The Scottish Government
Riaghaltas na h-Alba

Scottish Marine and Freshwater Science

Volume 5 Number 2

A Protocol for Implementing the Interim Population Consequences of Disturbance (PCoD) Approach: Quantifying and Assessing the Effects of UK Offshore Renewable Energy Developments on Marine Mammal Populations

J Harwood, S King, R Schick, C Donovan and C Booth

marine scotland

Scottish Marine and Freshwater Science Vol 5 No 2

A Protocol for Implementing the Interim Population Consequences of Disturbance (PCoD) Approach: Quantifying and Assessing the Effects of UK Offshore Renewable Energy Developments on Marine Mammal Populations

J Harwood, S King, R Schick, C Donovan and C Booth

Published by Marine Scotland Science

ISSN: 2043-7722

Marine Scotland is the directorate of the Scottish Government responsible for the integrated management of Scotland's seas. Marine Scotland Science (formerly Fisheries Research Services) provides expert scientific and technical advice on marine and fisheries issues. *Scottish Marine and Freshwater Science* is a series of reports that publishes results of research and monitoring carried out by Marine Scotland Science. It also publishes the results of marine and freshwater scientific work that has been carried out for Marine Scotland under external commission including collaborative working with other statutory bodies.

These reports are not subject to formal external peer-review.

This report presents the results of marine and freshwater scientific work carried out under external commission for The Crown Estate and six other partners, including Marine Scotland.

Marine Scotland Science
Marine Laboratory
375 Victoria Road
Aberdeen
AB11 9DB

Copies of this report are available from the Marine Scotland website at
www.scotland.gov.uk/marinescotland

SMRU MARINE

understand · assess · mitigate

A Protocol for Implementing the Interim Population Consequences of Disturbance (PCoD) approach: Quantifying and Assessing the Effects of UK Offshore Renewable Energy Developments on Marine Mammal Populations

Foreword

Our understanding of the effects of underwater noise and other disturbing activities on marine mammals, and of how to assess and quantify potential impacts, is rapidly evolving. The Steering Group for the Interim PCoD work emphasise that this framework is very much an interim measure, that is, the Interim PCoD approach has been developed to help developers, regulators and advisers working on offshore renewable energy projects now. It is expected that the framework will be further refined and built upon over time as more evidence becomes available. The Interim PCoD approach should be regarded as another tool among others already available for assessing potential impacts of disturbance on marine mammal populations. How appropriate it will be for use with particular projects and situations should be decided on a case by case basis. **It is important that developers considering using the Interim PCoD approach seek advice from the SNCBs and/or regulators at an early stage.**

A PROTOCOL FOR IMPLEMENTING THE INTERIM POPULATION CONSEQUENCES OF DISTURBANCE (PCOD) APPROACH: QUANTIFYING AND ASSESSING THE EFFECTS OF UK OFFSHORE RENEWABLE ENERGY DEVELOPMENTS ON MARINE MAMMAL POPULATIONS

AUTHORS: JOHN HARWOOD, STEPHANIE KING, ROB SCHICK, CARL DONOVAN, CORMAC BOOTH.

DATE: 14TH NOVEMBER 2013

REPORT CODE: SMRUL-TCE-2013-014

THIS REPORT IS TO BE CITED AS: HARWOOD, J., KING, S., SCHICK, R., DONOVAN, C. & BOOTH, C. (2014) A PROTOCOL FOR IMPLEMENTING THE INTERIM POPULATION CONSEQUENCES OF DISTURBANCE (PCoD) APPROACH: QUANTIFYING AND ASSESSING THE EFFECTS OF UK OFFSHORE RENEWABLE ENERGY DEVELOPMENTS ON MARINE MAMMAL POPULATIONS. REPORT NUMBER SMRUL-TCE-2013-014. *SCOTTISH MARINE AND FRESHWATER SCIENCE*, **5**(2).

CONTENTS

EXECUTIVE SUMMARY

This report describes a protocol for implementing an interim version of the Population Consequences of Disturbance (PCoD) approach for assessing and quantifying the potential consequences for marine mammal populations of any disturbance and/or injury that may result from offshore energy developments. It has been designed to use the kinds of information that are likely to be provided by developers in their Environmental Statements and Habitats Regulations Assessments. **We emphasise the interim nature of this approach, which was developed to deal with the current situation, where there are limited data on the way in which changes in behaviour and hearing sensitivity may affect the ability of individual marine mammals to survive and to reproduce.** The research that is needed to improve our knowledge and understanding of these processes has been identified by Harwood & King (2012) and some of this work is currently underway. Results from this research, and any other relevant developments (such as reports from the Habitats and Birds Directives – Marine Evidence Group convened by Defra) should be incorporated into the approach as they become available.

The interim PCoD approach is a formal, mathematical version of the Population Consequences of Acoustic Disturbance (PCAD) conceptual model developed by the US National Research Council (2005). It uses the opinions of international experts, solicited through a formal elicitation process, to quantify the transfer functions that describe the relationships between the different compartments of the PCAD model (see Figures 1 and 2).

The assessments of the likely changes in abundance of any marine mammal population provided by this approach rely heavily on expert opinions and a number of strong assumptions. They should therefore be interpreted as illustrations of the consequences of those opinions, not as predictions of future population size. There is clearly a pressing need to collect more empirical data on the potential consequences of disturbance and hearing damage for marine mammal populations in order to refine and replace these opinion-based values. However, in the absence of those empirical data, the interim approach described here provides a rigorous, auditable and quantitative methodology, supported by the best available evidence, and can be used to inform the consenting and decision-making processes for offshore energy projects. In particular, it provides the only currently available tool for assessing the cumulative effects of a single development over the course of construction on a range of marine mammal populations, and for assessing the cumulative impacts of multiple developments that use different technologies.

We explain how this interim approach has been implemented and show how it could be used to examine the potential cumulative effects of the construction of two hypothetical wind farms and the operation of a hypothetical tidal energy array off the Aberdeenshire coast on relevant Management Units for five priority species: harbour

seal, grey seal, bottlenose dolphin, harbour porpoise and minke whale. We also examine the sensitivity of these potential effects to some of the assumptions used in the approach. **We stress that the results presented in these examples are purely illustrative and should not be interpreted in any way as providing predictions of the potential effects of any actual proposed offshore renewable energy development on marine mammal populations.**

Glossary of acronyms and terms used in the Interim PCOD protocol.

Acronym / Term	**Definition**
IAMMWG	Inter-Agency Marine Mammal Working Group
JNCC	Joint Nature Conservation Committee
MU	Management Unit: see below for definition
NE	Natural England
NERC	Natural Environment Research Council
NRC	National Research Council of the United States National Academy of Sciences
NRW	Natural Resources Wales
ONR	US Office of Naval Research
PCAD	Population Consequences of Acoustic Disturbance
PCOD	Population Consequences of Disturbance
PTS	Permanent Threshold Shift: a non-recoverable elevation of the hearing threshold that occurs under conditions that cause a 40dB temporary shift in the threshold **(TTS**) for hearing at a particular frequency
SEL	Sound Exposure Level
SMRU	Sea Mammal Research Unit
SNCB	Statutory Nature Conservation Body
SNH	Scottish Natural Heritage
TTS	Temporary Threshold Shift: a recoverable elevation of the hearing threshold at a particular frequency
Acute effect	The indirect effect of a change in behaviour or physiology on vital rates via individual health
Body condition	A measure of an individual's energy stores. In marine mammals, usually blubber thickness or total body lipid
Carrying capacity	The maximum number of individuals of a species that can be supported in the long term by the resources available in a given area. A population that is at carrying capacity is neither increasing nor decreasing. Most equations describing the operation of **density dependence** in a population require an estimate of the carrying capacity for the population being modelled.
Chronic effect	The direct effect of a change in behaviour or physiology on vital rates
Demographic rates	The average survival and **fertility** rates experienced by all members of a population in a particular year
Demographic stochasticity	Variation among individuals in their realised vital rates as a result of random processes
Density dependence	The process whereby **demographic rates** change in response to changes in population density, resulting in an increase in the population growth rate when density decreases and a decrease in that growth rate when density increases
Delphi process	An established process whereby experts are asked to reconsider their opinions in the light of what other experts have said in answer to the same set of questions
Disturbance - high level	The total number of days on which **significant disturbance events** occur that is required before disturbance results in the maximum reduction in vital rates suggested by the results of the expert elicitation process

Disturbance - Moderate	A level of disturbance sufficient to cause a reduction in vital rate, but less than that required to cause the maximum reduction in these rates
Environmental Impact Assessment (EIA)	The process of evaluating the likely environmental impacts of a proposed project or development, prior to decision-making, taking into account inter-related socio-economic, cultural and human-health impacts, both beneficial and adverse
Environmental Statement (ES)	The report produced as part of the EIA process by, or on behalf of, a developer, which must be submitted with the application for consent or authorisation. The ES describes the project, gathers and presents relevant environmental information, predicts and describes the environmental effects of the project; and defines ways of avoiding, reducing or compensating for the adverse effects
Environmental variation	Variation in **demographic rates** 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
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
Habitats Regulations Assessment (HRA)	The process of evaluating the likely effects of a proposed project or development, prior to decision-making, on European sites (SACs and SPAs) or Ramsar sites and their designated features
Health	All internal factors that may affect individual **fitness** and homeostasis, such as **condition**, 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 (Anon. 2013)
Population size	The number of animals of a species estimated to occur in a particular **Management Unit**, as defined by the IAMMWG (Anon. 2013)
'Residual' disturbance	The persistence of the effects of a **significant disturbance event** beyond the day on which it actually occurs. The number of days of residual disturbance associated with 1 day of significant disturbance is set by the user of the protocol
'Significant' behavioural response	A change in an individual's behaviour pattern that may affect its ability to survive, breed, reproduce or raise young, or that is likely to result in that individual being displaced from an area for a longer period than normal
'Significant' disturbance event	An event that may causes a '**significant' behavioural or physiological response** that is likely to impair an individual's ability to survive, breed, reproduce, or raise young,
'Significant' physiological response	A change in an individual's physiology (e.g. in hearing ability , hormone levels or immune status) that may affect its ability to survive, breed, reproduce or raise young
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 sub-population	Those members of the population within a **Management Unit** that are likely to be at risk of exhibiting **significant disturbance events** associated with a particular development

INTRODUCTION

This report describes a protocol for implementing an interim version of the Population Consequences of Disturbance (PCoD) approach to assess and quantify the potential consequences for marine mammal populations of any disturbance and/or injury that may result from offshore energy developments. The basic PCoD approach was developed by a US Office of Naval Research (ONR) Working Group on the Population Consequences of Acoustic Disturbance (PCAD). It provides a formal, mathematical structure that can be used to implement the conceptual framework for investigating PCAD that was presented by the US National Research Council's Committee on Characterizing Biologically Significant Marine Mammal Behavior in its 2005 report (NRC, 2005). The interim PCoD approach has been designed to be suitable for assessing the potential effects associated with the construction and operation of all types of marine renewables devices on populations of marine mammals in UK waters. It was developed during discussions that took place at a 2012 workshop on 'Assessing the Risks to Marine Mammal Populations from Renewable Energy Devices' (Lusseau *et al.* 2012), which was jointly funded by Countryside Council for Wales (CCW – now Natural Resources Wales (NRW)), the Joint Nature Conservation Committee (JNCC) and the Natural Environment Research Centre (NERC). The approach has benefited greatly from subsequent consultations with stakeholders, and feedback from presentations at meetings of the ONR Working Group. We have also made use of discussions and presentations given at a workshop funded by NERC and Marine Scotland on 'The Use of Individual-based Models of Animal Movement to Assess the Effects of Marine Renewables'. The latter workshop allowed us to develop a methodology for scaling up estimates of the effects of one day of construction on individual animals to cover the entire duration of construction, and for evaluating the cumulative effects of multiple developments on individual Management Units (MUs) for affected species.

We believe that this protocol can be used by regulators and developers to evaluate the potential effects of individual project proposals over the course of their construction and operation, and to assess the cumulative impacts of multiple developments on marine mammal populations. In particular, we have attempted to provide a rigorous, auditable and quantitative methodology for determining how the potential disturbance and injury to marine mammals that may be associated with these proposals might impair the ability of individual animals to survive, breed, reproduce, or rear young, and to quantify how this impairment may affect the abundance of the species concerned within the Management Units (MUs) identified by the Inter-agency Marine Mammal Working Group established by the Statutory Nature Conservation Bodies (SNCBs)(Anon. 2013). The overall approach described here is similar to that developed independently by Thompson *et al.* (2013) to assess the potential effects of pile driving on harbour seals in the Moray Firth MU. However, it has a more formal structure, accounts for more sources of uncertainty, and has been generalised to a range of marine mammal species.

Specifically, our aim has been to provide a protocol that can be used in the preparation of Environmental Statements (ESs), to inform project-level Habitats Regulations Appraisals (HRAs), including Appropriate Assessments, and in the determination of licence applications and conditions. The protocol provides estimates of the potential effects of death, injury, and behavioural disturbance associated with proposals for marine renewable energy developments on the conservation status of the populations of five priority marine mammal species:

- harbour seal (*Phoca vitulina*)
- grey seal (*Halichoerus grypus*)
- bottlenose dolphin (*Tursiops truncatus*)
- harbour porpoise (*Phocoena phocoena*)
- minke whale (*Balaenoptera acutorostrata*)

The protocol has been designed to use the kinds of information that are likely to form part of an offshore energy project's ES and HRA. Methods for estimating the number of marine mammals of each species that may experience death, injury or behavioural disturbance during one day of construction for offshore wind farms are currently available (e.g. Donovan *et al.* 2012, Nedwell *et al.* 2007) , and we have assumed that developers will provide such estimates. Ideally, these methods should also be used to provide estimates of the uncertainties involved in the calculation of these values (see 'Sources of Uncertainty' section). Sparling & Lonergan (2013) were able to estimate the risk of collision between harbour seals and the SeaGen tidal energy array at Strangford Lough. However, we appreciate that providing such estimates will be problematic for most developments of this kind. In such circumstances it is possible to use a range of values for the number of animals that may be affected, and to investigate the population implications of these values.

In order to illustrate how the protocol could be used in practice, we consider the potential effects of the construction of two hypothetical wind farms off the Aberdeenshire coast over a period of two years on the five priority species in their relevant MUs. Additionally, we investigate the cumulative effects of the simultaneous operation of a hypothetical tidal energy array in the same region at the same time as this hypothetical construction work.

PCAD, PCOD AND THE INTERIM PCOD APPROACH

In 2005, a panel convened by the National Research Council of the United States National Academy of Sciences (NRC) published a report on biologically significant effects of noise on marine mammal populations (NRC, 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 or ‘PCAD’ (Fig. 1).

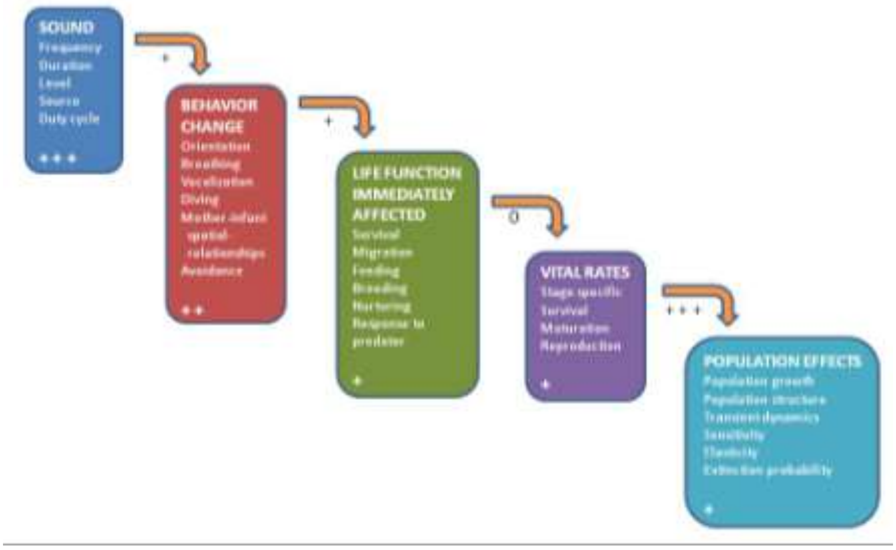

Figure 1. The Population Consequences of Acoustic Disturbance (PCAD) model developed by the National Research Council’s panel on the biologically significant effects of noise. After Fig. 3.1 in NRC (2005). The number of + signs indicates the panel’s evaluation of the relative level of scientific knowledge about the links between boxes, 0 indicates no knowledge. These links were described by the panel as “transfer functions”.

In 2009 the ONR set up a working group to transform this conceptual model 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 also extended the PCAD model 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 model, 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*. (in press).

The PCoD model shows how disturbance may affect both the behaviour and physiology states of an individual, and how changes in these states may influence that individual’s vital rates (see Glossary) 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) through a permanent increase in the threshold for hearing at a particular frequency (Permanent Threshold Shift - PTS). This could have an acute effect on survival, because the affected individual might be 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 body condition, if they result in the disturbed animal spending less time feeding or in activities that conserve energy, such as resting.

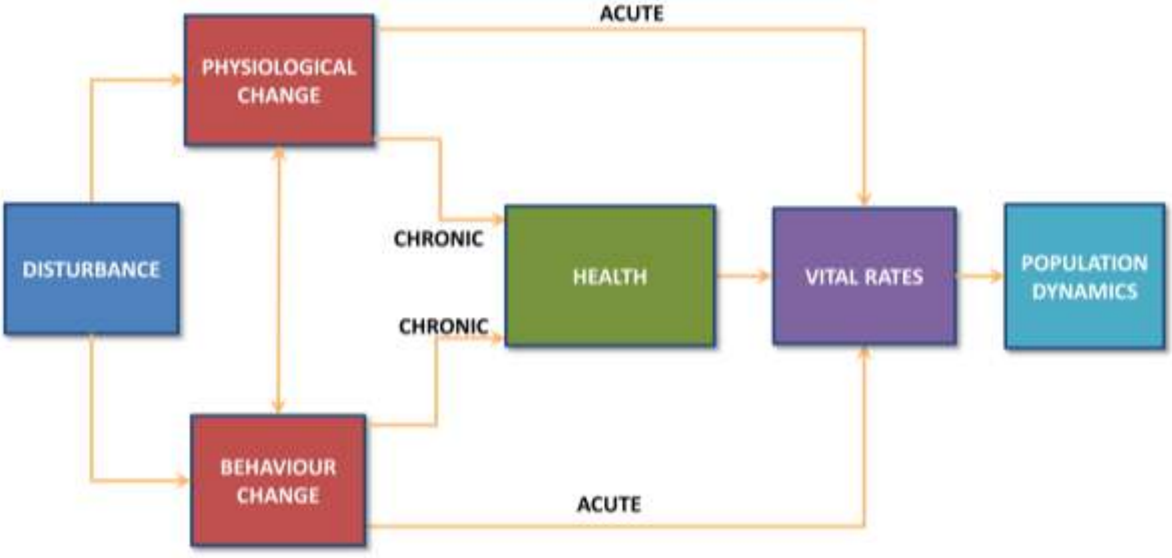

Figure 2. The PCoD model of the population consequences of disturbance developed by the ONR working group on PCAD (modified from Fig.4 of New *et al*., in press). See Glossary for a definition of the terms used in the diagram.

Using case studies of elephant seals (New *et al*. (in press), and Schick *et al*. (2013)) and bottlenose dolphins (New *et al*. 2013) it was possible 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 part. Nabe-Nielsen *et al.* (2011) used a similar approach to assess the potential impacts of wind farm operation on harbour porpoises in Inner Danish Waters.

Unfortunately, the empirical information that is required to parameterise the PCoD model developed by the ONR Working Group does not exist for the five priority species we are considering here. We have therefore used a simplified version of this model (Figure 3) which was developed at the workshop on 'Assessing the Risks to

Marine Mammal Populations from Renewable Energy Devices' (Lusseau *et al.* 2012). The information required to quantify the potential effects of behavioural and physiological changes on vital rates, shown by the dotted lines in Figure 3, was obtained using an expert elicitation process (Runge *et al*. 2011, Martin *et al*. 2012) which is described in the next section.

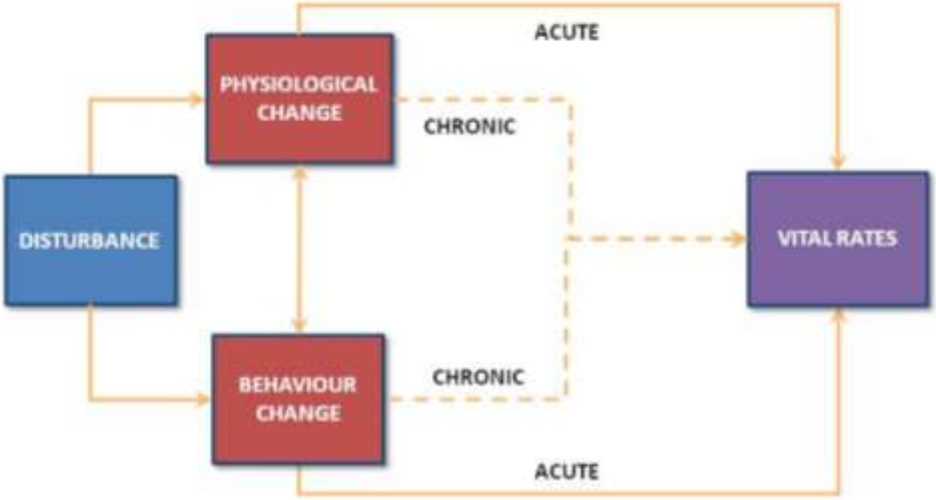

Figure 3. A simplified version of the PCoD model shown in Figure 2 that is being used in the interim PCoD approach. The transfer functions that determine the chronic effects of physiological change and behavioural change on vital rates are represented with dotted lines to indicate that the form of these functions has been determined using the results of an expert elicitation process rather than using empirical evidence. See Glossary for definitions of the terms used in this diagram.

EXPERT ELICITATION: BACKGROUND AND METHODOLOGY

Expert elicitation is a formal technique that is now widely used in conservation science to combine the opinions of many experts in situations where there is a relative lack of data but an urgent need for conservation decisions (Martin *et al*. 2012). Martin *et al.* (2012) describe how this technique can be used to access substantive knowledge on particular topics held by experts The technique can also be used to translate and combine information obtained from multiple experts into quantitative statements that can be incorporated into a model, minimize bias in the elicited information, and ensure that uncertainty is accurately captured. The formal process of expert elicitation therefore avoids many of the well documented problems, described in detail by Kahneman (2012), that arise when the judgements of only a few experts are canvassed.

We developed our elicitation procedure in collaboration with Professor Mark Burgman, director of the Australian Centre of Excellence for Risk Analysis at the University of Melbourne, who has worked closely with the ONR PCAD working group. In particular, we used 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. In addition, we took account of research which has shown that the reliability of results from an expert elicitation process can be improved if experts are asked to consider their opinions in the light of what other experts have said (Burgman et al. 2011). This is known as the Delphi process (Delbecq *et al.* 1975). MacMillan & Marshall (2006) provide an example of the use of this process in a study of the environmental requirements of capercaillie in Scotland. The procedures used in the expert elicitation, the criteria used in the initial selection of experts, and the statistical analysis used to estimate the parameters of the relationships required by the interim PCoD model from the results of this elicitation are described in detail in Appendix 1 and in Donovan *et al*. (in press).

We asked the experts who agreed to participate in our survey to focus on the potential population consequences of changes in hearing ability resulting from PTS, and on disturbance caused by noise and increased vessel traffic associated with offshore renewable energy developments. We hypothesized that the vital rates most likely to be affected by PTS are survival (for all age classes) and the probability of giving birth. The ONR PCAD working group has concluded that disturbance is most likely to affect calf and juvenile survival, and the probability of giving birth. We therefore only asked the experts for their opinions on these vital rates.

We also asked the experts to consider both PTS and disturbance as binary responses. That is, an individual can be categorised as either having experienced PTS or not having experienced PTS (although we recognise that the extent of PTS will vary depending on the sound exposure level that the individual experienced), and as either being disturbed for one day or not disturbed. Following Southall *et al.* (2007), PTS was defined as a non-recoverable elevation of the hearing threshold that occurs under conditions that cause a 40dB temporary shift in the threshold for hearing. Currently, most Environmental Statements use Southall *et al*.'s (2007) injury criteria to calculate the sound pressure or sound exposure levels that are likely to result in PTS as defined in this way.

We defined disturbance as any change in behaviour that is likely to impair an individual's ability to survive, breed, reproduce, or raise young, or that is likely to result in that individual being displaced from an area for a longer period than normal. This is roughly equivalent to all the behaviours with a score of 5* or higher on the "behavioural response severity scale" drawn up by Southall *et al*. (2007). These behaviours include changes in swimming and breathing patterns, sustained avoidance of an area, and prolonged changes in vocal behaviour.

We asked the experts to choose values for the two parameters which determine the shape of the relationship between the number of days of disturbance experienced by an individual and its vital rates shown in Figure 4 so that it best represented the way in which they thought disturbance might have an effect. We recognise that the proposed relationship between days of disturbance and changes in vital rates is highly simplified. However, in the absence of any empirical data on the shape of this relationship for the five priority species, it is hard to justify proposing a more complex form. There is clearly an urgent need for research on the actual form of this relationship.

We also asked experts to comment on the opinions they had provided and on the expert elicitation process itself. These comments are summarised in Appendix 1.

This expert elicitation process was designed specifically to provide parameter values for the functions that form part of the model shown in Figure 3. Those values should not be used to infer how disturbance might affect vital rates outside of the context of this model. In addition, the expert elicitation and the subsequent analysis of the results from the elicitation process were designed to capture the uncertainty expressed by individual experts, and the variability among experts in their opinions. It would therefore be entirely inappropriate to derive simple summary statistics from this analysis.

METHODS

GENERAL DATA REQUIREMENTS FOR THE PCOD APPROACH

Harwood & King (2012) describes ten critical sets of information that are required to implement a full PCOD approach for offshore renewable energy developments (Box 1). Here we describe how these sets of information can be obtained, and the assumptions that must be made when there is insufficient, or no, empirical data to estimate the relevant parameters.

There are a number of computer models that can be used to predict the way in which noise produced during the construction of a particular development propagates through the marine environment (item 1 in Box 1). Under ideal conditions, the predictions of these models are likely to be accurate. However those predictions are sensitive to variations in the temperature and salinity across the water column, bottom topography and bottom sediment characteristics and it is important that these variations are accounted for. Southall *et al.* (2007) provide suggestions for the sound exposure levels (SEL) that are likely to result in PTS for different marine mammal groups (items 2. and 3. in Box 1). They also provide weighting functions that can be used to account for way in which the hearing sensitivity of marine mammals varies with sound frequency. Nedwell *et al.* (2007) have suggested a different set of weighting functions that are based explicitly on audiograms. The experimental data on which Southall *et al.* (2007) based their conclusions can be used to construct dose-response relationships that relate the probability of developing PTS to the SEL experienced by an individual, as was done by Thompson *et al.* (2013) for harbour seals and the SAFESIMM computer package (Donovan *et al.,* 2012), which includes dose-response relationships for all of the marine mammal groups identified by Southall *et al*..

BOX 1. INFORMATION REQUIRED TO IMPLEMENT A PCoD APPROACH

1. **The sound field produced during construction and operation of a particular development (with associated uncertainty).**
2. **The sound levels that are likely to cause Permanent Threshold Shift (PTS), preferably in the form of a dose-response relationship, with associated uncertainty, for each priority species.**
3. **The sound levels that are likely to result in a behavioural response that may impair an individual's ability to survive, breed, reproduce, or raise young, or that may result in that individual being displaced from an area for a longer period than normal. We refer to this as a 'significant' behavioural response. This information should, preferably, be in the form of a dose-response relationship, with associated uncertainty, for each priority species.**
4. **Estimates of the number of animals of each species that may be exposed to sound levels that could result in PTS, and of the number that may show a 'significant' behavioural response during one day of construction of an offshore wind farm. Estimates of the number of animals of each species that may collide with or become entrapped in a marine renewables device, or be exposed to sound levels that could result in a 'significant' behavioural response, during one day of construction or operation of this device.**
5. **The number of animals that are likely to be exposed to sound levels likely to result in PTS or a 'significant' behavioural response over the entire course of construction of an offshore wind farm. The number of animals that might be killed or injured during one year of operation for an operational wave or tidal project (given that the probability of collision or entanglement per day is likely to be low), or a range of possible values, if it is impossible to provide an actual estimate.**
6. **The potential effect of experiencing PTS at a specified frequency on the vital rates for an individual of each species, by age/stage class (e.g. adult males, adult females, calves, juveniles), with associated uncertainty;**
7. **A mathematical function linking the number of days on which an individual experiences a 'significant' behavioural response and its vital rates, with associated uncertainty, for the different age classes of each priority species.**
8. **The current population size and population history for each Management Unit (MU) of the five priority species, with associated uncertainty.**
9. **Estimates of the key demographic parameters (adult survival, calf survival, juvenile survival, annual probability of pupping/calving, age at first pupping/calving, longevity) for each species, in each MU (if parameters are likely to vary between MUs) with an indication of likely levels of variation between years.**

Thresholds and weighting functions for the onset of a 'significant' behavioural response (item 4. in Box 1) are more difficult to define, but Southall et al. (2007) include some suggestions for these, while acknowledging that thresholds are likely to vary with the context in which disturbance occurs. Thompson *et al.* (2013) were able to develop a relationship between the probability of a 'significant' behavioural response (in this case, a prolonged change in vocal behaviour) by harbour porpoises and exposure to noise associated with piling operations, which they used to predict the response of harbour seals to the same kind of noise.

The number of animals that may experience PTS, or exhibit a ‘significant’ behavioural response (item 5. in Box 1) can be calculated by combining estimates from items 1.-4. with information on the anticipated density of each species in the immediate vicinity of the noise source. These density estimates may come from developers’ own surveys or meta-analyses of data from many surveys, such as those in Paxton *et al.* (2012). It may also be appropriate to take account of the way in which animals respond to noise exposure. Individuals that flee directly away from the source of the sound are likely to be exposed to lower SELs than those that follow a more circuitous path; this will reduce the probability that they experience PTS. The interim PCOD approach does not make any adjustments for the different potential noise assessment approaches from which such values are derived.

As noted above, published methods are available for estimating all of the quantities specified in items 1.-4. Therefore, we have not attempted to estimate them as part of the PCoD approach. As a result, the approach can only be implemented if the ESs and HRAs provided for UK offshore renewable energy developments include the information described in item 4. of Box 1. That is, the ES and HRA for a wind farm should include estimates of the number of animals that may be exposed to sound levels that could result in PTS or a ‘significant’ behavioural response during one day of construction. The equivalent documents for a tidal or wave energy array should include an estimate of the number of animals that might be killed or injured during one year of operation (given that the probability of collision or entanglement per day is likely to be low), or a range of possible values, if it is impossible to provide an actual estimate.

As noted above, there are a number of different ways in which these estimates can be calculated and there is considerable uncertainty associated with some of the values, such as the estimated density of different marine mammal species in the vicinity of a development, that must be used in the estimation process. Ideally, the estimates provided in ESs and HRAs should attempt to quantify these uncertainties. However, we recognise this may not be practicable, and we have therefore assumed a pre-specified level of uncertainty in these estimates, which can be replaced with specific estimates if these are available.

The interim PCoD approach uses highly simplified models of the way in which individual animals within a MU may be exposed to the noise associated with the construction of these developments over the course of a year to estimate the information specified in item 6. of Box 1. The results of the expert elicitation have provided the information required for item 7. of Box 1.

It should be recognised that all of these estimates are based either on strong assumptions or on the opinions of the experts we consulted. They are not based on empirical data, and there is clearly an urgent need to collect the information that can be used to provide more realistic estimates of the parameters that define these relationships.

The report of the IAMMWG on Management Units for Marine Mammals in UK Waters (Anon. 2013) provides estimates of the current size of the populations of the priority species in each MU (item 8. in Box 1). Harwood and King (in prep.), which will be made available together with the software for implementing the interim approach, provide preliminary estimates of the demographic parameters specified in item 9. in Box 1 for each MU of the five priority species. These values should be refined as further evidence becomes available.

MODEL STRUCTURE

THE EFFECTS OF A ‘SIGNIFICANT’ BEHAVIOURAL RESPONSE AND PTS ON SURVIVAL AND FERTILITY

As noted above, we asked the experts who participated in our elicitation process for their best estimate of the likely impact of experiencing PTS on survival (for pups/calves, and juvenile animals) or the probability of giving birth (for breeding age adults) for each priority species. We also asked them for the likely range for each estimate, which was used to calculate uncertainty levels. The results were then summarised in a series of probability distributions. We assumed that animals which experience PTS incur the additional mortality or reduction in fertility, suggested by these distributions for the remainder of their lives. However, if regulators and their scientific advisors consider this assumption is inappropriate, the computer code can easily be modified to incorporate Thompson *et al*.’s (2013) assumption that the effects of PTS on vital rates are only evident in the year in which PTS is first experienced.

We asked the same experts for their best estimates of the number of days of disturbance that an individual calf or juvenile animal of each species could tolerate before it would have any effect on its probability of survival, and that an individual mature female could tolerate before it had an effect on the probability of giving birth (labelled as B in Fig. 4), and on the likely range for these estimates. We also asked what they thought the maximum effect of disturbance on these probabilities might be (A in Fig. 4), and how many days of disturbance would be required to have this effect (vertical line C in Fig. 4). We assumed that the maximum effect of disturbance on the probability of giving birth would be to reduce it to zero. These estimates were used to define a relationship between days of disturbance and the effect on vital rates that took account of the uncertainty each expert associated with his or her judgements, and the variation among experts.

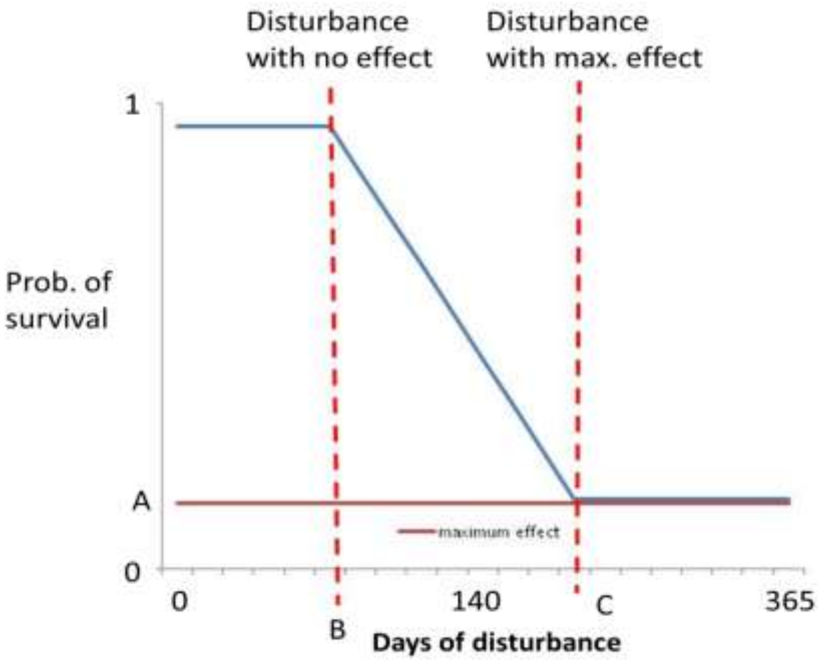

Figure 4. Hypothetical relationship between the number of days of disturbance experienced by an individual marine mammal and its survival used as the basis for the expert elicitation process. B is the number of days of disturbance an individual can tolerate before its probability of survival is affected, A is the maximum effect of disturbance on this probability, and C is the number of days of disturbance required to cause this maximum effect.

When the computer software that implements the interim approach is run, any simulated animal that experiences less than B days of disturbance is categorised as undisturbed. Those that experience between B and C days of disturbance are categorised as experiencing ‘moderate’ disturbance, and their survival or fertility is reduced by (1 + A)/2 (i.e. the mid-point between 1 and A). For example, if A was 0.5, the undisturbed survival rate was multiplied by (1 + 0.5)/2 = 0.75. Individuals that experience more than C days of disturbance are categorised as experiencing ‘high’ levels of disturbance and their survival rate is multiplied by the value for A.

DEFINING VULNERABLE SUB-POPULATIONS

The way in which animals use the space within an MU will almost certainly vary between individuals and, as a result, their risk of injury or disturbance from a particular development will also vary. At present, we do not know enough about this variation to model it explicitly, although existing telemetry data could be analysed to provide this information for grey seals and harbour seals. We have therefore adopted a broad modelling approach to characterise the range of population consequences of this variation. At one extreme, users may choose to specify that all members of the population within an MU are equally vulnerable to the effects of a particular development. This is most likely to be the case where the geographical extent of the MU is relatively small and/or the development is at a key location for the species concerned. At the other extreme, users can specify that only a proportion of the population within an MU is likely to spend time in the region around a particular development where sound exposure levels are sufficiently high that they will cause a behavioural response or injury. We refer to these animals as being members of a vulnerable sub-population (see Glossary). For example, wind farm construction in the northern North Sea may only affect a small proportion of the harbour porpoise population in the North Sea MU, and these animals may be unaffected by wind farm construction in the southern North Sea. Similarly, harbour porpoises that spend most of their time in the southern North Sea may be unaffected by the construction of wind farms in the northern North Sea. Figure 5 shows boundaries that could be used to define two vulnerable sub-populations of harbour porpoises within this MU in relation to planned wind farm developments. Paxton *et al.* (2013) provide estimates of the proportion of the North Sea harbour porpoise population in a number of “areas of interest for offshore development”. The proportion of the MU population in the northern vulnerable sub-population shown in Figure 5 could be calculated from the total proportion of harbour porpoises that are estimated to occur in the Moray Firth and Firth of Forth “areas of interest” (or a simple multiple of this proportion). The proportion of the MU population in the southern vulnerable sub-population could be calculated from the total proportion (or a simple multiple) of harbour porpoises that Paxton *et al.* estimate to occur in the Norfolk Bank, southern Dogger Bank and Dogger Bank “areas of interest”. The results of simulations assuming the entire population within the MU is vulnerable to disturbance and those which assume only a proportion of that population is vulnerable can then be compared to determine which assumption results in the worst case scenario for this harbour porpoise population.

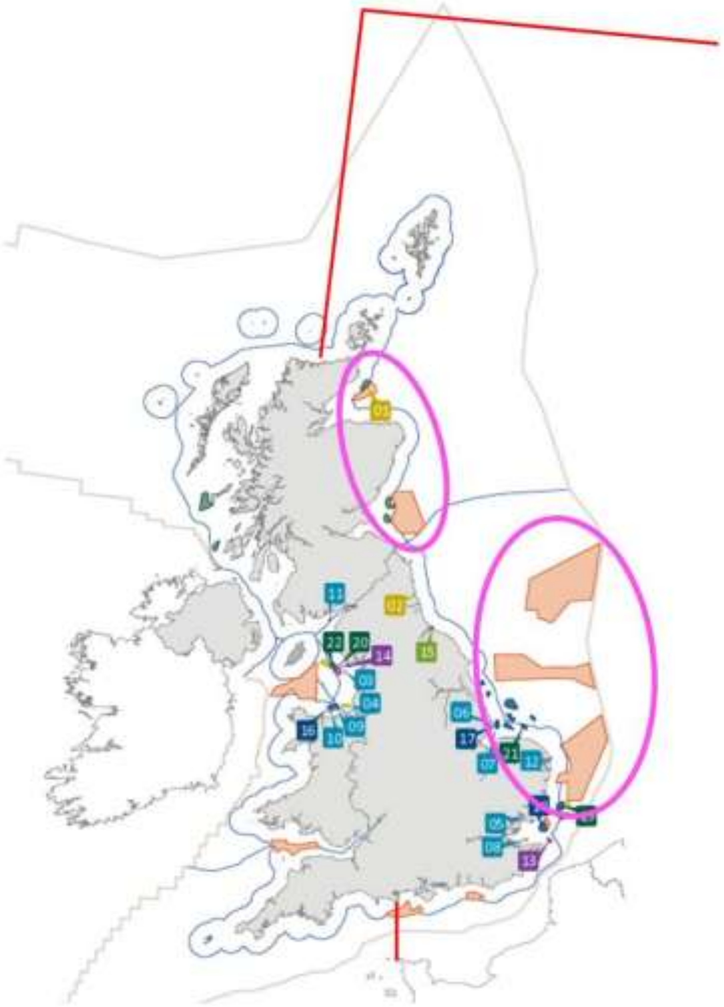

Figure 5. Potential boundaries for two vulnerable sub-populations (see Glossary for a definition) of harbour porpoises within the North Sea MU (as defined by Anon. 2013) that could be used in assessing the effects of disturbance associated with UK wind farm developments in the southern and northern North Sea. These are overlayed on a map showing the location of offshore wind farms that are in development taken from p10 of The Crown Estate's UK Offshore Wind Report 2012 . Numbered sites indicate wind farms (or demonstrators) that are in operation or under construction, unnumbered sites are those that are under development. The blue line indicated the limit of UK territorial waters, and the grey line the limit of the UK continental shelf. The approximate boundaries of the North Sea MU for harbour porpoises is shown in red.

MODELLING DISTURBANCE AND PTS WITHIN A YEAR

Modelling the cumulative impact of an offshore renewable energy development over the entire period of construction requires a series of assumptions about the way in which marine mammals respond to the disturbance associated with the development. There is considerable evidence (Brandt *et al.,* 2011; Teilmann & Carstensen, 2012) that harbour porpoises which have been disturbed by piling noise do not return to the area where piling occurred until some time after piling ceases (which may vary from hours to years). We have therefore assumed that a marine mammal which is disturbed by a single piling event will vacate the area around that event for the remainder of the day on which piling occurs. This allows us to use one day as the smallest time interval that is modelled. However, the available evidence for harbour porpoises suggests that animals may not return to an area where disturbance occurred for several days after that event, and this ‘residual’ exclusion from an area may also have a negative effect on their vital rates. We have therefore allowed users to specify the number of ‘residual’ days of disturbance that may be associated with each day of actual disturbance. We assume that individual marine mammals exhibiting ‘residual’ disturbance are not vulnerable to PTS or any direct disturbance associated with construction during the time they are experiencing this effect because they will not be exposed to additional noise during this time.

The basic model assumes that animals are at risk of PTS every time they enter the region around a development where they may be disturbed by construction noise. However, the area where they are at risk of PTS is likely to be relatively small. It is therefore possible that they will avoid the immediate vicinity of operations after they have been disturbed once. We have therefore included a capability to model a scenario in which animals are only at risk of experiencing PTS on the first day they experience a sound exposure level sufficient to cause disturbance, although we recognise that this probably underestimates the risk of experiencing PTS.

The probability of experiencing PTS can be modelled in many ways; we have implemented only a few of these and we are not proposing that any one of them is definitive. As we will see later in the report, the choice of model for the risk of PTS has a substantial effect on predictions of the population consequences of construction activities. More research is clearly required to clarify the way in which marine mammals respond to repeated exposure to noise levels that might cause PTS.

MODELLING THE EFFECTS OF RENEWABLE ENERGY DEVICES OTHER THAN WIND TURBINES

The interim PCoD approach has been designed to assess the potential effects of a range of offshore renewable energy developments on marine mammal populations. However, its focus is on assessing the potential effects of the construction of large offshore wind farms, and the cumulative effects of multiple renewable energy developments in the same geographical area. Although it can be used to assess the potential population effects of any mortality that may be associated with the operation of an individual tidal or wave energy development, it is better suited to assessing the cumulative effects of such devices if they are operating at the same time as wind farm construction. We have not, therefore, developed a separate protocol for assessing the potential population effects of a particular tidal or wave energy development in isolation.

To the best of our knowledge, the only empirical information on the potential effects of renewable energy devices other than wind turbines on marine mammals comes from studies of the movements of harbour seals and harbour porpoises around the tidal turbine installed in the Narrows of Strangford Lough in Northern Ireland (although, to date, there have been no collisions observed or recorded at this site). We assume that developers of other similar devices will attempt to provide a range of values for the potential number of individuals from a particular MU that might collide with them during the course of a year's operation as part of their ES. The interim PCoD approach can accept these values and can be used to assess their effects in combination with those of other offshore renewable energy developments, as long as some value for the probability of death following a collision is available. In the absence of empirical information about the probability of death following a collision, a precautionary approach would be for the model to assume that all collisions are fatal. In the current implementation we assume that adult and juvenile animals are equally likely to be involved in collisions, and that a collision always results in death. However, this assumption can easily be modified if evidence emerges that certain age classes are more vulnerable than others. The effects of any disturbance that may be associated with the operation of these devices can be handled in the same way as for other renewable energy devices.

SOURCE OF UNCERTAINTY

The interim PCoD protocol attempts to model many of the major sources of uncertainty involved in the calculation of the potential effects of an offshore renewable energy development on a population of marine mammals. These are shown in Box 2.

BOX 2 – SOURCES OF UNCERTAINTY IN THE INTERIM PCOD APPROACH

1. **Uncertainty about the size of the population in a particular MU;**
2. **Uncertainty about what proportion of that population will be affected a particular development;**
3. **Uncertainty in the predictions of the number of animals that will experience disturbance and PTS as a result of one day of construction or operation;**
4. **Uncertainty about predictions of the total number of days of disturbance an individual animal will experience during the course of construction of a development and of the total number of animals that will experience PTS;**
5. **Uncertainty about the effects of disturbance and PTS on vital rates;**
6. **The effects of demographic stochasticity and environmental variation.**

The way in which these uncertainties are modelled is described in detail in Appendix 2. However, we note that accounting for demographic stochasticity, the fact that, even if survival and fertility rates are constant, the number of animals in a population that die and give birth will vary from year to year because of chance events, can produce predictions that appear counter-intuitive. For example, two otherwise identical populations that experience exactly the same sequence of environmental conditions will follow slightly different trajectories over time. As a result, it is possible for the size of a ‘lucky’ population that experiences the effects of disturbance and PTS associated with an offshore renewable energy development to increase over time, whereas an identical undisturbed but ‘unlucky’ population may decrease.

DENSITY DEPENDENCE

The concept of density dependence is central to an understanding of the way in which animal and plant populations respond to a reduction in their size. The standard assumption is that resources (such as food, or suitable places to breed or escape from predators) will become more abundant as population density declines, and this should result in an increase in fertility and survival among at least some members of the remaining population. This assumption underpins the Potential Biological Removals (PBR) formula that is currently used by the Sea Mammal Research Unit (SMRU) to estimate the number of ‘unnatural’ deaths that different Scottish seal populations can sustain (e.g. SMRU, 2012). These values are then used by the Scottish Government to decide the number of licences that may be granted. However, it should be recognised that Wade (1998) developed the PBR formula specifically for use in the context of the US Marine Mammal Protection Act. Wade (1998) estimated that, if annual, human-induced mortality is restricted to a level below the PBR limit, there was a very high probability (>95%) that populations which were at their maximum net productivity level (MNPL), which is approximately 60% of carrying capacity - see Glossary, would “stay there or above after 20 years”. Populations that were at 30% of carrying capacity would have an equally high probability of recovering to their MNPL after 100 years. It is not immediately obvious how these performance measures relate to the requirement that the Habitats Directive places on member states to maintain favourable conservation status for certain species. Lonergan (2011) provides an interesting critique of the use of PBR for management purposes. PBR does provide a valuable benchmark for assessing the potential population consequences of any mortality that may be associated with the **operation** of an offshore energy development. However, it is of limited value for assessing the population consequences of the short-term effects associated with the construction of such a development.

With the exception of grey seals, there is no published evidence for density dependence in UK populations of marine mammals. It is therefore difficult to know how to incorporate density dependence into the interim PCoD protocol in a scientifically-justifiable way. For example, density dependence in grey seals seems to be the result of a relationship between pup survival and the density of adult females on individual breeding colonies (Harwood & Prime, 1978). However, Russell et al. (2013) used telemetry data to show that female grey seals tagged in the East Coast and Northeast England MUs are more likely to breed at colonies in other MUs than they are to breed at colonies in their own MU. As a result, changes in the size of the populations in those MUs will have a negligible effect on the density of adult females on individual breeding colonies, and therefore on the survival of pups born to females from those MUs.

Ultimately, agent-based population models (also known as individual-based models, Grimm *et al.* 2007) that track changes in the energy expenditure and energy intake of individual animals over time, can provide an insight into the way in which survival and fertility are likely to change with population size. Nabe-Nielsen *et al*. (2011) have developed such a model for harbour porpoises in Danish waters. However, such models are not yet available for any UK marine mammal populations.

For these reasons, we have not included density dependence for any species in the current implementation of the interim PCoD protocol. The implications of this are discussed later.

MODEL OUTPUTS

The interim PCoD protocol can provide a large, and probably unmanageable, amount of information about the changes in population size and structure that are forecast to occur in response to a particular development scenario. We have chosen to focus on the information which we believe is most relevant to national implementation of the Habitats Directive. For each iteration (i.e. each occasion on which the statistical distributions that are used to capture uncertainty are resampled) of each scenario, we have also simulated the dynamics of an identical undisturbed population which experiences exactly the same history of environmental variation as the disturbed population. We then compare the sizes of the two populations at regular intervals to determine the effects of disturbance, and then summarise the results across all iterations. We also provide a summary figure that indicates the probability that the simulated disturbed population will have declined by at least 1%, 2% or 5% from its initial size immediately after construction work ends, and the decline experienced by 50% of the simulated populations (roughly equivalent to the mean decline) over this period.

A PROTOCOL `FOR APPLYING THE INTERIM PCOD APPROACH

The Interim PCoD approach has been implemented in the R statistical computing environment (R Development Core Team 2010). We have assumed that users of the PCoD approach will be familiar with creating suitable comma delimited (.csv) data files in Microsoft Excel, or a similar spreadsheet package, and with reading such files into the R environment, and with the editing and running of R program files. The R program files, together with a set of supporting documents and instructions, are available for download at The Scottish Government's website.

The approach has been designed to investigate the potential population consequences of disturbance and injury to marine mammals associated with an individual offshore renewable energy development, or the combined effects of a number of different developments. The same set of decisions will be required whether the approach is being used to assess a single development, or to assess the cumulative effects of a number of developments. The steps required to implement the approach are shown in Box 3. **We recognise that there will be a need for iterative discussion between developers, regulators and advisory bodies (e.g. SNCBs) about the values used for many of the variables and assumptions that form part of this protocol.** These will include whether or not to define vulnerable sub-populations, the appropriate number of days of 'residual' disturbance, and agreed thresholds for significant population decline.

BOX 3 - A PROTOCOL FOR IMPLEMENTING THE INTERIM PCoD APPROACH

1. **Identify the marine mammal MUs that may be affected by each development. If the boundaries of the development site extend over more than one MU, the effects on each MU should be modelled separately.**
2. **For each MU, look up the estimate for the current size of the population in Anon. (2013).**
3. **Look up the appropriate values for these key demographic rates in Harwood & King (in prep.):**
    - **annual survival rate for pups or calves,**
    - **annual survival rate for juveniles (animals that are not yet able to give birth)**
    - **annual survival rate for adults**
    - **average age at which females give birth for the first time, and**
    - **fertility rate (probability of giving birth) for mature females**
4. **Decide on a range of values for the proportion (or proportions) of this population that is likely to be vulnerable to the effects of each development. If the area over which disturbance is expected to occur is large relative to the size of the MU, or the area around the development site is known to be important for the species, then this proportion should be set to 1.0 (i.e. all members of the population in the MU are equally likely to be affected by the development). It is possible to specify that one sub-population is vulnerable to the effects of several different developments, but it is not possible to specify that the same development will affect more than one sub-population.**
5. **Prepare a schedule of information on the estimated days on which activity (e.g. piling or turbine operation) are expected to take place for each development. We appreciate that developers will not be able to specify in advance the exact days on which construction work is likely to occur, because this will depend on many factors, including weather and the availability of suitable equipment. However, they should be able to specify whether their preference is to carry out all construction work within the shortest period possible, which would result in many days of consecutive construction work, or for the work to be conducted sporadically and thus be spread over an extended period.**
6. **Compile estimates of the number of animals of the species under consideration that may be disturbed and experience PTS on each day of construction work. The default is to assume that these values are constant throughout the year. However, it is possible to specify different values for summer (May - October) and winter (November - April), or for spring (March, April, May), summer (June, July, August), autumn (September, October, November) and winter (December, January, February) if these are available. For example, the number of animals may vary as a result of seasonal changes in marine mammal density or sound propagation loss.**
7. **Decide on an appropriate range of values for the number of days of 'residual' disturbance associated with one day of actual disturbance, which model for vulnerability to PTS will be used, and the likely effectiveness of mitigation measures to reduce the risk of animals experiencing SELs sufficient to cause PTS.**
8. **If the approach is being used to assess the cumulative effects of a number of developments that include tidal energy arrays, compile estimates of the number of animals in the same MU that may be involved in collisions or entanglement during each year of operation. Decide on the probability of death following such incidents.**
9. **Prepare appropriate data files, run the R program files and compare the results of the different scenarios.**

    Note: There will be a need for iterative discussion between developers, regulators and advisory bodies (e.g. SNCBs) about many of the variable values and assumptions that will be used within this protocol.

ILLUSTRATIVE SCENARIOS

PARAMETERS VALUES USED IN THE ILLUSTRATIVE SCENARIOS

In order to illustrate how the interim PCoD protocol might be applied in practice, we used the protocol to simulate the effects of construction for two wind farms at hypothetical locations off the east coast of Scotland (Figure 6) on the relevant MUs for each priority species. We arbitrarily assumed that piling at both sites occurred intermittently on 52 days in the first year and on 42 days in the second year. The pattern of piling within a year was based on data kindly supplied by Centrica. Exactly the same pattern was used for each site, but the first day of piling at one site was offset by 2 days from the first day of piling at the other site, so that on some days piling occurred simultaneously at both sites and on others it occurred at only one site. For each marine mammal species we have provided a value for the number of individuals that may be disturbed or experience PTS as the result of one day of piling at each site (i.e. the values specified in item 4. of Box 1). These numbers are approximations of estimates provided in ES chapters for developments in areas with similar densities of animals. We assume that no mitigation measures to reduce the risks of PTS will be implemented. We recognise that developers will almost certainly take steps to mitigate these effects, although it is not clear at the moment how effective these will be. However, if regulators and their scientific advisors are satisfied that these measures will eliminate the risk of PTS, the values for the number of animals that may experience PTS can be set to 0, or some low value.

The comparatively large numbers of seals predicted to suffer PTS in these development scenarios reflect the fact that Southall *et al.* (2007) recommend a threshold for the onset of PTS in seals and sea lions that is 12dB lower than the one they recommend for other marine mammals.

For purely illustrative purposes, we assumed that one day of actual disturbance resulted in an additional 2 days of ‘residual’ disturbance for all species, based on values for harbour porpoise in Fig. 7 of Brandt *et al.* (2011). We also considered a number of values for the size of the sub-population(s) that might be vulnerable to the effects of disturbance associated with the two developments. These values were chosen purely for illustrative purposes and should not be considered as recommendations as to the actual size of these sub-populations.

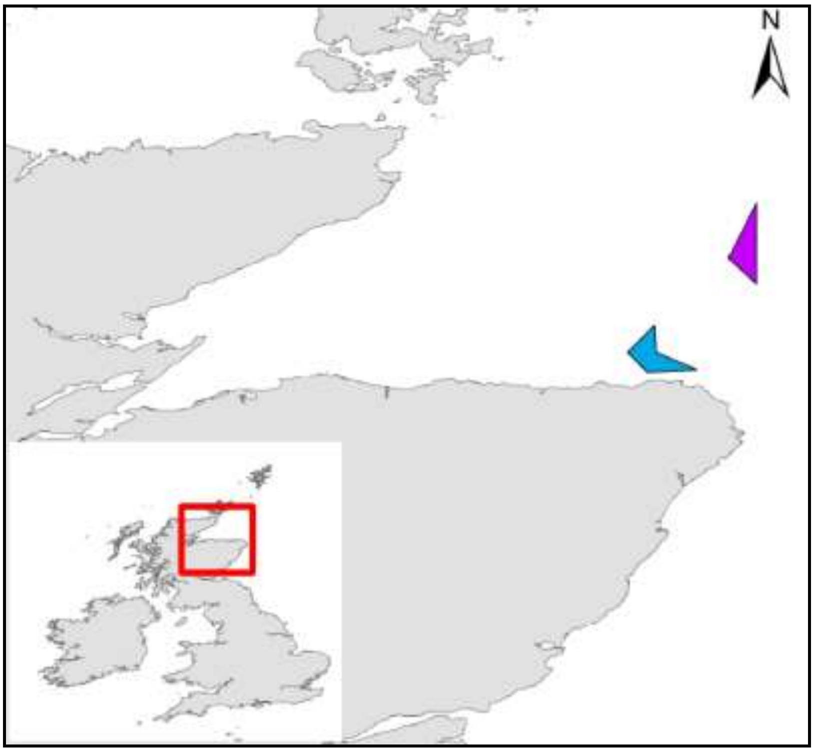

Figure 6. Locations of the two hypothetical wind farm developments used in the simulations.

The following sections outline the decisions made on steps 1.- 7. of the interim PCoD protocol (Box 3) for each priority species :

HARBOUR SEAL

1. Relevant Management Unit: Moray Firth

2. Estimated current population size[1]: 1431 individuals, based on the minimum population size estimate in Anon. (2013) scaled up by 50% to allow for animals that were not hauled out at the time of the survey, as suggested by SMRU (2012: 2 “an alternative approach would be to assume that the proportion hauled out was 2/3, a value supported by telemetry data”).

3. Demographic rates: Rates were adjusted so that the undisturbed population was neither increasing nor decreasing, as reported by SMRU (2012).

Category	Value
Age at first birth	4
Pup survival	0.6
Juvenile survival	0.822
Adult survival	0.85
Fertility	0.9

---

4. Size of the vulnerable population: We considered the following illustrative scenarios:

- All of the population is vulnerable to the effects of piling at both sites;
- 50% of the population is vulnerable to the effects of piling at one site and a different 50% is vulnerable to the effects of piling at the second site;
- 50% of the population is vulnerable to the effects of piling at both sites, the remaining 50% of the population is not affected by piling at either site.

5. Schedule of activities: as described above

6. Number of animals that may experience disturbance and PTS (assuming no mitigation measures to reduce PTS):

Category	**Inshore site**	**Offshore Site**
Number of harbour seals disturbed	200	100
Number of harbour seals experiencing PTS	50	25

7. Number of days of ‘residual’ disturbance assumed: 2

GREY SEALS

1. Relevant Management Unit: Moray Firth

2. Estimated current population size: 3750 individuals, based on the estimate in Anon. (2013). We assumed that 58% of this population was female (SCOS, 2013, p 51).

3. Demographic rates: demographic rates were adjusted so that the undisturbed population was increasing by 1% per year, the same as the overall growth rate of the British grey seal population (SCOS, 2012).

Category	**Value**
Age at first birth	5
Pup survival	0.235
Juvenile survival	0.94
Adult survival	0.94
Fertility	0.84

4. Size of the vulnerable population: We considered the following illustrative scenarios:

- All of the population is vulnerable to the effects of piling at both sites;
- 50% of the population is vulnerable to the effects of piling at both sites, the remaining 50% of the population is not affected by piling at either site.

Only two scenarios were considered for grey seals because they generally have a wider foraging distribution than harbour seals.

5. Schedule of activities: as described above

6. Number of animals that may experience disturbance and PTS (assuming no mitigation measures to reduce PTS):

Category	**Inshore site**	**Offshore Site**
Number of grey seals disturbed	500	250
Number of grey seals experiencing PTS	50	50

7. Number of days of 'residual' disturbance assumed: 2

BOTTLENOSE DOLPHIN

1. Relevant Management Unit: Coastal East Scotland

2. Estimated current population size: 195 individuals, based on the estimate of Cheney *et al*. (2013) used by Anon. (2013).

3. Demographic rates: We adjusted the demographic rates so that the undisturbed population was neither increasing nor decreasing.

Category	**Value**
Age at first birth	9
Calf survival	0.8
Juvenile survival	0.94
Adult survival	0.94
Fertility	0.25

4. Size of the vulnerable population: We considered the following illustrative scenarios:

- All of the population is vulnerable to the effects of piling at both sites;
- 50% of the population is vulnerable to the effects of piling at both sites, the remaining 50% of the population is not affected by piling at either site.

5. Schedule of activities: as described above

6. Number of animals that may experience disturbance and PTS (assuming no mitigation measures to reduce PTS):

Category	**Inshore site**	**Offshore Site**
Number of bottlenose dolphins disturbed	6	6
Number of bottlenose dolphins experiencing PTS	1	1

7. Number of days of 'residual' disturbance assumed: 2

HARBOUR PORPOISE

1. Relevant Management Unit: North Sea

2. Estimated current population size: 227,298 individuals, based on the estimate in Anon. (2013). This estimate has a wide confidence interval, but this is captured in the uncertainty that the interim approach incorporates into the estimates of the number of animals that may experience PTS and disturbance (see Appendix 2).

3. Demographic rates: We adjusted the demographic rates suggested by Winship & Hammond (2006) so that the undisturbed population was neither increasing nor decreasing, as suggested by the trend analysis in Paxton *et al*. (2012).

Category	**Value**
Age at first birth	5
Calf survival	0.6
Juvenile survival	0.85
Adult survival	0.925
Fertility	0.48

4. Size of the vulnerable population: We considered the following illustrative scenarios:

- All of the population is vulnerable to the effects of piling at both sites;
- 10% of the population is vulnerable to the effects of piling at both sites, the remaining 90% of the population is not affected by piling at either site. These percentages were chosen because of the large extent of the MU relative to the area of the two development sites.

5. Schedule of activities: as described above

6. Number of animals that may experience disturbance and PTS (assuming no mitigation measures to reduce PTS):

Category	**Inshore site**	**Offshore Site**
Number of harbour porpoises disturbed	200	500
Number of harbour porpoises experiencing PTS	2	5

7. Number of days of 'residual' disturbance assumed: 2

MINKE WHALE

1. Relevant Management Unit: European waters.

2. Estimated current population size: 23,163 individuals, based on the estimate in Anon. (2013).

3. Demographic rates: We adjusted the demographic rates so that the undisturbed population was decreasing slightly, as suggested by the trend analysis in Paxton *et al*. (2013).

Category	**Value**
Age at first birth	9
Calf survival	0.7
Juvenile survival	0.76
Adult survival	0.96
Fertility	0.86

4. Size of the vulnerable population: We considered the following illustrative scenarios:

- All of the population is vulnerable to the effects of piling at both sites;
- 10% of the population is vulnerable to the effects of piling at both sites, the remaining 90% of the population is not affected by piling at either site. These percentages were chosen because of the large extent of the MU relative to the area of the two development sites.

5. Schedule of activities: as described above

6. Number of animals that may experience disturbance and PTS (assuming no mitigation measures to reduce PTS):

Category	Inshore site	Offshore Site
Number of minke whales disturbed	100	100
Number of minke whales experiencing PTS	10	10

7. Number of days of 'residual' disturbance assumed: 2

RESULTS FROM THE ILLUSTRATIVE SCENARIOS

The results described here are intended to demonstrate how the interim PCoD protocol could be implemented and to illustrate the kinds of output and summary information that it can generate. They should not be interpreted as predictions of the likely population-level effects of any actual offshore renewable energy developments.

We present detailed results for only one species (the harbour porpoise) in this section. For the other four priority species we present one figure, which summarises the risk that the population will have declined by at least 1%, 2% or 5% from its initial size immediately after construction work ends, for each species. The other figures may be found in Appendix 3.

NORTH SEA HARBOUR PORPOISES

ENTIRE POPULATION VULNERABLE

Figure 7 shows the forecast trajectories for a sample of pairs of disturbed and undisturbed populations to illustrate the kinds of changes in population size that are expected to occur as a result of environmental variation, demographic stochasticity and disturbance. Most simulated disturbed populations showed no decline, reflecting the fact that no more than 0.5% of the population is likely to be disturbed on each day that piling occurs, and less than 0.01% of the population is likely to experience PTS on those days. Figure 8 summarises the changes, in absolute and relative terms, for all 500 simulated harbour porpoise populations, and Figure 9 shows the probability of various levels of decline in the year after construction work ends if the entire population is vulnerable to the effects of piling.

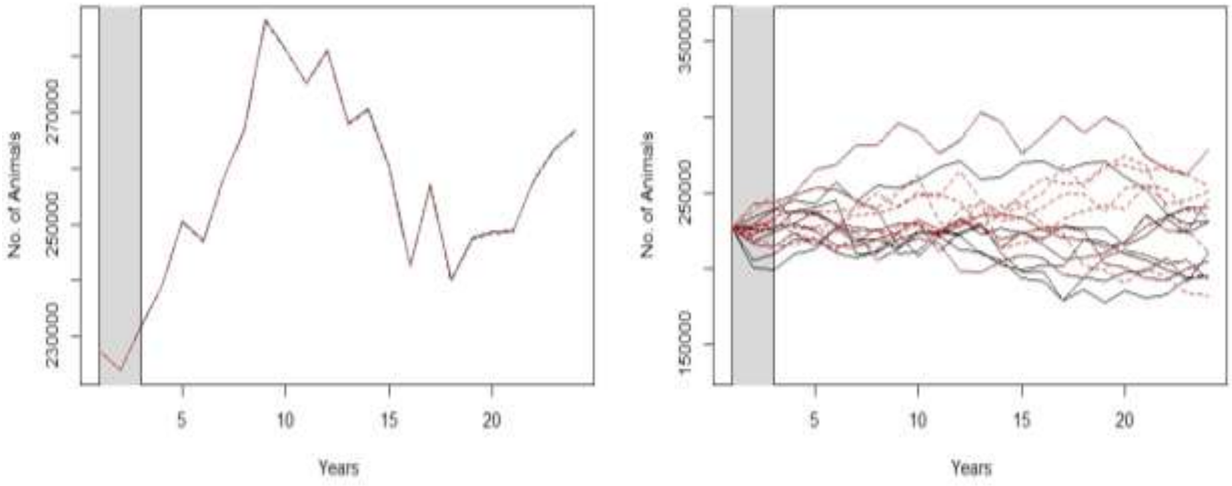

Figure 7. Examples of the predicted changes in abundance of the North Sea harbour porpoise population in the 24 years following the construction of two hypothetical wind farms. The left panel shows the trajectory of one disturbed population (shown as red dotted line) and the matching undisturbed population (shown as black solid line). The right panel shows the trajectories of 10 disturbed (shown as red dotted lines) and undisturbed (shown as black solid lines) populations.

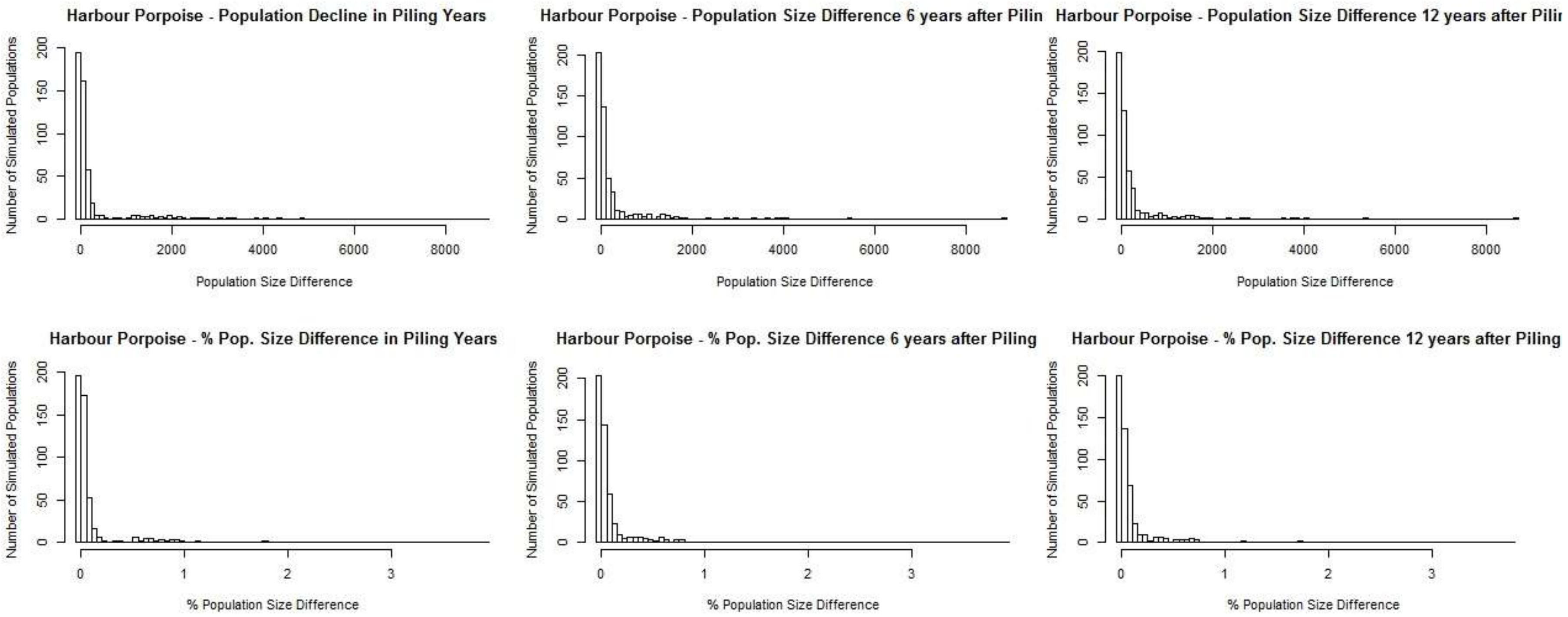

Figure 8. The predicted effects of disturbance and injury associated with the construction of two hypothetical wind farms on 500 simulated harbour porpoise populations when all of the population is vulnerable to the effects associated with both wind farms. The top panels show the predicted differences between the size of the undisturbed and disturbed populations immediately after construction, and at 6-year intervals thereafter. Positive values indicate that the disturbed population is smaller than the undisturbed one. The lower panels show these differences expressed as a percentage of the population size before the start of construction.

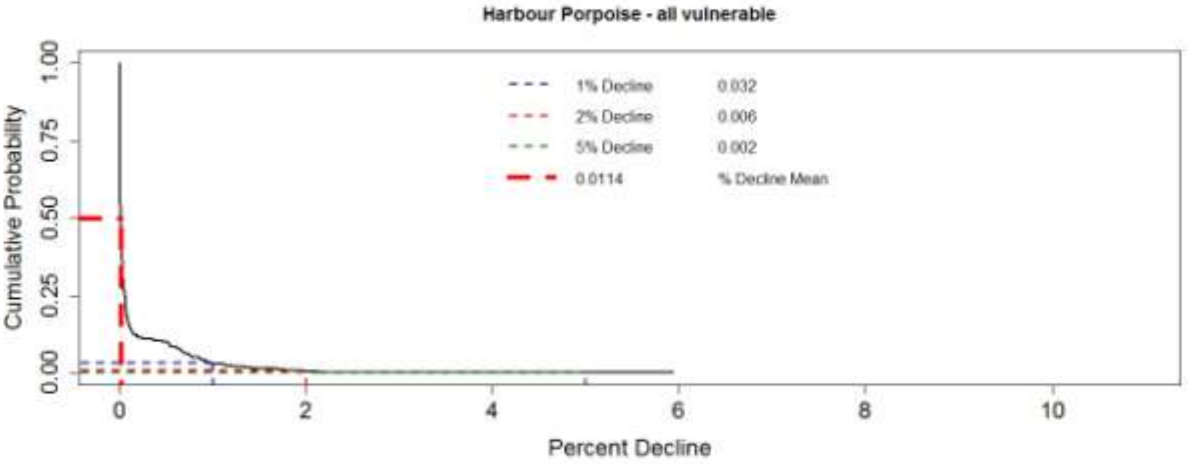

Figure 9. The predicted effects of disturbance and injury associated with the construction of two hypothetical wind farms on 500 simulated harbour porpoise populations when all of the population is vulnerable to the effects associated with both wind farms. The figure shows *the proportion of simulated populations* that experienced declines of at least 1%, at least 2% and at least 5% at the end of the construction period, and the mean decline in abundance over this period.

ONE VULNERABLE SUB-POPULATION

Figures 10 and 11 show the equivalent information for a scenario in which only a proportion of the population is vulnerable to the effects of the piling operations. The differences are small, but a slightly higher proportion of the simulated disturbed populations showed some evidence of decline under this scenario.

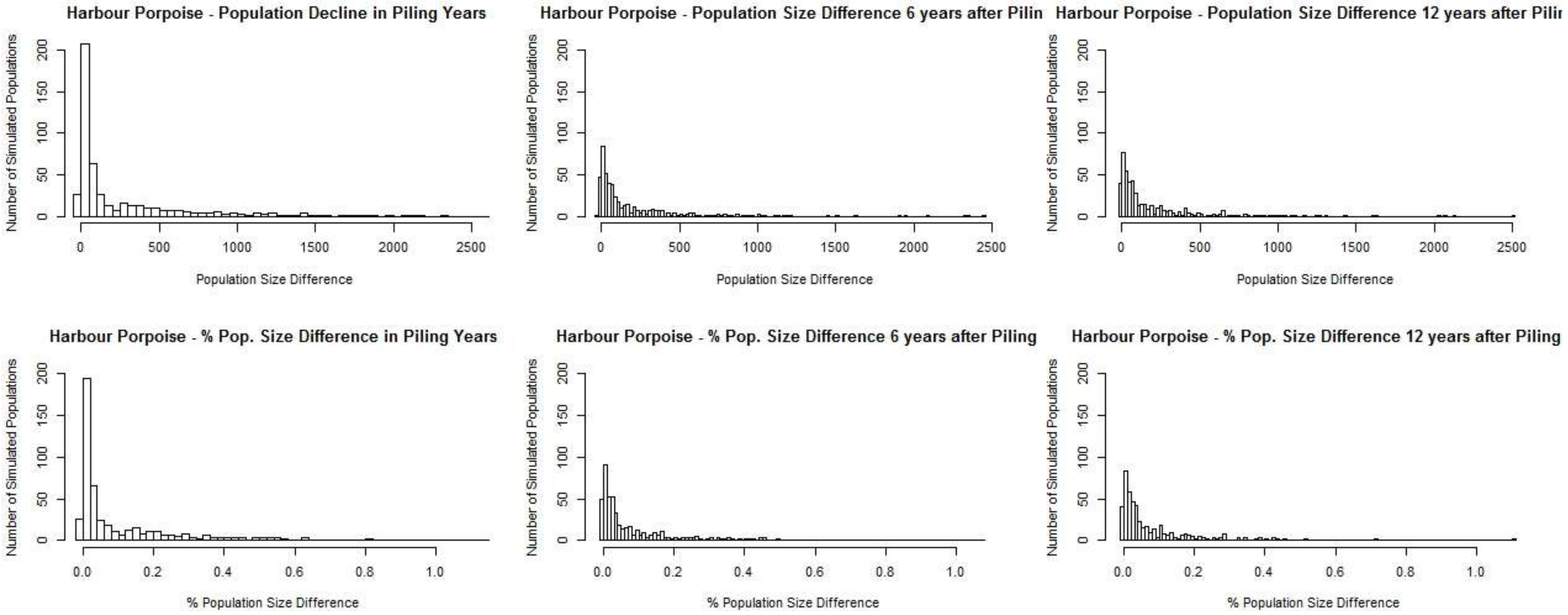

Figure 10. The predicted effects of disturbance and injury associated with the construction of two hypothetical wind farms on 500 simulated harbour porpoise populations when 10% of the population is vulnerable to the effects associated with both construction sites and the remaining 90% of the population is not affected by either operation. The top panels show the predicted differences between the size of the undisturbed and disturbed populations immediately after construction, and at 6-year intervals thereafter. Positive values indicate that the disturbed population is smaller than the undisturbed one. The lower panels show these differences expressed as a percentage of the population size before the start of construction.

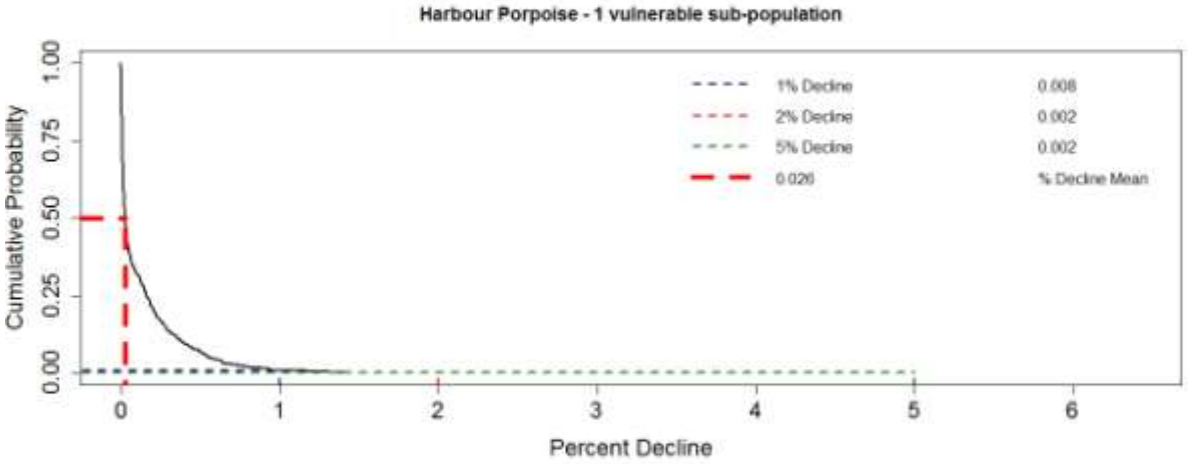

Figure 11. The predicted effects of disturbance and injury associated with the construction of two hypothetical wind farms on 500 simulated harbour porpoise populations when 10% of the population is vulnerable to the effects associated with both construction sites and the remaining 90% of the population is not affected by either operation. The figure *shows the proportion of simulated populations* that experienced declines of at least 1%, at least 2% and at least 5% at the end of the construction period, and the mean decline in abundance over this period.

MORAY FIRTH HARBOUR SEALS

Figures for harbour seals, equivalent to those shown for harbour porpoises, can be found in Appendix 3. Fig. 12 shows the probability of different levels of decline at the end of the construction period. The estimates of the number of animals likely to be disturbed or experience PTS during one day of construction resulted in more than 20% of the population being disturbed each day, and more than 5% experiencing PTS. As a result, the implications for the population are much greater than they were for harbour porpoises. Most simulated populations showed a decline of more than 5%, and more than half had declined by at least 20% by the time construction ended. These declines continued, although not so steeply, in subsequent years because of the persistent effects of PTS on survival and fertility.

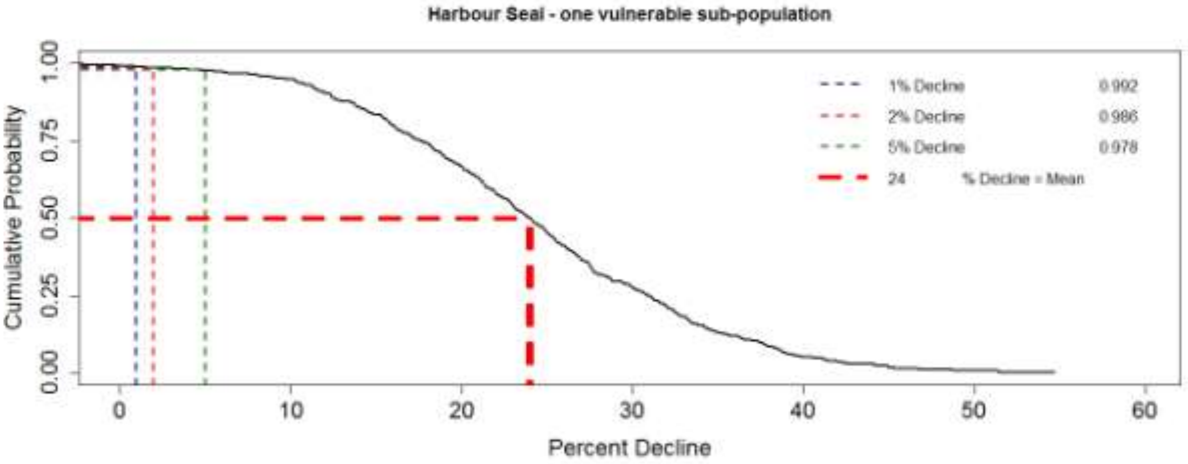

Figure 12. The predicted effects of disturbance and injury associated with the construction of two hypothetical wind farms on 500 simulated harbour seal populations when 50% of the population is vulnerable to the effects associated with both construction sites and the remaining 50% of the population is not affected by either operation. The figure shows the proportion of simulated populations that experienced declines of at least 1%, at least 2% and at least 5% at the end of the construction period, and the mean decline in abundance over this period.

MORAY FIRTH GREY SEALS

Figures for grey seals equivalent to those shown for harbour porpoises can be found in Appendix 3. Here we only show summary figures that illustrate the probability of different levels of decline at the end of the construction period. Figure 13 shows these probabilities for a scenario in which all animals in the population are vulnerable to disturbance, and Fig. 14 shows the equivalent probabilities when only half the population is vulnerable. The scenarios we have chosen resulted in 20% of the population being exposed to disturbance on each day of construction, and nearly 3% experiencing PTS on each day. Most simulated populations showed a decline of more than 2%, and nearly half of all simulated population had declined by at least 10% by the time construction ended. These declines continued, although not so steeply, in subsequent years because of the persistent effects of PTS on survival and fertility. The forecast declines are slightly higher when only half the population is vulnerable to disturbance because, on average, each individual in the vulnerable sub-population is disturbed on more days than is the case when all members of the population are equally vulnerable to disturbance.

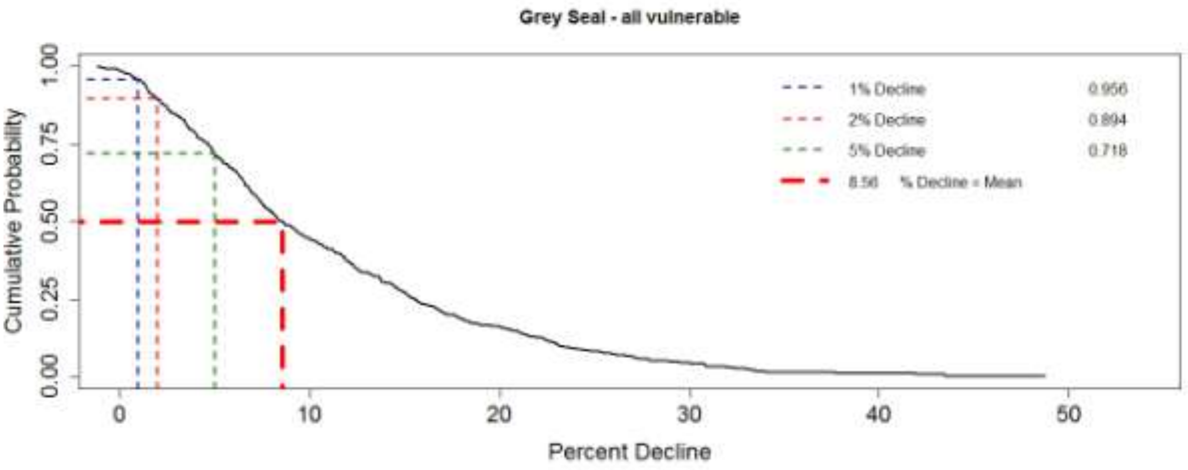

Figure 13. The predicted effects of disturbance and injury associated with the construction of two hypothetical wind farms on 500 simulated grey seal populations when all of the population is vulnerable to the effects associated with both wind farms. The figure shows the proportion of simulated populations that experienced declines of at least 1%, at least 2% and at least 5% at the end of the construction period, and the mean decline in abundance over this period.

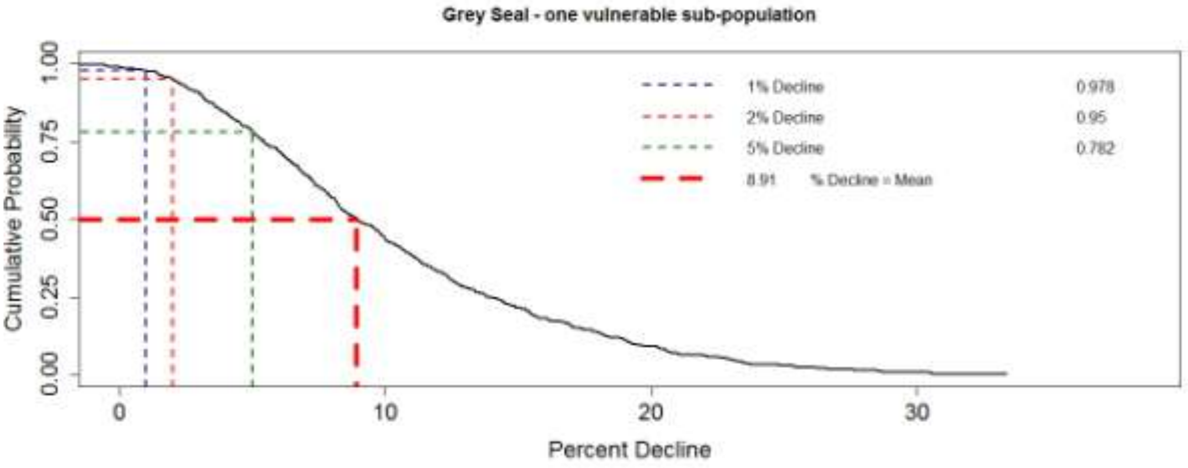

Figure 14. The predicted effects of disturbance and injury associated with the construction of two hypothetical wind farms on 500 simulated grey seal populations when 50% of the population is vulnerable to the effects associated with both construction sites and the remaining 50% of the population is not affected by either operation. The figure shows the proportion of simulated populations that experienced declines of at least 1%, at least 2% and at least 5% at the end of the construction period, and the mean decline in abundance over this period.

COASTAL EAST SCOTLAND BOTTLENOSE DOLPHINS

Figures for bottlenose dolphins that are equivalent figures to those shown for harbour porpoises can be found in Appendix 3. Here we only show summary figures that illustrate the probability of different levels of decline at the end of the construction period. Figure 15 shows these probabilities for a scenario in which half the population is vulnerable to disturbance. The scenarios we chose resulted in around 5% of the total population being exposed to disturbance on each day of construction, and 1% experiencing PTS on each day. As a result, the implications for the population are greater than they were for harbour porpoises but substantially less than they were for harbour seals and grey seals. Most of the simulated populations had declined by less than 5% by the time construction ended.

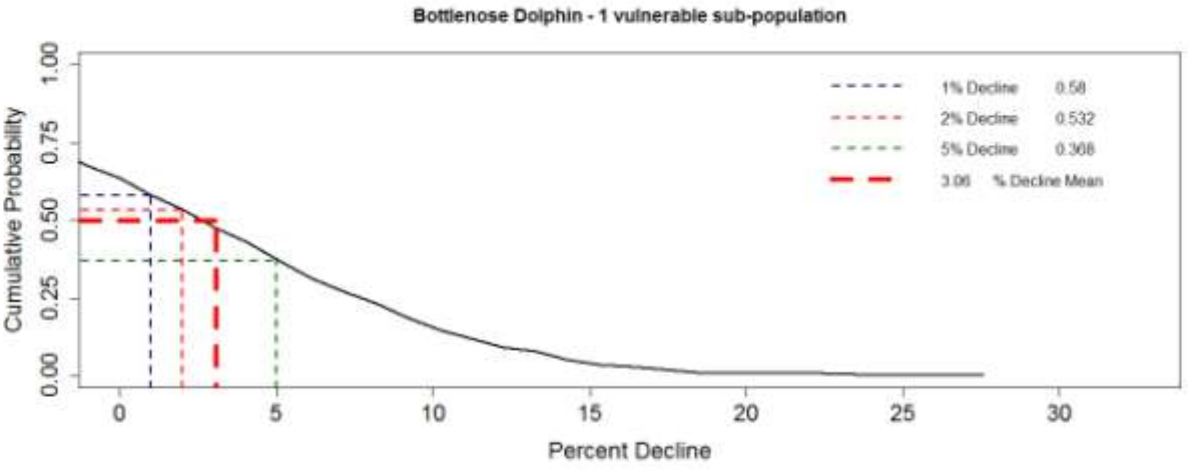

Figure 15. The predicted effects of disturbance and injury associated with the construction of two hypothetical wind farms on 500 simulated bottlenose dolphin populations when 50% of the population is vulnerable to the effects associated with both construction sites and the remaining 50% of the population is not affected by either operation. The figure shows the proportion of simulated populations that experienced declines of at least 1%, at least 2% and at least 5% at the end of the construction period, and the mean decline in abundance over this period.

MINKE WHALES

Figures for minke whales that are equivalent figures to those shown for harbour porpoises can be found in Appendix 3. Here we only show summary figures that illustrate the probability of different levels of decline at the end of the construction period. Figure 15 shows these probabilities for a scenario in which 10% of the population is vulnerable to disturbance. The scenarios we chose resulted in less than 1% of the total population being exposed to disturbance on each day of construction, and only 1 in 1000 animals experiencing PTS on each day. As a result, the implications for the population are similar to those for harbour porpoises with very few simulated populations declining by more than 1%.

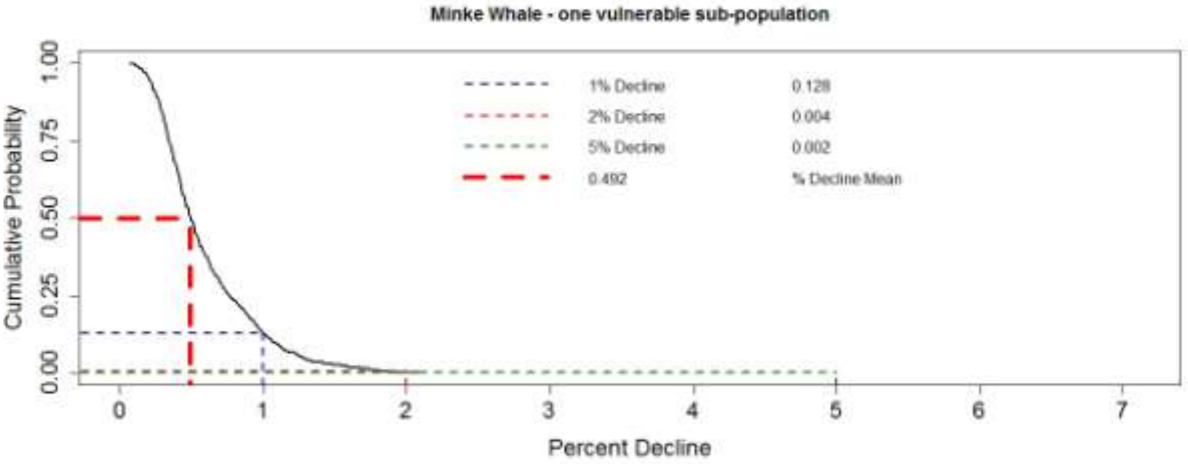

Figure 16. The predicted effects of disturbance and injury associated with the construction of two hypothetical wind farms on 500 simulated minke whale populations when 10% of the population is vulnerable to the effects associated with both construction sites and the remaining 90% of the population is not affected by either operation The figure shows the proportion of simulated populations that experienced declines of at least 1%, at least 2% and at least 5% at the end of the construction period , and the mean decline in abundance over this period.

SENSITIVITY ANALYSIS

Harwood *et al.* (2013) investigated the sensitivity of the interim PCoD approach to assumptions made in estimating the number of animals that might experience PTS and 'significant' disturbance over the entire course of construction of an offshore renewable energy development. They found that these estimates were particularly sensitive to three of the assumptions of the model: the proportion of the population that is expected to be vulnerable to the effects of disturbance, the model used to assess the risk of PTS, and the duration of the 'residual' effect of disturbance. Here, we extend that analysis to investigate the sensitivity of forecasts of population-level effects to the same set of assumptions.

PROPORTION OF POPULATION VULNERABLE TO EFFECTS

Figure 17 shows a comparison of the predicted declines for a minke whale population in which 10%, 5% and 1% of the population is vulnerable to disturbance and PTS effects. Reducing the size of the vulnerable sub-population also reduces the predicted mean decline in population size.

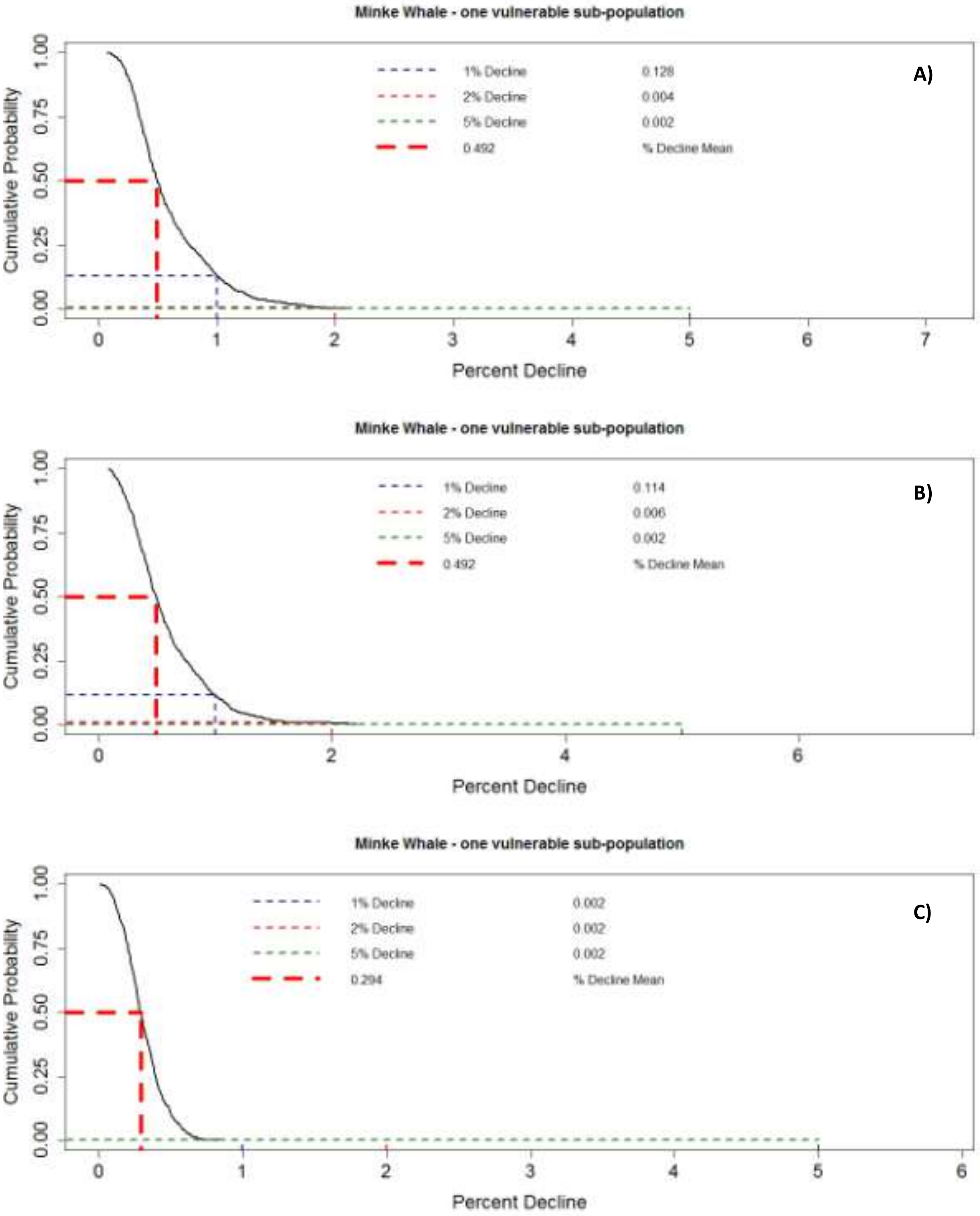

Figure 17 A-C. Effect of the size of the vulnerable sub-population on the probability of various levels of decline in the entire population over the period of construction for a simulated, disturbed minke whale population. A 10% of population vulnerable, B. 5% of population vulnerable, C. 1% of population vulnerable.

MODEL USED TO ASSESS THE RISK OF PTS OVER THE DURATION OF CONSTRUCTION

Figure 18 shows the consequences of using different models for the vulnerability of bottlenose dolphins to PTS. If animals are only vulnerable to PTS on the first occasion that they are subject to disturbance, the predicted mean population decline in the first 6 years is reduced from around 3% to 2%.

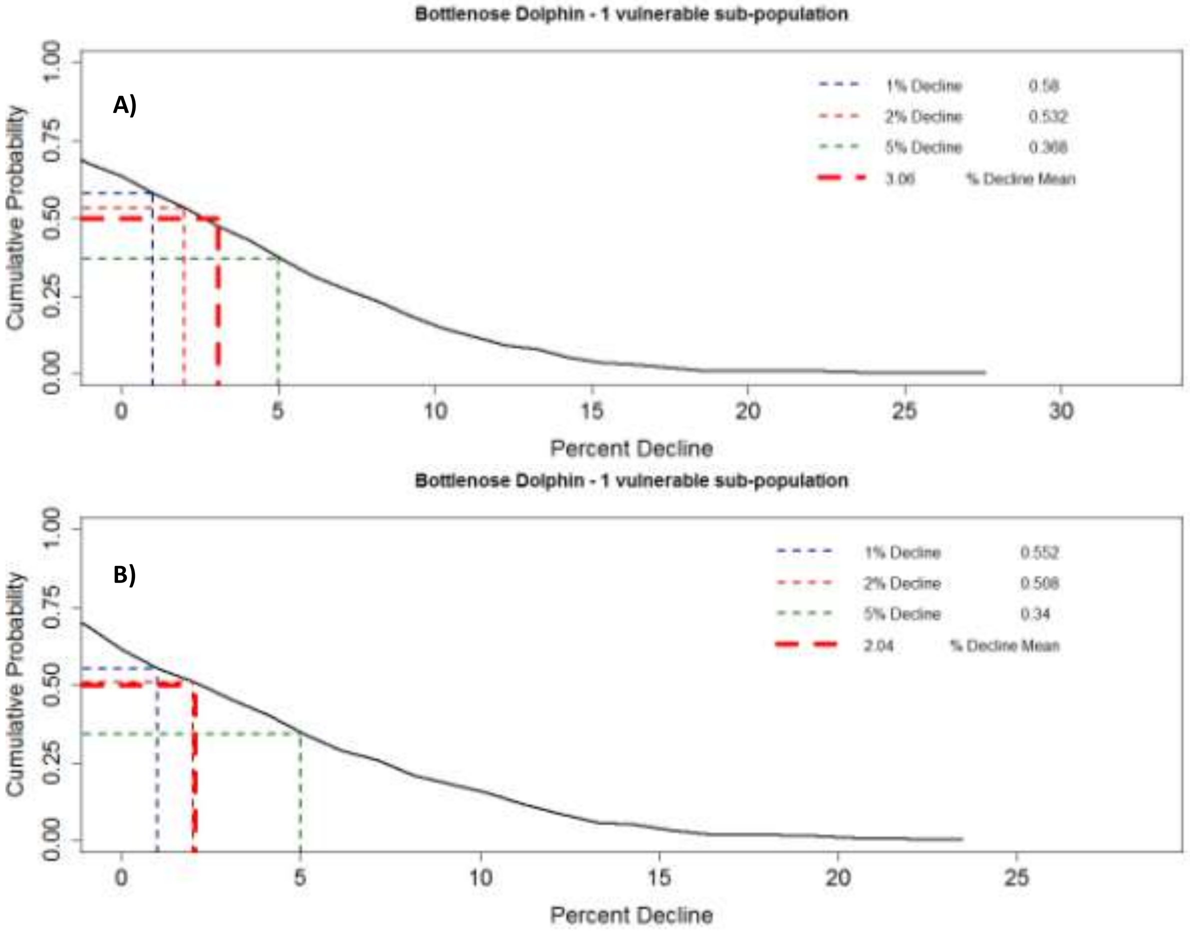

Figure 18 A & B. Effect of the model of vulnerability to PTS on the probability of decline over the period of construction for a simulated bottlenose dolphin population in which 50% of the population is vulnerable to disturbance. A. Animals are always vulnerable to PTS; B. Animals are only vulnerable to PTS on the first occasion that they are disturbed.

DAYS OF ‘RESIDUAL’ DISTURBANCE

We also investigated the effect of varying the number of days of residual disturbance associated with one day of actual disturbance between 0 and 2 days for a simulated bottlenose dolphin population in which 50% of the population was vulnerable to disturbance. Reducing the ‘residual’ disturbance to 0 or 1 day reduced the predicted mean decline in population size from 3% to 2%.

ADDITIONAL POTENTIAL EFFECTS OF HYPOTHETICAL TIDAL ARRAY

Finally, we examined the sensitivity of the model outputs for the Moray Firth harbour seal population when there was additional mortality of four animals per year associated with a hypothetical tidal energy array located in the same region. Figure 19 A & B shows the summary results. The additional mortality has little effect on the observed population declines.

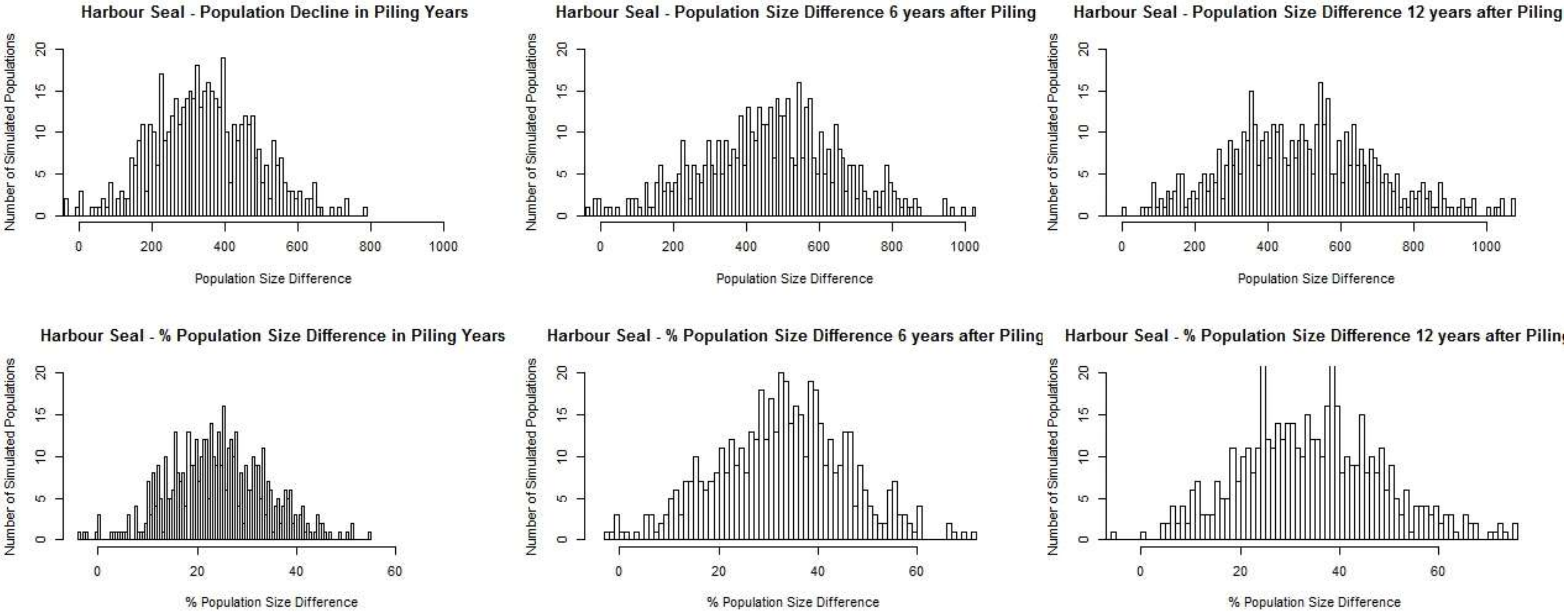

Figure 19 A – Investigating the effect of including additional mortality associated with a hypothetical tidal turbine on a simulated harbour seal population in which 50% of the population is vulnerable to disturbance. ***This figure shows the harbour seal population with no additional mortality.***

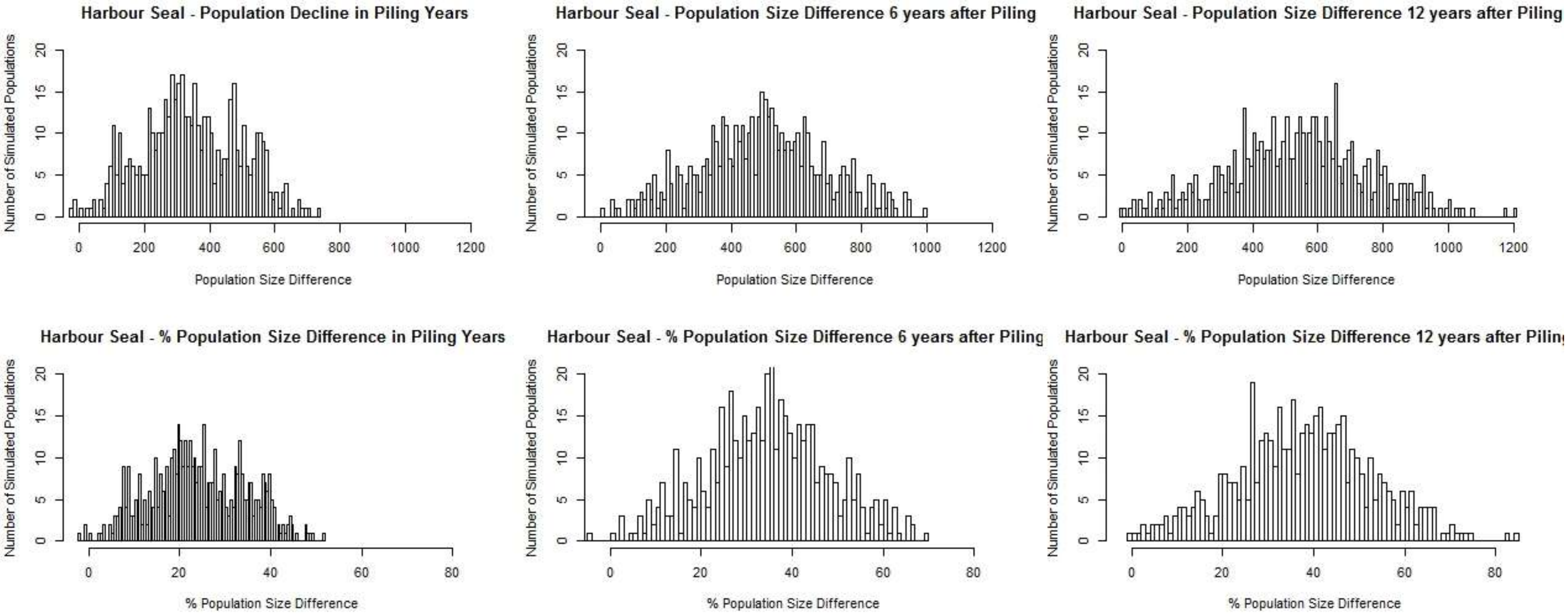

Figure 19 B. The effect of including additional mortality associated with a hypothetical tidal turbine on a simulated harbour seal population in which 50% of the population is vulnerable to disturbance. ***Under this scenario four animals are predicted to die each year as a result of collisions.***

INTERPRETATION OF THE OUTPUTS FROM THE INTERIM PCOD SCENARIOS

The interpretation of the results of implementing the interim PCoD protocol for North Sea harbour porpoises and European minke whales using the hypothetical disturbance scenarios outlined above is relatively straightforward. The forecast effects are relatively small (a very high probability that the population will decline by less than 1% over the period of construction) and these predicted effects are not sensitive to assumptions made about the relative vulnerability of individual animals within the population to the effects of PTS and disturbance.

The results for coast east Scotland bottlenose dolphins suggest that there is a relatively high probability (more than 50%) that construction scenario we have used as an illustration could result in a short term decline of 1% or more. This would be classified as “significant” using the UK approach for assessing conservation status under the Habitats Directive (Joint Nature Conservation Committee, 2007). However, the sensitivity analysis indicates that these forecasts are affected by the choice of assumption about the way in which the vulnerability of animals to PTS varies over time. This suggests that mitigation measures designed to reduce the number of animals that experience PTS could substantially reduce the risk of a significant decline in the size of this population. Developers could therefore be encouraged to propose such measures and estimate their likely effectiveness in reducing the risk of PTS. The population consequences of these mitigation measures could then be assessed by re-running the interim protocol using the revised values.

The results for both Moray Firth harbour seals and Moray Firth grey seals indicate that the disturbance scenarios we have chosen could result in substantial (around 20% in the case of harbour seals and 10% in the case of grey seals) short term declines in abundance. These are a consequence of the high proportion of the population that is predicted to experience disturbance and PTS on each day of construction. These high proportions are themselves a consequence of the fact that Southall et al. (2007) recommend the use of a substantially lower sound threshold for the onset of TTS and PTS in seals than for cetaceans. The use of different values for these thresholds, and the implementation of mitigation measures to reduce the risk of PTS would reduce the calculated risks of substantial population decline. For example, if the estimate of the number of harbour seals that may experience PTS on one day of construction is reduced to zero, but the estimate of the number of animals that may experience disturbance remains the same, then the median forecast decline in the Moray Firth population at the end of construction is reduced from around 20% to less than 10%.

The interim PCoD approach 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 and PTS have ceased. In practice, because of the factors described in the preceding section on density dependence, there is likely to be some increase in vital rates, provided that there are no other threats to the population. With current information, it is not possible to predict or model these changes with any confidence. Even if we chose to use a standard function for density dependence, such as the generalised logistic equation used by Thompson et al. (2013) for harbour seals in the Moray Firth relationships, we would have to make a large number of arbitrary choices about which parameter values to use to define the shape of this function. This process would have to be repeated for each demographic rate that might show a density dependent response for each species. In addition, we would have to arbitrarily define a carrying capacity for each MU of each species. Figure 9 of Thompson *et al*. (2013) demonstrates that the value chosen for carrying capacity can have a substantial effect on the predicted trajectory of a population that is subject to disturbance from a renewable energy development.

Nevertheless, if is possible to draw some broad conclusions about the long term responses of marine mammal populations to disturbances of this kind. Seal populations are likely, on average, to recover relatively rapidly (probably within a decade following a 10-20% reduction) from the effects of short-term disturbance, provided all other factors affecting the population (such as deliberate killing, prey availability and other environmental conditions) remain unchanged. This is because of their potentially high maximum population growth rate and the fact that disturbance is likely to have a greater effect on young animals than on adult females, resulting in a population with a higher than normal proportion of adult females. Cetacean populations are also likely to show the same changes in population age structure as seals, but their maximum population growth rate is likely to be substantially lower than that of an equivalent seal population (Wade 1998) so they will take longer to recover from the effects of disturbance.

DISCUSSION

We stress again that the results presented here are only intended to demonstrate how the interim PCoD protocol could be implemented and to illustrate the kinds of output and summary information that it can generate. They should not be interpreted as predictions of the likely population-level effects of actual offshore renewable energy developments. Similarly, we reiterate that the relationships between the number of days of disturbance experienced by an individual marine mammal and its vital rates, derived from the expert elicitation process described in Appendix 1, were developed

specifically for use within the interim PCoD framework. They should not be used outside this context.

We would also like to emphasise that the approach we have developed for assessing the potential effects of offshore renewable energy developments on marine mammals in UK waters is very much an interim one, designed to cope with the almost complete absence of the empirical data that are required to develop an evidence-based approach. In the absence of those data, we believe that the interim approach described here provides a rigorous, auditable and quantitative methodology, based on the best available evidence, which can be used to inform the consenting and decision-making processes for offshore energy projects. In particular, it provides the only currently-available tool for assessing the cumulative effects of a single development over the course of construction on a range of marine mammal populations, and for assessing the cumulative impacts of multiple developments that use different technologies.

However, it is important that empirical data to implement a full PCoD approach are collected as soon as possible in order to reduce the large degree of uncertainty that will be associated with any assessments performed using the interim approach. At present the interim approach relies heavily on a series of strong assumptions (summarised in Box 4) and the opinions of a large number of experts. However, these opinions have been gathered and collated using internationally recognised techniques and statistical methods.

BOX 4 – ASSUMPTIONS OF INTERIM PCoD PROTOCOL

This protocol assumes that an Environmental Statement will contain:

- **Estimates of the number of animals of each species likely to be exposed to sound levels that could result in PTS or a 'significant' behavioural response during one day of construction or operation of this device.**
- **A range of values for the number of individuals (if any) that may be injured during the course of a year of operation.**

The expert elicitation process assumes that:

- **The simple function of Fig. 4 that relates the probability of survival or giving birth to the number of days of disturbance experienced by an individual animal, is correct.**
- **The experts who participated in our survey were a representative sample of suitably qualified individuals and that they understood the questions they were asked.**
- **The vital rates most likely to be affected by PTS are survival and the probability of giving birth (fertility).**
- **The vital rate most likely to be affected by disturbance for calves/pups and juveniles is survival.**
- **The vital rate most likely to be affected by disturbance for adults is fertility.**
- **PTS and disturbance are binary responses: all animals that experience any kind of PTS or one day of disturbance will have their vital rates affected in the same way.**
- **The maximum effect of PTS or disturbance on fertility is to reduce it to zero.**

The model which estimates the total number of animals that may experience PTS within one year and the number of days of disturbance experienced per year assumes that:

- **Uncertainty in the estimates of the number of animals experiencing PTS and disturbance during one day of construction is accurately captured by the variance term used in the model.**
- **All individuals within the population (or the vulnerable sub-population) within a MU are equally likely to be exposed to SELs likely to cause PTS or disturbance on a particular day.**
- **The effect of one day of disturbance on vital rates is independent of the number of times an animal is disturbed on that day.**
- **Animals that are not part of a vulnerable sub-population are unaffected by the development(s) being modelled.**
- **All individuals that experience a high level of disturbance have their vital rate(s) reduced by the maximum amount suggested by the expert elicitation.**
- **All individuals that experience a moderate level of disturbance have their vital rate(s) reduced by the half the amount caused by high levels of disturbance.**
- **Animals are equally likely to experience PTS every time they are sufficiently close to a noise source to be exposed to SELs above the threshold for PTS (Model 1).**
- **Animals are only likely to experience PTS on the first occasion that they are sufficiently close to the noise source to be exposed to SELs above the threshold for PTS (Model 2).**
- **Animals that have experienced disturbance on a particular day will not return to the location where they experienced disturbance for X 'residual' days, where X is an integer, defined by the user, which may be zero.**

BOX 4 – ASSUMPTIONS OF INTERIM PCoD PROTOCOL (continued)

- **The effect of one day of 'residual' disturbance on vital rates is the same as that of one day of actual disturbance.**
- **Animals that are experiencing 'residual' disturbance are not at risk of actual disturbance or PTS.**
- **Adults, juveniles and calves/pups are equally at risk of collision with or entanglement in tidal energy arrays.**

The population dynamics model assumes:

- **The effects of environmental variation on survival and fertility are adequately captured by the range of values obtained from the expert elicitation.**
- **The effects of environmental variation on survival and fertility are independent.**
- **Survival and fertility rates are not affected by population size (i.e. there is no density dependent response).**
- **The effects of experiencing PTS on survival or fertility persist throughout an animal's life.**

The sensitivity analysis described above has revealed that the assessments are likely to be particularly sensitive to assumptions about the way in which individual marine mammals respond to repeated exposure to the noise associated with the construction and operation of offshore renewables devices and, to a lesser extent, the proportion of the population within an MU that is vulnerable to the effects of a development. It is also clear that the effect of experiencing PTS on survival and fertility has a large impact on the population consequences of a particular renewable energy development. We have had to rely on expert opinion for the values used to assess the effects of PTS, given the complete lack of empirical information on the subject. Nevertheless, the results demonstrate the importance of mitigation measures designed to reduce the risk that any individuals will suffer PTS.

Although we have tried to account for the more obvious sources of uncertainty in the approach we have developed, there is one major source of uncertainty that we have not addressed. This is model uncertainty: the fact that the highly simplistic model linking number of days of disturbance to changes in individual vital rates may not accurately reflect this relationship. Further research to develop more realistic relationships that can be parameterised with empirical data is urgently required to address this.

As noted in the Methods section and discussed in the section on interpretation of model outputs, we have not incorporated any form of density dependent response in the current version of the interim protocol. As a consequence, any additional mortality, or decline in fertility, caused by disturbance or PTS will result in a decrease in the size of the disturbed population compared to an identical undisturbed population that will persist for many years. Most of the standard procedures used to set limits on the number of animals that might die as a result of human activities, such as the PBR (Potential Biological Removals) formula that SMRU has use to advise the Scottish Government on the number of ‘unnatural’ deaths that a seal population can sustain, assume some form of density dependence. Therefore, ignoring density dependence will probably result in an over-estimate of the long-term effects of the disturbance associated with offshore renewable energy developments on marine mammal populations and thus can be considered precautionary.

Unfortunately, the only priority species for which we have strong evidence of density dependence is the grey seal. However, grey seal pup survival appears to be related to the density of animals at individual breeding colonies (Harwood & Prime 1978) rather than the size of the population within any of the MUs identified in Anon. (2013). Russell *et al*. (2013) have shown that grey seals from individual MUs on the east coast breed at many different colonies around the UK. As a result, the effect on a particular breeding colony of a decline in the size of the population in one of these MUs will be diluted by animals from other, unaffected MUs and so there is unlikely to be any concomitant increase in pup survival at that colony.

Density dependence is an emergent property of agent-based population models that use an individual’s energy budget to predict variations in its vital rates. Nabe-Nielsen *et al*. (2012) used a model of this kind to investigate the effects of operational noise associated with offshore wind farms on harbour porpoises in Danish waters, and the development of similar agent-based models for the priority species in UK waters would make it possible to incorporate realistic models of density dependence into the interim PCoD protocol.

ACKNOWLEDGEMENTS

Work on the development of the interim PCoD protocol benefited greatly from discussions with participants in a working group supported by Office of Naval Research grants N00014-09-1-0896 to the University of California, Santa Barbara and N00014-12-1-0274 to the University of California, Davis.

LITERATURE CITED

Anon.(2013). Management units for marine mammals in UK waters. Report of Interagency Marine Mammal Working Group established by UK Statutory Nature Conservation Agencies Chief Scientist Group.

Brandt, M., Diederichs, A, Betke, K., & Nehls, G. (2011). Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. *Marine Ecology Progress Series*, *421*, 205–216. doi:10.3354/meps08888

Burgman, M. A, McBride, M., Ashton, R., Speirs-Bridge, A., Flander, L., Wintle, B., … Twardy, C. (2011). Expert status and performance. *PloS one*, *6*(7), e22998. doi:10.1371/journal.pone.0022998

Cheney, B., Thompson, P. M., Ingram, S. N., Hammond, P. S., Stevick, P. T., Durban, J. W., … Costa, M. (2012). Integrating multiple data sources to assess the distribution and abundance of bottlenose dolphins Tursiops truncatus in Scottish waters. *Mammal Review*.

Delbecq, A.L., Van de Ven, A.H. & Gustafson, D.H. (1975). Group techniques for program planning: a guide to nominal group and Delphi processes. Glenview, IL: Scott, Foresmanand Company.

Donovan C.R., Harris C., Harwood J., & Milazzo L.A. (2012). Simulation-Based Method for Quantifying and Mitigating the Effects of Anthropogenic Sound on Marine Mammals. Acoustical Society of America; p. 070043. http://dx.doi.org/10.1121/1.4772738

Donovan, C., Harwood, J, King, S., Booth, C., Caneco, B., & Walker, C. (in press). Expert elicitation methods in quantifying the consequences of acoustic disturbance from offshore renewable energy developments. In: Popper AN, Hawkins AD (eds) Effects of Noise on Aquatic Life II. Springer, New York

Finneran, J. J., Schlundt, C. E., Branstetter, B. & Dear, R. L. (2007). Assessing temporary threshold shift in a bottlenose dolphin (*Tursiops truncatus*) using multiple simultaneous auditory evoked potentials. *Journal of the Acoustical Society of America*, 122(2), 1249–1264.

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., … DeAngelis, D. L. (2006). A standard protocol for describing individual-based and agent-based models. *Ecological Modelling*, *198*(1-2), 115–126. doi:10.1016/j.ecolmodel.2006.04.023

Harwood, J. & King, S. (in prep.)*The Sensitivity of UK Marine Mammal Populations to Marine Renewables Developments.* Report SMRUL-NER-2012-027 prepared by SMRU Ltd for the Natural Environment Research Council.

Harwood, J. & King, S. (2012). *Data Required to Implement an Interim and Full PCOD Approach*. Report number SMRUL-TCE-2012-031 to The Crown Estate October, 2012 (unpublished).

Harwood, J., King, S. & Schick, R. (2013). *An Analysis of the Sensitivity of Some Predictions from the Interim PCoD Framework to Uncertainty in Key Parameter Values*. Report number SMRUL-TCE-2013-012 to The Crown Estate March 2013 (unpublished).

Harwood, J., & Prime, J. H. (1978). Some factors affecting the size of British grey seal populations. *Journal of Applied Ecology*, *15*(2), 401–411.

Joint Nature Conservation Committee. (2007). Second Report by the UK under Article 17 on the implementation of the Habitats Directive from January 2001 to December 2006. Peterborough: JNCC. Available from: www.jncc.gov.uk/article17

Kahneman, D. (2012). Thinking, Fast and Slow. Penguin.

Lonergan, M. (2011). Potential biological removal and other currently used management rules for marine mammal populations: A comparison. *Marine Policy*, *35*(5), 584–589. doi:10.1016/j.marpol.2011.01.020

Lusseau D., Christiansen F., Harwood J., Mendes S., Thompson P.M., Smith K. & Hastie G.D. 2012. Assessing the risks to marine mammal populations from renewable energy devices – an interim approach. Report to NERC, JNCC, and CCW: Edinburgh, UK. 29pp. available at: https://ke.services.nerc.ac.uk/Marine/Members/Documents/Workshop outputs/CCW JNCC NERC workshop final report.pdf

MacMillan, D. C., & Marshall, K. (2006). The Delphi process - an expert-based approach to ecological modelling in data-poor environments. *Animal Conservation*, *9*(1), 11–19

Martin, T. G., Burgman, M. A., Fidler, F., Kuhnert, P. M., Low-Choy, S., McBride, M., & Mengersen, K. (2012). Eliciting Expert Knowledge in Conservation Science. *Conservation Biology*, *26*(1), 29–38.

Nabe-Nielsen, J., Tougaard, J., Teilmann, J., & Sveegaard, S. (2011). *Effects of wind farms on harbour porpoise behaviour and population dynamics*. Report commissioned by The Environmental Group under the Danish Environmental Monitoring Programme.

National Research Council. (2005). *Marine Mammal Populations and Ocean Noise: Determining when noise causes biologically significant effects*. The National Academy Press. Washington D.C.

Nedwell, J. R., Turnpenny, A. W. H., Lovell, J., Parvin, S. J., Workman, R., Spinks, J. A. ., & Howell, D. (2007). *A validation of the dB ht as a measure of the behavioural and auditory effects of underwater noise*. Subacoustech Report No. 534R1231.

New, L. F., Harwood, J., Thomas, L., Donovan, C., Clark, J. S., Hastie, G., Thompson, P. M., et al. (2013). Modelling the biological significance of behavioural change in coastal bottlenose dolphins in response to disturbance. *Functional Ecology* 27, 314-322.

New, L.F., Clark, J.S., Costa, D.P., Fleishman, E., Hindell, M.A., Klanjšček, T., Lusseau, D., Kraus, S., McMahon, C.R., Robinson, P.W., Schick, R.S., Schwarz, L.K., Simmons, S.E., Thomas, L., Tyack, P. & Harwood, J. (submitted) Using short-term measures of behaviour to estimate long-term fitness of southern elephant seals. *Marine Ecology Progress Series*.

Paxton, C. G. M., Mackenzie, M., & Rexstad, E. (2012).*Revised Phase III Data Analysis of Joint Cetacean Protocol Data Resource.* Report to Joint Nature Conservation Committee on Contract number C11-0207-0421 Centre for Research into Ecological and Environmental Modelling, University of St Andrews (pp. 170).

R Development Core Team. (2010). R: A language and environment for statistical computing. (Version 2.12).Vienna.: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org/

Runge, M. C., Converse, S. J. & Lyons, J. E. (2011). Which uncertainty? Using expert elicitation and expected value of information to design an adaptive program. *Biological Conservation,* 144, 1214-1223.

Russell, D. J. F., McConnell, B., Thompson, D., Duck, C., Morris, C., Harwood, J., & Matthiopoulos, J. (2013). Uncovering the links between foraging and breeding regions in a highly mobile mammal. *Journal of Applied Ecology*, *50*(2), 499–509. doi:10.1111/1365-2664.12048

Schick, R. S., New, L. F., Thomas, L., Costa, D. P., Hindell, M.A, McMahon, C. R., … Clark, J. S. (2013). Estimating resource acquisition and at-sea body condition of a marine predator. *Journal of Animal Ecology*. doi:10.1111/1365-2656.12102

Schlundt, C. E., Finneran, J. J., Carder, D. A., & Ridgway, S. H. (2000). Temporary shift in masked hearing thresholds (MTTS) of bottlenose dolphins and white whales after exposure to intense tones. *Journal of the Acoustical Society of America*, 107, 3496-3508.

SCOS. (2012). *Scientific Advice on Matters Related to the Management of Seal Populations : 2012*. NERC Special Committee on Seals. http://www.smru.st-and.ac.uk/documents/1199.pdf

SMRU (2012). Provisional regional PBR for Scottish seals in 2012. Report to Marine Scotland.

Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, J.J., Gentry, R.G., Greene, C.H., Kastak, D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, J.A., Tyack, P.L. (2007). Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. *Aquatic Mammals* 33, 411-521.

Sparling, C. & Lonergan, M. (2013). Collision risk modelling: Harbour seals and SeaGen at Strangford Lough. SMRU Ltd Report. February 2013 (unpublished).

Speirs-Bridge, A., Fidler, F., McBride, M., Flander, L., Cumming, G., & Burgman, M. (2010).Reducing overconfidence in the interval judgments of experts.*Risk Analysis*, *30*(3), 512–23.

Teilmann, J., & Carstensen, J. (2012). Negative long term effects on harbour porpoises from a large scale offshore wind farm in the Baltic—evidence of slow recovery. *Environmental Research Letters*, *7*(4), 045101. doi:10.1088/1748-9326/7/4/045101

Thompson, P. M., Hastie, G. D., Nedwell, J., Barham, R., Brookes, K. L., Cordes, L. S., & McLean, N. (2013). Framework for assessing impacts of pile-driving noise from offshore wind farm construction on a harbour seal population. *Environmental Impact Assessment Review*, *43*, 73–85. doi:10.1016/j.eiar.2013.06.005

Wade, P.R. (1998). Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. *Marine Mammal Science* 14(1), 1-37.

Winship, A.J. & Hammond, P.S. (2006). *Assessment of the dynamics and status of harbour porpoise populations in the North Sea and European Atlantic using a population model to synthesize information on life history, abundance and bycatch.*Appendix D1.2 to the Final Report on LIFE Project Number LIFE04NAT/GB/000245 Small Cetaceans in the European Atlantic and North Sea (SCANS-II).

APPENDIX 1: EXPERT ELICITATION PROCESS AND RESULTS

SUMMARY

We approached 150 leading experts in the field of marine mammal science. These experts were chosen because they actively work in the field of marine mammal population biology, on the impacts of noise on marine mammal hearing, or on the effects of disturbance on marine mammals. The criteria for the initial selection of experts were:

- Published on the population biology of one or more of the five priority species (or a closely related species) over the last 5 years
- Published on the impacts of noise on the hearing of one or more of the five priority species (or a closely related species) over the last 5 years
- Published on the effects of disturbance on one or more of the five priority species (or a closely related species) over the last 5 years

We also approached members of advisory groups that are involved with the conservation of any of the priority species, or closely related species (e.g. IUCN Seal Specialist Group, IUCN Cetacean Specialist Group, Society of Marine Mammalogists Conservation Committee, relevant ICES Working Group, and the UK Special Committee on Seals).

Forty-one experts (27%) completed the PCOD questionnaire, some for multiple species. The total number of questionnaires completed is shown in Figure A1.1.

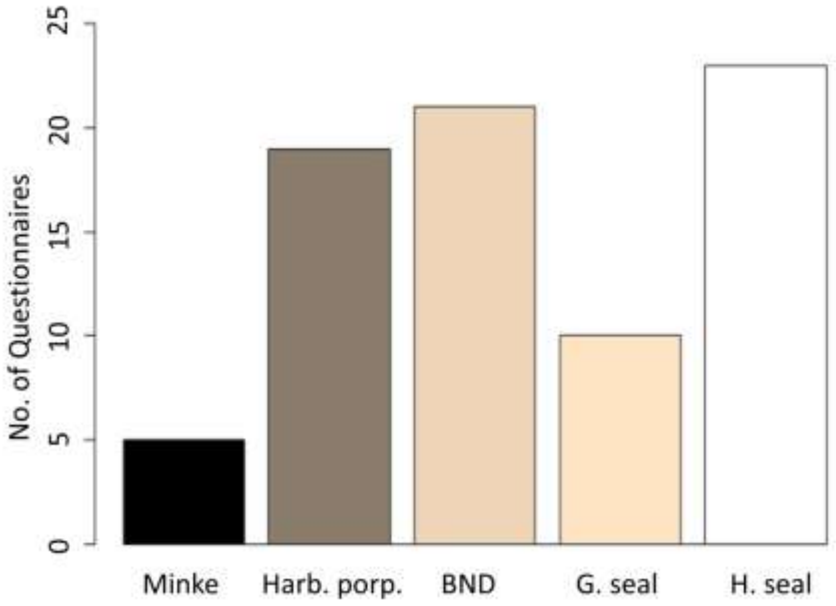

Figure A1.1. The number of questionnaires completed for each species (inclusive of all age classes) in the first round of expert elicitation for the interim PCoD framework.

ANALYTICAL APPROACH – NON-TECHNICAL SUMMARY

Expert elicitation seeks to accumulate opinions from experts about parameters for which there are currently few or no data. In this process each expert provides estimates of, and some indications of uncertainty surrounding, the parameters of interest.

In order to generate the most accurate and robust results, we used a 4-step method, based on the approach developed by Spiers-Bridge *et al*. (2010) for each question in our questionnaire (as recommended by Burgman *et al*. 2011). Using this established method, experts are asked for their estimates of the lowest and highest realistic value for the parameter in question, their best estimate of the parameter and their level of confidence that the interval they provided contains the true value.

Each expert was solicited for best estimates that reflected his or her understanding of two sets of parameters:

- the potential effect of hearing damage (a permanent shift in the threshold for hearing - PTS - in a specified frequency range) on survival and, for mature females, on the probability of giving birth and;
- three parameters that determined the relationship between the number of days of disturbance an individual might experience in a year and its survival and, for mature females, the probability of giving birth. Figure A1.2, below, shows how

these parameters determine the shape of the relationship between disturbance and survival or fertility. Parameter A defines the maximum effect of disturbance on survival (we assumed that the maximum effect of disturbance would be to reduce the probability of giving birth to zero), parameter B defines the amount of disturbance an individual can tolerate before it has any effect on survival or fertility, and C defines how many days of disturbance are required to have the maximum effect on survival or fertility.

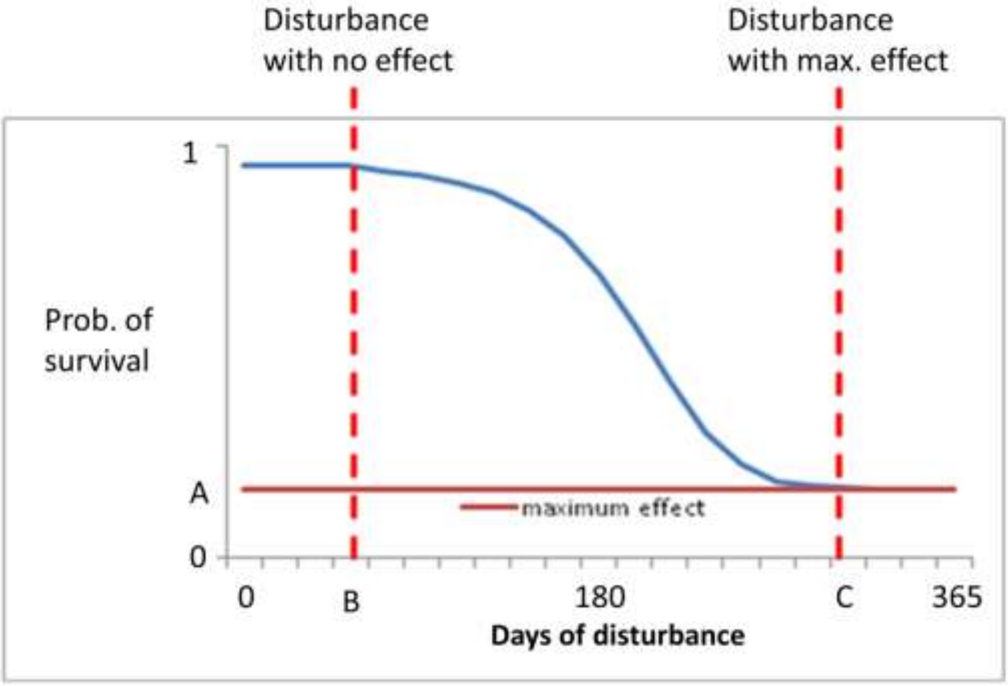

Figure A1.2. Hypothetical relationship between days of disturbance and the probability of survival.

Experts were also prompted to provide information on the confidence/uncertainty associated with their estimates. The uncertainty in the expert's estimates were provided by a) a range that 'bounds' the estimate and b) a level of confidence about their estimate. Statistical models that were consistent with each expert's best estimate and associated uncertainty were generated using some of the approaches described in Albert *et al*. (2010), Garthwaite *et al*. (2005), and Genest & Zidek (1986). For example, their best guess and bounds could define a triangular Probability Density Function (PDF), or lead to a particular Beta distribution. In this way, each expert's opinion was encapsulated in an individualised statistical distribution. All of the experts' distributions were then combined into an overall PDF, which was used to provide a representative sample of parameter values or as a set of random draws, as required. As discussed in Appendix 2, for each iteration of the model, the software selects a set of parameter values at random from these statistical distributions derived from the results of the expert elicitation process. This is equivalent to soliciting the opinions of one ‘virtual’ expert for each iteration and at least 500 random draws were conducted for each development scenario.

ANALYTICAL APPROACH – TECHNICAL SUMMARY

Two main outputs are required here: univariate distributions for single parameters (e.g. the effect of PTS at 1-2 kHz on the probability of survival), and bi- or trivariate distributions that characterise curves (e.g. the relationship between the number of days of disturbance and the probability of giving birth). These will be used in a Monte-Carlo fashion to provide inputs to the PCOD protocol (i.e. random draws will be required from these distributions).

For basic univariate treatments the experts’ estimates were used to fit Gamma, Beta, truncated Normal, Uniform or Triangular PDFs. For multivariate treatments, copula-based simulation methods were used (Iman & Conover, 1982). These allow a multivariate distribution of correlated variables to be defined using arbitrary marginal distributions and a separate correlation structure. The general process in these two cases is described below.

In the univariate case, where the parameter has a 0-1 bounded domain:

- The expert’s estimates were used to define Beta or Triangular PDFs.
- The individual distributions were combined as a weighted sum, subsequently normalised, to give a collected PDF for the parameter.

In the bi- and trivariate cases, where the parameters are a mix of 0-1 bounded and non-negative domains:

- The experts’ estimates were used to define Beta or Triangular distributions for the 0-1 bounded parameters.
- The experts’ estimates were used to define Gamma, Triangular or truncated Normal distributions for the 0-*infinity* bounded parameters.
- Correlation matrices were calculated for the sets of parameters.
- Collectively these distributions and matrices define the margins and correlation structure for the parameters, allowing copula methods to be applied. Correlation was provided by a truncated multivariate Normal distribution.
- Random draws from each expert’s multivariate distribution, which is a mix of estimated marginal distributions and governing correlation structure, could then be made.
- Experts’ multivariate distributions were sampled intensively, in proportion with their confidence, to build an overarching two- or three-dimensional PDF.

RESULTS

HARBOUR SEALS – MATURE FEMALES

1. What do you think would be the effect of experiencing PTS at around 1-2 kHz on the survival of a mature female?

Most experts felt that missing an octave wide band (1-2 kHz) in an animal's hearing would affect survival by less than 10%, but a few felt that it might have a larger effect (around 50%).

2. Do you think experiencing PTS at around 2-10 kHz will affect the survival of a mature female?

Most experts felt that missing a 2.5 octave wide band (2-10 kHz) in an animal's hearing would affect survival by less than 20%, but a few felt that it might have a larger effect (~50%).

3. Do you think experiencing PTS at around 1-2 kHz or 2-10 kHz will affect the probability that an adult female will give birth in the future?

Some experts suggested that PTS may reduce a female's ability to hear males calling during the breeding season and therefore there will be a reduced opportunity to find mates, leading to missed breeding opportunities. In addition, foraging efficiency might be reduced, leading to reduced body condition which may impact on fecundity and fertility. Expert opinion leant towards a change of less than 30% in fertility, but a wide range of values was suggested.

4. Disturbance curves: Are you able to indicate the minimum and maximum number of days of disturbance that a mature female can tolerate before it has any effect on the probability of giving birth and what do you think is the minimum and maximum number of days of disturbance that would be necessary to have the maximum effect, in which the probability of giving birth is reduced to zero?

Experts felt that disturbance which lasted for more than 20 days may result in reduced foraging efficiency and lead to reduced body condition and fertility. Some experts felt a female may not be able to encounter males during oestrus if she was displaced to unfamiliar locations as a result of chronic noise (disturbance) resulting in missed mating opportunities. Most experts believe that a substantial amount of disturbance

(150-280 days) was necessary to reduce the probability of giving birth down to 0.5, but some thought that this could occur at relatively low levels of disturbance (<50 days).

HARBOUR SEALS – JUVENILES

1. Do you think experiencing PTS at around 1-2 kHz or 2-10 kHz will affect the survival of a juvenile?

Most experts felt that missing an octave wide band at lower frequencies (1-2 kHz) or experiencing PTS in slightly higher frequencies (2-10 kHz) would not influence mortality, but some thought that animals would have a reduced ability to detect predators or other hazards, or reduced foraging efficiency leading to a decrease in survival of more than 20 %.

2. Disturbance curves: Are you able to indicate (i) the minimum and maximum number of days of disturbance that a juvenile can tolerate before survival is affected (ii) the lowest and highest plausible values for the maximum effect of disturbance on calf survival and (iii) the minimum and maximum number of days of disturbance that would cause this maximum effect.

Experts felt disturbance would affect juvenile survival due to the disruption of foraging (reduced time in prime foraging habitat) and problems associated with displacement to unfamiliar areas which would affect feeding behaviours and resting at known haul-out sites. One expert thought if a juvenile animal was disturbed, as well as experiencing a reduced ability to forage, the animal would be less able to detect predators. Most experts thought that about 50 days of disturbance would be required to have any effect on survival, and that the maximum effect of disturbance on survival would be to reduction to around 0.6. However, some experts thought that relatively small levels of disturbance (<50 days) could result in certain death.

HARBOUR SEALS – PUPS

1. Do you think experiencing PTS at around 1-2 kHz or 2-10 kHz will affect the survival of a pup?

Experts felt that PTS may cause separation between mother and pup or interfere with mother-pup vocal exchanges, resulting in starvation if separation was prolonged. Pups *may also be unable to detect hazards in air (predators) and water (vessels, turbines) or other anthropogenic impacts. Most experts thought that the reduction in survival would be less than 30%.*

2. Disturbance curves: Are you able to indicate (i) the minimum and maximum number of days of disturbance that a mother-calf pair can tolerate before pup survival is affected (ii) the lowest and highest plausible values for the maximum effect of disturbance on calf survival and (iii) the minimum and maximum number of days of disturbance that would cause this maximum effect.

Experts felt that disturbance would affect pup survival through reduced lactation opportunities if adult females spend more time alert and moving as a consequence of being disturbed. Experts also thought pup survival would be affected if mother and pup became separated when the mother moved to a new location as a result of disturbance and there would be interference with the mother-pup bond through vocal exchanges. Most experts thought that pups could tolerate around 20 days of disturbance before it had some effect on survival, but some believed this much disturbance could result in certain death. Others believed that much longer periods of disturbance were required to have the maximum effect on survival, and that the maximum reduction in survival ranged between 5 and 70%.

GREY SEALS – MATURE FEMALES

1. Do you think experiencing PTS at around 1-2 kHz or 2-10 kHz will affect the survival of a mature female?

Experts thought PTS may result in reduced forging efficiency through reduced ability to detect prey using passive acoustics (i.e. active listening), and thus poor condition in grey seal adult females. It may also lead to a reduced ability to detect predators and anthropogenic threats. Predicted effects on survival varied widely.

2. Do you think experiencing PTS at around 1-2 kHz or 2-10 kHz will affect the probability that an adult female will give birth in the future?

There were only a small number of responses for this question. Most experts thought that PTS may affect foraging efficiency leading to poor body condition and could result in a reduction in fertility of around 40%.

3. Disturbance curves: Are you able to indicate the minimum and maximum number of days of disturbance that a mature female can tolerate before it has

any effect on the probability of giving birth and what do you think is the minimum and maximum number of days of disturbance that would be necessary to have the maximum effect where the probability of giving birth is reduced to 0?

Experts felt disturbance may result in reduced foraging efficiency which could affect fertility and interfere with mating opportunities due to habitat displacement. One expert said 'changes in the probability of giving birth as a result of disturbance may occur due to reduced energy intake, resulting in reduced allocation of energy to foetus, and subsequently early abortion due to reduced energy intake'. There was broad agreement that animals could tolerate a small number of days of disturbance before it had any effect on fertility. However, some experts believed that 50 days of disturbance would reduce the probability of giving birth by 50%, whereas others thought that around 100 days would only reduce the probability of giving birth to 0.7 (i.e. a reduction of 0.3) .

GREY SEALS – JUVENILES

1. Do you think experiencing PTS at around 1-2 kHz or 2-10 kHz will affect the survival of a juvenile?

There were only a small number of responses for this species. *Experts thought PTS may result in inability to detect and avoid hazards in the environment, and a reduction in ability to detect prey using passive acoustics. This could result in a reduction in survival of around 50%.*

2. Disturbance curves: Are you able to indicate (i) the minimum and maximum number of days of disturbance that a juvenile can tolerate before survival is affected (ii) the lowest and highest plausible values for the maximum effect of disturbance on calf survival and (iii) the minimum and maximum number of days of disturbance that would cause this maximum effect.

Experts felt that between 10 and 100 days of disturbance would affect juvenile survival due to reduced foraging efficiency, leading to reduced body condition and even starvation. One expert said 'if animals were disturbed by a noise source and moved away from an area of residence then it would be exposure to predators that would likely increase mortality rather than any direct effect of noise'. Another expert felt that disturbance would result in a juvenile animal's inability to hear and avoid vessels and other potentially traumatic devices in the environment which would affect survival.

There was considerable uncertainty about the maximum effect of disturbance on survival and the number of days of disturbance necessary to cause this, although there was most support for a maximum reduction of 50-60% in the probability of survival.

HARBOUR PORPOISE – MATURE FEMALES

Note: Although some experts said that 1-2 kHz / 2-10kHz is at the lower end of the effective hearing range of porpoises, and well below the frequency range they use for echolocation, other experts pointed out that noise that was sufficiently loud to cause a TTS of 40dB (the criterion for PTS), was also likely to affect hearing at higher frequencies to some degree. Impairment at these higher frequencies would have effects on the likelihood of survival in harbour porpoises.

1. Do you think experiencing PTS at around 1-2 kHz or 2-10 kHz will affect the survival of a mature female?

Experts thought that PTS may reduce an animal's ability to detect predators, prey and hazards in the environment (particularly fishing gear), and affect communication. Most experts believed the effect on survival would be less than 20%, but some thought it could be as high as 40%.

2. Do you think experiencing PTS at around 1-2 kHz will affect the probability that an adult female will give birth in the future?

Experts thought PTS could result in reduced ability to communicate, reduced foraging efficiency and therefore reduced body condition, although, in general, the effects on fertility were likely to be less than 20%. Results for 2-10 kHz were similar to those for PTS at 1-2 kHz, although there was some support for larger effects on fertility (up to 40% or more).

3. Disturbance curves: Are you able to indicate the minimum and maximum number of days of disturbance that a mature female can tolerate before it has any effect on the probability of giving birth and what do you think is the minimum and maximum number of days of disturbance that would be necessary to have the maximum effect where the probability of giving birth is reduced to zero?

Most experts felt that disturbance lasting more than 50-100 days may result in reduced foraging efficiency which could affect fertility, or induce pregnancy failure, and interfere with mating opportunities due to habitat displacement. Experts also *highlighted that 'elevated stress levels as a result of being displaced from a known location may impact fecundity'. The maximum effect on the probability of giving birth was thought to be a 50% reduction.*

HARBOUR PORPOISE – JUVENILES

1. Do you think experiencing PTS at around 1-2 kHz will affect the survival of a juvenile?

Experts thought that PTS at 1-2 kHz or 2-10 kHz in juvenile harbour porpoise might reduce their ability to detect predators, their foraging efficiency and their ability to avoid anthropogenic hazards. Most predicted that the effect on survival would be less than 20%, but some felt this could be as high as 40% for 1-2 kHz and 60% for 2-10 kHz.

2. Disturbance curves: Are you able to indicate (i) the minimum and maximum number of days of disturbance that a juvenile can tolerate before survival is affected (ii) the lowest and highest plausible values for the maximum effect of disturbance on calf survival and (iii) the minimum and maximum number of days of disturbance that would cause this maximum effect.

Most experts felt disturbance lasting 20-100 days would affect juvenile survival due to reduced foraging efficiency, leading to reduced body condition and even starvation. Others felt 100-200 days disturbance would be required. Inexperienced animals were thought to be more likely to be disturbed and therefore experience a reduction in foraging success. Juvenile animals were thought to have very limited energy stores and therefore more susceptible to starvation. If animals were displaced to an unfamiliar area they have difficulties in finding "shelter" as well as food. Most believed that continuing disturbance could reduce survival by a maximum of 60%, but one expert believed that any disturbance lasting more than 20 days would result in certain death.

HARBOUR PORPOISE - CALVES

1. Do you think experiencing PTS at around 1-2 kHz or 2-10 kHz will affect the survival of a calf?

Experts thought PTS at 1-2 kHz may affect the ability of mothers and calves to stay in contact, which could have consequences for survival, and that the calf may be unable to detect predators or anthropogenic hazards. Most believed that the effects on survival would be less than10%, but some thought that they could be as high as 50%. Results for 2-10 kHz were similar to those for PTS at 1-2 kHz. However, one expert noted that 'If PTS is assumed to begin at 40 dB of TTS the hearing of the calf will also be impaired at higher frequencies, which in turn will increase the chance of losing contact to its mother (especially after disturbance).

2. Disturbance curves: Are you able to indicate (i) the minimum and maximum number of days of disturbance that a mother-calf pair can tolerate before calf survival is affected (ii) the lowest and highest plausible values for the maximum effect of disturbance on calf survival and (iii) the minimum and maximum number of days of disturbance that would cause this maximum effect.

Experts felt that 10-50 days of disturbance would affect calf survival if mothers and their calves were separated as a result of the mothers' response to disturbance, which would affect amount of milk transferred to the calf. This reduced food intake for the calf, coupled with an increased activity budget (following their mother's response to sound) could affect calf survival. Opinions were divided, however, on the maximum effects of disturbance on survival. Some believed that this was likely to be a reduction in survival of 80-100% and was likely to occur after 10-40 days of disturbance, whereas others believed that the maximum effect was likely to be a reduction in survival of 5-50%.

BOTTLENOSE DOLPHINS – MATURE FEMALES

1. Do you think experiencing PTS at around 1-2 kHz will affect the survival of a mature female?

Some experts thought PTS at 1-2 kHz for bottlenose dolphins may result in a reduction in an animal's ability to obtain prey (reduction in foraging efficiency) which would lead to poor body condition, but the predicted effects were less than 5%. Experts thought that PTS at 2-10 kHz for bottlenose dolphins may result in a reduction in an animal's ability to obtain prey (reduction in foraging efficiency) which would lead *to poor body condition, in an inability to hear conspecific whistles which would disrupt social behaviour and reduce the distance over which social cohesion is maintained, but most thought the effect of this on survival would be small.*

2. Do you think experiencing PTS at around 1-2 kHz or 2-10 kHz will affect the probability that an adult female will give birth in the future?

Experts thought PTS at 1-2 kHz would affect an animal's ability to capture prey and thus reduce foraging efficiency, reduce body condition and impact on fecundity such as pregnancy failure. Most thought that the effect on fertility would be less than 10%, and one expert thought there would be no long term impact from small PTS at these frequencies. Experts thought PTS at 2-10 kHz could affect an animal's ability to capture prey and thus reduce foraging efficiency, reduce body condition and have an impact on fertility, but the effect would be less than 20%. One expert thought that 'Given a small PTS, it would have little consequence in the long term. The TTS preceding it, which could last for days/weeks, would be the more severe issue if it affected reproductive effort by impeding social communication'.

3. Disturbance curves: Are you able to indicate the minimum and maximum number of days of disturbance that a mature female can tolerate before it has any effect on the probability of giving birth and what do you think is the minimum and maximum number of days of disturbance that would be necessary to have the maximum effect where the probability of giving birth is reduced to zero?

Experts felt disturbance could result in reduced foraging efficiency and displacement from critical foraging area that would place a severe strain on a female's energy budget; this might affect fertility or result in pregnancy failure. Experts also highlighted that 'elevated stress levels as a result of being displaced from a known location may impact fecundity'. There was wide variation in the number of days of disturbance that experts believed a female could tolerate before it would have any effect on fertility and in the number of days of disturbance required to reduce the probability of giving birth down to 0.5.

BOTTLENOSE DOLPHINS – JUVENILES

1. Do you think experiencing PTS at around 1-2 kHz or 2-10 kHz will affect the survival of a juvenile?

Experts thought that PTS at 1-2 kHz for bottlenose dolphin juveniles may result in a reduction in the animal's ability to obtain prey and thus a reduction in foraging *efficiency. One expert was not sure, but felt that some level of precaution should be applied, whereas another thought a small PTS at these frequencies would not affect survival. Experts thought that PTS at 2-10 kHz for bottlenose dolphin juveniles may result in a reduction in the animal's ability to obtain prey (through its effect on sensory biology – echolocation) and thus a reduction in foraging efficiency. There were potential social effects if it reduced the animal's ability to detect conspecific whistles. Most thought that the effect would be less than 10%, and one expert thought the effect would be negligible.*

2. Disturbance curves: Are you able to indicate (i) the minimum and maximum number of days of disturbance that a juvenile can tolerate before survival is affected (ii) the lowest and highest plausible values for the maximum effect of disturbance on calf survival and (iii) the minimum and maximum number of days of disturbance that would cause this maximum effect.

Experts felt that disturbance in excess of 50 days could affect juvenile survival due to reduced foraging efficiency and increased stress levels, leading to reduced body condition. One expert said disturbance may disrupt a juvenile learning foraging behaviours and will disrupt social interactions. Most experts believed that the maximum effect of disturbance would be to reduce survival by less than 10%.

BOTTLENOSE DOLPHINS – CALVES

1. Do you think experiencing PTS at around 1-2 kHz or 2-10 kHz will affect the survival of a calf?

Experts thought that PTS at 1-2 kHz for bottlenose dolphin calves may result in an increased risk of losing contact with their mother, which could lead to starvation. One expert thought a small PTS at these frequencies would not affect survival. Experts thought that PTS at 2-10 kHz for bottlenose dolphin calves may result in an increased risk of losing contact with their mother which could lead to starvation. One expert thought a small PTS at these frequencies would not affect survival but that the TTS that precedes it is more likely a factor, depending on the magnitude and duration of the shift.

2. Disturbance curves: Are you able to indicate (i) the minimum and maximum number of days of disturbance that a mother-calf pair can tolerate before calf survival is affected (ii) the lowest and highest plausible values for the maximum

effect of disturbance on calf survival and (iii) the minimum and maximum number of days of disturbance that would cause this maximum effect.

Experts felt that disturbance could affect calf survival if it exceeded 30-50 days, because it could result in mothers becoming separated from their calves and this could affect the amount of milk transferred from the mother to her calf. One expert said 'in instances where masking or a threshold shift may also occur, the reuniting of a separated mother-calf pair may be impeded'. Opinions were divided on the maximum effect of disturbance on survival: some suggested that this was likely to be around 80%, whereas others thought it would be around 30%. One expert thought that < 10 days of disturbance would result in the probability of survival dropping to 10%.

MINKE WHALES – MATURE FEMALES

1. Do you think experiencing PTS at around 1-2 kHz or 2-10 kHz will affect the survival of a mature female?

Experts thought that PTS may affect minke whale mature female survival if it impairs the animal's ability to detect acoustic indications of predators and prey fields for foraging. This would lead to poor condition and ultimately affect survival. Predicted effects varied from a 90% reduction in survival probability to no effect, with most support for a reduction of less than 20%.

2. Do you think experiencing PTS at around 1-2 kHz or 2-10 kHz will affect the probability that an adult female will give birth in the future?

Experts thought PTS at 1-2 kHz may affect fertility in mature female minke whales if it impacts on mating opportunities or if reduced foraging means reduced body condition which affected pregnancy, specifically 'Disturbance of feeding activity will reduce the body condition of the female which will lower the amount of energy the female can invest in the foetus. If her body condition becomes very poor the only way for the female to [compensate] is to reduce investment in the foetus. Predicted effects varied widely between a 5% and a 90% reduction in probability of giving birth, although there was most support for a reduction of less than 40%. Opinions about the effect of PTS at 2-10 kHz were more consistent than for 1-2 kHz, with most experts suggesting a reduction in the probability of giving birth of less than 20%.

3. Disturbance curves: Are you able to indicate the minimum and maximum number of days of disturbance that a mature female can tolerate before it has any effect on the probability of giving birth and what do you think is the

minimum and maximum number of days of disturbance that would be necessary to have the maximum effect where the probability of giving birth is reduced to zero?

Experts felt disturbance may result in reduced feeding and an increase in energetic costs of movement and therefore a reduction in body condition and elevated stress levels, if disturbance exceeded for 10-100 days it could affect fertility. One expert suggested that 'reduced body condition will have a negative effect on foetus growth which will reduce the size of the calf at birth and consequently calf survival. If the reduction in energy investment in foetus is large enough then foetus would be aborted'.

DISCUSSION

The results from this round of expert elicitation have provided us with a preliminary set of parameter values for the relationships between injury (onset of PTS), disturbance and vital rates for the five priority species that we can use for a preliminary implementation of the PCOD protocol. However, it is clear from the expert elicitation literature and from face-to-face discussions with Professor Mark Burgman (Director of the Australian Centre of Excellence for Risk Analysis, University of Melbourne) that we would obtain more robust and reliable estimates of these parameters by adopting the Delphi process (as used, for example, by MacMillan & Marshall (2006) in a study of the environmental requirements of capercaillie in Scotland). We therefore consulted the same panel of experts again, showed them the results from the first round of the elicitation and asked them if they would like to modify their original responses. Any modified responses were then used in the final analysis, instead of the experts' original responses.

GENERAL COMMENTS ON THE PCOD QUESTIONNAIRE

Here we provide a short summary of the points and concerns raised by experts as part of elicitation process. A number of experts provided feedback on what they felt was either missing from the questionnaire, or was not properly assessed.

The most common concern raised was the treatment of the degree of PTS onset, or lack thereof. Experts rightly pointed out that PTS is not synonymous with profound or total hearing loss and that a PTS of less than 3 dB would probably be imperceptible to an animal as loss, whereas a PTS of 60 dB could have significant impacts. Experts felt the more relevant effect is the magnitude and duration of the preceding TTS. We certainly agree with this point in the general sense and we have already acknowledged that the impact will differ depending on the degree of threshold shift in the PCoD background information that was provided alongside the questionnaire. For the purpose of the questionnaire, however, it was decided that it would be too difficult to provide a range of threshold shifts or, given the uncertainty surrounding PTS onset, try and force an agreement on what level of threshold shift would cause a significant impact or not. In the context of environmental impact assessments and currently applied noise exposure criteria, we wanted to know the potential effects on an animal exposed to an SEL that is 20dB or more above the threshold for TTS onset (i.e. the level recommended by Finneran & Jenkins (2012) for calculating the likely onset of PTS); we fully admit that currently we have no idea what kind of shift in hearing threshold this will actually induce and this does highlight that further research in this area is needed.

Another point raised was that the absence of frequency bands for PTS made it difficult to provide a likely impact. For example, some experts suggested that impacts for harbour porpoise are likely to be far more severe for higher frequency sources and that there were unlikely to be many acoustic signals of interest in the 1-10 kHz region. Although some experts said that 1-2 kHz / 2-10kHz is at the lower end of the effective hearing range of porpoises, and well below the frequency range they use for echolocation, other experts pointed out that noise that was sufficiently loud to cause a TTS of 40dB (the criterion for PTS), was also likely to affect hearing at higher frequencies to some degree. Impairment at these higher frequencies would have effects on the likelihood of survival of some species.

A few experts also noted their dissatisfaction with the definition of disturbance and felt exposure time needed to be better defined for them to be able to judge the effects on the animals. It is correct, for example, that a 1-hour exposure would have a different effect than a 300 day exposure. We have, however, discussed the difficulties in presenting a number of different scenarios and we treated disturbance in number of days, rather than number of hours, as this was thought to be a time period that was salient to the animal in terms of measuring population level effects over a number of years.

One expert felt that the probability of giving birth was not a reasonable metric for assessing the effect of PTS on an animal’s vital rates. They felt that adult females with hearing difficulties may still reproduce but that it would be less likely that they would raise the calf to maturity. We feel our approach still accounts for this, whether the calf/pup is born and dies or is not born at all, we still see a reduction in surviving calves/pups that are recruited into the population.

Some experts also raised the point that disturbance and PTS may lead to elevated stress levels which may also incur a fitness cost and have population level impacts. We certainly agree with this and the effect of stress on individuals and populations does warrant further investigation. However, given that estimates of stress are not provided in developers ES chapters it was out with the scope of this approach, at least for now.

Finally, one expert was concerned that the lack of information on parameters asked in the questionnaire made the results of the expert elicitation very questionable. They felt there was a risk of giving regulators the wrong impression of certainty and they hoped that this uncertainty would be reflected in the outcome of the study. We have indeed discussed the different measures of uncertainty inherent in this interim approach in the full report and have highlighted the need for further research.

LIST OF THE EXPERTS WHO PARTICPATED IN THE PCOD QUESTIONNAIRE

Expert	**Affiliation**
Ailsa Hall	SMRU, University of St Andrews
Ben Wilson	SAMS
Carol Sparling	SMRU Marine Ltd, University of St Andrews
Clive McMahon	Charles Darwin University, Australia
Cormac Booth	SMRU Marine Ltd, University of St Andrews
Darlene Ketten	WHOI, USA
Dave Thompson	SMRU, University of St Andrews
David Lusseau	University of Aberdeen
Dorian Hauser	National Marine Mammal Foundation, US
Elizabeth Slooten	University of Otago, New Zealand
Enrico Pirotta	University of Aberdeen
Fredrick Christiansen	University of Aberdeen
Frances Gulland	Marine Mammal Centre, Sausalito, US
Garry Stenson	Fisheries and Oceans Canada
Gordon Hastie	SMRU, University of St Andrews
Isabelle Charrier	CNRS, France
Jacob Nabe Nielsen	Arhus University, Denmark
Jacob Tougaard	Arhus University, Denmark
John Harwood	SMRU Marine Ltd, University of St Andrews
John Terhune	University of New Brunswick, Canada
Jonas Teilmann	Arhus University, Denmark
Klaus Lucke	IMARES, Holland
Leslie New	Marine Mammal Commission, US
Lisa Schwarz	University of California, Santa Cruz, US
Luke Rendell	SMRU, University of St Andrews
Marla Holt	NWFSC, US

Mike Hammill	Fisheries and Oceans Canada
Mike Weise	Office Naval Research, US
Patrick Miller	SMRU, University of St Andrews
Paul Nachtigall	University of Hawaii
Paul Thompson	University of Aberdeen
Petter Kvadsheim	Norwegian Defense Research Establishment (FFI)
Philip Hamilton	New England Aquarium, US
Rob Harcourt	University of Macquarie, Australia
Rob Schick	CREEM, University of St Andrews
Rob Williams	Oceans Initiative
Sophie Smout	SMRU, University of St Andrews
Stephanie Watwood	NUWC Newport, US
Tim Ragen	Marine Mammal Commission, US
Ulf Lindstrøm	Institute of Marine Research, Norway
Veronique Lesage	Fisheries and Oceans Canada

APPENDIX 1 – LITERATURE CITED

Albert, I., Donnet, S., Guihenneuc-Jouyaux, C., Low-Choy, S., Mengersen, K and Rousseau, J. (2012).Combining Expert Opinions in Prior Elicitation.*Bayesian Anal*. 7(3), 503-532.

Burgman, M. A., McBride, M., Ashton, R., Speirs-Bridge, A., Flander, L., Wintle, B., Fidler, F., et al. (2011).Expert status and performance.*PloS one*, *6*(7), e22998.doi:10.1371/journal.pone.0022998

Finneran, J. J., & Jenkins, A. K. (2012). *Criteria and Thresholds for U . S . Navy Acoustic and Explosive Effects Analysis*. SPAWAR Marine Mammal Program.

Garthwaite, P.H., Kadane, J.B. and O'Hagan, A. (2005).Statistical Methods for Eliciting Probability Distributions.*Journal of the American Statistical Association*. 100(470), 680-701. DOI:10.1198/016214505000000105

Genest, C. and Zidek, J.V. (1986).Combining Probability Distributions: A Critique and an Annotated Bibliography.Statist. 1(1), 114-135.

Iman, R. L. & Conover, W. J. (1982).A distribution-free approach to inducing rank correlation among input variables. *Communications in Statistics – Simulation and Computation.11(3).*

MacMillan, D. C., & Marshall, K. (2006). The Delphi process - an expert-based approach to ecological modelling in data-poor environments.*Animal Conservation*, *9*(1), 11–19.

Speirs-Bridge, A., Fidler, F., McBride, M., Flander, L., Cumming, G., & Burgman, M. (2010). Reducing overconfidence in the interval judgments of experts.*Risk Analysis*, *30*(3), 512–23. doi:10.1111/j.1539-6924.2009.01337.x

APPENDIX 2: STRUCTURE OF THE INTERIM PCOD MODEL

The interim PCoD approach uses the same stochastic population dynamic modelling framework as population viability analysis (PVA) - see, for example, Morris & Doak (2002) - and we have adopted the terminology used by Morris & Doak in describing its details. PVAs are generally carried out to estimate the probability that a population will become extinct, or fall below some critical population size, over a defined time horizon. However, the same general approach can be used to model any series of population events where small numbers and uncertainty are expected to play a large role.

We divide each population that we model into 10 age or stage classes:

- pups or calves (depending on the species being modelled),
- one-year olds,
- two-year olds,
- etc., up to age eight,
- all animals aged nine years and above, combined into a single stage class.

Each of these classes is divided into six disturbance categories. First, we divide animals on the basis of whether or not they have experienced PTS. Within each of these two broad classes, we further divide animals into those that have experienced no disturbance, and those that have experienced ‘significant’ disturbance that is sufficient to affect their chances of survival or, in the case of adult females, giving birth. Finally, we divide animals in the significant disturbance classes into two categories depending on whether they have experienced ‘moderate’ or ‘high’ levels of disturbance. This results in the following six disturbance categories:

(1) Animals that experience PTS
  - but no significant disturbance
  - and ‘moderate’ levels of disturbance
  - and ‘high’ levels of disturbance

(2) Animals that do **not** experience PTS
  - and experience no significant disturbance
  - but do experience ‘moderate’ levels of disturbance
  - but do experience ‘high’ levels of disturbance

The criteria for assigning animals to each of these categories are described in the next section. Animals that experience disturbance in one year are reassigned to the relevant undisturbed age or stage class at the beginning of the next year. However, animals that experience PTS remain in one of the PTS categories throughout their simulated lives.

The six disturbance categories and 10 age/stage classes result in 60 age-disturbance combinations that are modelled as a 60-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 age/stage class to the next one at the end of the year. 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. This has two implications: the start date for a year of simulation should coincide with the time at which most pups/calves are born, and changes in numbers within a year have to be modelled separately. We discuss the way we have dealt with the second implication in the next section. The first implication can be addressed by starting the year on 1 June for all the priority species except grey seals, which pup in October/November. The model is run using numbers of females only. The simulated population is scaled to the full population at the end of the simulations assuming a 50:50 sex ratio, except in the case of grey seals, whose population structure is believed to be strongly skewed towards females as a result of the high mortality suffered by male pups (Hall *et al*. 2001).

In the current implementation we model the dynamics of each population over a period of 24 years (equivalent to four of the six-year reporting cycles specified in Article 11 of the Habitats Directive).

Simulations are conducted using code written in the R statistical computing environment (R Development Core Team 2010).

DEFINING VULNERABLE SUB-POPULATIONS AND THE PROBABILITIES OF EXPERIENCING DISTURBANCE AND PTS

It is quite possible, and highly likely for large MUs, that only a proportion of the population within an MU will spend time in the region around a particular development where sound exposure levels are sufficiently high that they will cause a behavioural response. We have therefore included a capability within the protocol to specify the proportion (which can, of course, be 1.0 - i.e., all animals in the population are vulnerable) of the population that is vulnerable to disturbance from each development. We refer to this as a vulnerable sub-population of the population of animals within an MU. It is possible to specify that members of a particular vulnerable sub-population may be affected by more than one development. We assume that individuals who are not part of a vulnerable sub-population are never exposed to disturbance associated with any of the developments being modelled.

We simulate the likely exposure to disturbance of up to 1000 individuals from each vulnerable sub-population on each day of construction or operation. Each individual in a vulnerable sub-population is assumed to be equally likely to be disturbed on each day of construction or operation. The probability that it will be disturbed is calculated from the ratio of the number of animals expected to experience disturbance (as provided in the developers ES) to the size of the vulnerable sub-population from the appropriate MU. We assume that animals are only likely to experience PTS if they also experience disturbance. We therefore calculate the probability that a disturbed animal would experience PTS from the ratio of number of animals expected to experience PTS to the number expected to experience disturbance (as provided in the developer's ES).

MODELLING DISTURBANCE AND PTS WITHIN A YEAR

There is considerable evidence (Brandt *et al.,* 2011; Teilmann & Carstensen, 2012) that harbour porpoises which have been disturbed by piling noise do not return to the area where piling occurred until some time (days to years) after piling ceases. We therefore assume that all of the priority species are likely to show this 'residual' effect of disturbance, and that 'residual disturbance' has the same negative effect on an individual's vital rates as that caused by the initial disturbance. Users of the protocol can specify how many days of residual disturbance are associated with each day of actual disturbance. Individuals exhibiting residual disturbance are assumed not to be vulnerable to PTS or any additional direct disturbance associated with construction or operation during the time they are experiencing this effect.

The basic model outlined above assumes that animals are at risk of PTS every time they enter the region where they may be disturbed by construction or operational noise. However, that risk is likely to be small, unless they are very close to the piling operation. It is therefore possible that they will avoid the immediate vicinity of operations after they have been disturbed once. We have therefore included a capability to model a scenario in which animals are only at risk of experiencing PTS on the first day they experience a sound exposure level sufficient to cause disturbance. The probability of experiencing PTS can be modelled in many ways; we have implemented only a few of these and we are not proposing that any one of them is definitive.

The within-year model estimates the potential exposure to disturbance for each individual in a vulnerable sub-population by conducting a random Bernoulli trial on each day that construction or operation is specified to take place using the probability of disturbance. If a simulated individual is scored as having experienced disturbance, a second Bernoulli trial is conducted using the probability that a disturbed animal will experience PTS. These within-year simulations therefore provide a day-by-day history of the exposure to sound levels sufficient to cause disturbance, ‘residual’ disturbance, and exposure to sound levels sufficient to cause PTS for every individual in each vulnerable sub-population. These histories are summarised to provide information on the total number of days of disturbance each individual experienced and whether or not it had suffered PTS. This information is then used to determine whether or not the simulated animals have experienced ‘significant’ disturbance and at what level using the criteria described below.

Figure A2.1 illustrates the process by which the number of animals in each age/stage class and disturbance category are calculated, and how the different sources of uncertainty are incorporated in the protocol.

MODELLING UNCERTAINTY

The interim PCoD protocol attempts to model many of the major sources of uncertainty involved in the calculation of the potential effects of an offshore renewable energy development on a population of marine mammals. These are:

1. Uncertainty about the size of the population in a particular MU;
2. Uncertainty about what proportion of that population will be vulnerable to the effects of a particular development;
3. Uncertainty in the predictions of the number of animals that will experience disturbance and PTS as a result of one day of construction or operation;
4. Uncertainty about predictions of the total number of days of disturbance an individual animal will experience during the course of construction of a development and of the total number of animals that will experience PTS;
5. Uncertainty about the effects of disturbance and PTS on vital rates;
6. 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 and PTS depend, among other things, on the estimate of total population size that is used in the calculation. The population-level effects of these numbers are determined by uncertainty about what proportion of the population is actually exposed to the sources of disturbance on a particular day. This is not the same as the proportion of the total population that is *potentially* vulnerable to these effects, it is the proportion of that vulnerable population that is exposed to the disturbance on a given day. Uncertainty about estimates of the proportion of animals within a population that is likely to occur within “areas of interest for offshore development where estimates of abundance are of special conservation interest" (see Figure 2 of Paxman *et al.* 2012) identified by the SNCBs for the three cetacean priority species (harbour porpoise, bottlenose dolphin and minke whale) are being determined as part of the continuing analysis of data collected under the Joint Cetacean Protocol. In the North Sea, these "areas of interest" correspond roughly to the Round 3 zones for offshore wind farms. These uncertainty estimates can therefore be used to provide an indication of the uncertainty that is likely to be associated with estimates of the proportion of animals within a population that is likely to be exposed to disturbance associated with the construction of these wind farms. Preliminary estimates (Paxton, pers. comm.) have suggested that the 95% confidence limits on the proportion of animals within an "area of interest" are approximately ± 50% of the mean value. We have therefore tried to capture this uncertainty by multiplying the estimate of the number of animals predicted to experience disturbance on one day of construction or operation 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 operation, 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).

We could find no empirical basis for modelling uncertainty in item 2. Instead, we have presented the results of simulations using a number of different assumptions for this parameter.

Some of the uncertainty in item 4 was modelled by treating the exposure of each simulated animal to the noise associate with a particular development as a series of Bernoulli trials. This resulted in each simulated individual experiencing a different history of sound exposure. We could find no empirical basis for modelling uncertainty in how long the effects of disturbance may persist or in how prior exposure to construction noise may affect the risk of experiencing PTS. For simplicity, we have used only one model in the illustrative examples that we present in this report. It assumes that the effects of 1 day of actual disturbance persist for a further 2 days and that individuals are always at risk of experiencing PTS when they within the sound field generated by construction activities. However, we investigated the implications of these assumptions for selected scenarios.

Uncertainty in item 5 was modelled by drawing at random from statistical distributions derived from the results of the expert elicitation process. For each iteration of the model, the software selects a set of parameter values at random from these distributions. This is equivalent to soliciting the opinions of one 'virtual' expert for each iteration. These values determine the number of days of disturbance required to have a ‘moderate’ and ‘high’ effect on vital rates, the effects of this disturbance on those vital rates, and the effects of PTS on survival and fertility. At least 500 random draws were conducted for each development scenario.

Year to year variations in environmental conditions are likely to affect the survival and fertility rates for all individuals in a population. We modelled this environmental variation 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 many survival and fertility rates for marine mammals are close to 1.0 it is not possible for them to vary symmetrically around the mean from year to year. We therefore modelled environmental variation in each demographic rate using a beta distribution, whose mean corresponded to the baseline value used in the protocol and whose variance was adjusted so that the lower 99% confidence limit corresponded to the mean percentage value chosen by the experts. We assumed that variation in demographic rates was uncorrelated, both among age/stage classes and among years. Table A2.1 summarises the values we used.

Demographic stochasticity is caused by the fact that, even if survival and fertility rates are constant, the number of animals in a population that die and give birth will vary from year to year because of chance events. Demographic stochasticity has its greatest effect on the dynamics of relatively small populations, and we have incorporated it in models for all situations where the estimated population within an MU is less than 3000 individuals. One consequence of demographic stochasticity is that two otherwise identical populations that experience exactly the same sequence of environmental conditions will follow slightly different trajectories over time. As a result, it is possible for a ‘lucky’ population that experiences disturbance effects to increase, whereas an identical undisturbed but ‘unlucky’ population may decrease.

Table A2.1. Values used to describe environmental variation in demographic rates. Each value represents the lower 99% confidence limit for the rate, expressed as a percentage of the mean. We did not ask experts for their opinion about the level of environmental variation in calf and juvenile survival rates for minke whales, because these age classes are rarely observed in UK waters. However, we required these values to simulate the full dynamics of the population, and we therefore used the same values as those provided by the experts for bottlenose dolphins. *Grey seal pups were treated as juveniles (i.e. independent of their mothers) as when they are pups (i.e. dependent on their mothers) they do not enter the water to a great extent and therefore are not exposed to the same level of disturbance associated with offshore renewable energy developments as adults and juveniles.

Species	**Pup/calf survival**	**Juvenile survival**	**Adult fertility**
Harbour Seal	30%	30%	25%
Grey Seal	30%*	30%	20%
Bottlenose dolphin	25%	20%	30%

Harbour Porpoise	25%	30%	25%
Minke Whale	(25%)	(20%)	20%

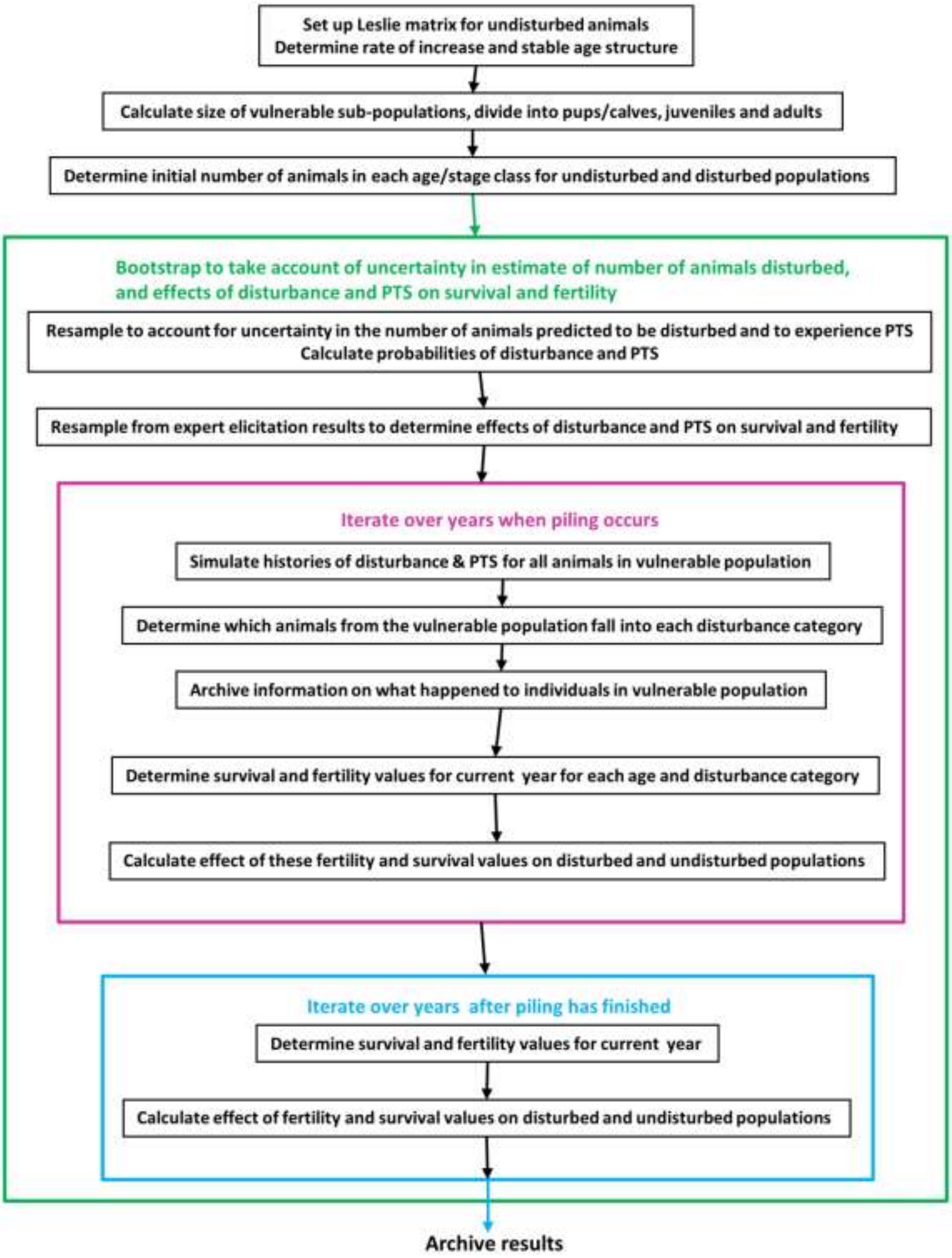

Figure A2.1. The calculations involved in the interim PCoD protocol, illustrating how uncertainty is captured.

APPENDIX 2 - LITERATURE CITED

Brandt, M., Diederichs, A, Betke, K., & Nehls, G. (2011). Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. *Marine Ecology Progress Series*, *421*, 205–216. doi:10.3354/meps08888

Caswell, H. (2001). *Matrix Population Models: Construction, Analysis and Interpretation*. 2nd Ed. Sinauer Associates, Sunderland, MA.

Hall, A.J. , McConnell, B.J..& Barker, R.J. (2001). Factors affecting first-year survival in grey seals and their implications for life history strategy. *Journal of Animal Ecology. 70*, 138-149.

Morris, W.F. & Doak, D.F. (2002).*Quantitative Conservation Biology*. Sinauer Associates, Sunderland, MA.

Nedwell, J. R., Turnpenny, A. W. H., Lovell, J., Parvin, S. J., Workman, R., Spinks, J. A. ., & Howell, D. (2007). *A validation of the dB ht as a measure of the behavioural and auditory effects of underwater noise*. Subacoustech Report No. 534R1231.

Paxton, C. G. M., Mackenzie, M., & Rexstad, E. (2012).*Revised Phase III Data Analysis of Joint Cetacean Protocol Data Resource.* Report to Joint Nature Conservation Committee on Contract number C11-0207-0421. Centre for Research into Ecological and Environmental Modelling , University of St Andrews (pp. 170).

R Development Core Team. (2010). R: A language and environment for statistical computing. (Version 2.12).Vienna.: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org/

Teilmann, J., & Carstensen, J. (2012). Negative long term effects on harbour porpoises from a large scale offshore wind farm in the Baltic—evidence of slow recovery. *Environmental Research Letters*, *7*(4), 045101. doi:10.1088/1748-9326/7/4/045101

APPENDIX 3: DETAILED RESULTS FROM SCENARIOS FOR OTHER PRIORITY SPECIES

MORAY FIRTH HARBOUR SEALS

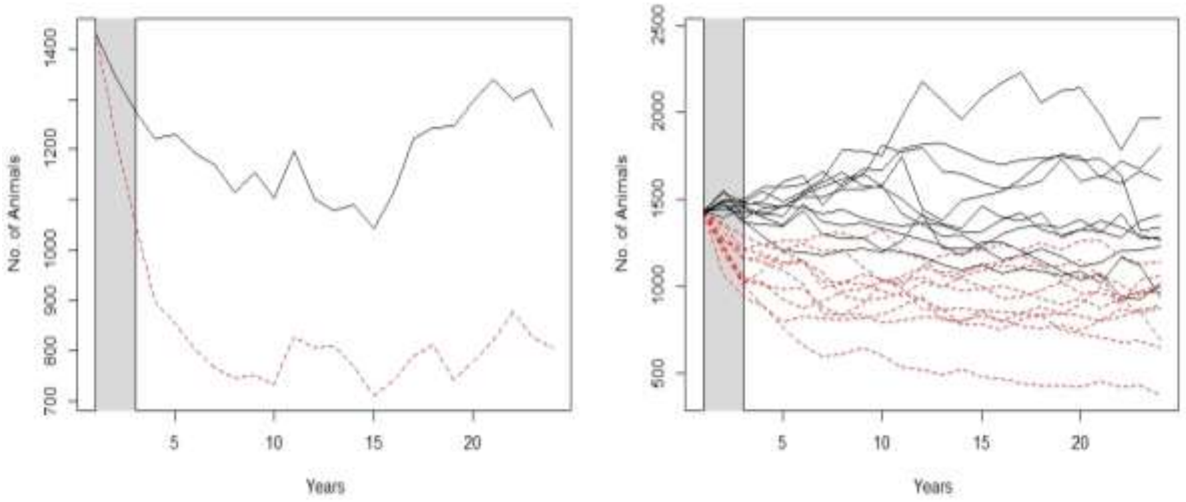

Figure A3.1. Examples of the predicted changes in abundance of the harbour seal population in the Moray Firth MU in the 24 years following the construction of two hypothetical wind farms. The left panel shows the trajectory of one disturbed population (shown as red dotted line) and the matching undisturbed population (shown as black solid line). The right panel shows the trajectories of 10 disturbed (shown as red dotted lines) and undisturbed (shown as black solid lines) populations.

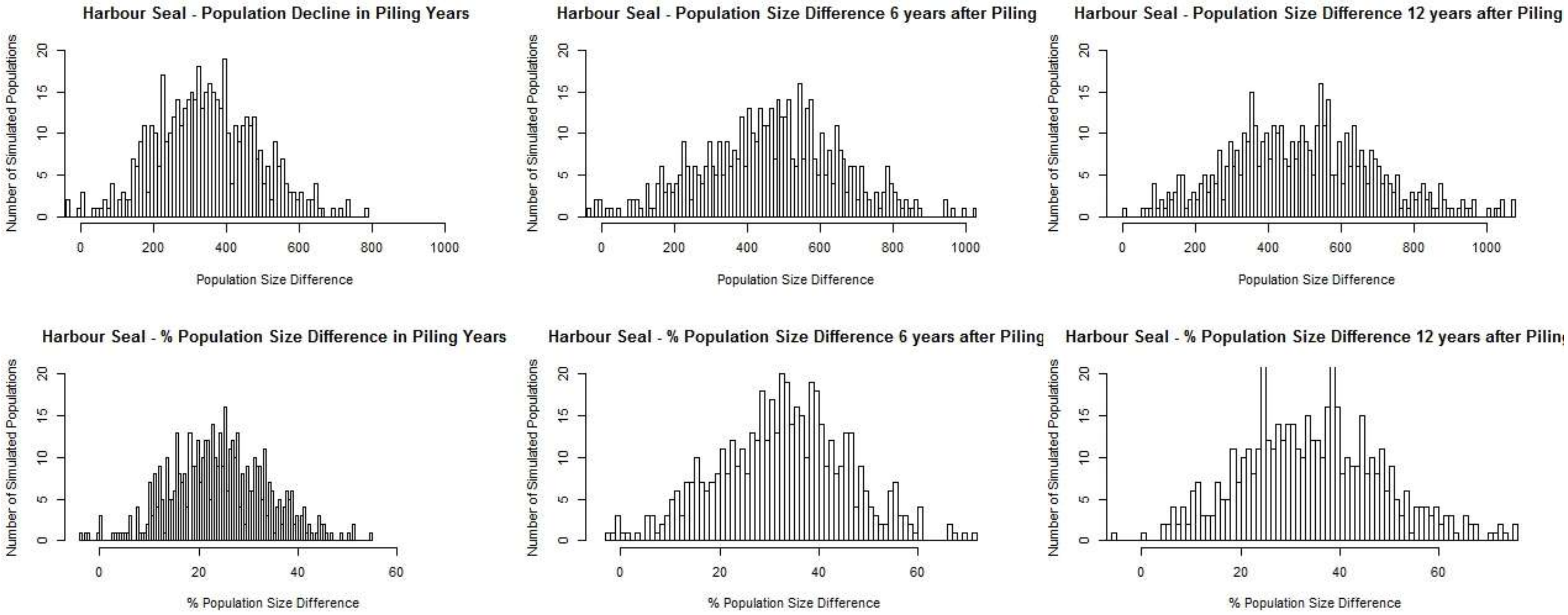

Figure A3.2 The predicted effects of disturbance and injury associated with the construction of two hypothetical wind farms on 500 simulated harbour seal populations when all of the population is vulnerable to the effects associated with both wind farms. Upper panels show the predicted differences between the size of the undisturbed and disturbed populations immediately after construction, and at 6-year intervals thereafter. Positive values indicate that the disturbed population is smaller than the undisturbed one. The lower panels show these differences expressed as a percentage of the initial population size.

MORAY FIRTH GREY SEALS

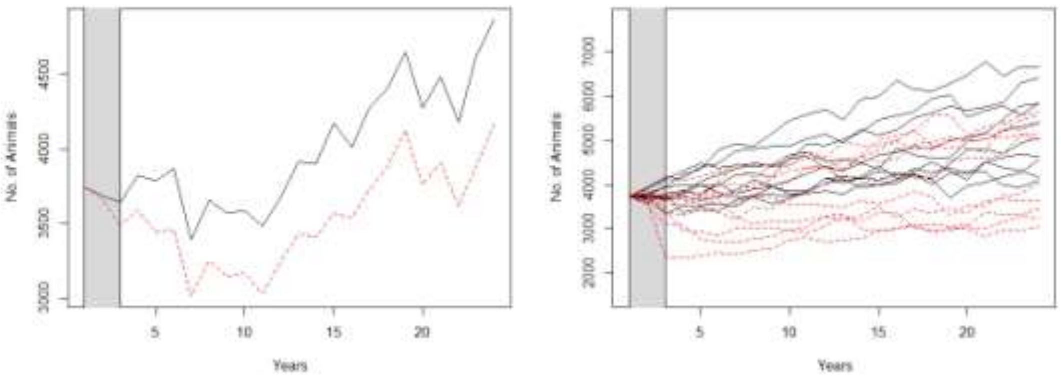

Figure A3.5 Examples of the predicted changes in abundance of the grey seal population in the 24 years following the construction of two hypothetical wind farms when all of the population is considered vulnerable. The left panel shows the trajectory of one disturbed population (shown as red dotted line) and the matching undisturbed population (shown as black solid line). The right panel shows the trajectories of 10 disturbed (shown as red dotted lines) and undisturbed (shown as black solid lines) populations.

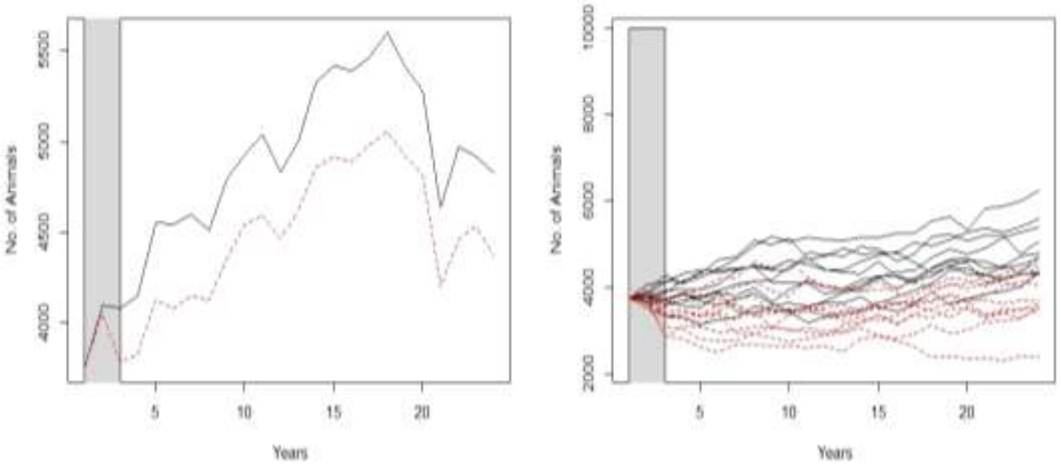

Figure A3.6 Examples of the predicted changes in abundance of the grey seal population in the 24 years following the construction of two hypothetical wind farms when 50% of the population is considered vulnerable. The left panel shows the trajectory of one disturbed population (shown as red dotted line) and the matching undisturbed population (shown as black solid line). The right panel shows the trajectories of 10 disturbed (shown as red dotted lines) and undisturbed (shown as black solid lines) populations.

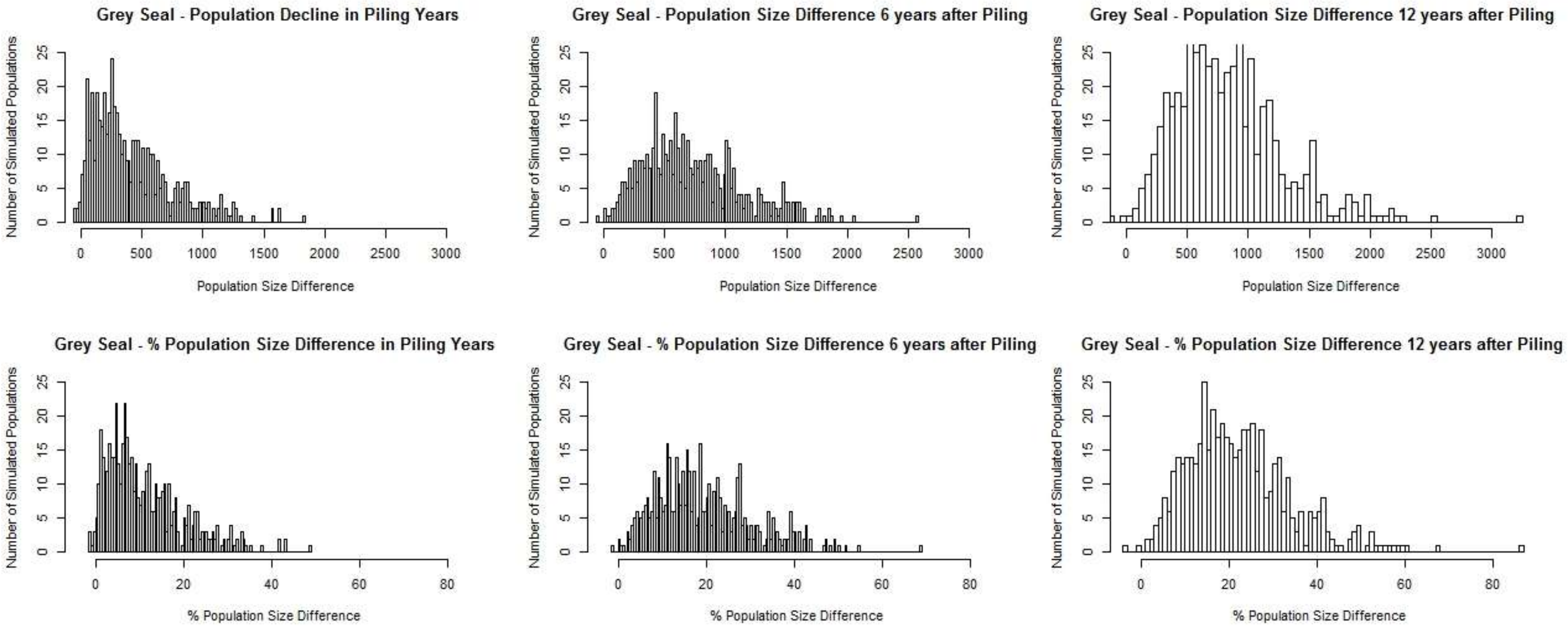

Figure A3.7 The predicted effects of disturbance and injury associated with the construction of two hypothetical wind farms on 500 simulated grey seal populations when all of the population is vulnerable to the effects associated with both wind farms. Upper panels show the predicted differences between the size of the undisturbed and disturbed populations immediately after construction, and at 6-year intervals thereafter. Positive values indicate that the disturbed population is smaller than the undisturbed one. The lower panels show these differences expressed as a percentage of the initial population size.

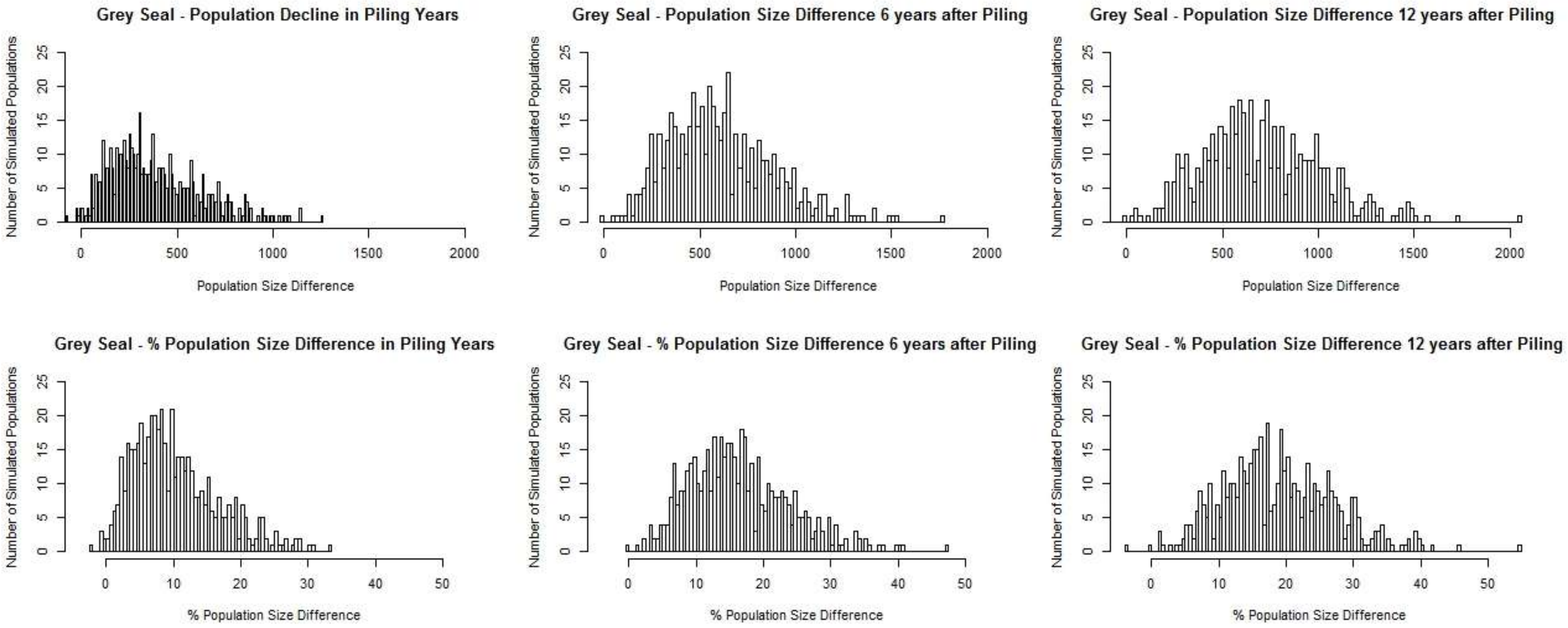

Figure A3.8 The predicted effects of disturbance and injury associated with the construction of two hypothetical wind farms on 500 simulated grey seal populations when 50% of the population is vulnerable to the effects associated with both wind farms and the remaining 50% is not affected. Upper panels show the predicted differences between the size of the undisturbed and disturbed populations immediately after construction, and at 6-year intervals thereafter. Positive values indicate that the disturbed population is smaller than the undisturbed one. The lower panels show these differences expressed as a percentage of the initial population size.

EAST COAST SCOTLAND BOTTLENOSE DOLPHINS

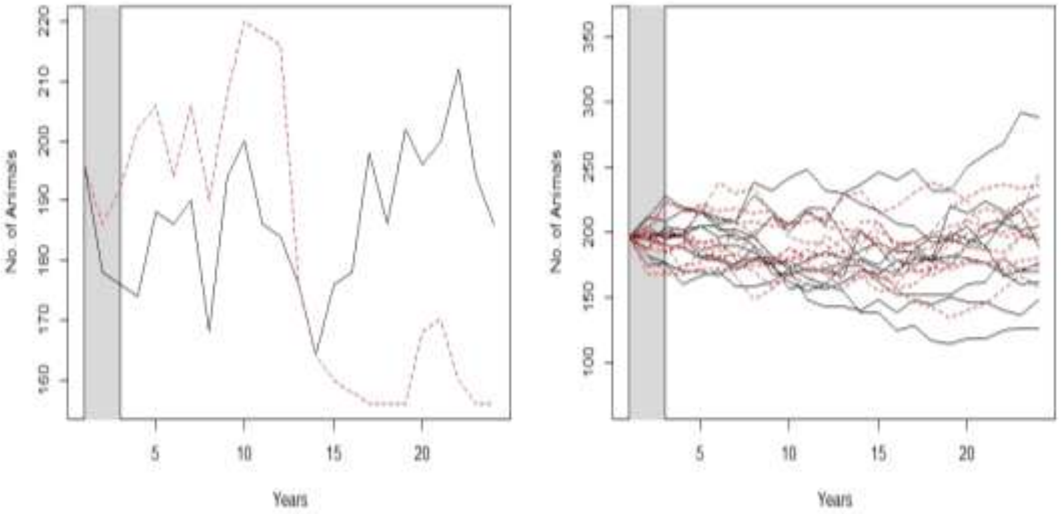

Figure A3.9 Examples of the predicted changes in abundance of the grey seal population in the 24 years following the construction of two hypothetical wind farms when 50% of the population is considered vulnerable. The left panel shows the trajectory of one disturbed population (shown as red dotted line) and the matching undisturbed population (shown as black solid line). The right panel shows the trajectories of 10 disturbed (shown as red dotted lines) and undisturbed (shown as black solid lines) populations.

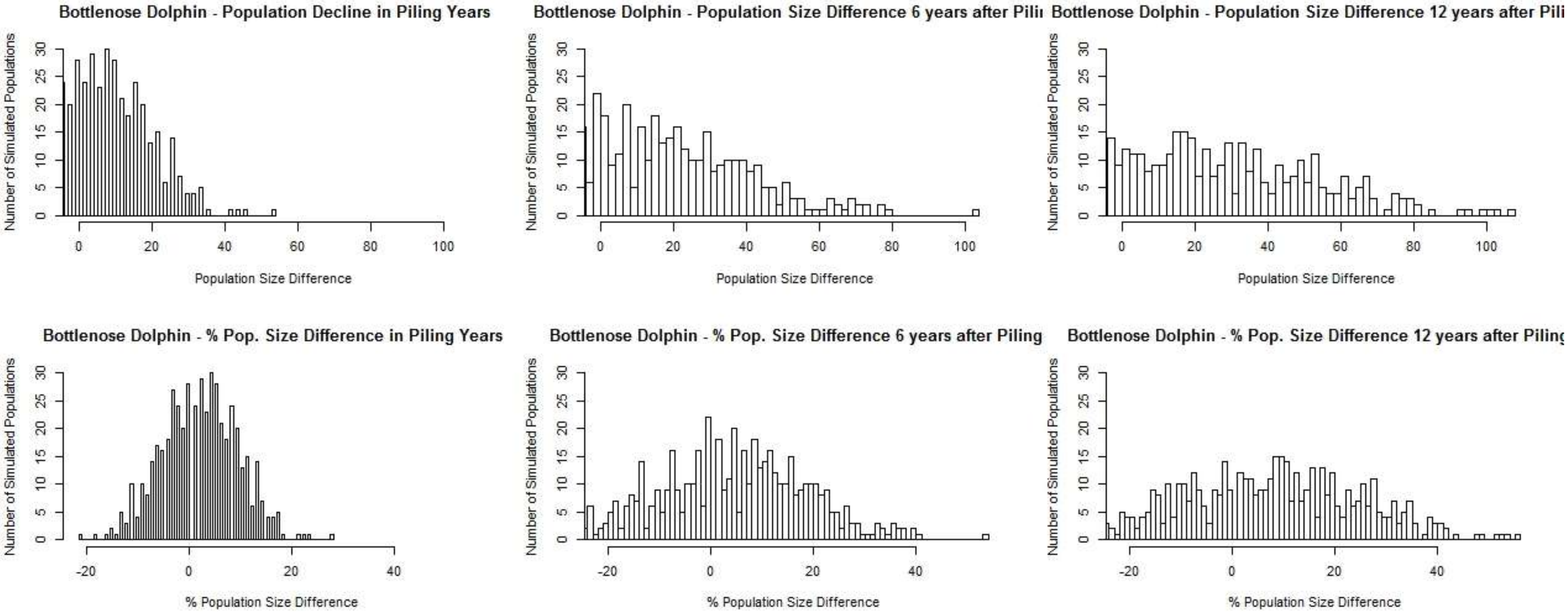

Figure A3.10 The predicted effects of disturbance and injury associated with the construction of two hypothetical wind farms on 500 simulated bottlenose dolphin populations when 50% of the population is vulnerable to the effects associated with both construction sites and the remaining 50% of the population is not affected by either operation. Upper panels show the predicted differences between the size of the undisturbed and disturbed populations immediately after construction, and at 6-year intervals thereafter. Positive values indicate that the disturbed population is smaller than the undisturbed one. The lower panels show these differences expressed as a percentage of the population size before the start of construction.

MINKE WHALES

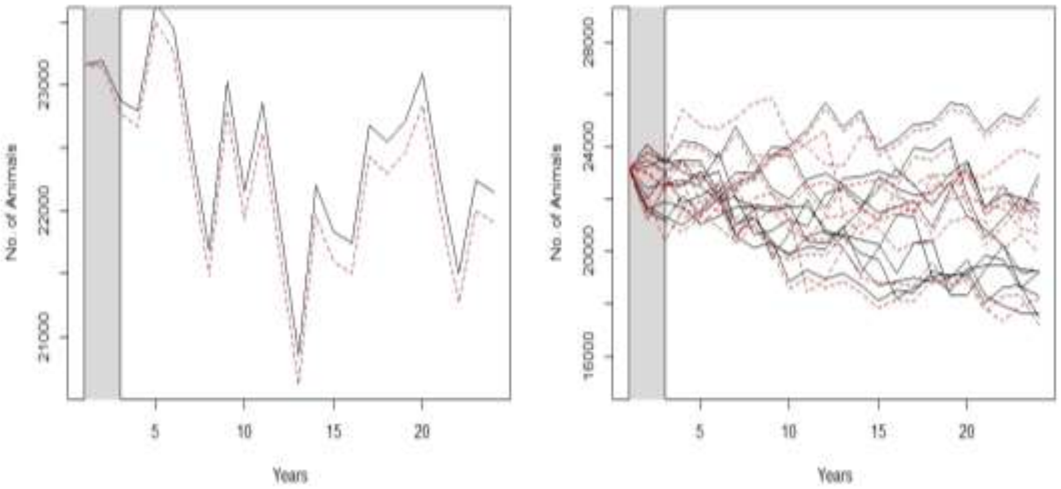

Figure A3.11 Examples of the predicted changes in abundance of the minke whale population in the 24 years following the construction of two hypothetical wind farms when 10% of the population is considered vulnerable and the other 90% is considered to be unaffected by the development. The left panel shows the trajectory of one disturbed population (shown as red dotted line) and the matching undisturbed population (shown as black solid line). The right panel shows the trajectories of 10 disturbed (shown as red dotted lines) and undisturbed (shown as black solid lines) populations.

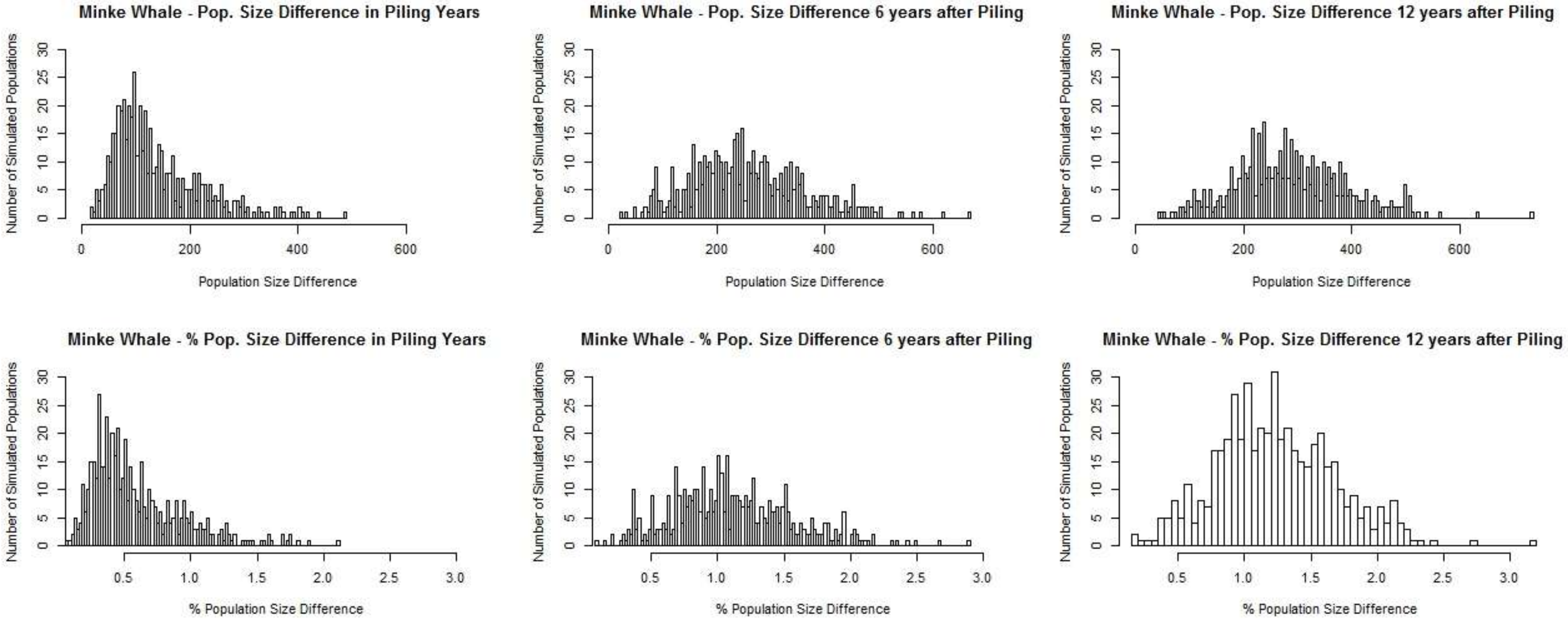

Figure A3.12 The predicted effects of disturbance and injury associated with the construction of two hypothetical wind farms on 500 simulated minke whale populations when 10% of the population is vulnerable to the effects associated with both construction sites and the remaining 90% of the population is not affected by either operation. Upper panels show the predicted differences between the size of the undisturbed and disturbed populations immediately after construction, and at 6-year intervals thereafter. Positive values indicate that the disturbed population is smaller than the undisturbed one. The lower panels show these differences expressed as a percentage of the population size before the start of construction.

ISSN: 2043-7722 ISBN: 978-1-78412-255-3 (web only)

The Scottish Government
St Andrew's House
Edinburgh
EH1 3DG

Produced for the Scottish Government by APS Group Scotland
DPPAS23612 (02/14)

Published by the Scottish Government, February 2014

www.scotland.gov.uk