From: Dominika Phillips <DOMPH@orsted.co.uk>
Sent: 08 February 2019 21:13
To: KJ Johansson <KJ.JOHANSSON@planninginspectorate.gov.uk>; Kay Sully <Kay.Sully@pins.gsi.gov.uk>; Hornsea Project Three <HornseaProjectThree@pins.gsi.gov.uk>
Cc: Andrew Guyton <ANGUY@orsted.co.uk>; Stuart Livesey <STLIV@orsted.co.uk>
Subject: Hornsea Project Three (UK) Ltd response to Deadline 6 (Part 6)

Dear Kay, K-J

Please find attached the 6th instalment of documents.

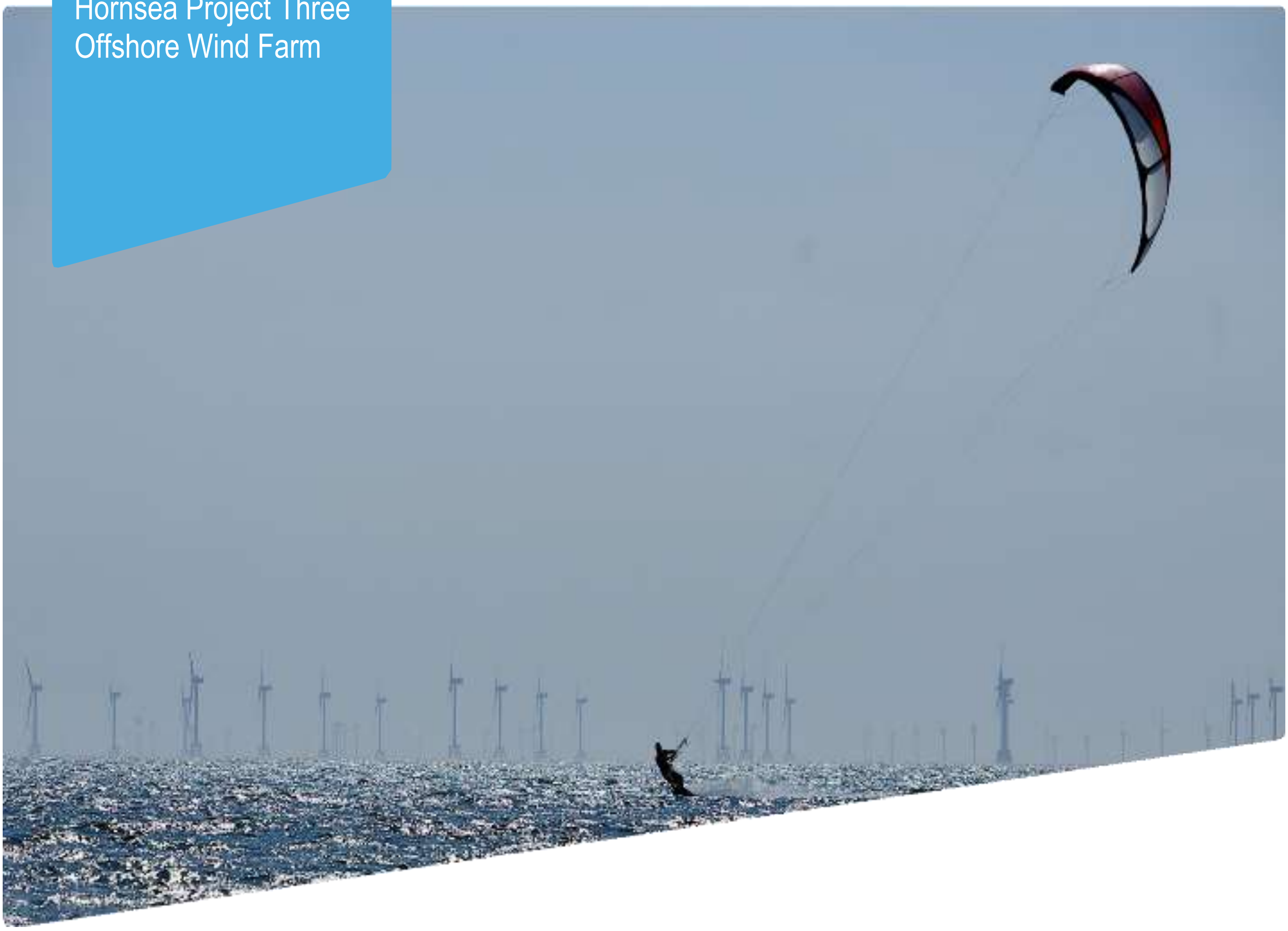
Best regards,
Dr Dominika Chalder PIEMA
Environment and Consent Manager

[redacted]

Environmental Management UK¦ Wind Power
5 Howick Place ¦ London ¦ SW1P 1WG

Orsted

Hornsea Project Three
Offshore Wind Farm



Hornsea Project Three

Offshore Wind Farm

Appendix 16 to Deadline 6 submission – Johnston et al., 2014 with Corrigendum

Date: 8th February 2019

Hornsea 3
Offshore Wind Farm

Ørsted

Document Control	
Document Properties	
Organisation	Ørsted Hornsea Project Three
Author	Johnston et al., 2014
Checked by	n/a
Approved by	n/a
Title	Appendix 16 to Deadline 6 submission – Johnston et al., 2014 with Corrigendum
PINS Document Number	n/a

Version History

Date	Version	Status	Description / Changes
08/02/2019	A	Final	Submitted at Deadline 6 (8th Feb 2019)

Ørsted

5 Howick Place,

London, SW1P 1WG

Front cover picture: Kite surfer near a UK offshore wind farm © Ørsted Hornsea Project Three (UK) Ltd., 2019.

50 YEARS WITH IMPACT
Journal of Applied Ecology
1913 2013 British Ecological Society CELEBRATING 100 YEARS

Journal of Applied Ecology 2014, **51,** 31–41 doi: 10.1111/1365-2664.12191

Modelling flight heights of marine birds to more accurately assess collision risk with offshore wind turbines

Alison Johnston[1]*†, Aonghais S. C. P. Cook[1†], Lucy J. Wright[1], Elizabeth M. Humphreys[2] and Niall H. K. Burton[1]

[1]British Trust for Ornithology, The Nunnery, Thetford, Norfolk IP24 2PU, UK; and [2]British Trust for Ornithology Scotland, School of Biological & Environmental Sciences, Cottrell Building, University of Stirling, Stirling, FK9 4LA, UK

Summary

1. The number of offshore wind farms is rapidly increasing as they are a critical part of many countries' renewable energy strategies. Quantifying the likely impacts of these developments on wildlife is a fundamental part of the impact assessments required in many regions before permission for developments is granted. A key concern related to wind turbines is the risk of birds colliding with turbine blades. We present a novel method to generate species-specific flight height distributions which can be used to improve the assessment of collision risk by better reflecting the proportion of in-flight populations at risk of collision.

2. Data describing the flight heights of birds from surveys of 32 potential offshore wind farm development sites were combined to estimate continuous distributions for 25 marine bird species. Observations of flying birds assigned to discrete height categories were treated as observations from independent multinomial distributions with a shared underlying continuous distribution. This analysis enables calculation of the uncertainty around the estimates of the proportion of the in-flight population at risk and consideration of different turbine designs.

3. The mean r^2 for model fit across species was 0·85, and for seven of the species, good independent model validation (80% of independent observations within 95% confidence intervals) provides some confidence for use of the results at alternative sites.

4. All species exhibited positively skewed flight height distributions. These results demonstrate that under the conditions in which the data were collected, raising hub height and using fewer, larger turbines are effective measures for reducing collision risk.

5. *Synthesis and applications*. The methods presented here for modelling continuous flight height distributions provide measures of uncertainty and enable comparison of collision risk between different turbine designs. This approach will improve the accuracy of impact assessments and provide estimates of uncertainty, allowing better evidence to inform decision-making.

Key-words: collision risk, Environmental Impact Assessment, flight behaviour, multinomial distribution, offshore wind farm, pre-construction survey, seabirds, wind turbine

Introduction

Offshore wind energy forms a significant part of international efforts to reduce reliance on fossil fuels. Much of the initial development of offshore wind capacity has occurred in Europe where there is a binding agreement for 20% of energy consumed to come from renewable sources by 2020 (Directive 2009/28/EC), a target which requires a substantial contribution from offshore wind farms (European Commission 2008). Elsewhere, the offshore wind industry is expected to experience significant growth in key markets, such as the United States and China (Snyder & Kaiser 2009; Da *et al*. 2011).

There are concerns about the potential for offshore wind farms (OWFs) to negatively impact wildlife including fish, marine mammals and birds (e.g. Wahlberg & Westerberg 2005; Drewitt & Langston 2006; Gilles, Scheidat & Siebert 2009) through effects such as noise pollution, displacement or direct collision. However, estimating the impacts of OWFs on species and populations is often difficult and imprecise. The estimates are

*Correspondence author. E-mail: alison.johnston@bto.org
†Joint first authors.

Figure S1. Observed and modelled proportions of birds in each height category by species.

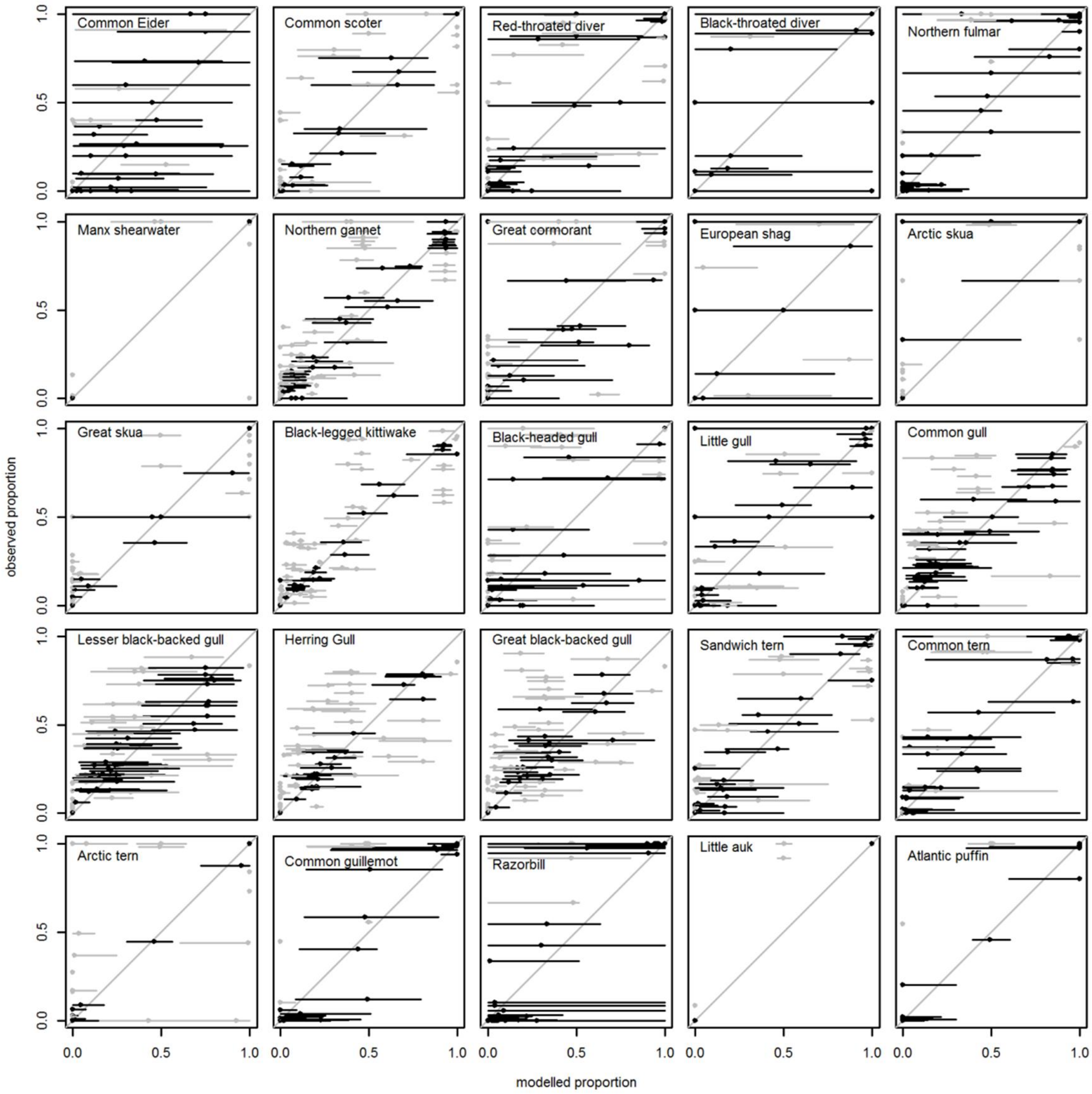


Figure S1: Modelled and observed proportion of birds in height categories at each site. Each data point is one height category at one site, with the x-axis the modelled proportion, and y-axis the observed proportion. The horizontal line represents the modelled 95% confidence interval, and the short vertical dash the modelled point estimate within the interval. Black data points are those in which the modelled 95% confidence interval includes the observed proportion (i.e. crosses the diagonal line of equality), and grey data points are those in which the modelled 95% confidence interval does not include the observed proportion.

Figure S2. Modelled estimates of the proportion of the population at risk for a 100m diameter turbine at varying heights.

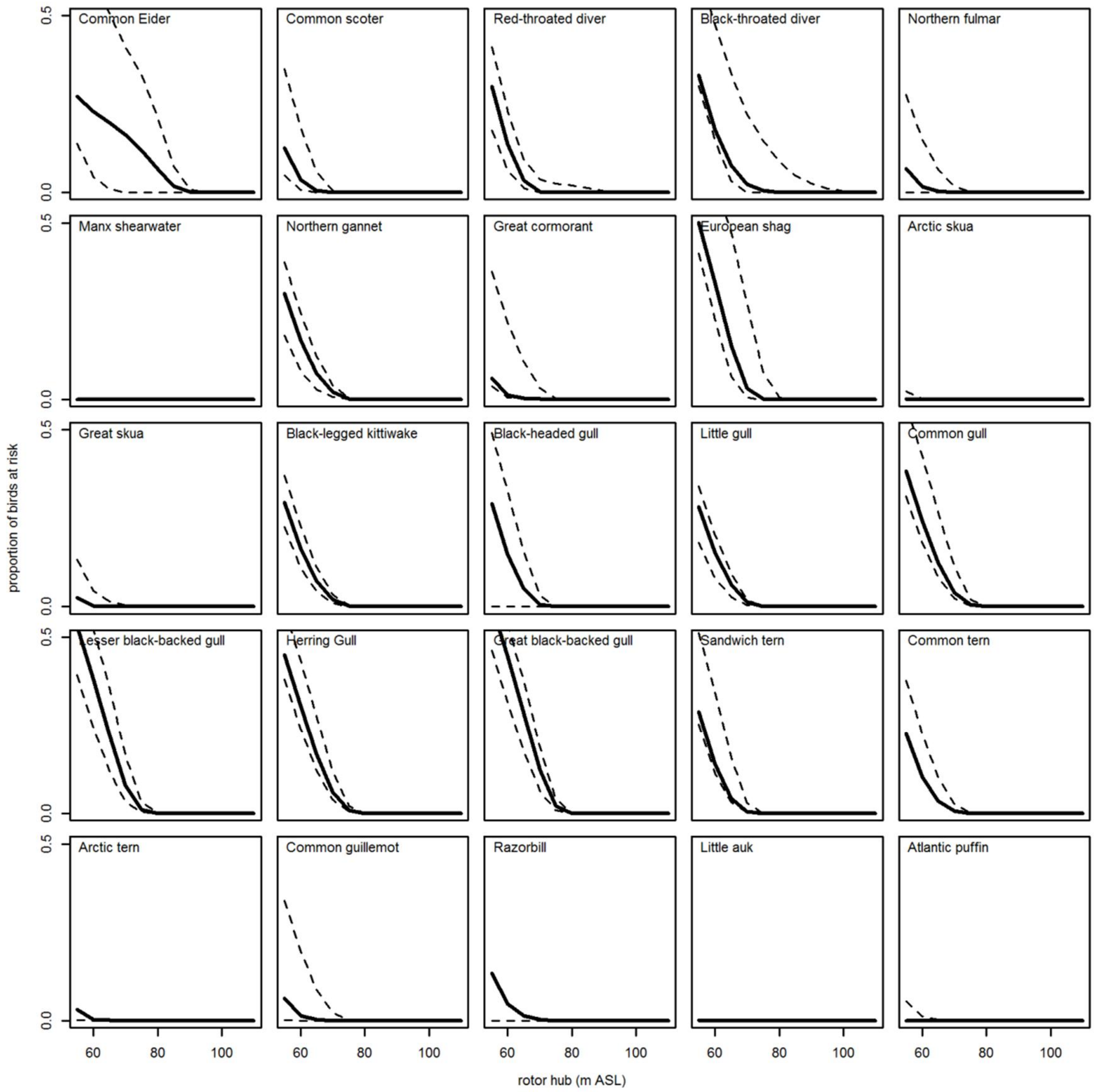


Figure S2: Estimated proportion of birds in a 100m width height column, flying within a circular area of 100m diameter, in relation to varying rotor hub heights. 95% bootstrap confidence intervals are indicated by dotted lines.

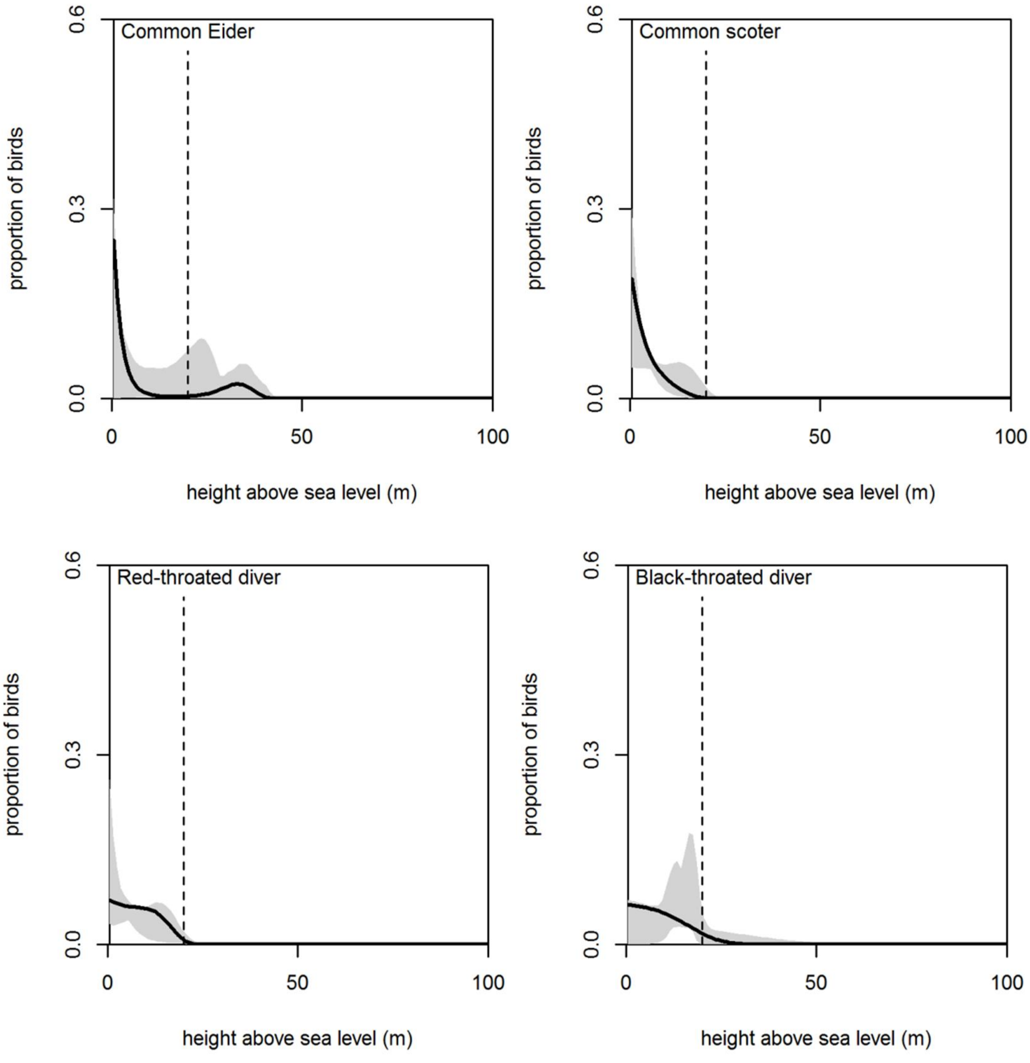
Table S1. Original sources for flight height data

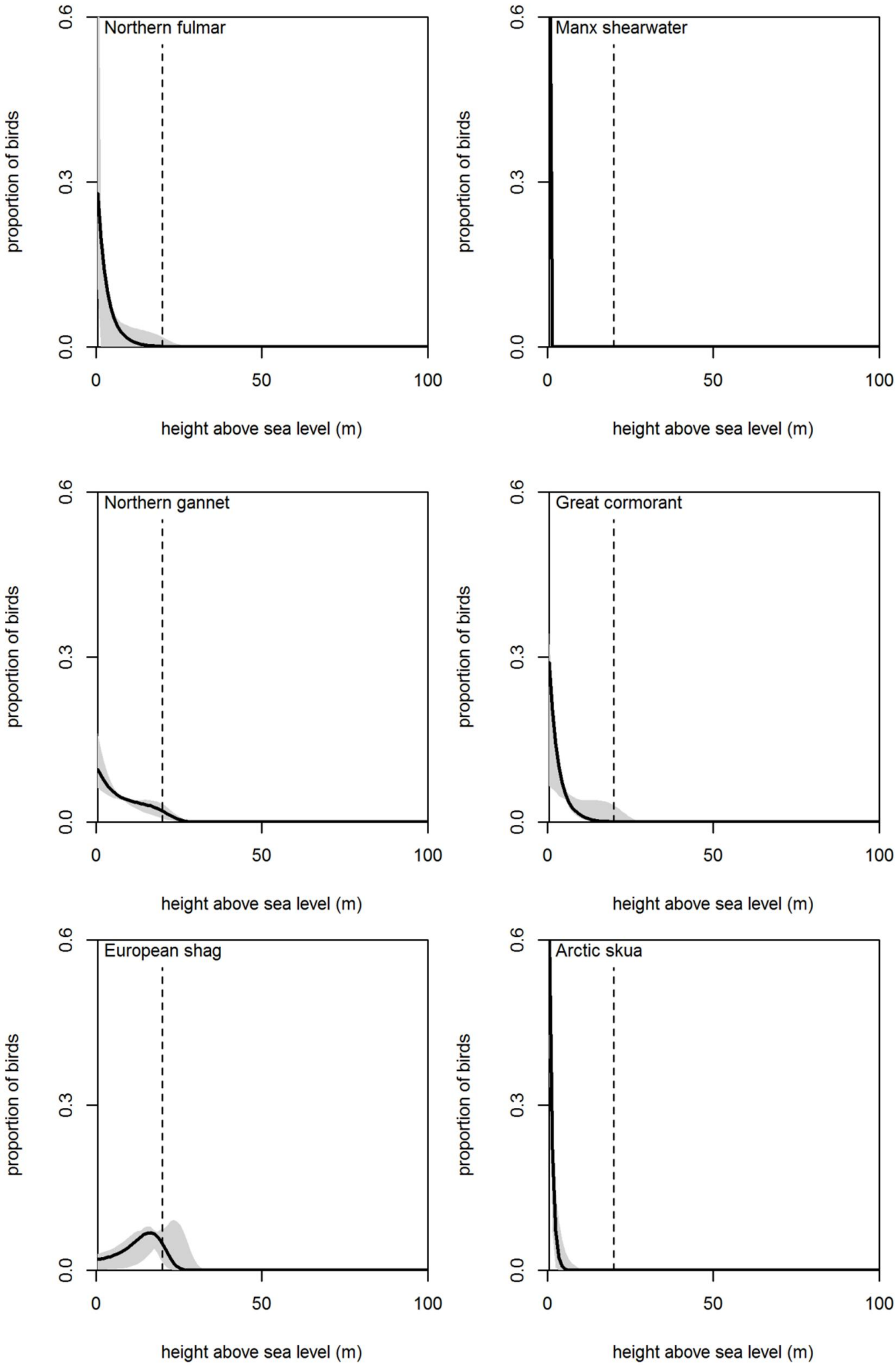
Wind Farm	Years	Months	Method	Reference
Argyll Array		All Year	Boat	Scottish Power Renewables. *unpublished data.*
Barrow		All Year	Boat	DONG Energy. 2006. *Barrow Offshore Wind Farm Environmental Statement*, DONG Energy, Essex
Blyth	1998-2000	All year	Shore	Rothery, p., Newton, I. & Little, B. 2009. Observations of seabirds at offshore wind turbines near Blyth in northeast England. *Bird Study*, 56, 1-14
Burbo Bank	2001-2002	Dec-Feb	Boat	Seascape Energy. 2008. *Burbo Bank Offshore Wind Farm Environmental Statement.* Available from [http://www.dongenergy.com/Burbo/Environment/statement/Pages/statement.aspx accessed 21/05/2013]
Docking Shoal		All Year	Boat	Centrica Energy. 2008. *Docking Shoal Offshore Wind Farm Environmental Statement. Centrica Renewables, Windsor*
Dogger Bank	2010-2011	All Year	Boat	Forewind Ltd. *unpublished data*
Dudgeon	2007-2008	All Year	Boat	Econ. 2009. *Ornithological assessment of the Dudgeon Offshore Wind Farm: Technical Report*, ECON Ecology, Norwich
Egmond aan Zee	2003 - 2004	All Year	Boat	Leopold, M. F., Camphuysen, C. J., van Lieshout, S. M. J., ter Braak, C. J. F., Dijkman, E. M. 2004. *Baseline studies North Sea Wind Farms: Lot 5 Marine Birds in and around the future site Nearshore Windfarm (NSW).* Alterra-rapport 1047, Alterra, Wageningen
Greater Gabbard	2004-2005	All Year	Boat	Banks, A. N., Burton, N. H. K., Austin, G. E., Carter, N., Chamberlain, D. E., Holt, C., Rehfisch, M. M., Wakefield, E., Gill, P. 2005. *The potential effects on birds of the Greater Gabbard Offshore Wind Farm Report for February 2004 to March 2005*. BTO Research Report No. 419, Thetford.
Gunfleet Sands	2005-2007	All Year	Boat	DONG Energy. 2005. *Gunfleet Sands 1 Environmental Statement,* DONG Energy, Essex DONG Energy. 2007. *Gunfleet Sands 2 Environmental Statement,* DONG Energy, Essex
Gwynt Y Mor	2002-2005	All Year	Boat	N Power Renewables. 2005. *Gwynt y Mor Offshore Wind Farm Environmental Statement*. N Power Renewables, Swindon
Horns Rev	2005-2006	Mar-May, Sept - Nov	Boat	Blew, J., Hoffmann, M., Nehls, G. & Hennig, V. 2008. *Investigations of the bird collision risk and the responses of harbour porpoises in the offshore wind farms Horns Rev, North Sea and Nysted, Baltic Sea, in Denmark Part 1: Birds.* University of Hamburg, Hamburg, Germany.
Humber Gateway	2003-2005	All Year	Boat	IECS. 2007. *Seabird Survey Programme Findings, Humber Gateway Windfarm*. Report to E.ON Renewables. IECS, Hull
Islay		All Year	Boat	SSE Renewables. *unpublished data*
Kentish Flats	2001-2002	All Year	Boat	Environmentally Sustainable Systems Ltd. 2008. *Kentish Flats Ornithological Monitoring Report*. Environmentally Sustainable Systems Ltd., Edinburgh available from [http://www.vattenfall.co.uk/en/file/2_Kentish_Flats_Bird_Monitoring.pdf_16360530.pdf accessed 21/05/13]
Lincs	2004-2006	All Year	Boat	Centrica Energy. 2007. *Lincs Offshore Wind Farm Environmental Statement.*
London Array	2002-2005	All Year	Boat	Dong Energy. 2005. *Environmental Statement Volume 1: Offshore Works London Array Limited*. Dong Energy, Essex
Lynn & Inner Dowsing	2001-2005	All Year	Boat	RPS. 2008. *Lynn & Inner Dowsing Offshore Wind Farm Boat-based Ornithological Monitoring Report*. RPS, Glasgow

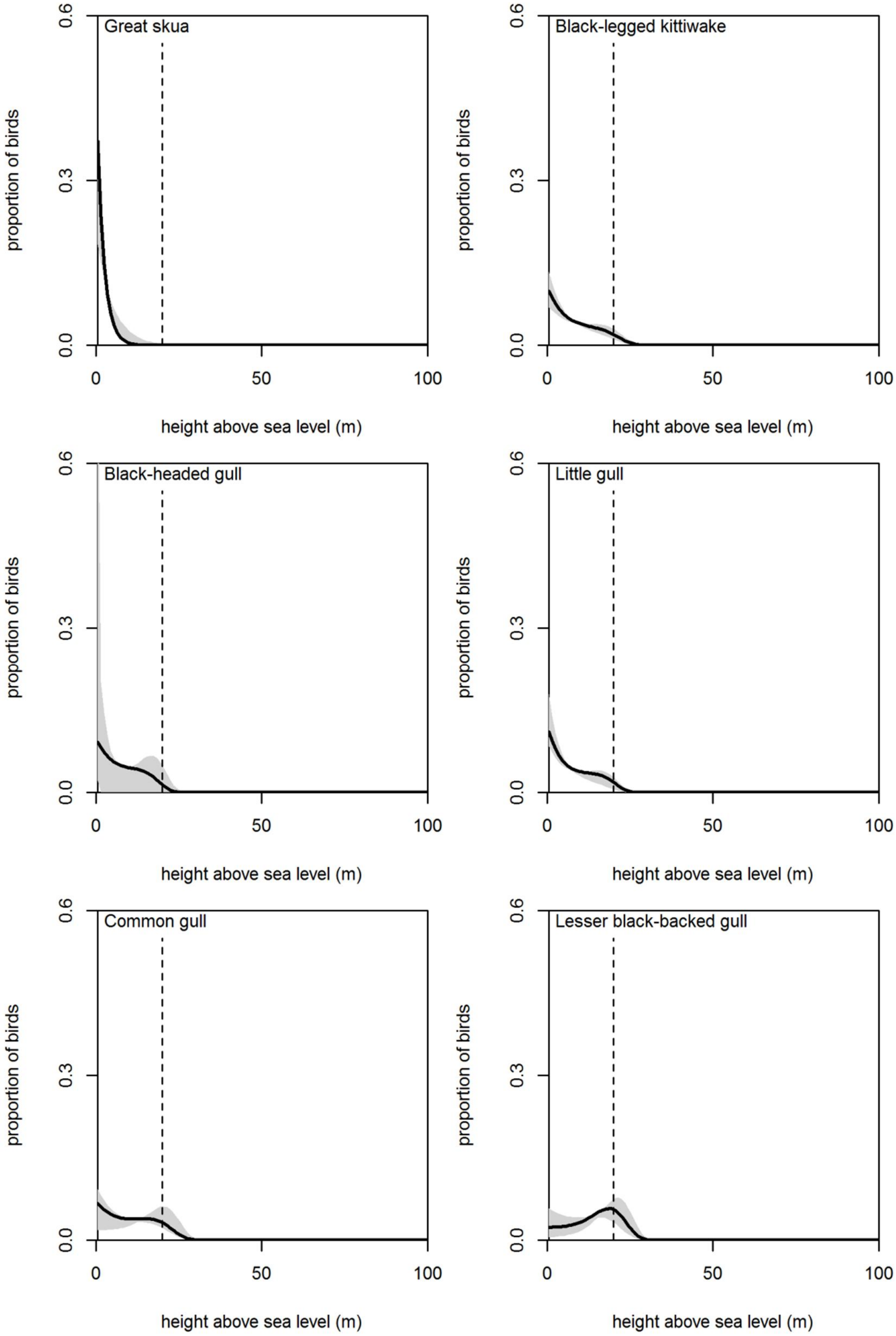
Meetpost Nordwijk	2003 - 2004	All Year	Offshore Platform	Krijgsveld, K. L., Lensink, R., Schekkerman, H., Wiersma, P., Poot, M. J. M., Meesters, E. H. W. G., Dirksen, S. 2005. *Baseline studies North Sea wind farms: fluxes, flight paths and altitudes of flying birds 2003-2004*. Alterra, Wageningen
Moray Firth	2010-2012	All Year	Boat	Moray Offshore Renewables Ltd. 2012. *Developing Wind Energy in the Outer Moray Firth Environmental Statement Telford, Stevenson and MacColl Wind Farms and Associated Transmission Infrastructure*. Available [http://morayoffshorerenewables.com/Document-Library.aspx?path=environmental+statement&page=1 accessed on 21/05/13]
Neart na Gaoithe	2009-2011	All Year	Boat	Mainstream Renewable Power Ltd. 2012. *Offshore Environmental Statement.* Available [http://www.neartnagaoithe.com/environmental-statement1.asp accessed on 21/05/13]
North Hoyle	2001	All Year	Boat	Innogy. 2002. *North Hoyle Environmental Statement.* Available from [http://www.rwe.com/web/cms/en/312146/rwe-innogy/sites/wind-offshore/in-operation/north-hoyle/environment/environmental-statement/ accessed 21/05/2013]
Nysted	2005-2006	Mar-May, Sept - Nov	Boat	Blew, J., Hoffmann, M., Nehls, G. & Hennig, V. 2008. *Investigations of the bird collision risk and the responses of harbour porpoises in the offshore wind farms Horns Rev, North Sea and Nysted, Baltic Sea, in Denmark Part 1: Birds.* University of Hamburg, Hamburg, Germany. Desholm, M. & Kahlert, J. 2005. Avian collision risk at an offshore wind farm. *Biology Letters* 1: 296-298.
Race Bank	2005-2007	All Year	Boat	Centrica Energy. 2009. *Race Bank Offshore Wind Farm Environmental Statement*. *Centrica Renewables, Windsor*
Rampion	2010-2012	All Year	Boat	E.ON Climate and Renewables. *unpublished data*
Sheringham Shoal	2004-2006	All Year	Boat	Scira Offshore Energy Ltd. 2006. *Sheringham Shoal Environmental Statement*, Scira Offshore Energy Ltd. [http://www.scira.co.uk/downloads/_Environmental%20Statement%20-%20main%20text.pdf accessed 21/05/2013]
Thorntonbank	2005-2007	All Year	Boat	Vanermen, N. & Stienen, E. W. M. 2008. *Seabirds & Offshore Wind Farms: Monitoring Results 2008.* INBO, Brussels
Tuno Knob	1998	Feb-Mar	Offshore Platform	Larsen, J.K. & Guillemette, M. 2007. Effects of wind turbines on flight behaviour of wintering Common Eiders: implications for habitat use and collision risk. *Journal of Applied Ecology* 44: 516-522.
Wangerooge	1999	Sept - Nov	Shore	Kruger, T. & Garthe, S. 2001. Flight altitudes of coastal birds in relation to wind direction and speed. *Atlantic Seabirds*, 3, 203-216
Westernmost Rough	2004-2006	All Year	Boat	DONG Energy. 2009. *Westernmost Rough Environmental Statement*. DONG Energy, Essex
West of Duddon Sands	2004-2005	All Year	Boat	Morecambe Wind Ltd. 2006. *West of Duddon Sands Offshore Wind Farm Environmental Statement*. Morecambe Wind Ltd., Morecambe
Zeebrugge	2004-2005	Jun-Jul	Shore	Everaert, J. & Stienen, E. W. M. 2007. Impact of wind turbines on birds in Zeebrugge. *Biodiversity and Conservation*, 16, 3345-3359

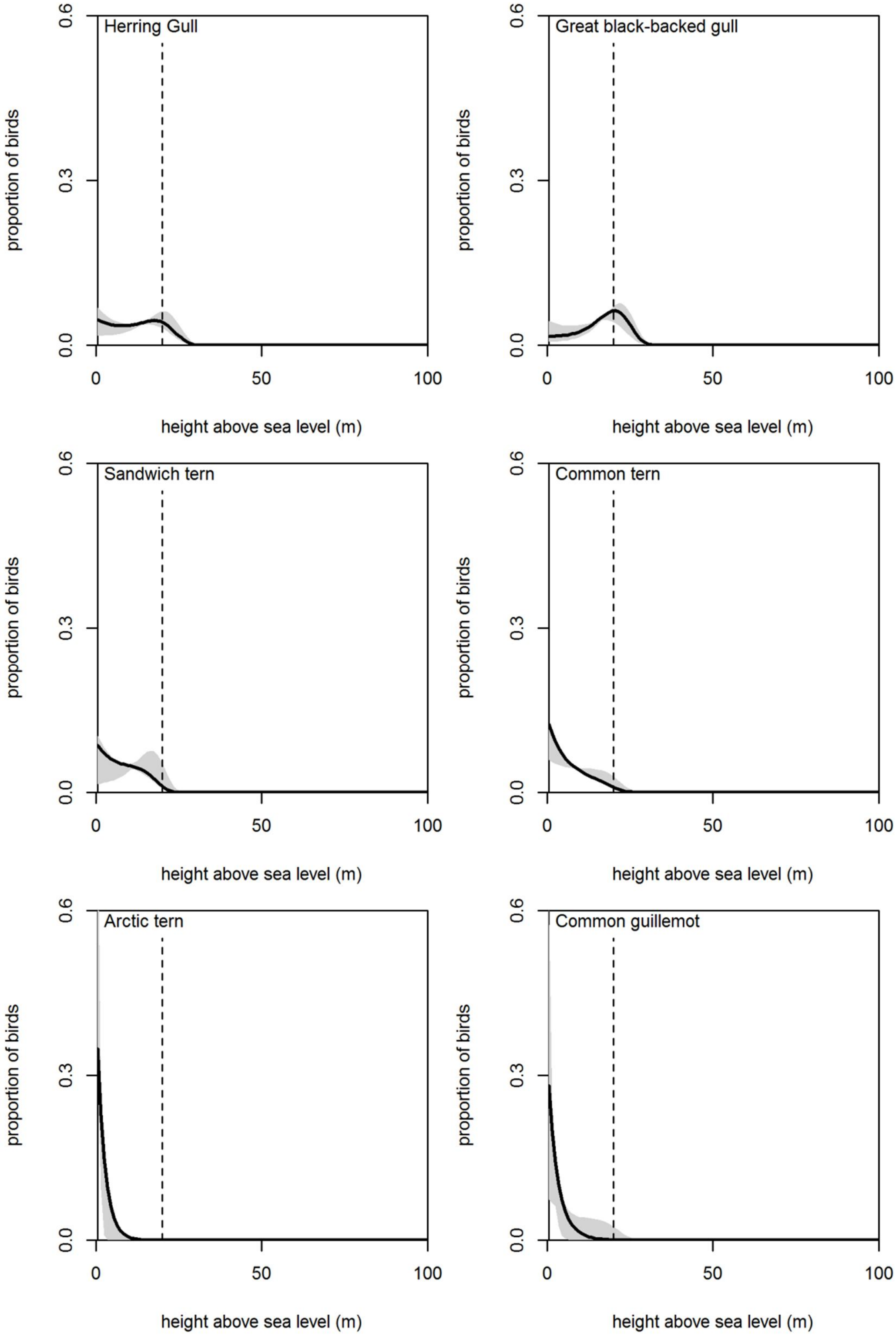
Supplementary Information: Large graphs of species flight height distributions

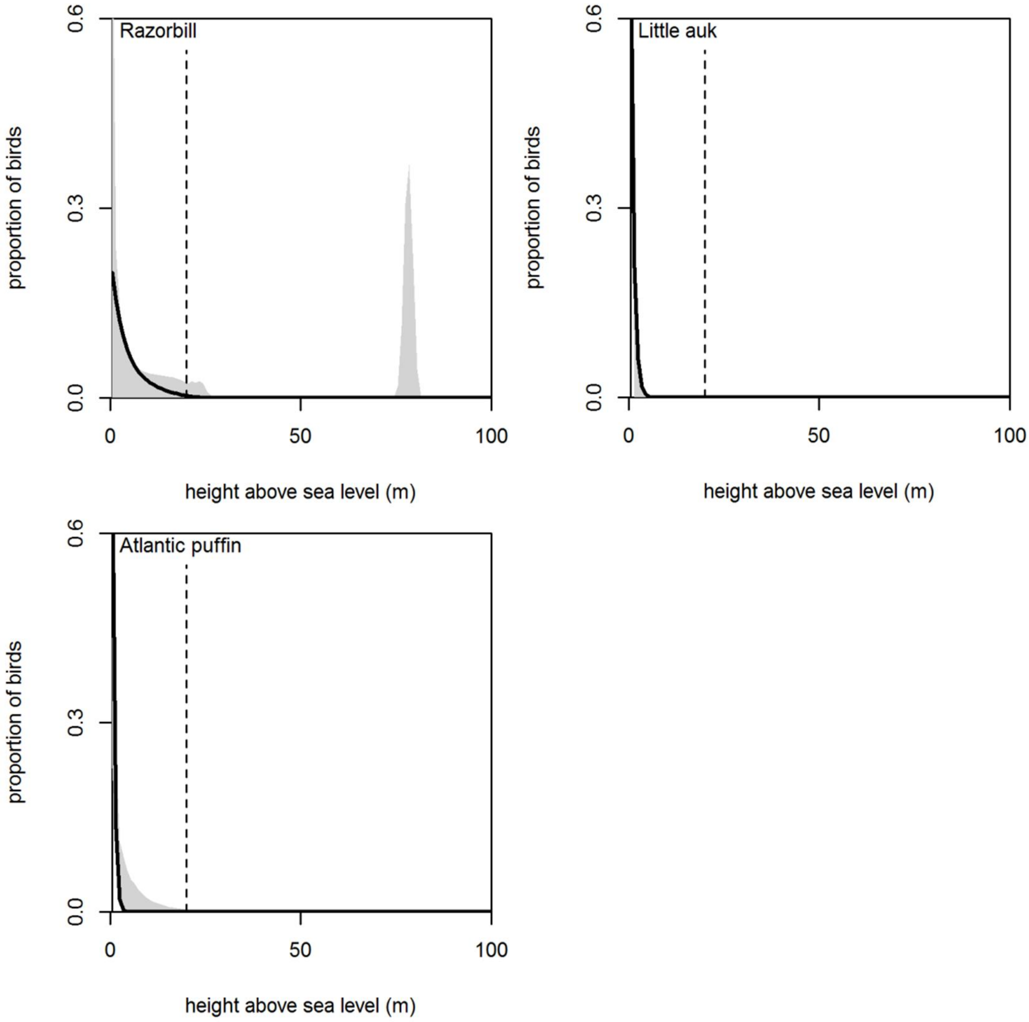
The following graphs are enlarged versions of the individual panels from Fig. 4 of the main manuscript. The vertical dotted line is at 20m above sea level, to enable visual inspection of the proportion of the population flying above 20m (Table 1 in the main manuscript). The graphs are truncated at 100m above sea level as extremely small proportions were modelled to be flying above this height, across all species. Truncation at 100m also enables easier interpretation of the distribution at lower heights.




Northern fulmar
Manx shearwater
Northern gannet
Great cormorant
European shag
Arctic skua
proportion of birds
height above sea level (m)
0.0
0.3
0.6
0
50
100


Great skua
Black-legged kittiwake
Black-headed gull
Little gull
Common gull
Lesser black-backed gull
proportion of birds
height above sea level (m)
0.0
0.3
0.6
0
50
100


Herring Gull
Great black-backed gull
Sandwich tern
Common tern
Arctic tern
Common guillemot
proportion of birds
height above sea level (m)
0.0
0.3
0.6
0
50
100


Razorbill
Little auk
Atlantic puffin
proportion of birds
0.0
0.3
0.6
0
50
100
height above sea level (m)

important in many regions for permission to develop OWFs and some projects have recently been cancelled or delayed, at a substantial financial cost, due to the impacts predicted for birds (e.g. DECC 2012; Gill 2012). As the industry expands globally, improving the evidence base and reducing the uncertainty surrounding these assessments (Hill & Arnold 2012) will enable more informed decisions to be made about OWFs, benefiting both the renewable industry and statutory national conservation advisors and regulators.

There has been much research into the potential impacts of wind farms on bird populations, in particular the risk of collision with turbines (e.g. Desholm & Kahlert 2005). Marine birds may be particularly sensitive to increases in adult mortality, as they are typically long-lived with low annual productivity (Boyd, Wanless & Camphuysen 2006). Estimates of the number of potential bird collisions with turbines reflect both the abundance of a species in the area concerned and flight behaviour, making some species more likely to collide than others (e.g. Lucas *et al.* 2008; Furness, Wade & Masden 2013). Models have been developed which estimate species-specific collision risk, accounting for characteristics including body length, wing span, flight speed and level of nocturnal activity (e.g. Band, Madders & Whitfield 2007; Band 2012). One key aspect of flight behaviour which contributes to estimates of collisions is the height at which birds fly (Chamberlain *et al.* 2006; Stumpf *et al.* 2011; Furness, Wade & Masden 2013). However, knowledge about the flight height distributions of birds is limited, and the precision of estimates is often not quantified.

To assess the impacts of proposed OWFs, ornithological surveys are carried out to estimate the abundance of species within an area, during which observed birds are usually assigned to a series of height bands (Camphuysen *et al.* 2004). These bands are often delineated by the upper and lower limits of the rotor-swept area of the turbines proposed for the site. This method of estimating the proportion at risk has a number of limitations. The proportion of birds flying between the upper and lower limits is defined here as the proportion flying 'at risk height'. However, as the rotor-swept area is circular, collision risk is not evenly distributed within this band. The greatest risk occurs where the horizontal width of the rotor-swept area is greatest (Fig. 1). Moreover, this overlaps with the central hub, the point at which the chance of being hit by a moving blade is the greatest. Additionally, by assigning birds to fixed height bands, the uncertainty surrounding estimates of the proportion of birds at risk is not calculated, making it hard to determine the precision of estimated collision rates (Cook *et al.* 2012).

We combine pre-construction monitoring data collected from OWF sites across Europe to estimate continuous flight height distributions for a range of marine birds to better estimate the proportion of birds at risk of collision. This distribution makes it possible to consider how different turbine designs and heterogeneous collision risk within the rotor-swept area may affect collision rate estimates.

Materials and methods

DATA COLLATION

We collated estimates of the flight heights of seabirds at sea from pre-construction surveys at OWF sites, by reviewing data contained in published impact assessments, technical reports and peer-reviewed publications and by contacting developers directly (Cook *et al.* 2012). In total, we obtained information for 25 species from 32 sites in the UK and Europe (Fig. 2 and see Table S1 in Supporting Information). In each of these studies, flying birds

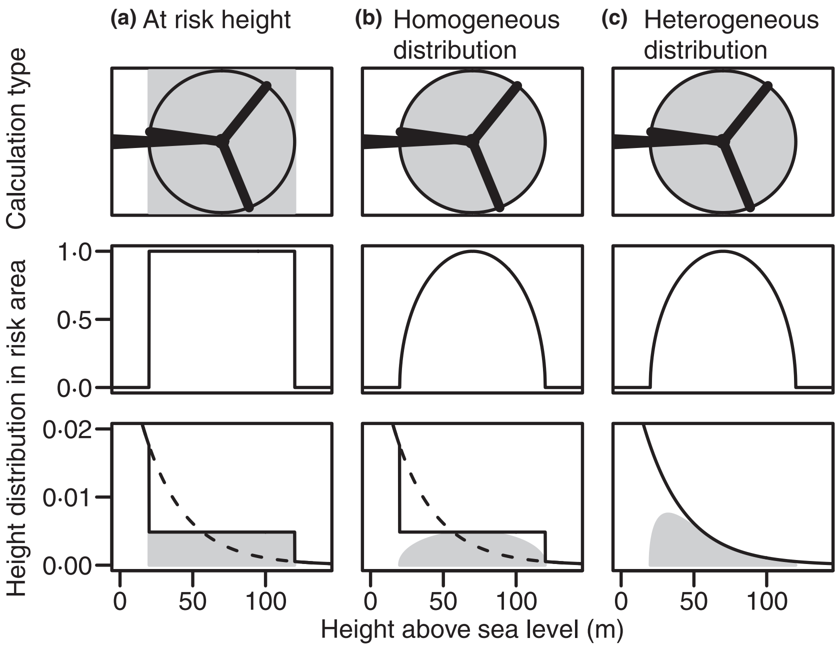


Fig. 1. Diagram representing three methods of calculating the proportion of the population at risk. (a) The proportion at risk height; (b) the proportion within the rotor-swept area assuming a homogeneous distribution within the risk heights; and (c) the proportion within the rotor-swept area assuming a heterogeneous distribution. The grey-shaded areas in the first row represent the areas which are used for each calculation. The second row represents the proportion of birds at each height which are in the risk area. The third row is a hypothetical flight height distribution and the grey-shaded part of this graph represents the estimated proportion of the population at risk. For (a) and (b), the homogeneous distribution is shown with a solid line, and the true heterogeneous distribution with a dotted line.

were assigned to one of several height bands. However, height bands varied between sites as they were typically chosen to reflect the proposed turbine design and to make use of fixed structures as reference points, for example the height of a ship's mast.

The majority of data sets (N = 27) were boat surveys, conducted by trained observers following standard industry protocol (Camphuysen *et al.* 2004). Data were limited to those collected during 'snapshot' counts of airborne birds, which excluded those birds following the survey vessel. Of the remaining data sets, three came from shore-based observations of birds at OWF sites close to shore (see Table S1). These followed a similar protocol (see Rothery, Newton & Little 2009) with trained observers assigning birds to height bands defined using fixed objects of known height. Lastly, two remaining data sets came from trained observers positioned on offshore platforms (e.g. Krijgsveld *et al.* 2011). In these studies, birds were assigned to height bands using trigonometry based on estimates of the distance and angle between the observer and the bird.

STATISTICAL METHODS

Continuous distributions of flight heights were estimated for each species, assuming the same distribution across all sites. These distributions were fitted with a flexible curve, not constrained to any specific distributional form. Details of the approach taken are described below.

The number of birds flying at different heights (N_h) was modelled with a cubic spline on the log scale with six knots (Wood 2006 p. 124). Splines are nonparametric, so unconstrained in the shapes they fit, and can be unimodal, bimodal or more complex. This flexibility is useful in fitting to data that may not conform to standard distributional forms. The number of knots defines the degree of flexibility, and six knots was chosen empirically by considering the degree of flexibility required to model bird flight height behaviour. The locations of the knots, k, were set at evenly spaced quantiles of the mid-points of the height categories across all sites, so that more knots were placed where the data were of a higher resolution. The equation for the cubic spline was given by:

$$log(N_h) = \beta * Z \quad \text{eqn 1}$$

where β is a vector of six coefficients which are estimated in the model fitting process, Z is a matrix of a polynomial function of differences between each height and each of the six knot locations and N_h is the estimated relative number of birds flying at height h (which were based on 1 m categories in this analysis).

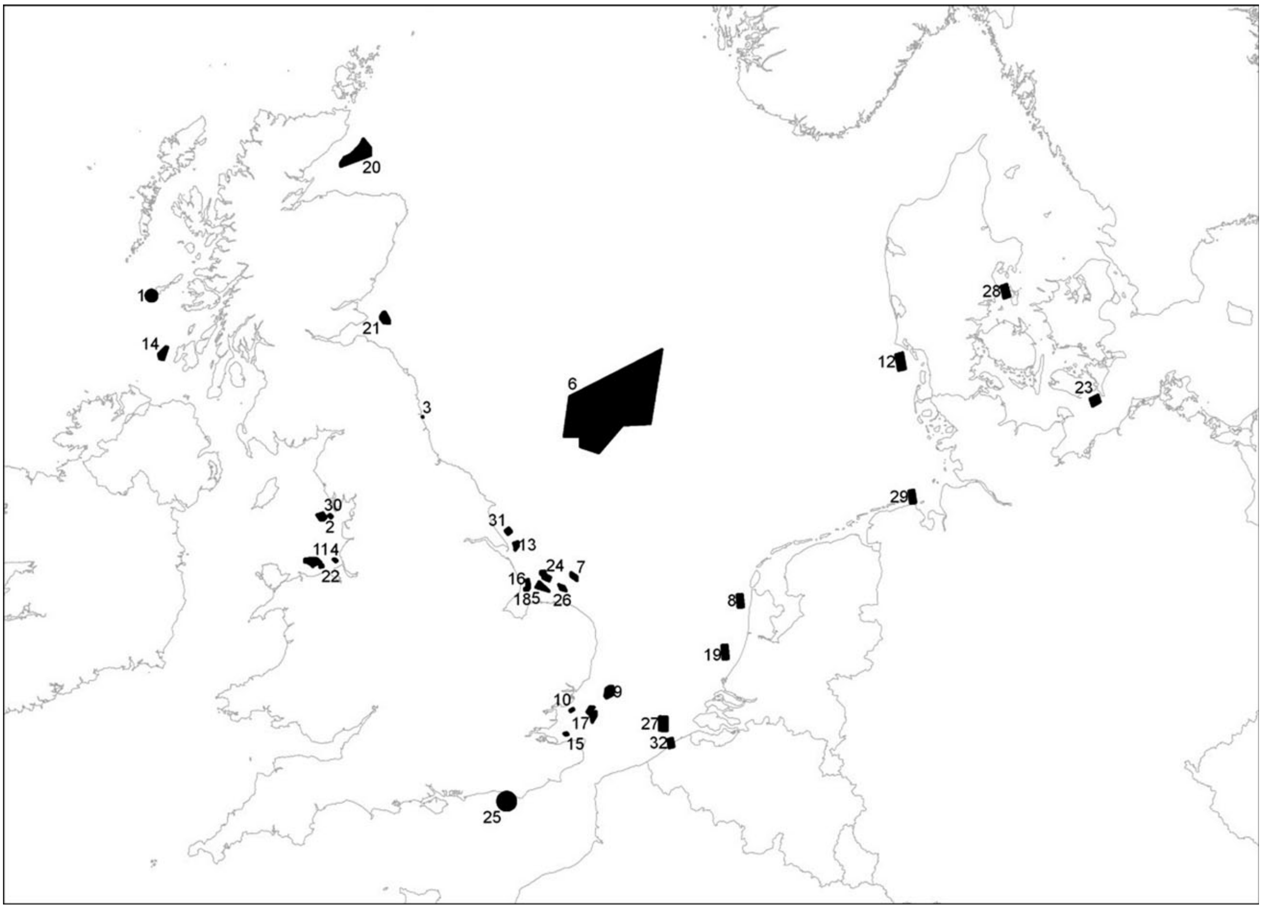


Fig. 2. Location and extent of 32 sites from which bird flight height data were available. These sites include areas of both constructed and proposed offshore wind farms; all data were collected during pre-construction surveys. Site names are: 1 Argyll Array, 2 Barrow, 3 Blyth, 4 Burbo Bank, 5 Docking Shoal, 6 Dogger Bank, 7 Dudgeon, 8 Egmond ann Zee, 9 Greater Gabbard, 10 Gunfleet Sands, 11 Gwynt y Mor, 12 Horns Rev, 13 Humber Gateway, 14 Islay, 15 Kentish Flats, 16 Lincs, 17 London Array, 18 Lynn & Inner Dowsing, 19 Meetpost Noordwijk, 20 Moray Firth, 21 Neart na Gaoithe, 22 North Hoyle, 23 Nysted, 24 Race Bank, 25 Rampion, 26 Sheringham Shoal, 27 Thorntonbank, 28 Tuno Knob, 29 Wangerooge, 30 West of Duddon Sands, 31 Westermost Rough, 32 Zeebrugge.

This spline was fitted to the categorical height data using the following procedure. The number of birds within each categorical height band at each site was assumed to have a multinomial distribution, so each flying bird had a given probability of being in each of the height bands, and the total probability for all height bands combined was one. The likelihood was therefore the product of a multinomial likelihood at each site (or on the log scale the sum of a multinomial likelihood at each site), which assumes the data from each site are independent. The log likelihood was therefore defined as:

$$\ln(\mathcal{L}(\beta|x,k)) = \sum_{s}\sum_{j} x_{s,j} \cdot \ln\left[\int_{h=j1}^{j2} N_h dh\right] \qquad \text{eqn 2}$$

where x represents the data, k is a vector of the knot locations, $x_{s,j}$ is the observed number of birds at site s in height band j, and $j1$ and $j2$ are the lower and upper limits of height band j. To fit the spline to the data, this log likelihood was maximized across all sites s and height bands j, using the function 'nlm' in R (R Development Core Team 2012).

Maximising the log likelihood produced estimates of β, which when inserted into eqn 1 described a continuous spline which was the best fit to all the categorical data for each species. The fitted spline provided an estimated number of birds in each height category, N_h, which were standardized *post hoc* to represent the proportion of birds flying in a given 1 m height category (p_h), between 0 and 300 m above sea level. We did not model above 300 m for two reasons: marine birds rarely fly at heights of >300 m (Spear & Ainley 1997; Garthe & Hüppop 2004) and it is hard for observers to accurately record heights over 300 m (Camphuysen *et al.* 2004).

Bootstrapping was carried out to estimate confidence intervals around this maximum likelihood estimate of the flight height distribution. Using the site as the bootstrap unit, 200 bootstrap samples were produced, with a balanced design, such that each site appeared 200 times across all bootstraps. The β coefficients were estimated for each bootstrap sample, by maximizing the log likelihood as above, and 95% confidence intervals for the flight height distribution were calculated from these bootstrapped estimates.

MODEL VALIDATION

To test for an effect of survey method, we examined with a linear model whether the residuals significantly differed by survey method (i.e. boat survey, offshore platform, shore-based count) and also examined interactions between height band and survey method. No effect of survey method was detected ($P > 0{\cdot}9$ for the survey variable and the interaction).

To check the model fit, we correlated the observed proportion of birds in each height category at each site with the modelled proportion of birds expected in each height category. This correlation was weighted by the number of birds at each site, so that sites with more birds contributed more to the correlation coefficient.

For a more independent model validation, each site was removed from the analysis in turn, to produce jackknifed samples, and the estimation and bootstrap procedure were carried out on the rest of the data set. Two hundred bootstraps were conducted on each jackknifed sample, and for each bootstrap estimate of the proportion in each category, 10000 random realisations of height category observations were produced, based on the total number of birds at a site. These were combined to produce a distribution of expected numbers in the category, incorporating uncertainty about the estimate, and random variation in observed numbers, given a fixed proportion. The 95% limits of the expected numbers were taken from the 2·5th and 97·5th quantiles of all 2 million estimates for each category (10000 random realizations × 200 bootstraps). The 95% limits of these distributions were then compared to the observed numbers from the removed site. This process was repeated for each jackknifed sample. If the results can be confidently applied to new sites, we would expect 95% of the observed proportions from the removed sites to lie within the modelled 95% confidence intervals.

Analysing the data in this way assumes that each flying bird observed is independent and therefore that no birds are observed in groups. Although this is not accurate for many species of marine bird, this assumption was necessary as the data did not contain information about group size. Violation of this assumption may be revealed by model predictions having a poor fit to removed sites. This analysis method also assumes that birds are correctly assigned to height categories. In practice, there is likely to be some error associated with assigning birds to height categories by human observers (Pearce-Higgins *et al.* 2009), but categorical measurements will reduce this error, particularly where height categories reflect physical structures. An additional assumption of combining data from several sites in this way is that the flight height distribution is the same at each site and during each survey. Although there are many factors which impact flight height distributions, for example time of year, time of day and wind speed, the data available precluded consideration of these factors.

Estimated proportions of the in-flight populations at risk of collision and associated 95% confidence intervals were calculated for turbines with a 100 m rotor sweep diameter and a hub 70 m above sea level (typical for turbines currently being installed). For each of the 200 bootstraps, we calculated the proportion of the in-flight population estimated to be flying: (a) within the upper and lower risk heights; and within the circular rotor-swept area assuming (b) a homogeneous distribution of birds or (c) a heterogeneous distribution of birds taken from the flight height distribution (Fig. 1). The estimated proportion of the population at risk and the lower and upper 95% confidence intervals were the 50th, 2.5th and 97.5th quantiles of the 200 bootstrap estimates, respectively.

TURBINE DESIGN

We considered two aspects of turbine design: hub height and turbine diameter. To examine the impact of hub height, we calculated the proportion of the heterogeneously distributed in-flight population within the rotor-swept area for 100-m diameter turbines with varying hub heights located 55–110 m above sea level. To examine the impact of turbine diameter, we selected three turbine designs currently deployed and arranged them in homogeneous 20-km arrays, each with a 30 MW total capacity. The outputs of the three turbine designs were 2, 3 and 5 MW, and the diameter of the rotor-swept areas was 80, 90 and 126 m, respectively. The number of turbines required to generate 30 MW output were therefore 15, 10 and 6 for the three arrays, respectively. Given the fixed total array size (20 km), there was great interturbine distance for the array with larger turbines. To remove the effect of height in the comparison of different designs, the hub heights of each turbine were set such that the lower limit of the rotor-swept area was 20 m above sea level. For each of the 30 MW arrays, we calculated the proportion of the heterogeneously distributed in-flight population estimated to fly in the rotor-swept area across the entire array.

Results

MODEL VALIDATION

Correlations between the observed and modelled proportion of flying birds within each height category indicated a good fit of the modelled spline to the data for most species (Fig. 3), with the mean correlation within species r^2=0·85 (Table 1). Common eider *Somateria mollissima* had particularly poor fit with r^2=0·20, as the differences between sites seemed particularly marked (see Fig. S1, Supporting Information). However, these differences led to larger confidence intervals (Fig. 3), and consequently the proportion of observations from removed sites within the modelled 95% confidence intervals was relatively high for common eider (Table 1). Auks and terns had good model fit with average r^2=0·94 and r^2=0·90, respectively. Application to removed sites was less good, with an average percentage of observations within 95% confidence intervals of 86% and 67%, for auks and terns, respec-

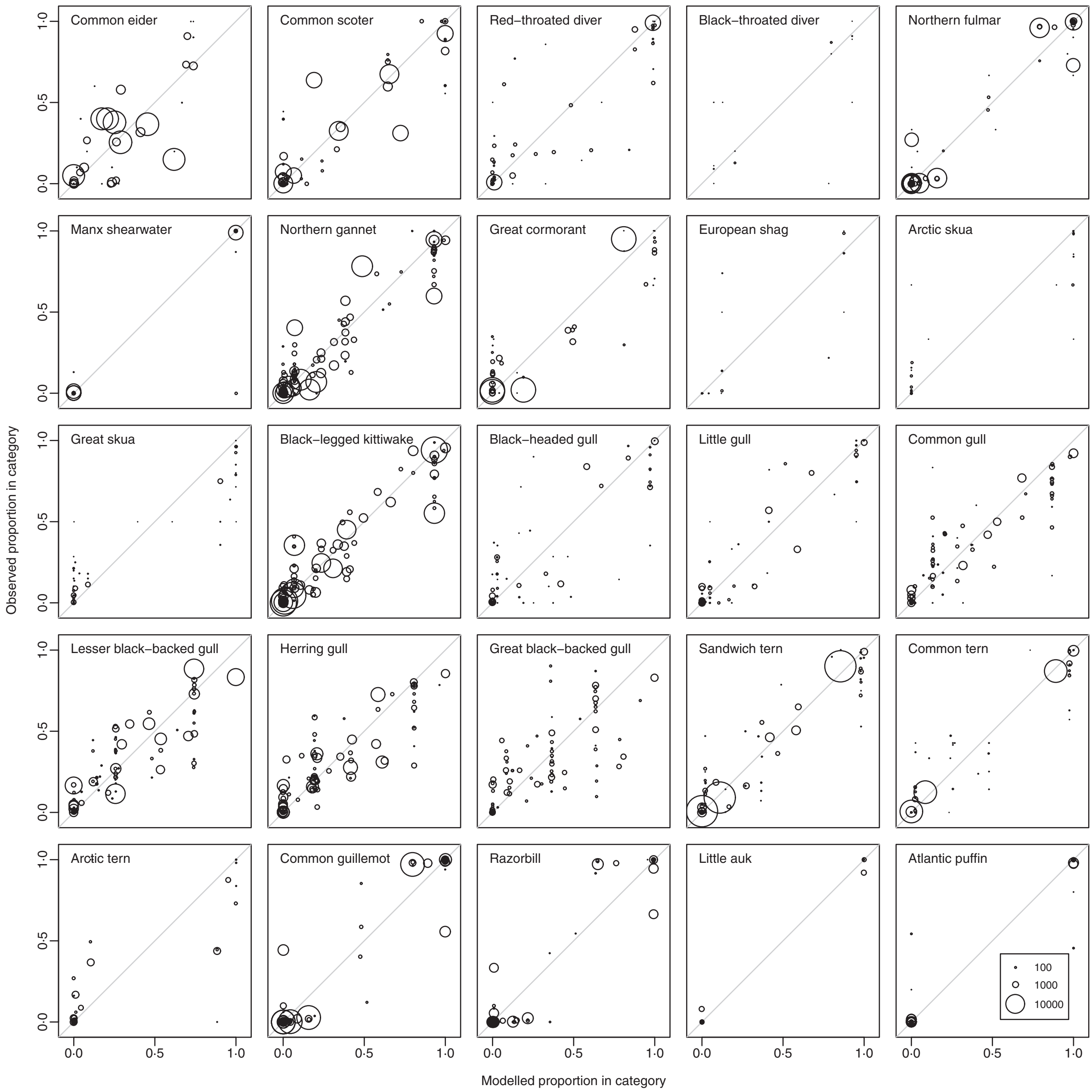


Fig. 3. Modelled and observed proportion of birds in each height category at each site. The relative area of the circle represents the total number of individuals of that species seen at the site. The grey line represents the line of equality (modelled and observed proportions are equal), and well-fitting models will therefore have most points near this line.

Table 1. Correlations and validation statistics for the models for each species. The correlation of model fit is the correlation between the observed and predicted (point estimate) proportions, weighted by the number of individuals of that species observed at the site. The model validation is the percentage of independent observations within the 95% confidence intervals. The proportions of birds estimated to be at risk of collision with a turbine 20–120 m above sea level and associated 95% confidence intervals are presented using three calculation methods

Species	Number of sites	Number of sites >1% of birds	Number of birds	Weighted correlation of model fit (r^2)	Model validation (%)	Proportion of birds at risk height (95% confidence interval)	Proportion of birds within rotor-swept area (95% confidence interval)	
							Homogeneous distribution	Heterogeneous distribution
Common eider *Somateria mollissima*	11	6	34513	0·203	82	0·262 (0·003, 0·683)	0·206 (0·002, 0·537)	0·162 (0·001, 0·411)
Common scoter *Melanitta nigra*	18	8	30847	0·748	55	0·001 (0·000, 0·026)	0·001 (0·000, 0·021)	0·000 (0·000, 0·006)
Red-throated diver *Gavia stellata*	18	9	9686	0·943	64	0·010 (0·003, 0·096)	0·008 (0·002, 0·075)	0·002 (0·001, 0·036)
Black-throated diver *Gavia arctica*	6	4	126	0·901	93	0·073 (0·000, 0·397)	0·058 (0·000, 0·312)	0·024 (0·000, 0·221)
Northern fulmar *Fulmarus glacialis*	22	10	29168	0·931	88	0·002 (0·000, 0·061)	0·001 (0·000, 0·048)	0·000 (0·000, 0·018)
Manx shearwater *Puffinus puffinus*	10	3	6801	0·970	79	0·000 (0·000, 0·000)	0·000 (0·000, 0·000)	0·000 (0·000, 0·000)
Northern gannet *Morus bassanus*	27	14	44851	0·810	45	0·070 (0·021, 0·130)	0·055 (0·016, 0·102)	0·020 (0·005, 0·039)
Great cormorant *Phalacrocorax carbo*	14	6	20227	0·922	58	0·001 (0·000, 0·107)	0·001 (0·000, 0·084)	0·000 (0·000, 0·031)
European shag *Phalacrocorax aristotelis*	4	4	233	0·812	71	0·125 (0·020, 0·704)	0·098 (0·016, 0·553)	0·031 (0·004, 0·272)
Arctic skua *Stercorarius parasiticus*	12	6	331	0·916	71	0·000 (0·000, 0·000)	0·000 (0·000, 0·000)	0·000 (0·000, 0·000)
Great skua *Stercorarius skua*	12	7	1202	0·958	46	0·000 (0·000, 0·013)	0·000 (0·000, 0·010)	0·000 (0·000, 0·004)
Black-legged kittiwake *Rissa tridactyla*	24	13	62939	0·874	44	0·068 (0·035, 0·116)	0·053 (0·028, 0·091)	0·019 (0·010, 0·034)
Black-headed gull *Chroicocephalus ridibundus*	16	9	4436	0·843	59	0·029 (0·000, 0·127)	0·022 (0·000, 0·100)	0·007 (0·000, 0·031)
Little gull *Hydrocoloeus minutus*	17	9	3907	0·880	72	0·048 (0·017, 0·080)	0·038 (0·013, 0·063)	0·012 (0·004, 0·021)
Common gull *Larus canus*	20	14	10190	0·908	62	0·132 (0·083, 0·340)	0·104 (0·065, 0·267)	0·040 (0·024, 0·113)
Lesser black-backed gull *Larus fuscus*	23	10	35045	0·808	55	0·258 (0·118, 0·481)	0·203 (0·093, 0·378)	0·080 (0·034, 0·165)
Herring gull *Larus argentatus*	20	14	25253	0·731	39	0·193 (0·130, 0·354)	0·151 (0·102, 0·278)	0·060 (0·039, 0·119)
Great black-backed gull *Larus marinus*	19	16	8911	0·635	42	0·365 (0·200, 0·520)	0·287 (0·157, 0·409)	0·122 (0·062, 0·185)
Sandwich tern *Sterna sandvicensis*	19	6	33982	0·988	59	0·020 (0·014, 0·124)	0·016 (0·011, 0·097)	0·004 (0·003, 0·030)
Common tern *Sterna hirundo*	18	5	19329	0·996	77	0·025 (0·024, 0·095)	0·020 (0·019, 0·074)	0·006 (0·006, 0·026)
Arctic tern *Sterna paradisaea*	9	6	2571	0·704	64	0·000 (0·000, 0·000)	0·000 (0·000, 0·000)	0·000 (0·000, 0·000)
Common guillemot *Uria aalge*	22	9	36256	0·912	87	0·001 (0·000, 0·081)	0·001 (0·000, 0·063)	0·000 (0·000, 0·023)
Razorbill *Alca torda*	19	10	13172	0·857	89	0·008 (0·000, 1.000)	0·006 (0·000, 0·785)	0·002 (0·000, 0·986)
Little auk *Alle alle*	4	2	1287	0·992	82	0·000 (0·000, 0·000)	0·000 (0·000, 0·000)	0·000 (0·000, 0·000)
Atlantic puffin *Fratercula arctica*	8	6	5979	0·990	86	0·000 (0·000, 0·002)	0·000 (0·000, 0·001)	0·000 (0·000, 0·000)

tively. With auks, particularly, the amount of information available to inform the distribution was small, as many height bands had all or none of the observations (Fig. 3). Gulls had a much greater range of observed proportions (Fig. 3) and fairly good model fit (average r^2=0·81). Application of the modelled proportions to removed sites was poor, with an average of removed observations within 95% confidence intervals of 53%, possibly reflecting the more aggregated behaviour of gulls.

For none of the 25 species were more than 95% of observations from removed sites within the modelled 95% confidence intervals, for only one species was the figure over 90%, and for a further six species, the figure was at least 80% (Table 1). Five species had very poor validation with <50% of observations from removed sites within modelled 95% confidence intervals. This validation revealed that for some species, a high proportion of independent sites conformed to the modelled distributions, but many species had large variation between sites. This may reflect violation of other assumptions, such as independence of observations.

SPECIES FLIGHT HEIGHTS

The modelled distributions of flight heights indicated that for all species of birds considered, the majority of flights

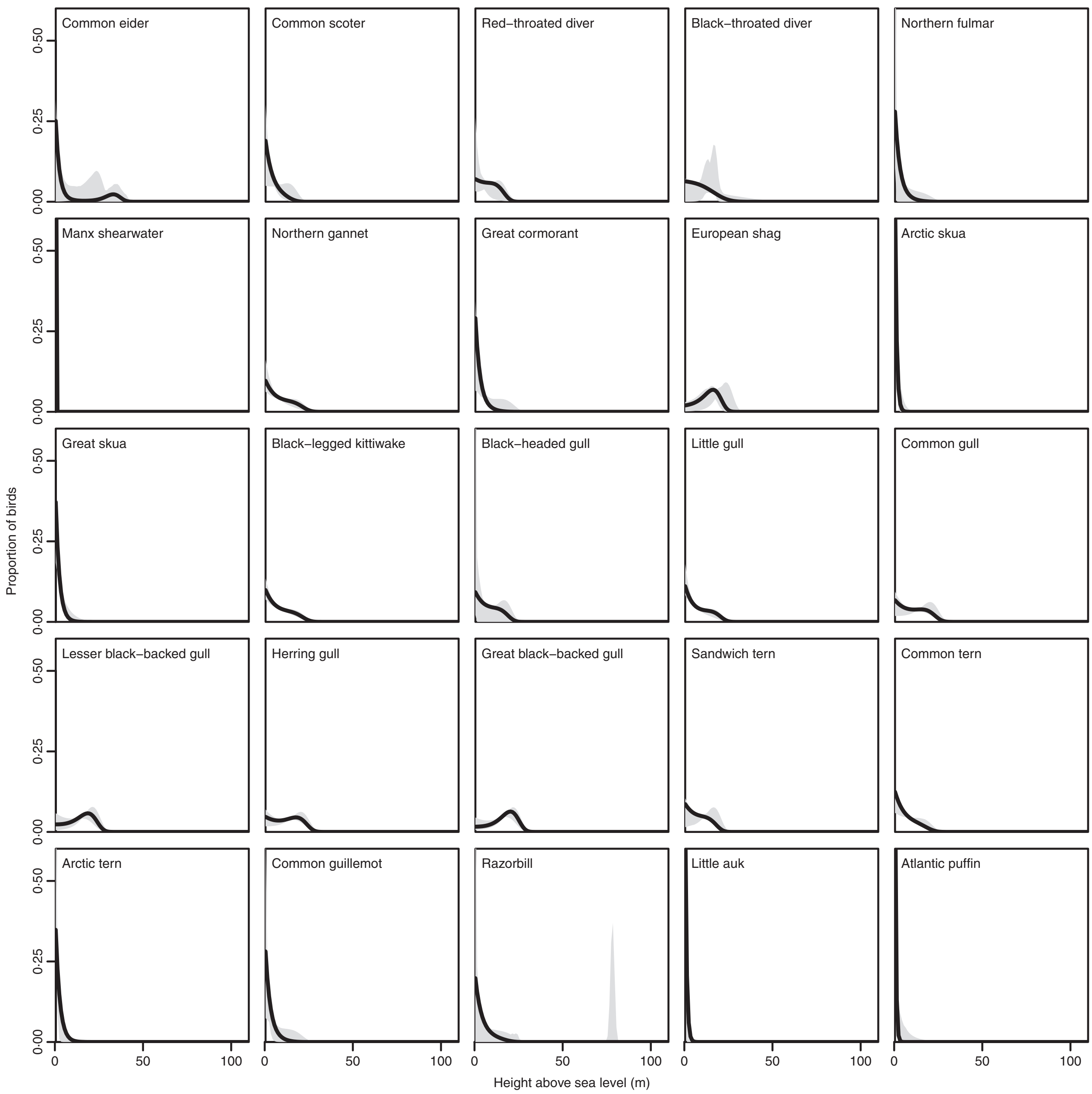


Fig. 4. Modelled flight height distributions (black line) and associated 95% bootstrap confidence intervals (grey area). Estimates are not always in the centre of the confidence limits, because the confidence limits are nonparametric, and proportions are calculated for each bootstrap.

were within 20 m of the sea surface (Fig. 4 and see Appendix S1 in Supporting Information). For several species, confidence intervals revealed a potential secondary peak in flight activity at greater heights (Fig. 4). Flight height distributions were most strongly weighted near the sea surface for Arctic skua *Stercorarius parasiticus*, Manx shearwater *Puffinus puffinus*, little auk *Alle alle* and Atlantic puffin *Fratercula arctica* (Fig. 4). The least skewed modelled distributions were for several of the gull species.

PROPORTION AT RISK

Across species, the proportion within the rotor-swept area from the heterogeneous distribution was on average 26% of the proportion flying at risk height and 33% of the homogenous distribution within the rotor-swept area (Fig. 1, Table 1). However, there was considerable inter-species variability in these figures, and those species with greater proportions flying at risk heights generally had less of a reduction in the proportion at risk when considering the heterogeneous distribution.

TURBINE DESIGN

As hub height increased, the proportion of birds estimated to be at risk of collision declined (see Fig. S2 in Supporting Information). Increasing turbine diameter led to a lower proportion of the in-flight population at risk of collision for most species (Fig. 5). Averaging across all 25 species in the analysis, the proportion of the population at risk of collision in the entire 20-km array was 0·16% with 2 MW turbines, halving to 0·08% with 5 MW turbines. This pattern holds within species; the proportion at risk across the array declined by 29% when the array changed from 2 to 3 MW turbines and by a further 29% when the array changed to 5 MW turbines.

Discussion

Estimating the number of birds likely to collide with turbines is a key part of the impact assessment process for OWFs and requires an understanding of the height at which birds fly. Currently, birds are assigned to site-specific height bands (often determined by a single turbine design) during pre-construction ornithological surveys (Camphuysen *et al.* 2004). This method of estimating the number of birds flying at risk height has three significant drawbacks: (i) It is only possible to consider collision risk with reference to the height bands recorded. Consequently, collision risk for alternate turbine designs cannot be assessed. (ii) It is not possible to account for interactions between a species flight height distribution and the properties of the rotor-swept area. (iii) Estimating uncertainty is difficult, which is vital for understanding the confidence surrounding the estimated impacts. By using a novel approach to combine data collected across multiple sites, we produced continuous flight height distributions that enable all three of these issues to be addressed.

IMPLICATIONS FOR COLLISION RISK AND MANAGEMENT

Our models are consistent with other studies demonstrating that the majority of marine birds have a positively skewed distribution of flight heights and many birds

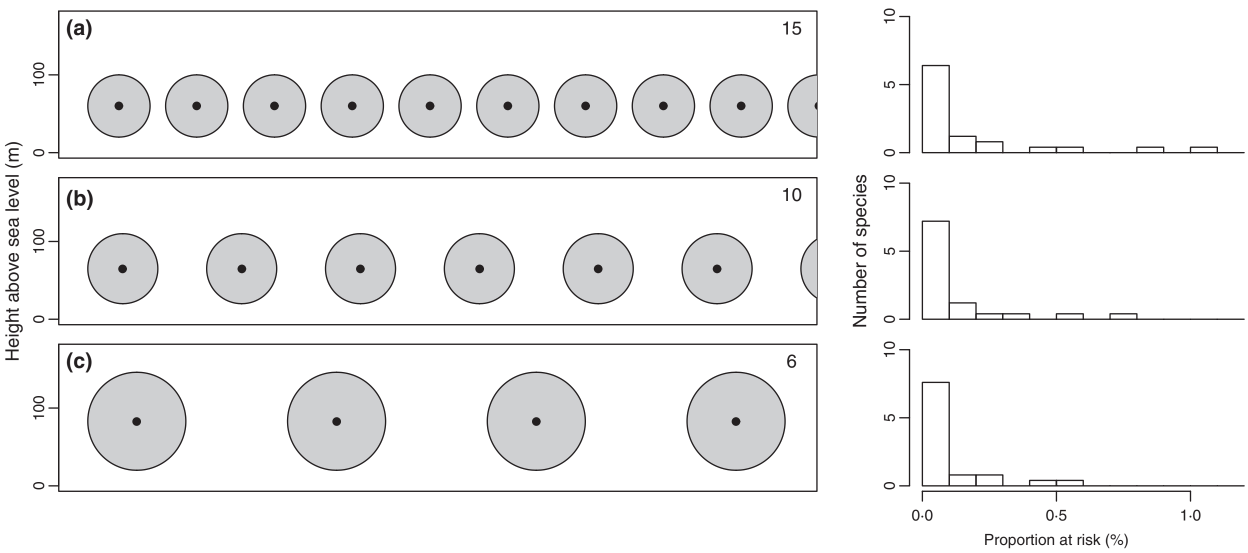


Fig. 5. Left-hand column is a schematic diagram of the rotor-swept area of a section of three 20-km-wide turbine arrays, each with a homogeneous set of turbines which produces 30 MW of electricity. The spaces between the turbines reflect relative spacing, but are not to the scale of the turbines. The number in the top right-hand corner of each turbine diagram indicates the number of turbines required to generate 30 MW of electricity. The right-hand column shows a histogram of the estimated percentage of each species at risk for the entire turbine array.

therefore fly within 20 m of the sea surface (e.g. Krijgsveld *et al.* 2011). Consequently, the proportion of birds within the rotor-swept area of the turbine was substantially lower when considering a heterogeneous rather than a homogeneous distribution within the risk heights. Existing methodologies assume the latter scenario, potentially resulting in an overestimate of the number of birds exposed to the risk of collision.

These results demonstrate that, for the conditions under which these data were collected, the use of higher hubs and larger turbines can be an effective mitigation measure with which to reduce the risk of collision in marine birds. While the total surface area of the turbine rotors remained similar across the three arrays we considered, by increasing rotor diameter, fewer turbines were required, interturbine distances increased and the mean hub height of the turbines was increased. As a consequence, by using turbines with a diameter of 126 m rather than 80 m, the proportion of in-flight populations at risk was on average halved across all species. However, mitigation by use of larger turbines or higher hubs must also take into account the greater altitudes used by migrating birds (Newton 2010; Krijgsveld *et al.* 2011), which may experience an increased collision risk as a result of the use of larger turbines.

The methods presented here to estimate flight height distributions may be of particular value for rare species, for which individual surveys may have small sample sizes and which may be at greater risk of population-level impacts from collisions. This method may also be applied to other situations where knowledge of species flight distributions is needed to inform collision risk, for example construction of power lines (Janss 2000; Martin & Shaw 2010) or onshore wind farms (Lucas *et al.* 2008).

The use of the figures presented here in collision risk models may be appropriate for species which demonstrate consistent distributions across sites and have good validation to independent sites. However, even for species with good validation, good practice should corroborate the figures presented here by comparison of the modelled distributions to site-specific data, as there may be some sites which have very different flight height patterns. It should also be noted that accurate outputs from collision risk models require accurate estimates of all the parameters in the model and associated estimates of uncertainty. Avoidance rates, if derived empirically from observed mortality rates, require an estimation of predicted mortality rates usually with a collision risk model. Birds which are flying in the lower part of the risk height band are at lower risk of collision due to the circular shape of the rotor-swept area. When using a homogeneous distribution, this is encompassed in the apparent 'avoidance' rates derived, however, when using the heterogeneous distribution, this is encompassed in the flight height distribution. There is therefore a need to generate accurate estimates of avoidance that better reflect actual bird avoidance behaviour.

DATA LIMITATIONS AND MODEL ASSUMPTIONS

While our results represent a substantial improvement on the estimates currently used in assessing the proportion of birds at risk of collision, there are nonetheless limitations associated with the data and the underlying model assumptions. It is important to note that most of these assumptions are inherent in the existing approach as well.

Two key assumptions are that heights have been estimated accurately and that birds are not attracted to or displaced by the survey vessel. As no data were available on group size, the model assumes that each bird was an independent observation. Consequently, flocking behaviour will lead to pseudoreplication, and in our model validation, we would expect more observations from removed sites to be outside the confidence limits. Membership of a group may boost foraging success in gulls (Gotmark, Winkler & Andersson 1986), possibly explaining the low proportion of independent observations within the confidence limits for gulls.

Individual birds may alter their flight height behaviour according to weather conditions, time of day, foraging strategy and whether commuting, migrating or foraging (Garthe & Hüppop 2004; Shamoun-Baranes *et al.* 2006; Blew *et al.* 2008; Newton 2010; Krijgsveld *et al.* 2011; Stumpf *et al.* 2011; Wright *et al.* 2012). However, as most data were collected as part of boat surveys, practicalities associated with observer safety and the detectability of birds limited the data collection to periods of daylight, with moderate winds and good visibility (Camphuysen *et al.* 2004; Hyrenbach *et al.* 2007). Evidence about variation in flight behaviour during different conditions is therefore limited. However, many of our study species are considered less likely to forage during the night than during the day (e.g. Daunt *et al.* 2002; Garthe & Hüppop 2004). Birds may avoid areas of heavy wind and rain or spend more time at or under the water surface in these conditions (Pinder 1989; Velando, Ortega-Ruano & Freire 1999), although Procellariiformes (such as northern fulmar *Fulmarus glacialis* and Manx shearwater *Puffinus puffinus*) may have higher flight altitudes during strong winds (Spear & Ainley 1997). Consequently, the absence of data collected during poor weather may bias estimates of the proportion of birds at risk, both when using the modelled distributions and existing methods. Data were also summarized across the year as a whole, again reflecting how they are currently used. Consequently, our data may include observations of migrating birds. During migration, birds are likely to fly at greater altitudes than when foraging or commuting between sites (Garthe & Hüppop 2004; Blew *et al.* 2008; Newton 2010; Krijgsveld *et al.* 2011; Wright *et al.* 2012). If the data do include migrating birds, this variation is likely to be captured by the estimates of precision surrounding our modelled distributions.

Considering these limitations, caution is required when using the presented results to estimate impact, and in general, a precautionary approach is necessary when assessing the potential impacts of developments on wildlife (Sanderson & Petersen 2002). As additional data become available, it will be possible to refine the outputs generated using our approach, increasing its value to the OWF industry by improving the accuracy of the estimates of collision risk.

ALTERNATIVE METHODS FOR ESTIMATING FLIGHT HEIGHT

A key concern about the use of visual observations to estimate flight altitudes is that the data will be negatively biased as recording birds at higher altitudes is difficult. Alternatives for assessing the flight heights of seabirds include tagging, high-definition imagery and radar. Tagging data may overcome some bias associated with weather conditions and diurnal behaviour (Bridge *et al.* 2011; Stumpf *et al.* 2011; Klaassen *et al.* 2012), but offers a restrictive sample size and is not suitable for all species (Burger & Shaffer 2008). High-definition digital imagery is increasingly common in aerial surveys of OWFs (Buckland *et al.* 2012), but data are hard to use on a species-specific basis (Mellor & Maher 2008; Hexter 2009). Radar may positively bias estimates of flight altitudes as low-flying birds are under-recorded due to reflections from the sea surface (Hüppop *et al.* 2006) and species-specific information is sparse (Schmaljohann *et al.* 2008). Consequently, migrants which may fly above 1000 m are included in data sets (Hüppop *et al.* 2006; Krijgsveld *et al.* 2011), positively biasing estimates of flight height. Studies using radar and visual observations suggest that seabird movements occur at lower altitudes, while observations at higher altitudes are migrating passerines or waders (Blew *et al.* 2008; Krijgsveld *et al.* 2011). These comparative studies suggest that the risk of overestimating flight heights of seabirds using radar data may exceed the risk of underestimating altitudes using visual observations. Underestimating seabird flight heights may underestimate the proportion of birds at risk of collision, which should be considered in all uses of visual observations to assess the proportion of birds at risk of collision.

CONCLUSIONS

Accurately estimating the collision risk is a step towards a better understanding of the potential impacts on birds of the rapidly expanding offshore wind energy industry. The standard assessment of the proportion of the in-flight population of birds occurring at a collision risk height is static and can only be used in the height categories in which the data were recorded and also measures the proportion of birds at risk height, overestimating those in the rotor-swept area. Continuous flight height distributions generated by the presented modelling approach enable different turbine designs to be considered, and for some species, the results can be applied with reasonable confidence to novel sites which have a similar use by birds to the sites in this study. Results demonstrate that increasing turbine height or diameter may be a good ways of reducing the risk of collision for many marine birds. This method provides a significant advance in estimating the collision risk of birds with wind turbines and opens up avenues for further refinement of these estimates.

Acknowledgements

This work was initially undertaken as part of project SOSS-02 under the Strategic Ornithological Support Services (SOSS) work programme put together to inform the offshore wind farm industry and funded by The Crown Estate (http://www.bto.org/soss), but has also been developed beyond this project. The work was initially developed by the SOSS steering group and overseen by a project working group comprising Ian Davies (Marine Scotland), Ross McGregor (SNH), Chris Pendlebury (Natural Power) and Pernille Hermansen (DONG Energy), together with Bill Band. Our thanks also to Graham Austin, Phil Bloor, Marcus Cross, Zoe Crutchfield, Sue King, Karen Krijgsveld, Jesper Kyed Larsen, Paula Low, Alastair Mackay, Eleri Owen and Maria Scarlett for their help in obtaining and collating information for seabird flight heights and/or their comments. We also particularly thank Colin Millar and Rob Fryer for useful discussion on the modelling methodology and James Pearce-Higgins and two reviewers for comments on earlier versions of this manuscript.

References

Band, W. (2012) *Using a collision risk model to assess bird collisions for offshore windfarms*. Report Commissioned by Strategic Ornithological Support Services (SOSS). http://www.bto.org/sites/default/files/u28/downloads/Projects/Final_Report_SOSS02_Band1ModelGuidance.pdf. Last accessed 14/12/2012.

Band, W., Madders, M. & Whitfield, D.P. (2007) Developing field and analytical methods to assess avian collision risk at wind farms. *Birds and Wind Farms: Risk Assessment and Mitigation* (eds M. de Lucas, G.F.E. Janss & M. Ferrer), pp. 259–275. Quercus Edicions, Madrid, Spain.

Blew, J., Hoffman, M., Nehls, G. & Hennig, V. (2008) *Investigations of the bird collision risk and the responses of harbour porpoises in the offshore wind farms Horns Rev, North Sea, and Nysted, Baltic Sea, in Denmark. Part I: Birds*. Universität Hamburg and BioConsult SH Report.

Boyd, I.L., Wanless, S. & Camphuysen, C.J. (eds.) (2006) *Top Predators in Marine Ecosystems: Their Role in Monitoring and Management*. Cambridge University Press, Cambridge.

Bridge, E.S., Thorup, K., Bowlin, M.S., Chilson, P.B., Diehl, R.H., Fleron, R.W. *et al.* (2011) Technology on the move: recent and forthcoming innovations for tracking migratory birds. *BioScience*, **61**, 689–698.

Buckland, S.T., Burt, M.L., Rexstad, E.A., Mellor, M., Williams, A.E. & Woodward, R. (2012) Aerial surveys of seabirds: the advent of digital methods. *Journal of Applied Ecology*, **49**, 960–967.

Burger, A.E. & Shaffer, S.A. (2008) Application of tracking and data-logging technology in research and conservation of seabirds. *The Auk*, **125**, 253–264.

Camphuysen, C.J., Fox, A.D., Leopold, M.F. & Petersen, I.K. (2004) *Towards standardised seabirds at sea census techniques in connection with environmental impact assessments for offshore windfarms in the U.K.* Report commissioned by COWRIE Ltd. Koninklijk Nederlands Instituut voor Onderzoek der Zee.

Chamberlain, D.E., Rehfisch, M.R., Fox, A.D., Desholm, M. & Anthony, S.J. (2006) The effect of avoidance rates on bird mortality predictions made by wind turbine collision risk models. *Ibis*, **148**(S1), 198–202.

Cook, A.S.C.P., Johnston, A., Wright, L.J. & Burton, N.H.K. (2012) *A review of flight heights and avoidance rates of birds in relation to offshore wind farms*. Strategic Ornithological Support Services Project SOSS-02. BTO Research Report No. 618. BTO, Thetford.

Da, Z., Xiliang, Z., Jiankun, H. & Qimin, C. (2011) Offshore wind energy development in China: current status and future perspective. *Renewable and Sustainable Energy Reviews*, **15**, 4673–4684.

Daunt, F., Benvenuti, S., Harris, M.P., Dall'Antonia, L., Elston, D.A. & Wanless, S. (2002) Foraging strategies of the black-legged kittiwake *Rissa tridactyla* at a North Sea colony: evidence for a maximum foraging range. *Marine Ecology Progress Series*, **245**, 139–247.

Department for Energy and Climate Change (DECC) (2012) https://www.og.decc.gov.uk/EIP/pages/projects/DockingDecision.pdf. Last accessed 24/04/2013

Desholm, M. & Kahlert, J. (2005) Avian collision risk at an offshore wind farm. *Biology Letters*, **1**, 296–298.

Drewitt, A.L. & Langston, R.H.W. (2006) Assessing the impacts of wind farms on birds. *Ibis*, **148**(S1), 29–42.

European Commission (2008) *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - Offshore Wind Energy: Action needed to deliver on the Energy Policy Objectives for 2020 and beyond COM/2008/0768*. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri = CELEX:52008DC0768:EN:HTML. Last accessed 09/11/2012.

Furness, R.W., Wade, H. & Masden, E.A. (2013) Assessing vulnerability of seabird populations to offshore wind farms. *Journal of Environmental Management*, **119**, 56–66.

Garthe, S. & Hüppop, O. (2004) Scaling possible adverse effects of marine wind farms on seabirds: developing and applying a vulnerability index. *Journal of Applied Ecology*, **41**, 724–734.

Gill, E. (2012) Argyll Array to be downsized. *Windpower Offshore*. Available from: http://www.windpoweroffshore.com/article/1190839/argyll-array-downsized. Last accessed 24/04/2013

Gilles, A., Scheidat, M. & Siebert, U. (2009) Seasonal distribution of harbour porpoises and possible interference of offshore wind farms in the German North Sea. *Marine Ecology Progress Series*, **383**, 295–307.

Gotmark, F., Winkler, D.W. & Andersson, M. (1986) Flock-feeding on fish schools increases individual success in gulls. *Nature*, **319**, 589–591.

Hexter, R. (2009) *High resolution video survey of seabirds and mammals in the Rhyl Flats Area*. Report commissioned by COWRIE Ltd., HiDef Aerial Surveying Ltd. Available from: http://www.thecrownestate.co.uk/media/354799/2009-07%20High%20Resolution%20Video%20Survey%20of%20Seabirds%20and%20Mammals%20in%20the%20Rhyl%20Flats%20Area.pdf. Last accessed 15/11/2013.

Hill, D. & Arnold, R. (2012) Building the evidence base for ecological impact assessment and mitigation. *Journal of Applied Ecology*, **49**, 6–9.

Hüppop, O., Diershcke, J., Exo, K.-M., Fredrich, E. & Hill, R. (2006) Bird migration studies and potential collision risk with offshore wind turbines. *Ibis*, **148**, 90–109.

Hyrenbach, K.D., Morgan, H.M.F., Welch, D.W. & Sydeman, W.J. (2007) Optimizing the width of strip transects for seabird surveys from vessels of opportunity. *Marine Ornithology*, **35**, 29–38.

Janss, G.F.E. (2000) Avian mortality from power lines: a morphologic approach of a species specific mortality. *Biological Conservation*, **95**, 353–359.

Klaassen, R.H.G., Ens, B.J., Shamoun-Baranes, J., Exo, K. & Bairlein, F. (2012) Migration strategy of a flight generalist, the lesser black-backed gull *Larus fuscus*. *Behavioural Ecology*, **23**, 58–68.

Krijgsveld, K.L., Fijn, R.C., Japink, M., van Horssen, P.W., Heunks, C., Collier, M.P., Poot, M.J.M. & Dirken, S. (2011) *Effect studies Offshore Wind Farm Egmond aan Zee: Final report on fluxes, flight altitudes and behaviour of flying birds*. Bureau Waardenburg report no. 10-219. Commissioned by NordzeeWind.

Lucas, M., Janss, G.F.E., Whitfield, D.P. & Ferrer, M. (2008) Collision fatality of raptors in wind farms does not depend on raptor abundance. *Journal of Applied Ecology*, **45**, 1695–1703.

Martin, G.R. & Shaw, J.M. (2010) Bird collisions with power lines: failing to see the way ahead? *Biological Conservation*, **143**, 2695–2702.

Mellor, M. & Maher, M. (2008) *Full scale trial of high definition video survey for offshore windfarm sites*. Report commissioned by COWRIE Ltd., HiDef Aerial Surveying Ltd., Cleator Moor.

Newton, I. (2010) *Bird Migration*. Collins, London.

Pearce-Higgins, J.W., Stephen, L., Langston, R.H.W., Bainbridge, I.P. & Bullman, R. (2009) The distribution of breeding birds around upland wind farms. *Journal of Applied Ecology*, **46**, 1323–1331.

Pinder, J.M. (1989) Kittiwakes *Rissa tridactyla* inland in Yorkshire 1981–1985. *Ringing & Migration*, **10**, 113–118.

R Development Core Team (2012) *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/

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

Sanderson, H. & Petersen, S. (2002) Power analysis as a reflexive scientific tool for interpretation and implementation of the precautionary principle in the European Union. *Environmental Science and Pollution Research*, **9**, 221–226.

Schmaljohann, H., Liechti, F., Bachler, E., Steuri, T. & Bruderer, B. (2008) Quantification of bird migration by radar – a detection probability problem. *Ibis*, **150**, 342–355.

Shamoun-Baranes, J., van Loon, E., van Gastern, H., van Belle, J., Bouten, W. & Buurma, L. (2006) A comparative analysis of the influence of weather on the flight height of birds. *Bulletin of the American Meteorological Society*, **87**, 47–61.

Snyder, B. & Kaiser, M.J. (2009) Ecological and economic cost-benefit analysis of offshore wind energy. *Renewable Energy*, **34**, 1567–1578.

Spear, L.B. & Ainley, D.G. (1997) Flight behaviour of seabirds in relation to wind direction and wing morphology. *Ibis*, **139**, 221–233.

Stumpf, J.P., Denis, N., Hamer, T.E., Johnson, G. & Verschuyl, J. (2011) Flight height distribution and collision risk of the marbled murrelet *Brachyramphus marmoratus*: methodology and preliminary results. *Marine Ornithology*, **39**, 123–128.

Velando, A., Ortega-Ruano, J.E. & Freire, J. (1999) Chick mortality in European shag *Stictocarbo aristotelis* related to food limitations during adverse weather events. *Ardea*, **87**, 51–59.

Wahlberg, M. & Westerberg, H. (2005) Hearing in fish and their reactions to sounds from offshore wind farms. *Marine Ecology Progress Series*, **288**, 295–309.

Wood, S.M. (2006) *Generalized Additive Models: An Introduction With R*. Chapman & Hall/CRC, Boca Raton, USA.

Wright, L.J., Ross-Smith, V.H., Austin, G.E., Massimino, D., Dadam, D., Cook, A.S.C.P., Calbrade, N.A. & Burton, N.H.K. (2012) *Assessing the risk of offshore wind farm development to migratory birds designated as features of UK Special Protection Areas (and other Annex 1 species)*. Strategic Ornithological Support Services Project SOSS-05. BTO Research Report No. 592. BTO, Thetford.

Received 20 June 2013; accepted 29 October 2013
Handling Editor: Morten Frederiksen

Supporting Information

Additional Supporting Information may be found in the online version of this article.

Fig. S1. Observed and modelled proportions of birds in each height category by species.

Fig. S2. Modelled estimates of the proportion of the population at risk for a 100-m diameter turbine at varying heights.

Table S1. Original sources for flight height data.

Appendix S1. Large graphs of species flight height distributions.

Figure S1. Observed and modelled proportions of birds in each height category by species.

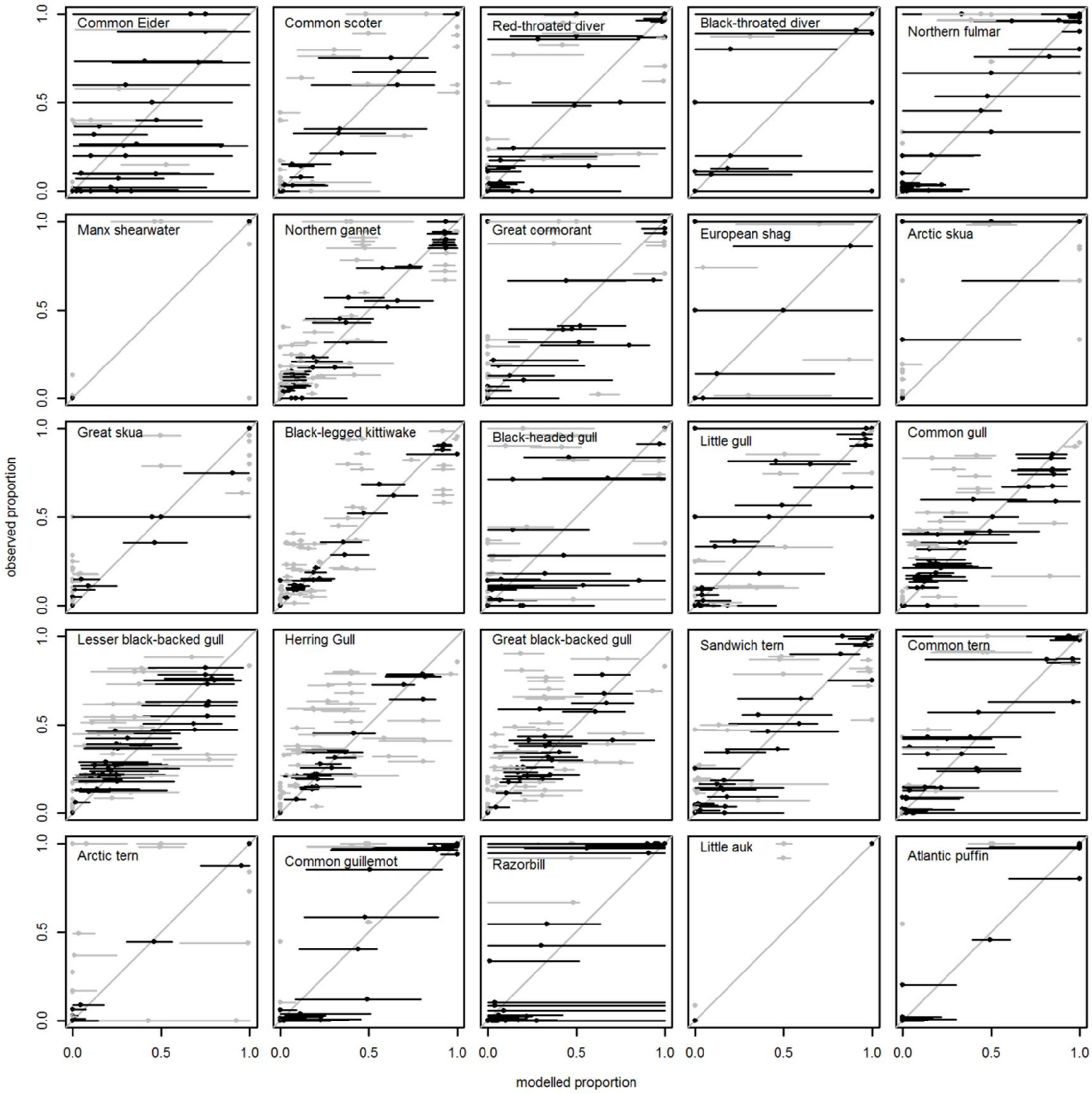


Figure S1: Modelled and observed proportion of birds in height categories at each site. Each data point is one height category at one site, with the x-axis the modelled proportion, and y-axis the observed proportion. The horizontal line represents the modelled 95% confidence interval, and the short vertical dash the modelled point estimate within the interval. Black data points are those in which the modelled 95% confidence interval includes the observed proportion (i.e. crosses the diagonal line of equality), and grey data points are those in which the modelled 95% confidence interval does not include the observed proportion.

Figure S2. Modelled estimates of the proportion of the population at risk for a 100m diameter turbine at varying heights.

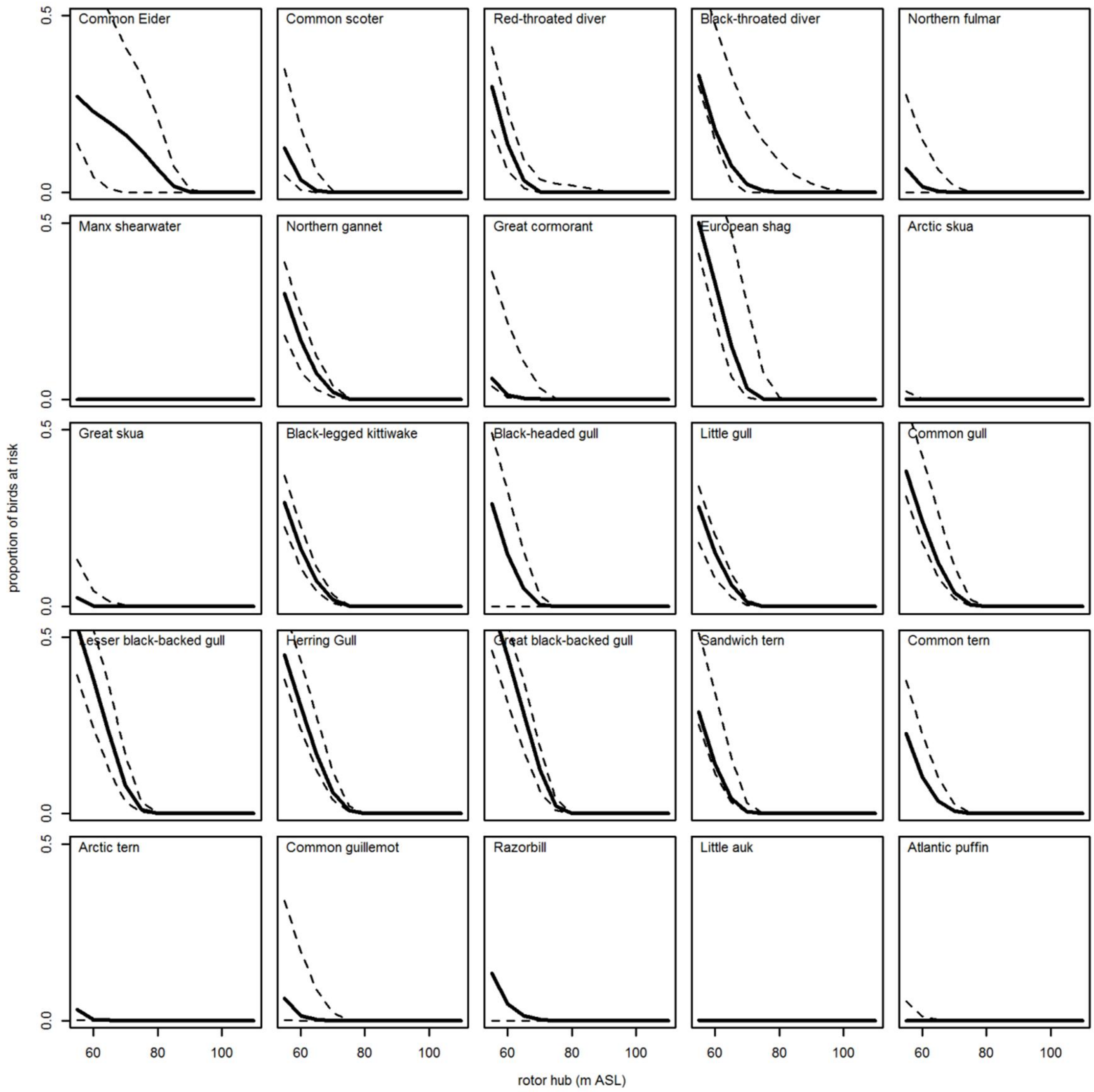


Figure S2: Estimated proportion of birds in a 100m width height column, flying within a circular area of 100m diameter, in relation to varying rotor hub heights. 95% bootstrap confidence intervals are indicated by dotted lines.

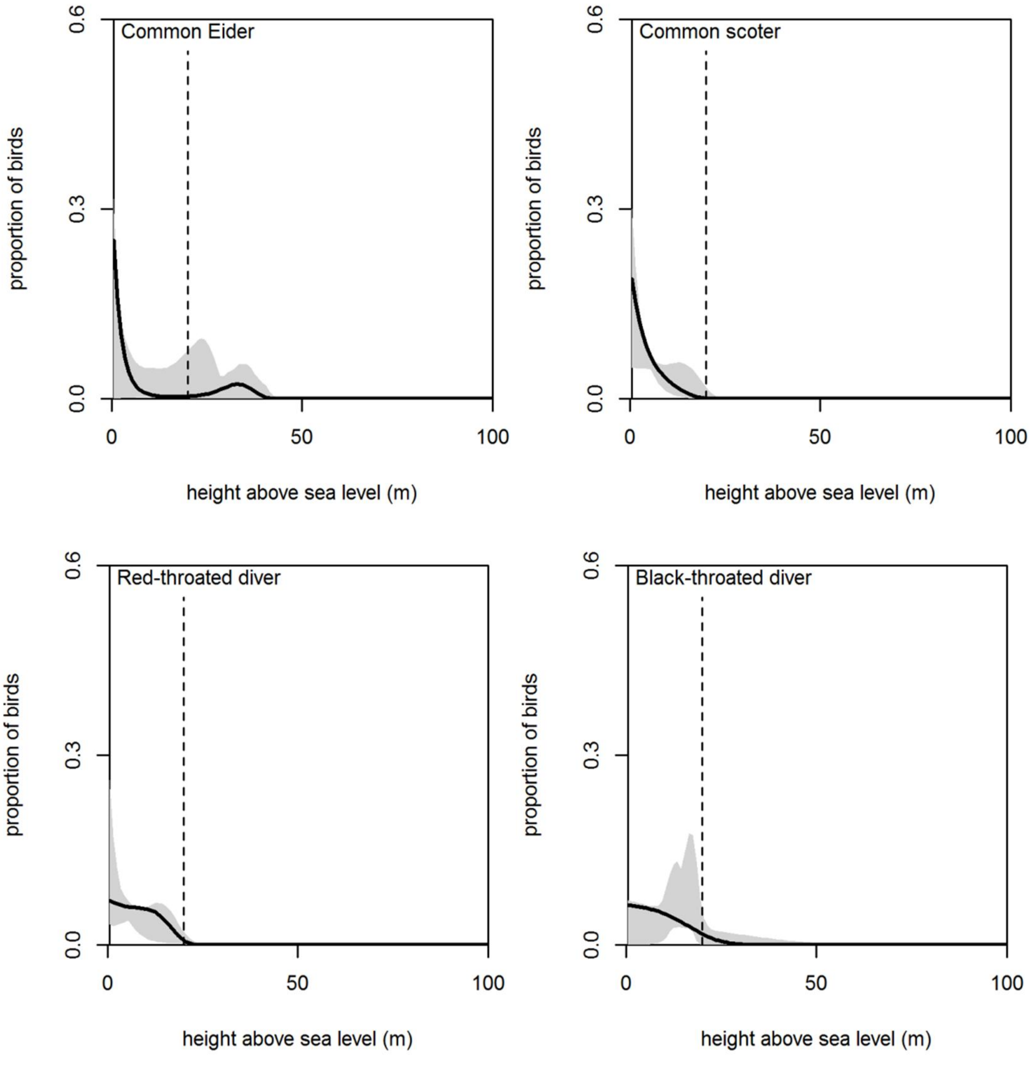
Table S1. Original sources for flight height data

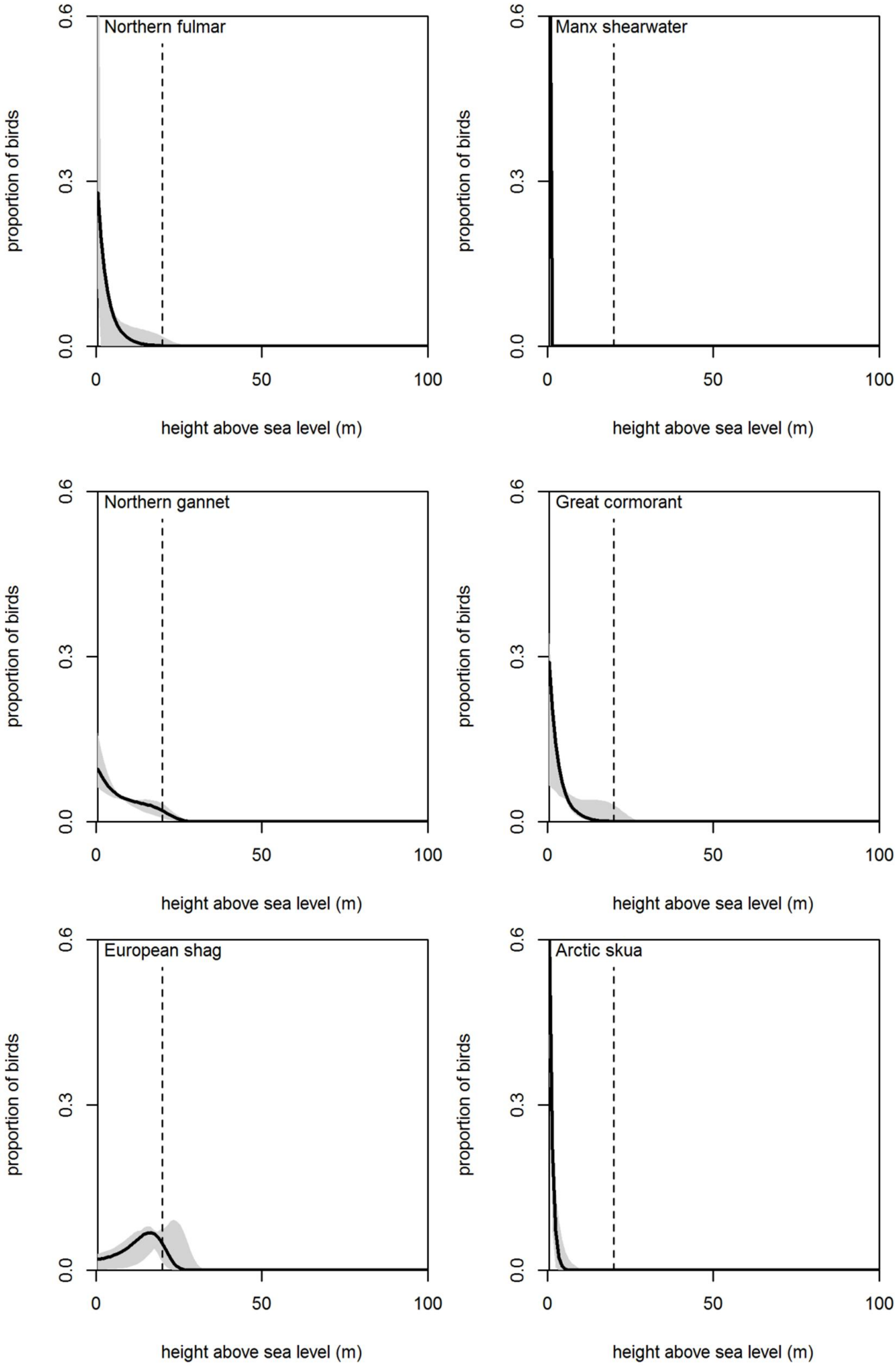
Wind Farm	Years	Months	Method	Reference
Argyll Array		All Year	Boat	Scottish Power Renewables. *unpublished data.*
Barrow		All Year	Boat	DONG Energy. 2006. *Barrow Offshore Wind Farm Environmental Statement*, DONG Energy, Essex
Blyth	1998-2000	All year	Shore	Rothery, p., Newton, I. & Little, B. 2009. Observations of seabirds at offshore wind turbines near Blyth in northeast England. *Bird Study*, 56, 1-14
Burbo Bank	2001-2002	Dec-Feb	Boat	Seascape Energy. 2008. *Burbo Bank Offshore Wind Farm Environmental Statement.* Available from [http://www.dongenergy.com/Burbo/Environment/statement/Pages/statement.aspx accessed 21/05/2013]
Docking Shoal		All Year	Boat	Centrica Energy. 2008. *Docking Shoal Offshore Wind Farm Environmental Statement. Centrica Renewables, Windsor*
Dogger Bank	2010-2011	All Year	Boat	Forewind Ltd. *unpublished data*
Dudgeon	2007-2008	All Year	Boat	Econ. 2009. *Ornithological assessment of the Dudgeon Offshore Wind Farm: Technical Report*, ECON Ecology, Norwich
Egmond aan Zee	2003 - 2004	All Year	Boat	Leopold, M. F., Camphuysen, C. J., van Lieshout, S. M. J., ter Braak, C. J. F., Dijkman, E. M. 2004. *Baseline studies North Sea Wind Farms: Lot 5 Marine Birds in and around the future site Nearshore Windfarm (NSW).* Alterra-rapport 1047, Alterra, Wageningen
Greater Gabbard	2004-2005	All Year	Boat	Banks, A. N., Burton, N. H. K., Austin, G. E., Carter, N., Chamberlain, D. E., Holt, C., Rehfisch, M. M., Wakefield, E., Gill, P. 2005. *The potential effects on birds of the Greater Gabbard Offshore Wind Farm Report for February 2004 to March 2005*. BTO Research Report No. 419, Thetford.
Gunfleet Sands	2005-2007	All Year	Boat	DONG Energy. 2005. *Gunfleet Sands 1 Environmental Statement,* DONG Energy, Essex DONG Energy. 2007. *Gunfleet Sands 2 Environmental Statement,* DONG Energy, Essex
Gwynt Y Mor	2002-2005	All Year	Boat	N Power Renewables. 2005. *Gwynt y Mor Offshore Wind Farm Environmental Statement*. N Power Renewables, Swindon
Horns Rev	2005-2006	Mar-May, Sept - Nov	Boat	Blew, J., Hoffmann, M., Nehls, G. & Hennig, V. 2008. *Investigations of the bird collision risk and the responses of harbour porpoises in the offshore wind farms Horns Rev, North Sea and Nysted, Baltic Sea, in Denmark Part 1: Birds.* University of Hamburg, Hamburg, Germany.
Humber Gateway	2003-2005	All Year	Boat	IECS. 2007. *Seabird Survey Programme Findings, Humber Gateway Windfarm*. Report to E.ON Renewables. IECS, Hull
Islay		All Year	Boat	SSE Renewables. *unpublished data*
Kentish Flats	2001-2002	All Year	Boat	Environmentally Sustainable Systems Ltd. 2008. *Kentish Flats Ornithological Monitoring Report*. Environmentally Sustainable Systems Ltd., Edinburgh available from [http://www.vattenfall.co.uk/en/file/2_Kentish_Flats_Bird_Monitoring.pdf_16360530.pdf accessed 21/05/13]
Lincs	2004-2006	All Year	Boat	Centrica Energy. 2007. *Lincs Offshore Wind Farm Environmental Statement.*
London Array	2002-2005	All Year	Boat	Dong Energy. 2005. *Environmental Statement Volume 1: Offshore Works London Array Limited*. Dong Energy, Essex
Lynn & Inner Dowsing	2001-2005	All Year	Boat	RPS. 2008. *Lynn & Inner Dowsing Offshore Wind Farm Boat-based Ornithological Monitoring Report*. RPS, Glasgow

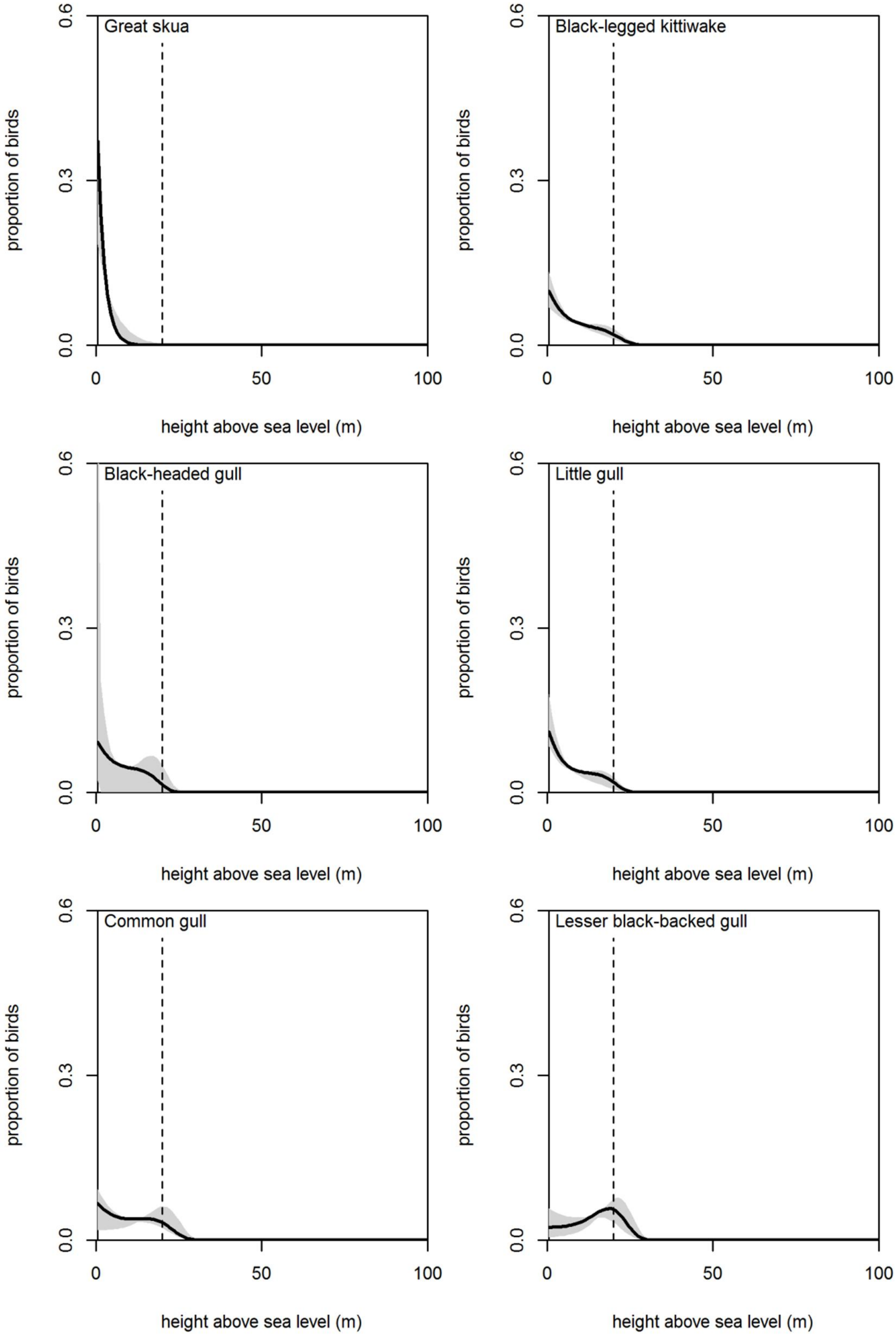
Meetpost Nordwijk	2003 - 2004	All Year	Offshore Platform	Krijgsveld, K. L., Lensink, R., Schekkerman, H., Wiersma, P., Poot, M. J. M., Meesters, E. H. W. G., Dirksen, S. 2005. *Baseline studies North Sea wind farms: fluxes, flight paths and altitudes of flying birds 2003-2004*. Alterra, Wageningen
Moray Firth	2010-2012	All Year	Boat	Moray Offshore Renewables Ltd. 2012. *Developing Wind Energy in the Outer Moray Firth Environmental Statement Telford, Stevenson and MacColl Wind Farms and Associated Transmission Infrastructure*. Available [http://morayoffshorerenewables.com/Document-Library.aspx?path=environmental+statement&page=1 accessed on 21/05/13]
Neart na Gaoithe	2009-2011	All Year	Boat	Mainstream Renewable Power Ltd. 2012. *Offshore Environmental Statement*. Available [http://www.neartnagaoithe.com/environmental-statement1.asp accessed on 21/05/13]
North Hoyle	2001	All Year	Boat	Innogy. 2002. *North Hoyle Environmental Statement.* Available from [http://www.rwe.com/web/cms/en/312146/rwe-innogy/sites/wind-offshore/in-operation/north-hoyle/environment/environmental-statement/ accessed 21/05/2013]
Nysted	2005-2006	Mar-May, Sept - Nov	Boat	Blew, J., Hoffmann, M., Nehls, G. & Hennig, V. 2008. *Investigations of the bird collision risk and the responses of harbour porpoises in the offshore wind farms Horns Rev, North Sea and Nysted, Baltic Sea, in Denmark Part 1: Birds.* University of Hamburg, Hamburg, Germany. Desholm, M. & Kahlert, J. 2005. Avian collision risk at an offshore wind farm. *Biology Letters* 1: 296-298.
Race Bank	2005-2007	All Year	Boat	Centrica Energy. 2009. *Race Bank Offshore Wind Farm Environmental Statement. Centrica Renewables, Windsor*
Rampion	2010-2012	All Year	Boat	E.ON Climate and Renewables. *unpublished data*
Sheringham Shoal	2004-2006	All Year	Boat	Scira Offshore Energy Ltd. 2006. *Sheringham Shoal Environmental Statement*, Scira Offshore Energy Ltd. [http://www.scira.co.uk/downloads/_Environmental%20Statement%20-%20main%20text.pdf accessed 21/05/2013]
Thorntonbank	2005-2007	All Year	Boat	Vanermen, N. & Stienen, E. W. M. 2008. *Seabirds & Offshore Wind Farms: Monitoring Results 2008.* INBO, Brussels
Tuno Knob	1998	Feb-Mar	Offshore Platform	Larsen, J.K. & Guillemette, M. 2007. Effects of wind turbines on flight behaviour of wintering Common Eiders: implications for habitat use and collision risk. *Journal of Applied Ecology* 44: 516-522.
Wangerooge	1999	Sept - Nov	Shore	Kruger, T. & Garthe, S. 2001. Flight altitudes of coastal birds in relation to wind direction and speed. *Atlantic Seabirds*, 3, 203-216
Westernmost Rough	2004-2006	All Year	Boat	DONG Energy. 2009. *Westernmost Rough Environmental Statement*. DONG Energy, Essex
West of Duddon Sands	2004-2005	All Year	Boat	Morecambe Wind Ltd. 2006. *West of Duddon Sands Offshore Wind Farm Environmental Statement*. Morecambe Wind Ltd., Morecambe
Zeebrugge	2004-2005	Jun-Jul	Shore	Everaert, J. & Stienen, E. W. M. 2007. Impact of wind turbines on birds in Zeebrugge. *Biodiversity and Conservation*, 16, 3345-3359

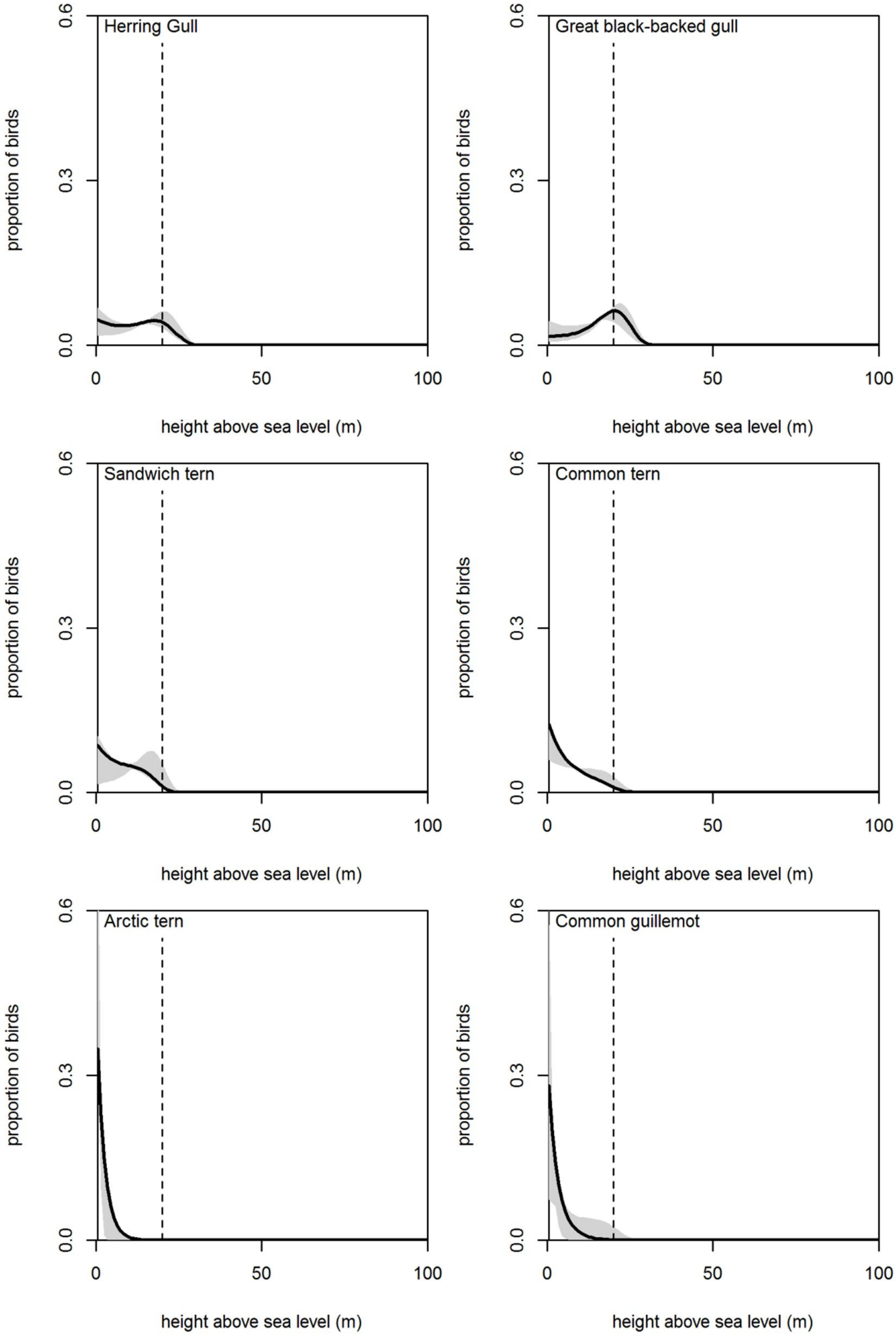
Supplementary Information: Large graphs of species flight height distributions

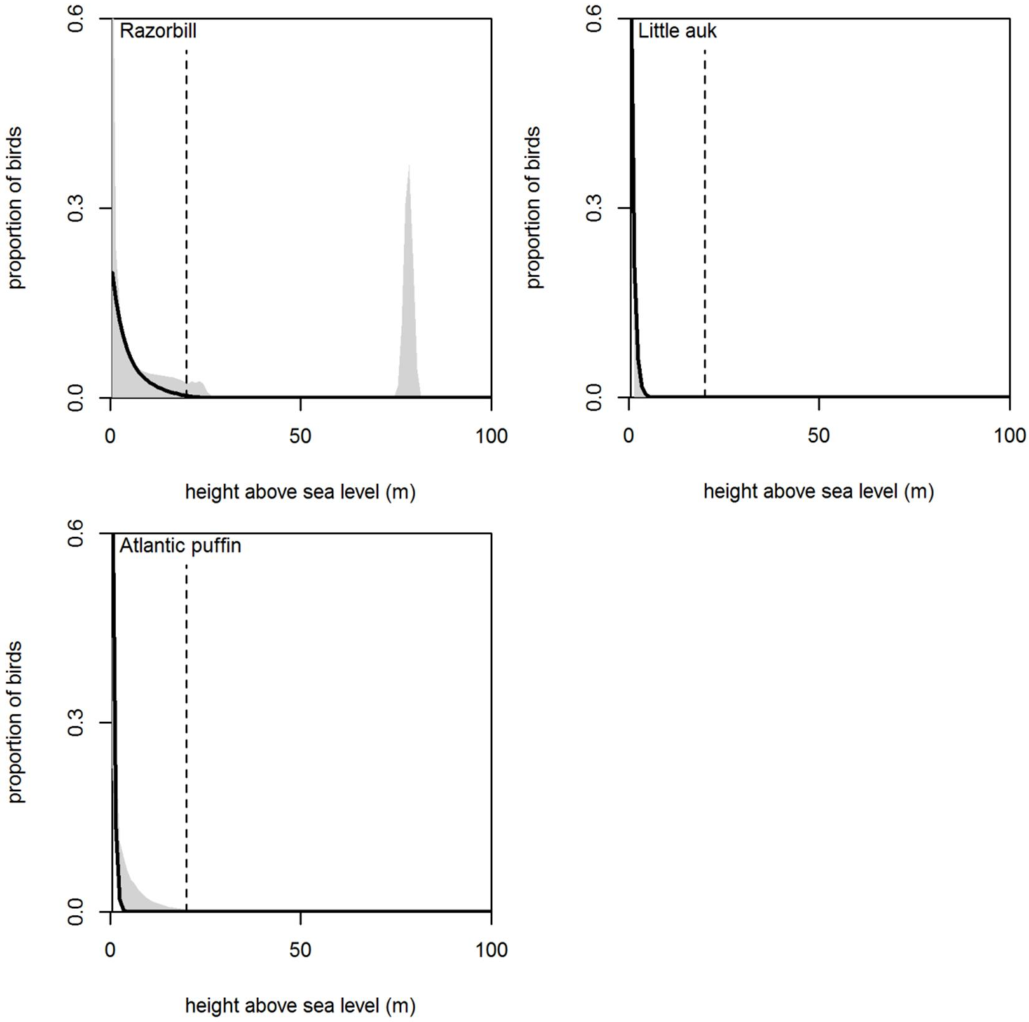
The following graphs are enlarged versions of the individual panels from Fig. 4 of the main manuscript. The vertical dotted line is at 20m above sea level, to enable visual inspection of the proportion of the population flying above 20m (Table 1 in the main manuscript). The graphs are truncated at 100m above sea level as extremely small proportions were modelled to be flying above this height, across all species. Truncation at 100m also enables easier interpretation of the distribution at lower heights.




Northern fulmar
Manx shearwater
Northern gannet
Great cormorant
European shag
Arctic skua
proportion of birds
0.0
0.3
0.6
height above sea level (m)
0
50
100


Great skua
Black-legged kittiwake
Black-headed gull
Little gull
Common gull
Lesser black-backed gull
proportion of birds
height above sea level (m)
0.0
0.3
0.6
0
50
100


Herring Gull
Great black-backed gull
Sandwich tern
Common tern
Arctic tern
Common guillemot
proportion of birds
0.0
0.3
0.6
0
50
100
height above sea level (m)


Razorbill
Little auk
Atlantic puffin
proportion of birds
0.0
0.3
0.6
0
50
100
height above sea level (m)

Journal of Applied Ecology

Journal of Applied Ecology 2014 doi: 10.1111/1365-2664.12260

Corrigendum

An error was found in the data formatting for Johnston *et al*. (2014), which resulted in incorrect knot locations for the spline, skewed towards the lower altitudes. As a consequence, the resultant flight height distributions were slightly skewed to lower altitudes. The corrected distributions for each species have been posted in the online Supporting Information files. Whilst we have recalculated one table and three figures for accuracy and provide minor associated changes to the text, our interpretation of the results and therefore the conclusions of the paper are unaffected by this error.

Columns 7–9 of Table 1 have changed as follows:

Species	Proportion of birds at risk height (95% confidence interval)	Proportion of birds within rotor-swept area (95% confidence interval)	
		Homogenous distribution	Heterogenous distribution
Common eider *Somateria mollissima*	0·346 (0·035, 0·558)	0·272 (0·028, 0·438)	0·222 (0·014, 0·410)
Common scoter *Melanitta nigra*	0·019 (0·001, 0·109)	0·015 (0·001, 0·086)	0·007 (0·000, 0·054)
Red-throated diver *Gavia stellata*	0·062 (0·015, 0·323)	0·049 (0·012, 0·254)	0·028 (0·006, 0·216)
Black-throated diver *Gavia arctica*	0·081 (0·068, 0·331)	0·064 (0·053, 0·260)	0·038 (0·031, 0·207)
Northern fulmar *Fulmarus glacialis*	0·010 (0·000, 0·092)	0·008 (0·000, 0·072)	0·004 (0·000, 0·044)
Manx shearwater *Puffinus puffinus*	0·000 (0·000, 0·000)	0·000 (0·000, 0·000)	0·000 (0·000, 0·000)
Northern gannet *Morus bassanus*	0·126 (0·062, 0·200)	0·099 (0·049, 0·157)	0·064 (0·028, 0·112)
Great cormorant *Phalacrocorax carbo*	0·017 (0·008, 0·271)	0·013 (0·006, 0·213)	0·006 (0·003, 0·166)
European shag *Phalacrocorax aristotelis*	0·126 (0·020, 0·643)	0·099 (0·016, 0·505)	0·063 (0·008, 0·496)
Arctic skua *Stercorarius parasiticus*	0·026 (0·017, 0·100)	0·020 (0·013, 0·079)	0·010 (0·006, 0·049)
Great skua *Stercorarius skua*	0·059 (0·035, 0·179)	0·046 (0·028, 0·141)	0·026 (0·015, 0·097)
Black-legged kittiwake *Rissa tridactyla*	0·150 (0·117, 0·173)	0·117 (0·092, 0·136)	0·079 (0·058, 0·095)
Black-headed gull *Chroicocephalus ridibundus*	0·139 (0·057, 0·255)	0·109 (0·045, 0·201)	0·072 (0·025, 0·153)
Little gull *Hydrocoloeus minutus*	0·000 (0·000, 1·000)	0·000 (0·000, 0·785)	0·000 (0·000, 0·941)
Common gull *Larus canus*	0·219 (0·190, 0·301)	0·172 (0·150, 0·236)	0·126 (0·105, 0·186)
Lesser black-backed gull *Larus fuscus*	0·282 (0·203, 0·431)	0·221 (0·159, 0·338)	0·172 (0·114, 0·294)
Herring gull *Larus argentatus*	0·319 (0·252, 0·412)	0·251 (0·198, 0·324)	0·201 (0·149, 0·278)
Great black-backed gull *Larus marinus*	0·325 (0·285, 0·428)	0·255 (0·224, 0·336)	0·206 (0·175, 0·294)
Sandwich tern *Sterna sandvicensis*	0·070 (0·061, 0·149)	0·055 (0·048, 0·117)	0·032 (0·027, 0·078)
Common tern *Sterna hirundo*	0·074 (0·044, 0·099)	0·058 (0·034, 0·077)	0·034 (0·019, 0·048)
Arctic tern *Sterna paradisaea*	0·040 (0·006, 0·143)	0·032 (0·004, 0·112)	0·017 (0·002, 0·074)
Common guillemot *Uria aalge*	0·004 (0·000, 0·102)	0·003 (0·000, 0·080)	0·001 (0·000, 0·050)
Razorbill *Alca torda*	0·027 (0·000, 0·137)	0·021 (0·000, 0·108)	0·011 (0·000, 0·071)
Little auk *Alle alle*	0·036 (0·000, 0·050)	0·028 (0·000, 0·040)	0·015 (0·000, 0·022)
Atlantic puffin *Fratercula arctica*	0·000 (0·000, 0·068)	0·000 (0·000, 0·053)	0·000 (0·000, 0·031)

The correct versions of Figures 3, 4 and 5 are reproduced below:

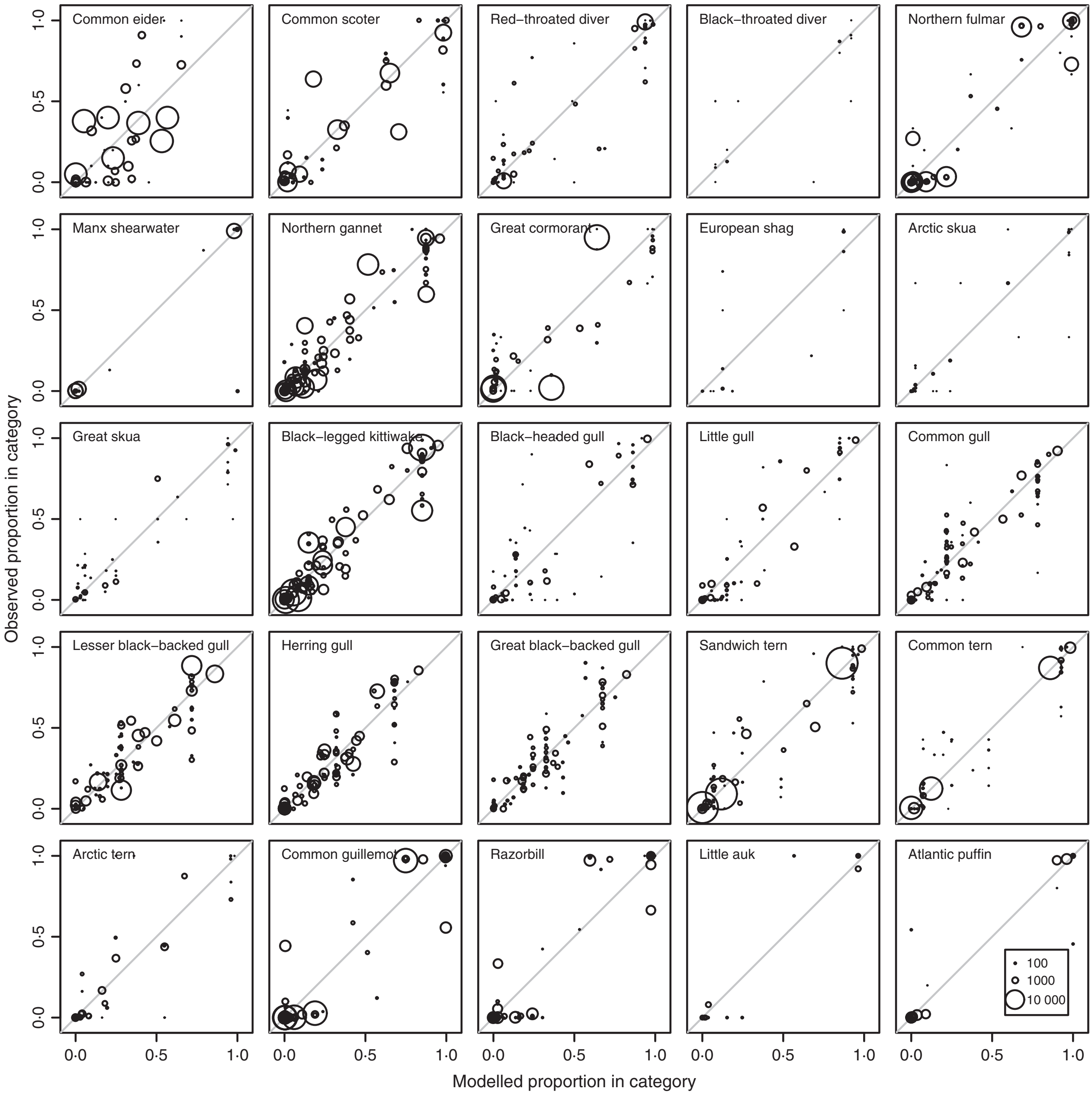


Fig. 3. Modelled and observed proportion of birds in each height category at each site. The relative area of the circle represents the total number of individuals of that species seen at the site. The grey line represents the line of equality (modelled and observed proportions are equal), and well-fitting models will therefore have most points near this line.

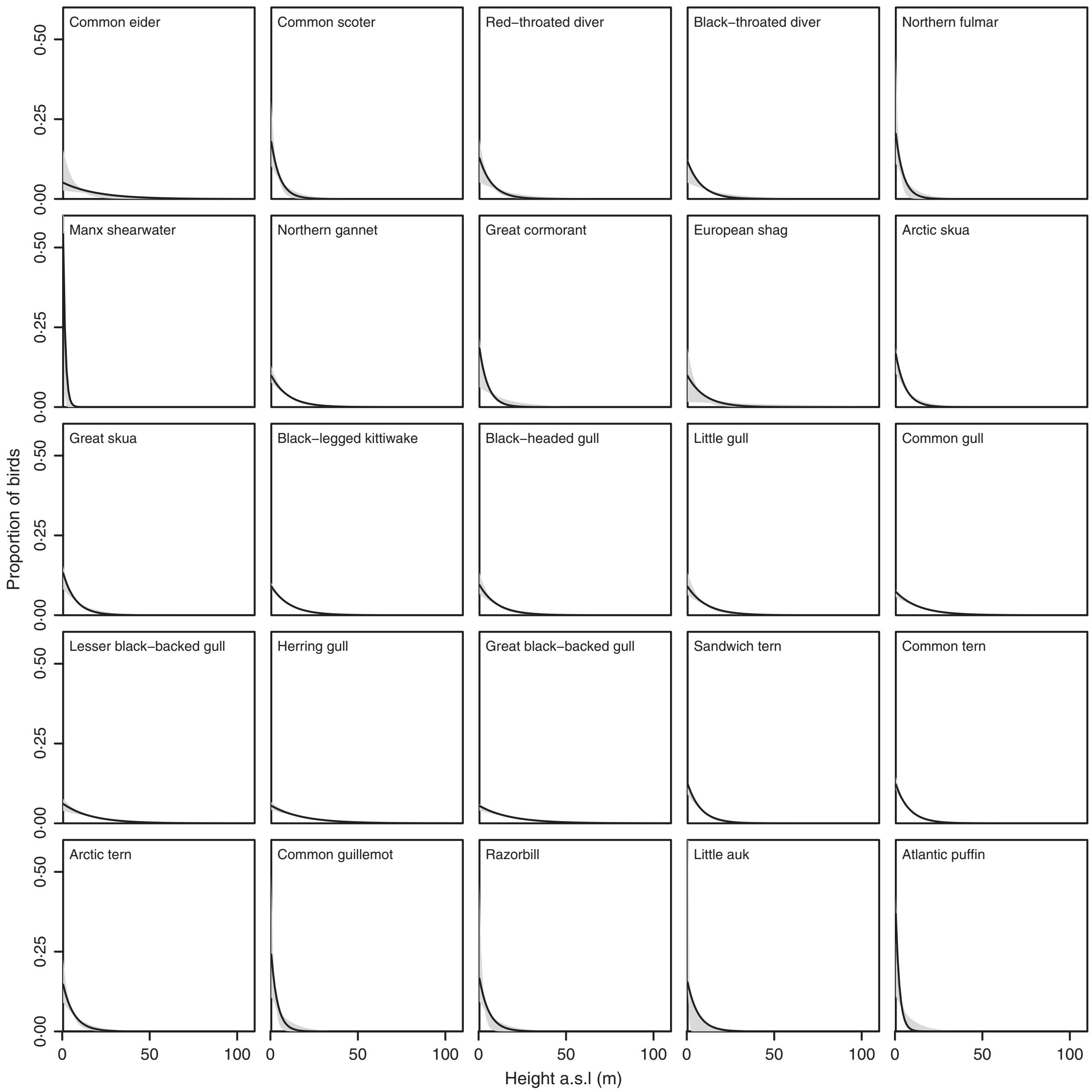


Fig. 4. Modelled flight height distributions (black line) and associated 95% bootstrap confidence intervals (grey area). Estimates are not always in the centre of the confidence limits, because the confidence limits are nonparametric, and proportions are calculated for each bootstrap.

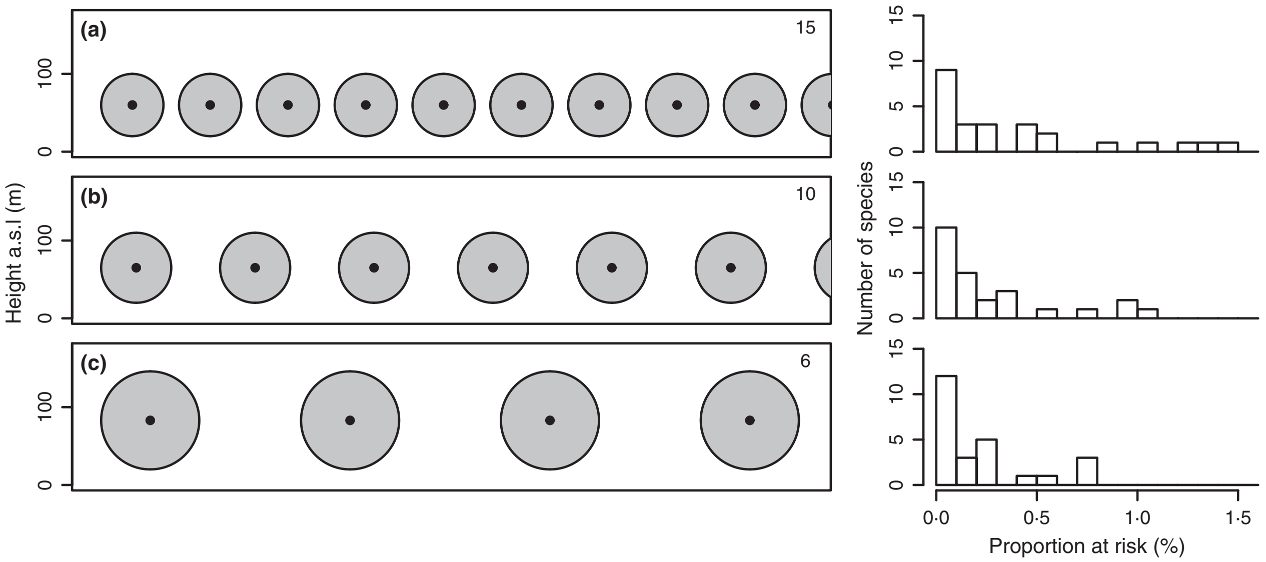


Fig. 5. Left-hand column is a schematic diagram of the rotor-swept area of a section of three 20-km-wide turbine arrays, each with a homogeneous set of turbines which produces 30 MW of electricity. The spaces between the turbines reflect relative spacing, but are not to the scale of the turbines. The number in the top right-hand corner of each turbine diagram indicates the number of turbines required to generate 30 MW of electricity. The right-hand column shows a histogram of the estimated percentage of each species at risk for the entire turbine array.

Minor changes to the text

Text location	Amended sentence
Summary	The mean r^2 for model fit across species was 0·92, and for eight of the species, good independent model validation (80% of independent observations within 95% confidence intervals) provides some confidence for use of the results at alternative sites.
Page 5	Correlations between the observed and modelled proportion of flying birds within each height category indicated a good fit of the modelled spline to the data for most species (Fig. 3), with the mean correlation within species r^2 = 0·92 (Table 1). Common eider *Somateria mollissima* had particularly poor fit with r^2 = 0·48, as the differences between sites seemed particularly marked (see Fig. S1, Supporting Information)
Page 5	Auks and terns had good model fit with average r^2 = 0·96 and r^2 = 0·97, respectively.
Page 5-7	Application to removed sites was less good, with an average percentage of observations within 95% confidence intervals of 82% and 69%, for auks and terns, respectively.
Page 7	Gulls had a much greater range of observed proportions (Fig. 3) and fairly good model fit (average r^2 = 0·94).
Page 7	For none of the 25 species were more than 95% of observations from removed sites within the modelled 95% confidence intervals, for only two species was the figure over 90%, and for a further six species, the figure was at least 80% (Table 1). Four species had very poor validation with $<50\%$ of observations from removed sites within modelled 95% confidence intervals.
Page 8	Across species, the proportion within the rotor-swept area from the heterogeneous distribution was on average 46% of the proportion flying at risk height and 58% of the homogenous distribution within the rotor-swept area (Fig. 1, Table 1).
Page 8	Averaging across all 25 species in the analysis, the proportion of the population at risk of collision in the entire 20-km array was 0·39% with 2 MW turbines, halving to 0·21% with 5 MW turbines. This pattern holds within species; the proportion at risk across the array declined by 27–29% when the array changed from 2 to 3 MW turbines and by a further 24–29% when the array changed to 5 MW turbines.

Reference

Johnston, A., Cook, A.S.C.P., Wright, L.J., Humphreys, E.M. & Burton, N.H.K. (2014) Modelling flight heights of marine birds to more accurately assess collision risk with offshore wind turbines. *Journal of Applied Ecology*, **51**, 31–41.

Supporting Information

Additional Supporting Information may be found in the online version of this article.

Fig. S1. Observed and modelled proportions of birds in each height category by species.

Fig. S2. Modelled estimates of the proportion of the population at risk for a 100-m diameter turbine at varying heights.

Table S1. Original sources for flight height data.

Appendix S1. Large graphs of species flight height distributions.