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Guide to Population Models used in Marine Mammal Impact Assessment

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The report was reviewed by John Harwood and Jacob Nabe-Nielsen and colleagues in the Marine Industries Group - Marine Mammals which comprises staff from JNCC, SNH, NRW, NE and DAERA.

Summary

A quick reference table on the different population models used in marine mammal impact assessments.

Table 1. Summary table comparing the three main 'population assessment' methods used in marine mammal impact assessment. Terms are defined in the main text and in the Glossary.

Approach	Knowledge requirements[1]	Handling Uncertainty & Stochasticity	Biggest sensitivities	Useful for	Less useful for
PBR	• A defined population management unit • Minimum abundance estimate (20th percentile or lower 60% confidence limit) • Appropriate estimate of maximum growth rate • General population health/status (to select appropriate recovery factor) • To compare to PBR output, need to have a predicted level of mortality from the activity being assessed • Knowledge of levels of other sources of man-made mortality	• Based on 20th percentile of population estimate • Uses a subjective recovery factor (F_R) set low as a precaution if uncertainty is high or if populations is in unfavourable status)	• Assumptions about the population: e.g. growth rates, density dependence, carrying capacity • Recovery factor	• Simple estimates of annual 'allowable' mortality for discrete populations which have an estimate of abundance and where levels of other sources of man-made mortality are well known	• Assessment of sub-lethal impacts (e.g. disturbance) • Assessing a single source of mortality in the absence of information on other man-made sources

[1] A combination of inputs required to run these models and information required to use them in an impact assessment context.

Approach	Knowledge requirements[1]	Handling Uncertainty & Stochasticity	Biggest sensitivities	Useful for	Less useful for
iPCoD	• A defined population management unit • Demographic info: - Population size - Age structure - Birth rates - Age specific survival rates - Age at first breeding - Sex ratio • Estimate of # of animals affected daily • Days of disturbance (e.g. piling schedule) • Relationship between days of disturbance and individual survival and reproductive rates (default currently based on the results of an expert elicitation for UK species and pile driving)	• Models environmental stochasticity by varying survival and birth rates from year to year • Models uncertainty in estimates of the # of animals affected/ population size, and demographic stochasticity (for small populations) • 1000 replicate simulations carried out, each time values for # disturbed and population size are drawn from a distribution of values	• Size of vulnerable section of population • # of days animals stay away from the disturbed area after each day of disturbance • Estimates of the relationship between days of disturbance and survival and reproductive rates derived from expert elicitation • Current version doesn't include any form of density dependence but new version that does is in development	• Cumulative impact assessment • Prediction of population level consequences of responses to pile driving for UK priority species • Exploring effects of direct mortality on populations	• Current version less useful for populations where density dependence is likely to be operating • Species/pressures with very limited data or no knowledge of relationship between number of days of disturbance and survival/reproductive rates

Approach	Knowledge requirements[1]	Handling Uncertainty & Stochasticity	Biggest sensitivities	Useful for	Less useful for
DEPONS	• A defined population • Demographic info: - Birth rates - Age at first breeding - Lactation period - Gestation period • Map of relative food availability (or animal density as a proxy for prey) • Response to noise – in relation to received level of sound or distance from noisy activity • Population specific movement patterns • Bioenergetics – relationship between energy status and survival and food intake and energy status	• Environmental stochasticity not included • To incorporate model uncertainty, several simulations of each scenario can be run to generate a distribution of outcomes (e.g. five replicates were run in Van Beest *et al* 2016)	• Comprehensive sensitivity analysis underway but sensitive to assumptions about prey distribution, movement patterns and energetics	• Cumulative impact assessments for harbour porpoise • Exploration of the effect of different spatial and temporal scenarios of impact • Exploring effects of different scenarios for thresholds below which porpoises do not react behaviourally	• Does not exist for mammal species/ populations other than harbour porpoise

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1 Introduction

The prediction of the population level consequences of impacts on marine mammals as a result of proposed marine developments is a crucial part of the impact assessment and decision making process. A variety of different population modelling approaches have been used in recent years to provide information for consenting decisions about the potential magnitude and significance of impacts. The range of models and approaches that have been adopted and presented in Environmental Statements and Habitat Regulations Appraisal (HRA) reports are quite complex and the variety can be confusing to the non-specialist.

This report is intended to be an accessible summary reference guide to marine mammal population modelling for statutory nature conservation body (SNCB) advisers and practitioners dealing with assessments of the potential impacts on marine mammal populations. It is also intended for SNCB marine mammal specialists to use as a resource to inform approaches to decision making and planning and carrying out strategic level assessments.

This guide first provides an overview of the main generic types of approaches used in population assessment/decision making (Section 2) before exploring a few specific examples in more detail in Section 3. Section 4 provides an overview of the main issues arising from this overview and examples and comments on recent developments and future directions. A glossary of terms is provided at the end of the guide.

2 Approaches to assessing population level consequences of impacts

There are two main approaches that have been taken in marine mammal impact assessment to assess the population level effects. These are shown in Figure 1. The first is the use of a rule-based method which results in a threshold for the number of deaths that should not be exceeded. The second method often adopted in impact assessments is the use of a Population Viability Analysis (PVA) or predictive modelling approach. The two primary approaches are explored in more detail below.

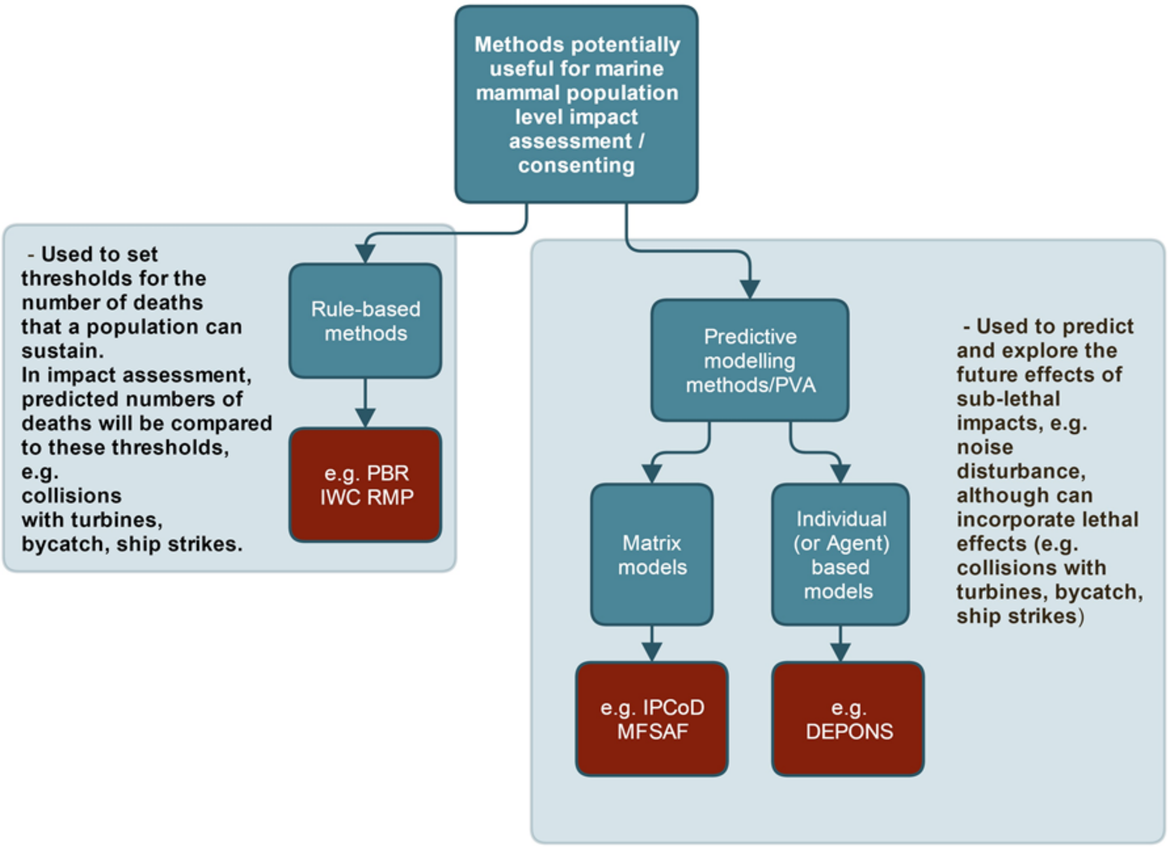

Figure 1. Overview of the main types of modelling approaches used to inform impact assessment and consenting. Please see the Glossary for explanation of acronyms and abbreviations.

2.1 Rule based methods

These methods originate from the management of populations where man-made mortality is the primary threat, and attempts have been made to set thresholds on number of man-made deaths that the population can sustain and still remain healthy. They use information on the current size and health of the population to set a threshold of ‘allowable mortality’ – i.e. the number of individuals that can be removed without having a significant detrimental effect on the population, or the safe number of ‘takes’ allowed while still allowing a depleted population to recover. One of these methods, Potential Biological Removal (PBR), is explained in more detail in Section 3.1. Another example of this type of approach is the International Whaling Commission Revised Management Procedure (IWC RMP) which was developed to set safe limits for sustainable harvesting of whale populations (Cooke 1999, https://iwc.int/rmpbw). To our knowledge, no other rule-based method has been used to inform consent decisions (EIA or HRA) in relation to marine mammal populations.

2.2 Predictive modelling methods

One of the most widely used predictive modelling methods is PVA, a process of quantitative risk assessment developed in the field of conservation biology which has been applied to a range of taxa. Originally PVA was used to estimate the probability that a population would go extinct within a given time frame. Today, the term is used to describe both the process itself and the set of predictive and simulation tools used. The process has been extended for a wide range of uses – including the prediction of the potential consequences of impacts of developments on marine mammal and bird populations (e.g. Maclean *et al* 2007; Thompson *et al* 2013). The exact approach and model structure will vary depending on the question being addressed. In their use in impact assessment the question being addressed is ultimately: what is the magnitude of the predicted long term effect on the population. See Box 1 for a definition of the various types of models used for the prediction of population level consequences of impacts. In general, there are two main types of modelling approaches to simulate population responses. 'Top-down' models where info on e.g. mortality and density dependence are required to simulate population responses (e.g. matrix models) and 'bottom-up' models where these characteristics emerge from the behaviour of individual simulated animals (e.g. individual based models; DeAngelis & Mooij 2005).

A number of off-the-shelf software packages have been developed to carry out predictive modelling as part of a PVA e.g. VORTEX (Lacy 2000) and ULM (Unified Life Models; Legendre & Clobert 1995). VORTEX has been used as a predictive modelling tool in the assessment of the impact of offshore wind farm construction on bottlenose dolphin populations in the Moray Firth and the outer Firth of Tay (De Silva *et al* 2014) and for cumulative assessments on the east coast of Scotland by Marine Scotland Science. VORTEX was selected as the modelling tool primarily because it had previously been used for PVA of the Moray Firth bottlenose dolphin population (e.g. Thompson *et al* 2000). In these assessments the effect of disturbance was modelled by incorporating assumptions about how exposure to noise might influence survival and reproduction. Any individual experiencing disturbance as a result of pile driving was predicted to not reproduce (this was incorporated in VORTEX by 'harvesting' calves) and hearing damage (i.e. permanent threshold shift - PTS) was modelled as a decrease in the probability of individual survival – i.e. the probability of dying increased by 25% in individuals with PTS. Similar assumptions were used in the 'Moray Firth Seal Assessment Framework' (MFSAF; Thompson *et al* 2012), whereby an existing stage based matrix model of the harbour seal population in the Moray Firth was used to simulate the future trajectory of an impacted and baseline population. This framework was used in the assessment of the impact of offshore wind farm construction on the Moray Firth harbour seal population.

All such predictive modelling approaches require information about the population under baseline (pre-impact) conditions as well as knowledge about the likely effects of impacts on individual behaviour and physiology and, ultimately, fitness. For matrix based predictive methods, estimates of population size, and of age- or stage-specific birth and death rates are required. Information on density dependence (i.e. how birth and death rates change as the population grows, DD) or an assumption of an absence of DD will also be required (see Box 2 for a definition of DD and why it is an important concept in the prediction of population change). For Individual Based models (IBM) or agent based models the survival (and often reproductive) rates of individuals are determined by their actions during simulation and therefore population vital rates and the carrying capacity of the environment (and therefore resultant DD) are emergent properties of simulated animals competing for food.

BOX 1A: SUMMARY OF TYPES OF MODELS USED IN THE PREDICTION OF POPULATION DYNAMICS	
INDIVIDUAL BASED MODEL (IBM)	*Sometimes called Agent Based Models, individual animal movements and energy balance are simulated over discrete time steps. The movements and energy balance of each individual depends on the conditions they encounter when moving around in their environment, their internal state, and what they have experienced in the past. IBMs typically incorporate life history information from the literature. The population dynamics and spatial distributions of animals emerge as a result of the simulation of many individuals.*
MATRIX MODELS	*A matrix is a mathematical tool which can be used to predict population growth. Matrices can be used to predict how many individuals of each age or stage class will be present in the population in different time steps (usually in steps of a year) as a result of the combined processes of age or stage class specific birth and death rates, given the numbers in the previous step.*
LESLIE MATRIX MODELS	*This is a particular type of matrix model that has the population structured into discrete age or stage classes with specific survival rate estimates used for each class.*
BOX 1B: PREDICTIVE MODELS CAN BE EITHER STOCHASTIC OR DETERMINISTIC:	
STOCHASTIC MODELS	*Stochastic models attempt to represent the uncertainty (either random or environmental) in prediction and will draw the values for each calculation from a range of possible values (the expected variation in input parameters therefore needs to be provided). By repeating the model calculations many times, a statistical distribution of predictions is produced from which a mean with associated estimate of variability can be calculated.*
DETERMINISTIC MODELS:	*A deterministic model has no random elements. All the parameters are fixed constants, which are either known or assumed. This approach is less useful when there is much potential variability in input parameters.*

The data requirements for a good IBM are considerable, Baker *et al* (2010) concluded that even for a well-studied population, data may be insufficient to satisfactorily parameterise an IBM. The data required are, however, mostly for defining the behaviour and energetics of individual animals, which may be easier to obtain for some species than data on population averages (e.g. average age-specific survival rates).

The interim Population Consequences of Disturbance model framework (iPCoD; Harwood *et al* 2013; King *et al* 2015) is an example of a modelling framework developed specially to carry out assessments of population consequences of impacts, adopting a PVA approach, but also including some elements of an IBM. The iPCoD framework is explored in further detail in Section 3.2.

The simulation model being developed as part of the DEPONS research programme (Disturbance Effects on the Harbour Porpoise Population in the North Sea; www.depons.au.dk) is an IBM based approach to assessing the effects of noise (construction of offshore wind farms, ship noise) on the North Sea Porpoise Population. DEPONS is covered in more detail in Section 3.3.

BOX 2: DENSITY DEPENDENCE (DD)

Populations cannot continue to grow indefinitely; they will eventually be limited by available resources. As density increases, population growth slows down and eventually halts. Mechanisms for this include reduced birth rates and decreased survival probability. This is as a result of a reduced availability of resources (food and space), and also sometimes the spread of disease and increased predation at higher population densities. However, the exact form and strength of DD is poorly understood for most species. Models without any form of DD included are often used in predicting population responses to impacts and such models are thought to be precautionary since they will not include any kind of compensatory increase in survival or birth rate when numbers decrease.

The PBR method was developed and tested with the assumption of a logistic population growth curve (a sigmoid curve) which assumes that the population will grow exponentially at low density and that DD effects will slow the growth rate as the population approaches the carrying capacity of the environment. The simulation studies of Wade (1998) demonstrate that the form of DD had a strong effect on PBR estimates. However, the basic method should be robust to changes in the shape of the DD function.

DD in marine mammal populations is not well understood and therefore mis-specification of the form of DD in predictive population models could result in unreliable predictions. There is evidence for DD in subsets of the grey seal population. The state space model (Thomas 2015) used to estimate the size of the UK grey seal population suggests that DD is affecting pup survival in Orkney and the Western Isles (SCOS 2015; Thomas 2015). By contrast, the grey seal population in the North Sea is growing exponentially (SCOS 2015). UK harbour seal populations show a range of dynamics, although Matthiopoulos et al *(2014) provides evidence for DD in the Moray Firth harbour seal population.*

3 Detailed examples of specific models

3.1 Potential Biological Removals (PBR)

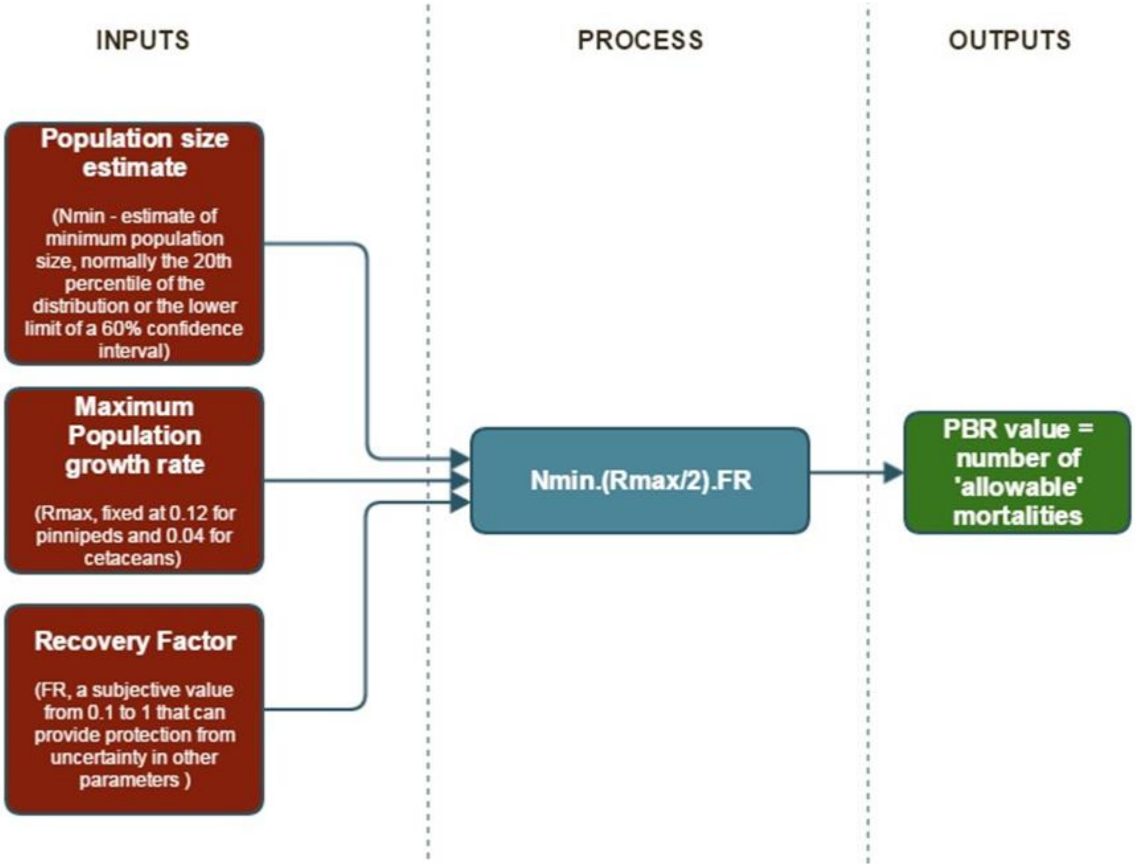

Figure 2. Schematic diagram of the PBR calculation, showing inputs required (left), the calculation equation (middle) and the output (right).

PBR is a widely-used method for assessing whether current or predicted levels of man-made mortality are consistent with reaching or exceeding a specific target population size. Such a target is built into the method: the Optimum Sustainable Population size (OSP), sometimes referred to as the Maximum Net Productivity Level (MNPL). PBR was developed as a tool to manage marine mammal populations depleted by bycatch. A schematic of the calculation is presented in Figure 2 and the approach and calculation are discussed in more detail in Wade (1998). A summary of advantages and disadvantages of the approach are presented in Table 2.

In practice, PBR is often regarded as a tool for estimating the number of individuals that can be “safely” removed from a population while still allowing that population to maintain or achieve a pre-determined target level. PBR is popular for two related reasons:

1) It is simple to calculate as it does not require any specific knowledge of the carrying capacity of the environment or direct estimates of population vital rates other than an estimate of unconstrained growth rate (known as Rmax) and requires only one recent/current population estimate. This simplicity was a deliberate response to the difficulty of collecting data on marine mammal populations (Wade 1998; Taylor *et al* 2007).

2) The method does not require the user to make any decisions about what is or is not acceptable in relation to population change – that decision is intrinsic to the calculations with the target being a population that is above MNPL or OSP. This is the population size at which the annual total increase in animal numbers is highest.

The approach implicitly assumes that the population is under density dependent control, i.e. that one or more of the age-specific survival and birth rates will decline as population density increases. The use of the minimum (rather than mean) population size estimate and the recovery factor are thought to ensure against uncertainties in the data and oversimplifications in the population model. Because of this, several authors have concluded that the PBR approach to determining the level of sustainable takes performs best in data poor situations where there is considerable uncertainty associated with our understanding of the population (Milner-Gulland *et al* 2001; Hammill *et al* 2015). The recovery factor is basically a scalar which reduces the resulting PBR value, e.g. a recovery factor of 0.5 will reduce the predicted PBR value by 50% and a recovery factor of 0.1 would reduce the PBR by 90%. Low value recovery factors are used where there are large uncertainties in population size and status and where populations are already known to be in unfavourable status.

In addition, the PBR relies on a reliable estimate of the maximum population growth rate, which is the rate of increase at low densities. The default values in the calculation are set at 0.12 for pinnipeds and 0.04 for cetaceans (based on published data from North American populations, but generally used as standard for all populations). Lonergan (2011) pointed out that if the true value of this growth rate is lower than the estimate used in the calculation, as a result of pollution or other causes, adopting PBR could result in a substantial reduction in population size.

The essential characteristics of a population to which a PBR calculation can be applied are that it:

- must be a functional, closed population unit;
- must have recent, reliable population estimates with some form of confidence intervals about the estimate;
- must have an estimate of the maximum rate at which the population can increase;
- must be subject to some form of DD such that productivity will be maximised at some intermediate population level.

In practice, these conditions are not often fulfilled on the geographical scales at which PBRs are applied. It is often difficult to define the geographical scale of the population to be used in calculating the PBR for a particular area. For a relatively well defined and isolated population for which a recent, accurate estimate of population size exists (e.g. harbour seals in the Moray Firth which are counted on an annual basis) this is straightforward, but for local effects within a population spread over a wider area with more sporadic monitoring (e.g. harbour porpoise in the Celtic and Irish Sea) it is much less clear. In practice, setting a conservative recovery factor may provide a safety factor against the violation of the assumptions listed above but this is largely a subjective process.

Table 2. Summary of the main advantages and disadvantages of the use of PBR for impact assessment.

Advantages	Disadvantages
Simple to calculate – relying only on a single population estimate.	Can only be used for lethal impacts/mortality/takes, not suitable for assessment of sub-lethal impacts (e.g. disturbance).
Doesn't require managers to make an explicit decision about the level of impact that is acceptable.	Most marine mammal populations are wide-ranging and not effectively closed at the scale at which PBR may be applied.
Subjective recovery factor allows for added precaution when uncertainty is high or populations are in unfavourable status (e.g. use of 0.1 is the most conservative).	The single PBR value must incorporate all sources of man-made mortality that the population might be subject to – good estimates of bycatch *etc*. are often lacking.
	Requires a reliable estimate of population size, not available for all marine mammal populations.
	Can still result in a decline of a population - this may not be compatible with legislative goals and conservation objectives.

3.1.1 Use in impact assessments and decision making

PBR was developed for bycatch regulation in the U.S. but has been adopted by the Scottish Government for setting limits to annual licences for shooting grey and harbour seals issued for fisheries protection (Thompson *et al* 2016). PBR has been recently applied to consenting decisions for marine renewable energy projects, where the most common application is for assessing the 'acceptability' of collision estimates for tidal energy developments. If the predicted number of annual collisions is less than the PBR value minus additional man-made mortality (e.g. bycatch or (licenced) shooting by fishermen) then the potential impact may be considered acceptable. In practice PBR values have been used to set thresholds for the adaptive management of tidal energy projects under uncertainty about the true rate of collisions – i.e. monitoring is put in place to ensure that collision related mortality will not exceed a PBR derived threshold (e.g. CCW 2010). Should these thresholds be approached, then mitigation would be required to reduce the risk of future mortality. Because the PBR calculation predicts the number of mortalities permissible in a single year, ideally it should be re-calculated annually. Whilst this is possible for populations which are monitored annually (e.g. Moray Firth harbour seal population, the Wash harbour seal population), this is not possible for most marine mammal populations which are monitored much less frequently, if at all. Because the PBR calculation is very dependent on current conditions (current population size, current levels of other sources of mortality), the use of PBR in consenting decision-making for projects likely to extend into the future needs careful consideration. Ongoing management would need to be iterative; a mechanism is required to respond to actual levels of mortality and future changes in other sources of mortality (although this is true of other types of model too).

3.2 The interim Population Consequences of Disturbance framework (iPCoD)

The iPCoD framework was developed to investigate the population consequences of the effects of exposure to noise, primarily from piling activity during offshore wind farm construction (Harwood *et al* 2013; King *et al* 2015). The model has its origins in a framework developed by working groups established by the US National Academy of Sciences and the US Office of Naval Research (National Research Council 2005).

Figure 3 provides a schematic representation of the iPCoD Framework and a summary of the advantages and disadvantages of the approach is presented in Table 3. The model generates two parallel future population predictions – one which represents the baseline or un-impacted population and one which represents the impacted population. This is done by incorporating the effects of the expected levels of impact on the vital rates, for example the effect that disturbance as a result of noise (e.g. pile driving) has on the ability of animals to survive or breed, or the effect that hearing damage from the exposure to noise (in the form of PTS) has on survival and reproduction. Typically, the outputs focus on the difference between un-impacted and impacted populations (referred to as a 'counterfactual' approach). However, for most species, there is little or no data to quantify the relationship between a given level of impact and the resulting behavioural or physiological changes in individuals and ultimately the effects of such changes on their individual fitness (their ability to survive and breed). Therefore, the iPCoD framework uses the opinions of experts, gathered through a formal expert elicitation process, to quantify the relationships between behavioural and physiological responses and changes in vital rates. In the absence of such data, the framework provides an auditable, formal, quantitative methodology that can be used to inform the decision-making process. This is why the current version of the model is called an 'interim' framework. The eventual goal is to replace this expert elicitation process with empirical data.

There are two principal stages involved in the iPCoD framework simulations – the first stage is a day-by-day simulation of up to 1000 individual animals (the precise number is determined by the size of the population) across the period of predicted disturbance to calculate both the number of animals experiencing disturbance and/or PTS and also the amount of disturbance experienced by each of the individuals, by the end of each year. This is done using a combination of an estimate of: 1) the number of animals predicted to be affected as a consequence of exposure to a single day of pile driving, 2) a schedule of the timing of the planned pile-driving and 3) the size of the section of the population that is thought to be vulnerable to the impacts. The first two of these are supplied by the developers from the impact assessment process, the last is a judgement based on the understanding of movements of individuals within the population in relation to the extent of the impact. With a smaller vulnerable section, fewer animals would experience disturbance but each animal experiencing disturbance would be exposed to a relatively larger amount of disturbance, compared to if all animals were equally vulnerable. Other than the ability to compare different vulnerable sections, the model is not spatially explicit.

The second stage scales these numbers up to the total population size to create a Leslie Matrix model that is used to calculate the future population growth of the impacted population using modified survival and birth rates for those animals that have experienced disturbance and PTS. In parallel, the baseline survival and birth rate values available for the population allow a Leslie Matrix model to project the future trajectory of the un-impacted population. This is repeated many times (1000 times is the default, and is the minimum recommended by King *et al* 2015, but this can be changed by the user) and each simulation draws parameter values from statistical distributions describing the uncertainty in the parameters. The distributions of the two trajectories can be compared to demonstrate the size of the long-term effect of the predicted impact on the population as well as demonstrating the uncertainty in predictions.

The outputs can be compared in a number of ways: 1) through visual representation of the population trajectories (Figure 4), 2) comparison of the predicted population sizes (counterfactuals), and/or 3) or a probabilistic comparison of the likelihood of a decline between impacted or un-impacted populations, e.g. with statements like "the simulated impact results in a 50% increase in the likelihood of a 1% annual population decline compared to baseline conditions”.

The framework can also be used to incorporate the number of predicted mortalities per year, e.g. from collisions with marine renewable energy devices – the number of surviving individuals in each year is simply reduced by the number of predicted collisions.

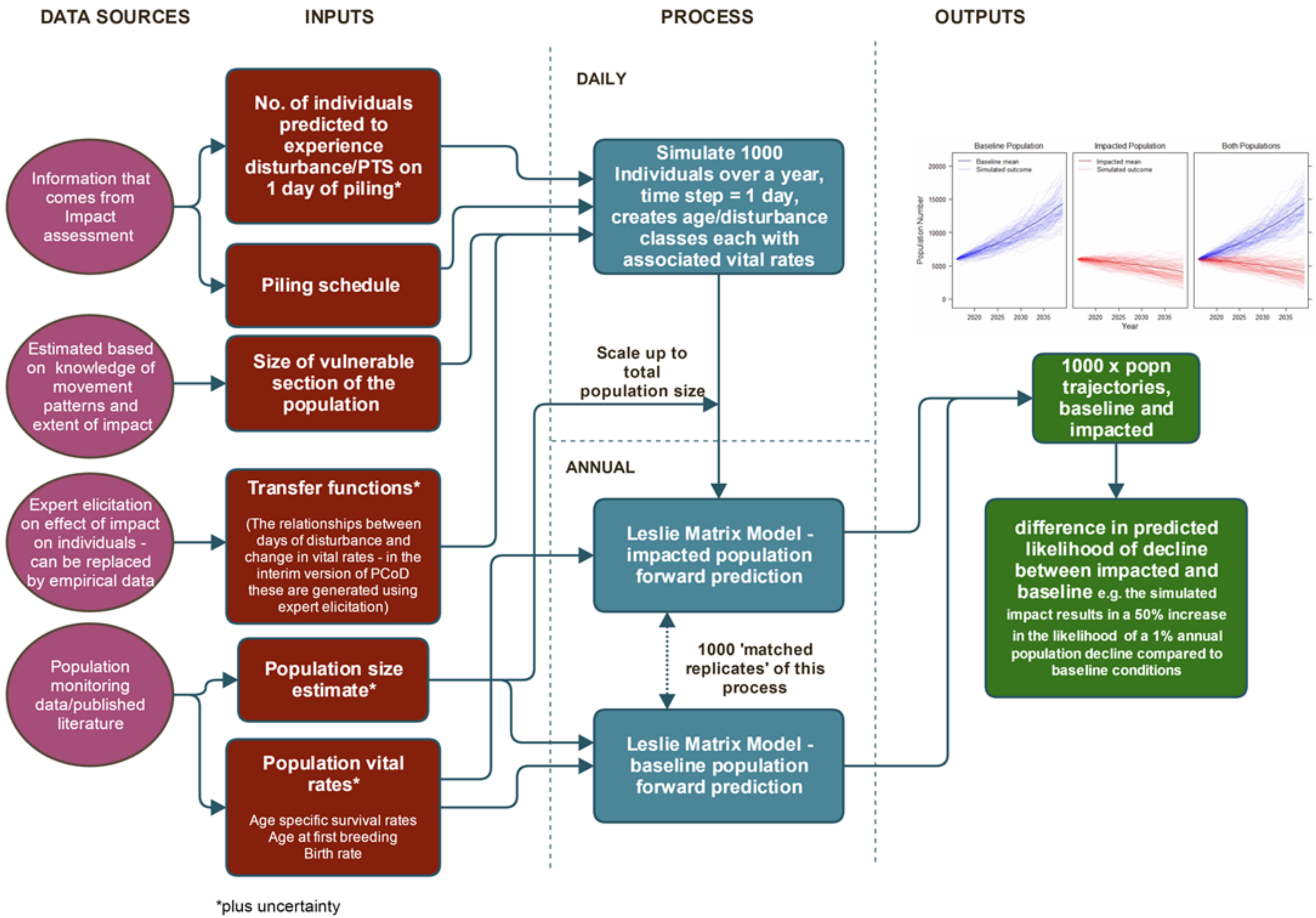

Figure 3. Schematic representation of the Interim PCoD Framework.

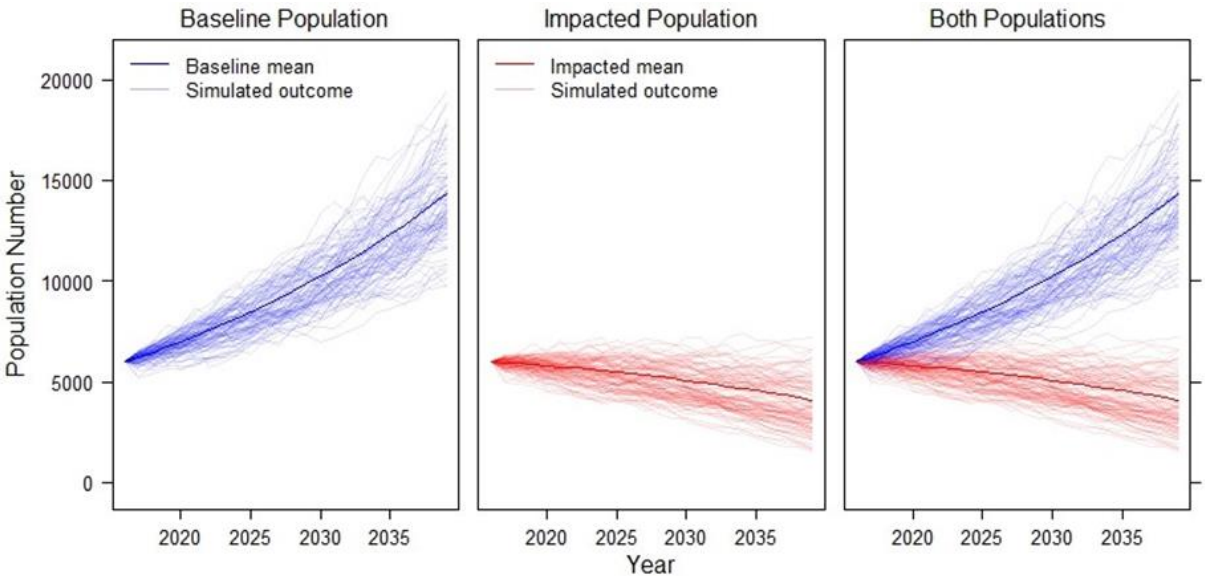

Figure 4. Example predicted population trajectories from the iPCoD framework. The left panel shows 1000 replicates of the simulated baseline (un-impacted) population trajectory (thin lines), plus the mean of all 1000 replicates (thick line). The middle panel shows the same for the impacted population trajectory and the right panel displays both plotted together.

Because of the lack of data on the effects of disturbance and hearing damage on vital rates, a formal expert elicitation process was carried out in 2012 for all five UK priority species (harbour porpoise, grey seal, harbour seal, bottlenose dolphin and minke whale) in relation to impacts caused by pile driving. The expert elicitation process produced estimates of survival and birth rates for animals predicted to experience disturbance and hearing damage, each with their associated uncertainty. For example, most experts thought that disturbance to a harbour porpoise lasting more than 50-100 days may result in reduced foraging efficiency which could cause a maximum 50% reduction in fertility. The associated uncertainty was related to the degree of consensus amongst experts (e.g. values had low uncertainty if all experts agreed, high uncertainty if experts disagreed). For details of the expert elicitation process and the questions asked, see Harwood *et al* (2013). For more details of the analysis of the expert elicitation see Donovan *et al* (2016).

The default iPCoD model does not include DD but this capability can be incorporated for specific populations/case studies and will be incorporated in a future release of the model. A recent example is the development of a version of the model for the Moray Firth harbour seal population (John Harwood, pers comm.). The lack of DD has generally been thought to lead to precautionary results, since the ability of populations to compensate for impact is not included in predictions, however Horswill *et al* (2016) reviews this issue with reference to bird impact assessment and concludes that density-independent models do not provide a fully precautionary approach to impact assessment for birds. Some testing of this assumption for marine mammals would be worthwhile. There is currently no evidence for DD across all UK populations, for example the North Sea harbour porpoise population. DD is, however, considered to be a ubiquitous process that prevents infinite growth of populations (Tavecchia *et al* 2007; Sæther *et al* 2016). DD is usually detected by analysing an extensive time series of estimates of population size. Such a time series is unlikely to be available for many marine mammal species in the foreseeable future. Although an exception to this is the UK grey seal population where observed changes in pup production imply that some DD is occurring (Duck & Thompson 2013). One consequence of the lack of DD in the underlying population model is that forecasts of abundance become increasingly unrealistic over time. In general, the effects of disturbance will be over-estimated if forecasts are extended too far into the future. As a rule of thumb, forecasts of population size more than 12 years after the cessation of disturbance activities should be treated with caution (Harwood *et al* 2013).

3.2.1 Use in impact assessments and decision making

The iPCoD framework has been explicitly used to predict the future impact of a small number of specific developments and for strategic cumulative impact assessments:

- By the Dutch Government to carry out a cumulative impact assessment of offshore wind farm construction in the North Sea (Heinis & de Jong 2015).
- By JNCC and Natural England to carry out an assessment of the cumulative impact of offshore wind farm construction on the east coast of England on the North Sea harbour porpoise management unit (Booth *et al* 2017).
- By WWF-UK to explore the potential benefits of noise reduction mitigation techniques on the North Sea harbour porpoise population (Verfuss *et al* 2016).
- Used during the EIA and HRA for the Minesto Deep Green tidal energy project in Holyhead Deep, Anglesey to provide context for the population consequences of a range of potential annual collision rates (Minesto 2016).
- Used in the EIA and HRA for the Brims tidal array in Orkney. It was also used on a Scottish Government project to understand the potential population consequences of all the currently consented tidal energy projects on the Orkney and North coast harbour seal management unit (Band *et al* 2016).

Table 3. Summary of the main advantages and disadvantages of the iPCoD approach for impact assessment.

Advantages	Disadvantages
Flexible, auditable quantitative framework- quick to run.	Interim version relies on expert judgement – lack of empirical data on effect of behavioural and physiological response on vital rates.
Incorporates uncertainty in all input parameters.	Doesn't take into account spatial pattern of activities.
Can also include mortality from human activities – e.g. collision rates.	Relies on estimates of the number of animals affected on a single day of piling, produced independently of the iPCoD model.
Includes a mechanism for including the effect of hearing damage and disturbance on survival and reproduction (currently parameterised via expert elicitation).	Does not currently include density dependence (although it will be incorporated in an updated version currently under developments).

3.3 DEPONS

The Disturbance Effects on the Harbour Porpoise Population of the North Sea (DEPONS; http://depons.au.dk/) is a research programme based at Aarhus University in Denmark. The programme involves a number of work streams with the ultimate aim of building a model which can be used for the assessment of disturbance from underwater noise generated during offshore wind farm construction. Although primarily developed for underwater noise the final product will be applicable for the assessment of the impacts of other human activities. DEPONS is built upon an individual based model of harbour porpoise movement and energetics developed by Jacob Nabe-Nielsen and colleagues (Nabe-Nielsen *et al* 2011, Nabe-Nielsen *et al* 2013, Nabe-Nielsen *et al* 2014). The model was made publicly available in April 2017 (doi: 10.5281/zenodo.556455; https://zenodo.org/badge/latestdoi/88900072).

Figure 5 provides a schematic representation of the DEPONS approach and a summary of advantages and disadvantages are presented in Table 4. The DEPONS model simulates individual porpoises moving around their environment consuming the food they find on their way. Only females are explicitly modelled – at the end of the simulation the resulting population size is doubled assuming a 50:50 sex ratio. The fine-scale movements of females are determined by prey availability (see Nabe-Nielsen *et al* 2013 for detail on this process). Porpoise are assumed to move towards areas where they have previously found food if they are unable to find food when moving at random. In the absence of data on prey availability, data on porpoise density is used as a proxy (under the assumption that density is related to prey availability). In the inner Danish waters porpoise density maps were obtained from Edrén *et al* (2010); for simulations of the North Sea population they were obtained from Gilles *et al* (2016). Individuals are characterised as either juveniles, adults with calf (lactating) or adults without calf.

Survival of adults and juveniles is determined by their energetic status (which depends on how much food they consume). Animals face an increasing risk of dying as their energy levels decrease. This is based on the assumption that the natural mortality of porpoises is directly related to their energy levels, as is the case for a wide range of animal species (Sibly *et al* 2013). Simulated animals spend energy at a constant rate, a rate which increases by 30% during the winter (based on captive studies by Lockyer 2003), and by 40% when lactating (cited in Nabe-Nielsen *et al* 2014, as Marcus Wahlberg, pers comm.). Dead animals are removed from the simulation. The survival of calves during each day of lactation is determined by the energy status of their mother. On the first day of lactation, a proportion of the adults become 'adults with calves'. This proportion is determined by the birth rate, which can be set by the user but a default of 0.68 is used based on data from porpoises in the Gulf of Maine (Read & Hohn 1995). On the last day of lactation the number of juveniles is increased by half the number of adults with calves on that day (to represent the addition of only females to the population), and all adults with calves revert to being normal adults.

The disturbance effects of noise are simulated by recreating the temporal and spatial patterns of the noise levels within the animal's environment and simulating individual animals' responses to these activities. The response of simulated animals is determined by their position relative to the piling sound source and the received sound level, which depends on the loudness of the sound source. The deterrence behaviour is currently parameterised by varying the animals' responses in relation to different sound levels in order to make sure that the model reproduces the relative population densities observed during construction of the Gemini offshore wind farm in the Dutch Sea. This response affects the animals' energy levels because they spend more time moving away and less time encountering food patches than undisturbed animals. The consequences of hearing damage as a result of exposure to noise is not included in the DEPONS model. The effects of PTS could be included in the model based on available data but as animals are predicted to move rapidly away from the pile driving areas during the ramp up phase, the number of animals that would be predicted to experience PTS would be very small.

In the DEPONS model all parameters are kept constant within each simulation but uncertainty and environmental stochasticity can be incorporated by running repeat simulations with the same disturbance scenarios.

3.3.1 Use in impact assessments and decision making

This model has not been explicitly used in any impact assessments to date. In the future it is likely to be used to predict the impacts of wind farm construction and to be used for assessing the cumulative impacts of pile driving and other sources of impulsive noise while taking the exact position and timing of these disturbances into account. The sensitivity assessment presented in van Beest *et al* (2015) noted that the results are very sensitive to the way in which the movement model is parameterised, and the underlying prey distribution. A subsequent full sensitivity analysis has revealed that the population size is more sensitive to variations in parameters related to energetics than to the parameters controlling movement (Jacob Nabe-Nielsen, pers comm.). Areas that have been included as improvements in the April 2017 version of the DEPONS model are:

- Improved movement models using data from the North Sea, the version planned for release in April 2017 has incorporated dispersal mechanisms that allows simulated animals to disperse in the same way as satellite tracked North Sea animals;

- Deterrence/recovery time – the time it takes porpoises to return after piling will have an influence on predictions (this has also been identified as a key sensitivity of iPCoD). The model version to be released by April 2017 is parameterized to reproduce the local population recovery observed at the Gemini wind farm during construction.

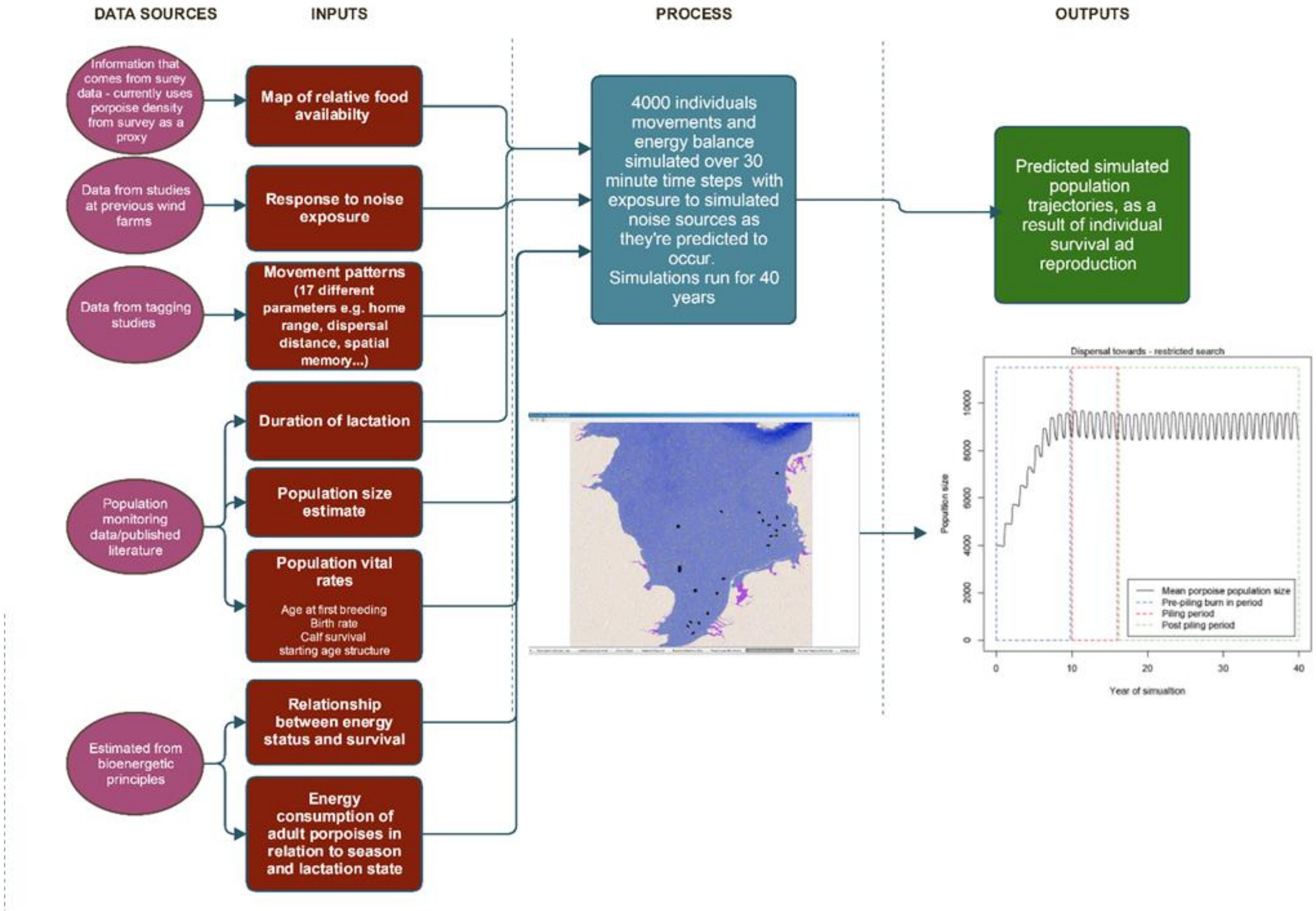

Figure 5. Schematic representation of the DEPONS model.

Table 4. Summary of the main advantages and disadvantages of the DEPONS model for impact assessment.

Advantages	Disadvantages
The use of a population model that explicitly incorporates animal movement (based on tagging data) and energetics (based on bioenergetic principles and data from captive studies) mean that it is potentially more biologically realistic.	Requires a large amount of data: until recently only sufficient data to parameterise for Inner Danish Waters harbour porpoise population - currently being extended to the rest of the North Sea.
Simulations are spatially and temporally explicit therefore they can be used to examine effects of different spatial and temporal scenarios.	Does not account for environmental stochasticity – related to this is a limited ability to respond to changes in dynamic parameters (e.g. food availability).
Includes density dependence as a direct consequence of individuals' competition for food – makes it possible to evaluate how long a population may take to recover after disturbance.	Uncertainty around some key parameters is not accounted for in the simulations.
Can also include mortality from other human activities (e.g. bycatch).	Computer intensive and relatively time-consuming to run.
	The effect of hearing damage is not included.

3.4 Main differences/similarities between iPCoD and DEPONS

In Nabe-Nielsen and Harwood (2016) there is a detailed and comprehensive breakdown comparing the two models (section 2.3) and what any differences mean in practice (section 3).

A key difference is the way they model survival. In iPCoD mean survival estimates for porpoises are derived from empirical data from North Sea animals (Winship & Hammond 2006). DEPONS by comparison, generates survival estimates via simulation based on the assumptions of the energetics and movement model which are based on the application of established principles of physiological ecology (Sibly *et al* 2013) and on porpoise tagging movement data (Nabe-Nielsen *et al* 2013), respectively. In terms of the relationship between disturbance and survival, and between disturbance and reproduction, the expert elicitation process in iPCoD attempts to parameterise a mean estimate for the relationship (with associated uncertainty), whereas DEPONS estimates this by simulating many individual animals' movements and energy budgets and 'measuring' the outcome on those simulated animals.

Another key difference is the mechanisms by which impacts are predicted to cause population change - in iPCoD the population trajectory changes via the effects of impacts on birth rates and the survival of calves/pups and juveniles (but not adults), whereas in DEPONS the population changes are as a result of the effects of impacts on the survival of individuals but not explicitly on birth rates.

iPCoD relies heavily on expert judgement, via a formal expert elicitation process to directly derive relationships between disturbance and survival/birth rates, DEPONS also employs a degree of expert judgement when choosing the precise form of the relationship between survival and energy status. Both models incorporate different judgements about the choice of which vital rates would be directly affected by alterations in energy balance as a result of disturbance. iPCoD incorporates changes in birth rates and the survival rates of pups/juveniles but does not include effects on adult survival, whereas DEPONS incorporates changes in survival of adults, juveniles and calves (based on energy status) but doesn't explicitly include an effect on birth rates. A full comparison of the consequences of these differences has not been carried out, as pointed out by Nabe-Nielsen and Harwood (2016), input parameters would need to be carefully aligned before direct comparison would be possible.

3.5 Accounting for existing anthropogenic mortality in assessing the population level consequences of an impact

How existing levels of anthropogenic mortality should be treated during assessments is an area of current debate. This section outlines how it should be treated when using both PBR and predictive population model approaches.

3.5.1 PBR

PBR is calculated using the most recent estimate of Nmin and provides an estimate of the number of animals that can be removed from that population in the following 12 months while still allowing it to tend towards its MNPL. The value of Nmin is recommended to be the lower 20th percentile of the current population estimate. It is implicit in the calculation of the PBR that Nmin is correct.

The method of calculation does not take into account any mortality that has occurred between the estimation of population size and the calculation of the PBR. If it is suspected that a major source of anthropogenic mortality is acting on the population between estimation of Nmin and calculation of PBR, then Nmin should be recalculated accordingly. If this is not feasible, e.g. if the level of that extra mortality is unknown, a partial solution would be to reduce the value of FR to reflect the reduced confidence in the Nmin value.

In an impact assessment context therefore, the PBR estimate should be compared to the sum of all anthropogenic removals likely over the following year not just that which is predicted to result from the plan or project under assessment. Any bycatch mortality predicted to occur in the following 12 months should be counted against the PBR.

3.5.2 Predictive population modelling

A good predictive population model relying on estimates of population-average demographic parameters should wherever possible be based on reliable, recent estimates of parameters for the population under assessment. This would include recent estimates of reproductive rates and survival. Empirically derived survival estimates over recent history would include current levels of baseline anthropogenic mortality such as bycatch and therefore it can be argued that unless the magnitude of such mortality is predicted to change, their effects are already incorporated into models. However in reality very few population models are built on reliable, recent estimates of demographic parameters and therefore this element requires careful consideration. Counterfactual approaches such as iPCoD, whereby the focus is on the relative comparison of the future size of impacted and non-impacted populations, should be relatively robust to the misspecification of baseline anthropogenic mortality. For individual based models which do not require the input of population estimates of mortality, any additional man-made mortality will need to be specifically included in simulations.

4 Emerging issues and future directions

Forecasting the population level consequences of impacts on marine mammal populations is an extremely complex and challenging task. This is particularly the case when considering impacts which have a sub-lethal effect on population dynamics via effects on animals' behaviour and energy balance. This is because there is a lack of empirical data to allow confident predictions but also because animal responses and the consequences of such responses can be very variable and highly context specific.

All methods employed to date require reliable estimates of current population status and trends – and this is difficult to achieve for many marine mammal species. Large amounts of data are required to predict the likely future population trajectories even without the consideration of any future impact. This is why relatively simple procedures like PBR were developed – for application to data-poor situations. The more detailed the models, the more information is required to parameterise them. IBMs generally require more data than other approaches.

In light of these data gaps, it is important to explicitly include the uncertainty in all parameter inputs in order to accurately reflect the degree of uncertainty in model predictions. Data to estimate these parameters are sparse and realistic estimates of uncertainty are even rarer. Models of UK seal populations tend to be better parameterised than most cetacean populations – the ability to census whilst on land and tag routinely provides much more information about population status, demography and movement patterns. The intensively studied coastal bottlenose dolphin populations on the east coast of Scotland (Cheney *et al* 2013) and in Cardigan Bay in Wales (Feingold & Evans 2013) are the only cetacean species for which extensive demographic data exist.

All methods have limited ability to predict accurately very far into the future, uncertainty will necessarily increase with the length of time into the future that predictions are projected. All methods are unreliable if other factors, not accounted for in the model, influence the future population parameters (new sources of mortality, impacts from unaccounted for sources *etc*).

None of these methods confidently predict the impact of hearing damage (auditory injury – PTS) in marine mammals, and only iPCoD considers it. This area of marine mammal science is extremely poorly understood, therefore it is unlikely that such impacts can be confidently modelled in any framework. Given these challenges, it is noteworthy that all other bespoke versions of iPCoD models developed to date have not included assessments of impact of hearing damage on populations (e.g. Booth *et al* 2016; Harwood & Booth 2016; Tollit *et al* 2016). There has been an assumption that routine mitigation measures (e.g. Marine Mammal Observers, Passive Acoustic Monitoring, ramp-up procedures and acoustic deterrent devices) reduce the risk of auditory injury to negligible levels but this assumption has not been rigorously tested.

Table 1 provides an overview of the main methods covered in this guide. Figure 6 presents a very basic 'decision' process for the choice of models/approaches available for use in different assessments for UK marine mammal populations. In summary, if the metric being assessed is a mortality rate, either PBR, iPCoD or DEPONS can be used (although alternative 'take-based' methods or any form of population predictive model-based PVA approach could be considered, e.g. VORTEX). If using iPCoD for an assessment of mortality it would only require the Leslie Matrix model element of the framework and not the expert elicitation informed disturbance transfer functions and therefore is a much simpler exercise. DEPONS could be used for the North Sea harbour porpoise population once it is available although it may be considered over-elaborate for predicting the population consequences of mortality alone, although may particularly useful for modelling both mortality and disturbance in relation to spatio-temporal variation in both.

Where sub-lethal effects need to be considered, e.g. noise disturbance, PBR cannot be used without a method to first translate the predicted level of impact to a probability of death so that the number of potential mortalities could be predicted. This would require data (that does not currently exist) or an expert elicitation of some kind. iPCoD could be used for assessments relating to any of the UK management units for the five priority species (IAMMWG 2015), using Harwood and King (2014) to define appropriate population parameters. iPCoD could be adapted for any other marine mammal population and impact combination by carrying out a new expert elicitation process (assuming empirical data are unavailable to parameterise the model). DEPONS is currently appropriate for the harbour porpoise population of the inner Danish Waters and will soon be available for the North Sea Population. Detailed movement and density/space use information would be required to apply it to any other harbour porpoise population.

IBMs similar to DEPONS could potentially be developed for other species of marine mammals. In terms of population data, telemetry based movement data and density/distribution patterns there are more extensive and intensive data sets for both grey and harbour seals than for porpoises in the North Sea. Recent data on movements of harbour seals relative to pile driving operations (Russell *et al* 2015; Gordon *et al* 2016) and telemetry based observations of reactions to Acoustic Deterrent Devices provide similar data to those available for porpoises. It is therefore feasible that a DEPONS type model could be developed for seals in the North Sea and indeed, a project developing an IBM for seals in the North Sea has recently been funded as a collaboration between St Andrews (UK) and Aarhus (Denmark) Universities.

Recent developments of PVA in impact assessment for bird populations have attempted to incorporate decision criteria into population models – i.e. used to explicitly ask the question does this level of impact constitute a significant deleterious population effect - yes or no? e.g. ‘Acceptable Biological Change’ and ‘Decline Probability Difference’ methods, see Green *et al* (2016) and Cook and Robinson (2017) for discussion of these methods. So far, similar methods have not been applied to marine mammal impact assessments. The use of these methods with built-in thresholds of acceptability in bird impact assessments have led to criticisms (e.g. Green *et al* 2016) and has resulted in debate over whether defining what is an acceptable level of population change is a societal, rather than strictly biological question. For example, Cook and Robinson (2017) suggested that predictive models that allow a counterfactual between impacted and non-impacted populations to be calculated are a preferable way of conveying the potential magnitude of population effect, leaving decisions about acceptability to regulators. To date in the UK, no specific acceptable thresholds of impact have been defined for marine mammal populations in impact assessment, other than by the use of PBR in decision making in relation to collision related mortality. However, the use of population predictive approaches is likely to become increasingly common, particularly for cumulative and plan-level assessments, although these will require updated and reliable demographic information for each population. Deciding on what is an ‘acceptable’ level of impact will require consideration of the legislation protecting the species/population, the conservation objectives for the relevant site or species as well as the biological status of the species/population concerned as well as the current conservation status and size of the population concerned.

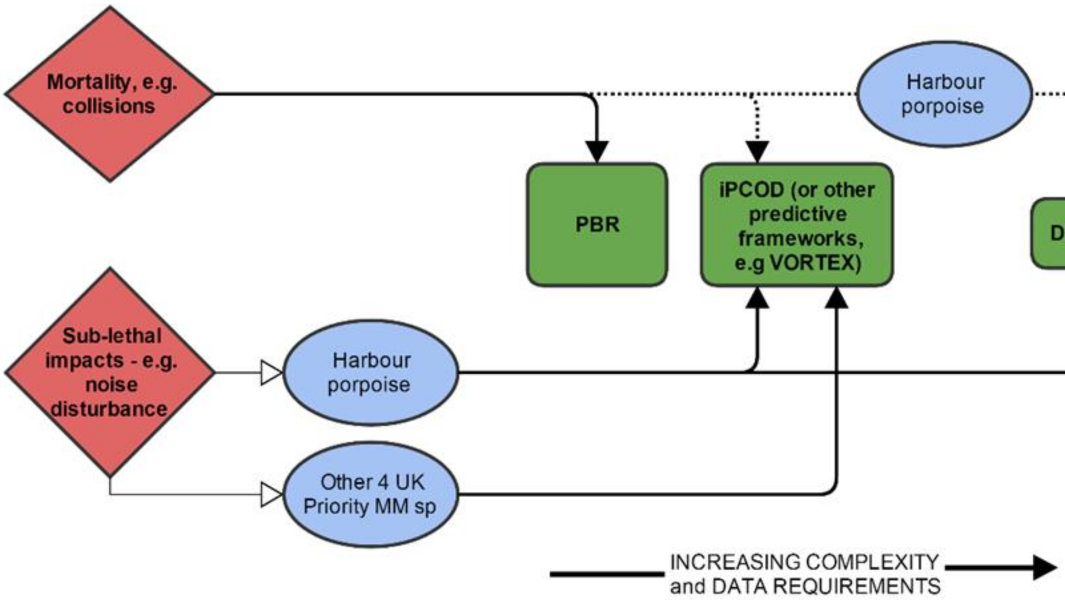

Figure 6. Basic 'decision tree' for the different approaches to marine mammal population level assessment of impacts covered in this guide – solid lines mean that the models/frameworks in the green boxes can be used to assess the impact in the red diamond, for the species indicated in the blue ovals. The dotted line means that it is possible to use but not the main focus of the method. Please note this is not intended to be exhaustive and does not rule out alternative methods that have not been included in this review.

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6 Glossary of Terms, Acronyms and Abbreviations

Term	Description
20th Percentile	The value below which 20% of the observations lie in a distribution.
ABC	Acceptable Biological Change – a method developed by Marine Scotland Science for the assessment of impacts on seabird populations from offshore wind farms. The method applies a threshold probability of an outcome for future unimpacted population size that is claimed to identify a threshold expected reduction of population size by wind farms that is acceptable on objective and scientifically defensible grounds.
Carrying capacity	The maximum stable population size that the environment can sustain indefinitely given the resources available.
CLA	Catch Limit Algorithm – an algorithm developed by the IWC to regulate whaling.
Counterfactual impact evaluation	A method of comparison which involves comparing two outcomes, similar in all respects other than the anticipated effects of the impact under evaluation. In the context of this guide, it refers to the difference in predicted outcome for an impacted versus unimpacted population
DEPONS	Disturbance Effects on the Harbour Porpoise population of the North Sea; a research programme at Aarhus University, Denmark. Led by Jacob Nabe-Nielsen and colleagues.
Density Dependence (DD)	The concept that populations cannot continue to grow indefinitely because, ultimately, they will be limited by available resources. As density increases, population growth slows down and eventually halts. This is as a result of a reduced availability of resources (food and space), and also sometimes the spread of disease and increased predation.
EIA	Environmental Impact Assessment
EPS	European Protected Species
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
FCS	Favourable Conservation Status
Fecundity	Birth rate of a population, expressed as the probability that an individual adult female will give birth to a viable offspring in any particular year
FR	Recovery Factor (used in PBR calculation)
HRA	Habitats Regulation Appraisal
IBM	Individual Based Model (see Box 1)
IPCOD	Interim Population Consequences of Disturbance
IWC	International Whaling Commission
Leslie Matrix Model	An age- or stage-structured population model of population growth which combines age or stage-specific values of mortality and fecundity to estimate population growth
Matrix model	A specific type of population model that uses Matrix algebra.
MFSAF	Moray Firth Seal Assessment Framework: a method used by Thompson *et al* (2013) to assess the potential impacts of pile driving on the Moray Firth Harbour Seal population. The approach used a stage

	based matrix model of population dynamics to predict the future trajectory of the population as a result of individual level impacts resulting from noise (disturbance and injury).
MMPA	Marine Mammal Protection Act (US)
MNPL	Maximum Net Productivity Level (see OSP)
MU	Management Unit
OFBM	Objective based fisheries management
OSP	Optimum Sustainable Population - a population size which falls within a range from the population level of a given species or stock which is the largest supportable within the ecosystem to the population level that results in maximum net productivity. Maximum net productivity is the greatest net annual increment in population numbers or biomass resulting from additions to the population due to reproduction and/or growth less losses due to natural mortality. http://www.nmfs.noaa.gov/pr/glossary.htm
PBR	Potential Biological Removal
PCoD	Population Consequences of Disturbance
PTS	Permanent Threshold Shift – auditory damage caused by exposure to loud noise whereby the threshold of hearing at a particular frequency increases.
PVA	Population Viability Analysis – historically, a method of population analysis used to predict the likelihood of a population becoming extinct. Now generally used to describe methods used to model a whole range of potential outcomes, including impacts.
Recovery Factor	A scaling factor between 0 and 1 which is used to reduce the prediction of allowable mortality in the application of the PBR framework
RMP	Revised Management Procedure
SNCB	Statutory Nature Conservation Body
Stochasticity	Randomness or noise – in population modelling stochastic variables can vary randomly. Often used to include the potential for environmental variability in demographic rates (e.g. bad weather in a particular year causing a decrease in pup survival).
Vital rates	Survival and birth rates
VORTEX	A software package for modeling population dynamics, often used in PVA.

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