An interim framework for assessing the population consequences of disturbance

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Summary

1. Changes in natural patterns of animal behaviour and physiology resulting from anthropogenic disturbance may alter the conservation status of a population if they affect the ability of individuals to survive, breed or grow. However, information to forecast population-level consequences of such changes is often lacking.

2. We developed an interim framework to assess the population consequences of disturbance when empirical information is sparse. We show how daily effects of disturbance, which are often straightforward to estimate, can be scaled to the disturbance duration and to multiple sources of disturbance.

3. We used expert elicitation to estimate parameters that define how changes in individual behaviour or physiology affect vital rates and incorporated them into a stochastic population model. Model outputs can be used to evaluate cumulative impacts of disturbance over space and time. As an example, we forecast the potential effects of disturbance from offshore wind farm construction on the North Sea harbour porpoise (Phocoena phocoena) population.

4. Synthesis and applications. The interim framework can be used to forecast the effects of disturbances from human activities on animal populations, to assess the effectiveness of mitigation measures and to identify priority areas for research that reduces uncertainty in population forecasts. The last two applications are likely to be important in situations where there is a risk of unacceptable change in a species’ conservation status. The framework should, however, be augmented with empirical data as soon as these are available.

Key-words: anthropogenic noise, behavioural response, expert elicitation, impact assessment, stochastic population models

Introduction

Policymakers and managers are increasingly concerned about the effects of disturbance on wildlife populations (Sutherland et al. 2006). However, forecasting population-level consequences of changes in individual behaviour is difficult (Sutherland et al. 2013). Recently, working groups established by the US National Academy of Sciences and the US Office of Naval Research developed conceptual models of the population consequences of disturbance (PCoD) for marine mammals (NRC 2005; New et al. 2014). These models build on the concept that many species appear to perceive human disturbance as a predation threat (Frid & Dill 2002; Beale & Monaghan 2004). Their approach reflects Sutherland’s (1996) definition of disturbance as ‘adverse behavioural changes in animals as a result of predators or humans’. New et al. (2014) considered behavioural and physiological responses to disturbance as adverse if they had a negative effect on individual health (all aspects affecting individual fitness). Using data from a long-term study of southern elephant seals (Mirounga leonina), they showed how a hypothetical reduction in foraging time resulting from disturbance could affect breeding females’ health (measured by lipid mass), reducing offspring survival and population growth rate.

Although an extensive literature documents the effect of human disturbance on wildlife behaviour (Blumstein et al. 2005), the fitness consequences of behavioural changes have been demonstrated for only a few species (Kerley et al. 2002; Rodriguez-Prieto & Fernandez-Juricic 2005; Kight & Swaddle 2007). For most species, there is little or no empirical evidence to quantify the relationship between behavioural or physiological change and fitness. To fill this knowledge gap, we have developed an interim version of the PCoD framework using expert elicitation (EE). The approach is ‘interim’, because the values provided by experts should be replaced with empirically derived values as soon as they become available.

Expert elicitation is a formal process in which multiple experts are asked to predict what may happen in a particular...
situation. These predictions are combined into quantitative statements that can be incorporated into mathematical models (Martin et al. 2012). The process is used in conservation science when data are lacking, but there is an urgent need for management decisions (Runge, Converse & Lyons 2011; Martin et al. 2012). It is designed to mitigate the well-documented problems (e.g. anchoring, availability bias, confirmation bias and overconfidence) that arise when expert judgements are canvassed naïvely (Cooke 1991). EE also provides calibrated estimates of the uncertainty associated with these judgements (Martin et al. 2012).

We describe the interim PCoD framework and illustrate its use to forecast the effects of disturbance from anthropogenic noise, an increasing problem for many taxa (Kight & Swaddle 2007; Morley, Jones & Radford 2014) in marine (Tyack 2008) and terrestrial environments (Barber, Crooks & Fristrup 2010). In particular, we examine the potential effects of noise from offshore wind farm construction, an area of policy concern in the UK and globally (Sutherland et al. 2006, 2009), on the North Sea harbour porpoise (Phocoena phocoena) population.

Materials and methods

Implementing the interim PCoD framework (Fig. 1) involves the following steps:

Step 1. Identify spatial boundaries for the population that may be affected by disturbance. These boundaries may define a closed biological population or a Management Unit (MU, ‘a group of animals of the target species in a geographical area to which management of human activities is also applied’ IAMWWG (2015)). We discuss the implications of this later.

Step 2. Characterise the ways in which human activities may disturb members of the population (equivalent to the process of hazard identification in environmental impact assessment).

Step 3. Identify a set of measurable behavioural or physiological responses that may affect individual fitness.

Step 4. Determine the relationship between the probability an individual will exhibit these responses and its exposure to the hazard (transfer functions A1 and A2 in Fig. 1). Ideally, this should be a probabilistic dose–response relationship that accounts for relevant contributory factors.

Step 5. Use information on the distribution of the hazard(s) and the target species in space and time to determine how often individuals are likely to be disturbed during a biologically meaningful time interval. For a species with birth-pulse dynamics (Caswell 2001), this is usually the interval between successive breeding seasons.

Step 6. Use EE to estimate the effect of different levels of disturbance on individual vital rates (transfer functions B1 and B2 in Fig. 1). We used the relationship in Fig. 2, which assumes that individuals have limited ability to compensate for a reduction in feeding by altering their activity budget (Houston, Prosser & Sans 2012). Once that limit is reached, the energy they can transfer to their offspring, their resistance to disease and their vulnerability to predation may be affected. The relationship is defined by three parameters, each with a clear biological interpretation.

Step 7. Incorporate the information obtained in the preceding steps into a stochastic dynamic model (Morris & Doak 2002) to forecast the potential effects of disturbance on population size and structure (transfer function C in Fig. 2), taking account of the uncertainties involved in the preceding steps. If the population is small, it should account for demographic stochasticity (the variation among years in the number of births and deaths because of chance events, even if vital rates are constant).

**USING THE INTERIM FRAMEWORK IN PRACTICE**

We now describe how these seven steps can be completed for a specific management issue: assessing the effects of anthropogenic noise on marine mammals.

Step 1. In general, the spatial boundaries of marine mammal populations are defined by regulatory authorities or their scientific advisors. Steps 2 and 3. There have been dramatic increases in the amount of underwater sound in the marine environment from shipping, military and research activities, construction and exploration (Tyack 2008). Marine mammals frequently avoid these sounds (Southall et al. 2007; Goldbogen et al. 2013). This may lead to individuals being displaced from preferred and potentially critical habitats, with acute adverse effects on vital rates (B1 in Fig. 1) if they are displaced into areas where the risk of predation or disease is elevated (Frid & Dill 2002), and chronic effects (B2 in Fig. 1) on health if they are displaced into areas where resources are less available. Other marine mammal behavioural responses ‘with higher potential to affect . . . reproduction or survival . . . and . . . likely to affect these vital rates’ (Southall et al. 2007) include shifts in group distri-

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**Fig. 1.** The interim population consequences of disturbance (PCoD) framework (modified from New et al. 2014, fig. 6). Circled letters identify transfer functions describing the relationship between the variables at either end of the arrow. Dotted lines indicate transfer functions that have been parameterised using expert elicitation (EE).
bution and interanimal distance, cessation of vocal behaviour and separation of females from their dependent offspring.

Step 4. In general, an individual’s response to sound will depend on many factors including the context in which exposure occurs, its internal states and its exposure history (Ellison et al. 2011). Recently, there has been considerable progress in fitting relationships that describe the response of marine mammals to anthropogenic sound and account for the effect of these covariates (Miller et al. 2014). However, we recognize that these relationships may change over time if individuals become more tolerant to disturbance. In the absence of such relationships, analysts may use threshold values for the received sound level (RL) or cumulative sound exposure level (SEL) above which disturbance is assumed to be certain to occur (Southall et al. 2007), although this will result in an underestimate of uncertainty.

Step 5. Methods for estimating the number of marine mammals disturbed by a sound source over a period of 1–5 days are described in Frankel, Ellison & Buchanan (2002) and Donovan et al. (2012). They involve modelling the way in which the sound field varies in space and time and simulating the three-dimensional movement of individuals through this field to estimate their RLs or SELs. These levels are used with the relationship from Step 4 to predict the probability of disturbance for each individual. The results are combined with estimates of animal density to calculate the number of individuals likely to be disturbed during the simulated time period.

If suitable information on individual movement, for example from telemetry devices (Edrën et al. 2010; Sharples et al. 2012; Russell et al. 2013), is available, this approach can be extended to estimate the number of times each member of the population is likely to be disturbed over a biologically meaningful time interval using approaches similar to those described in Langrock et al. (2012).

Step 6. Juvenile survival and fertility are the vital rates most sensitive to changes in resource availability in long-lived vertebrates, such as marine mammals (Eberhardt 2002). As a first step, we suggest that these are the vital rates most sensitive to disturbance.

Experts’ opinions about parameters and confidence bounds can be used to define marginal distributions and correlation structure for multivariate treatment of parameters via copula-type simulation methods (Iman & Conover 1982). Random draws from each expert’s multivariate distribution can then be used to build two-dimensional probability density functions (pdfs) for the relationships that are being estimated. This approach captures the uncertainty expressed by individual experts and the variability in their opinions (Fig. 3).

Step 7. We use a population model in which individuals are divided into calves (animals still dependent on their mothers), juveniles and adults. Animals up to age 9 are assigned to individual age-classes. Animals aged 9 and above are combined into a single stage-class. This model structure is appropriate for many marine mammal species.

Animals in each class can be divided into three categories: individuals that experience ≤B days of disturbance (Fig. 2), individuals that experience moderate disturbance (>B days, but ≤C days) and individuals that experience severe (>C days) disturbance. The mean number of days of disturbance experienced by all the individuals in the moderate disturbance category for each stage-class within the modelled year is then calculated. The resulting values are used with the relationships in Fig. 2 to determine the effect of disturbance on vital rates in that year.

The three disturbance categories and 10 stage-classes result in 30 stage-disturbance combinations, modelled as a 30-element vector using a Leslie matrix structure (Caswell 2001). That matrix provides information on the survival and fertility rates for each element and moves animals between stages at the end of the year. We suggest running the model using the estimated number of females in the population and scaling results to the full population at the end of the simulations using the estimated sex ratio.

Year-to-year variations in environmental conditions will also affect survival and fertility. Many survival and fertility rates for marine mammals are close to 1.0, so they cannot vary symmetrically around the mean. We therefore model environmental stochasticity using a beta distribution, whose mean corresponds to the best estimate of the relevant vital rate, and whose lower 99% confidence limit (equivalent to a once in 50 years event) corresponds to a value provided by EE.

A SPECIFIC APPLICATION OF THE INTERIM FRAMEWORK

We used the interim PCoD framework with publicly available information and results from an EE to investigate how noise associated with the construction of five UK Round 3 offshore wind farms (locations shown in Fig. 4) might affect the North Sea harbour porpoise population.

Step 1. An interagency working group of scientific advisors to the UK government (IAMWWG 2015) provided estimates of the size and range of the North Sea harbour porpoise population.

Steps 2–4. Brandt et al. (2011), Tougaard et al. (2012) and Dähne et al. (2013) observed that harbour porpoises were displaced from the area around a wind farm by construction noise and that they did not immediately re-enter that area when construction ceased. Dähne et al. (2013) recorded reduced densities of harbour porpoises at distances of up to 25 km from pile-driving activity that produced an SEL of 164–179 dB re 1 μPa² s at 750 m. This is similar to the estimated SEL for the smallest turbine piles proposed for the Round 3 wind farms. We therefore assumed that all porpoises within 25 km of such piles would be displaced on any day during which piling occurred. The number of porpoises likely to be disturbed was calculated using mean density estimates for the relevant survey blocks from the most recent survey of the MU (Hammond et al. 2013; Table 1). We investigated the sensitivity of population forecasts to these values by also assuming that porpoises were displaced if they were up to 35 km from the source. This doubled the estimated number of animals affected by 1 day of piling at each wind farm.

We used the estimate of the mean number of animals likely to be disturbed on each day of piling and the relevant population size to calculate the probability that an individual vulnerable to disturbance will be displaced during 1 day of construction. We captured uncertainty in this probability by multiplying the calculated value by a scalar drawn at random from:

\[ \exp(N(\mu = 0, \sigma = 0.25)) \]

This resulted in 95% confidence limits that were similar to those reported for estimates of the proportion of the North Sea harbour porpoise population likely to occur in the immediate vicinity of wind farm sites (C. Paxton, pers. comm.).

Although Dähne et al. (2013) found that harbour porpoise densities returned to pre-disturbance levels within 1 day, Teilmann & Carstensen (2012) reported longer-lasting displacement. We therefore investigated the population consequences of displacement that persisted for 1

![Fig. 3. The degree of support among experts for different relationships linking days of disturbance to (a) fertility, (b) calf survival and (c) juvenile survival. Individual experts' suggestions (black lines) are superimposed on heat maps showing overall support among experts for particular combinations of values. Reds and yellows indicate well-supported combinations that are more likely to be sampled in simulations. Shades of blue indicate poorly supported combinations.](image-url)
and 2 days after piling ceased. We assumed that the effects of this 'residual' disturbance on fitness would be the same as the initial displacement and that individuals experiencing residual disturbance would avoid the area from which they were displaced during this time.

We lacked data to develop an explicit long-term movement model for harbour porpoises in the North Sea. As an interim measure, we defined the range for the number of times individuals are likely to be disturbed within a biologically meaningful time period by considering two extreme scenarios. Under the first, we assumed every individual is equally likely to be present in the region where disturbance may occur, unless it has previously been disturbed. This reflects cases in which the geographical range of the population is relatively small or the sound source is located within an area of critical habitat. Under the second, we assumed only a fraction of the population, termed the 'vulnerable subpopulation', is exposed to disturbance. All individuals within this subpopulation are assumed to be equally vulnerable, and all other members of the population are assumed to be unaffected. Unique vulnerable subpopulations can be defined for individual sites, or groups of sites. The probability that an individual will be disturbed on a day when piling occurs is calculated from the proportion of the relevant population or subpopulation predicted to experience disturbance on 1 day. In practice, the risk of exposure will vary among individuals and over time. However, in the absence of empirical data, these scenarios encapsulate a realistic range of vulnerabilities.

Step 5. We used published information on the total number of wind turbines planned for each wind farm and the number of years over which construction will take place (Table 1). We assumed each turbine requires 1 day of piling and that all construction work will take place on randomly chosen days between April and September, when sea conditions are most favourable. We estimated the potential exposure to disturbance over the course of a year for each of 1000 simulated individuals in each vulnerable subpopulation by conducting a random Bernoulli trial on each day that construction was predicted to take place, using the probabilities calculated in Step 4. This provided a day-by-day history of disturbance for every simulated individual. To investigate the effects of residual disturbance, we increased the total number of days of disturbance associated with each disturbance event to 2 or 3 days. We deleted any disturbance events from the same operation that fell within this period of residual disturbance. We then calculated the total number of days of disturbance experienced by each individual in every year during which construction occurred.

Because we used a birth-pulse model, in which all births and deaths are calculated at the end of each year, we assumed that survival and fertility rates for each individual were determined by the total number of days of disturbance it experienced in the preceding 12 months. All surviving simulated individuals were assigned to the relevant undisturbed category at the beginning of each year.

Step 6. The harbour porpoise is one of the smallest cetaceans and is unable to store large reserves of potential energy in its blubber. As a result, harbour porpoises probably cannot survive extended periods of behavioural disruption that affect their feeding ability. Indeed, Koopman (1994) suggested that 'the potential energy stored in the blubber layer would be sufficient to sustain a starving porpoise for only a few days'.

We approached 150 experts working on marine mammal population biology, the impacts of noise on marine mammal hearing, or the effects of disturbance on marine mammals to provide estimates of the effects of acoustic disturbance on the vital rates of five marine mammal species in the north-east Atlantic. Experts were provided with background

Table 1. Total number of piling-days associated with the construction, predicted number of disturbed porpoises on one piling-day and vulnerable subpopulation size for each wind farm development

<table>
<thead>
<tr>
<th>Wind farm development</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
<th>Site 4</th>
<th>Site 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Years in which construction occurs</td>
<td>1–4 (4 years)</td>
<td>2–5 (4 years)</td>
<td>2–6 (5 years)</td>
<td>1–4 (4 years)</td>
<td>1–4 (4 years)</td>
</tr>
<tr>
<td>Total piling-days</td>
<td>186</td>
<td>156</td>
<td>600</td>
<td>332</td>
<td>240</td>
</tr>
<tr>
<td>Number of porpoises disturbed during 1 piling-day</td>
<td>25 km radius</td>
<td>403</td>
<td>289</td>
<td>552</td>
<td>276</td>
</tr>
<tr>
<td></td>
<td>35 km radius</td>
<td>806</td>
<td>578</td>
<td>1104</td>
<td>552</td>
</tr>
<tr>
<td>Vulnerable subpopulations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 1</td>
<td>227 298</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 2 (%)</td>
<td>56 824 (25)</td>
<td>113 649 (50)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 3 (%)</td>
<td>10 228 (4.5)</td>
<td>47 733 (21)</td>
<td>88 646 (39)</td>
<td></td>
<td>27 276 (12)</td>
</tr>
</tbody>
</table>

information on what disturbance these species might experience, their likely behavioural responses and how these might affect their vital rates. Further details of the criteria used to select experts, the names of those who responded, the justifications they gave for the values they provided and the analytical methodology can be found in appendix 1 of Harwood et al. (2014).

We asked experts for their best estimates of the maximum effect of disturbance on calf and juvenile survival (line A in Fig. 2), and the number of days of disturbance required to have this effect (line C in Fig. 2). We also asked them to estimate how many days of disturbance an individual calf or juvenile could tolerate before its survival was affected, and how many days an individual mature female could tolerate before her fertility was affected (line B in Fig. 2). We assumed the maximum effect of disturbance is to reduce fertility to zero, but we allowed experts to choose a different value for the maximum effect of disturbance on calf and juvenile survival. Finally, we asked experts to choose which of six values (0, ±10, ±20, ±30, ±40 or ±50%) best reflected yearly variability in vital rates for each species in an undisturbed situation. We assumed environmental variation in vital rates is uncorrelated, both among stage-classes and among years.

We used the 4-step question format developed by Speirs-Bridge et al. (2010) to obtain confidence bounds for estimates (shaded areas in Fig. 2). Subsequently, we asked experts to reconsider the values they had provided in the light of other experts’ estimates. This generally improves the reliability of EE results (Burgman et al. 2011). Answers were provided independently and anonymously to minimise the effects of dominance and status that can compromise group expert judgments. Forty-one experts responded, and nineteen provided information on harbour porpoises. Figure 3 shows the support among experts for the pdfs derived from their responses for this species. Uncertainty in relationships was captured by taking random draws from the underlying pdfs derived from their responses for this species. Uncertainty in vital rates is uncorrelated, both among stage-classes and among years.

We considered three scenarios (Table 2) for the vulnerability of individual porpoises to disturbance:

1. All individuals are equally vulnerable to the effects of all five wind farm developments.
2. There are two vulnerable subpopulations: one affected by construction in the southern North Sea and the other by construction in the northern North Sea.
3. There are four vulnerable subpopulations: three of which are affected by construction at individual sites and one that is affected by construction at sites 3 and 4.

Subpopulation boundaries are shown in Fig. 4.

For each scenario, we forecast trajectories for 1000 identical pairs of populations over a 12-year period. One member of a pair was subject to the effects of disturbance and the other was not. For each pair of simulation runs, we randomly selected the opinions of one virtual expert, a set of values for the effects of environmental stochasticity and an estimate of the number of animals likely to be disturbed by 1 day of piling at each site from the underlying statistical distributions.

**Results**

There was no consensus among experts on the amount of disturbance harbour porpoises might tolerate before their survival or fertility is affected, nor on the maximum effect of disturbance (Fig. 3). As a result, there was substantial uncertainty associated with the forecasts of the population-level effects of wind farm construction. The median difference between simulated population pairs in year 6 (immediately after construction work ceased) was highest when animals were divided into four vulnerable subpopulations (Scenario 3), and increased exponentially as the number of days of residual disturbance increased. Doubling the number of animals predicted to be disturbed resulted in an order of magnitude increase in the median decline. However, even in the most extreme case, the median decline was <0.5% of initial population size.

European Union Member States may issue a licence to disturb protected species, such as the harbour porpoise, provided this has no negative effect on their favourable conservation status. Evans & Arvela (2012) advise that a population decline of more than 1% per year over a 12-year period represents unfavourable conservation status. A decline of more than this amount was forecast for 23–28% of the disturbed populations, and 24% of the undisturbed populations, suggesting that most of the decline was the result of environmental variation. We therefore calculated the additional risk of decline due to wind farm construction for each scenario-parameter combination as the difference between the proportion of disturbed and the proportion of undisturbed simulated populations that were forecast to decline by 1%. In most cases, this risk was <0.01. However, the risk was consistently higher under Scenario 3 and was 0.04 in the most extreme case (Table 3).

**Discussion**

We have demonstrated how the interim PCoD framework can be used to forecast the cumulative effects of disturbance over
time (multiple activities on a multiyear time scale) and space (simultaneous activities in different parts of a species’ range) on a population in a data-poor situation. Other authors (Thompson et al. 2013; Nabe-Nielsen et al. 2014) have developed similar approaches, but these are location and/or species specific.

The example we present is purely illustrative and must not be interpreted as a prediction of the actual effects of offshore wind farm construction on the North Sea harbour porpoise population, because the way we estimated the number of animals disturbed during 1 day of construction is unrealistic. A formal assessment should account for the precise method of construction and the sound propagation characteristics at each site, the relationship between sound exposure and the probability of disturbance (Thompson et al. 2013), the local density of harbour porpoises at the time of construction and any mitigation measures. With this important caveat, we now describe how our results could be interpreted for management purposes.

The risk that wind farm construction might affect favourable conservation status was only >0.01 if animals are disturbed over a radius of 35 km, rather than 25 km. Such information would provide regulators with a robust, auditable, scientific basis for issuing a licence to disturb, even in a situation where there are many unknowns.

However, using the framework in such data-poor situations requires a series of strong assumptions. These should be carefully documented and the consequences of their violation investigated. For example, we assumed that the harbour porpoise MU defined a closed population. PCoD will have been underestimated if the animals within the MU are actually part of a larger biological population not affected by the same human activities and underestimated if there are distinct biological populations within the MU that experience different levels of disturbance.

We assumed the experts who responded to our survey held opinions that were representative of the scientific community and unbiased, or at least held biases that would compensate across the range of experts involved. Bias can be addressed by including calibration questions whose answers are known to the investigators but not the participating experts. Group estimates may be improved by weighting the experts’ responses by their performance on these questions (Cooke 1991). We provided only limited scope for experts to modify the form of the relationships between disturbance and vital rates. This situation could have been improved by conducting interactive workshops, rather than relying on an online questionnaire.

We further assumed there was no variation among individual porpoises in the effect of the number of days of disturbance on vital rates. Accounting for this variability would have increased the uncertainty around the population forecasts. We also assumed that all disturbance-days had an equal effect on vital rates. In reality, being disturbed many times in 1 day or on consecutive days may have a greater effect than being disturbed the same number of times over a longer time interval. Individual tolerance of disturbance may also increase following repeated exposure, resulting in changes in the relationship between disturbance and vital rates over time. If these sources of variation are believed to be important, a full PCoD model that takes account of the effect of disturbance on individual health (New et al. 2014) should be used.

We only considered behavioural responses to disturbance. However, some disturbed individuals may remain in an area, particularly if it contains a high-quality resource (Gill & Sutherland 2001). This may have physiological consequences (Beale & Monaghan 2004) including increased stress (Rolland et al. 2012) that can affect survival and fertility (Wright et al. 2007). These effects can be incorporated into the interim framework if the number of animals likely to experience stress can be estimated (transfer function A1 in Fig. 1).

In our example, forecasts of population decline were sensitive to assumptions about among-individual variation in vulnerability to disturbance and the duration of the effects of disturbance on individual behaviour. If regulators considered the risks to North Sea harbour porpoise populations were unacceptable, they could insist that developers use mitigation methods such as bubble curtains (Dähne et al. 2013) to reduce piling noise and ensure no harbour porpoises are disturbed beyond 25 km. Research on the movements of individual porpoises and the spatial structure of the North Sea population would reduce uncertainty in population forecasts, and inform key model assumptions about the size of vulnerable subpopulations and residual disturbance. Pirotta et al. (2014) describe how such data can be used to parameterise a full PCoD model that accounts explicitly for the effects of disturbance on individual health.

The interim PCoD framework can be used to assess population-level effects of other sources of disturbance for a wide range of taxa and environments using the seven steps described above. For example, we could have included the effects of noise from seismic surveys and shipping in our analysis if we had access to estimates of the number of animals predicted to be disturbed by these activities and their extent in time and space.

**Table 3.** Effects of distance over which porpoises are disturbed by piling noise and number of days of residual disturbance on risk of a 1% annual decline over 12 years when the North Sea is divided into four subpopulations

<table>
<thead>
<tr>
<th>Distance over which animals are disturbed</th>
<th>Days of residual disturbance</th>
<th>Additional risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 km</td>
<td>0 1 2</td>
<td>0.001 0.006 0.008</td>
</tr>
<tr>
<td>35 km</td>
<td>0 1 2</td>
<td>0.001 0.007 0.041</td>
</tr>
</tbody>
</table>

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Data accessibility
Simulation code was written in the R statistical computing environment (R Development Core Team 2010). The program files, together with a set of supporting documents and instructions, can be downloaded at http://www.gov.scot/Topics/marine/science/MSInteractive/Themes/pool.

References


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