assessment represents the state of knowledge on the sensitivity of bird features to pressures (and the activities that can exert these pressures).

Manx shearwater is thought to be sensitive to the following direct pressures at sea:

- removal as a non-target species (bycatch)
- introduction of microbial pathogens
- visual disturbance
- litter
- introduction of light
- collision with static or moving objects (above and below sea surface)
- noise (above and below water)
- changes in suspended solids
- barriers to species movement.

Activities that can exert these pressures at sea include:

- Fishing activity
- Aquaculture
- Extraction of non-living resources
- Energy generation (renewable and hydrocarbon)
- Transport (shipping)
- Recreational activities
- Defence and national security
- Waste management
- Marine research
- Other man-made structures

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[6] Sensitivity is defined as a measure of tolerance (or intolerance) to changes in environmental conditions, Tillin et al. 2010.

Given the importance of prey availability as a supporting feature, pressures which impact on prey species are also important. Little is known about pressures to which prey species are sensitive but it is likely that removal of target (and non-target) species is an important pressure for prey species which are of commercial interest (such as some clupeids).

Any activity that can cause a pressure or pressures to which the feature may be sensitive could present a risk to the feature of not achieving the conservation objective and should be assessed against the attributes listed in table 1.

The next section looks at which of the potentially damaging activities i.e. can cause pressures to which Manx shearwater are sensitive are occurring at present or are planned to occur within or near the pSPA. This is provided, to highlight where JNCC advises that more immediate management effort be focused.

3.2 Advice on existing operations

This section provides advice on those activities that might impact the species and are known to be occurring within the pSPA at present (April 2015). Our advice does not go into detail about the level of exposure to associated pressures caused by these activities and therefore the level of impact that might be expected on the species. Detailed information on current exposure levels held by the relevant authorities responsible for management should be used to inform the management of any activity that might impact upon the site's integrity. This section should therefore be considered as the starting point for discussions about the appropriate management actions relating to the pSPA.

The comments below (at pre-classification stage) are general and should not be considered to be definitive. They are made without prejudice to any comments JNCC may provide or any assessment that may be required for individual plans or projects to be considered by a competent or relevant authority. The level of any impact will depend on the location, intensity and duration of the specific activity. Our advice is provided to assist and focus the authorities in their consideration of the management of these operations.

Only operations which are known to occur, or are planned to occur, within or overlapping the pSPA, and which are thought to cause pressures to which the species are sensitive, are discussed in this section.

Whilst the Royal Yachting Association published cruising routes for the general area around the pSPA, leisure craft are not expected to be of particular concern for the listed species. The wider area is a busy shipping area however and so potential disturbance to Manx Shearwater from commercial shipping (e.g.via noise or visual disturbance pressures) may need to be considered, depending upon the specific nature and level of such activity. There are telecommunication cables overlapping the proposed site and the maintenance activities associated with these cables may need to be considered.

There is fishing activity within the Irish Sea Front pSPA, with both mobile and static gear types: dredging, demersal trawling, pelagic trawling, seines (encircling) and set nets. The Manx Shearwater is thought to be particularly sensitive to the pressure bycatch and so may be sensitive to static and mobile fishing activities if deployed in a way which may interact with Manx shearwaters.

There may be military activity in the general vicinity of the Irish Sea Front pSPA, and dialogue with the Ministry of Defence will be necessary to ensure that any potential interactions between military activity and Manx Shearwater are adequately addressed within the MoD Environmental Protection Guidelines.

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5. Appendix I Supporting Information

Table AI.1. Species and site specific supporting information, providing additional detail to support the supplementary advice.

Species	Explanatory notes
Manx shearwater	Manx shearwater have a large foraging range, with a mean maximum foraging range from the colony of 330km (Thaxter *et al.* 2012). There are therefore several UK breeding colonies within foraging range of the Irish Sea Front pSPA, including Britains two largest on the islands of Rhum and on the Pembrokeshire islands of Skokholm, Skomer and Middleholm. These represent a huge proportion of the world breeding population of Manx Shearwaters (90% breed in Britain and Ireland). Manx Shearwater at Welsh colonies within the vicinity of the Irish Sea Front pSPA returning to feed their chicks had eaten fish, with limited analysis of the contents of regurgitate but many clupeids were noted, of size around 15cm in length (Brooke 1990). Although there is very little known about what Manx Shearwaters at colonies within foraging range of the Irish Sea Front pSPA are foraging on, adult Manx Shearwater on the Isle of Rum, west Scotland (out with the foraging range of the Irish Sea Front pSPA) feed on squid and a variety of fish species including sandeels, clupeids and sprat, with the proportion of fish in the diet of adults increasing during the chick rearing period (Thompson 1987). The Irish Sea Front pSPA overlaps low intensity spawning grounds for sandeel (*Ammodytidae* species) (Ellis *et al*. 2012). The Irish Sea is thought to be a productive area for cephalopods (including squid), with Massy (1928) listing thirty-two cephalopod species in the waters around Ireland, and Collins *et al*. (1995) more recently found further species in the Irish Sea. Hydrographic fronts such as the Irish Sea Front are thought to indirectly attract seabirds; they bring small organisms up towards the surface, which attracts smaller fish which feed on these small organisms, which in turn attracts seabirds (Alldredge and Hamner, 1980, Camphuysen 2005). This enhances forage opportunities for higher-level consumers such as fish and marine birds. By promoting high prey densities and easy accessibility, oceanographic fronts can broaden the range of prey sizes taken by marine predators (Vliestra 2005). Site-fidelity in foraging seabirds has been demonstrated for several species, and should be strongest in situations where prey availability is predictable, and where prey are unlikely to be depleted quickly (e.g. fronts). Rees and Jones (1982) recorded Manx shearwater at higher abundance in the vicinity of the Irish Sea Front, and Fogg *et al*. (1985) found increased activity of

	seabirds over the front.

Document version control

Version	Date	Amendments made	Includes comments from
1.0	26/03/15	First draft	
2.0	30/03/15	Advanced draft	Internal comments
3.0	10/03/15	Advanced draft	High level QA
4.0	18/07/16	Finalised draft	Internal comments and updates in line with other offshore pSPA conservation objectives.

Citation

Directive 2009/147/EC of the European Parliament and of the Council on the conservation of wild birds (this is the codified version of Directive 79/409/EEC as amended)

CITATION FOR SPECIAL PROTECTION AREA (SPA)

RUM
(UK9001341)

(INCLUDING MARINE EXTENSION)

Site Description:
Rum SPA includes the Inner Hebridean Island of Rum, which has a largely rocky coast with cliffs rising to 210m, and adjacent coastal waters. There are a few exposed beaches and a more sheltered shingle and boulder beach with intertidal mudflats in the inlet of Loch Scresort. Submaritime grasslands and heaths are widely distributed along the coast, notably on cliff tops and above exposed beaches on the west coast. The interior consists almost entirely of mountain and moorland with numerous streams and small lochs. Vestigial saltmarsh is restricted to small areas on gravelly silt deposits and there is a small sand-dune system backed by machair grading into alluvial marsh on the flood plain of the Kilmory River. The island is largely treeless with fragments of natural woodland and scrub only in a few rocky gullies, though there are additional areas of planted woodland.

The boundary of the Special Protection Area overlaps with Rum SSSI and the seaward extension extends approximately 4 km into the marine environment to include the seabed, water column and surface. Immediately offshore of Rum the sediments are a mixture of mud and sand with water depth generally less than 40 m although round much of the island this increases rapidly up to 80m. Maximum tidal currents generally vary between 0.5 and 1.0 m/sec.

A number of fish species spawn off the north-west coast of Scotland with the seas around the Small Isles particularly important as nursery areas for saithe and cod. Many of these species will form the food resource for marine waterbirds.

Qualifying interest (N.B. All figures relate to numbers at the time of classification):
Rum qualifies under **Article 4.1** by regularly supporting a population of European importance of the **Annex 1** species **red-throated diver** *Gavia stellata* (13 pairs in 2010, 1% of Great Britain population), and at least a total of 18 pairs able to feed in the marine area, and **golden eagle** *Aquila chrysaetos* (4 pairs, 1% of the Great Britain population).

The site also qualifies under **Article 4.2** by regularly supporting populations of European importance of the migratory species **Manx shearwater** *Puffinus puffinus* (61,000 pairs, 23% of the world biogeographic population).

Rum further qualifies under **Article 4.2** by regularly supporting in **excess of 20,000 individual seabirds.** It regularly supports 130,000 seabirds including nationally important populations of the following species: **black-legged kittiwake** *Rissa tridactyla* (1,500 pairs, 0.3% of the Great Britain population), **common guillemot** *Uria aalge* (4,000 individuals, 0.4% of Great Britain population), and **Manx shearwater** (61,000 pairs).

Area: 467.24 km^2 (46,724.16 ha)
Location: 56° 59.876’ N, 006° 24.482’ W (coordinates are supplied in WGS 1984)
OS: 1:50,000 sheet - 39

Classified on 31st August 1982, with marine extension classified on 25th September 2009 and red-throated diver added to the marine extension on 3rd December 2020.

03/12/2020
NatureScot

NatureScot
Scotland's Nature Agency
Buidheann Nàdair na h-Alba

RUM SPECIAL PROTECTION AREA (SPA) CONSERVATION OBJECTIVES

The box below provides the draft high-level Conservation Objective statements for Rum SPA.

NatureScot is currently preparing Conservation and Management Advice for all inshore marine protected areas. The Conservation and Management Advice documents will include the full Conservation Objectives which incorporates site-specific supplementary advice and information to assist in the interpretation of the high-level Conservation Objectives. Whilst the site-specific advice and information is developed, the high-level Conservation Objectives will remain as draft but are unlikely to change. **These draft high-level Conservation Objectives should be used for Habitats Regulations Appraisals of plans or projects.**

The Conservation and Management Advice documents will also include NatureScot's initial advice to support management at these marine protected areas.

The * denotes a qualifying feature that is an assemblage feature only.

Rum SPA

Qualifying features:

- Red-throated diver (*Gavia stellata*)
- Common guillemot* (*Uria aalge*)
- Black-legged kittiwake* (*Rissa tridactyla*)
- Manx shearwater (*Puffinus puffinus*)
- Golden eagle (*Aquila chrysaetos*)

Draft Conservation Objectives:

1. To ensure that the qualifying features of Rum SPA are in favourable condition and make an appropriate contribution to achieving Favourable Conservation Status.

2. To ensure that the integrity of Rum SPA is restored in the context of environmental changes by meeting objectives 2a, 2b and 2c for each qualifying feature:

2a. The populations of the qualifying features are viable components of Rum SPA.

2b. The distributions of the qualifying features throughout the site are maintained by avoiding significant disturbance of the species.

2c. The supporting habitats and processes relevant to qualifying features and their prey/food resources are maintained, or where appropriate, restored at Rum SPA.

Black-legged kittiwake is considered to be in an unfavourable condition at Rum SPA and therefore an overarching 'restore' objective is set for the site.

For the Rum SPA, when carrying out appraisals of plans or projects, the focus of the appraisal should be to understand the impact of the plan or project on site integrity. For qualifying features that are in favourable condition this means maintaining that condition. For black-legged kittiwake that is in unfavourable condition, it means ensuring that the plan or project does not prevent or reduce the potential for recovery. The expectation is not for the plan or project to restore site integrity. Should the plan or project compromise the ability of the black-legged kittiwake to recover (e.g. result in a further decline or accelerate the rate of decline, or prevent a recovery from occurring), then the Rum SPA will not make an appropriate contribution to achieving FCS across the Atlantic Biogeographic Region.

November 2021

EC Directive 79/409 on the Conservation of Wild Birds

CITATION FOR SPECIAL PROTECTION AREA (SPA)

ST KILDA
(UK9001031)

INCLUDING MARINE EXTENSION

Site Description:

St Kilda is a group of remote Scottish islands lying in the North Atlantic about 70 km west of North Uist in the Outer Hebrides. The islands are steep, with precipitous cliffs reaching 430 m on Hirta and 380 m on Soay and Boreray. The vegetation is strongly influenced by sea spray and the presence of seabirds and livestock. Inland on Hirta, species-poor acidic grassland and sub-maritime heaths occupy extensive areas. The islands provide a strategic nesting locality for seabirds that feed in the rich waters to the west of Scotland. The total population of seabirds exceeds 600,000 individuals, making this one of the largest concentrations in the North Atlantic and the largest in the UK.

The boundary of the SPA overlaps with the boundary of St. Kilda SSSI, and the seaward extension extends approximately 4 km into the marine environment to include the seabed, water column and surface.

Qualifying Interest:

St Kilda SPA qualifies under **Article 4.1** by regularly supporting populations of European importance of the **Annex 1** species: **Leach's storm-petrel** *Oceanodroma leucorhoa* (5,000 pairs, 9.1% of the GB population); and **European storm-petrel** *Hydrobates pelagicus* (850 pairs, 1.0% of the GB population).

St Kilda SPA also qualifies under **Article 4.2** by regularly supporting populations of European importance of the **migratory** species: **Northern gannet** *Morus bassanus* (50,050 pairs, 19.0% of the world biogeographic population); **great skua** *Stercorarius skua* (270 pairs, 1.9% of the world biogeographic population); and **Atlantic puffin** *Fratercula arctica* (155,000 pairs, 17.2% of the *F.a.grabae* biogeographic population).

St Kilda SPA also qualifies under **Article 4.2** by regularly supporting **in excess of 20,000 individual seabirds**. It regularly supports 600,000 seabirds including nationally important populations of the following species: **razorbill** *Alca torda* (3,810 individuals, 3% of the GB population); **common guillemot** *Uria aalge* (22,700 individuals, 2% of the GB population); **black-legged kittiwake** *Rissa tridactyla* (7,830 pairs, 2% of the GB population); **Manx shearwater** *Puffinus puffinus* (up to 5,000 pairs, about 1% of the GB population); **Northern fulmar** *Fulmarus glacialis* (62,800 pairs, 12% of the GB population); **Atlantic puffin** (155,000 pairs, 35% of the GB population); **great skua** (270 pairs, 3.2% of the GB population); **Northern gannet** (50,050 pairs, 32% of the GB population); **Leach's storm-petrel** (5,000 pairs, 9.1% of the GB population) and **European storm-petrel** (850 pairs, 1.0% of the GB population).

Area: 29,014.62ha
National Grid Reference: NA 100 000
OS 1:50,000 sheet: 18

Classified on 31st August 1992, with marine extension classified on 25th September 2009

Scottish Natural Heritage
September 2009

ST KILDA SPECIAL PROTECTION AREA (SPA) AND SEAS OFF ST KILDA SPA DRAFT CONSERVATION OBJECTIVES

The box below provides the draft high-level Conservation Objective statements for St Kilda SPA and Seas off St Kilda SPA.

NatureScot is currently preparing Conservation and Management Advice for all inshore marine protected areas. The Conservation and Management Advice documents will include the full Conservation Objectives which incorporates site-specific supplementary advice and information to assist in the interpretation of the high-level Conservation Objectives. Whilst the site-specific advice and information is developed, the high-level Conservation Objectives will remain as draft but are unlikely to change. **These draft high-level Conservation Objectives should be used for Habitats Regulations Appraisals of plans or projects.**

The Conservation and Management Advice documents will also include our initial advice to support management at these marine protected areas.

For the Seas off St Kilda SPA our Conservation and Management Advice is being developed in partnership with the Joint Nature Conservation Committee (JNCC).

The * denotes a qualifying feature that is an assemblage feature only.

<table>
<tr><th>St Kilda SPA</th><th>Seas off St Kilda SPA</th></tr>
<tr><td>Qualifying features:
• Atlantic puffin (<i>Fratercula arctica</i>)
• Black-legged kittiwake* (<i>Rissa tridactyla</i>)
• Common guillemot* (<i>Uria aalge</i>)
• European storm petrel (<i>Hydrobates pelagicus)</i>
• Great skua (<i>Stercorarius skua</i>)
• Leach’s storm petrel (Oceanodroma leucorhoa)
• Manx shearwater* (<i>Puffinus puffinus</i>)
• Northern fulmar* (<i>Fulmarus glacialis</i>)
• Northern gannet (<i>Morus bassanus</i>)
• Razorbill* (<i>Alca torda</i>)</td><td>Qualifying features:
• Atlantic puffin* (<i>Fratercula arctica</i>)
• Common guillemot* (<i>Uria aalge</i>)
• European storm petrel* (<i>Hydrobates pelagicus)</i>
• Northern fulmar* (<i>Fulmarus glacialis</i>)
• Northern gannet (<i>Morus bassanus</i>)</td></tr>
<tr><td colspan="2">Draft Conservation Objectives:
1. To ensure that the qualifying features of St Kilda SPA and the Seas off St Kilda SPA are in favourable condition and make an appropriate contribution to achieving Favourable Conservation Status.

2. To ensure that the integrity of St Kilda SPA and the Seas off St Kilda SPA is restored in</td></tr>
</table>

the context of environmental changes by meeting objectives 2a, 2b and 2c for each qualifying feature:

2a. The populations of qualifying features are viable components of St Kilda SPA and Seas off St Kilda SPA.

2b. The distributions of the qualifying features throughout St Kilda SPA and Seas off St Kilda SPA are maintained by avoiding significant disturbance of the species.

2c. The supporting habitats and processes relevant to qualifying features and their prey/food resources are maintained, or where appropriate restored, at St Kilda SPA and/or Seas off St Kilda SPA.

Northern fulmar, razobill, common guillemot and black-legged kittiwake are considered to be in an unfavourable condition at St Kilda SPA, with northern fulmar and common guillemot also considered to be in an unfavourable condition at the Seas off St Kilda SPA. Therefore an overarching ‘restore’ objective is set for the sites.

For the St Kilda SPA and Seas off St Kilda SPA, when carrying out appraisals of plans or projects, the focus of the appraisal should be to understand the impact of the plan or project on site integrity. For qualifying features that are in favourable condition this means maintaining that condition. For northern fulmar, razobill, common guillemot and black-legged kittiwake that are in unfavourable condition, it means ensuring that the plan or project does not prevent or reduce the potential for recovery. The expectation is not for the plan or project to restore site integrity. Should the plan or project compromise the ability of the respective unfavourable qualifying features to recover (e.g. result in a further decline or accelerate the rate of decline, or prevent a recovery from occurring), then the St Kilda SPA and Seas off St Kilda SPA will not make an appropriate contribution to achieving FCS across the Atlantic Biogeographic Region.

November 2021

EC Directive 79/409 on the Conservation of Wild Birds
Citation for Potential changes to Special Protection Area (SPA)

Name: Glannau Aberdaron ac Ynys Enlli / Aberdaron Coast and Bardsey Island

Counties/Unitary Authorities: The SPA and potential extension lie within or adjacent to Gwynedd Unitary Authority and the seaward part of the site is entirely within UK territorial waters.

Boundary of the potential SPA: See potential SPA map. The proposed site sits entirely within UK territorial waters extending almost to the 6 nautical mile limit with approximately half the proposed site lying within the 3 nautical mile limit. The proposed marine extension follows the mean low water mark at the landward edge where it does not abut the existing (terrestrial) SPA. The new site includes the existing terrestrial areas designated as Glannau Aberdaron ac Ynys Enlli / Aberdaron Coast and Bardsey Island Special Protection Area by the Secretary of State for Wales in June 1992 under the 1979 EC Directive on the Conservation of Wild Birds (79/409/EEC).

Just over half of the proposed marine extension lies within the Pen Llŷn a'r Sarnau / Lleyn Peninsula and the Sarnau SAC, which was designated by the National Assembly for Wales in December 2004 under the 1992 EC Habitats and Species Directive (92/43/EEC). The existing terrestrial SPA is partly co-incident with Clogwyni Pen Llŷn / Seacliffs of Lleyn Special Area of Conservation (SAC).

It is not intended to include any additional land areas within the potential SPA, other than a small number of very small coastal rock outcrops that lie within the 9 km proposed extension, as it would not be practical to exclude these tiny areas from the possible amended SPA boundary.

Size of SPA: The existing terrestrial site and the potential SPA combined cover an area of 33,942ha approximately.

Site description: Glannau Aberdaron ac Ynys Enlli / Aberdaron Coast and Bardsey Island is located at the very tip of the Llŷn Peninsula in north-west Wales. The site consists of Ynys Enlli / Bardsey Island and a length of adjacent coastline together with two small islands Ynysoedd y Gwylanod/ Gwylan Islands, in addition to an area of sea extending approximately 9km out from Bardsey. The coastline is rocky, with many crags and low cliffs, heather-covered hills and grassy valleys in a distinctive landscape of small fields and "cloddiau" (stone-faced banks). The site supports a population of chough which depend on the low intensity pastoral management of this mix of habitats. Bardsey Island holds a large breeding colony of Manx shearwaters which forage widely across the ocean and also loaf on adjacent areas of the sea for a number of essential activities, such as preening, bathing and displaying, before attempting their hazardous approach to the nest site after nightfall.

Qualifying species: The site qualifies under **article 4.1** of the Directive (79/409/EEC) as it is used regularly by 1% or more of the Great Britain population of the following species listed in Annex I in any season:

Annex I species	Count and season	Period	% of GB population
Chough *Pyrrhocorax pyrrhocorax* (breeding)	12 pairs	count as at late 1990s	3.5%
Chough *Pyrrhocorax pyrrhocorax* (non-breeding)	24 individuals	count as at late 1990s	3.5%

The site also qualifies under **article 4.2** of the Directive (79/409/EEC) as it is used regularly by 1% or more of the biogeographical population of the following regularly occurring migratory species (other than those listed in Annex I) in any season:

Migratory species	Count and season	Period	% of subspecies or population
Manx shearwater *Puffinus puffinus* (breeding)	6,930 pairs	count as at 1996	2.6%

DATA: The 2001 SPA Review (Stroud *et al.,* 2001) updated the earlier assessment of UK SPAs published in 1992 in view of new information and possible gaps. The Government requested the Joint Nature Conservation Committee (JNCC) to review the UK SPA network and to recommend a definitive list of sites, identified against explicit selection guidelines. This established a baseline throughout the UK against which the need for future change can be assessed. The data quoted above is taken from this 2001 review, which was based on the most current and comprehensive data that was available at the commencement of the review. They provide a comparative assessment and a fixed baseline, even though more recent data have since become available.

Principal bird data sources:

ANON, 2005. **Developing the Chough SPA suite; report from the Chough subgroup**. SPA & Ramsar Scientific Working Group, May 2005.

BROOKE, M. 1990. **The Manx shearwater**. T & AD Poyser, Academic Press Ltd. London.

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Volume 2: Species accounts. 438 pp.
Volume 3: Site accounts. 392 pp.

CYNGOR CEFN GWLAD CYMRU
COUNTRYSIDE COUNCIL FOR WALES

CORE MANAGEMENT PLAN
INCLUDING CONSERVATION OBJECTIVES

FOR
GLANNAU ABERDARON AND YNYS ENLLI /ABERDARON COAST AND BARDSEY ISLAND SPA

(including part of CLOGWYNI PEN LLŶN/LLEYN SEACLIFFS SAC and PEN LLŶN A'R SARNAU SAC.
These sites are underpinned by GLANNAU ABERDARON SSSI, YNYS ENLLI SSSI, AND YNYSOEDD Y GWYLANOD SSSI)

Version: 2.0

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Approved by: Mike Willis

More detailed maps of management units can be provided on request.
A Welsh version of all or part of this document can be made available on request.

CONTENTS

PREFACE

This document provides the main elements of CCW's management plan for the sites named. It sets out what needs to be achieved on the sites, the results of monitoring and advice on the action required. This document is made available through CCW's web site and may be revised in response to changing circumstances or new information. This is a technical document that supplements summary information on the web site.

One of the key functions of this document is to provide CCW's statement of the Conservation Objectives for the relevant Natura 2000 sites. This is required to implement the Conservation (Natural Habitats, &c.) Regulations 1994, as amended (Section 4). As a matter of Welsh Assembly Government Policy, the provisions of those regulations are also to be applied to Ramsar sites in Wales.

1. VISION FOR THE SITE

This is a descriptive overview of what needs to be achieved for conservation on the site. It brings together and summarises the Conservation Objectives (part 4) into a single, integrated statement about the site.

This site encompases an extensive stretch of the Lleyn Penisula from Porth Oer on the northern coast, around the tip of the Lleyn to Aberdaron on the southern coast, including the islands of Bardsey (Enlli) and the Gwylans. This geologically diverse coast supports maritime and coastal heath and grassland habitats, which in turn support a range of important vascular and non-vascular plants, and an internationally important population of chough. Bardsey island is the home of one of the largest breeding populations of the Manx shearwater in the UK, for which the island is internationally important.

The site should continue to support a strong breeding population of chough with at least 14 nesting pairs, with 4 of these on Ynys Enlli. The site should also continue to provide sufficient habitat of sufficient quality to support this breeding population, and the non-breeding flocks. Maintenance of grazing of the grassland and heath, bracken control and rotational repair of the traditional cloddiau should be undertaken to maximise available feeding habitat.

Ynys Enlli should continue to sustain a breeding population of at least 10,000 pairs of Manx shearwaters. Their nest sites in the earth banks (cloddiau) in the lowlands of the island and in old rabbit burrows on Mynydd Enlli, and access to them, will remain undisturbed by boundary maintenance or heath management.

There will be no decrease in the areas of heathland present, and we will encourage restoration of the heathland, in terms of its extent and condition, aiming towards re-establishing the areas of heathland that existed (according to mapped evidence) in the early 20th century. This could be achieved by managed rotational cutting and/or burning of the dry heath, grazing management and the control of bracken and European gorse. Maintaining an open structure and diverse age-structure will ensure that the heath is available as a feeding habitat for chough.

The intertidal habitat will continue to support the full range of associated communities. The cliffs offer breeding sites for chough, and the intertidal area is also used by chough as an occasional feeding resource, while Manx shearwaters rely entirely on the sea for feeding.

The heath at Trwyn y Gwyddel is also very important as it supports one of only two UK locations for the spotted rockrose, *Tuburaria guttata.* This plant is hanging on at the edge of its range, and is succeptible to overgrazing and trampling pressures, and control of these factors is necessary to ensure its continued survival, Also present at this site, and more abundantly on the south western slopes of Mynydd Enlli, are two nationally rare heathland lichens, the ciliate strap lichen *Heterodermia leucomela* and the golden hair moss *Teloschistes flavicans.* Peny Cil supports a population of the prostate broom *Cytisus scoparius* subsp, *maritimus,* occurring here as a very isolated outlier at the north of its range. The sites should continue to support healthy populations of all these species.

The site also supports notable breeding populations of cormorant *Phalacrocorax carbo,* shag *P. aristotelis*, peregrine *Falco peregrinus*, herring gull *Larus argenatus* and puffin *Fratercula arctica*, particularly on Ynysoedd y Gwylanod, and should continue to do so.

2. SITE DESCRIPTION

2.1 Area and Designations Covered by this Plan

Grid references: SH167263 to SH167301, SH120220, SH184246 and SH182243.

Unitary authority: Gwynedd Council

Area (hectares): 512.8ha

Designations covered:
Glannau Aberdaron and Ynys Enlli Special Protection Area (SPA) is underpinned by three Sites of Special Scientific Interest (SSSIs): Glannau Aberdaron SSSI, Ynys Enlli SSSI and Ynysoedd y Gwylanod SSSI. The intertidal habitat within these sites is part of Pen Llyn a'r Sarnau Special Area of Conservation (SAC) and the entire remainder of the terrestrial habitat is also part of Clogwyni Pen Llyn SAC. Ynys Enlli/Bardsey Island is also a National Nature Reserve (NNR), and the entire site falls within the Llyn Area of Outstanding Natural Beauty (AONB). The coast is also designated a Heritage Coast.

Detailed maps of the designated sites are available through CCW's web site:
http://www.ccw.gov.uk/interactive-maps/protected-areas-map.aspx

For a summary map showing the coverage of this document is see separate Unit Map.

2.2 Outline Description

The site lies at the very southwestern tip of the Lleyn Peninsula, almost surrounded by the Irish Sea and exposed to the prevailing winds and weather systems. Its habitats are necessarily influenced by its location, geology and the climate, and the coastal area supports some of the best remaining examples of coastal and maritime heaths and grasslands on the Lleyn, while areas further inland supporting more agriculturally improved areas. The site includes three islands, Ynys Enlli and two small islands known as Ynysoedd y Gwylanod. The site is designated an SPA for its ornithological interest, and is particularly important for its chough and Manx shearwater breeding populations.

The area has long been a stronghold for the chough, and over 14 pairs regularly nest here. Chough thrive in the area which supports 5% of the UK population because of the variety of short turf and thin soil feeding habitats and available breeding sites - the sea cliffs and caves provide breeding sites, while the cliffs, heath, maritime grassland, and inland pasture and arable fields provide feeding sites throughout the year for these specialist invertebrate feeders.

Manx shearwaters spend most of their lives out in the open sea, but congregate at breeding sites to which they faithfully return throughout their lives. Theses tend to be offshore islands that are free of predators, and Bardsey supports over 2% of the UK breeding population. They are long-lived birds (a bird ringed in 1955 was recorded again in 2002 and 2003) but productivity is typically low, with a single egg produced by adults (>5years) annually. They are present on the island from mid-March to mid-October, and nest in burrows on the mountain, cliff slopes and in man-made banks and walls.

Ynysoedd y Gwylanod, and particularly the larger Ynys Gwylan Fawr, are important for supporting the largest breeding colony of puffin in North Wales, and razorbills and guillemots also nest in small numbers. There is also a healthy population of breeding cormorant which is in excess of 1% of the UK breeding population.

The site is also important for several vascular and non-vascular plant species, particularly spotted rockrose, *Tuburaria guttata* and prostate broom *Cytisus scoparius* subsp, *maritimus* and two nationally rare heathland lichens, the ciliate strap lichen *Heterodermia leucomela* and the golden hair moss *Teloschistes flavicans.*

2.3 Outline of Past and Current Management

This site includes a long stretch of the coast including two areas of common land, Mynydd Anelog and Mynydd Bychestyn, and three offshore islands, Ynys Elli, Ynys Gwylan Fawr and Ynys Gwylan Fach, and management of different areas has obviously varied over time. Grazing levels and stock type have varied historically, although it is likely that grazing levels were much heavier previously. Areas of heath on the Lleyn have suffered severe decline since the war (Rees 1929) because of overgrazing and agricultural improvements, and that which remains is only a remnant of what once existed. More common problems these days relate to undergrazing and neglect leading to rank heath and bracken areas, and uncontrolled and too frequent burning, although there is still localised overgrazing. Continued sheep overgrazing is particularly a concern at Trwyn y Gwyddel where the last mainland UK site for spotted rockrose, *Tuburaria guttata* is clinging on. The overgrazing problem here is compounded by trampling problems due to walkers accessing the site.

The structure and composition of the heathland habitats vary across the site. Some good quality coastal heath is to be found, particularly on Ynys Enlli (where maritime heath is well represented), Mynydd Mawr (Trwyn y Gwyddel and Braich y Pwll) and Mynydd Anelog, but in places this has become invaded by bracken. Bracken used to be cut and used for bedding historically, but this practice has not been carried through to the modern day. In some places, for instance at Mynydd Bychestyn, western gorse dominates, possibly due to climatic change since it is susceptible to frosts which occur less frequently nowadays, but almost certainly due to past overburning, and sheep grazing patterns which have an emphasis towards heavier grazing in the autumn and winter. There would be a great advantage in introducing heavy stock at Bychestyn, and many other sections of this site, and cattle and/or pony grazing could be appropriate all year round at low levels. Trampling will help control bracken and open up new areas for heath colonisation. Cattle grazing has recently been reintroduced to Mynydd Enlli following gorse control and it is hoped this will help prevent gorse regeneration and bracken growth. Sheep grazing on these sites should be heaviest in the spring and early summer (April-July) as this will encourage livestock to remove young palatable gorse and grasses whilst allowing ericoids to regenerate. Sheep stocking levels should be much reduced or removed in autumn and winter (September-March) in heathland area as this is the period when they do most damage to ericoids. Young gorse used to be milled locally, and used as nutritious feed, but this practice has died out. Burning favours bracken and western gorse, so this should not be used as a management tool where these species are likely to invade. Large areas, particularly at Mynydd Anelog and along the coast from Porth y Pistyll northwards (where sections are not grazed at all due to fear of losing stock on open cliff slopes), are now dominated by bracken, which limits the areas available for chough to feed and for heathland vegetation to develop. NT has been active in controlling bracken at its holding at Muriau, and work has been carried out recently at Pen y Cil and on Ynys Enlli, but plenty remains to be managed. In 2005, a Management Schedule was drawn up for four sections of the site, Mynydd Anelog, Mynydd Mawr, Mynydd Bychestyn and Pen y Cil, involving partners including NT, RSPB, Cyngor Gwynedd and CYMAD. Some of the work was implemented under the Cadw'r Lliw yn Llyn project, and further work will be implemented as part of the Llyn Heaths Project which has just gained Heritage lottery funding. Sympathetic grazing regimes with heavy stock, the establishment of cutting and burning of heath blocks on long rotation, and control of gorse and bracken form the backbone of these plans.

The UK chough population has suffered a significant decline in the 20th Century as a result of persecution and changing agricultural practice. These pressures led to a contraction of the species range and the fragmentation and reduction of most remaining populations. This national trend mirrored one seen throughout Europe where the species was estimated to be in decline in 90% of its range (Tucker & Heath, 1994). The past two or three decades have seen the UK chough population as a whole stabilising while populations around the Welsh coast appear to be making a recovery in numbers. Despite the population now stabilising in most of its European range, ongoing declines in some areas mean that is still regarded as a declining species (Birdlife International 2004).

Glannau Aberdaron and Bardsey are important feeding and breeding areas for chough. The current grazing regime provides the areas of suitable short turf for feeding chough over a good proportion of the site. Management to open up areas of dense heath and provide a wider range of age structure and to clear areas of European gorse and bracken should increase the area of feeding habitat. Areas of pasture, arable land and semi-improved and improved pasture are associated with the coastal strip and within easy reach of the cliff breeding sites.

The Manx shearwater population on Ynys Enlli is largely self-maintaining, and requires little in the way of active management. They simply require suitable nesting locations which are available in abundance on Enlli, access to fish in the open sea, and minimal disturbance. They are entirely pelagic outside the breeding season, and are ill-adapted to movement on land and particularly vulnerable to predation. For this reason, breeding birds are largely restricted to offshore islands with no predators. There used to be rabbits on the island, but they died out on the island in 1996. Prior to this, Manx shearwaters and rabbits coexisted and were even known to share entrance burrows. Manx shearwaters can excavate their own burrows, but will also make use of unoccupied rabbit burrows and may have benefitted from the recent extinction of rabbits and the increased availability of empty burrows. Many of the burrows in use on Enlli are in man-made earthbanks and walls, and restoration management of boundary features must take their presence into account, along with minimising disturbance by human access and management in all other areas with active burrows.

2.4 Management Units

The plan area has been divided into management units to enable practical communication about features, objectives, and management. This will also allow us to differentiate between the different designations where necessary. In this plan, the management subunits have been based on tenure, but these have been lumped together into identifiable management blocks, often related to NT ownership. The National Trust is a major landowner on this section of the coast and an important partner in managing the sites. None of the land within this site belongs to CCW.

The following table confirms the relationships between the management units and the designations covered:

Unit No	**SPA**	**Clogwyni Pen Llín SAC**	**Pen Llín a'r Sarnau SAC**	**SSSI**	**NNR**
Glannau Aberdaron SSSI					
1	✓		✓	✓	
2	✓	✓		✓	
3	✓	✓		✓	
4	✓	✓		✓	
5	✓	✓		✓	
6	✓	✓		✓	
8	✓	✓		✓	
9	✓	✓		✓	
10	✓	✓		✓	
11	✓	✓		✓	
12	✓	✓		✓	
13	✓	✓		✓	
14	✓	✓		✓	
15	✓	✓		✓	
16	✓	✓		✓	
17	✓	✓		✓	
18	✓	✓		✓	
43	✓	✓		✓	
19	✓	✓		✓	
20	✓	✓		✓	
21	✓	✓		✓	
22	✓	✓		✓	
23	✓	✓		✓	
24	✓	✓		✓	
25	✓	✓		✓	
26	✓	✓		✓	
27	✓	✓		✓	
28	✓	✓		✓	
29	✓	✓		✓	
31	✓	✓		✓	
34	✓	✓		✓	
39	✓		✓	✓	
Ynys Enlli SSSI					
35	✓	✓		✓	✓
36	✓	✓		✓	
41	✓	✓		✓	✓
42	✓		✓	✓	
Ynysoedd y Gwylanod SSSI					
37	✓	✓		✓	
38	✓	✓		✓	

3. THE SPECIAL FEATURES

3.1 Confirmation of Special Features

Designated feature	*Relationships, nomenclature etc*	*Conservation Objective in part 4*
SPA features		
Annex 1 species that are a primary reason for selection of ***Glannau Aberdaron and Ynys Enlli/ Aberdaron Coast and Bardsey Island SPA*** **1.** The site qualifies under Article 4.1 of the Directive (79/409/EEC) as it is used regularly by 1% or more of the Great Britain population of a species listed on Annex 1, in the breeding and non-breeding season: **Chough *Pyrrhocorax pyrrhocorax*** 14^{P} breeding 5% GB 28^{i} wintering 5% GB ^{P} = pairs i = individuals Data source = RSPB 2000	Chough utilise both the mainland and offshore islands for breeding and feeding.	Conservation Objective 1.
2. The site qualifies under Article 4.1 of the Directive (79/409/EEC) as it is used regularly by 1% or more of the Great Britain population of a species listed on Annex 1, in the breeding season: **Manx shearwater** ***Puffinus puffinus:*** Data submitted Natura 2000: 6930 pairs (count as at late 1990s, 3.5% of the British population) Bird data submitted at time of classification (updated citation April 1992): About 4.300 pairs (2% of the British breeding population)	Manx shearwaters breed on Ynys Enlli.	Conservation Objective 2.

SAC features		
Annex 1 habitats that are a primary reason for selection of ***Clogwyni Pen Llŷn SAC:*** **3. Vegetated sea cliffs of the Atlantic and Baltic coast** for which this is considered to be one of the best areas in the United Kingdom (EU Habitat code: 1230)	Atlantic sea cliff is also taken to include coastal heath (dry and maritime), and this feature covers the H8 *Calluna vulgaris-Ulex gallii* lowland heathland SSSI feature	Conservation Objective 3.
Annex 1 habitats that are a primary reason for selection of ***Pen Llŷn a'r Sarnau SAC:*** **4. Reefs** for which this is considered to be one of the best areas in the United Kingdom. (EU Habitat code: 1170)	The intertidal area is used by chough for occasional feeding at low tides and the cliffs include nesting sites. Manx shearwaters fish in the open sea habitat.	[Conservation Objectives for Pen Llyn a'r Sarnau covered in Reg 33 package]
Ramsar features		
Not applicable		
SSSI features		
5. Coastal heath and grassland communities, including seacliff slope vegetation	Occurring on the mainland coast and on the islands.	Conservation Objective 3.
6. Nationally important flowering plants, including the vulnerable spotted rockrose, *Tuburaria guttata* and prostrate broom *Cytisus scoparius* subsp, *maritimus.*	Spotted rockrose occurs on Trwyn y Gwyddel on the mainland. Prostrate broom occurs on cliffs above Paradwys on the mainland	Conservation Objective 3.
7. Two nationally rare heath lichens: Ciliate strap-lichen *Heterodermia leucomela* and golden hair lichen *Teloschistes flavicans*	Occurring at Trwyn y Gwyddel on the mainland and on the southwestern slopes of Mynydd Enlli.	Conservation Objective 3.
8. Assemblages of nationally important lichens, characteristic of different habitats: • An assemblage of lichens found growing on trees and other plants. • An assemblage of lichens of natural rock habitats. • An assemblage of lichens found growing on man-made structures.	Occurring on Ynys Enlli.	

9. A population of chough, an internationally protected bird species.	Also SPA feature. Birds use both the mainland and islands.	Conservation Objective 1.
10. A variety of high-quality shore types which represent the range and variation present on wave-exposed rocky shores in Cardigan Bay. Marine habitats and communities: • good examples of wave-exposed and tide-swept rocky shore communities • communities on overhanging bedrock and in rockpools • complete zonation of rocky shore communities. • Seaweeds in sediment-floored rockpools • Brown seaweeds and kelps in deep rockpools • Coral weed and encrusting coralline seaweed in shallow rockpools • Serrated wrack and under-boulder animals on lower shore boulders • Sponges and red seaweeds on overhanging lower shore bedrock	Occurring off the coast of the mainland and the islands.	[Conservation Objectives for Pen Llyn a'r Sarnau covered in Reg 33 package]
11. Important geological exposures: • Porth Oer: Rocky raised shore platform and sediment sequences associated with glacial events about 20,000 years ago. • Braich y Pwll – Parwyd: Remarkably varied sequence of Precambrian rocks (over 670 million years old) overlain by younger Ordovician sediments (about 500 million years old).	Occurring on the mainland.	

12. Nationally important flowering plants, including the rare rock sea-lavender, *Limonium britannicum* subsp. *pharense,* nationally scarce small adder's tongue, *Ophioglossum azoricum,* western clover, *Trifolium occidentale* and sharp rush *Juncus acutus.*	Occuring on Ynys Enlli in therophyte and maritime grassland and cliffs.	Conservation Objective 3.
13. An assemblage of moss and liverwort species with restricted European distributions, including a number of rare and scarce species.	Occuring on Ynys Enlli.	
14. Breeding population of the seabird Manx shearwater of European importance.	SPA feature. Occuring on Ynys Enlli.	Conservation Objective 2.
15.An important breeding population of puffin *Fratercula arctica* and cormorant *Phalacrocorax carbo.*	Occuring primarily on Ynysoedd y Gwylanod.	

3.2 Special Features and Management Units

This section sets out the relationship between the special features and each management unit. This is intended to provide a clear statement about what each unit should be managed for, taking into account the varied needs of the different special features. All special features are allocated to one of seven classes in each management unit. These classes are:

Key Features

KH - a 'Key Habitat' in the management unit, i.e. the habitat that is the main driver of management and focus of monitoring effort, perhaps because of the dependence of a key species (see KS below). There will usually only be one Key Habitat in a unit but there can be more, especially with large units.

KS – a 'Key Species' in the management unit, often driving both the selection and management of a Key Habitat.

Geo – an earth science feature that is the main driver of management and focus of monitoring effort in a unit.

Other Features

Sym - habitats, species and earth science features that are of importance in a unit but are not the main drivers of management or focus of monitoring. These features will benefit from management for the key feature(s) identified in the unit. These may be classed as 'Sym' features because:

a) they are present in the unit but may be of less conservation importance than the key feature; and/or

b) they are present in the unit but in small areas/numbers, with the bulk of the feature in other units of the site; and/or

c) their requirements are broader than and compatible with the management needs of the key feature(s), e.g. a mobile species that uses large parts of the site and surrounding areas.

Nm - an infrequently used category where features are at risk of decline within a unit as a result of meeting the management needs of the key feature(s), i.e. under Negative Management. These cases will usually be compensated for by management elsewhere in the plan, and can be used where minor occurrences of a feature would otherwise lead to apparent conflict with another key feature in a unit.

Mn - Management units that are essential for the management of features elsewhere on a site e.g. livestock over-wintering area included within designation boundaries, buffer zones around water bodies, etc.

x – Features not known to be present in the management unit.

The tables below sets out the relationship between the special features and management units identified in this plan:

Glannau Aberdaron SSSI	**Management unit**							
	1	**2**	**3**	**4**	**5**	**6**	**8**	**9**
SPA	✓	✓	✓	✓	✓	✓	✓	✓
Clogwyni Pen Llyn SAC		✓	✓	✓	✓	✓	✓	✓
Pen Llyn a’r Sarnau SAC	✓							
SSSI	✓	✓	✓	✓	✓	✓	✓	✓
NNR								
SPA features								
1. Chough	**Sym**	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**
2. Manx shearwaters	**Sym**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
SAC features								
3.Dry heath (Atlantic Sea Cliff)	**x**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**
4. Reefs	**KH**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
SSSI features								
5.Coastal heath and grassland communities, including seacliff slope vegetation.	**x**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**
6. Nationally important flowering plants, including the vulnerable spotted rockrose and prostrate broom	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
7. Two nationally rare heath lichens: ciliate strap-lichen and golden hair lichen.	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
9. A population of chough, an internationally protected bird species.	**Sym**	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**
10. A variety marine habitats and communities including high-quality shore types which represent the range and variation present on wave-exposed rocky shores in Cardigan Bay.	**KH**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
11. Important geological exposures at Porth Oer and Braich y Pwll – Parwyd.	**x**	**Sym**	**x**	**x**	**x**	**x**	**x**	**x**

Glannau Aberdaron SSSI	Management unit									
	10	11	12	13	14	15	16	17	18	43
SPA	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Clogwyni Pen Llyn SAC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pen Llyn a'r Sarnau SAC										
SSSI	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NNR										
SPA features										
1. Chough	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**	**Sym**
2. Manx shearwaters	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	x
SAC features										
3.Dry heath (Atlantic Sea Cliff)	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**
4. Reefs	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
SSSI features										
5.Coastal heath and grassland communities, including seacliff slope vegetation.	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**
6. Nationally important flowering plants, including the vulnerable spotted rockrose and prostrate broom	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**Sym**	**x**	**KS**
7. Two nationally rare heath lichens: ciliate strap-lichen and golden hair lichen.	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**Sym**	**x**	**Sym**
9. A population of chough, an internationally protected bird species.	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**	**Sym**
10. A variety marine habitats and communities including high-quality shore types which represent the range and variation present on wave-exposed rocky shores in Cardigan Bay.	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	x
11. Important geological exposures Braich y Pwll – Parwyd.	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**Sym**	**Sym**	**Sym**

Glannau Aberdaron SSSI	Management unit								
	19	20	21	22	23	24	25	26	27
SPA	✓	✓	✓	✓	✓	✓	✓	✓	✓
Clogwyni Pen Llyn SAC	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pen Llyn a'r Sarnau SAC									
SSSI	✓	✓	✓	✓	✓	✓	✓	✓	✓
NNR									
SPA features									
1. Chough	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**
2. Manx shearwaters	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
SAC features									
3.Dry heath (Atlantic Sea Cliff)	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**
4. Reefs	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
SSSI features									
5.Coastal heath and grassland communities, including seacliff slope vegetation.	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**	**KH**

6. Nationally important flowering plants, including the vulnerable spotted rockrose and prostrate broom	**x**	**x**	**x**	**x**	**x**	**Sym**	**x**	**x**	**x**
7. Two nationally rare heath lichens: ciliate strap-lichen and golden hair lichen.	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
9. A population of chough, an internationally protected bird species.	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**	**KS**
10. A variety marine habitats and communities including high-quality shore types which represent the range and variation present on wave-exposed rocky shores in Cardigan Bay.	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
11. Important geological exposures at Braich y Pwll – Parwyd.	**Sym**	**Sym**	**Sym**	**Sym**	**Sym**	**Sym**	**Sym**	**Sym**	**x**

Glannau Aberdaron SSSI	**Management unit**				
	28	**29**	**31**	**34**	**39**
SPA	✓	✓	✓	✓	✓
Clogwyni Pen Llyn SAC	✓	✓	✓	✓	✓
Pen Llyn a'r Sarnau SAC					
SSSI	✓	✓	✓	✓	✓
NNR					
SPA features					
1. Chough	**KS**	**KS**	**KS**	**KS**	**KS**
2. Manx shearwaters	**x**	**x**	**x**	**x**	**x**
SAC features					
3.Dry heath (Atlantic Sea Cliff)	**KH**	**KH**	**KH**	**KH**	**x**
4. Reefs	**x**	**x**	**x**	**x**	**x**
SSSI features					
5.Coastal heath and grassland communities, including seacliff slope vegetation.	**KH**	**KH**	**KH**	**KH**	**x**
6. Nationally important flowering plants, including the vulnerable spotted rockrose and prostrate broom	**x**	**x**	**x**	**x**	**x**
7. Two nationally rare heath lichens: ciliate strap-lichen and golden hair lichen.	**x**	**x**	**x**	**x**	**x**
9. A population of chough, an internationally protected bird species.	**KS**	**KS**	**KS**	**KS**	**KS**
10. A variety marine habitats and communities including high-quality shore types which represent the range and variation present on	**x**	**x**	**x**	**x**	**x**

wave-exposed rocky shores in Cardigan Bay.					
11. Important geological exposures at Porth Oer and Braich y Pwll – Parwyd.	**x**	**x**	**x**	**x**	

Ynys Enlli SSSI	**Management unit**			
	42	**35**	**36**	**41**
SPA	✓	✓	✓	✓
Clogwyni Pen Llyn SAC		✓	✓	✓
Pen Llyn a'r Sarnau SAC	✓			
SSSI	✓	✓	✓	✓
NNR		✓	✓	✓
SPA features				
1. Chough	**Sym**	**KS**	**KS**	**KS**
2. Manx shearwaters	**Sym**	**KS**	**KS**	**KS**
SAC features				
3.Dry heath (Atlantic Sea Cliff)	**x**	**KH**	**KH**	**x**
4. Reefs	**KH**	**x**	**x**	**x**
SSSI features				
5.Coastal heath and grassland communities, including seacliff slope vegetation.	**x**	**KH**	**KH**	**x**
7. Two nationally rare heath lichens: ciliate strap-lichen and golden hair lichen.	**x**	**Sym**	**x**	**x**
8. Assemblages of nationally important lichens, characteristic of different habitats.	**x**	**Sym**	**Sym**	**Sym**
9. A population of chough, an internationally protected bird species.	**Sym**	**KS**	**KS**	**KS**
10. A variety marine habitats and communities including high-quality shore types which represent the range and variation present on wave-exposed rocky shores in Cardigan Bay.	**KH**	**x**	**x**	**x**
12.Nationally important flowering plants, including the rock sea-lavender, small adder's tongue, western clover and sharp rush.	**x**	**Sym**	**x**	**x**
13. An assemblage of moss and liverwort species with restricted European distributions, including a number of rare and scarce species.	**x**	**Sym**	**x**	**Sym**
14. Breeding population of the seabird Manx shearwater of European importance.	**Sym**	**KS**	**KS**	**KS**

Ynysoedd y Gwylanod SSSI	**Management unit**	
	37	**38**
SPA	✓	✓
Clogwyni Pen Llyn SAC		
Pen Llyn a'r Sarnau SAC		
SSSI	✓	✓
NNR		
SPA features		
1. Chough	**KS**	**KS**
2. Manx shearwaters	**x**	**x**
SAC features		
3.Dry heath (Atlantic Sea Cliff)	**x**	**x**
4. Reefs	**x**	**x**
SSSI features		
5.Coastal heath and grassland communities, including seacliff slope vegetation.	**Sym**	**x**
10. A variety marine habitats and communities including high-quality shore types which represent the range and variation present on wave-exposed rocky shores in Cardigan Bay.	**x**	**x**
15. An important breeding population of puffin and cormorant.	**Sym**	**Sym**

Given that spotted rockrose occurs at its only mainland Wales location within Glannau Aberdaron SSSI, the management of the coastal heath (dry and maritime heath) (Atlantic Sea Cliff) in Management Unit 7d where it occurs should aim to maintain or increase the population.

4. CONSERVATION OBJECTIVES

Background to Conservation Objectives:

a. Outline of the legal context and purpose of conservation objectives.

Conservation objectives are required by the 1992 ‘Habitats’ Directive (92/43/EEC). The aim of the Habitats Directives is the maintenance, or where appropriate the restoration of the ‘favourable conservation status’ of habitats and species features for which SACs and SPAs are designated (see Box 1).

In the broadest terms, 'favourable conservation status' means a feature is in satisfactory condition and all the things needed to keep it that way are in place for the foreseeable future. CCW considers that the concept of favourable conservation status provides a practical and legally robust basis for conservation objectives for Natura 2000 and Ramsar sites.

Box 1
Favourable conservation status as defined in Articles 1(e) and 1(i) of the Habitats Directive

“The conservation status of a natural habitat is the sum of the influences acting on it and its typical species that may affect its long-term natural distribution, structure and functions as well as the long term survival of its typical species. The conservation status of a natural habitat will be taken as favourable when:

- Its natural range and areas it covers within that range are stable or increasing, and
- The specific structure and functions which are necessary for its long-term maintenance exist and are likely to continue to exist for the foreseeable future, and
- The conservation status of its typical species is favourable.

The conservation status of a species is the sum of the influences acting on the species that may affect the long-term distribution and abundance of its populations. The conservation status will be taken as ‘favourable’ when:

- population dynamics data on the species indicate that it is maintaining itself on a long-term basis as a viable component of its natural habitats, and
- the natural range of the species is neither being reduced nor is likely to be reduced for the foreseeable future, and
- There is, and will probably continue to be, a sufficiently large habitat to maintain its populations on a long-term basis.”

Achieving these objectives requires appropriate management and the control of factors that may cause deterioration of habitats or significant disturbance to species.

As well as the overall function of communication, Conservation objectives have a number of specific roles:

- Conservation planning and management.

  The conservation objectives guide management of sites, to maintain or restore the habitats and species in favourable condition.

- Assessing plans and projects.

  Article 6(3) of the ‘Habitats’ Directive requires appropriate assessment of proposed plans and projects against a site's conservation objectives. Subject to certain exceptions, plans or projects may not proceed unless it is established that they will not adversely affect the integrity of sites. This role for testing plans and projects also applies to the review of existing decisions and consents.

- Monitoring and reporting.

  The conservation objectives provide the basis for assessing the condition of a feature and the status of factors that affect it. CCW uses ‘performance indicators’ within the conservation objectives, as the basis for monitoring and reporting. Performance indicators are selected to provide useful information about the condition of a feature and the factors that affect it.

The conservation objectives in this document reflect CCW’s current information and understanding of the site and its features and their importance in an international context. The conservation objectives are subject to review by CCW in light of new knowledge.

b. Format of the conservation objectives

There is one conservation objective for each feature listed in part 3. Each conservation objective is a composite statement representing a site-specific description of what is considered to be the favourable conservation status of the feature. These statements apply to a whole feature as it occurs within the whole plan area, although section 3.2 sets out their relevance to individual management units.

Each conservation objective consists of the following two elements:
1. Vision for the feature
2. Performance indicators

As a result of the general practice developed and agreed within the UK Conservation Agencies, conservation objectives include performance indicators, the selection of which should be informed by JNCC guidance on Common Standards Monitoring[1].

There is a critical need for clarity over the role of performance indicators within the conservation objectives. **A conservation objective, because it includes the vision for the feature, has meaning and substance independently of the performance indicators, and is more than the sum of the performance indicators**. The performance indicators are simply what make the conservation objectives measurable, and are thus part of, not a substitute for, the conservation objectives. Any feature attribute identified in the performance indicators should be represented in the vision for the feature, but not all elements of the vision for the feature will necessarily have corresponding performance indicators.

As well as describing the aspirations for the condition of the feature, the Vision section of each conservation objective contains a statement that the factors necessary to maintain those desired conditions are under control. Subject to technical, practical and resource constraints, factors which have an important influence on the condition of the feature are identified in the performance indicators.

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[1] Web link: http://www.jncc.gov.uk/page-2199

4.1 Conservation Objective for Feature 1: Internationally important population (1% or more of the Great Britain population) of breeding and non-breeding season chough *Pyrrhocorax pyrrhocorax.*

Vision for feature 1: Chough.

The vision for this feature is for it to be in a favourable conservation status, where all of the following conditions are satisfied:

- The breeding population of chough is at least 14 pairs, or 5% of the GB population.
- The wintering population of chough is at least 28 individuals, or 5% of the GB population.
- Sufficient suitable habitat is present to support the populations.
- Breeding population is stable or increasing.
- Productivity is stable.
- Non-breeding flocks are stable or increasing (summer and winter).
- Breeding and non-breeding birds use Ynys Enlli for feeding throughout the year.
- Chough feeding habitats are themselves in a favourable conservation status and that the specified and operational limits and grazing prescriptions for these habitats incorporate chough feeding requirements (i.e. sward height and bare ground).
- Disturbance of breeding and feeding chough is minimal.
- The factors affecting the feature are under control.

Performance indicators for Feature 1: Chough.

> The performance indicators are part of the conservation objective, not a substitute for it. Assessment of plans and projects must be based on the entire conservation objective, not just the performance indicators

Performance indicators for chough feature condition		
Attribute	***Attribute rationale and other comments***	***Specified limits***
A1. Population size	The Glannau Aberdaron chough (Pyrrhocorax pyrrhocorax) population will be considered in favourable condition when (based on performance indicators and targets as set out in the SPA review site account):	***Upper limit***: Not required. ***Lower limit:*** The SPA wintering population is at least 28 individuals. The SPA population represents at least 5% of the GB breeding and wintering populations
A2. Population extent	The Glannau Aberdaron chough (Pyrrhocorax pyrrhocorax) population will be considered in favourable condition when (based on performance indicators and targets as set out in the SPA review site account):	***Upper limit***: Not required. ***Lower limit***: >14 pairs are breeding in the SPA, and where traditional breeding sites are occupied in at least 4 of Sections 1, 2, 3, 4, 5 and 6. Sections are defined as: Section 1 = Units 8,9,10,11 Section 2 = Units 13,14 Section 3 = Units 15,16,17,18,43 Section 4 = Units19,20,21,22,23,24,25,26 Section 5 = Units 27,28,29,31,34 Section 6 = Units 35,36,41,42

A3. Forage habitat extent	The foraging habitat for chough will need to be in favourable condition for chough to be favourable.	***Upper limit***: None set (although other interest features on the site need to considered, and should not be compromised). ***Lower limit***: The Vegetated sea cliffs of the Atlantic and Baltic coasts (H7 *Calluna vulgaris –Scilla verna* heath, H8d *Calluna vulgaris-Ulex galli* heath, *Scilla verna* sub-community, MC8 *Festuca rubra – Armeria maritima,* MC9 *Festuca rubra – Holcus lanatus* and MC10 *Festuca rubra – Plantago spp* maritime grassland communities, coastal grassland and maritime cliff and slope feature within Clogwyni Pen Llŷn SAC must achieve favourable condition. >50% of earthbank is suitable for chough feeding. The approximate extent of heath and short-grazed grassland should be as present in 2001
A4. Habitat quality	Open heath is defined as vegetation where ericoids or Ulex gallii form >30% cover with >20% open ground (occupied by bare soil, annual plants and/or terricolous macro-lichens) or closely-grazed grassland in any 1m radius.	***Upper limit***: None set (although other interest features on the site need to considered, and should not be compromised). ***Lower limit***: Within each of plots A - F on the Uwchmynydd, Mynydd Bychestyn, Pen y Cil, and Bardsey sections of the site, there should

	Closely grazed grassland is defined as vegetation in which >50% of the sward is <3cm high in any 1m radius Six monitoring plots, spread across three of the mainland sections of the site (Uwchmynydd, Pen y Cil, Mynydd Bychestyn) were established in 2001. (Refer to Annex 2 of the Clogwyni Pen Llyn 2004 SAC Monitoring Report). Further plots will need to be established on Bardsey. These four sections of the site are known to be the most important both in terms of numbers of breeding pairs and usage by birds outside the breeding season.	be no significant decrease in the proportion of short grazed grassland and open heath relative to that seen in 2001 The lower limits for the proportion of open heath and closely grazed grassland in the monitoring plots is as follows: A, B & E = 55% C = 70% D = 60% F = 65%.
Performance indicators for factors affecting the feature		
Factor	***Factor rationale and other comments***	***Operational Limits***
F1. Livestock grazing	The site is grazed to various levels, but in some sections, not at all. There is a reluctance to put stock on habitat open to cliffs, but lack of grazing is usually due to the dominance of gorse or bracken scrub, which, in a vicious circle, is due to lack of heathland management, including grazing. Grazing pasture land overwinter is important for chough as the invertebrates found in their dung is an important food source over winter. The use of avermectins should not occur within this site too allow natural invertebrate flora to develop in dung	***Upper limit*:** Not set (although other interest features on the site need to considered, and should not be compromised). ***Lower limit*:** Grazing levels will ensure extent of forage of sufficient quality to support the chough population.
F2 Disturbance	Nest and roost sites are considered to be subject to few direct threats, as climbing near known nest sites is effectively controlled by voluntary codes of conduct.	***Upper limit*:** no breeding attempts to be know to fail because of impact of human disturbance ***Lower limit*:** None set

Performance indicators for chough feature condition specifically on Ynys Elli		
Attribute	***Attribute rationale and other comments***	***Specified limits***
A1. Breeding population	On Ynys Enlli, the breeding population is stable or increasing .	***Upper limit***: None set ***Lower limit***: 5 pairs in 3 out of 5 consecutive years. Lowest acceptable annual population of 4 pairs or 1% of the UK population or 2% of the Welsh population.
A2. Productivity/ breeding success	On Ynys Enlli, productivity is stable.	***Upper limit***: None set ***Lower limit***: 15 chicks fledging in 3 out of 5 consecutive years or > 2.5 fledglings per breeding pair
A3. Non-breeding population	On Ynys Enlli, the non-breeding flocks are stable or increasing (summer and winter).	***Upper limit*:** None set ***Lower limit***: 10 non-breeding individuals (in addition to breeding pairs and their young), summer and winter.
A4 Chough feeding	Breeding and non-breeding birds use Ynys Enlli for feeding throughout the year	***Upper limit*:** None set ***Lower limit*:** All breeding pairs, fledglings and non-breeding individuals observed feeding on the island.

4.2 Conservation Objective for Feature 2: Internationally important population (1% or more of the Great Britain population) of breeding Manx shearwaters *Puffinus puffinus.*

Vision for Feature 2: Manx shearwater.

The vision for this feature is for it to be in a favourable conservation status, where all of the following conditions are satisfied:

- Breeding population of Manx shearwater (confined to Ynys Enlli) is stable or increasing.
- Reproductive rates remain stable.
- Deaths from the lighthouse attractions, fencing and other infrastructure are minimal.
- No ground predators are introduced.
- Nesting birds are not disturbed by restoration works on boundary walls or recreational activities.
- All factors affecting the achievement of these conditions are under control.

Performance indicators for Feature 2: Manx shearwater.

The performance indicators are part of the conservation objective, not a substitute for it. Assessment of plans and projects must be based on the entire conservation objective, not just the performance indicators.

Performance indicators for feature condition		
Attribute	***Attribute rationale and other comments***	***Specified limits***
A1. Breeding population size	Breeding population of Manx shearwater (confined to Ynys Enlli) is stable or increasing	***Upper limit*:** None set ***Lower limit***: 10,000 pairs or 1% of the UK population
A2. Productivity /breeding success	Reproductive rates remain stable.	***Upper limit***: None set ***Lower limit**:* 5 year mean of 0.6 per pair. Lowest tolerable limit of >0.5 for 3 consecutive years
Performance indicators for factors affecting the feature		
Factor	***Factor rationale and other comments***	***Operational Limits***
F1. Deaths from lighthouse attraction	On dark moonless nights or when there is poor visibility due to fog, drizzle, cloud cover or rain the lighthouse attracts night flying birds. Individuals may collide with the lighthouse or become exhausted from flying repeatedly round the light.	***Upper limit:*** 30 fatalities per year or <0.3% of the Enlli population. ***Lower limit:*** Gantry lights and light exclusion zone in place annually.
F2. Deaths from barbed wire/ other fencing and similar materials.	A small number of Manx shearwater mortalities occur each year as a direct result of entanglement in barbed wire on existing fences, or fence netting. BBFO keep annual records of the number and locations of fatalities.	***Upper limit:*** 5 fatalities per year or <0.05% of the Enlli population. No unnecessary barbed wire erected. ***Lower limit:*** All unnecessary barbed wire removed.
F3. Ground-based predators	At present ground predators, such as common rat, fox, mink or hedgehog do not inhabit the island. Should such predators be introduced they could severely threaten the Manx Shearwater population. All measures must be taken to avoid their introduction.	***Upper limit:*** No domestic or wild predators introduced to the island ***Lower limit:*** None set.

F4. Avian predators	In recent years crows have been observed taking Manx shearwater eggs from burrows. If not controlled, this apparent learnt behaviour could become more widespread.	***Upper limit***: None set ***Lower limit***: All crows seen predating in burrows should be controlled
F5. Boundary wall maintenance practice	Many Manx shearwaters dig nesting burrows into both stone-faced and earth walls. Maintenance can only be carried out carefully and on a rotation, as Manx shearwaters seem to be site faithful and perhaps even burrow faithful. Although burrowing Manx shearwaters appear to benefit from easier access in derelict stone/earth boundary walls, landscape issues and other conservation features would benefit from restoration and *repair of such boundaries.* All burrows are protected under UK law. They are protected while in use by the birds as nest sites, and protected outside the nesting season by the provisions or the SSSI legislation.	***Upper limit:*** None set ***Lower limit:*** All boundary restoration work must take account of the potential effects on Manx shearwaters and must only be carried out to the strict guidelines guidelines set out in the Ynys Enlli Management Plan. All staff, contractors or volunteers working on field boundaries must be made aware of the guidelines. All field boundaries have been surveyed and the number of Manx shearwater burrows in each recorded. Boundaries have thus been categorised as to whether they are of importance to Manx shearwaters. Significant boundaries are those with 5 or more burrows per 100m
F6. Marine pollution incidents	Manx shearwaters frequently settle on the water surface to rest, swim and dive for food. They are therefore, particularly vulnerable to pollution at sea, particularly oil pollution.	***Upper limit:*** No incidences of island generated pollution. No major pollution incidents within 30 miles of Ynys Enlli ***Lower limit:*** None set.
F7. Human disturbance/ trampling	Human disturbance can be through erosion or collapse of shearwater burrows or by disturbing individuals on land at night. Collapse of burrows during the breeding season would be particularly detrimental to breeding success	***Upper limit:*** 2 burrows accidentally damaged per year ***Lower limit:*** All promoted paths should avoid Manx shearwater burrows. All visitors to be advised of sensitive areas.

4.3 Conservation Objective for Feature 3: Vegetated sea cliffs of the Atlantic and Baltic coasts (H7 *Calluna vulgaris –Scilla verna* heath, H8d *Calluna vulgaris-Ulex galli* heath, *Scilla verna* sub-community, MC8 *Festuca rubra – Armeria maritima,* MC9 *Festuca rubra – Holcus lanatus* and MC10 *Festuca rubra – Plantago spp* maritime grassland communities, coastal grassland and maritime cliff and slope).

Vision for Feature 3: Coastal heath (Dry and maritime heath) (Atlantic Sea Cliff).

The vision for this feature is for it to be in a favourable conservation status, where all of the following conditions are satisfied:

- Extent of coastal or maritime heath is stable or increasing.
- At least 2 different coastal or maritime heath NVC community types are present and support a range of characteristic plant species.
- Areas of heath form a mosaic with maritime grassland with patches of bare ground – no blanket heath cover
- Pioneer heath plants are present
- Grazing occurs annually at a level which prevents a long sward developing but does not suppress heather growth or flowering. A low sward height in grassland habitats and an open, varied structure in heath will be maintained within the cliff top habitats for feeding chough, without causing a decline in the extent or quality of the grassland and heathland.
- The coastal heath will comprise vegetation with *Ulex gallii* present and at least 30% ericoid cover, usually *Calluna vulgaris*, with at least one maritime indicator present such as *Armeria maritima, Plantago maritima, Plantago coronopus* or *Scilla verna.*
- Healthy populations of the rare vascular plants (including spotted rockrose, *Tuburaria guttata,* prostrate broom *Cytisus scoparius* subsp*, maritimus,* rock sea-lavender *Limonium britannicum* subsp. *pharense,* small adder's tongue, *Ophioglossum azoricum,* western clover, *Trifolium occidentale* and sharp rush *Juncus acutus* will be present.
- Healthy populations of rare non-vascular plant species, including moss and liverwort species with restricted European distributions, and the soil-living lichens, ciliate strap-lichen *Heterodermia leucomela* and golden hair lichen *Teloschistes flavicans* will be present.
- Species indicative of rank or unmanaged conditions including European gorse, *Ulex europeaus,* bracken *Pteridium aquilinum,* foxglove *Digitalis purpurea*, ragwort species *Senecio sp,* dock *Rumex obtusifolius* and nettle *Urtica dioica* should be largely absent:
- Grass species indicative of improvement including creeping bent *Agrostis stolonifera,* cock's foot *Dactylus glomerata,* perennial rye-grass *Lolium perenne* and Yorkshire fog *Holcus lanatus* should be largely absent.
- Associated important species such as feeding Chough and nesting Manx shearwater are recorded in coastal or maritime heath areas.
- All factors affecting the achievement of these conditions, including grazing intensity and burning, will be under control.

Performance indicators for Feature 3: Coastal heath (Dry and maritime heath) (Atlantic Sea Cliff).

The performance indicators are part of the conservation objective, not a substitute for it. Assessment of plans and projects must be based on the entire conservation objective, not just the performance indicators

Performance indicators for feature condition		
Attribute	***Attribute rationale and other comments***	***Specified limits***
A1. Extent of the coastal heath (dry and maritime)	Lower limit is based on 2003 mapped extent (mainland) and 1996 survey of Ynys Enlli.	***Upper limit*:** As limited by other habitats, but not set. ***Lower limit*:** 92.7 ha Recording should initially target those Management Units where dry heath is a Key Habitat (KH). These are all units except 1, 37, 38, 39, 41, 42
A2. Condition of of the coastal heath (dry and maritime)	At least 75% of coastal heath should be good quality open heath • Dwarf-shrubs should make up between 25-75% cover • *Ulex gallii* cover should be <50% of the dwarf-shrub cover • A quarter of the heathland vegetation will be in early pioneer stage (0-3 years old) at any time (i.e. $^{1}/_{12}$ vegetation managed in each year giving a total of ¼ in 3 years. Three year old heather is taken to be less than 5cm high). • There should be less than 5% of unbroken stands of bracken, European gorse and other scrub. • There should be no more than 5 fronds bracken or European gorse >50cm tall within a 2m radius in 75% of the habitat. • There should be less than 5% of the following grasses and weedy species indicative of improvement within a 1m radius over 75% of the site: *Agrostis stolonifera, Dactylus glomerata, Lolium perenne, Holcus lanatus, Urtica dioica and Cirsium spp.* • In maritime heath one of the following should be present: *Scilla verna, Armeria maritime* or *Plantago maritima.*	***Upper limit*:** Not required ***Lower limit*:** At least 75% of coastal heath should be good quality open heath Recording should initially target those Management Units where dry heath is a Key Habitat (KH). These are all units, except 1, 37, 38, 39, 41, 42 The specified limits also meet the requirements for maritime grassland, chough and lichen interests.
A3. Associated significant features	This habitat needs to meet the requirements for other habitats and species associated with coastal or maritime heath, including maritime grassland, chough, lichens (ciliate strap-lichen *Heterodermia leucomela* and golden hair lichen *Teloschistes flavicans)* and rare vascular plants (particularly spotted rockrose, *Tuberaria guttata).*	***Upper limit:*** Same as lower limit. ***Lower limit:*** Chough should be recorded using all areas of maritime heath for feeding. Nationally significant lichen species should be present. Healthy populations of nationally rare vascular plants should be present.

Performance indicators for factors affecting the feature		
Factor	***Factor rationale and other comments***	***Operational Limits***
F1. Grazing	Coastal heath and grasslands require grazing to maintain a good open structure and to prevent the heath becoming dominated by scrub, bracken and gorse. Ideally, cattle and ponies are preferable to sheep as they are less- selective grazers. Graziers must be encouraged to appropriately graze the two blocks of common in this site: Mynydd Anelog and Mynydd Bychestyn. The number of active graziers has been falling in recent years. At present, only two graziers are associated with Mynydd Bychestyn, and exact graziers of Mynydd Anelog are unknown.	***Upper limit:*** Grazing levels will not lead to excessive poaching damage or reduction of dwarf-shrub cover to below 25%. ***Lower limit:*** The site will be lightly grazed by a mixture of stock during the spring and summer.
F2 Burning	Burning is likely to favour bracken and western gorse, so this should not be used as a management tool where these species are likely to invade. Cutting may be more appropriate in these areas. Some cutting or burning management is necessary to maintain a diverse age structure. This should occur as long-term small-patch burning on a 12-year rotation. Burning should not occur unless followed up by grazing.	***Upper limit:*** To maintain open heathland the dwarf-shrub vegetation will be managed by burning or cutting on a 12 year rotation so that $^{1}/_{12}$ of the habitat will be managed each year. ***Lower limit:*** A quarter of the heathland vegetation will be in early pioneer stage (0-3 years old) at any time.
F3 Bracken	Bracken does dominate large areas of the cliffs and has spread up into the heath in places. This has happened due to decreased grazing pressure and a shift away from cattle grazing. Heavy stock control bracken by damaging the rhizomes and crushing new growth.	***Upper limit:*** There should be no more than 5 fronds bracken within a 2m radius in 75% of the habitat. ***Lower limit***: There should no more than 5% of unbroken stands of bracken.

Site-specific habitat definitions	
Open coastal heath	Dwarf-shrub vegetation where ¼ of the vegetation has been cut or burnt within the last 3 years and is in early pioneer stage. To maintain open heathland the dwarf-shrub vegetation will be managed by burning or cutting on a 12 year rotation so that $^1/_{12}$ of the habitat will be managed each year. On *Ulex gallii* dominated heath the minimum rotation recommended is 12 years to help break *Ulex* dominance. On sites with no particular species interest a longer rotation is recommended, however where chough are present there is a need to maintain open vegetation so the minimum 12 year rotation is considered most appropriate. Rapid *Ulex* re-growth will be controlled by appropriate grazing.

5. ASSESSMENT OF CONSERVATION STATUS AND MANAGEMENT REQUIREMENTS

This part of the document provides:

- A summary of the assessments of the conservation status of each feature.
- A summary of the management issues that need to be addressed to maintain or restore each feature.

5.1 Conservation Status and Management Requirements of Feature 1: Internationally important population (1% or more of the Great Britain population) of breeding and non-breeding season chough *Pyrrhocorax pyrrhocorax.*

Conservation Status of Feature 1: Chough.

The condition of the chough population at January 2008 is **Favourable, Maintained.**

The past two or three decades have seen the UK chough population as a whole stabilising while populations around the Welsh coast appear to be making a recovery in numbers. At a local level the breeding population has been stable over the last 10 years and there is no evidence that the area included within the SPA boundary as a whole has ever supported significantly higher numbers of breeding birds.

However, it is important to note that recent grazing regimes on Ynys Enlli have led to decline in some areas of chough feeding habitat and that non-breeding summer flocks have declined in recent years. The non-breeding flock may have been lost to nearby areas on the mainland where chough feeding habitat may have increased in quality and extent. It cannot be assumed that breeding and non-breeding populations on Ynys Enlli will be secure in the medium or long term. Suitable alterations in habitat management, particularly grazing regimes have the potential to improve the quality and extent of chough feeding areas on the island and reverse the recent decline in some areas.

Management Requirements of Feature 1: Chough

Habitat Type

Choughs use a wide variety of invertebrate-rich habitats, including improved semi-improved and unimproved pasture, lowland, coastal and maritime heath, arable stubble and maritime grassland. In addition, Ynys Enlli is the only place in Wales where choughs have regularly been recorded feeding on invertebrates in accumulated rotting seaweed, regularly sighted on the beach at Solfach. Stone features such as rocky outcrops and traditional cloddiau are also important, particularly where bare earth is evident. Grazed earth banks provide an additional important feeding habitat. Management to maintain short swards, through for example grazing, is important to allow choughs easy access to the ground. Adjacent area of grazed pasture outside the boundary of the site are also important to the population as they are also used by chough who access them for feeding.

Breeding choughs nest on rocky ledges, the majority of which are around the mainland coast, but some sites have been recorded on Mynydd Enlli. Due to their inaccessibility, these areas are largely self-maintained. Climbing near known nest sites apparently being effectively controlled by voluntary codes of conduct.

Grazing and Sward Height

Short swards and bare ground are important for feeding choughs as they allow easy access to invertebrate food in the soil and on the ground surface. In some areas, these conditions can be created and maintained by natural conditions (e.g. wind and salt spray, naturally formed thin soils over/around rock outcrops); elsewhere management is a necessity. In most cases management of short swards and bare ground is maintained through suitable grazing regimes. Grazing animals also provide an additional source of food for chough by creating dung invertebrate habitats. Burning can also be an important management activity, reducing vegetation height and exposing bare ground.

Winter grazing should be carried out to help maintain a short sward throughout the year. Wherever possible, a variety of stock type (sheep, cattle or ponies) should be used. Grazing with cattle or ponies should be should be encouraged in any areas where they will not compromise other conservation interests. The feasibility of introducing more cattle or ponies should be investigated

Stock Type

The type of stock used will affect the type of sward achieved and dung produced. Beetles and other insects associated with animal dung are a major component of the chough's diet (McCracken & Foster 1990). The practice of wintering stock outside provides an ongoing supply of dung. Sheep tend to graze close to the ground and produce close-cropped swards beneficial to feeding chough. Cattle tend to graze longer vegetation and can deal with rank grasses, which sheep leave. Cattle do not tend to produce close-cropped swards, but they do create a large amount of bare ground through poaching/scuffing and help control the spread of bracken/scrub which would be beneficial to feeding chough. In addition, cattle dung has been reported to support greater invertebrate populations. Grazing ponies would provide similar benefits to those of cattle.

In practice, it is the effect of the type of grazing on sward height, bare ground and dung invertebrate habitat that is important rather than the actual type of stock used. In North Wales choughs use areas grazed by sheep, ponies and cattle. Mixed grazing regimes providing a variety of chough feeding habitats would be most beneficial to chough.

Pesticides

Livestock suffer from the livestock pests, liver fluke and blowfly. The use of certain anti-parasitic drugs or worming agents such as the avermectins results in the release of chemical treatments into the wider environment through livestock dung and urine. This subsequently destroys those insects that feed on, or lay eggs in, dung. The use of such pesticides potentially reduces food supply for chough. Batten (1990) states that recently fledged birds may rely heavily on dung insects for food; as such they would be particularly affected by the use of these treatments. **A** precautionary approach is advised, and use of avermectins should be avoided.

Bracken Control

Choughs have been observed feeding in areas where bracken had been cleared but not recorded feeding in areas with thick bracken cover. Bracken control could provide additional feeding habitat to benefit chough, and may help restore heathland habitat. Bracken control on on Ynys Enlli may also help encourage non-breeding summer flocks back to feed. Control should only be undertaken where suitable grazing follow-up can be ensured to prevent bracken re-growth, which could take the form of grazing with heavier stock, or where repeat cutting is possible.

Fencing of Cloddiau

Earth and stone-faced field boundaries (cloddiau) provide an important feeding habitat for chough. It is necessary that these are grazed to prevent excessive growth of vegetation which would be of little value to feeding chough. The position of fencing on walls is therefore significant. A fence located close to the base of the wall (on one or both sides) will prevent livestock access to the wall and hence grazing.

Preferred options for the alignment of fences which also allows grazing access would be:

- along the top of walls
- along one side of the wall to allow livestock access from the other side. Fencing should be positioned at a distance which allows access to both sides of the wall from the open side.

On Ynys Enlli, if fencing along the top of the wall is proposed, potential damage to Manx shearwater burrows and the integrity of the wall itself must be evaluated.

Seaweed Clearance

On Ynys Enlli, large quantities of seaweed can be washed-up at Porth Solfach and other shores around the island. The washed up seaweed creates an important invertebrate habitat and these areas are known to be important sources of insect food for choughs (Roberts, 1983).

The presence of large quantities may be considered by some to be detrimental to aesthetics of the island. However, its removal will result in the loss of a food supply, particularly in winter when other invertebrate sources tend to be limited.

The retention of natural strandline seaweed should also occur on mainland beaches.

Arable Crops

Choughs have been recorded feeding on invertebrates and grains in cereal arable fields (McCracken & Foster 1990) and were found to use spring barley stubbles on the mainland following an RSPB trial. In general, a small number of fields are cultivated each year. Where cereals are grown, the retention of winter stubble is desirable.

Anthills

Anthills provide an important feeding habitat for chough. A number of areas on the mainland and Ynys Enlli contain anthills. In general, anthills are not under threat but activities such as mowing with a tractor driven flail may harm them and should be avoided.

Predation

Avian predators, particularly peregrine falcon *(Falco peregrinus*), may predate choughs. Control of raptors is illegal in the UK. The current impact on the chough population is thought to be low and does not require intervention.

Human Disturbance

Breeding birds are vulnerable to human disturbance during the breeding season. Disturbance may be by informal scrambling close to nest sites. Most nest sites are naturally protected from disturbance as they are in inaccessible cliff areas. Birds at the nest could potentially be disturbed by boating or diving activity in the immediate vicinity of the cliffs.

Feeding birds may also be disturbed by walkers, although chough seem generally unperturbed by passers by unless directly approached. Increases in visitor pressure may prove a cause for concern, and monitoring should be undertaken with necessary mitigation where problems exist.

5.2 Conservation Status and Management Requirements of Feature 2: Internationally important population (1% or more of the Great Britain population) of breeding Manx shearwaters *Puffinus puffinus.*

Conservation Status of Feature 2: Manx shearwaters.

The condition of the Manx shearwater population at January 2008 is **Favourable, Maintained.**

Data are not currently available for all the performance indicators listed, however the increase in population figures over a long period combined with sustained reproductive success indicates that the feature can be considered ‘favourable maintained’.

Management Requirements of Feature 2: Manx shearwaters.

The Manx shearwater population is largely self-maintaining and requires little in the form of active management. However, precautions are required to ensure that that birds are not disturbed in any way or that boundary restoration works are not harmful to breeding birds or burrow sites.

Introduction of Ground Predators

At present ground predators, such as common rat, fox, weasels, mink, hedgehog or snakes do not inhabit the island. Should such predators be introduced ,they could severely threaten the Manx shearwater population. All measures must be taken to avoid their introduction. Domestic animals, particularly cats, ferrets, and some dog breeds could pose a serious risk to shearwaters and must not be introduced. No wild or domestic animal may be brought onto Ynys Enlli without prior permission from CCW.

Predation by Birds

Leaper (2001) observed 73 corpses of Manx shearwater during the May to June survey period. 70% showed signs of attack by peregrine falcon (*Falco peregrinus*). A resident breeding pair is thought to be responsible. It is likely that a considerable proportion of the remaining casualties were due to predation by ravens, crows and gulls. Gull populations have increased considerably in the last 100 years but there is no evidence to suggest that this increase has seriously affected the numbers of Manx shearwaters in British colonies, presumably because Shearwaters come to land, and change over at the nest burrow, only at night. In recent years crows have been observed taking Manx shearwater eggs from burrows. If not controlled, this apparent learnt behaviour could become more widespread. Protected predator species such as peregrine falcon (*Falco peregrinus*) cannot be controlled. Any pairs of crows, magpies etc known to harm Manx shearwaters through, for example, the taking of eggs from burrows, should be eliminated to prevent the spread of learned behaviour. CCW consent and permit must be sought in advance of any control. Control must be by shooting or the use of Larsen traps. Control of gulls should only be undertaken if new evidence suggests that they are a serious predation problem.

Fencing and Stone/Earth Field Boundary Maintenance

Many Manx shearwaters dig nesting burrows into both stone-faced and earth walls. Of the 1,750 pairs breeding recorded in the lowlands in 1997, 94% were found to nest in boundary walls. Even remnant walls (low linear banks where stone-work has been removed) contain numerous burrows. Access can be gained more easily into remnant walls and it appears that a period of less meticulous wall repair in the middle and latter part of the 20th Century has encouraged Manx shearwaters to burrow in these remnant boundaries.

Although burrowing Manx shearwaters appear to benefit from easier access in derelict stone/earth boundary walls, landscape issues and other conservation features would benefit from restoration and repair of such boundaries. All burrows are protected under UK law. They are protected while in use by the birds as nest sites, and protected outside the nesting season by the provisions or the SSSI legislation. To ensure the interests of the island's Manx shearwater population, all boundary restoration work must take account of the potential effects on Manx shearwaters and must only be carried out to the strict guidelines outlined in the Ynys Enlli Management Plan. All staff, contractors or volunteers working on field boundaries must be made aware of the guidelines.

The island's stock proof fences are erected either on top of boundary walls or along the base of the wall. Fencing posts (particularly large straining posts) erected on the bank itself may damage the bank and interfere with burrowing sites. If such fencing is carried out during the breeding season inserted posts may intrude into a burrow and cause the burrow to cave in; obstruct the burrow entrance; or cause direct damage to eggs, nestlings or adults. Again, guidelines on fencing are available in the Ynys Enlli Management Plan. All staff, contractors or volunteers working on field boundaries must be made aware of the guidelines.

Gorse Burning

In some locations Manx shearwaters burrow beneath gorse, and some areas of gorse scrub contain a high density of Manx shearwater. It is not known whether the presence of gorse, possibly providing additional cover from predators, affects the desirability of these sites. Loss of gorse cover through burning may prove detrimental in such areas. Under UK law, lowland gorse can be burned from 1 November to 31 March. However, since Manx shearwater can be present on the island from mid-March, burning during the breeding season could potentially damage adults, eggs or chicks.
Gorse burning should be avoided in areas with a high density of burrows. Gorse burning must not be carried out between mid-February and mid-October to avoid the breeding season.

Lighthouse Attractions

On dark moonless nights or when there is poor visibility due to fog, drizzle, cloud cover or rain the lighthouse attracts night flying birds. Individuals may collide with the lighthouse or become exhausted from flying repeatedly round the light. Down-lights are fitted on each corner of the lighthouse to light the surrounding ground and encourage birds to land. Portable floodlights placed outside the lighthouse compound with the aim of attracting birds to the ground have been shown to have little or no effect in attracting Manx Shearwaters away from the lighthouse. Birds will often come to land, but once rested will return to circling the light.

On nights when large numbers of birds are attracted to the light, landed birds are collected and placed in sheds during the night to protect them from predation and prevent them from returning to circling the light. Likewise, birds found around the lighthouse compound in daylight are also collected and held in sheds to prevent attack by crows or other predators. The stored birds are released safely at dusk.

Between 1953 and 1999 660 Manx Shearwaters were killed by attraction to the lighthouse. Annual numbers vary between 1 and 42 (BBFO reports) and have risen over the period, probably in line with the overall population rise, but perhaps also due to an increase in intensity of the light in 1986. Between 1985 and 1999 the average has been nearly 25 per year (BBFO reports). Attractions peak in late May and August and early September, the latter corresponding to the time when juveniles embark on their first flight. The majority of casualties are not ringed, indicating that they are likely to be either juveniles of that year or individuals returning to land for the first time to breed.

It is not known whether measures to reduce mortalities significantly reduce the number of resultant deaths, however, they will have some positive impact. The current mortality rate of Manx shearwaters resulting from lighthouse attractions is a small proportion of the overall population (<0.25%) and therefore not considered a cause for concern.

- The two down-pointing sodium lights positioned immediately below the balcony railings at the NE and SW corners of the lighthouse tower should be maintained and in operation. These light the ground below the lighthouse.
- Maintain the blocked-off section of glazing in the lighthouse to produce a 'dark area' which breaks the circle of the beams and creates a non-lit area towards Mynydd Enlli in the NE.

- Manx shearwaters landing in the lighthouse compound during attractions should continue to be collected and placed in sheds before being released the following evening. Collection should take place both during the attraction and the following morning if necessary

Human Disturbance

Human disturbance can be through erosion or collapse of shearwater burrows or by disturbing individuals on land at night. Collapse of burrows during the breeding season would be particularly detrimental to breeding success. Boating and diving activity in the vicinity of the island may lead to the disturbance of feeding Manx shearwater. There are currently no official constraints on any vessels operating around the island, either in terms of speed restrictions or exclusion zones/periods.

- Visitors and new residents should be informed of the presence of Manx shearwaters and the importance of the island's population. They should be advised to avoid sensitive areas and to avoid disturbance.
- Paths should be diverted away from sensitive areas.
- Visitors should be advised not to walk on burrows or field boundary walls.

Disturbing Manx shearwaters in the course of scientific research (ringing, intrusive survey techniques etc) is strictly regulated by law. CCW permits and ringing permits are required for individuals studying/ringing Manx shearwaters. In general all activity on the island complies with the necessary regulations and is not considered a threat to the well being of the birds.

Egg Collecting and Taking of Birds for Scientific Purposes

Earlier this century, collecting eggs and chicks for food may have been significant on the island. Today the collection of birds or their eggs is prohibited under UK law. There is the possibility that eggs could be taken illegally for collections; however, it is thought that, if at all, this is a very rare occurrence on Enlli. The taking of birds and eggs for scientific research is also strictly regulated by law and require a permit from CCW. Current activities on the island comply with the necessary regulations.

Pollution at Sea

Manx shearwaters frequently settle on the water surface to rest, swim and dive for food. They are therefore, particularly vulnerable to pollution at sea, particularly oil pollution. Small-scale oil or chemical pollution may be caused by discharges from small boats in the vicinity of Ynys Enlli or spill during the transfer of oil or diesel supplies to the island from boats. Providing such discharges are small and infrequent, natural currents around the island should disperse pollutants and therefore will not pose a great threat. Manx shearwaters may also suffer through ingestion of discarded plastic articles. The species features little among beached corpses and the actual affects of localised marine pollution are not known.

There is also a risk of a major oil spill from heavy tanker traffic in the Irish Sea and the potential for future oil and gas exploration or drilling in nearby waters. Large-scale oil or chemical pollution incidents are rare but could have devastating consequences. Prevention of such incidents is outside of the scope of this management plan. Ensuring that appropriate emergency response plans are in place will help to minimise impact in such an event.

Fishing, Food Availability and Feeding Conditions

Food supply is clearly a key factor in influencing Manx shearwater populations, however, they feed over very large sea areas and fish stocks and fishing pressures are beyond the scope of this management plan. Certain fishing practices may also harm Manx shearwaters, as they may become trapped and drown in monofilament nets as they dive for fish. Such pressures are also outside of the remit of this plan.

5.3 Conservation Status and Management Requirements of Feature 3: Vegetated sea cliffs of the Atlantic and Baltic coasts (H7 *Calluna vulgaris –Scilla verna* heath, H8d *Calluna vulgaris-Ulex galli* heath, *Scilla verna* sub-community, MC8 *Festuca rubra – Armeria maritima,* MC9 *Festuca rubra – Holcus lanatus* and MC10 *Festuca rubra – Plantago spp* maritime grassland communities, coastal grassland and maritime cliff and slope).

Conservation Status of Feature 2: Coastal heath (Dry and maritime heath) (Atlantic Sea Cliff)

The condition of the dry coastal and maritime heaths (Atlantic Sea Cliff) at January 2008 is **Unfavourable, Recovering.**
The condition of the feature was assessed by using sample plots placed in key areas of maritime grassland and maritime or coastal heath (SAC Monitoring Report 09/01/04). Overall, the vegetated sea cliffs were recorded to be in an unfavourable condition, although separate monitoring of the coastal or maritime heath on Ynys Enlli in 2003 found that it was Favourable, Recovering.

On Ynys Enlli, areas of coastal heath which were historically overgrazed have recovered considerably since the 1980's and early 90's. In all grazing compartments heather cover is at an acceptable level and pioneer and mature plants are present along with characteristic species. There is no immediate risk of loss or sudden decline. Choughs are known to feed in all areas and associated soil lichens and notable vascular plants are present in healthy populations. All compartments are grazed annually and are not at risk of agricultural improvement or other development. Bracken, gorse and other negative species are within specified limits. Erosion is restricted to a few narrow paths. However, some areas are currently under-grazed where sward height exceeds specified limits. Future adjustments to the grazing regime should address this issue; hence the condition of coastal or maritime heath is considered 'favourable recovering'.

(Note caution regarding the definition of dry heath. This is not officially is not a feature of this the Clogwyni Pen Llŷn SAC. Considering that dry heath is makes up a large percentage of this site and it is a notified feature of the component SSSIs it makes little sense that it has not been designated as a SAC feature, and it is intended to rectify this situation).

The populations of rare vascular plants on the mainland, particularly spotted rockrose, *Tuberaria guttata* and prostrate broom *Cytisus scoparius* subsp, *maritimus*, **and the mainland soil-lichens** ciliate strap-lichen <u>*Heterodermia leucomela*</u> and golden hair lichen *Teloschistes flavicans* are all considered to be Unfavourable, Declining.

Management Requirements of Feature 3: Dry heath (Atlantic Sea Cliff)

<u>**Rare vascular and non-vascular plants:**</u>
Myndd Mawr is an extremely important site for spotted rockrose *Tuberaria guttata* which is found on the summit and slopes of Mynydd y Gwyddel. This is the only site for the species on mainland Wales. The population has been closely monitored and shows fluctuations in size and extent, although the ephemeral life cycle of this species means that such counts may not give a complete picture. The plants are much smaller and less luxuriant than plants at a comparable location on Anglesey. Sheep grazing is thought to reduce the vigour of the population and is therefore threatening its long-term survival. There are proposals to reduce sheep grazing in favour of ponies which should help halt the decline of this species in particular.
Prostrate broom *Cytisus scoparius* subsp, *maritimus* occurs on the cliff above the important geological exposure at Parwyd. The cliff top is fenced off from the heavily grazed improved fields behind, although the fence doesn't quite meet the cliff edge and the sheep can get around the fence at the edges and obviously do graze occasionally. A 1993 survey found plants occuring on both the actual cliff and on the cliff top fenced off section. Growth on the cliff was recorded as more luxuriant than the stunted, grazed plants on the cliff top, and repair of the fencing would prevent grazing and allow further recovery of this species.

The two rare soil lichen species, golden hair lichen *Teloschistes flavicans* and ciliate strap lichen *Heterodermia leucomela* are present on the Mynydd Mawr. The former is found on rocky outcrops and short turf the latter is found primarily at the heathland/coastal grassland transition. Again, they are both less luxuriant than at their Ynys Enlli locations. Both species of lichen and the spotted rockrose are very sensitive to burning and every effort should be made to prevent burning where they occur.

Grazing:

The 2004 assessment of condition was based on the fact that habitat was under-grazed in parts and overgrazed in parts. Some good quality western gorse heath is found on the National Trust land but in places this has become invaded by bracken due to undergrazing. Bracken encroachment is also a serious problem in some sections of the site. There has been a more active management of sections of the heath since this assessment, including bracken control and rotational cutting of some areas, hence the current qualifier that it is recovering. The NT has been active in controlling bracken at its holding at Muriau, and work has been carried out recently at Pen y Cil and on Ynys Enlli.

In 2005, a Management Schedule was drawn up for four sections of the site, Mynydd Anelog, Mynydd Mawr, Mynydd Bychestyn and Pen y Cil, involving partners including NT, RSPB, Cyngor Gwynedd and CYMAD. Some of the work was implemented under the Cadw’r Lliw yn Llyn project, and further work will be implemented as part of the Llyn Heaths Project which has just gained Heritage lottery funding. Sympathetic grazing regimes with heavy stock, the establishment of cutting and burning of heath blocks on long rotation, and control of gorse and bracken form the backbone of these plans.

In the long-term favourable condition of the vegetation will only be achieved with appropriate grazing. Grazing should remove excess grass growth preventing the build-up of litter and a dense thatch. Grazing should also remove young western gorse and a small proportion of ericoid (heather) growth. Heavy grazing in the autumn can result in excessive removal of ericoids resulting in their gradual replacement by western gorse. Grazing is best focused early in the season when grasses and young gorse are most palatable. Heavy livestock such as cattle or ponies are better than sheep at controlling both gorse and bracken regeneration.

Burning/Cutting

Management will promote the development of more diverse heathland vegetation with an increase in the cover and abundance of ericoids (bell heather *Erica cinerea* and common heather *Calluna vulgaris*) and a concurrent decrease in the dominance of western gorse *Ulex gallii*. Structural diversity will be improved by rotational management to provide areas of short open heath with all the intermediate stages through to tall mature heath. A rotation of 12 years or more is recommended to break the dominance of western gorse. Burning tends to encourage the spread and dominance of western gorse and bracken therefore burning of heathland will be discouraged during the restoration phase but may be reintroduced at a later date for maintenance management. Restoration management will be carried out by patch cutting with patches measuring approximately 0.5-1ha.

6. ACTION PLAN: SUMMARY

This section takes the management requirements outlined in Section 5 a stage further, assessing the specific management actions required on each management unit. This information is a summary of that held in CCW's Actions Database for sites, and the database will be used by CCW and partner organisations to plan future work to meet the Wales Environment Strategy targets for sites.

Unit Number	CCW Database Number	Unit Name	Summary of Conservation Management Issues	Action needed?
001	001683	Unit 1 Intertidal	Identify any issues and remedies through the updating and revision of the SAC management plan for Pen Llyn a'r Sarnau SAC in 2008-09. This work to be led by the relevant authorities for the SAC (Countryside Council for Wales, Gwynedd Council, Ceredigion County Council, Powys County Council, Snowdonia National Park Authority, North Western & North Wales Sea Fisheries Committee, Environment Agency Wales, Dwr Cymru, Severn Trent Water and Trinity House), working with the SAC Liaison Group and other groups, organisations and individuals.	No
002	001684	Unit 2a Porth Oer	Overgrazing with sheep an issue here - needs to be lighter, possibly the timing adjusted to allow for heavier grazing in the spring. Ideally heavier stock are needed - cattle or ponies. The coastal path is a constraint for cattle grazing - long-term aim to open up the coastal corridor a field back to allow freer stock movement or incorporate 'break-outs' along the path.	Yes
003	001685	Unit 2b Porth Oer	Overgrazing with sheep an issue here - needs to be lighter, possibly the timing adjusted to allow for heavier grazing in the spring. Ideally heavier stock are needed - cattle or ponies. The coastal path is a constraint for cattle grazing - long-term aim to open up the coastal corridor a field back to allow freer stock movement or incorporate 'break-outs' along the path.	Yes
004	001686	Unit 3a Carreg Farm	Overgrazing with sheep an issue here - needs to be lighter, possibly the timing adjusted to allow for heavier grazing in the spring. Ideally heavier stock are needed - cattle or ponies. The coastal path is a constraint for cattle grazing - long-term aim to open up the coastal corridor a field back to allow freer stock movement or incorporate 'break-outs' along the path.	Yes
005	001687	Unit 3b Carreg Farm	Problem here possibly undergrazing - need to negotiate increased grazing levels and appropriate stock management - again heavier stock would be desirable.	Yes
007	001689	Unit 3c Carreg Farm	Units 34 and 35 run together. Land tends to be grazed in winter, with nothing in spring. Emphasis of grazing pattern needs to change to spring grazing.	Yes
008	001690	Unit 4a Mynydd Anelog	Units 34 and 35 run together. Land tends to be grazed in winter, with nothing in spring. Emphasis of grazing pattern needs to be changed to spring grazing. Previous issues with illegal spreading of slurry on heath and cutting. Shetland ponies recently introduced.	Yes

Unit Number	CCW Database Number	Unit Name	Summary of Conservation Management Issues	Action needed?
009	001701	Unit 4b Mynydd Anelog	Common land, open to Unit 37. However ownership of the common unclear, and grazing levels are unmanaged. Heath used to overgrazed, now probably undergrazed, but good quality.	Yes
010	001702	Unit 4c Mynydd Anelog	Common land belonging to the National Trust. Used to be heavily overgrazed, but stocking levels have dramatically dropped in recent years, and now undergrazed. Only active grazier is at Anelog Farm. The common is open to Unit 36. Bracken control is needed. Heavy stock grazing, ideally ponies, would be desirable here.	Yes
011	001703	Unit 4d Mynydd Anelog	Very small unit. Management unknown.	Yes
012	001704	Unit 4e Mynydd Anelog	Very small unit. Management unknown.	Yes
013	001707	Unit 5a Porth Llanllawen	Historically deliberately heavily grazed for Chough. Now managed along with land under S15 Management Agreement and heath in good condition. Gorse control under the agreement, and bracken controlled 2007 by NT.	Yes
014	001711	Unit 5b Porth Llanllawen	Historically deliberately heavily grazed for Chough. Now managed along with land under S15 Management Agreement and heath in good condition. Gorse control under the agreement, and bracken controlled 2007 by NT.	Yes
015	001713	Unit 6 Llanllawen Fawr	Historically deliberately heavily grazed for Chough. Now managed along with land under S15 Management Agreement and heath in good condition. Gorse control under the agreement, and bracken controlled 2007 by NT.	Yes
016	001714	Unit 7a Braich y Pwll	Historically deliberately heavily grazed for Chough. Now managed along with land under S15 Management Agreement and heath in good condition. Gorse control under the agreement, and bracken controlled 2007 by NT.	Yes
017	001716	Unit 7b Braich y Pwll	Generally overgrazed, with most serious effects in Unit 46, which is open to adjoining units. Tuberaria guttata occurs here at its only mainland site and is suffering from the effects of sheep grazing. To protect this species, the grazing needs to be modified to lighter pony grazing, with possibly a complete break from grazing for a period to allow the population to recover. Impacts also on soil lichens Heterodermia and Teloschistes which also occur here. Burning at this site inappropriate at this stage due to areas over-burned in the past, and cutting favoured instead, along with bracken and gorse control. RSPB involvement necessary due to importance of area for chough, but the mosaic habitat which should develop will support both heath and associated vascular and non-vascular species and chough. TG agreement being negotiated.	Yes

Unit Number	CCW Database Number	Unit Name	Summary of Conservation Management Issues	Action needed?
018	001721	Unit 7c Braich y Pwll	Generally overgrazed, with most serious effects in Unit 46, which is open to adjoining units. Tuberaria guttata occurs here at its only mainland site and is suffering from the effects of sheep grazing. To protect this species, the grazing needs to be modified to lighter pony grazing, with possibly a complete break from grazing for a period to allow the population to recover. Impacts also on soil lichens Heterodermia and Teloschistes which also occur here. Burning at this site inappropriate at this stage due to areas over-burned in the past, and cutting favoured instead, along with bracken and gorse control. RSPB involvement necessary due to importance of area for chough, but the mosaic habitat which should develop will support both heath and associated vascular and non-vascular species and chough. TG agreement being negotiated.	Yes
019	001722	Unit 8 Porth Felen	Possible issues with grazing type and timing. Narrow strip above cliffs with improved pasture behind.	Yes
020	001724	Unit 9	This section has become quite rank in recent years, and the timing of grazing is probably the problem. NT tenancy renewed recently with conservation clause for variation of grazing regime as necessary. Stocking will be 50 sheep in Spring then remove half for the rest of the grazing season. Cattle will be run in the field adjoining with access to the coastal strip. Gorse control by NT.	Yes
021	001728	Unit 10a Mynydd Bychestyn	Common dominated by western gorse with very little heather. Currently sheep grazed autumn/winter, but stock absent in spring, so grazing regime issues need to be resolved. Studies have revealed an absence of heather seed in the soil seed bank, almost certainly due to past frequent over-burning. Seedbank needs to be restored artificially, by cutting patches and putting on heather brash harvested by brush-cutter from adjoining land in Sept/Oct, or burning heather brash on scarified land to stimulate seed. Subsequently, cattle grazing could be introduced, through management agreement with CCW.	Yes
022	001729	Unit 10b Mynydd Bychestyn	Common dominated by western gorse with very little heather. Currently sheep grazed autumn/winter, but stock absent in spring, so grazing regime issues need to be resolved. Studies have revealed an absence of heather seed in the soil seed bank, almost certainly due to past frequent over-burning. Seedbank needs to be restored artificially, by cutting patches and putting on heather brash harvested by brush-cutter from adjoining land in Sept/Oct, or burning heather brash on scarified land to stimulate seed. Subsequently, cattle grazing could be introduced, through management agreement with CCW.	Yes

Unit Number	CCW Database Number	Unit Name	Summary of Conservation Management Issues	Action needed?
023	001730	Unit 10c Mynydd Bychestyn	Common dominated by western gorse with very little heather. Currently sheep grazed autumn/winter, but stock absent in spring, so grazing regime issues need to be resolved. Studies have revealed an absence of heather seed in the soil seed bank, almost certainly due to past frequent over-burning. Seedbank needs to be restored artificially, by cutting patches and putting on heather brash harvested by brush-cutter from adjoining land in Sept/Oct, or burning heather brash on scarified land to stimulate seed. Subsequently, cattle grazing could be introduced, through management agreement with CCW.	Yes
024	001732	Unit 11 Parwyd	Prostrate broom occurs here on the cliffs of Parwyd. Fenced off section at the top of the cliff is not fully stockproof, allowing some sheep access, and the broom may be being constrained to the inaccessible cliff because of this. Improved land above heavily grazed, but on thin soils and very exposed to salt-laden wind so potential for restoration/expansion of martime grassland area. Possible management agreement or Llyn Partnership project.	Yes
025	001734	Unit 12a Pen y Cil	Moderate to heavy sheep grazing, with areas that are grassy with agricultural weeds due to previous stock feeding. Some nice areas of maritime grassland. Heavier stock would help break up the land and create opportunities for heath colonisation/expansion. Burning plan needs to be developed - burning on the coastal slopes with dense gorse has been consented previously to allow stock access.	Yes
026	001736	Unit 12b Pen y Cil	Moderate to heavy sheep grazing, with areas that are grassy with agricultural weeds due to previous stock feeding. Some nice areas of maritime grassland. Heavier stock would help break up the land and create opportunities for heath colonisation/expansion. Burning plan needs to be developed - burning on the coastal slopes with dense gorse has been consented previously to allow stock access.	Yes
027	001738	Unit 12c Pen y Cil	Small unit. No known issues.	No
028	001742	Unit 13a Porth y Pistyll	No known issues.	No
029	001743	Unit 13b Porth y Pistyll	No known issues.	No
031	001745	Unit 15 Cwrt (inc Porth Meudwy)	Large unit owned by NT and tenanted by Cwrt includes coast from Porth y Pistyll to Porth Simdde. Issues with accessibility to stock, leading to areas which are dominated by bracken and scrub. Water supply also an issue if grazing to be encouraged. Cwrt has an existing TG agreement.	Yes
034	001748	Unit 16. Porth Simdde	No known issues. Scrub?	No

Unit Number	CCW Database Number	Unit Name	Summary of Conservation Management Issues	Action needed?
035	001749	Unit 17a Ynys Enlli	Interior land on Ynys Enlli; mainly agricultural land with the SAC features mainly confined to the coastal areas and Mountain in Unit 66. Land covered by Management Agreements with BITL, BBFO and new agreement being negotiated with RSPB and sub-tenant with project proposals identified annually. Lowland gorse burning on rotation, annual bracken cutting, drainage and boundary management issues in this area.	Yes
036	001750	Unit 17b Ynys Enlli	Lighthouse compound. Current issues relate to proposals for wind turbines and solar panels.	Yes
037	001751	Unit 18a Ynys Gwylan Fawr	This unit is considered to be under appropriate conservation management.	No
038	001752	Unit 18b Ynys Gwylan Fach	This unit is considered to be under appropriate conservation management.	No
039	002054	Unit 1a Intertidal	Porth Oer. Not included in Pellyn a'r Sarnau SAC, but part of Clogwyni Penllyn SACand Glannau Aberadaron SPA, underpinned by Glannau Aberdaron SSSI.	Yes
041	002056	Unit 17c Ynys Enlli	Unit includes coastal land and mountain land which supports th majority of the SAC features. A management agreement exists with BBFO, BITL and a new agreement is being negotiated with RSPB as BITL tenant, and their sub-tenant. Management under this agreement already being implemented, including cattle grazing of the mountain and gorse burning on 7 year rotation. The overall condition of the site features are favourable or unfavourable improving, and this will be maintained by this management.	Yes
042	002383	Unit 14 Bardsey Island SSSI-marine 1	Identify any issues and remedies through the updating and revision of the SAC management plan for Pen Llyn a'r Sarnau SAC in 2008-09. This work to be led by the relevant authorities for the SAC (Countryside Council for Wales, Gwynedd Council, Ceredigion County Council, Powys County Council, Snowdonia National Park Authority, North Western & North Wales Sea Fisheries Committee, Environment Agency Wales, Dwr Cymru, Severn Trent Water and Trinity House), working with the SAC Liaison Group and other groups, organisations and individuals.	No
043	002925	Unit 7d Braich y Pwll	This unit is considered to be under appropriate conservation management.	No

7. GLOSSARY

This glossary defines the some of the terms used in this **Core Management Plan**. Some of the definitions are based on definitions contained in other documents, including legislation and other publications of CCW and the UK nature conservation agencies. None of these definitions is legally definitive.

Action	A recognisable and individually described act, undertaking or **project** of any kind, specified in section 6 of a **Core Management Plan** or **Management Plan**, as being required for the **conservation management** of a site.
Attribute	A quantifiable and monitorable characteristic of a **feature** that, in combination with other such attributes, describes its **condition**.
Common Standards Monitoring	A set of principles developed jointly by the UK conservation agencies to help ensure a consistent approach to **monitoring** and reporting on the **features** of sites designated for nature conservation, supported by guidance on identification of **attributes** and monitoring methodologies.
Condition	A description of the state of a feature in terms of qualities or **attributes** that are relevant in a nature conservation context. For example the condition of a habitat usually includes its extent and species composition and might also include aspects of its ecological functioning, spatial distribution and so on. The condition of a species population usually includes its total size and might also include its age structure, productivity, relationship to other populations and spatial distribution. Aspects of the habitat(s) on which a species population depends may also be considered as attributes of its condition.
Condition assessment	The process of characterising the **condition** of a **feature** with particular reference to whether the aspirations for its condition, as expressed in its **conservation objective**, are being met.
Condition categories	The **condition** of **feature** can be categorised, following **condition assessment** as one of the following[2]: Favourable: maintained; Favourable: recovered; Favourable: un-classified Unfavourable: recovering; Unfavourable: no change; Unfavourable: declining; Unfavourable: un-classified Partially destroyed; Destroyed.
Conservation management	Acts or undertaking of all kinds, including but not necessarily limited to **actions,** taken with the aim of achieving the **conservation objectives** of a site. Conservation management includes the taking of statutory and non-statutory measures, it can include the acts of any party and it may take place outside site boundaries as well as within sites. Conservation management may also be embedded within other frameworks for land/sea management carried out for purposes other than achieving the conservation objectives.
Conservation objective	The expression of the desired **conservation status** of a **feature,** expressed as a **vision for the feature** and a series of **performance indicators**. The conservation objective for a feature is thus a composite statement, and each feature has one conservation objective.

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[2] See JNCC guidance on Common Standards Monitoring http://www.jncc.gov.uk/page-2272

Conservation status	A description of the state of a **feature** that comprises both its **condition** and the state of the **factors** affecting or likely to affect it. Conservation status is thus a characterisation of both the current state of a feature and its future prospects.
Conservation status assessment	The process of characterising the **conservation status** of a **feature** with particular reference to whether the aspirations for it, as expressed in its **conservation objective**, are being met. The results of conservation status assessment can be summarised either as ‘favourable’ (i.e. conservation objectives are met) or unfavourable (i.e. conservation objectives are not met). However the value of conservation status assessment in terms of supporting decisions about **conservation management**, lies mainly in the details of the assessment of feature **condition**, **factors** and trend information derived from comparisons between current and previous conservation status assessments and condition assessments.
Core Management Plan	A CCW document containing the conservation objectives for a site and a summary of other information contained in a full site **Management Plan**.
Factor	Anything that has influenced, is influencing or may influence the **condition** of a **feature**. Factors can be natural processes, human activities or effects arising from natural process or human activities, They can be positive or negative in terms of their influence on features, and they can arise within a site or from outside the site. Physical, socio-economic or legal constraints on **conservation management** can also be considered as factors.
Favourable condition	See **condition** and **condition assessment**
Favourable conservation status	See **conservation status** and **conservation status assessment.**[3]
Feature	The species population, habitat type or other entity for which a site is designated. The ecological or geological interest which justifies the designation of a site and which is the focus of conservation management.
Integrity	See **site integrity**
Key Feature	The habitat or species population within a **management unit** that is the primary focus of **conservation management** and **monitoring** in that unit.
Management Plan	The full expression of a designated site’s legal status, **vision**, **features**, **conservation objectives**, **performance indicators** and management requirements. A complete management plan may not reside in a single document, but may be contained in a number of documents (including in particular **the Core Management Plan**) and sets of electronically stored information.
Management Unit	An area within a site, defined according to one or more of a range of criteria, such as topography, location of **features**, tenure, patterns of land/sea use. The

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[3] A full definition of favourable conservation status is given in Section 4.

	key characteristic of management units is to reflect the spatial scale at which **conservation management** and **monitoring** can be most effectively organised. They are used as the primary basis for differentiating priorities for conservation management and monitoring in different parts of a site, and for facilitating communication with those responsible for management of different parts of a site.
Monitoring	An intermittent (regular or irregular) series of observations in time, carried out to show the extent of compliance with a formulated standard or degree of deviation from an expected norm. In **Common Standards Monitoring**, the formulated standard is the quantified expression of favourable **condition** based on **attributes**.
Operational limits	The levels or values within which a **factor** is considered to be acceptable in terms of its influence on a **feature**. A factor may have both upper and lower operational limits, or only an upper limit or lower limit. For some factors an upper limit may be zero.
Performance indicators	The **attributes** and their associated **specified limits**, together with **factors** and their associated **operational limits,** which provide the standard against which information from **monitoring** and other sources is used to determine the degree to which the **conservation objectives** for a **feature** are being met. Performance indicators are part of, not the same as, conservation objectives. See also **vision for the feature**.
Plan or project	**Project:** Any form of construction work, installation, development or other intervention in the environment, the carrying out or continuance of which is subject to a decision by any public body or statutory undertaker. **Plan**: a document prepared or adopted by a public body or statutory undertaker, intended to influence decisions on the carrying out of **projects.** Decisions on plans and projects which affect Natura 2000 and Ramsar sites are subject to specific legal and policy procedures.
Site integrity	The coherence of a site's ecological structure and function, across its whole area, that enables it to sustain the habitat, complex of habitats and/or the levels of populations of the species for which it is designated.
Site Management Statement (SMS)	The document containing CCW's views about the management of a site issued as part of the legal notification of an SSSI under section 28(4) of the Wildlife and Countryside Act 1981, as substituted.
Special Feature	See **feature**.
Specified limit	The levels or values for an **attribute** which define the degree to which the attribute can fluctuate without creating cause for concern about the **condition** of the **feature**. The range within the limits corresponds to favourable, the range outside the limits corresponds to unfavourable. Attributes may have lower specified limits, upper specified limits, or both.
Unit	See **management unit.**
Vision for the feature	The expression, within a **conservation objective**, of the aspirations for the **feature** concerned. See also **performance indicators.**

Vision Statement	The statement conveying an impression of the whole site in the state that is intended to be the product of its **conservation management.** A ‘pen portrait’ outlining the **conditions** that should prevail when all the **conservation objectives** are met. A description of the site as it would be when all the **features** are in **favourable condition**.

8. REFERENCES

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K. Alexander, W. Lutley & K. Hearn, 1981. National Trust Biological Survey Lleyn Peninsula (1) Aberdaron Area, Dwyfor, Gwynedd.

EC Directive 79/409 on the Conservation of Wild Birds
Citation for Potential changes to Special Protection Area (SPA)

Name: Skokholm and Skomer

Counties/Unitary Authorities: The SPA and potential extension lie within or adjacent to Pembrokeshire Unitary Authority and the landward area sits within Pembrokeshire Coast National Park. The seaward part of the proposed site sits entirely within UK territorial waters.

Boundary of the potential SPA: See potential SPA map. The proposed site extends almost to the 3 nautical mile limit with most of the site lying within the 1 nautical mile limit. Although the entire SPA sits within the Pembrokeshire Marine / Sir Benfro Forol Special Area of Conservation (SAC), only that area of the potential SPA below mean high water mark is co-incident with the SAC, which was designated by the National Assembly for Wales in December 2004 under the 1992 EC Habitats and Species Directive (92/43/EEC).

It is not intended to include any additional land areas within the potential SPA, other than a small number of very small rock outcrops that lie within the 4km radius. It would not be practical to exclude these tiny areas from the proposed extension to the SPA.

The new site includes the existing terrestrial areas designated as Skokholm and Skomer SPA by the Secretary of State for the Environment in August 1982, and as extended in 1991 under the 1979 EC Directive on the Conservation of Wild Birds (79/409/EEC).

Size of SPA: The existing site and the potential SPA combined cover an area of 14,348ha approximately.

Site description: These islands are located off the extreme south-west tip of Pembrokeshire in south-west Wales and support internationally important numbers of breeding seabirds, particularly petrels, gulls and auks. Especially notable is the high proportion, well over half, of the world population of Manx shearwater that breed here. The coastal habitats of the potential SPA also support important resident populations of chough and short-eared owl. Many of the seabirds use the sea around the islands for a number of essential activities such as preening, bathing and displaying. The nesting seabirds using the site also feed both within and outside the SPA in surrounding marine areas, as well as more distantly.

Qualifying species: The site qualifies under **article 4.1** of the Directive (79/409/EEC) as it is used regularly by 1% or more of the Great Britain population of the following species listed in Annex I, in any season:

Annex I species	Count and season	Period	% of GB population
Storm petrel *Hydrobates pelagicus* (breeding)	3500 pairs	count as at 1995	4.1%
Chough *Pyrrhocorax pyrrhocorax* (breeding)	4 pairs	count as at late 1990s	1.2%
Short-eared owl *Asio flammeus* (breeding)	6 pairs	count as at 1998	0.6%*

*Short-eared owl qualifies as an Annex 1 Species under the JNCC, UK Selection Guidelines for SPAs

The site also qualifies under **article 4.2** of the Directive (79/409/EEC) as it is used regularly by 1% or more of the GB or biogeographical population of the following regularly occurring migratory species (other than those listed in Annex I) in any season:

Migratory species	Count and season	Period	% of subspecies or population
Manx shearwater *Puffinus puffinus* (breeding)	150,968 pairs	count, as at late 1990s	56.9% of the global breeding population
Puffin *Fratercula arctica* (breeding)	9500 pairs	count as at mid 1980s	1.1% of the global breeding population
Lesser black-backed gull *Larus fuscus* (breeding)	20,300 pairs	4 year mean 1993-1997	16.4% of the breeding biogeographic region population

Assemblage qualification: The site qualifies under **article 4.2** of the Directive (79/409/EEC) as it is used regularly by over 20,000 waterbirds in any season.
In the breeding season the site regularly supports at least 394,260 individual seabirds including razorbill *Alca torda*, guillemot *Uria aalge*, kittiwake *Rissa tridactyla*, puffin *Fratercula arctica,* lesser black-backed gull *Larus fuscus,* Manx shearwater *Puffinus puffinus,* storm petrel *Hydrobates pelagicus*.

DATA: The 2001 SPA Review (Stroud *et al.,* 2001) updated the earlier assessment of UK SPAs, published in 1992, in view of new information and possible gaps. The UK Government requested the Joint Nature Conservation Committee (JNCC) to review the UK SPA network and to recommend a definitive list of sites, identified against explicit selection guidelines. This established a baseline throughout the UK against which the need for future change can be assessed. The data quoted above are taken from this 2001 review, which was based on the most current and comprehensive data that was available at the commencement of the review. They provide a comparative assessment and a fixed baseline, even though more recent data have since become available.

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Volume 3: Site accounts. 392 pp.

CYNGOR CEFN GWLAD CYMRU
COUNTRYSIDE COUNCIL FOR WALES

CORE MANAGEMENT PLAN
INCLUDING CONSERVATION OBJECTIVES

FOR

SKOMER AND SKOKHOLM SPA (SPECIAL PROTECTION AREA)

Version: 6

Date: 2 April 2008

Approved by: Tracey Lovering

A Welsh version of all or part of this document can be made available on request.

CONTENTS

PREFACE

This document provides the main elements of CCW's management plan for the site named. It sets out what needs to be achieved on the site, the results of monitoring and advice on the action required. This document is made available through CCW's web site and may be revised in response to changing circumstances or new information. This is a technical document that supplements summary information on the web site.

One of the key functions of this document is to provide CCW's statement of the Conservation Objectives for the relevant Natura 2000 site. This is required to implement the Conservation (Natural Habitats, &c.) Regulations 1994, as amended (Section 4). As a matter of Welsh Assembly Government Policy, the provisions of those regulations are also to be applied to Ramsar sites in Wales.

1. VISION FOR THE SITE

This is a descriptive overview of what needs to be achieved for conservation on the site. It brings together and summarises the Conservation Objectives (part 4) into a single, integrated statement about the site.

The maritime cliff and crevice communities, and the littoral rock communities will be present in those areas where they occur naturally around the periphery of the islands. These communities and habitats tend to be self-maintaining and do not require active intervention. Maritime grassland will be restricted to the more seaward extremities of the islands. The sward will be open and mainly close-cropped but with occasional hummocks and occasional areas of bare ground. The sward species composition will be much modified by a combination of rabbit grazing and disturbance and/or nutrient enrichment by the thousands of seabirds, and will be dominated by species characteristic of this habitat, including thrift, often found in hummocks, red fescue, sea campion, and spring squill. Bracken, scrub and Yorkshire fog will be restricted in cover.

The nationally rare and scarce plants on Skomer, including the Red Data Book species three-lobed crowfoot *Ranunculus tripartitus* and golden hair lichen *Teloschistes flavicans*, will be maintained. Objectives for each species will be developed with advice from the local BSBI recorder, and CCW specialists.

CCW's aim for the grey seal populations on the islands will be to continue to contribute towards maintaining the West Wales population.

The Skomer vole, endemic to Skomer, is strongly associated with bracken and therefore the retention of sufficient areas of bracken will be crucial to the maintenance of this species in favourable conservation status. There will be at least 15,000 individuals present every 10 years when sampled using the method as outlined by Dr. T Healing in 1992.

The populations of qualifying SPA features: chough, short-eared owl, storm petrel, lesser black backed gull, Manx shearwater and puffin, together with razorbill, guillemot, kittiwake, will meet the targets set out in their individual conservation objectives.

Vegetation of variable structure together with a much-indented and variable coastline will provide a good variety of microclimates for the numerous invertebrates that have been recorded on the island. More work will be required on the island's invertebrates and their habitat requirements before objectives can be set.

2. SITE DESCRIPTION

2.1 Area and Designations Covered by this Plan

Grid references: Skomer Island (centre) SM724094
Middleholm Island (centre) SM 746090
Skokholm Island (centre) SM 736050

Unitary authority: Pembrokeshire Coast National Park

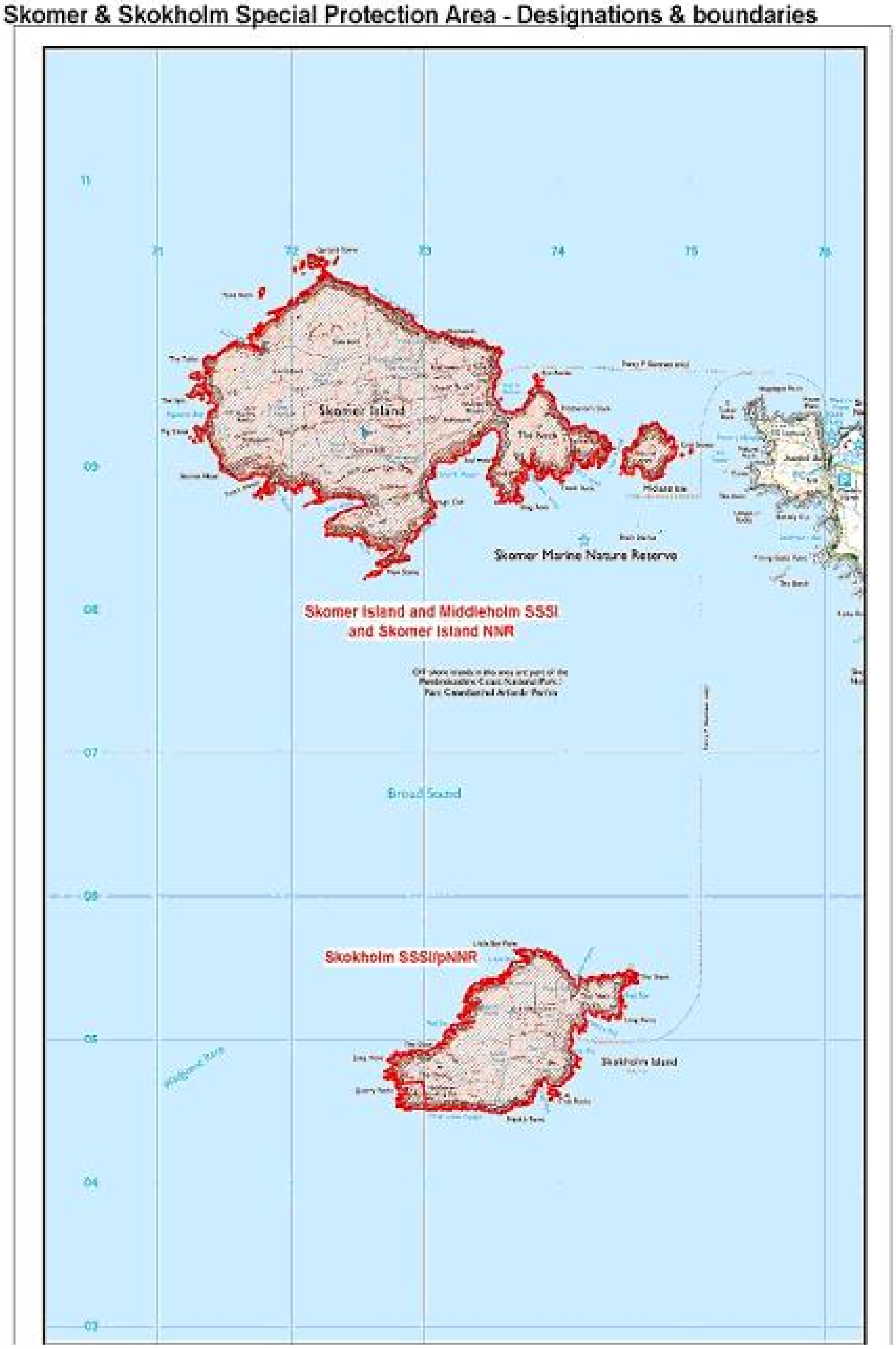
Area (hectares): 427.71

Designations covered: Skokholm SSSI
Skomer Island and Middleholm SSSI
Skomer Island NNR
Skokholm pNNR
Pembrokeshire Marine SAC (intertidal sections)
Skomer Marine Nature reserve (to HAT)

Detailed maps of the designated sites are available through CCW’s web site:

A summary map showing the coverage of this document is shown below

Skomer & Skokholm Special Protection Area - Designations & boundaries



2.2 Outline Description

Skomer Island is owned by the Countryside Council for Wales (CCW) and leased to the Wildlife Trust, South and West Wales (WTSWW). The foreshore around both Skomer and Middleholm is leased to CCW from the Crown Estate. Middleholm is owned by the National Trust. Skomer Island down to Mean Low Water Mark, and the foreshore around Middleholm, is designated as a National Nature Reserve. The foreshore from Highest Astronomical Tide (HAT) seawards is included within Skomer Marine Nature Reserve. The foreshore and the cliff faces are also included within Pembrokeshire Marine/Sir Benfro Fôrol Special Area for Conservation (SAC) for its reef and grey seal features, and for otter, an occasional visitor to the islands. Skomer Island and Middleholm are part of the Skomer and Skokholm Special Protection Area (SPA).

Skokholm Island is owned mainly by the WTSWW, except for a small area around the lighthouse that is owned by Trinity house Lighthouse Service. The foreshore (up to MHWM) is also included within Pembrokeshire Marine/Sir Benfro Fôrol Special Area for Conservation (SAC) for its reef and grey seal features. Skokholm form the remaining part of the Skomer and Skokholm Special Protection Area (SPA).

The site as a whole is of special interest for its breeding seabird colonies, in particular for Manx shearwater *Puffinus puffinus*, puffin *Fratercula arctica*, storm petrel *Hydrobates pelagicus*, razorbill *Alca torda*, guillemot *Uria aalge*, lesser black-backed gull *Larus fuscus*, kittiwake *Rissa tridactyla*, as well as for breeding chough *Pyrrhocorax pyrrhocorax* and short-eared owl *Asio flammeus.* Skomer and Skokholm islands are part of the National Seabird Monitoring Programme, and as a result there is considerable research, monitoring and surveillance effort undertaken here, which allows us to monitor and report back on a good range of attributes of these species, including breeding productivity, and survival rates. Grey seal *Halichoerus grypus* regularly use the site to haul-out and/or breed. The endemic Skomer vole *Clethrionomys_glareolus skomerensis* also breeds on Skomer Island, and a number of nationally rare and scarce plants and lichens occur including three-lobed crowfoot *Ranunculus tripartitus* the scheduled golden hair lichen *Teloschistes flavicans* and an assemblage of nationally scarce lichens.

2.3 Outline of Past and Current Management

The islands' flora and fauna have been created and maintained by a combination of traditional farming methods such as grazing and mowing (and to a lesser extent, burning), and by natural processes such as exposure to wind, salt spray, waves, and drought conditions. The many thousands of seabirds which use the islands have also contributed to the vegetation types and species present, principally through disturbance, or through the deposition of guano, both of which has resulted in local nutrient enrichment. The majority of present day management is directed towards the management of visitors and visitor facilities such as footpaths. There is some vegetation management including bracken control but, for the most part, these habitats are maintained by natural processes. Habitat and species management tends to be restricted to scything, hand pulling, 'bruising' and brush cutting of bracken along all path edges, rabbit exclosures and other small areas, and occasional use of Asulam for chemical bracken control where mechanical control is problematic. Maintenance of the rabbit exclosures is on-going.

2.4 Management Units

The plan area has been divided into management units to enable practical communication about features, objectives, and management. This will also allow us to differentiate between the different designations where necessary. In this plan the management units have been based on tenure. Detailed maps showing the management units referred to in this plan are attached.

The following tables confirm the relationships between the management units and the designations covered:

Unit 1	Skokholm separate ownership unit. SPA
Unit 2	Skokholm separate ownership unit. SPA and marine SAC overlap. SPA extends down to MLWM, marine SAC extends up to top of cliff
Unit 3	Skokholm main island. SPA
Unit 4	Skokholm main island. SPA and marine SAC overlap. SPA extends down to MLWM, marine SAC extends up to top of cliff
Unit 5	Skomer. SPA
Unit 6	Skomer. SPA and marine SAC overlap. SPA extends down to MLWM, marine SAC extends up to top of cliff
Unit 7	Middleholm. SPA
Unit 8	Middleholm. SPA and marine SAC overlap. SPA extends down to MLWM, marine SAC extends up to top of cliff
Unit 9	Middleholm. SPA, marine SAC and MNR overlap. SPA extends down to MLWM, marine SAC extends up to top of cliff, MNR extends up to HAT.
Unit 10	Skomer. SPA, marine SAC and MNR overlap. SPA extends down to MLWM, marine SAC extends up to top of cliff, MNR extends up to HAT

Unit number	**SPA**	**SSSI**	**Marine SAC**	**CCW owned**	**NT owned**	**MNR**	**NNR**	**pNNR**
Skokholm SSSI								
1	✓	✓						✓
2	✓	✓	✓					✓
3	✓	✓						✓
4	✓	✓	✓					✓
Skomer Island and Middleholm SSSI								
5	✓	✓	✓	✓		✓	✓	
6	✓	✓	✓	✓			✓	
7	✓	✓			✓			
8	✓	✓	✓				✓	
9	✓	✓	✓			✓	✓	
10	✓	✓	✓	✓		✓	✓	

3. THE SPECIAL FEATURES

3.1 Confirmation of Special Features

Designated feature	*Relationships, nomenclature etc*	*Conservation Objective in part 4*
SAC features		
Reef, grey seal, otter	Dealt with in the Pembrokeshire Marine SAC Regulation 33 package	
SPA features		
Populations of European importance of the following species listed on Annex I of the Directive:		
Chough *Pyrrhocorax pyrrhocorax*	SPA & SSSI feature	**4.1**
Short-eared owl *Asio flammeus*	SPA & SSSI feature	**4.2**
Storm petrel *Hydrobates pelagicus*	SPA & SSSI feature	**4.3**
Populations of European importance of the following migratory species:		
Lesser black-backed gull *Larus fuscus*	SPA & SSSI feature	**4.4**
Manx shearwater *Puffinus puffinus*	SPA & SSSI feature	**4.5**
Puffin *Fratercula arctica*	SPA & SSSI feature	**4.6**
Assemblage qualification: Seabird assemblage of international importance including:		
Razorbill *Alca torda* Guillemot *Uria aalge,* Kittiwake *Rissa tridactyla* Puffin *Fratercula arctica* Lesser black-backed gull *Larus fuscus* Manx shearwater *Puffinus puffinus* Storm petrel *Hydrobates pelagicus*	During the breeding season, the area regularly supports 67,278 individual seabirds (Count period ongoing). This assemblage is an SPA feature, not an SSSI feature. However, the individual members of the assemblage are all independently qualifying SSSI features,and the site also qualifies as an SSSI since there is a total of more than 10,000 breeding seabirds.	**4.7**
Ramsar features		
Not applicable		
SSSI features		
SSSI features have not been included in this management plan as some features do not yet have conservation objectives whilst others are currently or soon to be the subject of monitoring contracts to develop objectives. Other SSSI features are also SAC features and do not require separate SSSI conservation objectives. It is likely that most of the management for SAC features will be sympathetic to these SSSI features.		
Maritime cliff and crevice communities		

Coastal Grassland		
Coastal heathland		
Flushes, springs and standing water		
Bracken/acid grassland		
Marshy grassland		
Wet heath		
Golden hair lichen *Teloschistes flavicans*		
Lichen *Parmelia tinctina*		
Grey Seal *Halichoerus grypus*	Marine SAC feature -see Reg. 33	
Skomer Vole *Clethrionomys glareolus skomerensis*		
Storm petrel *Hydrobates pelagicus*	SPA feature	
Manx shearwater *Puffinus puffinus*	SPA feature,	
Razorbill *Alca torda*	SPA feature	
Puffin *Fratercula arctica*	SPA feature	
Guillemot *Uria aalge*	SPA feature	
Lesser black-backed gull *Larus fuscus*	SPA feature	
Kittiwake *Rissa tridactyla*	SPA feature	
Chough *Pyrrhocorax pyrrhocorax*	SPA feature	
Short-eared owl *Asio flammeus*	SPA feature	
Seabird assemblage		
Assemblages of RDB and Nationally Scarce lichens		
Assemblage of RDB and/or Nationally Scarce vascular plants		
Coastal invertebrate assemblage		
Littoral rock	Marine SAC feature	
Surge gullies	Marine SAC feature	
Silurian igneous rock		

3.2 Special Features and Management Units

This section sets out the relationship between the special features and each management unit. This is intended to provide a clear statement about what each unit should be managed for, taking into account the varied needs of the different special features. All special features are allocated to one of seven classes in each management unit. These classes are:

Key Features

KH - a ‘Key Habitat’ in the management unit, i.e. the habitat that is the main focus of management and monitoring effort, perhaps because of the dependence of a key species (see KS below). There will rarely be more than one Key Habitat in a unit.
KS – a ‘Key Species’ in the management unit, often driving both the selection and management of a Key Habitat.
Geo – an earth science feature that is the main focus of management and monitoring effort in a unit.

Other Features

Sym - habitats, species and earth science features that are of importance in a unit but are not the main focus of management or monitoring. These features will benefit from management for the key feature(s) identified in the unit. These may be classed as ‘Sym’ features because:

a) they are present in the unit but are of less conservation importance than the key feature; and/or
b) they are present in the unit but in small areas/numbers, with the bulk of the feature in other units of the site; and/or
c) their requirements are broader than and compatible with the management needs of the key feature(s).

Nm - an infrequently used category where features are at risk of decline within a unit as a result of meeting the management needs of the key feature(s), i.e. under Negative Management. These cases will usually be compensated for by management elsewhere in the plan, and can be used where minor occurrences of a feature would otherwise lead to apparent conflict with another key feature in a unit.
Mn - Management units with no special feature present but which are of importance for management of features elsewhere on a site e.g. livestock over-wintering area included within designation boundaries.
x – Features not present in the management unit.

The table below sets out the relationship between the special features and management units identified in this plan:

Skomer and Skokholm SPA	**Management unit**	
	Skokholm Island SSSI	**Skomer Island and Middleholm SSSI**

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
SPA	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SAC		✓		✓		✓		✓	✓	✓
SSSI	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NNR/CCW owned	pNNR	pNNR	pNNR	pNNR	✓	✓		✓	✓	✓
MNR									✓	✓
SPA features										
Chough *Pyrrhocorax pyrrhocorax*	**KS**	*	**KS**	*	**KS**		**KS**	*	*	*
Short-eared owl *Asio flammeus*	**KS**		**KS**		**KS**		**KS**			
Storm petrel *Hydrobates pelagicus*	**KS**		**KS**		**KS**		**KS**			
Lesser black-backed gull *Larus fuscus*	**KS**		**KS**		**KS**		**KS**			
Manx shearwater *Puffinus puffinus*	**KS**		**KS**		**KS**		**KS**			
Puffin *Fratercula arctica*	**KS**		**KS**		**KS**		**KS**			
Assemblage qualification: A seabird assemblage of international importance.	**KS**		**KS**		**KS**		**KS**			
SSSI features										
Maritime cliff and crevice communities										
Coastal grassland	**KH**		**KH**		**KH**		**KH**			
Coastal heathland	**KH**		**KH**		**KH**		**KH**			
Flushes, springs and standing water										
Bracken/acid grassland										
Marshy grassland										
Wet heath										
Golden hair lichen *Teloschistes flavicans*										
Lichen *Parmelia tinctina*										
Grey seal *Halichoerus grypus*										
Skomer vole *Clethrionomys glareolus skomerensis*										
Storm petrel *Hydrobates pelagicus*										
Manx shearwater *Puffinus puffinus*										
Razorbill *Alca torda*										
Puffin *Fratercula arctica*										
Guillemot *Uria aalge*										

Lesser black-backed gull *Larus fuscus*										
Kittiwake *Rissa tridactyla*										
Chough *Pyrrhocorax pyrrhocorax*										
Short-eared owl *Asio flammeus*										
Seabird assemblage										
Assemblages of RDB and Nationally Scarce lichens										
Assemblage of RDB and/or Nationally Scarce vascular plants										
Coastal invertebrate assemblage										
Littoral rock		*		*		*		*	*	*
Surge gullies		*		*		*		*	*	*
Silurian igneous rock										

***See Pembrokeshire Marine SAC plan**

4. CONSERVATION OBJECTIVES

Background to Conservation Objectives:

a. Outline of the legal context and purpose of conservation objectives.

Conservation objectives are required by the 1992 ‘Habitats’ Directive (92/43/EEC). The aim of the Habitats Directives is the maintenance, or where appropriate the restoration of the ‘favourable conservation status’ of habitats and species features for which SACs and SPAs are designated (see Box 1).

In the broadest terms, 'favourable conservation status' means a feature is in satisfactory condition and all the things needed to keep it that way are in place for the foreseeable future. CCW considers that the concept of favourable conservation status provides a practical and legally robust basis for conservation objectives for Natura 2000 and Ramsar sites.

Box 1
Favourable conservation status as defined in Articles 1(e) and 1(i) of the Habitats Directive

“The conservation status of a natural habitat is the sum of the influences acting on it and its typical species that may affect its long-term natural distribution, structure and functions as well as the long term survival of its typical species. The conservation status of a natural habitat will be taken as favourable when:

- Its natural range and areas it covers within that range are stable or increasing, and
- The specific structure and functions which are necessary for its long-term maintenance exist and are likely to continue to exist for the foreseeable future, and
- The conservation status of its typical species is favourable.

The conservation status of a species is the sum of the influences acting on the species that may affect the long-term distribution and abundance of its populations. The conservation status will be taken as ‘favourable’ when:

- population dynamics data on the species indicate that it is maintaining itself on a long-term basis as a viable component of its natural habitats, and
- the natural range of the species is neither being reduced nor is likely to be reduced for the foreseeable future, and
- There is, and will probably continue to be, a sufficiently large habitat to maintain its populations on a long-term basis.”

Achieving these objectives requires appropriate management and the control of factors that may cause deterioration of habitats or significant disturbance to species.

As well as the overall function of communication, conservation objectives have a number of specific roles:

- Conservation planning and management.

  The conservation objectives guide management of sites, to maintain or restore the habitats and species in favourable condition.

- Assessing plans and projects.

  Article 6(3) of the ‘Habitats’ Directive requires appropriate assessment of proposed plans and projects against a site's conservation objectives. Subject to certain exceptions, plans or projects may not proceed unless it is established that they will not adversely affect the integrity of sites. This role for testing plans and projects also applies to the review of existing decisions and consents.

- Monitoring and reporting.

  The conservation objectives provide the basis for assessing the condition of a feature and the status of factors that affect it. CCW uses ‘performance indicators’ within the conservation objectives, as the basis for monitoring and reporting. Performance indicators are selected to provide useful information about the condition of a feature and the factors that affect it.

The conservation objectives in this document reflect CCW’s current information and understanding of the site and its features and their importance in an international context. The conservation objectives are subject to review by CCW in light of new knowledge.

b. Format of the conservation objectives

There is one conservation objective for each feature listed in part 3. Each conservation objective is a composite statement representing a site-specific description of what is considered to be the favourable conservation status of the feature. These statements apply to a whole feature as it occurs within the whole plan area, although section 3.2 sets out their relevance to individual management units.

Each conservation objective consists of the following two elements:

1. Vision for the feature
2. Performance indicators

As a result of the general practice developed and agreed within the UK Conservation Agencies, conservation objectives include performance indicators, the selection of which should be informed by JNCC guidance on Common Standards Monitoring[1].

There is a critical need for clarity over the role of performance indicators within the conservation objectives. **A conservation objective, because it includes the vision for the feature, has meaning and substance independently of the performance indicators, and is more than the sum of the performance indicators**. The performance indicators are simply what make the conservation objectives measurable, and are thus part of, not a substitute for, the conservation objectives. Any feature attribute identified in the performance indicators should be represented in the vision for the feature, but not all elements of the vision for the feature will necessarily have corresponding performance indicators.

As well as describing the aspirations for the condition of the feature, the Vision section of each conservation objective contains a statement that the factors necessary to maintain those desired conditions are under control. Subject to technical, practical and resource constraints, factors which have an important influence on the condition of the feature are identified in the performance indicators.

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[1] Available through www.jncc.gov.uk and follow links to Protected Sites and Common Standards Monitoring.

4.1 Conservation Objective for Feature 1: Chough *Pyrrhocorax pyrrhocorax*

Vision for feature 1

The vision for this feature is for it to be in a favourable conservation status, where all of the following conditions are satisfied:

- The Skomer breeding population will be at least 3 pairs
- The Skokholm breeding population will be at least 1 pair
- The SPA breeding population will be 4 pairs, (this currently represents around 5 % of the Pembrokeshire chough population and 1.2% of the GB population)
- Breeding success will be 1.5 chicks/pair
- Sufficient suitable habitat will be present to support the populations
- The factors affecting the feature are under control

Performance indicators for Feature 1

The performance indicators are part of the conservation objective, not a substitute for it. Assessment of plans and projects must be based on the entire conservation objective, not just the performance indicators.

Performance indicators for feature condition		
Attribute	***Attribute rationale and other comments***	***Specified limits***
A1. Breeding population	Based on performance indicators and targets as set out in Skomer Island SSSI management plan (part 5), Skokholm Island management statement and SPA review site account.	*Upper limit*: None set *Lower limit*: To contribute towards maintaining the chough population in a favourable condition where, in 3 out of 5 consecutive years: • The Skomer breeding population is at least 3 pairs • The Skokholm breeding population is at least 1 pair
A2. Breeding productivity	Based on performance indicators and targets as set out in Skomer Island SSSI management plan and Skokholm Island management statement	*Upper limit*: None set *Lower limit*: To contribute towards the maintenance of the chough population in a favourable condition where, in 3 out of 5 consecutive years: • Breeding success is at least 1.5 chick/pair
Performance indicators for factors affecting the feature		
Factor	***Factor rationale and other comments***	***Operational Limits***
F1. Disturbance	Based on performance indicators and targets as set out in Skomer Island SSSI management plan and Skokholm Island management statement	*Upper limit*: there will be no unauthorised access away from the footpaths *Lower limit*: None set
F2. Foraging habitat condition	Feeding choughs require short-sward and invertebrate-rich habitats. The maintenance of Rabbits grazing and areas of bare earth, particularly amongst the coastal grassland is important on Skomer.	Existing forage areas both within and outside the SSSI will be maintained as being suitable for the chough as appropriate.

4.2 Conservation Objective for Feature 2: Short-eared owl *Asio flammeus*

Vision for feature 2

The vision for this feature is for it to be in a favourable conservation status, where all of the following conditions are satisfied:

- The breeding population will be at least 6 pairs
- Breeding success will be at least 1 chicks/pair
- Sufficient suitable habitat will be present to support the populations
- The factors affecting the feature are under control

Performance indicators for Feature 2

The performance indicators are part of the conservation objective, not a substitute for it. Assessment of plans and projects must be based on the entire conservation objective, not just the performance indicators.

Performance indicators for feature condition		
Attribute	***Attribute rationale and other comments***	***Specified limits***
A1. Breeding population size	Based on performance indicators and targets as set out in Skomer Island SSSI management plan (part 5).	*Upper limit*: None set *Lower limit*: To contribute towards the maintenance of the short-eared owl population in a favourable condition where, in 3 out of 5 consecutive years: • The Skomer breeding population is 6 pairs
A3. Availability of nest sites	Current distribution records are being followed up, will be digitised and specified limits will follow as appropriate.	To be developed.
Performance indicators for factors affecting the feature		
Factor	***Factor rationale and other comments***	***Operational Limits***
F1. Disturbance	Based on performance indicators and targets as set out in Skomer Island SSSI management plan.	*Upper limit*: Skomer: there will be no unauthorised access away from the footpaths *Lower limit*: None set
F2. Prey availability	Based on performance indicators as set out in Skomer Island SSSI management plan. Targets apply only to Skomer Island.	*Upper limit*: None set Lower limit: Skomer Island only: The density of voles should be: • In Grid C (high density) is 370/ha (5 yr mean) • In Grid E (low density) is 30/ha (5 yr mean) • Wood mice should be present in Grid C.

4.3 Conservation Objective for Feature 3: Storm petrel *Hydrobates pelagicus*

Vision for feature 3

The vision for this feature is for it to be in a favourable conservation status, where all of the following conditions are satisfied:

- The population of storm petrel will be at least 3500 pairs within the SPA,
- Sufficient suitable nesting sites will be present to support at least the current populations
- The factors affecting the feature are under control

NB. *Breeding success is not examined in this species due to its sensitivity to disturbance*

Performance indicators for Feature 3

The performance indicators are <u>part of</u> the conservation objective, not a substitute for it. Assessment of plans and projects must be based on the entire conservation objective, not just the performance indicators.

Performance indicators for feature condition		
Attribute	***Attribute rationale and other comments***	***Specified limits***
A1. Breeding population size	Based on SPA review site account.	*Upper limit*: None set *Lower limit*: The population of storm petrel should be at least 3500 pairs within the SPA,
A2. Breeding productivity	Not measured for this species because of their sensitivity to disturbance.	*Upper limit*: None set Lower limit: None set
A3. Availability of nest sites	Current distribution records are being followed up, will be digitised and specified limits will follow as appropriate.	To be developed.
Performance indicators for factors affecting the feature		
Factor	***Factor rationale and other comments***	***Operational Limits***
F1. Disturbance	Based on performance indicators and targets as set out in Skomer Island SSSI management plan and Skokholm Island management statement.	*Upper limit*: Whole SPA: there will be no unauthorised access away from the footpaths. *Lower limit*: None set
F2. Predators	Based on performance indicators and targets as set out in Skomer Island SSSI management plan and Skokholm Island management statement. Little owl targets apply only to Skomer Island.	*Upper limit*: There should be no mammalian land predators present in the SPA and there should be no more than 5 breeding pairs of little owl on Skomer. *Lower limit*: None set
F3. Food availability	Sufficient preferred fish species will need to be available to maintain breeding populations. Management of this factor needs to be undertaken at national/international level therefore limits have not been set.	*N/A*
F4. Oil Spill	Contingency plans are in place in West Wales area to ensure that response to any spill will take these species into account.	*N/A*

4.4 Conservation Objective for Feature 4: Lesser black-backed gull *Larus fuscus*

Vision for feature 4

The vision for this feature is for it to be in a favourable conservation status, where all of the following conditions are satisfied:

- During the breeding season the population of lesser black-backed gull will be at least 20,300 pairs within the SPA. This re presents around 16.4% of the current breeding Western European/Mediterranean/western African population
- Breeding success will be at least 0.4 chicks/pair
- Sufficient suitable nesting sites will be present to support at least the current populations
- The factors affecting the feature are under control

Performance indicators for Feature 4

The performance indicators are part of the conservation objective, not a substitute for it. Assessment of plans and projects must be based on the entire conservation objective, not just the performance indicators.

Performance indicators for feature condition		
Attribute	***Attribute rationale and other comments***	***Specified limits***
A1. Population size	Based on SPA review site account.	*Upper limit*: None set *Lower limit*: During the breeding season the population of lesser black-backed gull should be at least 20,300 pairs within the SPA
A2. Adult survival rate	Based on performance indicators and targets as set out in Skomer Island SSSI management plan and Skokholm Island management statement.	*Upper limit*: None set *Lower limit*: Adult survival rates should be at least 80%
A3. Breeding productivity	Based on performance indicators and targets as set out in Skomer Island SSSI management plan and Skokholm Island management statement.	*Upper limit* None set *Lower limit* Breeding success rate should be at least 0.4 chicks per pair
A4. Availability of nest sites	Current distribution records are being followed up, will be digitised and specified limits will follow as appropriate.	*See also F3 below*
Performance indicators for factors affecting the feature		
Factor	***Factor rationale and other comments***	***Operational Limits***
F1. Disturbance	Based on performance indicators and targets as set out in Skomer Island SSSI management plan and Skokholm Island management statement.	*Upper limit*: there will be no unauthorised access away from the footpaths. *Lower limit*: None set
F2. Predators	Based on performance indicators and targets as set out in Skomer Island SSSI management plan and Skokholm Island management statement.	*Upper limit*: There should be no mammalian land predators present in the SPA Lower limit: None set

Performance indicators for factors affecting the feature (cont.d)		
Factor	***Factor rationale and other comments***	***Operational Limits***
F.3 Nest siting & distribution on heathland	Based on performance indicators as set out in Skomer Island SSSI management. plan.	*Upper limit*: None set *Lower limit:* the distribution of breeding gulls will be allowed to develop, but there should be no lesser black-backed gulls successfully nesting in or within 2m of any of the heather enclosures.
F3. Food availability	Sufficient preferred fish species will need to be available to maintain breeding populations. Management of this factor needs to be undertaken at national/international level therefore limits have not been set.	*N/A*
F4. Oil spill	Contingency plans are in place in West Wales area to ensure that response to any spill will take these species into account.	*N/A*

4.5 Conservation Objective for Feature 5: Manx shearwater *Puffinus puffinus*

Vision for feature 5

The vision for this feature is for it to be in a favourable conservation status, where all of the following conditions are satisfied:

- During the breeding season the population of Manx shearwater will be at least 150,000 pairs within the SPA (this represents around half of the current breeding population).
- Breeding success will be at least 0.5 chicks per egg laid
- The factors affecting the feature are under control

Performance indicators for Feature 5

The performance indicators are part of the conservation objective, not a substitute for it. Assessment of plans and projects must be based on the entire conservation objective, not just the performance indicators.

Performance indicators for feature condition		
Attribute	***Attribute rationale and other comments***	***Specified limits***
A1. Population size	Based on SPA review site account.	*Upper limit*: None set *Lower limit*: During the breeding season the population of Manx shearwater should be at least 150,000 pairs within the SPA.
A2. Adult survival rate	Based on performance indicators and targets as set out in Skomer Island SSSI management plan and Skokholm Island management statement (Seabird Monitoring programme data)	*Upper limit*: None set *Lower limit*: Adult survival rates should be at least 85%
A3. Breeding productivity	Based on performance indicators and targets as set out in Skomer Island SSSI management plan and Skokholm Island management statement	*Upper limit* None set *Lower limit* The annual breeding success in 3 of any 5 consecutive years is 0.5 per egg laid.
Performance indicators for factors affecting the feature		
Factor	***Factor rationale and other comments***	***Operational Limits***
F1. Disturbance	Based on performance indicators and targets as set out in Skomer Island SSSI management plan and Skokholm Island management statement	*Upper limit*: there will be no unauthorised access away from the footpaths *Lower limit*: None set
F2. Predators	Based on performance indicators and targets as set out in Skomer Island SSSI management plan and Skokholm Island management statement	*Upper limit*: There should be no mammalian land predators present in the SPA *Lower limit*: None set
F3. Soil erosion	Based on performance indicators as set out in Skomer Island SSSI management plan. Targets apply only to Skomer Island. Since natural soil erosion is not something that can be controlled, this target relates to anthropogenic soil erosion (e.g. around footpaths etc)	*Upper limit*: Skomer only: Soil erosion should not exceed 0.5cm/year (See SSSI management plan for details) *Lower limit:* None set

Performance indicators for factors affecting the feature (cont.d)		
Factor	***Factor rationale and other comments***	***Operational Limits***
F4. Bracken distribution	Based on performance indicators as set out in Skomer Island SSSI management plan Targets apply only to Skomer Island.	*Upper limit*: Skomer only: Coastal bracken distribution will not exceed that in Bray 1981. (See SSSI management plan for details) *Lower limit:* None set
F3. Food availability	Sufficient preferred fish species will need to be available to maintain breeding populations. Management of this factor needs to be undertaken at national/international level therefore limits have not been set.	*N/a*
F4. Oil Spill	Contingency plans are in place in West Wales area to ensure that response to any spill will take these species into account.	*N/a*

4.6 Conservation Objective for Feature 6: Puffin *Fratercula arctica*

Vision for feature 6

The vision for this feature is for it to be in a favourable conservation status, where all of the following conditions are satisfied:

- During the breeding season the population of puffins will be at least 9,500 pairs within the SPA, (this represents at least 1.1% of the current breeding population)
- Breeding success will be 0.7 chicks/pair
- The factors affecting the feature are under control

Performance indicators for Feature 6

The performance indicators are part of the conservation objective, not a substitute for it. Assessment of plans and projects must be based on the entire conservation objective, not just the performance indicators.

Performance indicators for feature condition		
Attribute	***Attribute rationale and other comments***	***Specified limits***
A1. Population size	Based on SPA review site account.	*Upper limit*: None set *Lower limit*: During the breeding season the population of puffins should be at least 9,500 pairs within the SPA
A2. Adult survival rate	Based on performance indicators and targets as set out in Skomer Island SSSI management plan and Skokholm Island management statement.	*Upper limit*: None set *Lower limit*: Adult survival rates should be at least 84%
A3. Breeding productivity	Based on performance indicators and targets as set out in Skomer Island SSSI management plan and Skokholm Island management statement.	*Upper limit* None set *Lower limit* The annual breeding success in 3 of any 5 consecutive years is 0.7 per egg laid
Performance indicators for factors affecting the feature		
Factor	***Factor rationale and other comments***	***Operational Limits***
F1. Disturbance	Based on performance indicators and targets as set out in Skomer Island SSSI management plan and Skokholm Island management statement	*Upper limit*: there will be no unauthorised access away from the footpaths. *Lower limit*: None set
F2. Predators	Based on performance indicators and targets as set out in Skomer Island SSSI management plan and Skokholm Island management statement.	*Upper limit*: There should be no mammalian land predators present in the SPA. *Lower limit*: None set
F3. Food availability	Sufficient preferred fish species will need to be available to maintain breeding populations. Management of this factor needs to be undertaken at national/international level therefore limits have not been set.	*N/A*
F4. Oil Spill	Contingency plans are in place in West Wales area to ensure that response to any spill will take these species into account.	*N/A*

4.7 Conservation Objective for Feature 7: Assemblage qualification: A seabird assemblage of international importance.

Vision for feature 7

The vision for this feature is for it to be in a favourable conservation status, where all of the following conditions are satisfied:

- Each of the component species of the seabird assemblage will be in favourable condition for the assemblage as a whole to achieve Favourable Condition
- During the breeding season the SPA will regularly support at least 67,000 individual seabirds of the following species, most of which also qualify independently as SPA features:
    - Razorbill *Alca torda*
    - Guillemot *Uria aalge*
    - Kittiwake Rissa tridactyla
    - Puffin *Fratercula arctica*
    - Lesser black-backed gull *Larus fuscus*
    - Manx shearwater *Puffinus puffinus*
    - Storm petrel *Hydrobates pelagicus*

Performance indicators for Feature 7

The performance indicators are part of the conservation objective, not a substitute for it. Assessment of plans and projects must be based on the entire conservation objective, not just the performance indicators.

Performance indicators for feature condition		
Attribute	***Attribute rationale and other comments***	***Specified limits***
A1. Population size	Based on SPA review site account.	*Upper limit*: None set *Lower limit*: During the breeding season the SPA should regularly support at least 67,000 individual seabirds of the following species, all of which also qualify independantly as SPA features: • Razorbill *Alca torda* • Guillemot *Uria aalge* • Kittiwake *Rissa tridactyla* • Puffin *Fratercula arctica* • Lesser black-backed gull *Larus fuscus* • Manx shearwater *Puffinus puffinus* • Storm petrel *Hydrobates pelagicus*
A2. Other attributes	There are a number of specific attributes relevant to individual species - see individual species Conservation Objectives.	*Upper limit*: See individual species targets *Lower limit*: See individual species targets.
Performance indicators for factors affecting the feature		
Factor	***Factor rationale and other comments***	***Operational Limits***
F1.	There are a number of specific factors relevant to individual species - see individual species Conservation Objectives.	*Upper limit*: See individual species targets *Lower limit*: See individual species targets.

5. ASSESSMENT OF CONSERVATION STATUS AND MANAGEMENT REQUIREMENTS

This part of the document provides:

- A summary of the assessment of the conservation status of each feature.
- A summary of the management issues that need to be addressed to maintain or restore each feature.

5.1 Conservation Status and Management Requirements of Feature 1: Chough *Pyrrhocorax pyrrhocorax*

Conservation Status of Feature 1

1-4 pairs have bred on Skomer, there were 3 in 1996, 5% of the Pembs populations. 1–2 pairs have bred on Skokholm. Breeding success has been within limits in recent years. The population is considered **FAVOURABLE MAINTAINED.**

Management Requirements of Feature 1

Chough feeding on Skomer and Skokholm is almost exclusively restricted to invertebrates on maritime cliffs and coastal grassland, although birds have been recorded on inland grassland. In the breeding season ants appear to be favoured (these are probably fed exclusively to nestlings, Meyer et al 1994). At other sites in West Wales beetles and dipterous larvae, especially tipulids, were found to be the predominant food. When invertebrate food is lean, dung fauna (which is limited on Skomer) is important. Cereal grain and winter stubbles are important in the winter.

Feeding choughs require short-sward and invertebrate-rich habitats. The maintenance of rabbit grazing and areas of bare earth, particularly amongst the coastal grassland is important on Skomer. Operational limits for rabbit grazing are based on current levels, this produces areas of short sward, but work is needed to see if this is an optimum condition.

There is an obvious need to consider the Pembs Chough Conservation Strategy. Amongst its broad policies the following are particularly pertinent; the continuation of monitoring and research programmes, mapping feeding areas (including outside the SPA), the provision of artificial nest sites where appropriate and land management. The first two are currently carried out however nest sites on Skomer are often inaccessible and have generally poor vantage points for nest observations. There has been no evidence of a shortage of nest sites in the SPA, but nest boxes will be considered if this was thought to be a limiting factor. The importance of management work on the Deer Park and at other sites on the Marloes Peninsula is recognised. There has been much discussion on land management on Skomer, notably the experimental ploughing of Calves Park could provide useful winter stubbles as well as potentially improving nesting habitat for ground nesting birds, which are also Features. Rabbit exclosure by fencing of the area is a prerequisite. Considerable management work is being undertaken on Ramsey to benefit chough and elsewhere in Wales. Liaison with relevant bodies will inform any land management decisions in the SPA.

A key role of island management is to limit human disturbance to breeding birds. The approach of visitors, staff and researchers to nest sites could cause disturbance.

5.2 Conservation Status and Management Requirements of Feature 2: Short-eared owl *Asio flammeus*

Conservation Status of Feature 2

Short-eared owls have bred on Skomer since at least the late 1900s. A pair bred from 1961-66. Since 1967 between 2-6 pairs have bred most years, but note there was no breeding in 1973 and 1974 and exceptional numbers of 14 (1993) and 9 pairs (1994). In 1997, 6 pairs bred. However, for the last 5 years, no more than 4 pairs have bred. The higher numbers form 1997 may reflect the level of effort at the time. Further survey and monitoring work needs to be undertaken of this species to ensure that the targets set for it accurately reflect the population. New monitoring Common Standard Monitoring methodology is being developed which should be considered for use here. At present, the population is considered **UNFAVOURABLE.**

Management Requirements of Feature 2

Breeding success can be difficult to determine and there is a risk that regular nest site visits could increase predation rates. Fledged birds can usually be identified by their darker faces, but a better assessment is to determine the number of chicks hissing from nest areas.

The population uses the island as a breeding site. It is subject to many external influences during and outside this period. Direct monitoring or surveillance of the Skomer breeding birds out of the breeding season is not possible. Despite ringing in the past there have been no recoveries to date. Owls are present in the winter but it has not been proved whether these are the breeding birds.

In the past short-eared owls appear to have used nest sites within heathland. Nests have been found in heather but also in dead bracken amongst bluebells. Food supply on the island is important, particularly small mammals. It has been estimated that owls may account for up to 25% of the voles and mice taken on Skomer each year, although rabbits also appear to form a proportion of prey. Data on the woodmouse population is obtained from the Vole monitoring Grid E. It is not ideal for mice studies but does provide an index of abundance.

A key role of island management is to limit human disturbance to breeding birds.

5.3 Conservation Status and Management Requirements of Feature 3: Storm petrel *Hydrobates pelagicus*

Conservation Status of Feature 3

The storm petrel population has been estimated using different methods since the 1960s and this makes meaningful comparison problematic. Some previous estimates were also made during July and August, and may have included prospecting non-breeders. Current work focuses on occupied sites, established by response to tape playback and site smell, although there are some inaccessible colonies that cannot be censused in this way. In 1996 some 69 occupied sites were identified. An additional 34 pairs were suggested from observations of inaccessible sites at night, using image intensification equipment. In c.1997, AOSs (apparently occupied sites) were identified. The overall population of c.100 pairs is certainly lower than most estimates in the past, although similar to that of James (1982). Certainly some colonies have disappeared since the 1960s, but the effect on the whole population is not known. Censusing methods mean that there is more concern over precise targets than for other features. There is some disagreement about whether storm petrels have declined substantially, it is the general view of the Management Plan Working Group (1997) that they had not. The feature appears tp be within limits for Skomer, but Skokholm is not. This may be because the monitoring methods used on Skokholm have not been entirely successful. It is therefore for the moment considered **UNFAVOURABLE unclassified.**

Management Requirements of Feature 3

The population uses the island as a breeding site. It is subject to many external influences during and outside this period. There is interchange with the much larger population on Skokholm.

Food availability during the breeding season, in their wintering quarters (the waters off South Africa), and on passage to and from it, is of vital significance. Monitoring or surveillance of relevant fish stocks is highly problematic and complex. In the long-term it is essential that national management of fish stocks take seabirds into account. It would be possible to monitor food brought to chicks and it would be interest to know whether chick growth on the island was normal. Such studies are probably more easily done on Skokholm.

The continued absence of mammalian land predators is fundamental.

An oil pollution incident during the breeding season could have a great impact on the adult population.

Predation by little owls may be locally significant although it may have been more so in the past and may vary between years. One pair of little owls were present 1960-64, then none until 1977 when two pairs bred. There have been 2-4 pairs since then (but 6 in 1985). Storm petrel remains have also been found in the pellets of short-eared owls. Predation by herring gulls can occur where they nest close to petrel colonies but is not significant island-wide.

A key role of island management is to limit human disturbance to breeding birds. The collapse of scree etc by visitors, staff and researchers away from the footpaths could cause damage to the breeding habitat (and be dangerous). Natural processes could damage but also create breeding habitat.

5.4 Conservation Status and Management Requirements of Feature 4: Lesser black-backed gull *Larus fuscus*

Conservation Status of Feature 4

The Skomer population has increased since 1946, dramatically so during the 1980s to a peak of over 20,000 pairs, as birds took advantage of increased fishery discards (Sutcliffe 1993). As this resource disappeared, breeding success fell and this has led to the current fall in the breeding population (to c.14, 300 pairs in 1997, with 111 AOTs on Middleholm). On Skokholm trends since the 1970s show a stable population in the early to mid 70s, an increase to a peak in the early 80s, and then a general gentle downward trend. The last 3 years adult numbers have increased again. Breeding success however remains low. Adult survival rates have not decreased. Its status is considered **UNFAVOURABLE no change**, since the lower limits set for breeding success have not been met on Skokholm.

Management Requirements of Feature 4

The population use the islands as a breeding site. It is subject to many external influences during and outside this period, which may be reflected in annual adult survival rates and productivity.

Food availability during the breeding season, in their wintering quarters (Spain, Portugal, Morocco and, increasingly, the UK), and on passage to and from it, is of vital significance. Direct monitoring or surveillance of relevant fish stocks is complex and problematic, and there is fundamental need for good data. Food supply during the breeding season will partly determine productivity. In the long-term it is essential that national management of fish stocks take seabirds into account.

Individual lesser black-backed gulls may practise cleptoparasitism of puffins and some may predate some pre-fledging puffin chicks outside the burrow, but this is not significant. Intra-specific predation can be high, particularly when a colony is disturbed. There is a relationship between bracken and lesser black-backed gull productivity. It is higher amongst bracken cover.

In the past there has been concern at the effects of high numbers of this species. The population on Skomer was controlled from 1981-87 and some 5000 adults were culled. Nesting sub-colonies can be very dense and few ground-nesting birds are found amongst them e.g. lapwing, curlew, meadow pipit, skylark, short-eared owl will be absent. Shearwaters may also be largely absent form regularly used gull sub-colonies. The gulls are considered a normal component of a healthy seabird colony. Academics suggest that upper limits on the numbers of gulls do not need to be set, although this is reviewed as populations or distribution changes or as other features are affected.

Gulls nesting in heather may cause considerable damage by trampling and eutrophication. When the population was expanding gulls favoured the edges of heather, if close to existing sub-colonies. Gull distribution is related to bracken distribution to some extent.

Breeding gulls are responsible for much of the eutrophication of the ponds and springs, but also a crucial factor on the presence and distribution of some lichen and lichen communities (including SSSI features), which depend upon guano enrichment.

The continued absence of mammalian land predators is important.

A key role of island management is to limit human disturbance to breeding birds.

5.5 Conservation Status and Management Requirements of Feature 5: Manx shearwater *Puffinus puffinus*

Conservation Status of Feature 5

The results of the 1994 Manx shearwater census revealed that between 10,808 and 11,288 birds successfully fledged from The Neck. It was concluded that there had been no evidence of any large change in the shearwater population on Skomer. Recent survival rates and breeding success on both Skokholm and Skomer, gauged form the study plot monitoring have been within limits. The condition of the population is **FAVOURABLE MAINTAINED.**

Management Requirements of Feature 5

The population uses the islands as a breeding site. It is subject to many external influences during and outside this period. Food availability and feeding conditions during the breeding season, in their wintering quarters (the waters off Brazil/Argentina/Uruguay), and on passage to and from it, is of vital significance. Direct monitoring or surveillance of relevant fish stocks is highly complex and problematic. It is difficult to monitor food brought to chicks. Annual survival rates and breeding success may reflect some of these factors to some extent. There is an international requirement for long term management of these feeding areas.

The size of the breeding population is useful information, but the resources needed to complete a whole island survey are significant, and it is not likely to be repeated regularly. Due to the large size and extent of the shearwater population, only that of a sample area is regularly estimated.

Predation by great black-backed gull can be high although evidence suggests a relatively low predation figure of 2% of adult shearwaters. This figure will clearly increase if the gull population increases. Shearwater remains have been recorded from 80-97% of all great black-backed gull nests monitored. There is a relatively large population of gulls on Middleholm that must also be taken into account. These predatory species are, of course, a normal component of a healthy seabird colony. Competition with puffins for good quality burrows occurs; although the situation is thought to be in balance with neither species having a great competitive advantage over the other. A radical increase in shearwater numbers may affect puffin numbers, although this appears unlikely. There is a relationship between rabbits and shearwaters in terms of burrow construction and usage, although Manx shearwaters do dig their own burrows. Rabbits may possibly be advantageous by keeping vegetation cropped around burrows. There may be a relationship between encroaching bracken and shearwater breeding success. Bracken has probably been present in the deep soil of the valleys for a considerable time. However there has been encroachment into some areas of coastal grassland, where there can also be a high density of shearwater burrows. Further investigation into the effects of bracken has been identified as a requirement.

A key role of island management is to limit human disturbance to breeding birds. The trampling of burrows by visitors, staff and researchers away from the footpaths could cause damage. Rafting birds at sea are vulnerable to water-borne human disturbance and oil pollution.

Natural processes (perhaps exacerbated by rabbit pressure) may lead to soil erosion, which may (in the long term) reduce breeding habitat. In the long-term, soil loss, particularly severe run-off, could alter the distribution of colonies.

Shearwater death from puffinosis is not thought to be significant. It could be to monitored, but seems to be concentrated amongst fledglings. Egg collecting has been known to occur, but is a rare occurrence. Fire could have a serious effect on breeding shearwaters/chicks.

The continued absence of mammalian land predators is fundamental.

5.6 Conservation Status and Management Requirements of Feature 6: Puffin *Fratercula arctica*

Conservation Status of Feature 6

The population of this burrow nesting bird is difficult to assess. Population estimates since 1963 have been of c. 7000 pairs, but this may be an overestimate. This is much lower than estimates in the 1940s. Annual counts of birds on land and sea on spring evenings of known high attendance are the most appropriate. Survival rates have fallen since the 1970s, but the population is stable, suggesting substantial immigration. Recent survival rates and productivity has been average to high and all within limits. Although the population is now lower than at times in the past it is considered **FAVOURABLE MAINTAINED.**

Management Requirements of Feature 6

The population uses the islands as a breeding site. It is subject to many external influences during and outside this period, some of which will be reflected in annual adult survival rates. Food availability during the breeding season, in their wintering areas, and on passage to and from it, is of vital significance. Direct monitoring or surveillance of relevant fish stocks is complex and problematic. Food supply during the breeding season will partly determine productivity. In the long-term it is essential that national management of fish stocks take seabirds into account. Low input assessment on feeding rates is carried out for JNCC as part of the national monitoring programme.

Although shearwaters will arrive on Skomer and occupy burrow sites earlier than puffins this does not appear to significantly affect puffin productivity, as the two species appear to be in balance. Puffins are today confined to the coastal edge and so the impact, if any, of encroaching bracken on puffin breeding success is not considered significant.

The relationship between rabbits and puffins may be complex. Although puffins can dig their own burrows, on Skomer they have not been seen excavating their own, although they will clear out burrows when they return in spring. Rabbits will control vegetation succession on some slopes

Predation by great black-backed gulls occurs, but the current levels are not thought to be a major impact. None of the other predatory species (lesser black-backed gulls, peregrine, jackdaw) are thought to make a significant impact. These predatory species are, of course, a normal component of a healthy seabird colony.

A key role of island management is to limit human disturbance to breeding birds. The trampling of burrows by visitors, staff and researchers away from the footpaths could cause damage and in the long-term, soil loss, particularly severe run-off, could alter the distribution of colonies. Fire along the coastal edge during the breeding season could have major consequences to these burrow nesting birds.

The continued absence of mammalian land predators is fundamental. Puffins are also vulnerable to oil pollution incidents.

Further information of puffin distribution is needed. A small number of chicks are ringed each year by Edward Grey Institute (EGI), University of Oxford.

5.7 Conservation Status and Management Requirements of Feature 7: Assemblage qualification: A seabird assemblage of international importance.

Conservation Status of Feature 7

The condition of the seabird assemblage is **UNFAVOURABLE unclassified** since both storm petrel and lesser black-backed gulls are considered to be in Unfavourable condition, as reported above**.**

Management Requirements of Feature 7

The populations use the island as a breeding site. They are subject to many external influences during and outside this period. Direct monitoring or surveillance of the populations out of the breeding season is impossible.

Food availability during the breeding season, in the wintering quarters, and on passage to and from them, is of vital significance. Direct monitoring or surveillance of relevant fish stocks is highly problematic and complex. Food availability during the breeding season will partially determine productivity.

A key role of island management is to limit human disturbance to breeding birds and the continued absence of mammalian land predators is fundamental.

There are some specific factors relevant to individual species; soil erosion and burrow nesting birds, possible effects of bracken encroachment into coastal grassland on shearwaters, lesser black-backed gulls and heathland, little owl predation on storm petrels etc. These factors are dealt with in the individual species management requirement sections.

6. ACTION PLAN: SUMMARY

This section takes the management requirements outlined in Section 5 a stage further, assessing the specific management actions required on each management unit. This information is a summary of that held in CCW's Actions Database for sites, and the database will be used by CCW and partner organisations to plan future work to meet the Wales Environment Strategy targets for sites.

Unit Number	**CCW Database Number**	**Unit Name**	**Summary of Conservation Management Issues**	**Action needed?**
1	000823	Trinity House	Wildlife Trust management takes account of all SPA/ SAC features. No outstanding management issues.	No
3	000824	Skokholm (main island)	Wildlife Trust management takes account of all SPA/ SAC features. No outstanding management issues.	No
5	000825	Skomer Island	Wildlife Trust management takes account of all SPA/ SAC features. No outstanding management issues.	No
7	000826	Middleholm Island	Wildlife Trust management takes account of all SPA/SAC features. No outstanding management issues.	No
2	002369	Trinity House SPA/SAC overlap	This unit is considered to be under appropriate conservation management.	No
4	002370	Skokholm SPA/SAC overlap	This unit is considered to be under appropriate conservation management.	No
6	002371	Skomer SPA/SAC overlap	This unit is considered to be under appropriate conservation management.	No
8	002372	Middleholm SPA/SAC overlap	This unit is considered to be under appropriate conservation management.	No
10	002783	Skomer SPA/SAC/MNR overlap	This unit is considered to be under appropriate conservation management.	No
9	002784	Middleholm SPA/SAC/MNR	This unit is considered to be under appropriate conservation management.	No

7. GLOSSARY

This glossary defines the some of the terms used in this **Core Management Plan**. Some of the definitions are based on definitions contained in other documents, including legislation and other publications of CCW and the UK nature conservation agencies. None of these definitions is legally definitive.

Action	A recognisable and individually described act, undertaking or **project** of any kind, specified in section 6 of a **Core Management Plan** or **Management Plan**, as being required for the **conservation management** of a site.
Attribute	A quantifiable and monitorable characteristic of a **feature** that, in combination with other such attributes, describes its **condition**.
Common Standards Monitoring	A set of principles developed jointly by the UK conservation agencies to help ensure a consistent approach to **monitoring** and reporting on the **features** of sites designated for nature conservation, supported by guidance on identification of **attributes** and monitoring methodologies.
Condition	A description of the state of a feature in terms of qualities or **attributes** that are relevant in a nature conservation context. For example the condition of a habitat usually includes its extent and species composition and might also include aspects of its ecological functioning, spatial distribution and so on. The condition of a species population usually includes its total size and might also include its age structure, productivity, relationship to other populations and spatial distribution. Aspects of the habitat(s) on which a species population depends may also be considered as attributes of its condition.
Condition assessment	The process of characterising the **condition** of a **feature** with particular reference to whether the aspirations for its condition, as expressed in its **conservation objective**, are being met.
Condition categories	The **condition** of **feature** can be categorised, following **condition assessment** as one of the following[2]: Favourable: maintained; Favourable: recovered; Favourable: un-classified Unfavourable: recovering; Unfavourable: no change; Unfavourable: declining; Unfavourable: un-classified Partially destroyed; Destroyed.

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[2] See JNCC guidance on Common Standards Monitoring [redacted]

Conservation management	Acts or undertaking of all kinds, including but not necessarily limited to **actions,** taken with the aim of achieving the **conservation objectives** of a site. Conservation management includes the taking of statutory and non-statutory measures, it can include the acts of any party and it may take place outside site boundaries as well as within sites. Conservation management may also be embedded within other frameworks for land/sea management carried out for purposes other than achieving the conservation objectives.
Conservation objective	The expression of the desired **conservation status** of a **feature,** expressed as a **vision for the feature** and a series of **performance indicators**. The conservation objective for a feature is thus a composite statement, and each feature has one conservation objective.
Conservation status	A description of the state of a **feature** that comprises both its **condition** and the state of the **factors** affecting or likely to affect it. Conservation status is thus a characterisation of both the current state of a feature and its future prospects.
Conservation status assessment	The process of characterising the **conservation status** of a **feature** with particular reference to whether the aspirations for it, as expressed in its **conservation objective**, are being met. The results of conservation status assessment can be summarised either as ‘favourable’ (i.e. conservation objectives are met) or unfavourable (i.e. conservation objectives are not met). However the value of conservation status assessment in terms of supporting decisions about **conservation management**, lies mainly in the details of the assessment of feature **condition**, **factors** and trend information derived from comparisons between current and previous conservation status assessments and condition assessments.
Core Management Plan	A CCW document containing the conservation objectives for a site and a summary of other information contained in a full site **Management Plan**.
Factor	Anything that has influenced, is influencing or may influence the **condition** of a **feature**. Factors can be natural processes, human activities or effects arising from natural process or human activities, They can be positive or negative in terms of their influence on features, and they can arise within a site or from outside the site. Physical, socio-economic or legal constraints on **conservation management** can also be considered as factors.
Favourable condition	See **condition** and **condition assessment**

Favourable conservation status	See **conservation status** and **conservation status assessment.**[3]
Feature	The species population, habitat type or other entity for which a site is designated. The ecological or geological interest which justifies the designation of a site and which is the focus of conservation management.
Integrity	See **site integrity**
Key Feature	The habitat or species population within a **management unit** that is the primary focus of **conservation management** and **monitoring** in that unit.
Management Plan	The full expression of a designated site's legal status, **vision**, **features**, **conservation objectives**, **performance indicators** and management requirements. A complete management plan may not reside in a single document, but may be contained in a number of documents (including in particular **the Core Management Plan**) and sets of electronically stored information.
Management Unit	An area within a site, defined according to one or more of a range of criteria, such as topography, location of **features**, tenure, patterns of land/sea use. The key characteristic of management units is to reflect the spatial scale at which **conservation management** and **monitoring** can be most effectively organised. They are used as the primary basis for differentiating priorities for conservation management and monitoring in different parts of a site, and for facilitating communication with those responsible for management of different parts of a site.
Monitoring	An intermittent (regular or irregular) series of observations in time, carried out to show the extent of compliance with a formulated standard or degree of deviation from an expected norm. In **Common Standards Monitoring**, the formulated standard is the quantified expression of favourable **condition** based on **attributes**.
Operational limits	The levels or values within which a **factor** is considered to be acceptable in terms of its influence on a **feature**. A factor may have both upper and lower operational limits, or only an upper limit or lower limit. For some factors an upper limit may be zero.
Performance indicators	The **attributes** and their associated **specified limits**, together with **factors** and their associated **operational limits,** which provide the standard against which information from **monitoring** and other sources is used to determine the degree to which the **conservation objectives** for a **feature** are being met. Performance indicators are part of, not the same as, conservation objectives. See also **vision for the feature**.

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[3] A full definition of favourable conservation status is given in Section 4.

Plan or project	**Project:** Any form of construction work, installation, development or other intervention in the environment, the carrying out or continuance of which is subject to a decision by any public body or statutory undertaker. **Plan**: a document prepared or adopted by a public body or statutory undertaker, intended to influence decisions on the carrying out of **projects.** Decisions on plans and projects which affect Natura 2000 and Ramsar sites are subject to specific legal and policy procedures.
Site integrity	The coherence of a site's ecological structure and function, across its whole area, that enables it to sustain the habitat, complex of habitats and/or the levels of populations of the species for which it is designated.
Site Management Statement (SMS)	The document containing CCW's views about the management of a site issued as part of the legal notification of an SSSI under section 28(4) of the Wildlife and Countryside Act 1981, as substituted.
Special Feature	See **feature**.
Specified limit	The levels or values for an **attribute** which define the degree to which the attribute can fluctuate without creating cause for concern about the **condition** of the **feature**. The range within the limits corresponds to favourable, the range outside the limits corresponds to unfavourable. Attributes may have lower specified limits, upper specified limits, or both.
Unit	See **management unit.**
Vision for the feature	The expression, within a **conservation objective**, of the aspirations for the **feature** concerned. See also **performance indicators.**
Vision Statement	The statement conveying an impression of the whole site in the state that is intended to be the product of its **conservation management.** A 'pen portrait' outlining the **conditions** that should prevail when all the **conservation objectives** are met. A description of the site as it would be when all the **features** are in **favourable condition**.

8. REFERENCES

Skomer Management Plan (2004 draft update – unpublished**)**
Skokholm Management Plan (2007 draft update – unpublished**)**
Skomer and Skokholm annual reports – various up to 2007
Pembrokeshire Marine Regulation 33 advice
Pembrokeshire Marine SAC management scheme

NB: Other more extensive references and bibliographies can be found in the management plans which are being redrafted.

EC Directive 2009/147/EEC on the Conservation of Wild Birds
Citation for Potential Changes to Special Protection Area (SPA)

Name: Grassholm

Counties/Unitary Authorities: The SPA and potential extension lie within or adjacent to Pembrokeshire Unitary Authority and the landward area sits within Pembrokeshire Coast National Park. The seaward part of the proposed site lies entirely within UK territorial waters.

Boundary of the potential SPA: See potential SPA map. The proposed boundary lies mostly within 1 nautical mile of the island of Grassholm, with a small portion lying just over 1 nautical mile from the island. Only that area of the potential SPA below mean high water mark is co-incident with Pembrokeshire Marine / Sir Benfro Forol Special Area of Conservation (SAC), which was designated by the National Assembly for Wales in December 2004 under the 1992 EC Habitats and Species Directive (92/43/EEC), and the entire potential SPA is surrounded by the SAC site.

The new site includes the existing terrestrial areas designated as the Grassholm SPA by the Secretary of State for the Environment in January 1986 under the 1979 EC Directive on the Conservation of Wild Birds (79/409/EEC).

Size of SPA: The existing site and the potential SPA combined cover an area of 1744ha approximately.

Site description: Grassholm is a low-lying basalt island, situated approximately 18km off the south-west Wales coast. The island has limited terrestrial vegetation owing to the effects of the large number of breeding seabirds and the influence of salt spray and exposure, and its foreshore and sublittoral habitats are amongst the most wave and tide-exposed in Britain. From January to October Grassholm island supports the third largest breeding population of the north Atlantic gannet (*Morus bassanus)* in the world.

Gannets use the marine waters immediately adjacent to the colony for a number of essential activities, such as preening, bathing and displaying. The nesting seabirds using the site also feed both within and outside the SPA in surrounding marine areas, as well as more distantly.

Qualifying species: The site qualifies under **article 4.2** of the Directive (79/409/EEC) as it is used regularly by 1% or more of the biogeographical population of the following regularly occurring migratory species (other than those listed in Annex I) in any season:

Migratory species	Count and season	Period	% of subspecies or population
Gannet *Morus bassanus*	33,000 pairs – breeding season	Count as at 1994/5	12.5% of the breeding North Atlantic population

DATA: The 2001 SPA Review (Stroud *et al.,* 2001) updated the earlier assessment of UK SPAs published in 1992 in view of new information and possible gaps. The UK Government requested the Joint Nature Conservation Committee (JNCC) to review the UK SPA network and to recommend a definitive list of sites, identified against explicit selection guidelines. This established a baseline throughout the UK against which the need for future change can be assessed. The data quoted above is taken from this 2001 review, which was based on the most current and comprehensive data that was available at the commencement of the review. They provide a comparative assessment and a fixed baseline, even though more recent data have since become available.

Principal bird data sources:

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MCSORLEY, C.A., DEAN, B.J., WEBB, A. & REID, J.B. 2003. **Seabird use of waters adjacent to colonies: Implications for seaward extensions to existing seabird breeding colony SPAs.** JNCC Report, No. 329

MCSORLEY, C.A., WILSON L.J., DUNN, T.E., GRAY, C., DEAN, B.J., WEBB, A. & REID, J. B. 2008. **Manx shearwater *Puffinus puffinus* evening rafting behaviour around colonies on Skomer, Rum and Bardsey: its spatial extent and implications for recommending seaward boundary extensions to existing colony Special Protection Areas in the UK.** JNCC Report No. 406.

REID, J.B. & WEBB, A. 2005. **Marine Natura 2000 – Recommendations for the extension of existing seabird (colony) Special Protection Areas into the marine environment.** JNCC Committee paper 05 P14B.

STROUD, D.A., CHAMBERS, D., COOK, S., BUXTON, N., FRASER, B., CLEMENT, P., LEWIS, I., MCLEAN, I., BAKER, H. & WHITEHEAD, S. 2001. **The UK SPA network: its scope and content.** JNCC, Peterborough.
Volume 1: Rationale for the selection of sites. 90 pp.
Volume 2: Species accounts. 438 pp.
Volume 3: Site accounts. 392 pp.

CYNGOR CEFN GWLAD CYMRU
COUNTRYSIDE COUNCIL FOR WALES

CORE MANAGEMENT PLAN
INCLUDING CONSERVATION OBJECTIVES
FOR
GRASSHOLM SPA

Version: 2

Date: 8 April 2008

Approved by: Tracey Lovering

A Welsh version of all or part of this document can be made available on request.

CONTENTS

PREFACE

This document provides the main elements of CCW's management plan for the site named. It sets out what needs to be achieved on the site, the results of monitoring and advice on the action required. This document is made available through CCW's web site and may be revised in response to changing circumstances or new information. This is a technical document that supplements summary information on the web site.

One of the key functions of this document is to provide CCW's statement of the Conservation Objectives for the relevant Natura 2000 site. This is required to implement the Conservation (Natural Habitats, &c.) Regulations 1994, as amended (Section 4). As a matter of Welsh Assembly Government Policy, the provisions of those regulations are also to be applied to Ramsar sites in Wales.

1. VISION FOR THE SITE

This is a descriptive overview of what needs to be achieved for conservation on the site. It brings together and summarises the Conservation Objectives (part 4) into a single, integrated statement about the site.

CCW's aim for the gannet colony is to see it contribute towards maintaining the North Atlantic gannet population in favourable conservation status. The population on Grassholm should not fall below 30,000 pairs in three consecutive years, nor should it drop by more than 25% of the previous year's figures in any one year. There should be no decline in the Grassholm/Ynys Gwales population which is significantly more than any decline in the North Atlantic population as a whole.

2. SITE DESCRIPTION

2.1 Area and Designations Covered by this Plan

Grid references: SM598093

Unitary authority: Pembrokeshire Coast National Park Authority

Area (hectares): 10.7 ha

Designations covered: Grassholm SSSI / SPA (areas below Mean High Water are part of Pembrokeshire Marine SAC and are covered by that plan)

Detailed maps of the designated sites are available through CCW's web site:
http://www.ccw.gov.uk/interactive-maps/protected-areas-map.aspx

See map of management units which show the area covered by this plan.

2.2 Outline Description

Grassholm Island is situated 10 miles off the Pembrokeshire coast, separated from the mainland by the often turbulent waters of the Irish sea.

In 1948 Grassholm became the first reserve to be purchased by the RSPB in Wales.

The island is a mere 9ha in size. It is a National Nature Reserve and is included within the Pembrokeshire Coast National Park. It is protected under both UK and EU legislation.

Grassholm is a tourist attraction within the St.Davids peninsula. During the breeding season the 32,000 pairs of gannets nesting on the reserve make it impossible for visitors to land without causing undue disturbance. However, boat trips around the island, run by local private operators, enable several thousand people every year to enjoy the spectacle.

The colony is of international importance, supporting approximately 12% of the world population of this species.

The island is a remnant of ancient lava flows, with shallow soils overlaying the basalt. No vegetation survives the guano and trampling of the gannets but the half of the island, as yet unoccupied by the gannets, supports a classic example of vegetation, typical of an ungrazed seabird island, including the grasses red fescue and Yorkshire fog.

Small colonies of lesser, herring and great black-backed gulls nest in the turf and rocks of the eastern side of the island, while the western rock ledges support small numbers of guillemot, razorbill and kittiwake. Small numbers of storm petrels are also thought to breed among the rock boulders.

Atlantic grey seals use the island as a seasonal haul-out, and the offshore currents and upwellings are a source of attraction for several species of cetacean including good numbers of common dolphin and frequent sightings of minke whale.

When the island is free of birds in the winter, traces of old stone walls and cairns can be seen across the summit implying human occupation in the past. The name “Grassholm” is Norse and refers to the island’s once green appearance. The Welsh name “Gwales” means “sanctuary” and may itself commemorate an ancient hermitage.

The first account of gannets occupying the island comes in the late 1800s with a record of up to 20 gannet nests in 1860 and anecdotal accounts of their presence as early as 1820.

2.3 Outline of Past and Current Management

Current management comprises the following work by the RSPB:

- Protect the nesting gannets by maintaining a no landing policy on the island.
- Monitor productivity of the gannets each year.
- Carry out a full population survey every 5 years.
- Visit the island each autumn to cut free chicks entangled in fishing line.
- Liaise with, and assist, local boat operators who run trips around the island to minimise disturbance to the colony.
- Monitor other breeding seabird numbers on a periodic basis.
- Encourage additional scientific research on gannet ecology

2.4 Management Units

The plan area has been divided into management units to enable practical communication about features, objectives, and management. This will also allow us to differentiate between the different designations where necessary. In this plan the management units have been based on tenure and enclosure pattern. In some cases where, there are numerous owners of small sections of the coastal strip, these have been amalgamated into larger units.

Grassholm has been split for the purposes of this plan into the area above Mean High Water, and the area below it which, in addition to being part of the SPA - is part of Pembrokeshire Marine SAC.

The following table confirms the relationships between the management units and the designations covered:

Unit number	**SSSI**	**SAC**	**SPA**	**Name**
1	✓		✓	Grassholm
2	✓	✓	✓	Grassholm marine

3. THE SPECIAL FEATURES

3.1 Confirmation of Special Features

Designated feature	***Relationships, nomenclature etc***	***Conservation Objective in part 4***
SPA features		
1. Gannet	*Sula bassana*	4.1
SSSI features		
2. Reefs (Littoral Rock)		
3. Grey Seal *Halichoerus grypus*		

3.2 Special Features and Management Units

This section sets out the relationship between the special features and each management unit. This is intended to provide a clear statement about what each unit should be managed for, taking into account the varied needs of the different special features. All special features are allocated to one of seven classes in each management unit. These classes are:

Key Features
KH - a ‘Key Habitat’ in the management unit, i.e. the habitat that is the main focus of management and monitoring effort, perhaps because of the dependence of a key species (see KS below). There will rarely be more than one Key Habitat in a unit.
KS – a ‘Key Species’ in the management unit, often driving both the selection and management of a Key Habitat.
Geo – an earth science feature that is the main focus of management and monitoring effort in a unit.

Other Features
Sym - habitats, species and earth science features that are of importance in a unit but are not the main focus of management or monitoring. These features will benefit from management for the key feature(s) identified in the unit. These may be classed as ‘Sym’ features because:

a) they are present in the unit but are of less conservation importance than the key feature; and/or
b) they are present in the unit but in small areas/numbers, with the bulk of the feature in other units of the site; and/or
c) their requirements are broader than and compatible with the management needs of the key feature(s) , e.g. a mobile species that uses large parts of the site and surrounding areas.

Nm **-** an infrequently used category where features are at risk of decline within a unit as a result of meeting the management needs of the key feature(s), i.e. under Negative Management. These cases will usually be compensated for by management elsewhere in the plan, and can be used where minor occurrences of a feature would otherwise lead to apparent conflict with another key feature in a unit.

Mn - Management units with no special feature present but which are of importance for management of features elsewhere on a site e.g. livestock over-wintering area included within designation boundaries, buffer zones around water bodies, etc.

x – Features not present in the management unit.

The table below sets out the relationship between the special features and management units identified in this plan:

Grassholm SPA		
	1	**2**
SSSI	✓	✓
SPA	✓	✓
SAC		✓
SPA feature		
1. Gannet	**KS**	**x**

4. CONSERVATION OBJECTIVES

Background to Conservation Objectives:

a. Outline of the legal context and purpose of conservation objectives.

Conservation objectives are required by the 1992 ‘Habitats’ Directive (92/43/EEC). The aim of the Habitats Directives is the maintenance, or where appropriate the restoration of the ‘favourable conservation status’ of habitats and species features for which SACs and SPAs are designated (see Box 1).

In the broadest terms, 'favourable conservation status' means a feature is in satisfactory condition and all the things needed to keep it that way are in place for the foreseeable future. CCW considers that the concept of favourable conservation status provides a practical and legally robust basis for conservation objectives for Natura 2000 and Ramsar sites.

Box 1
Favourable conservation status as defined in Articles 1(e) and 1(i) of the Habitats Directive

“The conservation status of a natural habitat is the sum of the influences acting on it and its typical species that may affect its long-term natural distribution, structure and functions as well as the long term survival of its typical species. The conservation status of a natural habitat will be taken as favourable when:

- Its natural range and areas it covers within that range are stable or increasing, and
- The specific structure and functions which are necessary for its long-term maintenance exist and are likely to continue to exist for the foreseeable future, and
- The conservation status of its typical species is favourable.

The conservation status of a species is the sum of the influences acting on the species that may affect the long-term distribution and abundance of its populations. The conservation status will be taken as ‘favourable’ when:

- population dynamics data on the species indicate that it is maintaining itself on a long-term basis as a viable component of its natural habitats, and
- the natural range of the species is neither being reduced nor is likely to be reduced for the foreseeable future, and
- There is, and will probably continue to be, a sufficiently large habitat to maintain its populations on a long-term basis.”

Achieving these objectives requires appropriate management and the control of factors that may cause deterioration of habitats or significant disturbance to species.

As well as the overall function of communication, Conservation objectives have a number of specific roles:

- Conservation planning and management.

  The conservation objectives guide management of sites, to maintain or restore the habitats and species in favourable condition.

- Assessing plans and projects.

  Article 6(3) of the 'Habitats' Directive requires appropriate assessment of proposed plans and projects against a site's conservation objectives. Subject to certain exceptions, plans or projects may not proceed unless it is established that they will not adversely affect the integrity of sites. This role for testing plans and projects also applies to the review of existing decisions and consents.

- Monitoring and reporting.

  The conservation objectives provide the basis for assessing the condition of a feature and the status of factors that affect it. CCW uses 'performance indicators' within the conservation objectives, as the basis for monitoring and reporting. Performance indicators are selected to provide useful information about the condition of a feature and the factors that affect it.

The conservation objectives in this document reflect CCW's current information and understanding of the site and its features and their importance in an international context. The conservation objectives are subject to review by CCW in light of new knowledge.

b. Format of the conservation objectives

There is one conservation objective for each feature listed in part 3. Each conservation objective is a composite statement representing a site-specific description of what is considered to be the favourable conservation status of the feature. These statements apply to a whole feature as it occurs within the whole plan area, although section 3.2 sets out their relevance to individual management units.

Each conservation objective consists of the following two elements:

1. Vision for the feature
2. Performance indicators

As a result of the general practice developed and agreed within the UK Conservation Agencies, conservation objectives include performance indicators, the selection of which should be informed by JNCC guidance on Common Standards Monitoring[1].

There is a critical need for clarity over the role of performance indicators within the conservation objectives. **A conservation objective, because it includes the vision for the feature, has meaning and substance independently of the performance indicators, and is more than the sum of the performance indicators**. The performance indicators are simply what make the conservation objectives measurable, and are thus part of, not a substitute for, the conservation objectives. Any feature attribute identified in the performance indicators should be represented in the vision for the feature, but not all elements of the vision for the feature will necessarily have corresponding performance indicators.

As well as describing the aspirations for the condition of the feature, the Vision section of each conservation objective contains a statement that the factors necessary to maintain those desired conditions are under control. Subject to technical, practical and resource constraints, factors which have an important influence on the condition of the feature are identified in the performance indicators.

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[1] Available through www.jncc.gov.uk and follow links to Protected Sites and Common Standards Monitoring.

4.1 Conservation Objective for Feature 1: Gannet

Vision for Gannet

The vision for this feature is for it to be in a favourable conservation status, where all of the following conditions are satisfied:

- The population will not fall below 30,000 pairs in three consecutive years,
- It will not drop by more than 25% of the previous year's figures in any one year.
- There will be no decline in this population significantly greater than any decline in the North Atlantic population as a whole.

Performance indicators for Gannet

The performance indicators are part of the conservation objective, not a substitute for it. Assessment of plans and projects must be based on the entire conservation objective, not just the performance indicators.

Performance indicators for feature condition		
Attribute	***Attribute rationale and other comments***	***Specified limits***
A1. Number of pairs	Lower limit is based on current extent	*Upper limit*: Not set *Lower limit*: 30,000
A2. Measurable change		*Upper limit*: Not required *Lower limit*: decline of 25% on previous year
Performance indicators for factors affecting the feature		
Factor	***Factor rationale and other comments***	***Operational Limits***
F1. Pollution	Oil spills and other pollution episodes may cause damage.	*Upper limit*: none set *Lower limit*: none set
F2. Litter	Marine litter, especially plastic, can result in wounding and/or death of individual gannets that become entangled. This may, for example, occur during feeding at sea, when entanglement can cause drowning, or because plastic or nylon line, together with other persistent litter is often used as a nesting material, causing entanglement on the nest of both adults and young	*Upper limit*: none set *Lower limit*: none set

Performance indicators for factors affecting the feature		
Factor	***Factor rationale and other comments***	***Operational Limits***
F3. Human disturbance	Human disturbance from visitors has been significantly reduced since landings on the island by the public were stopped in 1997. Tourist boats now circumnavigate the island, and there is a code of conduct agreed with tourist boat operators to minimise disturbance from the sea. There is still the potential for private boats to cause disturbance, although the remote nature of the island tends to deter all but the most intrepid visitors. Disturbance by RAF aircraft has occurred on occasion in the past, but there has been an agreement with the RAF in place since 1998 regarding air avoidance areas, which are avoided except in emergencies.	*Upper limit*: none set *Lower limit*: none set
F4. Fisheries Management	Changes in the availability of food due to changes in fisheries policy or fishing methods are likely to have a significant impact on the population.	*Upper limit*: none set *Lower limit*: none set

5. ASSESSMENT OF CONSERVATION STATUS AND MANAGEMENT REQUIREMENTS

This part of the document provides:

- A summary of the assessment of the conservation status of each feature.
- A summary of the management issues that need to be addressed to maintain or restore each feature.

5.1 Conservation Status and Management Requirements of Feature 1: Gannet

Conservation Status of Gannet
2004: Favourable Maintained

Monitoring has demonstrated a year-on-year increase to a current estimate of 32,409 pairs.

Management Requirements of Gannet

None.

6. ACTION PLAN: SUMMARY

This section takes the management requirements outlined in Section 5 a stage further, assessing the specific management actions required on each management unit. This information is a summary of that held in CCW's Actions Database for sites, and the database will be used by CCW and partner organisations to plan future work to meet the Wales Environment Strategy targets for sites.

Unit Number	CCW Database Number	Unit Name	Summary of Conservation Management Issues	Action needed?
1	001968	Grassholm	This unit is considered to be under appropriate conservation management	No
2	002450	Grassholm SPA unit	This unit is considered to be under appropriate conservation management	No

7. GLOSSARY

This glossary defines the some of the terms used in this **Core Management Plan**. Some of the definitions are based on definitions contained in other documents, including legislation and other publications of CCW and the UK nature conservation agencies. None of these definitions is legally definitive.

Action	A recognisable and individually described act, undertaking or **project** of any kind, specified in section 6 of a **Core Management Plan** or **Management Plan**, as being required for the **conservation management** of a site.
Attribute	A quantifiable and monitorable characteristic of a **feature** that, in combination with other such attributes, describes its **condition**.

Common Standards Monitoring	A set of principles developed jointly by the UK conservation agencies to help ensure a consistent approach to **monitoring** and reporting on the **features** of sites designated for nature conservation, supported by guidance on identification of **attributes** and monitoring methodologies.
Condition	A description of the state of a feature in terms of qualities or **attributes** that are relevant in a nature conservation context. For example the condition of a habitat usually includes its extent and species composition and might also include aspects of its ecological functioning, spatial distribution and so on. The condition of a species population usually includes its total size and might also include its age structure, productivity, relationship to other populations and spatial distribution. Aspects of the habitat(s) on which a species population depends may also be considered as attributes of its condition.
Condition assessment	The process of characterising the **condition** of a **feature** with particular reference to whether the aspirations for its condition, as expressed in its **conservation objective**, are being met.
Condition categories	The **condition** of **feature** can be categorised, following **condition assessment** as one of the following[2]: Favourable: maintained; Favourable: recovered; Favourable: un-classified Unfavourable: recovering; Unfavourable: no change; Unfavourable: declining; Unfavourable: un-classified Partially destroyed; Destroyed.
Conservation management	Acts or undertaking of all kinds, including but not necessarily limited to **actions,** taken with the aim of achieving the **conservation objectives** of a site. Conservation management includes the taking of statutory and non-statutory measures, it can include the acts of any party and it may take place outside site boundaries as well as within sites. Conservation management may also be embedded within other frameworks for land/sea management carried out for purposes other than achieving the conservation objectives.
Conservation objective	The expression of the desired **conservation status** of a **feature,** expressed as a **vision for the feature** and a series of **performance indicators**. The conservation objective for a

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[2] See JNCC guidance on Common Standards Monitoring http://www.jncc.gov.uk/page-2272

	feature is thus a composite statement, and each feature has one conservation objective.
Conservation status	A description of the state of a **feature** that comprises both its **condition** and the state of the **factors** affecting or likely to affect it. Conservation status is thus a characterisation of both the current state of a feature and its future prospects.
Conservation status assessment	The process of characterising the **conservation status** of a **feature** with particular reference to whether the aspirations for it, as expressed in its **conservation objective**, are being met. The results of conservation status assessment can be summarised either as ‘favourable’ (i.e. conservation objectives are met) or unfavourable (i.e. conservation objectives are not met). However the value of conservation status assessment in terms of supporting decisions about **conservation management**, lies mainly in the details of the assessment of feature **condition**, **factors** and trend information derived from comparisons between current and previous conservation status assessments and condition assessments.
Core Management Plan	A CCW document containing the conservation objectives for a site and a summary of other information contained in a full site **Management Plan**.
Factor	Anything that has influenced, is influencing or may influence the **condition** of a **feature**. Factors can be natural processes, human activities or effects arising from natural process or human activities, They can be positive or negative in terms of their influence on features, and they can arise within a site or from outside the site. Physical, socio-economic or legal constraints on **conservation management** can also be considered as factors.
Favourable condition	See **condition** and **condition assessment**
Favourable conservation status	See **conservation status** and **conservation status assessment.**[3]
Feature	The species population, habitat type or other entity for which a site is designated. The ecological or geological interest which justifies the designation of a site and which is the focus of conservation management.
Integrity	See **site integrity**
Key Feature	The habitat or species population within a **management unit** that is the primary focus of **conservation management** and **monitoring** in that unit.

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[3] A full definition of favourable conservation status is given in Section 4.

Management Plan	The full expression of a designated site's legal status, **vision**, **features**, **conservation objectives**, **performance indicators** and management requirements. A complete management plan may not reside in a single document, but may be contained in a number of documents (including in particular **the Core Management Plan**) and sets of electronically stored information.
Management Unit	An area within a site, defined according to one or more of a range of criteria, such as topography, location of **features**, tenure, patterns of land/sea use. The key characteristic of management units is to reflect the spatial scale at which **conservation management** and **monitoring** can be most effectively organised. They are used as the primary basis for differentiating priorities for conservation management and monitoring in different parts of a site, and for facilitating communication with those responsible for management of different parts of a site.
Monitoring	An intermittent (regular or irregular) series of observations in time, carried out to show the extent of compliance with a formulated standard or degree of deviation from an expected norm. In **Common Standards Monitoring**, the formulated standard is the quantified expression of favourable **condition** based on **attributes**.
Operational limits	The levels or values within which a **factor** is considered to be acceptable in terms of its influence on a **feature**. A factor may have both upper and lower operational limits, or only an upper limit or lower limit. For some factors an upper limit may be zero.
Performance indicators	The **attributes** and their associated **specified limits**, together with **factors** and their associated **operational limits,** which provide the standard against which information from **monitoring** and other sources is used to determine the degree to which the **conservation objectives** for a **feature** are being met. Performance indicators are part of, not the same as, conservation objectives. See also **vision for the feature**.
Plan or project	**Project:** Any form of construction work, installation, development or other intervention in the environment, the carrying out or continuance of which is subject to a decision by any public body or statutory undertaker. **Plan**: a document prepared or adopted by a public body or statutory undertaker, intended to influence decisions on the carrying out of **projects.** Decisions on plans and projects which affect Natura 2000 and Ramsar sites are subject to specific legal and policy procedures.
Site integrity	The coherence of a site's ecological structure and function, across its whole area, that enables it to sustain the habitat, complex of habitats and/or the levels of populations of the species for which it is designated.

Site Management Statement (SMS)	The document containing CCW’s views about the management of a site issued as part of the legal notification of an SSSI under section 28(4) of the Wildlife and Countryside Act 1981, as substituted.
Special Feature	See **feature**.
Specified limit	The levels or values for an **attribute** which define the degree to which the attribute can fluctuate without creating cause for concern about the **condition** of the **feature**. The range within the limits corresponds to favourable, the range outside the limits corresponds to unfavourable. Attributes may have lower specified limits, upper specified limits, or both.
Unit	See **management unit.**
Vision for the feature	The expression, within a **conservation objective**, of the aspirations for the **feature** concerned. See also **performance indicators.**
Vision Statement	The statement conveying an impression of the whole site in the state that is intended to be the product of its **conservation management.** A ‘pen portrait’ outlining the **conditions** that should prevail when all the **conservation objectives** are met. A description of the site as it would be when all the **features** are in **favourable condition**.

8. REFERENCES

Minimum Format Management Plans for Tyddewi / St David’s cSAC (LIFE – Nature Reports, CCW 1999)
St David’s SAC Monitoring Report (Wilkinson, 2006)

EC Directive 79/409 on the Conservation of Wild Birds

CITATION FOR SPECIAL PROTECTION AREA (SPA)

AILSA CRAIG
(UK9003091)

INCLUDING MARINE EXTENSION

Site Description:

Ailsa Craig SPA is an island rising to 338 metres, situated in the outer part of the Firth of Clyde. Cliffs up to 100 metres encircle the island and provide nesting sites for a variety of seabirds, notably one of the largest Northern gannet colonies in the world.

The boundary of Ailsa Craig SPA is coincident with Ailsa Craig SSSI. The seaward extension extends approximately 2 km into the marine environment to include the seabed, water column and surface.

Qualifying Interest (N.B. All figures relate to numbers at the time of classification except where amended by the 2001 SPA Review)**:**

Ailsa Craig SPA qualifies under **Article 4.2** by regularly supporting populations of European importance of the **migratory** species; **Northern gannet** *Morus bassanus* (23,000 pairs 8.7% of the world biogeographic population) and **lesser black-backed gull** *Larus fuscus* (1,800 pairs, 1.4% of the total *L.f. greallsii* biogeographic population).

Ailsa Craig SPA also qualifies under **Article 4.2** by regularly supporting **in excess of 20,000 individual seabirds**. It regularly supports 65,000 seabirds including nationally important populations of the following species: common guillemot *Uria aalge* (3,350 pairs, 0.5% of the GB population), black-legged kittiwake *Rissa tridactyla* (3,100 pairs, 0.6% of the GB population) and herring gull *Larus argentatus* (2,250 pairs, 1.4% of the GB population).

Area: 2,759.57ha
National Grid Reference: NX 019 998
OS Sheet 1:50,000 – 76

Classified on 25th April 1990, with marine extension classified on 25th September 2009

Scottish Natural Heritage
September 2009

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Conservation Objectives for Ailsa Craig
Special Protection Area

To avoid deterioration of the habitats of the qualifying species (listed below) or significant disturbance to the qualifying species, thus ensuring that the integrity of the site is maintained; and

To ensure for the qualifying species that the following are maintained in the long term:

- **Population of the species as a viable component of the site**
- **Distribution of the species within site**
- **Distribution and extent of habitats supporting the species**
- **Structure, function and supporting processes of habitats supporting the species**
- **No significant disturbance of the species**

Qualifying Species:

- Gannet (*Morus bassanus*)
- Guillemot (*Uria aalge*)*
- Herring gull (*Larus argentatus*)*
- Kittiwake (*Rissa tridactyla*)*
- Lesser black-backed gull (*Larus fuscus*)

- Seabird assemblage

* indicates assemblage qualifier only

National Parks and Wildlife Service

Conservation Objectives Series

Saltee Islands SAC 000707
Saltee Islands SPA 004002

An Roinn
Ealaíon, Oidhreachta agus Gaeltachta
Department of
Arts, Heritage and the Gaeltacht

National Parks and Wildlife Service,
Department of Arts, Heritage and the Gaeltacht,

7 Ely Place, Dublin 2, Ireland.

Web: www.npws.ie
E-mail: natureconservation@environ.ie

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Series Editors: Rebecca Jeffrey & Naomi Kingston

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Introduction

The overall aim of the Habitats Directive is to maintain or restore the favourable conservation status of habitats and species of community interest. These habitats and species are listed in the Habitats and Birds Directives and Special Areas of Conservation and Special Protection Areas are designated to afford protection to the most vulnerable of them. These two designations are collectively known as the Natura 2000 network.

European and national legislation places a collective obligation on Ireland and its citizens to maintain habitats and species in the Natura 2000 network at favourable conservation condition. The Government and its agencies are responsible for the implementation and enforcement of regulations that will ensure the ecological integrity of these sites.

A site-specific conservation objective aims to define favourable conservation condition for a particular habitat or species at that site.

The maintenance of habitats and species within Natura 2000 sites at favourable conservation condition will contribute to the overall maintenance of favourable conservation status of those habitats and species at a national level.

Favourable conservation status of a habitat is achieved when:

- its natural range, and area it covers within that range, are stable or increasing, and
- the specific structure and functions which are necessary for its long-term maintenance exist and are likely to continue to exist for the foreseeable future, and
- the conservation status of its typical species is favourable.

The favourable conservation status of a species is achieved when:

- population dynamics data on the species concerned indicate that it is maintaining itself on a long-term basis as a viable component of its natural habitats, and
- the natural range of the species is neither being reduced nor is likely to be reduced for the foreseeable future, and
- there is, and will probably continue to be, a sufficiently large habitat to maintain its populations on a long-term basis.

Notes/Guidelines:

1. The targets given in these conservation objectives are based on best available information at the time of writing. As more information becomes available, targets for attributes may change. These will be updated periodically, as necessary.
2. An appropriate assessment based on these conservation objectives will remain valid even if the targets are subsequently updated, providing they were the most recent objectives available when the assessment was carried out. It is essential that the date and version are included when objectives are cited.
3. Assessments cannot consider an attribute in isolation from the others listed for that habitat or species, or for other habitats and species listed for that site. A plan or project with an apparently small impact on one attribute may have a significant impact on another.
4. Please note that the maps included in this document do not necessarily show the entire extent of the habitats and species for which the site is listed. This should be borne in mind when appropriate assessments are being carried out.
5. When using these objectives, it is essential that the relevant backing/supporting documents are consulted, particularly where instructed in the targets or notes for a particular attribute.

Qualifying Interests

**** indicates a priority habitat under the Habitats Directive***

000707 Saltee Islands SAC

1140	Mudflats and sandflats not covered by seawater at low tide
1160	Large shallow inlets and bays
1170	Reefs
1230	Vegetated sea cliffs of the Atlantic and Baltic coasts
1364	Grey Seal *Halichoerus grypus*
8330	Submerged or partially submerged sea caves

004002 Saltee Islands SPA

A009	Fulmar *Fulmarus glacialis*	breeding
A016	Gannet *Morus bassanus*	breeding
A018	Shag *Phalacrocorax aristotelis*	breeding
A188	Kittiwake *Rissa tridactyla*	breeding
A199	Guillemot *Uria aalge*	breeding
A200	Razorbill *Alca torda*	breeding
A204	Puffin *Fratercula arctica*	breeding

Supporting documents, relevant reports & publications (listed by date)

Supporting documents, NPWS reports and publications are available for download from: www.npws.ie/Publications

Title: Reef Investigations in Saltee Islands cSAC (Site Code: IE000707), Co. Wexford
Year: 2011
Author: Aquafact
Series: Unpublished Report to NPWS

Title: Subtidal Benthic Investigations in Saltee Islands cSAC (Site Code: IE000707), Co. Wexford
Year: 2011
Author: Aquafact
Series: Unpublished Report to NPWS

Title: BirdLife International Seabird Ecology and Foraging Range Database
Year: 2011
Author: BirdLife International
Series: http://seabird.wikispaces.com

Title: Seabird Monitoring Programme (SMP) Database
Year: 2011
Author: JNCC
Series: http://jncc.defra.gov.uk/smp/Default.aspx

Title: Saltee Islands SAC (000707): Conservation objectives supporting document - marine habitats and species [Version 1]
Year: 2011
Author: NPWS
Series: Unpublished Report to NPWS

Title: Saltee Islands SAC (000707): Conservation objectives supporting document - coastal habitats [Version 1]
Year: 2011
Author: NPWS
Series: Unpublished Report to NPWS

Title: An assessment of the breeding population of grey seals in the Republic of Ireland, 2005
Year: 2008
Author: Ó Cadhla, O.; Strong, D.; O'Keeffe, C.; Coleman, M.; Cronin, M.; Duck, C.; Murray, T.; Dower, P.; Nairn, R.; Murphy, P.; Smiddy, P.; Saich, C.; Lyons, D.; Hiby, L.
Series: Irish Wildlife Manuals No. 34

Title: Grey seal moult population survey in the Republic of Ireland, 2007
Year: 2007
Author: Ó Cadhla, O.; Strong, D.
Series: Unpublished Report to NPWS & CMRC

Title: Marine Natura 2000 recommendations for the extension of existing seabird (colony) special protection areas into the marine environment
Year: 2005
Author: Reid, J.; Webb, A.
Series: JNCC Committee Paper 05P14B

Title: Harbour seal population assessment in the Republic of Ireland: August 2003
Year: 2004
Author: Cronin, M.; Duck, C.; Ó Cadhla, O.; Nairn, R.; Strong, D.; O'Keeffe, C.
Series: Irish Wildlife Manuals No. 11

Title: Summary of National Parks & Wildlife Service surveys for common (harbour) seals (*Phoca vitulina*) and grey seals (*Halichoerus grypus*), 1978 to 2003
Year: 2004
Author: Lyons, D.O.
Series: Irish Wildlife Manuals No. 13

Title: Seabird Populations of Britain and Ireland
Year: 2004
Author: Mitchell, P.I.; Newton, S.F.; Ratcliffe, N.; Dunn, T.E.
Series: Poyser, London

Title: The status of breeding grey seals (*Halichoerus grypus*) on the east and south-east coast of Ireland
Year: 2001
Author: Lidgard, D.C.; Kiely, O.; Rogan, E.; Connolly, N.
Series: Mammalia 65 (3): 283-294

Title: Grey Seals: Status & Monitoring in the Irish & Celtic Seas
Year: 2000
Author: Kiely, O.; Lidgard, D.C.; McKibben, M.; Baines, M.E.; Connolly, N.
Series: Maritime Ireland/Wales INTERREG Report no. 3. Marine Institute

Title: Population biology of grey seals (*Halichoerus grypus* Fabricius 1791) in western Ireland
Year: 1998
Author: Kiely, O.R.M.
Series: Unpublished PhD. Thesis, National University of Ireland, University College Cork

Title: The BioMar biotope viewer: a guide to marine habitats, fauna and flora in Britain and Ireland
Year: 1997
Author: Picton, B.E.; Costello, M.J.
Series: Trinity College Dublin

Title: Seabird monitoring handbook for Britain and Ireland: a compilation of methods for survey and monitoring of breeding seabirds.
Year: 1995
Author: Walsh, P.; Halley, D.J.; Harris, M.P.; del Nevo, A.; Sim, I.M.W.; Tasker, M.L.
Series: JNCC, Peterborough

Spatial data sources

Year: Interpolated 2011
Title: 1994 BioMar Survey; 2010 subtidal and intertidal surveys
GIS operations: Polygon feature classes from marine community types base data sub-divided based on interpolation of marine survey data. Expert opinion used as necessary to resolve any issues arising
Used for: Marine community types, 1140, 1170 (maps 2, 4 and 5)

Year: 2005
Title: OSi Discovery series vector data
GIS operations: High Water Mark (HWM) polyline feature class converted into polygon feature class; clipped to SAC boundary. Seaward boundary defined by expert judgement
Used for: 1160 (map 3)

Year: 2005
Title: OSi Discovery series vector data
GIS operations: High water mark (HWM) and low water mark (LWM) polyline feature classes converted into polygon feature classes and combined
Used for: Marine community types base data (map 5)

Year: 2011
Title: Internal NPWS files
GIS operations: Digitised using the OSi six inch (1:10560) mapping series with reference to draft conservation plan map (2000). Clipped to SAC boundary. Expert opinion used as necessary to resolve any issues arising
Used for: 1230 (map 6)

Year: Derived 2011
Title: Coast of Ireland Oblique Imagery Survey 2003
GIS operations: Point dataset created from visual inspection of survey
Used for: 8330 (map 6)

Year: 2011
Title: NPWS rare and threatened species database
GIS operations: Dataset created from spatial references in database records. Expert opinion used as necessary to resolve any issues arising
Used for: 1364 (map 7)

Year: 2005
Title: OSi Discovery series vector data
GIS operations: High Water Mark (HWM) polyline feature class converted into polygon feature class; clipped to SAC boundary. Expert opinion used as necessary to resolve any issues arising
Used for: 1364 (map 7)

1140 Mudflats and sandflats not covered by seawater at low tide

To maintain the favourable conservation condition of Mudflats and sandflats not covered by seawater at low tide in the Saltee Islands SAC, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Habitat area	Hectares	The permanent habitat area is stable or increasing, subject to natural processes. See map 2	Habitat area was estimated using OSi data as 20ha. See marine supporting document for further details
Community extent	Hectares	The following community should be maintained in a natural condition: Intertidal sand to muddy sand dominated polychaetes community complex. See map 5	Based on information from a intertidal survey (EcoServe, 2011). See marine supporting document for further details

1160 Large shallow inlets and bays

To maintain the favourable conservation condition of Large shallow inlets and bays in the Saltee Islands SAC, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Habitat area	Hectares	The permanent habitat area is stable or increasing, subject to natural processes. See map 3	Habitat area was estimated using OSi data as 3651ha. See marine supporting document for further details
Community extent	Hectares	The following communities should be maintained in a natural condition: Coarse sediment with *Pomatoceros* spp. and *Pisidia longicornis* community. See map 5	Based on information from 1994 BioMar Survey (Picton and Costello, 1997) and a subtidal survey (Aquafact, 2011). See marine supporting document for further details

1170 Reefs

To maintain the favourable conservation condition of Reefs in the Saltee Islands SAC, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Distribution	Occurrence	The distribution of reefs should remain stable, subject to natural processes. See map 4	Reef mapping based on information from 1994 BioMar Survey (Picton and Costello, 1997), subtidal survey (Aquafact, 2011) and intertidal survey (EcoServe, 2011). See marine supporting document for further details
Habitat area	Hectares	The permanent habitat area is stable, subject to natural processes. See map 4	Habitat area was estimated from the 2010 survey data as 4,595ha. See marine supporting document for further details
Community structure	Biological composition	The following reef community complexes should be maintained in a natural condition: Intertidal reef community complex; and Subtidal reef dominated by echinoderms and sponges community complex. See map 5	Reef mapping based on information from 1994 BioMar Survey (Picton and Costello, 1997), subtidal survey (Aquafact, 2011) and intertidal survey (EcoServe, 2011). See marine supporting document for further details
Community extent	Hectares	The extent of *Laminaria* dominated community should be conserved, subject to natural processes. See map 5	Based on information from 1994 BioMar Survey (Picton and Costello, 1997) and subtidal reef survey (Aquafact, 2011). See marine supporting document for further details
Community structure	Biological composition	The biology of the *Laminaria* dominated community should be conserved, subject to natural processes	Based on information from 1994 BioMar Survey (Picton and Costello, 1997) and subtidal reef survey (Aquafact, 2011). See marine supporting document for further details

1230 Vegetated sea cliffs of the Atlantic and Baltic coasts

To maintain the favourable conservation condition of Vegetated sea cliffs of the Atlantic and Baltic coasts in the Saltee Islands SAC, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Habitat length	Kilometres	Area stable, subject to natural processes, including erosion. For sub-sites mapped: Great Saltee Island - 5.51km and Little Saltee Island - 3.11km. See map 6	Two sub-sites were identified giving a total estimated area of 8.62km within the SAC. Cliffs are linear features and are therefore measured in kilometres. See coastal habitats supporting document for further details
Habitat distribution	Occurrence	No decline, subject to natural processes. See map 6	See coastal habitats supporting document for further details
Physical structure: functionality and hydrological regime	Occurrence of artificial barriers	No alteration to natural functioning of geomorphological and hydrological processes due to artificial structures	Maintaining natural geomorphological processes including natural erosion is important for the health of a vegetated sea cliff. Hydrological processes maintain flushes and in some cases tufa formations that can be associated with sea cliffs, although it is not known if such formations occur on the Saltee Islands. See coastal habitats supporting document for further details
Vegetation structure: zonation	Occurrence	Maintain range of sea cliff habitat zonations including transitional zones, subject to natural processes including erosion and succession	See coastal habitats supporting document for further details
Vegetation structure: vegetation height	Centimeters	Maintain structural variation within sward	See coastal habitats supporting document for further details
Vegetation composition: typical species and sub-communities	Percentage cover at a representative sample of monitoring stops	Maintain range of sub-communities with typical species listed in the Irish Sea Cliff Survey (Barron et al., 2011)	See coastal habitats supporting document for further details
Vegetation composition: negative indicator species	Percentage	Negative indicator species (including non-natives) to represent less than 5% cover	See coastal habitats supporting document for further details
Vegetation composition: bracken and woody species	Percentage	Cover of bracken (*Pteridium aquilinum*) on grassland less than 10%. Cover of woody species on grassland less than 20%	See coastal habitats supporting document for further details

1364 Grey Seal *Halichoerus grypus*

To maintain the favourable conservation condition of Grey Seal in the Saltee Islands SAC, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Access to suitable habitat	Number of artificial barriers	Species range within the site should not be restricted by artificial barriers to site use. See map 7	See marine supporting document for further details
Breeding behaviour	Breeding sites	The breeding sites should be maintained in a natural condition. See map 7 for known sites	Attribute and target based on background knowledge of Irish breeding populations; review of data from Kiely et al. (2000); Lidgard et al. (2001); Lyons (2004); a comprehensive breeding survey in 2005 (Ó Cadhla et al., 2007); and unpublished National Parks & Wildlife Service records. See marine supporting document for further details
Moulting behaviour	Moult haul-out sites	The moult haul-out sites should be maintained in a natural condition. See map 7 for known sites	Attribute and target based on background knowledge of Irish populations; research by Kiely et al. (2000); a national moult survey (Ó Cadhla and Strong, 2007); and unpublished National Parks & Wildlife Service records. See marine supporting document for further details
Resting behaviour	Resting haul-out sites	The resting haul-out sites should be maintained in a natural condition. See map 7 for known sites	Attribute and target based on review of data from Kiely (1998); Kiely et al. (2000); Lyons (2004); Cronin et al. (2004); Ó Cadhla et al. (2007); Ó Cadhla and Strong (2007); and unpublished National Parks & Wildlife Service records. See marine supporting document for further details
Population composition	Number of cohorts	The grey seal population occurring within this site should contain adult, juvenile and pup cohorts annually	Attribute and target based on review of data from Kiely (1998), Kiely et al. (2000), Lyons (2004), Ó Cadhla et al. (2007), Ó Cadhla and Strong (2007); and unpublished National Parks & Wildlife Service records. See marine supporting document for further details
Disturbance	Level of impact	Human activities should occur at levels that do not adversely affect the grey seal population	See marine supporting document for further details

8330 Submerged or partially submerged sea caves

To maintain the favourable conservation condition of submerged or partly submerged sea caves in the Saltee Islands SAC, which is defined by the following list of attributes and targets subject to natural variation

Attribute	Measure	Target	Notes
Distribution	Occurrence	The distribution of sea caves should remain stable, subject to natural processes. See map 6 for known distribution	Sea cave distribution was derived from an oblique aerial survey and therefore only detects the presence of sea caves visible intertidally in the flight path
Community structure	Biological composition	Human activities should occur at levels that do not adversely affect the ecology of sea caves	

A009 Fulmar *Fulmarus glacialis*

To maintain the favourable conservation condition of Fulmar in the Saltee Islands SPA, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Breeding population abundance: apparently occupied sites (AOSs)	Number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). Mitchell et al. (2004) provides summary population information. The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Productivity rate	Mean number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Distribution: breeding colonies	Number; location; area (hectares)	No significant decline	Typically, fulmar nest near the tops of grassy cliffs on relatively wide ledges (Mitchell et al., 2004)
Prey biomass available	Kilogrammes	No significant decline	Key prey items: broad diet encompassing fish, zooplankton, squid, offal and fishery discards. Key habitats: relatively clear 'oceanic' water with high salinity, thermally stratified in summer. Shelf breaks, offshore banks, frontal zones, tide and rip currents may also be important. Foraging range: max. 664km, mean max. 311.43km, mean 69.35km (BirdLife International Seabird Database (Birdlife International, 2011))
Barriers to connectivity	Number; location; shape; area (hectares)	No significant increase	Seabird species can make extensive use of the marine waters adjacent to their breeding colonies for non site-specific behaviours (e.g. courtship, bathing, preening). Work carried out in the UK found that highest densities of fulmar performing these behaviours occurred within 2km of the breeding colony (Reid and Webb, 2005). Foraging range: max. 664km, mean max. 311.43km, mean 69.35km (BirdLife International Seabird Database (Birdlife International, 2011))
Disturbance at the breeding site	Level of impact	No significant increase	Typically, fulmar nest near the top of grassy cliffs on relatively wide ledges (Mitchell et al., 2004)
Disturbance at marine areas immediately adjacent to the colony	Level of impact	No significant increase	Seabird species can make extensive use of the marine waters adjacent to their breeding colonies for non site-specific behaviours (e.g. courtship, bathing, preening). Work carried out in the UK found that highest densities of fulmar performing these behaviours occurred within 2km of the breeding colony (Reid and Webb, 2005)

A016 Gannet *Morus bassanus*

To maintain the favourable conservation condition of Gannet in the Saltee Islands SPA, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Breeding population abundance: apparently occupied nests (AONs)	Number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). Mitchell et al. (2004) provides summary population information. The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Productivity rate	Mean number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Distribution: breeding colonies	Number; location; area (hectares)	No significant decline	Gannetries are conspicuous with high densities of nests built with seaweed, other vegetation and earth stuck together with excreta
Prey biomass available	Kilogrammes	No significant decline	Key prey items: surface schooling fish, fisheries waste; discards important for some colonies and/or in some seasons. Key habitats: Deep-water depressions, tidal mixing fronts, shelf breaks, sandbanks, inshore and coastal waters. Foraging range: max. 640km, mean max. 308.36km, mean 140.09km (BirdLife International Seabird Database (Birdlife International, 2011))
Barriers to connectivity	Number; location; shape; area (hectares)	No significant increase	Seabird species can make extensive use of the marine waters adjacent to their breeding colonies for non site-specific behaviours (e.g. courtship, bathing, preening). Work carried out in the UK found that highest densities of gannet performing these behaviours occurred within 2km of the breeding colony (Reid and Webb, 2005). Foraging range: max. 640km, mean max. 308.36km, mean 140.09km (BirdLife International Seabird Database (Birdlife International, 2011))
Disturbance at the breeding site	Level of impact	No significant increase	Gannetries are conspicuous with high densities of nests bulit with seaweed, other vegetation and earth stuck together with excreta. Often 'clubs' of immature and adult plumage non-breeders are discrete from the breeding birds

A016 Gannet *Morus bassanus*

To maintain the favourable conservation condition of Gannet in the Saltee Islands SPA, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Disturbance at marine areas immediately adjacent to the colony	Level of impact	No significant increase	Seabird species can make extensive use of the marine waters adjacent to their breeding colonies for non site-specific behaviours (e.g. courtship, bathing, preening). Work carried out in the UK found that highest densities of gannet performing these behaviours occurred within 2km of the breeding colony (Reid and Webb, 2005)

A017 Cormorant *Phalacrocorax carbo*

To maintain the favourable conservation condition of Cormorant in the Saltee Islands SPA, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Breeding population abundance: apparently occupied nests (AONs)	Number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). Mitchell et al. (2004) provides summary population information. The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species.
Productivity rate	Mean number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Distribution: breeding colonies	Number; location; area (hectares)	No significant decline	Cormorant colonies are usually sited on flat or rocky islets or sea stack tops, less often on cliffs (Walsh et al., 1995)
Prey biomass available	Kilogrammes	No significant decline	Key prey items: fish (mostly benthic), some crustaceans. Key habitats: populations use sandy areas, rocky and vegetated substrate. Foraging range: max. 50km, mean max. 31.67km, mean 8.46km (BirdLife International Seabird Database (Birdlife International, 2011))
Barriers to connectivity	Number; location; shape; area (hectares)	No significant increase	Foraging Range: max. 50km, mean max. 31.67km, mean 8.46km (BirdLife International Seabird Database (Birdlife International, 2011))
Disturbance at the breeding site	Level of impact	No significant increase	Cormorant colonies are usually sited on flat or rocky islets or stack stops, less often on cliffs (Walsh et al., 1995)

A018 Shag *Phalacrocorax aristotelis*

To maintain the favourable conservation condition of Shag in the Saltee Islands SPA, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Breeding population abundance: apparently occupied nests (AONs)	Number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). Mitchell et al. (2004) provides summary population information. The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Productivity rate	Mean number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Distribution: breeding colonies	Number; location; area (hectares)	No significant decline	Shags can nest in small groups spread along several kilometres of coastline. In general, colonies are discrete and normally on cliffs/offshore islands (Mitchell et al., 2004)
Prey biomass available	Kilogrammes	No significant decline	Key prey items: benthic, demersal and schooling pelagic fish- especially sandeels (Ammodytes spp.). Key habitats: shallow waters, particularly over sand and gravel banks, areas of high tidal flow. Foraging range: max. 20km, mean max. 16.42km, mean 6.53km (BirdLife International Seabird Database (Birdlife International, 2011))
Barriers to connectivity	Number; location; shape; area (hectares)	No significant increase	Foraging range: max. 20km, mean max. 16.42km, mean 6.53km (BirdLife International Seabird Database (Birdlife International, 2011))
Disturbance at the breeding site	Level of impact	No significant increase	Shags can nest in small groups spread along several kilometres of coastline. In general colonies are discrete and normally on cliffs/offshore islands (Mitchell et al., 2004)

A183 Lesser Black-backed Gull *Larus fuscus*

To maintain the favourable conservation condition of Lesser Black-backed Gull in the Saltee Islands SPA, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Breeding population abundance: apparently occupied nests (AONs)	Number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). Mitchell et al. (2004) provides summary population information. The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Productivity rate	Mean number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Distribution: breeding colonies	Number; location; area (hectares)	No significant decline	Lesser black-backed gull nests colonially, often with other gull species on offshore islands and coastal cliffs often within vegetated areas (Mitchell et al., 2004)
Prey biomass available	Kilogrammes	No significant decline	Lesser black-backed gulls are surface feeders whose diet includes fish, invertebrates and fishery-related discards. max. foraging range 40km
Barriers to connectivity	Number; location; shape; area (hectares)	No significant increase	Foraging range: max. 40km
Disturbance at the breeding site	Level of impact	No significant increase	Lesser black-backed gull nests colonially, often with other gull species on offshore islands and coastal cliffs often within vegetated areas (Mitchell et al., 2004)

A184 Herring Gull *Larus argentatus*

To maintain the favourable conservation condition of Herring Gull in the Saltee Islands SPA, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Breeding population abundance: apparently occupied nests (AONs)	Number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). Mitchell et al. (2004) provides summary population information. The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Productivity rate	Mean number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Distribution: breeding colonies	Number; location; area (hectares)	No significant decline	Rocky coastline with cliffs, islets and offshore islands, is the preferred breeding habitat (Mitchell et al., 2004)
Prey biomass available	Kilogrammes	No significant decline	Primarily a coastal feeder, mainly in the littoral and shallow sub-littoral zones; also targets anthropogenic sources of food in both marine and terrestrial areas. max. foraging range approximately 50km
Barriers to connectivity	Number; location; shape; area (hectares)	No significant increase	Foraging range: max. 50km
Disturbance at the breeding site	Level of impact	No significant increase	Herring gull colonies are usually sited on flat or rocky islets or stack stops, less often on cliffs (Walsh et al., 1995)

A188 Kittiwake *Rissa tridactyla*

To maintain the favourable conservation condition of Kittiwake in the Saltee Islands SPA, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Breeding population abundance: apparently occupied nests (AONs)	Number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). Mitchell et al. (2004) provides summary population information. The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Productivity rate	Mean number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Distribution: breeding colonies	Number; location; area (hectares)	No significant decline	In general, kittiwake colonies are found on vertical rocky sea cliffs
Prey biomass available	Kilogrammes	No significant decline	Key prey items: small pelagic shoaling fish, marine invertebrates. Key habitats: fronts, tidal upwellings and eddies, offshore sandbanks, areas over rocky seabed. Foraging range: max. 200km, mean max. 65.81km, mean 25.45km (BirdLife International Seabird Database (Birdlife International, 2011))
Barriers to connectivity	Number; location; shape; area (hectares)	No significant increase	Foraging range: max. 200km, mean max. 65.81km, mean 25.45km (BirdLife International Seabird Database (Birdlife International, 2011))
Disturbance at the breeding site	Level of impact	No significant increase	In general, kittiwake colonies are found on vertical rocky sea cliffs

A199 Guillemot *Uria aalge*

To maintain the favourable conservation condition of Guillemot in the Saltee Islands SPA, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Breeding population abundance: individual adult	Number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). Mitchell et al. (2004) provides summary population information. The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Productivity rate	Mean number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Distribution: breeding colonies	Number; location; area (hectares)	No significant decline	In general, guillemot colonies are found on vertical rocky sea cliffs and sea stacks
Prey biomass available	Kilogrammes	No significant decline	Key prey items: schooling pelagic fish, crustaceans. Key habitats: fronts and other ocean features that concentrate prey, offshore sandbanks, areas of sandy sediment. Foraging range: max. 200km, mean max. 60.61km, mean 24.49km (BirdLife International Seabird Database (Birdlife International, 2011))
Barriers to connectivity	Number; location; shape; area (hectares)	No significant increase	Seabird species can make extensive use of the marine waters adjacent to their breeding colonies for non site-specific behaviours (e.g. courtship, bathing, preening). Work carried out in the UK found that highest densities of guillemot performing these behaviours occurred within 1km of the breeding colony (Reid and Webb, 2005). Foraging range: max. 200km, mean max. 60.61km, mean 24.49km (BirdLife International Seabird Database (Birdlife International, 2011))
Disturbance at the breeding site	Level of impact	No significant increase	In general, guillemot colonies are found on vertical rocky sea cliffs and sea stacks
Disturbance at marine areas immediately adjacent to the colony	Level of impact	No significant increase	Seabird species can make extensive use of the marine waters adjacent to their breeding colonies for non site-specific behaviours (e.g. courtship, bathing, preening). Work carried out in the UK found that highest densities of guillemot performing these behaviours occurred within 1km of the breeding colony (Reid and Webb, 2005)

A200 Razorbill *Alca torda*

To maintain the favourable conservation condition of Razorbill in the Saltee Islands SPA, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Breeding population abundance: individual adult	Number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). Mitchell et al. (2004) provides summary population information. The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Productivity rate	Mean number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Distribution: breeding colonies	Number; location; area (hectares)	No significant decline	Razorbill breed mainly on small ledges or in cracks of rocky cliffs and in associated screes, and on boulder fields (Mitchell et al., 2004)
Prey biomass available	Kilogrammes	No significant decline	Key prey items: Sandeels (*Ammodytes* spp.), clupeids. Key habitats: shallow waters, sandy seabeds, upwelling areas and tidal fronts. Foraging range: max. 51km, mean max. 31km, mean 10.27km (BirdLife International Seabird Database (Birdlife International, 2011))
Barriers to connectivity	Number; location; shape; area (hectares)	No significant increase	Seabird species can make extensive use of the marine waters adjacent to their breeding colonies for non site-specific behaviours (e.g. courtship, bathing, preening). Work carried out in the UK found that highest densities of razorbill performing these behaviours occurred within 1km of the breeding colony (Reid and Webb, 2005). Foraging range: max. 51km, mean max. 31km, mean 10.27km (BirdLife International Seabird Database (Birdlife International, 2011))
Disturbance at the breeding site	Level of impact	No significant increase	Razorbill breed mainly on small ledges or in cracks of rocky cliffs and in associated screes, and on boulder fields (Mitchell et al., 2004)
Disturbance at marine areas immediately adjacent to the colony	Level of impact	No significant increase	Seabird species can make extensive use of the marine waters adjacent to their breeding colonies for non site-specific behaviours (e.g. courtship, bathing, preening). Work carried out in the UK found that highest densities of razorbill performing these behaviours occurred within 1km of the breeding colony (Reid and Webb, 2005)

A204 Puffin *Fratercula arctica*

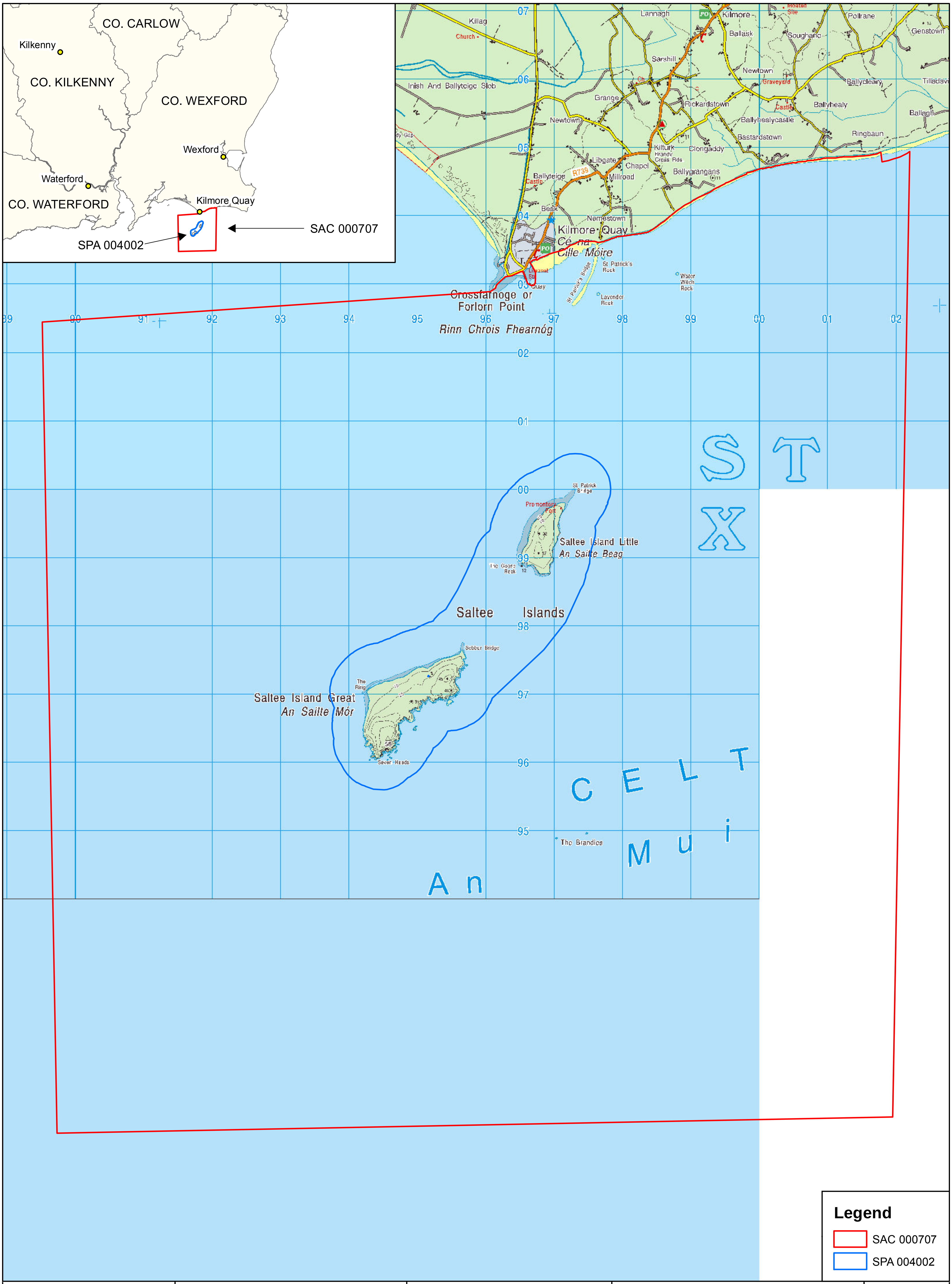
To maintain the favourable conservation condition of Puffin in the Saltee Islands SPA, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Breeding population abundance: apparently occupied burrow (AOB)	Number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). Mitchell et al. (2004) provides summary population information. The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species.
Productivity rate	Mean number	No significant decline	Measure based on standard survey methods (see Walsh et al., 1995). The Seabird Monitoring Programme (SMP) online database (JNCC, 2011) provides population data for this species
Distribution: breeding colonies	Number; location; area (hectares)	No significant decline	Highly colonial species with pairs typically nesting underground in burrows dug in the soil of offshore islands. If such habitat is in short supply puffins can nest among boulder screes or at low densities in cracks in sheer cliffs (Mitchell et al., 2004)
Prey biomass available	Kilogrammes	No significant decline	Key prey items: mid-sized schooling mid-water fish, especially sandeels (Ammodytes spp.). Key habitats: shallow waters, tidal fronts. Foraging range: max. 200km, mean max. 62.2km, mean 30.35km (BirdLife International Seabird Database (Birdlife International, 2011))
Barriers to connectivity	Number; location; shape; area (hectares)	No significant increase	Seabird species can make extensive use of the marine waters adjacent to their breeding colonies for non site-specific behaviours (e.g. courtship, bathing, preening). Work carried out in the UK found that highest densities of puffin performing these behaviours occurred within 1km of the breeding colony (Reid and Webb, 2005). Foraging range: max. 200km, mean max. 62.2km, mean 30.35km (BirdLife International Seabird Database (Birdlife International, 2011))
Disturbance at the breeding site	Level of impact	No significant increase	Highly colonial species with pairs typically nesting underground in burrows dug in the soil of offshore islands. If such habitat is in short supply Puffins can nest among boulder screes or at low densities in cracks in sheer cliffs (Mitchell et al., 2004)

A204 Puffin *Fratercula arctica*

To maintain the favourable conservation condition of Puffin in the Saltee Islands SPA, which is defined by the following list of attributes and targets

Attribute	Measure	Target	Notes
Disturbance at marine areas immediately adjacent to the colony	Level of impact	No significant increase	Seabird species can make extensive use of the marine waters adjacent to their breeding colonies for non site-specific behaviours (e.g. courtship, bathing, preening). Work carried out in the UK found that highest densities of puffin performing these behaviours occurred within 1km of the breeding colony (Reid and Webb, 2005)
Occurrence of mammalian predators	Level of impact	Absent or under control	Puffin and other cavity/burrow nesting seabirds can be particularly susceptible to rat (*Rattus* spp.) predation



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MAP 1: SALTEE ISLANDS CONSERVATION OBJECTIVES SAC & SPA DESIGNATIONS

Map to be read in conjunction with the NPWS Conservation Objectives Document.

CO. WEXFORD

0 0.5 1 1.5 2 km

N

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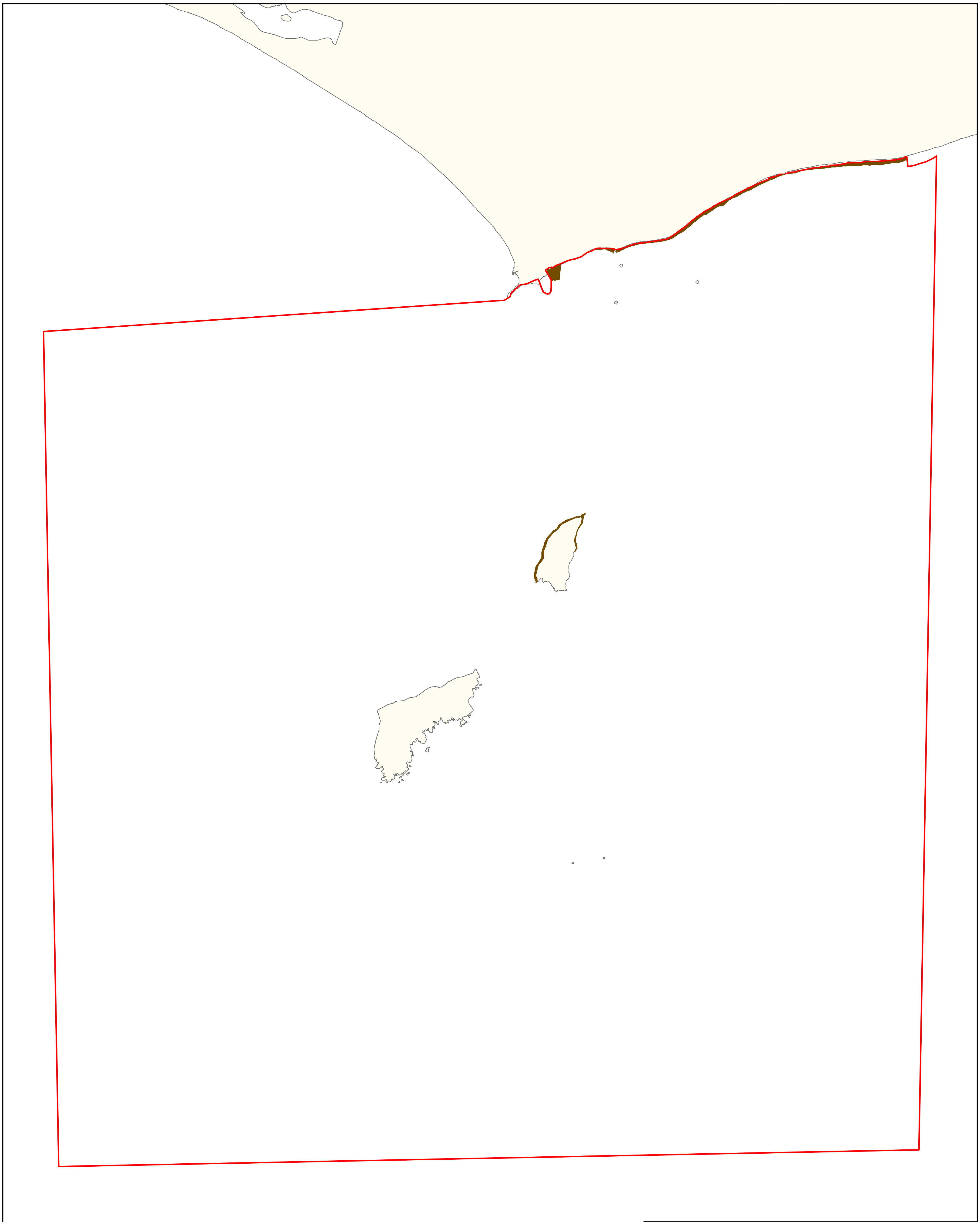
comharthaithe. Macasamhail d'ábhar na Suirbhéarachta Ordonáis
le chead ón Rialtas (Ceadunas Uimh. EN 0059208)

SITE CODE
SAC 000707
Version 1
SPA 004002
Version 2.01
Map Version 1
Date: August 2011



Legend

☐	SAC 000707
🟫	1140 Mudflats and sandflats not covered by sea water at low tide
⬜	OSi Discovery Series Coastal Boundary

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MAP 2:
SALTEE ISLANDS
CONSERVATION OBJECTIVES
MUDFLATS AND SANDFLATS

Map to be read in conjunction with the NPWS Conservation Objectives Document.

CO. WEXFORD

0 0.4 0.8 1.2 1.6 km

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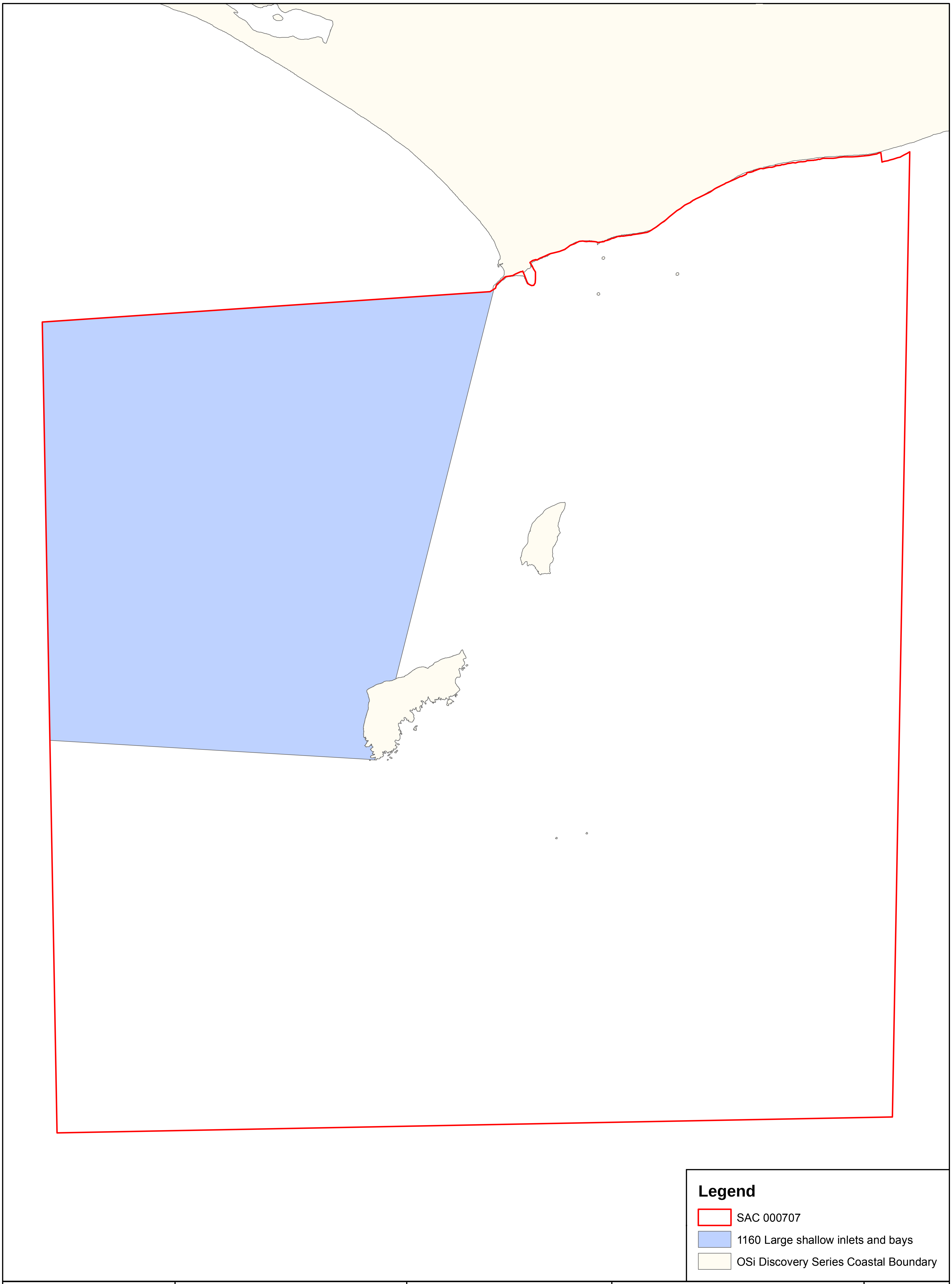

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MAP 3:
SALTEE ISLANDS
CONSERVATION OBJECTIVES
LARGE SHALLOW INLETS & BAYS

Map to be read in conjunction with the NPWS Conservation Objectives Document.

CO. WEXFORD

0 0.5 1 1.5 2 km

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MAP 4:
SALTEE ISLANDS CONSERVATION OBJECTIVES REEFS

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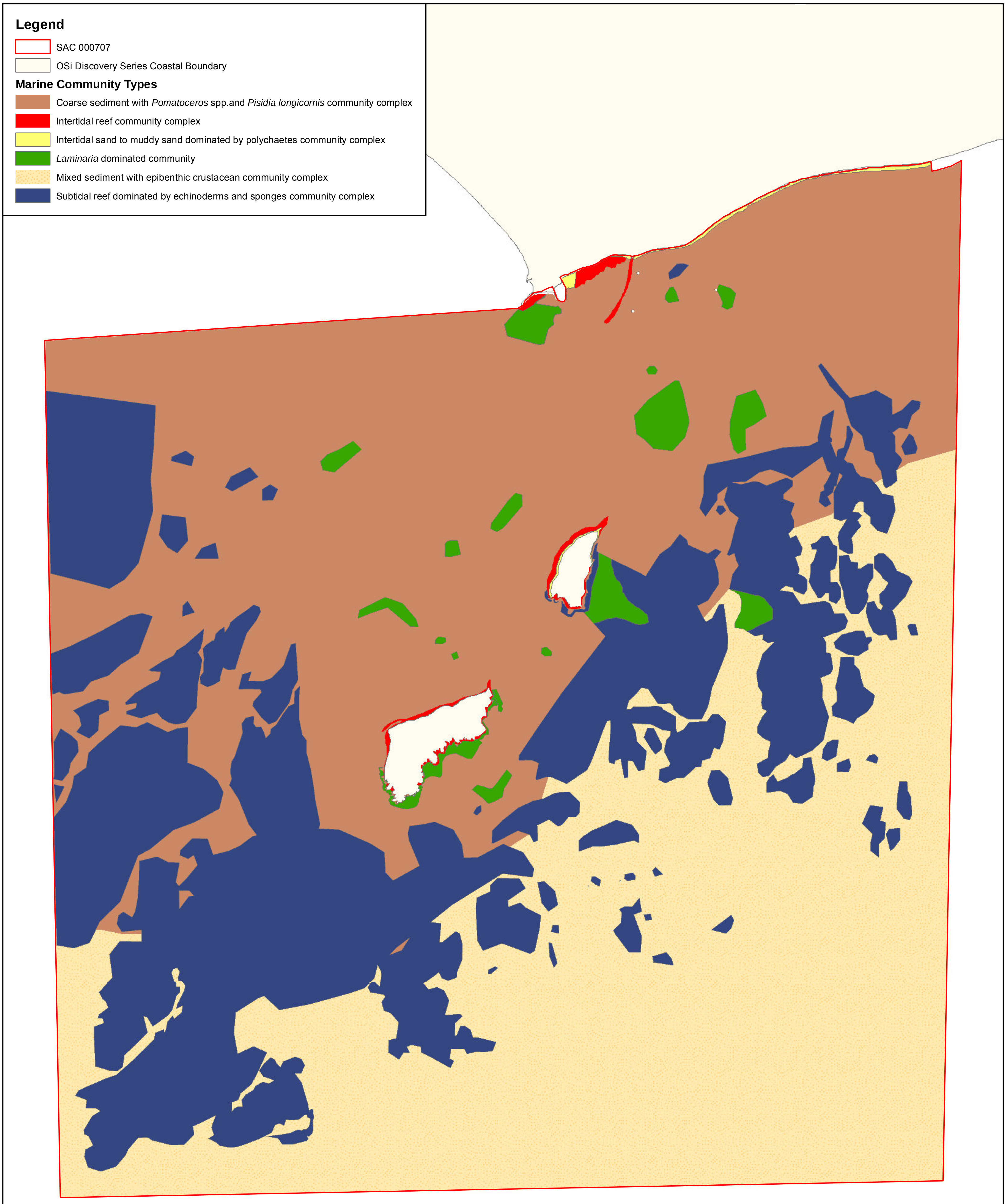

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MAP 5:
SALTEE ISLANDS
CONSERVATION OBJECTIVES
MARINE COMMUNITY TYPES

Map to be read in conjunction with the NPWS Conservation Objectives Document.

CO. WEXFORD

0 0.5 1 1.5 2 km N

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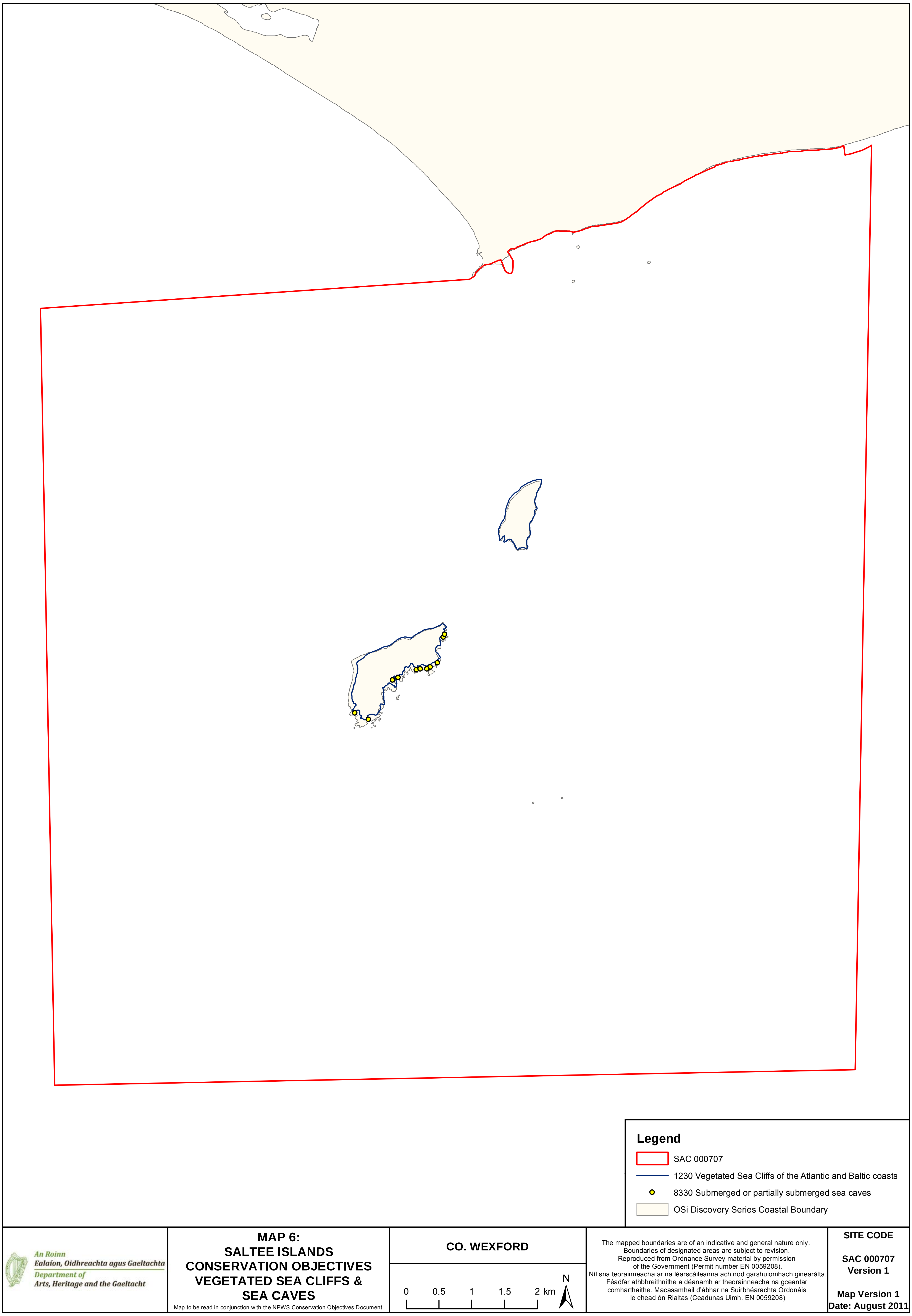

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MAP 6:
SALTEE ISLANDS
CONSERVATION OBJECTIVES
VEGETATED SEA CLIFFS & SEA CAVES

Map to be read in conjunction with the NPWS Conservation Objectives Document.

CO. WEXFORD

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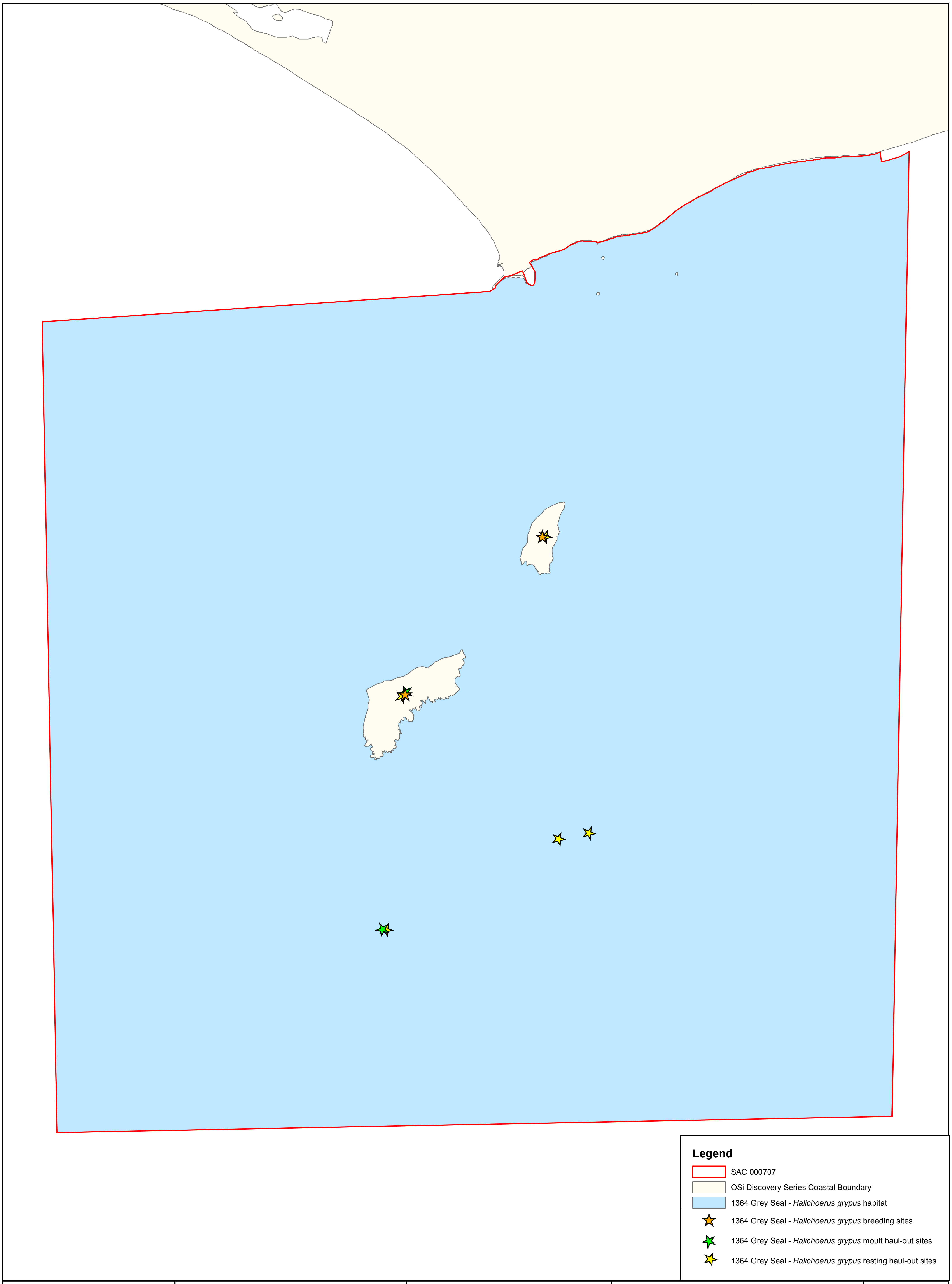

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MAP 7:
SALTEE ISLANDS CONSERVATION OBJECTIVES GREY SEAL

Map to be read in conjunction with the NPWS Conservation Objectives Document.

CO. WEXFORD

0 0.5 1 1.5 2 km

N

SITE CODE

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Version 1

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SITE SYNOPSIS

SITE NAME: SALTEE ISLANDS SPA

SITE CODE: 004002

The Saltee Islands SPA is situated some 4-5 km off the coast of south Co. Wexford and comprises the two islands, Great Saltee and Little Saltee, and the surrounding seas both between them and to a distance of 500 m from them. The bedrock of the islands is of Precambrian gneiss and granite. Both islands have exposed rocky cliffs on their south and east – those on Great Saltee being mostly *c*. 30 m high, those on Little Saltee about half this height. The northern and western sides of both islands are fringed with shingle and boulder shores, backed by boulder clay cliffs, as well as small areas of intertidal sandflats. Sea caves occur at the base of the cliffs on Great Saltee.

The site is a Special Protection Area (SPA) under the E.U. Birds Directive, of special conservation interest for the following species: Fulmar, Gannet, Cormorant, Shag, Lesser Black-backed Gull, Herring Gull, Kittiwake, Guillemot, Razorbill and Puffin. The site is also of special conservation interest for holding an assemblage of over 20,000 breeding seabirds.

The Saltee Islands are internationally important for holding an assemblage of over 20,000 breeding seabirds. The nationally important Gannet colony on Great Saltee has been well documented since its establishment in the1920s and 2,446 pairs were present in 2004. The following species have populations of national importance (all counts in the 1998-2000 breeding seasons): Fulmar (520 pairs), Cormorant (273 pairs), Shag (268 pairs), Lesser Black-backed Gull (164 pairs), Herring Gull (73 pairs), Kittiwake (2,125 pairs), Guillemot (14,362 pairs), Razorbill (2,505 pairs) and Puffin (1,822 pairs). An estimated 250 pairs of Manx Shearwater occur on these islands. Seabird populations are monitored annually and large numbers of chicks, especially of Gannets, auks and Shags, are ringed.

Peregrine Falcon breeds (1-2 pairs) and Chough (1 pair) occurs at the eastern edge of its Irish range. Hen Harrier uses the site for autumn passage and overwintering.

Great Saltee is a major site for spring and autumn landbird migration and was the site for Ireland’s first bird observatory. While the observatory is no longer operational, substantial numbers of migrants are still ringed annually. Large numbers of pipits, swallows and martins, thrushes, warblers and finches occur, while smaller numbers of a great variety of other species (some very rare in Ireland) are also recorded.

The Saltee Islands SPA is of international importance for breeding seabirds; it also supports populations of three species that are listed on Annex I of the E.U. Birds Directive, i.e. Peregrine, Chough and Hen Harrier. It is one of the best-documented sites in the country and is monitored annually.

10.2.2012