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PERSPECTIVES AND NOTES

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A decision framework to identify populations that are most vulnerable to the population level effects of disturbance

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Abstract

We present a decision framework to identify when detailed population-level assessments are required to understand the potential impacts of a disturbance-inducing activity on a marine mammal population and discuss how the framework can be applied to other taxa. Species at high risk of population-level effects can be identified using information on the number of individuals that are likely to be disturbed by the activity, total population size, the probability of repeated disturbance, the species' reproductive strategy, and the life stages (e.g., feeding, pregnant, and lactating) of the individuals most likely to be exposed. This hierarchical approach provides those responsible for conducting impact assessments with a time-efficient, cost-effective and reproducible workflow that allows them to prioritize their efforts and assign funds to those species with the most pressing conservation needs. A fully worked case study using marine mammals in the vicinity of a naval training activity is supplied.

KEYWORDS

anthropogenic disturbance, conservation management, impact assessment, life-history strategy, noise, population consequences of disturbance, reproductive strategy, risk assessment

1 | INTRODUCTION

Disturbance, defined by Frid and Dill (2002) as a deviation in an animal's physiology or behavior from patterns occurring without predator or human influences, can affect wildlife population dynamics (Creel & Christianson, 2008). As a result, assessment of the population-level effects of disturbance caused by human activities is a component of many impact assessments for example, under the European Habitats Directive 92/43/EEC. Observed physiological responses to disturbance-inducing activities include changes in hormone levels (e.g., Garcia Pereira, Barbanti Duarte, & Negrão, 2006), morphology and ontogeny (e.g., Aguilar de Soto et al., 2013), and body condition (e.g., Schick et al., 2013). Behavioral responses can result in changes in habitat use (e.g., Russell et al., 2016), vigilance (e.g., Armitage, 2004), and movement patterns (e.g., Fortin et al., 2005). Such responses can have a direct (acute) effect on an individual's vital rates, as defined by Morris and Doak (2002, p. 16). For example, disturbance may increase the risk of predation, or permanently separate dependent offspring from their parent. However, these responses may also have an indirect (chronic) effect on individual vital rates (e.g., probabilities of survival and giving birth, age at first reproduction) if foraging opportunities are lost, or energy expenditure is increased.

The potential chronic effects of disturbance have been the focus of much attention (e.g., Harris et al., 2018; Steven, Pickering, & Castley, 2011), but quantifying the links between disturbance-induced behavioral and physiological responses and their population-level effects is not straightforward (see Pirotta et al., 2018 for discussion). This is due to limited foundational knowledge on how responses are mediated—for example, how an individual's response to a stressor is likely to be affected by the context of the disturbance and the individual's motivation, experience, and condition (Götz & Janik, 2010), but also how these responses affect the health and/or vital rates of individuals. As a result of time constraints and limited empirical data, population consequences are rarely assessed in impact assessments, even when this is a requirement. This highlights the need for a documented workflow that allows practitioners to advance impact assessments and decision-making in a way that highlights and prioritizes populations at greatest risk.

Here, we present a decision framework that allows for a cost-effective assessment of disturbance impact at the population level. The framework was developed to assess the potential effects of disturbance on marine mammal populations but we explain how it can be adapted to other taxonomic groups. A draft of the framework was refined by a group of invited experts consisting of marine mammal scientists and those involved in regulation, impact assessment, and policy. It was then applied to scenarios involving a range of stressors, disturbance durations, and species. The resulting decision framework allows populations at high risk to be identified and prioritized for subsequent assessment. In Supplementary Information (SI-Case study), we present a worked example based on the interactions between marine mammals and a U.S. Navy training and testing activity.

2 | THE FRAMEWORK

The decision framework (Figure 1) consists of a series of questions concerning: the spatio-temporal overlap between the disturbance-inducing activities and the populations predicted to be exposed to them; the proportion of each population that is exposed; the probability of repeated disturbance; the reproductive strategy of each species; and knowledge of the "life stages" (e.g., feeding, pregnant, lactating—following the terminology of Villegas-Amtmann, Schwarz, Sumich, & Costa, 2015) of the individuals that are likely to be disturbed.

The framework should be applied to all species whose range overlaps with the area that is likely to be affected by an activity (henceforth referred to as the "affected area") over the time frame of the planned activities (the "activity period").

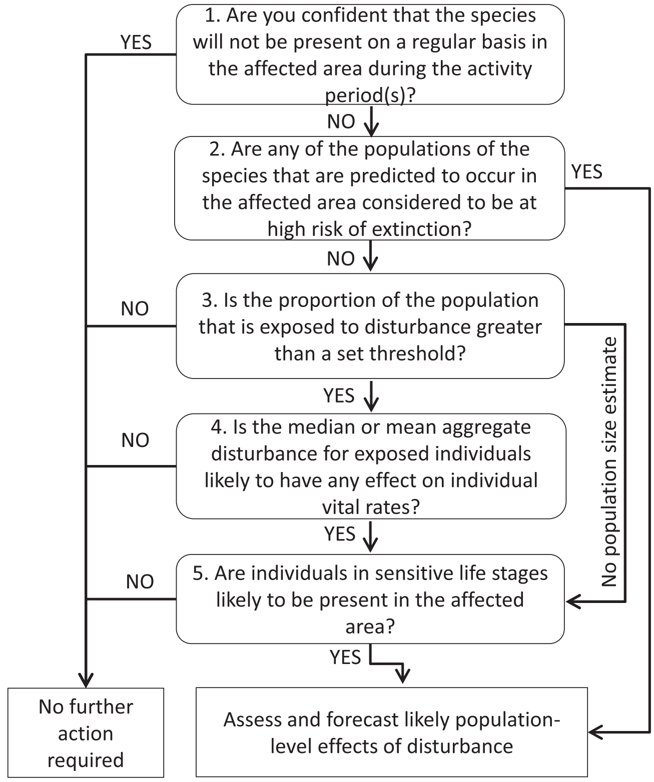

FIGURE 1 A decision framework to identify when population level assessments might be necessary to understand the impact of disturbance on a population

The questions in the decision framework require the user to gather data and information, and define key parameter values. In the examples presented here, we use the Interim Population Consequences of Disturbance (iPCoD) approach (King et al., 2015; http://www.smruconsulting.com/products-tools/pcod/ipcod/; accessed on February 18, 2019) to illustrate one way in which the key parameter values can be defined. iPCoD uses results from an expert elicitation described in Donovan et al. (2016) to forecast the potential effects of different levels of disturbance on the individual vital rates of a number of marine mammal species.

3 | DECISION FRAMEWORK QUESTIONS

The five questions that make up the framework allow practitioners to identify species that do not require any assessment because they are unlikely to be present in the affected area during the activity period (Question 1), and identify populations whose conservation status is unlikely to be adversely affected by disturbance, either because only a small proportion of the population is disturbed (Question 3), or because the levels of disturbance individuals experience is unlikely to affect their vital rates (Questions 4 and 5).

Question 1. Are you confident that the species will not be present on a regular basis in the affected area during the activity period(s)?

It is advisable to decide what level of confidence about a species' geographical range is necessary to answer this question. For example, the preliminary list of species that occur in the affected area may include species that have only been recorded on rare occasions. These species can be excluded from further consideration if the affected area has been routinely surveyed. However, they should not be excluded if species' occurrence in the area is poorly documented.

If the answer to Question 1 is "yes", no further action is required. If it is "no" then proceed to Question 2.

*Question 2. Are any of the populations of the species that are predicted to occur in the affected area considered to be at high risk of extinction (*e.g.*, classified as "endangered" or "critically endangered" according to IUCN criteria, or listed under the U.S. Endangered Species Act)?*

If the answer to this question is "yes" for any population, an assessment of the population-level consequences of disturbance needs to be considered. For populations that are not considered to be at high risk of extinction then continue with the remaining questions.

If the answer to any of the following questions is "no", no further analysis is required for that population.

Question 3. Is the proportion of the population that is exposed to disturbance greater than a set threshold?

Two quantities are required to estimate the proportion of a population exposed to disturbance: the number of individuals likely to be disturbed by the activity, and the total size (N) of the population of which these individuals are a part. The definition of a population should be appropriate for the specific activity period, affected area and local regulatory authority. For example, one could use the stock definition contained in the U.S. Marine Mammal Protection Act: a group of marine mammals of the same species or smaller taxa in a common spatial arrangement, that interbreed when mature. For species for which no reliable estimate N is available, a precautionary approach would be to proceed directly to Question 5.

The number of individuals assessed as likely to be disturbed is an essential requirement of most impact assessments. For example, in the United States, harassment of marine mammals, is generally prohibited unless authorized under a permit or authorization pursuant to the Marine Mammal Protection Act of 1972 as amended 2007 (MMPA). To obtain an authorization under the MMPA requires the applicant to estimate the number of marine mammal "behavioral takes", in addition to other types of takes, as part of the assessment of impacts. The "behavioral take" estimate can be used for the number of individuals assessed as likely to be disturbed.

3.1 | Identifying a "set threshold" for Question 3

We cannot provide definitive advice on how a suitable threshold for the proportion of a population exposed to disturbance might be set, because this will be specific to the taxa, regions and legislation under consideration. However, for illustrative purposes, we show how iPCoD can be used to identify a suitable threshold for three marine mammal species with different breeding strategies. We ran a scenario that was likely to cause substantial disturbance: wind farm construction occurring on 180 days each year, continuing for 20 years, and with a 0.05 probability that an individual within the affected area would be disturbed on a particular day. We simulated the effect of this disturbance on populations of 5,000 harbor seals (*Phoca vitulina*), harbor porpoise (*Phocoena phocoena*) and bottlenose dolphin (*Tursiops truncatus*), varying the proportion of those populations likely to be exposed. Mean vital rates were set so that an undisturbed population would neither increase nor decline over the 20 year period. We used two sets of mean vital rates for harbor porpoise. In the high-fertility scenario females were expected to breed annually, while in the low-fertility scenario females were expected to breed biennially. For each scenario we ran 500 simulations and determined the median decline over 20 years relative to the predicted change in an identical, undisturbed population. We chose the median decline because Jitlal, Burthe, Freeman, and Daunt (2017) concluded this was the population simulation metric likely to be least sensitive to inaccuracies in input parameters. Figure 2 indicates that, there is no threshold value for the proportion of the population exposed to disturbance that results in zero decline. However, when 0.025 or less of the population was exposed to disturbance the median relative decline over 20 years was less than 1% for all four species/fertility scenarios, and no simulated population went extinct. Therefore, for this example, 0.025 of the population might be an appropriate "set threshold."

It should be noted that, if disturbance is sufficient to affect the vital rates of some individuals in the population, then population numbers will inevitably decline until density dependent processes result in compensatory increases in mean vital rates, or the disturbance-inducing events cease. The iPCoD model used here does not include density dependence and therefore probably over-

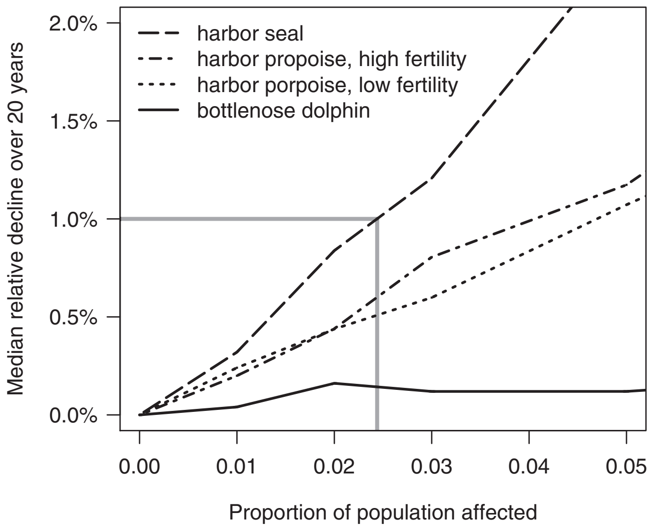

FIGURE 2 The relationship between median relative decline over 20 years and the proportion of the population exposed to disturbance from wind farm construction for otherwise stable populations of harbor seals, harbor porpoises (with high- and low-fertility rates) and bottlenose dolphins

estimates the long-term effects of disturbance. An alternative approach to setting a threshold would be to use a variant of the formula for calculating the allowable mortality (termed the Potential Biological Removal—PBR) under the U.S. MMPA (Wade, 1998), where:

$$PBR = 1/2 \cdot N_{MIN} \cdot R_{MAX} \cdot F_R \quad (1)$$

N_{MIN} is a minimum population estimate (usually the lower 20th percentile of a log-normal distribution, based on an estimate of population size and its coefficient of variation), R_{MAX} is the maximum productivity rate of the population, and F_R is a recovery factor between 0.1 and 1. Wade (1998) used simulations of various populations with density dependence modeled by a theta-logistic function to show that populations which experienced this level of mortality did not decline or actually increased in size. Use of PBR as a proportion of total population size for the set threshold would be unnecessarily prescriptive, because this would assume that all individuals in the affected area are likely to die as a result of disturbance. In practice, only a fraction of the animals in this area will experience disturbance that may cause a reduction in vital rates. We therefore suggest that a PBR value calculated using $F_R = 1$ and replacing N_{MIN} with $\hat{N}$ (i.e., the best available estimate of population size) could be a useful rule of thumb for setting the threshold. Wade (1998) used an R_{MAX} value of 0.12 for pinnipeds and 0.04 for cetaceans. These values would give a set threshold for marine mammals between 0.02 and 0.06, which brackets the value we propose based on the iPCoD simulations.

Question 4. Is the median or mean aggregate disturbance for exposed individuals likely to have any effect on individual vital rates?

This question examines the likelihood that animals will be disturbed repeatedly within the affected area. This will be determined by a variety of factors that affect the distribution of individuals in space and time, including the size of a population's range, the size of individual home ranges, and individual movement patterns. For example, Costa et al. (2016) demonstrated that a small affected area and short activity period may result in many individuals being disturbed if the activity overlaps with a migration corridor and time period. However, these individuals may only be briefly exposed to disturbance. Conversely, fewer individuals might be disturbed in the same area if the population is resident and individuals have small home ranges relative to the affected area, but these individuals are more likely to be disturbed repeatedly.

Even the confirmed presence of individuals from a population in the affected area during the activity period(s) does not necessarily imply they will experience levels of disturbance sufficient to affect their vital rates. This will depend on the total amount of time each individual is disturbed during the activity period(s). One way to estimate this aggregate level of disturbance is to simulate individual exposure histories and use these to predict the statistical distribution of disturbance durations experienced by different individuals in the population. This distribution can then be used to estimate the probability that an individual will be disturbed multiple times.

Computer code for conducting such simulations for marine mammals and other long-lived species, under the assumption that disturbed animals are not displaced from the affected area, is provided in Supplementary Information: SI-Sim R Code. We recognize this will over-estimate the level of aggregate exposure for individuals that leave the affected area in response to disturbance. The minimum time step is 1 day, although shorter time steps will be more appropriate for species whose life expectancy is lower than marine mammals (see below). Required input parameters for the simulation are: the probability that an individual will be disturbed on each day of activity, the number of individuals expected to be in the affected area during each activity period, and the mean number of days they are resident in the area (their mean residency time).

The probability of disturbance for an individual can be estimated from the ratio of the number of individuals assessed as likely to be disturbed on each day of the activity to the estimated number of individuals within the affected area. As for Question 3, an estimate of the number of individuals likely to be disturbed by an activity is

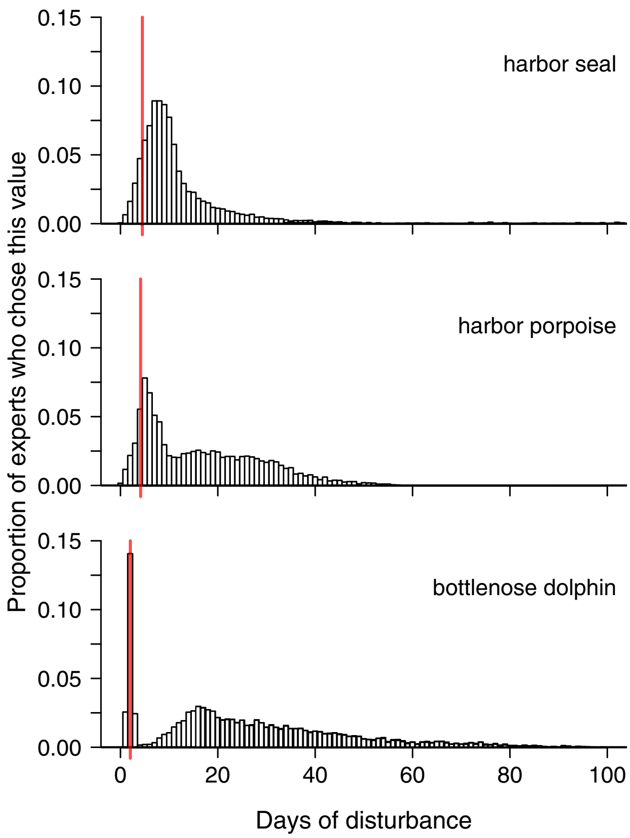

FIGURE 3 The pooled distributions of the predictions of the experts who took part in the elicitation described by Donovan et al. (2016) for the maximum number of days of disturbance that could be tolerated by individual harbor seals, harbor porpoise and bottlenose dolphins without any effect on calf survival. The vertical red lines represent the 10th percentile of each distribution

typically required for impact assessments of activities that are regulated by law.

Mean residency time can be estimated directly from telemetry (e.g., Russell, Jones, & Morris, 2017), and photo-identification data (e.g., Bejder & Dawson, 2001; Wilson, Hammond, & Thompson, 1999), or inferred from information on site fidelity, migration behavior, and home range size. If no suitable data are available, a precautionary approach would be to assume that individuals are resident throughout the activity periods.

Results from the expert elicitation described by Donovan et al. (2016) suggest that a mean or median aggregate disturbance ≥2 days may affect an individual marine mammal's vital rates. Figure 3 shows the pooled distribution of the experts' predictions of the maximum number of days of disturbance that can be tolerated before it has any effect on calf survival for harbor seals, harbor porpoise, and bottlenose dolphins. In all cases, 90% of the predicted values were greater than 2 days. Clearly, this threshold will not be appropriate for all taxa: species with low body weights and high basic metabolic rates (such as rodents and songbirds) may only be able to tolerate short periods of disturbance, whereas large poikilotherms may be able tolerate much longer periods. If data on this tolerance is lacking it may be possible to obtain suitable values using expert elicitation or bio-energetic modeling (e.g., Hin, Harwood, & de Roos, 2019; McHuron, Costa, Schwarz, & Mangel, 2016).

Question 5. Are individuals in sensitive life stages likely to be present in the affected area?

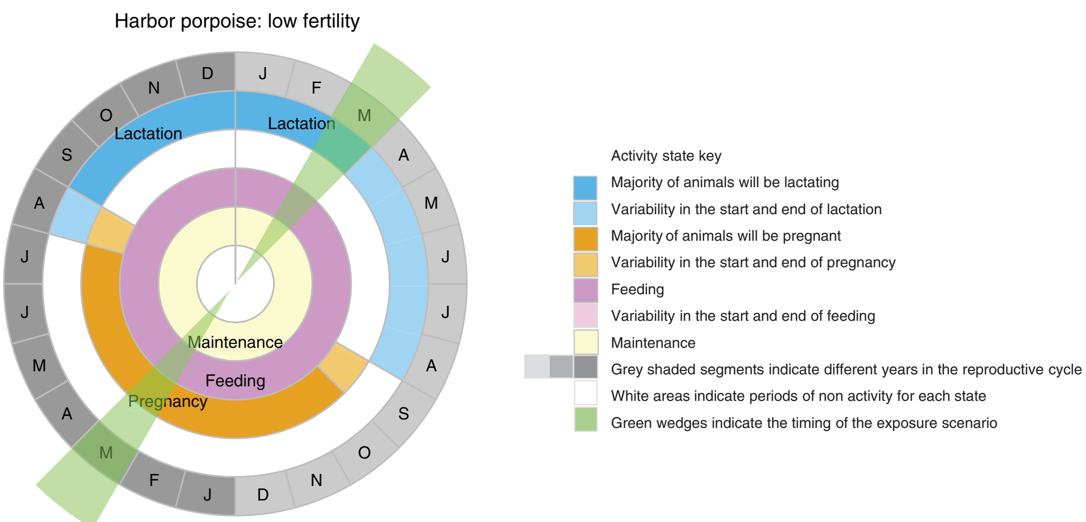

FIGURE 4 Female harbor porpoise reproductive cycle plot showing timing and duration of life stages on a 2-year cycle (low-fertility scenario), with a disturbance-inducing activity occurring during March (highlighted by green wedges). Code for creating this plot is provided in Supplementary Information: SI-LHP code

The population level effects of disturbance will be influenced by each individual's sensitivity to disturbance and what proportion of the most sensitive individuals in the population are in the affected area at the time of the disturbance. Individuals with high daily energy requirements are likely to be most sensitive to the effects of disturbance that result in either reduced energy intake or increased energy expenditure. For example, bioenergetic models of the energy requirements of different marine mammal species have identified "pregnant" as the life-stage most sensitive to disturbance for species that adopt a capital breeding strategy. These species rely almost entirely on stored energy reserves accumulated immediately before and during pregnancy to cover the costs of lactation (McHuron et al., 2016; Villegas-Amtmann et al., 2015). For species that rely on an increase in energy intake to cover these costs (income breeders), "lactating" is the life stage that is potentially most sensitive to disturbance (McHuron et al., 2016), particularly in situations where food resources are limited (Hin et al., 2019; Pirotta, Schwarz, Costa, Robinson, & New, 2019).

By understanding the timing of an activity period in relation to a species' reproductive strategy and the life stages that are likely to be present, we can determine whether the individuals that are most vulnerable to disturbance are likely to be exposed. Reproductive cycle plots (Figure 4) are a useful tool for identifying temporal overlap between individuals in sensitive life stages and the activity period (code for plots is provided in Supplementary Information: SI-LHP Code).

4 | CONCLUDING REMARKS

We have outlined a decision framework to help prioritize the development of population models to support impact assessment. The example presented in SI-Case study demonstrates the utility of the framework for those faced with the daunting task of assessing the population level effects for a disturbance-inducing activity. Use of the framework reduced the list of 41 marine mammal stocks that were known to occur in the affected area to 13 stocks that should be considered further in terms of population consequences. The data collated to reach this point can be used to inform the next step in the process for those stocks remaining on the list. For example, Pirotta et al. (2018) describe a decision tree that can be used to identify the most appropriate PCoD modeling approach, given data availability. Combining that decision tree with the decision framework presented here provides a streamlined approach that allows practitioners to assess the population-level effects of disturbance in an efficient, transparent, reproducible and citeable way.

The examples we have described involve exposure to only one disturbance-inducing stressor. However, it is relatively straightforward to include other stressors that may cause disturbance by expanding the affected area used in the calculations for each question, as illustrated in King et al.'s (2015) assessment of the potential effects of the construction of multiple wind farms on harbor porpoises in the North Sea. Although it is not possible to assess the cumulative effects of all the stressors to which a population is exposed in other parts of its range using the framework described here, their potential effect can be accounted for by setting the recovery factor (F_R) in Equation (1) to a value less than one.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

AUTHOR CONTRIBUTIONS

Harwood and Booth conceptualized this work. Wilson and Harris led the development of the framework and the application to case studies. Wilson, Harris, Harwood and Booth took part in the workshop which reviewed and refined the framework. Wilson, Harris and Harwood drafted the manuscript, with Booth and Joy contributing to subsequent drafts. Joy produced all of the R code and figures. All authors contributed to the final version of the manuscript.

ETHICS STATEMENT

No ethics approval was required for this research.

DATA AVAILABILITY STATEMENT

All data and software code are freely available either within the supporting information document, or available at the referenced sources.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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