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Dear Kay, K-J

Please find attached the 4th instalment of documents.

Best regards,
Dr Dominika Chalder PIEMA
Environment and Consent Manager

[redacted]

Environmental Management UK│ Wind Power
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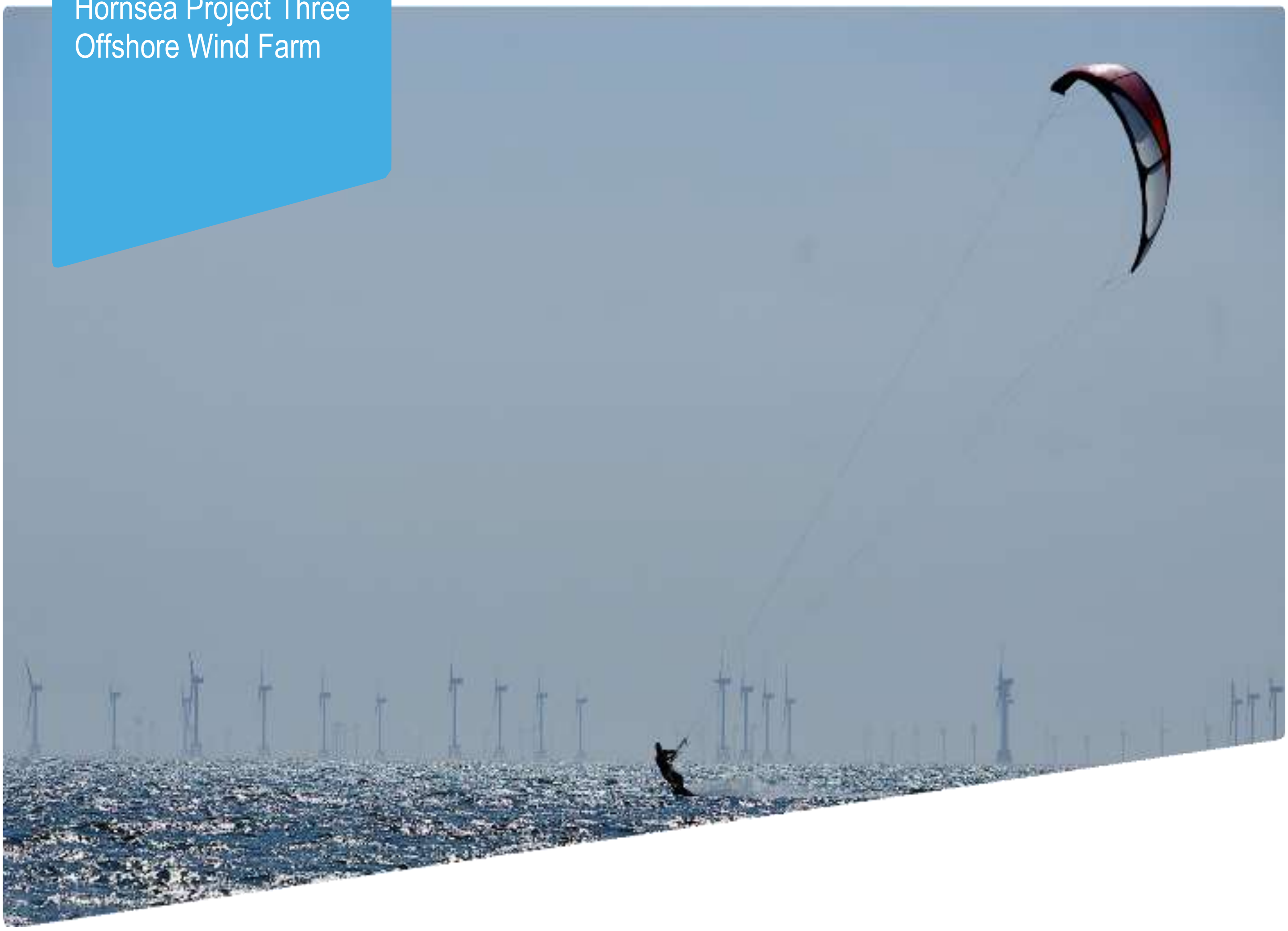
Hornsea Project Three
Offshore Wind Farm



Hornsea Project Three

Offshore Wind Farm

Appendix 9 to Deadline 4 Submission – Booth et al., 2017

Date: 15th January 2019

Hornsea 3
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Natural England Joint Publication JP024

Using the Interim PCoD framework to assess the potential impacts of offshore wind developments in Eastern English Waters on harbour porpoises in the North Sea

First published 12 June 2017

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Foreword

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England or the JNCC.

Background

Wind farm construction can impact harbour porpoise primarily as a result of the underwater noise generated by the installation of foundations. Mitigation is available to prevent death and injury, but the wider consequences of disturbance on the harbour porpoise population remain unclear.

This study uses a population assessment model (the interim Population Consequences of Disturbance model – known as the iPCoD framework) to investigate the potential aggregate or cumulative effects that could arise from the currently planned 12 years of English wind farm construction on the North Sea harbour porpoise population.

There are limitations with such predictive models and also uncertainties in our knowledge of harbour porpoise ecology, movements, and in particular how disturbance affects vital rates. These are clearly stated within the report.

Population modelling exercises such as this one help to identify which elements of the interaction between noise and species might be the most important in influencing population outcomes. This in turn informs which key areas of uncertainty should be the focus of further work.

Natural England and JNCC will use these findings to advise on wind farm construction and noise management, particularly in important areas for harbour porpoise.

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Key words – Wind farms, noise, harbour porpoise, modelling, disturbance, iPCoD.

Further information
This report can be downloaded from the Natural England Access to Evidence Catalogue: **http://publications.naturalengland.org.uk/** . For information on Natural England publications contact the Natural England Enquiry Service on 0300 060 3900 or e-mail **enquiries@naturalengland.org.uk**.

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understand • assess • mitigate

Using the 'Interim PCoD' framework to assess the potential effects of planned offshore wind developments in Eastern English Waters on harbour porpoises in the North Sea

Authors:	Cormac Booth, John Harwood, Rachael Plunkett, Sonia Mendes & Rebecca Walker
Report Code:	SMRUC-NEN-2016-005

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CONTENTS

Glossary

Acute effect	The direct effect of a change in behaviour or physiology on vital rates
Body condition	A measure of an individual's energy stores. In marine mammals, usually blubber thickness or total body lipid. One component of health (q.v.)
Chronic effect	The indirect effect of a change in behaviour or physiology on vital rates (q.v.) via individual health (q.v.)
Aggregate Exposure	Aggregate Exposure is defined here as the combined exposure to one stressor from multiple sources or pathways (here we are concerned with noise from pile driving) following CEMM (2016)
Demographic rates	The average survival and fecundity rates, and ages at independence and first breeding experienced by all members of a population in a particular year
Demographic stochasticity	Variation among individuals in their realised vital rates (q.v.) as a result of random processes
Environmental variation	Variation in demographic rates (q.v.) among years as a result of changes in environmental conditions
Expert elicitation	A formal technique for combining the opinions of many experts. Used in situations where there is a relative lack of data but an urgent need for conservation decisions
Fecundity	The average of individual fertility rates for all members of a population
Fertility	The probability that an individual adult female will give birth to a viable offspring in any particular year
Fitness	A relative term reflecting the potential contribution of the genotype of an individual to future generations. The fittest individuals leave the greatest number of descendants relative to the number of descendants left by other individuals in the population
Health	All internal factors that may affect individual fitness (q.v.) and homeostasis, such as body condition (q.v.), and nutritional, metabolic, and immunological status
Management Unit (MU)	The animals of a particular species in a geographical area to which management of human activities is also applied (IAMMWG 2015)
Population size	The number of animals of a species estimated to occur in a particular Management Unit (q.v.) as defined by the UK inter-Agency Marine Mammal Working Group (Anon. 2014)
Uncertainty	Incomplete information about a particular subject. In this report, we are only concerned with those components of uncertainty that can be quantified
Vital rates	The probability that an individual will survive from one year to the next, the probability that an individual adult female will give birth in one year
Vulnerable grouping	The members of the population within an MU whose behaviour may be affected by noise associated with a particular development or group of developments. The vulnerable grouping may include all animals in the MU, or just a proportion of that population. In the latter case, all animals that are not part of the vulnerable grouping are assumed to be unaffected by the development(s) being considered. This is the same as “Vulnerable sub-population” as described in King et al 2015.

1 Summary

The Interim Population Consequences of Disturbance Framework (iPCoD) was a model developed in 2013 to evaluate the potential effects of offshore marine renewable energy construction and operation on UK marine mammal populations (King et al. 2015). In this report, iPCoD is used to investigate the potential 'aggregate effects' (see Glossary) that could arise from the currently planned 12 years of English wind farm construction on the North Sea harbour porpoise population. iPCoD simulations are run 1000s of times and the differences between (otherwise identical) pairs of disturbed and undisturbed populations compared. The objective of the study was to explore the forecasts of aggregate impact based on the planned construction activities via a suite of different scenarios to provide a range of plausible outcomes.

Information was collated from 10 wind farms on the planned construction schedules, estimated disturbance impact ranges and numbers of porpoise affected. Initially the information presented in the licensing documents (e.g. environmental statements (ESs)) was used for each site and simulations run exploring how the disturbance associated with construction of these sites could impact the porpoise population. However, as licensing documents are prepared years in advance of construction and due to uncertainties in final wind farm design, they tend to represent the worst case (i.e. longest construction period and largest estimates of disturbance). Therefore a second set of up-to-date scenarios was built by liaising directly with the relevant offshore wind farm developers. In addition, the estimates of porpoises disturbed were refined by applying the adapted dose-response relationship from Thompson et al. (2013) to more realistically represent the gradient of effect due to distance from the pile-driving location. The recovery times (i.e. how long it takes for porpoises to return to the area) were also graded according to distance from the pile-driving location by using the data presented in Brandt et al (2011).

Using the worst case from the ESs, the predictions of a risk of a population annual decline equal or greater than 1% occurred in between approximately 1 in 5 and 1 in 8 of scenarios when assessed 12 years after the start of construction (i.e. in year 12). The updated, more realistic simulations resulted in a lowering of this risk, with between approximately 1 in 16 and 1 in 333 of scenarios predicting of a risk of a population annual decline greater than 1% 12 years after the start of construction. In general, the observed variation in predicted risk in different scenarios depended on the impact density estimates, predicted noise impact ranges and dose response functions used. In addition, they also varied depending on the assumptions made about how porpoises use their environment and the longevity of disturbance effects on porpoises.

It is important to consider that this study has investigated the potential impacts of certain explicit scenarios and forecasts are only indicative of what is projected to happen under there assumptions made in each simulation. Furthermore, it is important to note that the forecast population-level effects of construction activity are sensitive to assumptions in simulation scenarios about what proportion of the North Sea harbour porpoise population is likely to be vulnerable to disturbance from piling activity, and they are particularly sensitive to assumptions about the longevity of the effect of disturbance on porpoise behaviour. If animals are only disturbed during the period when pile driving is actually taking place, the aggregate effects of windfarm construction are forecast to be

relatively small, even if the maximum estimated number of animals that are disturbed on each day of piling. More research on the response of individual harbour porpoises to pile-driving noise in the open sea is required to reduce this uncertainty.

The forecasts made using the iPCoD model rely heavily on the opinions of experts about the potential effects of disturbance on harbour porpoise survival and reproduction. Although the elicitation process that was used to canvas these opinions was designed to minimise potential biases and to provide a realistic measure of among- and within-expert uncertainty, these forecasts should be interpreted with caution until more empirical data are available.

2 Introduction

The Interim Population Consequences of Disturbance (iPCoD) model was developed by SMRU Consulting and the University of St Andrews in 2013 to forecast the potential effects on marine mammal populations in UK waters of any disturbance, hearing damage or collisions that might result from the construction or operation of offshore renewable energy devices. A detailed description of the approach can be found in Harwood et al. (2014) and King et al. (2015). The iPCoD framework was designed to cope with the current situation, in which there is only limited knowledge about the potential effects of these developments on marine mammals. It should be recognised that it is very much an interim solution to the evaluation of these effects, and that there is an urgent need for additional scientific research to address the knowledge gaps that were identified by Harwood et al. (2014).

In this report, we describe how the software developed for the iPCoD framework (i.e. the iPCoD model) can be used to forecast the potential aggregate impacts of planned windfarm construction off the east coast of England over the period 2016 - 2027 on harbour porpoise in the North Sea. In 2016, the US National Academies of Sciences, Engineering, and Medicine published a report on 'Approaches to Understanding the Cumulative Effects of Stressors on Marine Mammals.' (National Academies of Sciences, Engineering, and Medicine. 2016). In that report, they highlight a crucial difference in terminology: "Aggregate Exposure is defined as the combined exposure to one stressor from multiple sources or pathways and Cumulative Risk as the combined risk from exposures to multiple stressors integrated over a defined relevant period: a day, season, year, or lifetime." Therefore here, as we are considering a single stressor (pile-driving) from multiple sources (a number of offshore wind farm developers), we believe that this study should be discussed in the context of 'aggregate' impact. This is not to be confused with any reference to any potential impact from activities associated with the aggregates industry.

We would like to stress that the framework was not designed to provide precise forecasts of changes in abundance but that the most appropriate use of the framework is as a tool to assess the potential relative benefits of different mitigation strategies, and to identify which research projects are most likely to reduce the uncertainties associated with the forecasts provided by the framework.

2.1 Basic Concepts

The intention of this section is to provide a brief overview of some of the elements used in this study and the key background references on the history of PCoD and the interim PCoD model.

2.1.1 The PCAD and PCoD frameworks

In 2005, a panel convened by the National Research Council of the United States National Academy of Sciences published a report on 'Marine Mammal Populations and Ocean Noise: Determining When Noise Causes Biologically Significant Effects' (National Research Council, 2005). The panel developed what they referred to as a "conceptual model" that outlines the way marine mammals respond to anthropogenic sound, and how the population level consequences of these responses could be inferred on the basis of observed changes in behaviour. They called this model Population Consequences of Acoustic Disturbance (PCAD; Figure 1).

In 2009 the US Office of Naval Research set up a working group to transform this framework into a formal mathematical structure and to consider how that structure could be parameterised using data from a number of case studies. The ONR working group extended the PCAD framework to consider forms of disturbance other than noise, and to address the impact of disturbance on physiology as well as behaviour. The current version of that framework, which is based on case studies of elephant seals, coastal bottlenose dolphins, northern right whales and beaked whales, is now known as PCoD (Population Consequences of Disturbance). It is shown in Figure 2, and described in more detail in New et al. (2014).

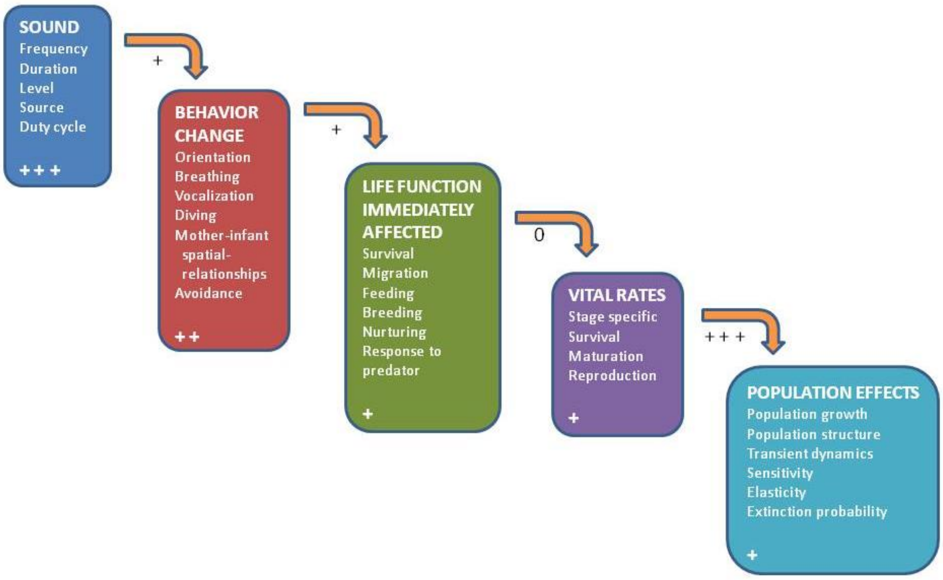

Figure 1 - The Population Consequences of Acoustic Disturbance (PCAD) framework developed by the National Research Council's (NRC) panel on the biologically significant effects of noise. After Figure 3.1 in NRC (2005). The number of + signs indicates the panel's evaluation of the level of scientific knowledge about the links between boxes, 0 indicates no knowledge.

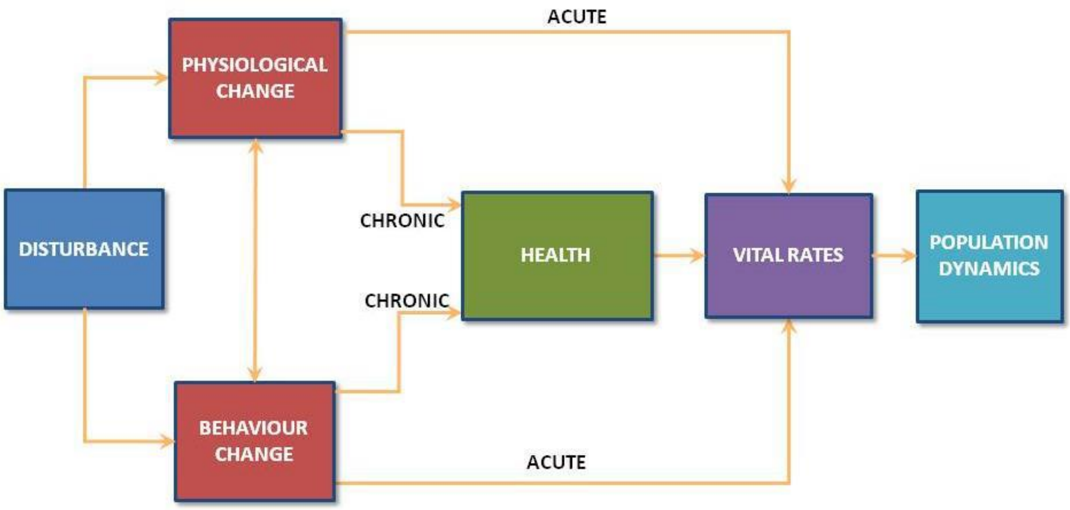

Figure 2 - The PCoD framework for modelling the population consequences of disturbance developed by the ONR working group on PCAD (modified from Figure 4 of New et al., 2014). See glossary for definitions of each relevant term.

The framework shows how disturbance may impact both the behaviour and physiology of an individual, and how changes in these characteristics may affect that individual's vital rates either directly (an acute effect) or indirectly via its health (a chronic effect). For example, exposure to high levels of sound may result in hearing damage (a physiological effect) as a result of a permanent threshold shift (PTS) at particular frequencies. This shift could have an acute effect on survival if the affected individual was less able to detect predators. It could also have a chronic effect on reproduction via the individual's health, because it might be less able to locate and capture prey. Similarly, behavioural changes in response to disturbance could have an acute effect on survival if they result in a calf being separated from its mother. They could have a chronic effect on reproduction, via health, if disturbed animals spend less time feeding or engaged in energy-conserving activities, like resting.

One of the potential consequences of a behavioural response to disturbance is that animals may be displaced into areas where predation risk is high. There is considerable evidence that the behaviour of marine mammals is shaped by the need to avoid predation. For example, bottlenose dolphins (*Tursiops truncatus*) in Shark Bay, Australia avoid areas where there is a high risk of shark attack (Heithaus & Dill, 2002), and Alaskan harbour seals (*Phoca vitulina*) appear to avoid spending time in parts of the water column where they are likely to be vulnerable to attacks from sleeper sharks (Frid et al., 2007). As a result of these behaviours, bottlenose dolphins in New Zealand and Australia appear to be reluctant to vacate areas where disturbance is high for neighbouring areas where there is a high risk of shark predation, even though remaining in the disturbed area has a potentially negative effect on calf survival and inter-calf interval (Bejder et al., 2006). For these reasons, the ONR working group concluded that marine mammals are unlikely to be displaced into regions of high predation risk by disturbance, and that the main effects of disturbance on vital rates are likely to be through changes in individual health as a result of changes in behavioural time budgets or physiology.

New et al. (2014), and Schick et al. (2013) used case studies of elephant seals (*Mirounga spp.*), and New et al. (2013) used a case study of bottlenose dolphins to show how changes in behaviour in response to disturbance could affect the energy reserves of adult females, and to estimate the implications of these changes for the probability of giving birth and offspring survival. The consequences of these changes for population dynamics could then be inferred from the number of animals that might be affected by disturbance and the size of the population of which they are a part. Nabe-Nielsen et al. (2014) and Van Beest et al. (2015) used a similar approach to assess the potential impacts of wind farm operation on harbour porpoises in Inner Danish Waters in the development of the Disturbance Effects of Noise on the Harbour Porpoise Population in the North Sea (DEPONS) model. However the DEPONS studies have not provided any empirical information on harbour porpoises vital rates or demography and the timeframe for this study meant that DEPONS was not available to be explored. A comparative report detailing similarities and differences between iPCoD and DEPONS is now available (Nabe-Nielsen & Harwood, 2016). The report also highlights how both the models might be further developed to improve their utility.

Unfortunately, the kinds of information required to estimate the parameters of the 'full' PCoD model used in some of these case studies (i.e. New et al 2013; 2014 and Schick et al 2013) are not available for most marine mammal populations. To cope with this lack of knowledge, the iPCoD framework is based on a simplified version of the full PCoD model, and is shown in Figure 3.

The parameters of the relationship between behavioural and physiological changes and individual vital rates illustrated in this model were obtained using an expert elicitation process (Runge et al., 2011; Martin et al., 2012) combined with the 4-step interval approach developed by Speirs-Bridge et al. (2010)(designed to help obtain robust expert judgements - see Harwood, et al 2014 for details). Donovan et al. (2016) and Appendix 1 of Harwood et al. (2014) describe how this approach was developed and implemented.

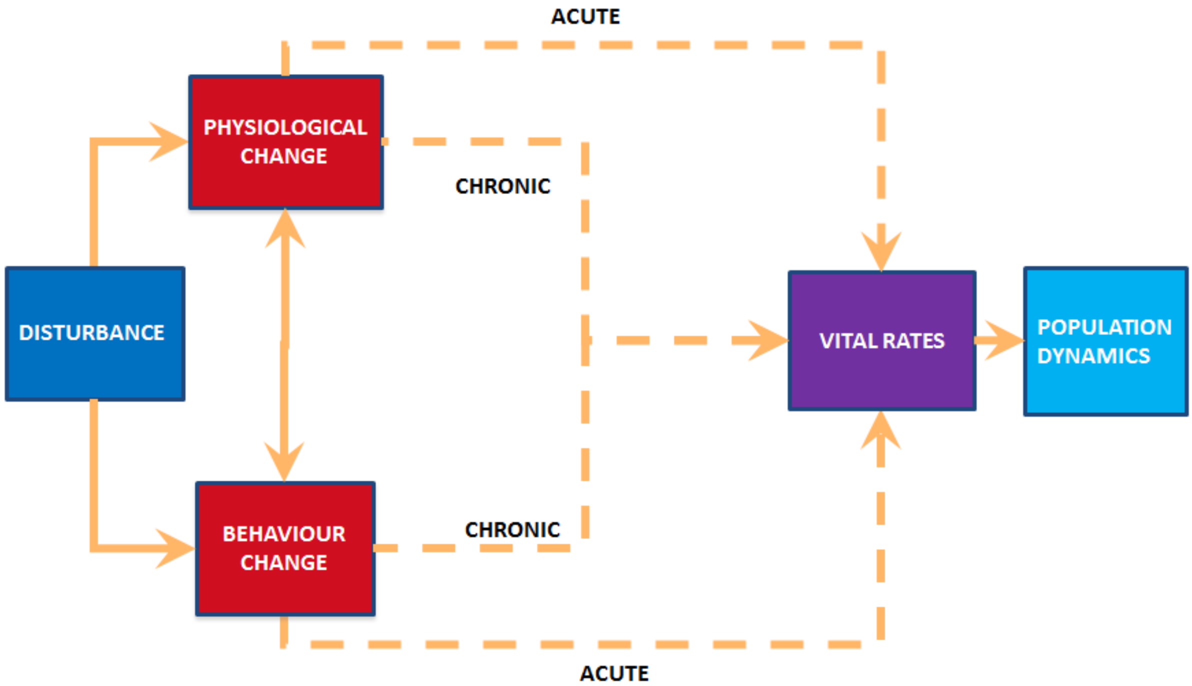

Figure 3 - A simplified version of the PCoD framework shown in Figure 2 that can be used as interim approach when empirical data on the effects of physiological and behavioural change in individual health is unavailable. The transfer functions that determine the chronic effects of physiological change and behavioural change on vital rates are represented with dotted lines to indicate that the form of these functions may be determined using the results of an expert elicitation process. See glossary for definitions of each relevant term.

2.2 An introduction to the Interim PCoD framework

During 2013, the 'iPCoD framework' was developed for five UK species of marine mammal including: harbour porpoise, grey seal, harbour seal, bottlenose dolphin and minke whale. In the following sections (2.2 – 2.2.7), we detail some of the elements of the general iPCoD framework. In the Methods section, we outline how the model was specifically implemented for the aggregate impact assessment in this project.

Estimates of the following quantities, and their associated uncertainties, are required to implement a PCoD approach for the effects of the construction of offshore renewable energy developments:

- The sound field produced during construction (i.e. an estimate of the area ensonified);
- The sound level that is likely to result in disturbance to an individual, preferably in the form of a dose-response relationship;
- The number of individuals that are likely to be disturbed during one day of construction;
- The number of days on which individual animals may experience disturbance during the entire course of construction;
- The effect of the number of days on which an individual in a particular age/stage class (e.g. adult males, adult females, calves, juveniles) experiences disturbance on its vital rates (distributions on these relationships were generated in the expert elicitation described in Harwood et al 2014 – see section 2.2.3);

- Current population size and population history for the affected species;
- Key demographic parameters (e.g. adult survival, calf survival, juvenile survival, annual probability of calving, age at first calving) for the species, with an indication of likely levels of variation between years.

2.2.1 Defining a disturbance response

In general, the duration and severity of behavioural responses to acoustic stimuli will depend on a suite of factors that includes the context in which exposure occurs, the individuals' internal states, and their exposure histories (Ellison et al., 2011). Despite these complicating factors, a number of authors (e.g. Miller et al. 2014; Moretti et al. 2014) have been able to define quantitative relationships between the probability that individual marine mammals will exhibit a disturbance response and received sound levels.

We defined a disturbance response as any change in behaviour that is likely to impair an individual's ability to survive, breed, reproduce, or raise young. This is roughly equivalent to all the behaviours with a score of 5 or higher on the 'behavioural response severity scale' for marine mammals outlined by Southall *et al*. (2007). These responses include changes in swimming and breathing patterns, sustained avoidance of an area, and prolonged changes in vocal behaviour. We categorise an individual that exhibits any one of these responses as having experienced disturbance on that day.

Donovan *et al.* (2012) and Nedwell *et al.* (2007) described ways in which the number of marine mammals that may be exposed to sound levels likely to cause a disturbance response around a noise generating activity, such as pile-driving, can be estimated. Estimates of these numbers are commonly provided by developers in their Environmental Statements (ES) and these estimates were used in Phase I of this study as an input to the models.

2.2.2 Defining variation among individuals in daily and aggregate exposure to disturbance

The risk of disturbance from a particular development may vary among individuals, because of variation in the amount of time they spend in the region around a particular development where sound exposure levels are sufficiently high to cause disturbance. There is evidence that suggests that porpoises may stay in relatively localised areas of potentially high quality habitat for periods of weeks (Teilmann, et al 2004; Nabe-Nielsen et al 2013) before moving on to exploit a new patch. Other studies involving simulated movement have explored how disturbance can impact at a population level (Aarts et al 2016). Porpoise movement patterns and ranges in the North Sea may vary between seasons and between individuals and more tagging studies are needed to better understand distribution and movement patterns and what may influence these.

In iPCoD, we can simulate that at one extreme, all members of the population may be equally vulnerable to the effects of a particular development. This is most likely to be the case where the geographical range of the population is relatively small or the development is located within an area of critical habitat for the species. It may also apply for a species like the harbour porpoise in the North Sea, where the limited telemetry data available indicates animals may range across wide areas

(Teilmann), thus over a >20 year simulation and many years of potential pile driving, a large proportion of animals in the MU have the potential to be exposed at some point. Alternatively, only a specific proportion of the population may be vulnerable to the effects of noise from a particular development. We refer to these animals as members of a "vulnerable grouping" (see Glossary). We have included the capability to model both of these alternatives within the framework. It is also possible to define unique vulnerable groupings for individual developments. We assumed that individuals who are not part of the vulnerable groupings do not experience disturbance for the duration of each simulation.

To estimate the variation among the individuals within a vulnerable grouping in the amount of disturbance they experience over the course of a year, we simulate the likely exposure to disturbance of 1000 individuals in each grouping on each day of construction. These numbers are then scaled up to provide an estimate of the amount of disturbance experienced by each of the individuals in the grouping. As a first approximation, we assume that each individual in a particular vulnerable grouping is equally likely to be disturbed on each of these days, with a probability calculated from the ratio of the number of animals expected to experience disturbance on one day to the total size of the vulnerable grouping.

2.2.3 Estimating the potential effects of aggregate disturbance on vital rates

We used an expert elicitation process to determine values for a set of parameters that define the effect of the total number of days of disturbance experienced by an individual during a year on its vital rates. That relationship, shown in Figure 4, was developed at a series of workshops of experts (with stakeholders – observing the process). .

Expert Elicitation Process

In 2013, we conducted the expert elicitation using the 4-step interval approach developed by Speirs-Bridge *et al*. (2010) to provide reliable estimates of the confidence that experts attached to their opinions. We then used the Delphi process (Delbecq et al., 1975) to improve the reliability of the elicitation results by asking experts to consider their opinions in the light of what other experts had said (Burgman et al., 2011). Answers were provided independently and anonymously, to minimize the effects of dominance, status and related phenomena that can compromise group expert judgments. Experts were selected using a set of eligibility criteria that included whether or not they had recently published on the population biology, the impact of noise on hearing, or the effects of disturbance on the species of interest. A total of 13 international experts took part in the expert elicitation process for harbour porpoises.

Elicitation Questions

We assumed that the vital rate most likely to be affected by disturbance for calves/pups and juveniles is survival and for adults is the probability of giving birth (which we henceforth refer to as fertility). We therefore only asked the experts for their opinions on the effects of disturbance on these specific vital rates. We conducted separate rounds of elicitation (thus generating distributions – for example see Figure 5) for each age/class. Experts were asked to provide their best estimate of the maximum effect of disturbance on survival (horizontal line A in Figure 4). We assumed that the maximum effect of disturbance on the probability of giving birth would be to reduce it to zero. Experts were also asked for their best estimate of the number of days of disturbance that an individual calf or juvenile animal could tolerate before it would have any effect on its probability of survival, and their best estimate of the number of days that an individual mature female could tolerate before it had an effect on its probability of giving birth (vertical line B in Figure 4). Experts were asked to specify how many days of disturbance would be required to have the maximum effect on survival or fertility (vertical line C in Figure 4). These three values defined the shape of the relationship. Finally, experts were asked to specify bounds for these estimates, which are shown as shaded areas in Figure 4.

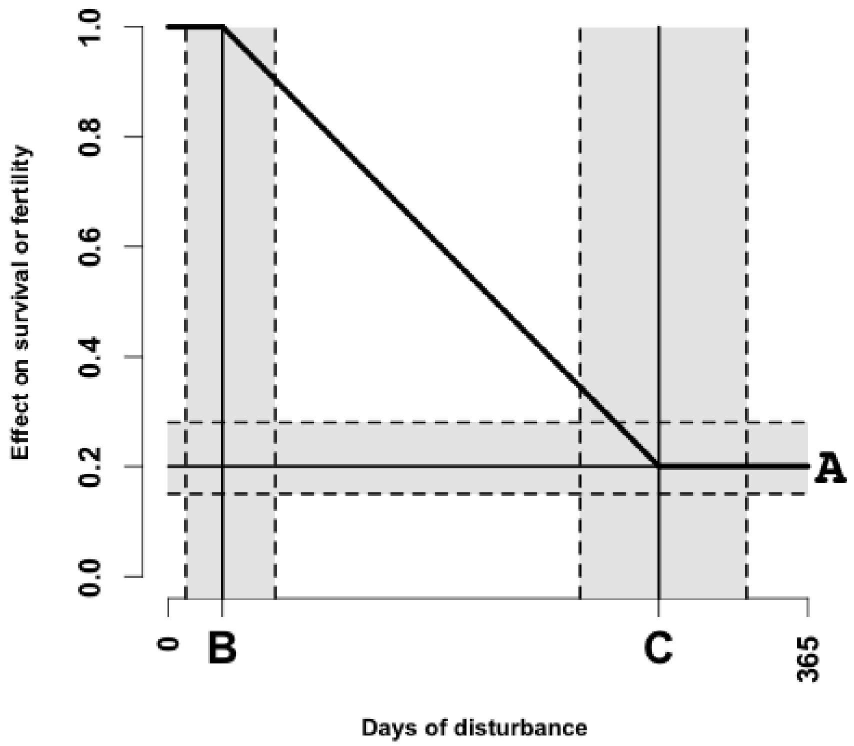

Figure 4 - A hypothetical relationship between the number of days of disturbance experienced by an individual marine mammal and its effect on the probability of survival or fertility. A is the maximum effect of disturbance on this probability (in this case, the actual probability will be the population survival rate multiplied by 0.2), B is the number of days of disturbance an individual can tolerate before its survival or fertility is affected, and C is the number of days of disturbance required to cause the maximum effect. The shaded areas indicate the likely range around the best estimates of A, B and C provided by each expert. The exact values presented in this example are purely indicative. Solid lines indicate best estimates. Dotted lines indicate the range around these best estimates.

Statistical Analysis of Elicitation Results

Here we provide a brief description of the statistical approach used to estimate the parameters of the relationships illustrated in Figure 4 from the results of the expert elicitation. Expert's opinions about the parameters were used to define Beta or Triangular probability distributions for parameter whose values were in the range 0-1, and Gamma, Triangular or truncated Normal distributions for each parameter relating to the number of days of disturbance. These distributions were then combined using copula-type methods to obtain a collective view. Full technical details can be found in Donovan et al. (2016).

Random draws from each expert's multivariate distribution were then used to build an overarching two-dimensional probability density function (Figure 5) that was designed to capture the uncertainty expressed by individual experts, and the variability among experts in their opinions. Random draws were taken from these overarching distributions to provide the opinions of a different "virtual' expert for each run of the simulation model described below.

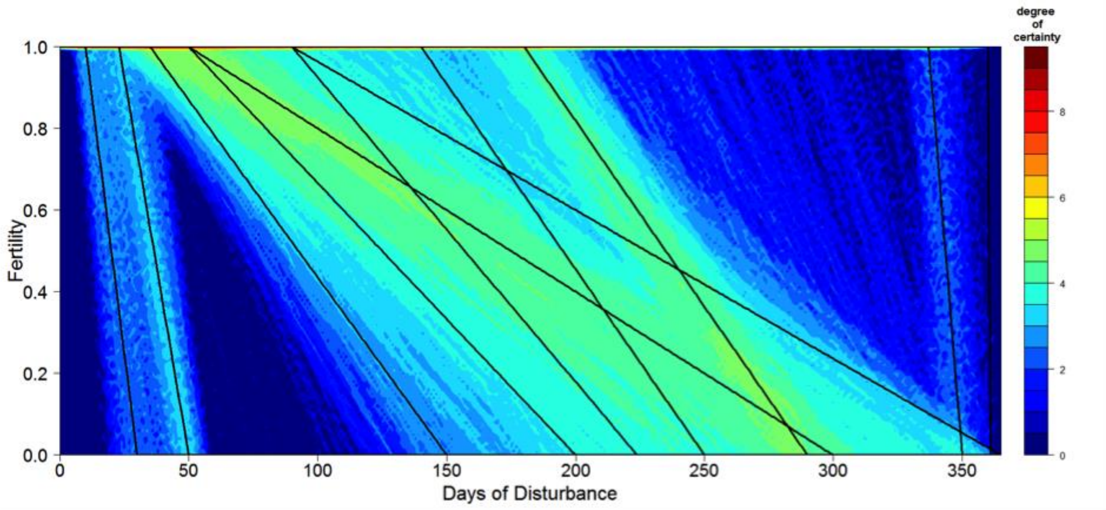

Figure 5 - Probability density function for the relationship between the number of days of disturbance experienced by an adult female harbour porpoise and the effect of that disturbance on her fertility. The black lines indicate the relationships suggested by individual experts (11 responded to this question). They are superimposed on a map that shows the overall support amongst the experts for particular combinations of values - "hot" colours (reds and yellows) indicate combinations for which there was a lot of support, and "cold" colours (various shades of blue) indicate combinations for which there was little or no support.

2.2.4 Modelling the persistence of disturbance effects

In order to model the aggregate impact of a wind farm over the entire period of construction we need to make a series of assumptions about the way in which disturbance effects persist over time. There is considerable evidence (Brandt et al., 2011; Dähne et al., 2013; Teilmann & Carstensen, 2012; Thompson et al., 2013; Tougard et al., 2012) that harbour porpoises are displaced from the area around a wind farm by construction noise, and that they do not re-enter that area until sometime after that noise ceases. We therefore assume that an animal which experiences disturbance will vacate the area around the wind farm for at least the remainder of the day on which construction work occurs. The available evidence on the duration of disturbance for harbour porpoises is reviewed in section 3.3.

The above studies indicate that some disturbed animals may not re-enter an area where disturbance occurred for days after that event. This "residual" displacement may also have a negative effect on their vital rates, and we therefore examined the effect of varying the number of "residual" days of disturbance that may be associated with each day of actual disturbance (section 3.3 and 4). Individuals exhibiting “residual” disturbance were assumed not to experience any additional direct disturbance during this time. However, it is still possible for other individuals in the MU to be disturbed in subsequent days.

For each individual in a vulnerable grouping we estimate the potential exposure to disturbance over the course of a year by conducting a random Bernoulli trial (Papoulis, 1984) on each day that construction was specified to take place. The model therefore provides a day-by-day history of the exposure of each simulated individual to disturbance and the number of “residual” days of disturbance experienced by these individuals in each vulnerable grouping. These histories are summarised to provide an estimate of the total number of days of disturbance each simulated individual experiences over the course of each year of construction.

2.2.5 Population Model Structure

The iPCoD framework uses a stochastic population dynamic modelling framework similar to that used in population viability analysis (Morris & Doak, 2002) to forecast the potential effects of the changes in individual vital rates as a consequence of disturbance. The population is divided into 10 age or stage classes: calves; 1-year olds; 2-year olds; 3-year olds; 4-year olds; 5-year olds; 6-year olds; 7-year olds; 8-year olds; and all animals aged 9 years and above, which were combined into a single stage class.

Animals in each class are then divided into three categories:

- those that experience no disturbance,
- those that experience moderate disturbance (more than B days, but less than C days – see Figure 4) and
- those that experience high levels of disturbance (more than C days).

In the original version of the iPCoD framework described in Harwood et al. (2014) we assumed that survival and fertility rates for all animals in the moderate disturbance category are reduced by the mean amount shown in Figure 4 (solid lines show the best estimates; dotted lines indicate bounds). However, this will over-estimate the effects of disturbance if most disturbed animals experience fewer days of disturbance than the mid-point between B and C in Figure 4. Careful examination of a large number of simulations has revealed that this is often the case. We have therefore revised the software so that we now calculate the mean number of days of disturbance experienced by all the individuals in the moderate disturbance category for each age class or stage within the year being modelled. We then use the relationship in Figure 4 to determine the effect of exactly this amount of disturbance on their vital rates.

We assume that the effects of disturbance in one year do not persist into the next year. Therefore, animals that experience disturbance in one year are reassigned to the relevant undisturbed age- or stage-class at the beginning of the next year. The three disturbance categories and 10 age or stage classes result in 30 age-disturbance combinations that are modelled as a 30-element vector using a

Leslie matrix structure (Caswell, 2001). The Leslie matrix provides information on the survival and fertility rates for each element and moves animals from one class to the next one at the end of the year. We chose a set of demographic rates to achieve the population growth rate suggested by Figure 7 of Winship & Hammond (2006)(derived using available life history data and Bayesian modelling). These demographic rates (see Table 1) include the effects of by-catch on survival. There are currently no more up-to-date information on (or recent data from which to derive) population demographic rates and current status of the population.

Table 1 – Annual demographic rates used for harbour porpoises in the North Sea. 'age1' is the age (in years) at independence and 'age2' is the age (in years) at first breeding.

Population Growth rate	age1	age2	Calf survival	Juvenile survival	Adult survival	Fecundity
1	1	5	0.6	0.85	0.85	0.96

This is a birth-pulse model, which does not attempt to model changes in population size during the course of a year, and which assumes that all births occur at the start of the year. The model was run using the estimated number of females in the population. This simulated population was then scaled to a full population at the end of the simulations assuming a 50:50 sex ratio. Simulations were conducted using code written in the R statistical computing environment (R Core Team 2013).

The iPCoD framework can provide forecasts of the possible size of a population many years after any disturbance associated with a particular development ceases. However, these forecasts are unlikely to be realistic because they assume that the vital rates within a population that has been reduced in size will not change as a result of density dependent processes. Therefore, simulated populations do not show any recovery once the effects of disturbance has ceased. In practice, disturbed populations are likely to show some recovery over time as a result of an increased per capita availability of resources, provided there is no change in any of the other threats to the population. However, there is currently no evidence for density dependence in the North Sea harbour porpoise population. Density dependence is usually detected by analysing an extensive time series of estimates (obtained with reasonable frequency) of population size. Such a time series is unlikely to be available for harbour porpoises in the foreseeable future.

One consequence of the lack of density dependence in the underlying population model is that forecasts of abundance become increasingly unrealistic over time. As a consequence, the effects of disturbance will be over-estimated if forecasts are extended too far into the future. As a rule of thumb, we would suggest that forecasts of population size more than 12 years after the cessation of disturbance activities should be treated with caution. In the case of the scenarios we have investigated, piling activity occurs over a period of 12 years. We have therefore included forecasts for up to 24 years (12 years after the projected end of planned piling), so that they cover two of the 12 year monitoring periods proposed by Evans & Arvela (2012) - see Section 2.2.7.

2.2.6 Accounting for Uncertainty

We attempt to quantify and model as many of the major sources of uncertainty involved in the calculation of the potential effects of disturbance on populations of marine mammals as we can. These include uncertainty associated with estimates of: (1) the size of the population; (2) the proportion of the population affected by a particular source of disturbance; (3) the number of animals predicted to exhibit a disturbance response as a result of one day of noise exposure; (4) the effects of the number of days of disturbance on vital rates, as provided by expert opinion; and (5) the effects of demographic stochasticity and environmental variation.

Items (1) and (3) are related, because calculations of the number of animals predicted to experience disturbance depend on the estimated total population size. The population-level effects are affected by uncertainty about what proportion of the population is actually exposed to disturbance on a particular day. We used preliminary estimates (C. Paxton, pers. comm.) of the 95% confidence limits on the proportion of the North Sea harbour porpoise population that is likely to occur in the immediate vicinity of North Sea wind farm sites to capture the combined uncertainty in items (1) and (3). These limits are approximately ± 50% of the mean value, although the actual values are likely to be log Normally distributed. We therefore multiplied the estimate of the number of animals predicted to experience disturbance on one day of construction by this scalar:

$$exp(N(\mu=0, \sigma=0.25))$$

This calculation does not, however, capture uncertainty in the estimate that could result from the use of different models for the propagation of the noise associated with construction, or from the use of different ways of modelling the effects of hearing sensitivity at different frequencies, such as M-weighting (Southall *et al.* 2007) or dB_{ht} (Nedwell *et al*. 2007). The number of animals predicted to experience disturbance would ultimately differ depending on the propagation model and hearing sensitivity weighting function used.

Uncertainty in item (2) was examined by using different values for the size of the grouping that was vulnerable to disturbance.

Uncertainty in item (4) was accommodated via random draws from statistical distributions derived from the results of the expert elicitation process, as described previously. For each iteration of the model, a set of parameter values is selected at random from these expert distributions. This is equivalent to soliciting the opinions of a different "virtual" expert for each iteration. This expert's "opinions" determine the number of days of disturbance required to have a moderate or high effect on vital rates (Figure 4), and the effects of this disturbance on those vital rates.

Year to year variations in environmental conditions are likely to affect the survival and fertility rates for all individuals in a population. We estimated the appropriate level for environmental variation (item 5) by asking experts 'by how much do you think survival or fertility is likely to vary from year to year for populations of this species in northern European waters in the absence of disturbance?' and invited them to choose one of six percentage values ranging from 0% to 50%. Because this is an estimate of the uncertainty associated with the demographic rates, we thought it would be confusing to ask experts to quantify bounds on this uncertainty. Many survival and fertility rates for marine mammals are close to 1.0, so it is not possible for them to vary symmetrically around the mean from year to year. We therefore model environmental variation in each demographic rate using a Beta distribution, whose mean corresponds to the baseline value and whose variance is adjusted so that the lower 99% confidence limit corresponds to the mean percentage value chosen by the experts. The values used are shown in Table 2. We assumed that variation in demographic rates is uncorrelated, both among age/stage classes and among years.

Table 2 - Values used to describe environmental variation in demographic rates for harbour porpoises in North-eastern Atlantic waters, taken from Table A2.1 of Harwood et al. (2014). Each value represents the lower 99% confidence limit for the rate, expressed as a percentage of the mean.

Species	Pup/calf survival	Juvenile survival	Adult fecundity
Harbour Porpoise	25%	30%	25%

2.2.7 Model outputs relating to favourable conservation status

Under the European Community Directive on the Conservation of Natural Habitats and of Wild Fauna and Flora (generally known as the Habitats Directive), Member States are allowed to issue a licence to disturb protected species, provided this will not have a negative effect on their 'favourable conservation status'. Favourable conservation status is not precisely defined, but Evans & Arvela (2012) advise that a population annual decline of **more than 1% on average over a 12 year period** represents unfavourable conservation status. We therefore provide a suite of model outputs that are relevant to this metric. For this report we have focused on presenting the additional risk of decline that the activity imposes on the population. This is important because some undisturbed populations decline by 1% or more simply as a result of environmental stochasticity. We therefore also calculated the probability of at least a 1% decline for the undisturbed, simulated populations. The additional risk of an annual decline of at least 1% as a result of construction work is therefore the difference between the probability calculated for the disturbed populations and that calculated for the undisturbed populations.

3 Methods

Here we describe how the iPCoD model was used to explore and assess the potential aggregate effects of planned windfarm construction over a 12 year period in English waters of the southern North Sea (NS) on the on the NS harbour porpoise population. The results of the SCANS III studies have recently been released (following the analyses presented here)(Hammond et al 2017) – indicating a stable population estimates across the 1994, 2005 and 2016 surveys. We assumed that these developments would affect the North Sea Management Unit (MU), as defined by the UK Inter-Agency Marine Mammal Working Group (IAMMWG, 2015). The boundaries of this MU are shown in Figure 6. IAMMWG (2015) estimated that there are 227,298 animals in this MU, based on results from the SCANS II surveys (Hammond et al., 2013). The report states: "MUs provide an indication of the spatial scales at which impacts of plans and projects alone, cumulatively and in-combination, need to be assessed for the key cetacean species in UK waters, with consistency across the UK".

Even though we are considering only English sites here, given the uncertainty over the ranging/movement patterns of porpoises in the North Sea, the entire NS management unit was considered the most biologically meaningful unit for an assessment of potential aggregate impacts. It is important to note, however, that there are other potential noise-generating activities occurring both in and outside English waters that have not been considered here. For example, this study is limited to pile-driving activities for the English wind farms below. It does not consider noise from other wind farms being constructed in the North Sea during the study period and does not explore other noise sources such as shipping, geophysical and/or seismic surveys that are likely occur over the North Sea region within the time period of the study.

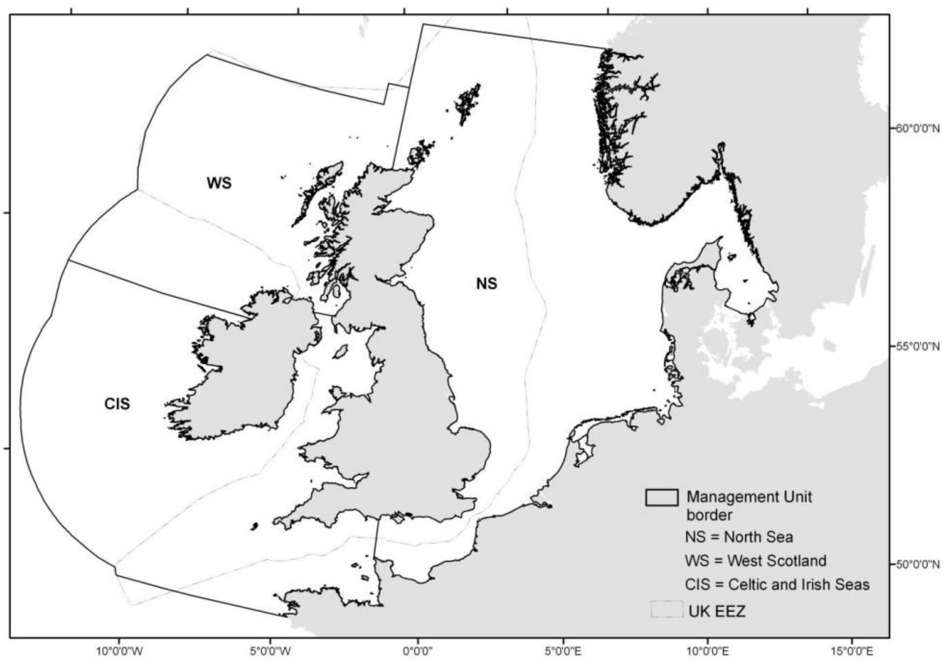

Figure 6 - Boundaries of the North Sea (NS) harbour porpoise Management Unit, as defined by IAMMWG (2015)

The sites (shown in Figure 7) that we considered in the aggregate impact scenarios were:

- Dogger Teesside A and B
- Dogger Creyke Beck A and B
- Hornsea 1 and 2
- East Anglia 1, 3 and 4
- Triton Knoll
- Race Bank
- Dudgeon
- Galloper

In order to assess the potential for impacts using iPCoD, we required information on the following:

- A schedule of piling activity for each wind farm site and
- An estimate of the number of porpoises disturbed on each day of pile-driving.

3.1 Piling schedule data

As noted above, a number of parameters must be specified in order to run the iPCoD framework. In order to collate these parameters, we conducted a literature search primarily focused on documents produced during the consent application process, such as Environmental Statements (ESs). We reached out to the developers of the sites above to request the most up-to-date information to be used in the simulations. Data that were provided in sufficient time were incorporated into the model simulations. For sites where key inputs were missing, we relied on publically available information. Because for most wind farm sites, schedules of when piling will occur (i.e. an actual piling schedule) are not publically available and in many cases have not yet been determined by the developer, it was necessary to extrapolate information on the number and type of foundations for each site using information from other sites. We assumed that it takes a single day to install either a monopile (single pile) or a jacket foundation (e.g. with 4 pin-piles). We also assumed a worst case scenario in which every wind farm foundation was installed via pile-driving (i.e. no suction bucket or gravity base foundations were used).

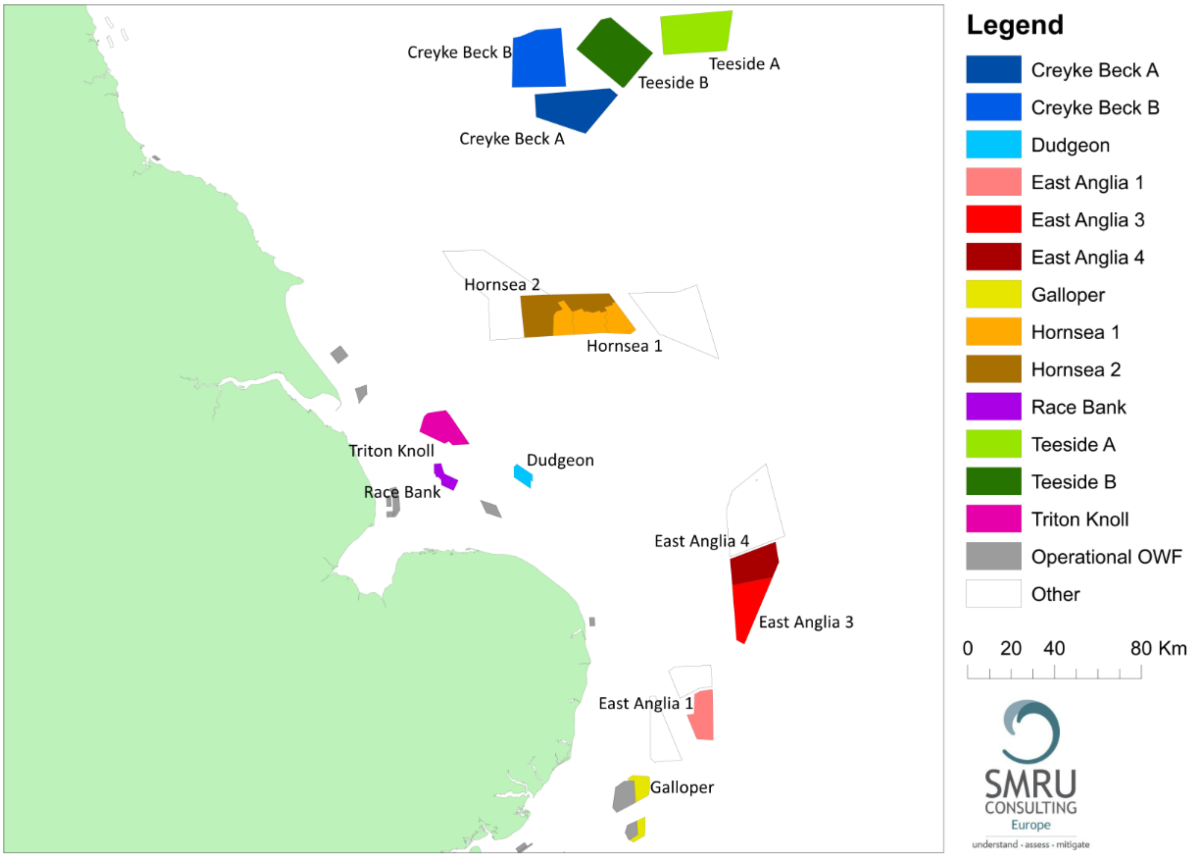

Figure 7 - The east of England with the existing and planned offshore wind development. (Note: Not all sites shown here were considered in the assessment)(Source: www.4coffshore.com).

We constructed a piling schedule for all sites, allowing for concurrent construction if developers specified this was an option for their site. We did not limit the number of piling operations that could occur simultaneously in the English waters of the North Sea. This was explored as a potential option, but limiting the number of vessels available to install turbines had little or no effect on the temporal sequence of the proposed piling. Predicted piling schedule data were generously provided by Mainstream RP and RPS for the Hornsea 2 development. The predicted schedule took into account factors such as weather windows, transit times, trips to and from port and the actual piling operations themselves. The pattern of those data were generalised and used to predict piling schedules for sites where detailed information on potential piling schedules was unavailable. Each piling schedule was created using the specific numbers of foundations temporally-scaled to the Hornsea 2 schedule (i.e. to match the proposed periodicity and spread of piling days as in the Hornsea 2 piling schedule) and site-specific construction start and completion dates (provided by developers or stated in licensing documents).

In an earlier stage of the project we made a preliminary assessment of the potential aggregate effects of offshore wind farm construction on harbour porpoises. This was conducted over a short timeframe and relied heavily on publically available information (such as ESs and other licensing application documents). Because the intention was to explore the maximum predicted aggregate effect, worst case estimates were chosen for the number of installed piles, time frame for construction and the number of concurrent operations. Following this initial assessment (presented in section 3), the project team decided to consult closely with developers to obtain the most realistic estimates of both the number and timing of proposed piling activities. Therefore an updated piling schedule was constructed to be used in the assessment presented herein (section 4). The piling schedule from the phase I of iPCoD simulations used here is shown below (Figure 8A) and the piling schedule using the latest and best information obtained directly from developers (October 2015) is presented in Figure 8B (used in phase II and III). The differences between the inputs are discussed in section 3.5. The updated information resulted in a refined estimate of total days of piling required to install all of the wind farms. This was driven by many of the wind farms being further along in the development process since the production of the ES, resulting in more refined estimates and updated plans being available. Phase I, II and III parameters are compared in section 3.5. It should also be noted that in this assessment, we have assumed that all of the planned offshore wind farm developments that are currently proposed will be built. These, and other assumptions – and their potential impact on predictions – are discussed further below in section 5.

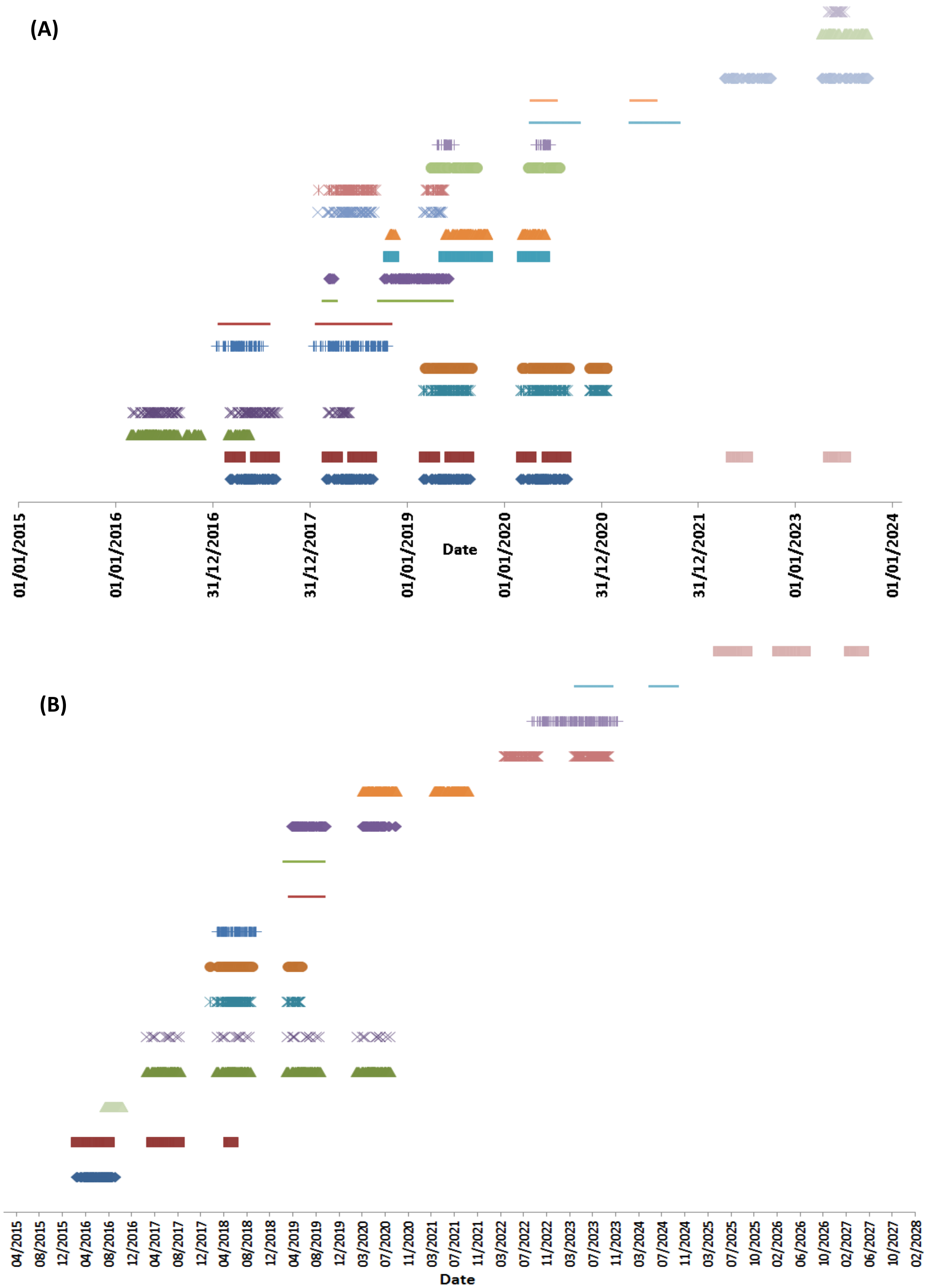

Figure 8 - Piling schedule developed and used in phase I iPCoD assessment simulation (A) and phase II and III runs following consultation with developers (B) for harbour porpoises and east of England wind farm developments. Each mark indicates a day with piling for one of the operations (some sites have multiple,

concurrent operations on the same day). Each row indicates a different wind farm operation but colours and symbols between A and B do not correspond.

3.2 Estimates of disturbance

As with the piling schedule information, an initial assessment was made by using the worst case estimates of disturbance which are presented in the ES of the relevant development. If no site-specific EIA has been carried out yet (as is the case for some of the future wind farms), the noise footprint and density estimate for the nearest planned wind farm (within the same Round 3 zone) was used for this wind farm.

For the analyses presented here, the intention was for iPCoD to be run with the most realistic scenarios of pile driving schedules across the developments considered and the best possible estimates of disturbance To achieve this a review was conducted of the approaches undertaken in deriving porpoise density and predicting impact footprints in the licensing documents. Some ESs had used SCANS II (Hammond et al 2013) as the density source, whilst other ESs used results from dedicated marine mammal surveys in the site vicinity, but had undertaken insufficient suitable survey effort and/or had not corrected the data for variations in effort. For the majority of cases therefore we used local density estimates derived from the most recent analysis of the Joint Cetacean Protocol (JCP) data (Paxton et al. 2016), because these provide a finer resolution of variations in porpoise density across the southern North Sea than those from SCANS II. The review identified that the Hornsea zone and Dogger Bank zone wind farms had calculated site specific porpoise density using robust approaches. We therefore used their values instead of those from the JCP, because they provided a finer level of resolution. A set of scenarios were constructed using estimates of disturbance based on combined ES and JCP data (henceforth described as 'combined' estimates) and using JCP derived density estimates alone (henceforth: 'JCP only').

As part of the review, we also collected data on the mean and suggested maximum impact ranges for harbour porpoises from ES impacts of noise assessment chapters – for the worst case, this consisted of the largest hammer blow energies presented in the ES documents (although it should also be noted that some developers have also since requested to increase the maximum hammer energy from that in their ES). Developers typically presented a mean and maximum value for the impact range (potentially due to differences in propagation at different locations). It should be noted that a number of different noise impact assessment approaches (i.e. different noise propagation models, disturbance thresholds, and behavioural response conditions) were used in individual ESs. It was out with the scope of this project to standardise these values and these different approaches may impact the outputs of the iPCoD framework. For each wind farm, estimates of the total number of porpoise disturbed were calculated by multiplying local density estimates (i.e. either from ES or JCP sources) by the areas equivalent to the mean and maximum impact range given in the development ES.

3.2.1 Dose-response functions

The worst case assessments of impact typically consider that all animals within the impact range were equally likely to be disturbed. In reality, it is expected that as the received level of sound decreases with increasing range from the source, animals are less likely to be disturbed. Therefore in this analysis we explored the use of dose-response functions to refine estimates of porpoises disturbed during each piling event. We used two dose-response functions; the first, a sigmoidal curve developed by Thompson et al. (2013) using the results of the Brandt et al. (2011) study (henceforth 'Thompson') (Figure 9) and a second, a linear relationship presented by MEG (2015) using the results from Dähne et al. (2013) (henceforth 'MEG')(Figure 10). These dose-response functions were used to reflect the diminishing effects of disturbance, as range from the source (i.e. piling location) increases, with probability of a response/occurrence dropping to 0 at 30km and 45km respectively. We conducted two sets of analyses using the different functions.

For each site, we scaled the dose-response function by the mean and maximum disturbance ranges presented in the development ES documents while maintaining its shape. Therefore the estimates of disturbance used as inputs in the iPCoD simulations were based on the mean and maximum impact ranges, on the 'combined' and 'JCP only' density estimates adjusted using dose-response functions (Table 3). Analyses in this study were phased and consequently, the mean and maximum estimates for both the combined and JCP only density estimates were adjusted using the Thompsonfunction. However, a later analysis was conducted on only the 'mean' impact ranges and the 'combined' density estimate adjusted with the MEG (2015) dose-response function (it was not possible to re-run every scenario in later analyses and therefore a subset what selected by the project team in discussions with NE and JNCC).

In order to adjust the density estimates using the dose-response functions, the following methodology was applied. Each dose-response function was broken down into a series of points along the 'Best' function from Thompson et al (2013) and the 'Model' dose-response function from MEG (2015). Because the data used to generate the dose-response functions were for different wind farms with different construction programs (e.g. different pile diameters and hammer energies used to install the piles), we have scaled the dose response function (preserving its shape) to the largest impact range for each wind farm (resulting in a slightly different dose-response function for each wind farm). The impact zone for each site was then divided into a series of concentric rings out from the source (the centre) to the maximum, each with a 'decreasing probability of occurrence' (from Thompson et al., 2013) or 'proportion displaced' (MEG, 2015). The number of animals in each concentric ring was calculated and multiplied by the probability/proportion to derive the number of animals 'disturbed' in that ring and then summed across rings.

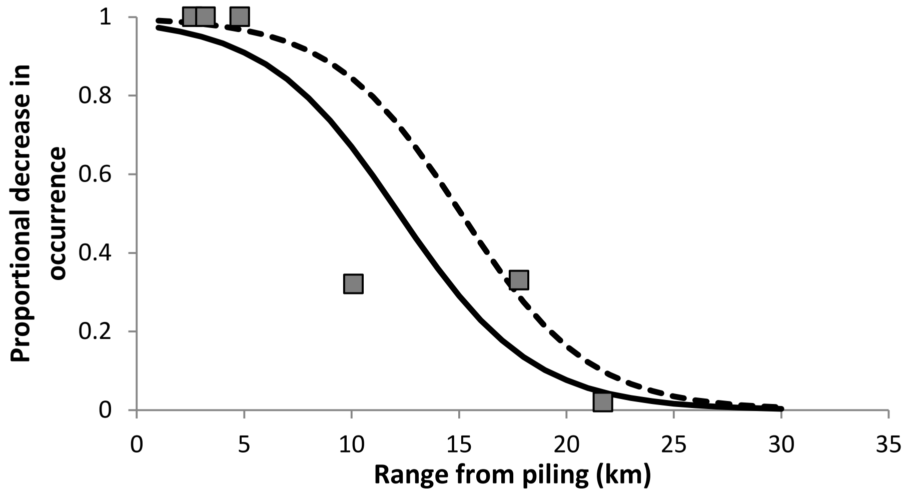

Figure 9 - Results from Brandt, et al 2011 converted into a Dose-Response curve by Thompson et al. 2013. The black line represents the model 'Best fit' as presented in the paper (i.e. the line of best through the data points) and this was used in this study.

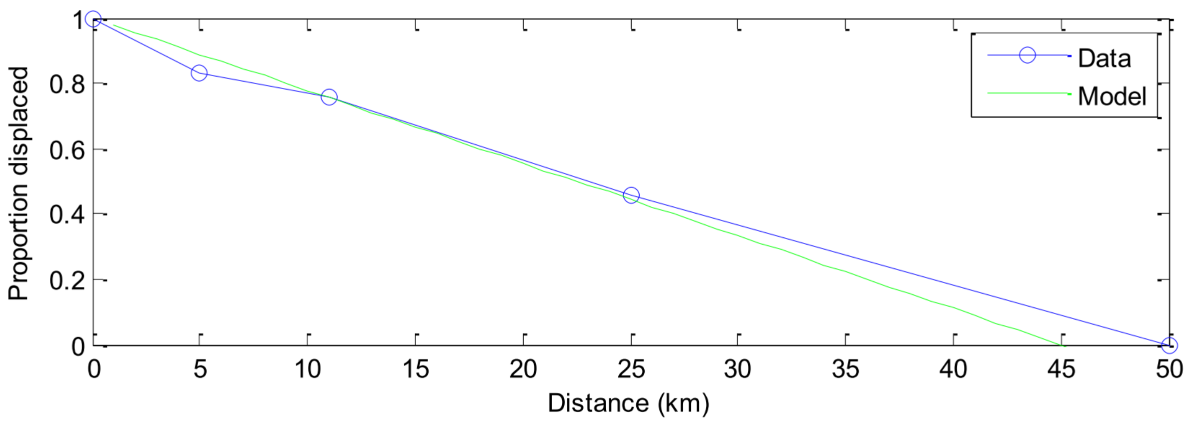

Figure 10- Results from Dahne et al. (2013) converted into a dose-response function by MEG (2015). The blue line represents a line drawn through each data point, the green line indicates a model line of best fit and was used in this study.

Table 3 – Estimates of animals disturbed from one day of piling used in iPCoD assessment scenarios. The estimates of disturbance used as inputs in the iPCoD simulations for the mean and maximum (italicised) impact ranges and the 'combined' (i.e. JCP & suitable ES) and 'JCP only' density estimates. Those calculated using the Thompson et al (2013) dose-response function are shown in a white shading and those using the MEG dose-response function in blue shading. * - indicates no values was available and so scaled using ratio of mean-max from other sites with both measurements available.

	Impact Range		Estimates of Disturbance				
Source	**(km)**		**Thompson DR**				**MEG DR**
			Combined		***JCP only***		***Combined***
Site	***mean***	***max***	***mean***	***max***	***mean***	***max***	***mean***
Hornsea 2	45.5	62	1961	*3641*	3835	*7121*	2903
Dudgeon	33.9	39	1386	*1834*	same		2052
Race Bank	29.6	35.2	593	*839*	same		879
Triton Knoll	34	38.9	1401	*1834*	same		2075
East Anglia 1	26.5	29.5	958	*1187*	same		1418
East Anglia 3	49.5	62	3233	*5071*	same		4787
East Anglia 4	48.5	61	3069	*4855*	same		4545
Hornsea 1	37.7	46.6	1201	*1834*	2860	*4370*	1778
Dogger Creyke A	24	28.5	719	*719*	650	*917*	1065
Dogger Creyke B	42	56	771	*771*	1426	*2536*	1142
Dogger Teesside A	27.5	33	939	*939*	562	*809*	1390
Dogger Teesside B	27.75	33.5	864	*864*	666	*971*	1279
Galloper	40.3*	49	1388	*2050*	same		2055
Subtotals			**18,482**	***26,439***	**22,029**	***34,396***	**27,369**

3.3 Residual days of disturbance

As noted previously, the iPCoD framework has the facility to specify the number of 'residual' days of disturbance experienced by disturbed animals (section 2.2.4). In order to develop the most realistic simulations, we reviewed the available studies of disturbance that contained information that could be used to inform the choice of this value. Each of these is described briefly below.

3.3.1 Brandt et al., 2011

The authors used TPODs to monitor the occurrence of harbour porpoise around the Horns Rev wind farm construction in Denmark using 3.9 m diameter monopiles (using a maximum hammer energy of ~900 kJ). They concluded: "Porpoise acoustic activity was reduced by 100% during 1 h after pile driving and stayed below normal levels for 24 to 72 h at a distance of 2.6 km from the construction site. This period gradually decreased with increasing distance. A negative effect was detectable out to a mean distance of 17.8 km. At 22 km it was no longer apparent, instead, porpoise activity temporarily increased. Out to a distance of 4.7 km, the recovery time was longer than most pauses between pile driving events." (Table 4). It is important to note that the pile diameter and hammer energy used at the Horns Rev wind farm are much smaller/lower than those being considered with English North Sea wind farms.

Table 4 - Table of 'recovery times' from Brandt et al 2011 at different ranges from the source. PPM/h is porpoise positive minutes per hour.

POD Station	Mean distance (km)	Duration of pile driving effect on PPM/h (h)
1	2.5	24-72
2	3.2	18-40
3	4.8	17-42
4	10.1	9-21
5	17.8	10-23
6	21.2	0

3.3.2 Dähne et al., 2013

Dähne et al. (2013) used CPOD data to the response of porpoise at the Alpha Ventus wind farm in the German North Sea where 2.6 m diameter piles were vibrated into position and then piled using 500 kJ hammer energy. They found that the first waiting time for porpoise clicks (a measure of how long porpoises are displaced during or after a piling event) increased by 9.9 hr during piling. This suggests that some harbour porpoises may return to an area within 24 hrs of the disturbance. However, again it is important to consider the small pile diameter and the relatively low hammer blow energy used at the site. Nevertheless, we have included a capability to model the effects of disturbance that lasts for *less* than one day in the version of the iPCoD framework used in this report.

3.3.3 Other studies considered

Tielmann & Carstensen (2012) looked at seasonal patterns in the occurrence of porpoises and difference in periods of silence (waiting time) in an impact area and a reference zone away from a windfarm). They found that periods of 10 mins or more with no porpoise clicks occurred significantly more frequently at the impact site, suggesting animals were either absent from, or present but not vocalising in, the impact site during construction. Unfortunately, this study does not provide information to parameterise the persistence of disturbance within the iPCoD model. Tougaard et al. (2012) exposed porpoise to piling noise (received level ~140dB re 1 µPa at 200 m from the speaker) and suggested that animals are more likely to vacate the impact area rather than remain there and cease vocalisations.

3.3.4 Modelling residual disturbance in this study

The persistence of the effects of disturbance are poorly understood with only a small number of passive acoustic monitoring (PAM) studies trying to explore this subject. Given the range of pile diameters and proposed hammer blow energies to be used at many of the sites in this assessment, it was deemed appropriate to explore a range of residual disturbance scenarios. Firstly, we considered a scenario in which animals that are disturbed within 10% of the total impact range of a piling operation were assumed to experience 2 days of residual disturbance (i.e. a total of 3 days of disturbance), whereas animals further away from the source (11-100% of the total impact range) were assumed to experience 1 day of residual disturbance (i.e. a total of 2 days of disturbance). We also explored a scenario where animals in the inner 10% of the impact range experienced a total of 3 days disturbance with the remainder receiving only 1 day (i.e. no residual disturbance beyond the day of disturbance). Furthermore we explored the inner 10% experiencing 3 days and the remainder receiving 2 days. We also explored a scenario where animals in the inner 25% of the impact range experienced a total of 2 days disturbance (the average upper range for the inner 25% of range) with the remainder experiencing a single day of disturbance (the lower range). Not all scenarios (datasets, and vulnerable groupings (see section 3.4)) were run for each set of parameters. These are outlined in Table 5 below.

3.4 Vulnerable groupings

We considered two scenarios with respect to the vulnerable grouping (see "Glossary") of animals in simulations – to explore population two possible bounds of how the harbour porpoise MU we have considered might be affected by disturbance. The first scenario assumed all animals within the North Sea MU are equally vulnerable to the disturbance resulting from the installation of wind farms in the Southern North Sea. This would be akin to a population that is widely ranging with high local turnover of individuals (i.e. none or a very small level of site fidelity). Under this scenario would typically result in a large number of animals each being exposed to a relatively small amount of disturbance. A second scenario was developed to explore the sensitivity of iPCoD simulations to this parameter. We assumed an alternative scenario in which there was a vulnerable grouping in the Southern North Sea based on the estimated number of animals in Block B and U of the SCANS II survey (Figure 10). These are equivalent to 39% and 12% (51% in total) of the total size of the MU population respectively. In this scenario only the animals in this group could be exposed to disturbance (and all animals outside this grouping are undisturbed for the duration of the simulation). This results in a smaller number of animals being exposed to a relatively larger amount of disturbance. This would be akin to a population whose individuals may show a higher degree of site fidelity.

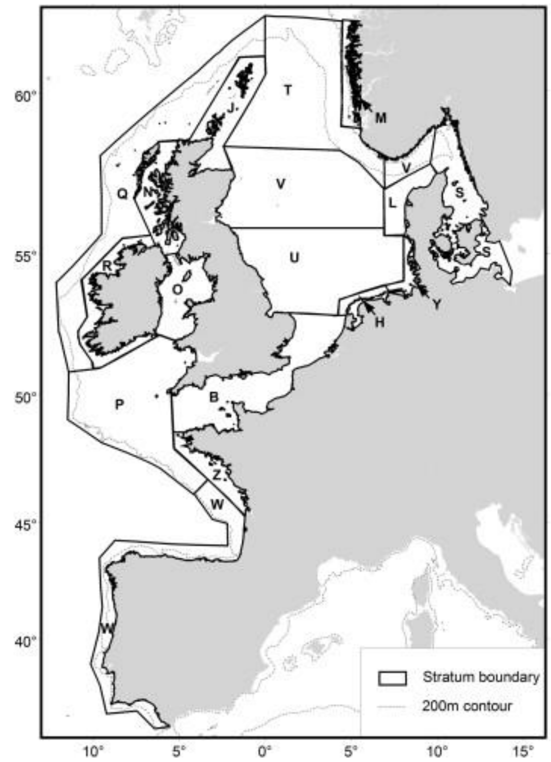

Figure 11 - Surveys blocks from SCANS II surveys.

3.5 Summary of differences between phases of assessment

The engagement and consultation with offshore wind site developers resulted in a more realistic set of input parameters for the iPCoD simulations. The key differences between phase I (based on a literature search) and phases II and III (information collated via consultation with developers and use of the dose-response curve) are summarized in Table 6. The consultation resulted in the most up-to-date and realistic estimates of the number of days of piling required. The phase I simulations used a total of 2,429 days of piling required across 22 operations and a 10 year construction period. The phase II and III simulations used a total of 1,827 days of piling across 16 operations (for a number of sites developers confirmed the option for concurrent piling from multiple installation vessels was removed from their plans) and a 12 year construction period.

Table 5 - Breakdown of key differences in piling operations between Phase I and Phase II simulations.

Phase	Total Piling Days	Operations	Years of Construction	Number of animals disturbed
Phase I	2,429	22	10	17,034 – 90,431
Phase II and III	1,827	16	12	19,761 – 34,396

The use of the dose-response curve, and the JCP and ES estimates of porpoise density resulted in a reduction in the estimates of the numbers of animals disturbed by each day of piling. The estimate of the total number of porpoises disturbed used in the phase I simulations was 17,031 – 90,431. This was reduced to 19,761 – 34,396 animals in the phase II and III simulations. A summary of all the scenarios is presented below (Table 7).

Table 7 - Overview of the variations among phase II and III iPCoD assessment scenarios considered in this study.

Density estimate sources	Dose response function	Total days of disturbance	Vulnerable Groupings?	Phase
JCP only –maximum impact ranges	Thompson et al 2013	3 days (inner 10%) and 1 (remainder)	All vulnerable & 1 VG (SCANS B & U)	II
JCP only – mean impact ranges	Thompson et al 2013	3 days (inner 10%) and 1 (remainder)	All vulnerable & 1 VG (SCANS B & U)	II
Combined – maximum impact ranges	Thompson et al 2013	3 days (inner 10%) and 1 (remainder)	All vulnerable & 1 VG (SCANS B & U)	II
Combined – mean impact ranges	Thompson et al 2013	3 days (inner 10%) and 1 (remainder)	All vulnerable & 1 VG (SCANS B & U)	II
Combined – mean impact ranges	Thompson et al 2013	3 days (inner 10%) and 2 (remainder)	All vulnerable & 1 VG (SCANS B & U)	III
Combined – mean impact ranges	MEG 2015	3 days (inner 10%) and 2 (remainder)	All vulnerable & 1 VG (SCANS B & U)	III
Combined – mean impact ranges	Thompson et al 2013	2 days (inner 25%) and 1 (remainder)	All vulnerable	III
Combined – mean impact ranges	MEG 2015	2 days (inner 25%) and 1 (remainder)	All vulnerable	III

4 Results

For this report we have focused on presenting the additional risk of decline that the construction activity may impose on the population. This is important because some undisturbed model populations were forecast to decline by 1% or more, simply as a result of environmental stochasticity (i.e. in the absence of any disturbance). We therefore calculated the probability of at least a 1% decline for the undisturbed, simulated populations. The "additional risk" of an annual decline of at least 1% as a result of construction work is therefore the difference between the probability calculated for the disturbed populations and that calculated for the undisturbed populations.

We present information on the probability of a greater than 1% annual decline (which we refer to as "additional risk" or "risk") 6, 12, 18 and 24 years after the start of construction work. As there are 12 years of proposed construction in the simulations, these first two values indicate the risk during construction to the population, in this case equivalent to the North Sea management unit. The second two values indicate the risk to the management unit following the end of proposed construction under the scenarios modelled.

Phase I scenarios were run using only the worst-case assessments of disturbance from the Environmental Statements and with no dose-response adjusted estimates – therefore it was assumed that all animals out to the maximum impact range were disturbed. We also used the phase I assessments of the number of foundations and piling plans. Using these worst-case estimates, the additional risk of >1% annual decline 12 years after construction started were between 1 in 5 and 1 in 8 (i.e. if such realities played out between 5 and 8 times, then in one of those instances there would be an annual decline of >1%). Follow that phase I assessment developers were contacted and more realistic scenarios were generated. These results are explored below and full results are presented in Table 7).

4.1 All animals vulnerable to disturbance

In scenarios using the Thompson DR function and assuming a 3 /1 (10% / 90%)(see Table 8 caption) the additional risk of an annual decline of >1%/yr at the end of construction was predicted to be highest (0.030, i.e. an annual decline >1% occurred in approximately 1 in 33 scenarios) when the maximum impact ranges and JCP only density estimates were used (Table 8). This decreased to 0.025 (1 in 40 scenarios) six years after the end of construction, and to 0.024 (1 in 42) 12 years after the end of construction (i.e. year 18 and 24 respectively). When the 'combined' JCP and ES estimates and mean impact ranges were used, the risk was reduced to 0.005 (i.e. an annual decline >1% occurred in 1 in 200 scenarios) at the end of construction and 0.003 (1 in 333) 12 years after the end of construction (i.e. year 24). With the combined mean estimates, when the day of disturbance was increased to 3 & 2 (10%/90%) the risk of a 1% annual decline at the end of construction was 0.019 (1 in ~50, decreasing to 0.01 (1 in 100), 12 years after the end of construction. When the days of disturbance was amended to 2 & 1 (25% / 75%), the corresponding additional risk was 0.003 (1 in ~333) at the end of construction. The same scenarios as above were modelled using the MEG dose-response function and the additional risks were 0.028 (3 & 2)(1 in 35) and 0.006 (2 & 1)(1 in ~166) at the end of construction.

4.2 One vulnerable grouping (SCANS B & U blocks)

In this scenario, we assumed that only 51% of the North Sea MU (i.e. equivalent to animals in SCANS II Blocks B and U) are likely to be exposed to disturbance from the modelled construction operations. This results in higher predicted additional risk of annual declines of > 1% (Table 8). This was as expected given that each animal will receive more days of disturbance as there are less animals in the vulnerable grouping compared to the entire MU grouping. The highest risk (0.061 - an annual decline >1% occurred in approximately 1 in 16 scenarios) was predicted to occur at the end of construction (year 12) when the maximum impact ranges and JCP only density estimates were used. This risk decreased to 0.048 (1 in 21) six years later and to 0.052 (1 in 19) 12 years after the end of the modelled construction. When the ‘combined’ (JCP and ES) estimates and mean impact ranges were used, the risk was 0.007 (i.e. an annual decline >1% occurred in 1 in 143 scenarios) at the end of construction and 0.005 (1 in 200) 12 years after the end of construction (i.e. year 24). With the combined mean estimates, when the day of disturbance was increased to 3 & 2 (10%/90%) the risk of a 1% annual decline at the end of construction was 0.043 (1 in ~23, decreasing to 0.029 (1 in 34), 12 years after the end of construction. The same scenarios as above were modelled using the MEG dose-response function and the additional risks were 0.058 (3 & 2)(1 in ~17) at the end of construction. As expected, in all scenarios run in this project, the risk of annual declines of greater than 2% or 5% were both lower than for the risk of a 1% annual decline across all the different scenarios.

Table 8 - Forecast effects of construction at windfarm sites in the English North Sea under a range of scenarios. The results are split into a series of column groupings indicating the parameters used in each scenario. The first is whether all animals in the North Sea were considered vulnerable (as advised in IAMMWG, 2015)(section 3.4) or whether only a sub-grouping of animals were vulnerable to disturbance (here - animals in SCANS II block B & U are vulnerable to disturbance – and no other animals in the population are disturbed). Scenarios were sub-setted by the density estimates (JCP or combined) and whether the mean or maximum impact range was used in the calculation of the number of animals disturbed (section 3.2). Scenarios run using different dose-response functions (section 3.2.1) are shown as either Thompson (for the function from Thompson et al (2013))(plain text) or MEG (from the Marine Expert Group (2015))(*italicized*). Different values were used to explore the effects on the population of different levels of the persistence of disturbance on individuals (section 3.3.4). In particular, for each scenario under 'Days Disturbance' the first value shows the number of days of disturbance experienced by animals close to the pile-driving (see % impact range vs DD) and the second value indicates the number of days of disturbance experienced by the remainder of exposed animals. The '% impact range vs. DD' indicates what proportion (expressed as a percentage) of animals receive the higher level of disturbance vs the remainder. For example a '3 / 1' and '10/90' respectively indicates that in this scenario animals in the inner 10% of the impact zone received 3 days of disturbance and the remaining 90% receive a single day of disturbance.

The values in each column indicate the probability of an annual population decline of 1% or greater 6, 12, 18 and 24 years after the start of construction. This can be interpreted as odds by dividing 1 by the probability. For example, a value of 0.04 corresponds to odds of 1 in 25 risk of a 1% annual decline. Shading indicates whether construction is ongoing at this stage of assessment.

Vulnerable Grouping	All vulnerable								1 vulnerable grouping (51% of MU)					
Density estimates used	JCP Max	JCP Mean	Comb. Max	Comb.Mean					JCP Max	JCP Mean	Comb. Max	Comb.Mean		
Dose response function	Thompson	Thompson	Thompson	Thompson	Thompson	Thompson	*MEG*	*MEG*	Thompson	Thompson	Thompson	Thompson	Thompson	*MEG*
Days Disturbance (DD)	3 / 1	3 / 1	3 / 1	3 / 1	3 / 2	2 / 1	*3 / 2*	*2 / 1*	3 / 1	3 / 1	3 / 1	3 / 1	3 / 2	*3 / 2*
% impact range vs. DD	10/90	10/90	10/90	10/90	10/90	25/75	*10/90*	*25/75*	10/90	10/90	10/90	10/90	10/90	*10/90*
Year 6	0.040	0.010	0.009	0.003	0.025	0.004	*0.034*	*0.011*	0.081	0.031	0.021	0.008	0.045	*0.062*
Year 12	0.030	0.004	0.008	0.005	0.019	0.003	*0.028*	*0.006*	0.061	0.032	0.025	0.007	0.043	*0.058*
Year 18	0.025	0.005	0.005	0.003	0.019	0.004	*0.025*	*0.001*	0.048	0.013	0.013	0.003	0.041	*0.054*
Year 24	0.024	0.003	0.007	0.003	0.010	0.003	*0.025*	*0.005*	0.052	0.016	0.014	0.005	0.029	*0.040*

5 Discussion

This iPCoD assessment has used the most-up to date and realistic scenarios of piling schedules for offshore wind farms off the east of England and estimated the additional risk that the proposed developments might pose upon the harbour porpoise North Sea management unit. By liaising with developers to get the most realistic predictions of the temporal and spatial scale of planned development and by utilising the latest information sources (e.g. the Joint Cetacean Protocol and estimated dose response functions), the assessment provides a range of potential outcomes. The results of the simulations conducted here indicate that the risk to the North Sea harbour porpoise management unit of a 1% or greater annual decline over the 12 year simulated construction period is likely to be low, but defining the precise level of risk is heavily dependent on a range of specified parameters. At the end of the construction period the additional risks of a 1% annual decline as a consequence of the planned construction were between 1 in 16 and 1 in 333. Variations in risk are not driven by different expert opinion (as these are sampled across via 1000s of simulations in each scenario), but instead by controlled factors in different scenarios. These factors include the longevity of disturbance effects (residual days of disturbance), porpoise density, the size of impact range (mean estimates va maximum estimates) and dose response functions (i.e. what proportion of animals respond within the impact zone).

It is important to consider that these simulations are only indicative of what is forecast in relation to under the scenarios we have developed. We urge caution in interpretation of the results herein and in interpolation/extrapolation of how factors not considered here impact forecasts of population decline risk. These are outlined below.

Crucially, as noted above, these forecasts from the iPCoD model are sensitive to a number of assumptions about harbour porpoise behaviour – particularly how the effects of pile-driving vary with range from the source (i.e. different dose response curves), and on the persistence of these disturbance effects on individuals – for example, the literature reviewed above and used in iPCoD scenarios here measured porpoise responses on isolated wind farms using smaller diameter piles and significantly lower hammer energies than is being proposed in the English North Sea. It is unclear how these porpoises respond to larger pile diameters and hammer energies. Another key parameter was the number of animals vulnerable to disturbance from the planned windfarms, i.e. whether all porpoises in the North Sea are equally vulnerable or not. Whilst this species is wide-ranging and individuals may display large scale movements, there is also evidence that individuals might undertake small scale movements for several weeks in a given area, possibly due to the quality of the habitat (Nabe-Nielsen, et al 2013) before travelling long distances (e.g. Teilmann et al 2004). This could potentially expose individuals multiple times to disturbance from the planned construction. The English North Sea wind farm sites are largely located within or in the vicinity of the Southern North Sea candidate Special Area of Conservation for harbour porpoise. This area was designated based on persistent, higher densities of porpoises than elsewhere in the UK North Sea[1]. **More empirical data is needed on the way in which individual harbour porpoises respond to piling**

[1] http://jncc.defra.gov.uk/pdf/SouthernNorthSeaSelectionAssessmentDocument.pdf

noise in the open sea, as well as on their movement patterns and ranges in the North Sea. Other studies have further explored the behaviour of porpoises around wind farm construction. For example, Heinis et al (2015) developed a cumulative (referred to here as aggregate) impact assessment assuming that windfarm indicative capacity (in GW) was representative of piling days. After the scenarios had been run this study, Brandt et al (2016) analysed the effect of construction of eight wind farms in the German North Sea on harbour porpoises, using PAM and aerial survey data. Further exploration of the data and analyses presented there may deliver new dose response functions for porpoise response to range of pile diameters (and blow energies). In addition to the points above, further work is required in order to apportion the uncertainty in forecasts to different sources - i.e. to identify improvements to the iPCoD model and associated input parameters – to aid aggregate assessments.

5.1 Limitations and Uncertainty

5.1.1 iPCoD framework

There are a number of sources of uncertainty and limitations in this assessment – some of which are noted above. Some of the limitations and uncertainties are incorporated into the iPCoD model and are detailed in Harwood, et al. (2014) and King et al (2015), the most important of which are noted below.

As noted in section 2.2.5, the population dynamics model that underpins the iPCoD framework does not include any density dependence. As a result, simulated populations that are predicted to decline in size as a result of the effects of disturbance do not recover once the source of disturbance is removed. Instead, they are forecast to remain at this reduced population size, with numbers fluctuating from year to year as a result of variations in environmental conditions. This is almost certainly unrealistic: one would expect some recovery because more resources will be available for each of the surviving animals, provided there is no change in any of the other threats to the population. However, it is not practicable, given the current state of knowledge about the North Sea harbour porpoise population, to provide any reliable guidance on the rate at which the population might recover from a reduction in size. Because density dependence is not included in the model (which would improve the chances the population would recover), in this respect the forecasts in this assessment can be considered conservative.

It is also important to stress that the forecasts made using the iPCoD framework rely on the opinions of experts about the potential effects of disturbance on harbour porpoise survival and reproduction. Although the elicitation process that was used to canvas these opinions in 2013 was designed to reduce potential biases and to provide a realistic measure of among- and within-expert uncertainty, these forecasts should be interpreted with caution until empirical data are available. It is unclear at this stage whether the assessments of experts in the expert elicitation are conservative or not and this can only be addressed by the robust collection of empirical data on the effects of disturbance on the vital rates of harbour porpoises.

5.1.2 Input data for models

Other elements which are independent of the iPCoD model but are equally important as they to drive the forecasts are the input data specified by the user. Here we have made assumptions, attempting to provide the most realistic scenarios possible for running iPCoD model. Some of the assumptions cover the following areas:

- The total number of wind farms that will be built in the region over the next 10-12? years.
- The total number of foundations that will be piled at each (as opposed to suction bucket/gravity base foundations).
- The total number of foundations that will require the blow energies stated in the development ESs (which dictated the size of the impact zone)

It is also important to note, however, that there are other potential noise-generating activities occurring both in and outside English waters that have not been considered here. For example, this study is limited to pile-driving activities for the English wind farms below. It does not consider noise from the other several wind farms being constructed in the North Sea during the study period and does not explore other noise sources such as shipping, geophysical and/or seismic surveys that are likely occur over the North Sea region within the time period of the study. Whilst we do not have information on other noise sources, Heinis et al (2015) projected that there were a total of 47 wind farms constructed in the North Sea between 2016 and 2024 (though it should be noted a number of these projects have not been developed (e.g. Seagreen) or have minimal or no pile-drivng (e.g. Hywind). If this were accurate, then this aggregate impact study has explored the effect of ~28% of total construction planned in the region. If there is more disturbance, then it would be expected that risk of decline would increase (though we cannot say by how much and we cannot be sure what the relationship is), though Heinis et al 2015 explored this further.

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7.2.1 Dogger Teesside A and B

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