


POLICY PERSPECTIVES

Marine Noise Budgets in Practice

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Abstract

Many countries have made statutory commitments to ensure that underwater noise pollution is at levels which do not harm marine ecosystems. Nevertheless, coordinated action to manage cumulative noise levels is lacking, despite broad recognition of the risks to ecosystem health. We attribute this impasse to a lack of quantitative management targets—or “noise budgets”—which regulatory decision-makers can work toward, and propose a framework of risk-based noise exposure indicators which make such targets possible. These indicators employ novel noise exposure curves to quantify the proportion of a population or habitat exposed, and the associated exposure duration. This methodology facilitates both place-based and ecosystem-based approaches, enabling the integration of noise management into marine spatial planning, risk assessment of population-level consequences, and cumulative effects assessment. Using data from the first international assessment of impulsive noise activity, we apply this approach to herring spawning and harbor porpoise in the North Sea.

Introduction

Anthropogenic noise is becoming widely recognized as a pervasive and significant threat to wildlife (Francis & Barber 2013). In the marine domain, noise pollution displaces animals (Tougaard *et al.* 2009), heightens physiological stress (Rolland *et al.* 2012), interferes with communication (Parks *et al.* 2007), disrupts foraging (Blair *et al.* 2016), and causes auditory damage (McCauley *et al.* 2003). Various human activities generate underwater noise, including shipping, pile driving, geophysical surveys, and military sonar. Policy makers are now considering how to manage cumulative noise pollution across these sectors, and in some cases have established ecosystem-level goals. For example, the Marine Strategy Framework Directive (MSFD) requires European Union Member States to attain noise levels “that do not adversely affect the marine environment” (Tasker *et al.* 2010). However, such qualitative commitments have yet to be substantiated by concrete and coordinated management action.

There are many reasons for this management gap, yet we contend that the major obstacle is an absence

of noise budgets: quantitative targets which regulatory decision-makers can work toward. Current noise management (where it exists) largely involves uncoordinated environmental impact assessments executed on a case-by-case basis, without overarching targets to manage cumulative levels of pollution (Wright & Kyhn 2015). To formulate such targets, the risk posed by noise pollution must first be quantified. Recent studies have made progress in this direction by producing risk maps (Erbe *et al.* 2014) and modeling projected changes in population growth due to noise disturbance (King *et al.* 2015; Verfuss *et al.* 2016). These approaches can inform marine spatial planning and the conservation of managed populations, respectively, however, neither offers a mechanism for setting scalable targets which can be cascaded to decision-makers.

In this article, we define and demonstrate risk-based noise-exposure indicators which address this need, enabling managers to quantify and reduce the exposure of managed populations to noise pollution. We first describe the rationale behind the indicator methodology, then demonstrate its implementation in two case studies of cumulative impulsive noise activity in the North Sea

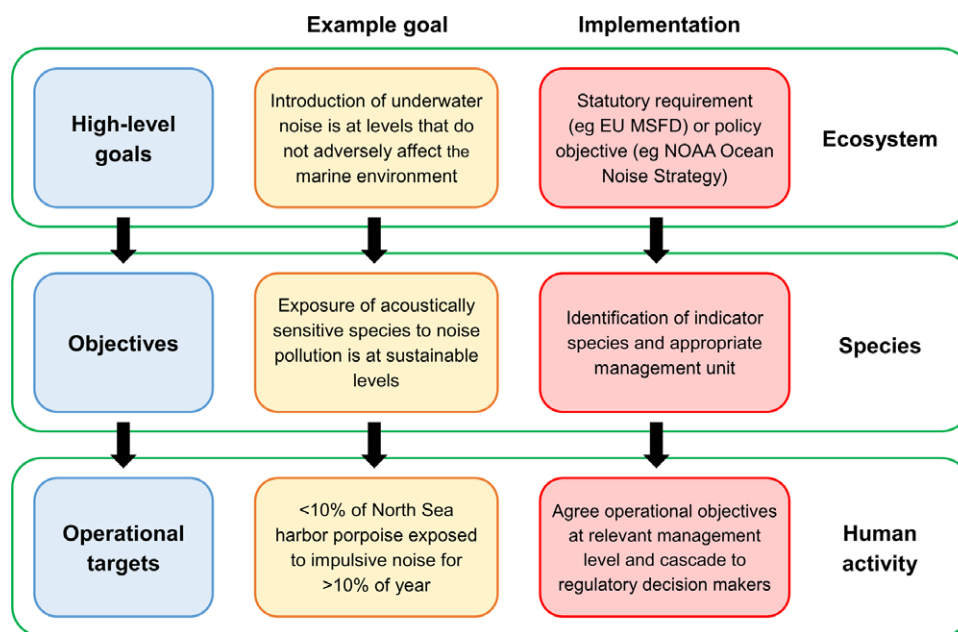


Figure 1 Hierarchy of objectives for underwater noise management, after Katsanevakis *et al.* (2011).

and the associated risk of effects on herring (*Clupea harengus*) spawning and harbor porpoise (*Phocoena phocoena*).

Identifying objectives

The challenge addressed here is one faced more broadly within marine environmental management: how to translate qualitative high-level goals into quantitative operational targets which can be implemented in practice (Levin *et al.* 2009; Katsanevakis *et al.* 2011). This translation is integral to ecosystem-based management frameworks (see example in Figure S1) and can be difficult to achieve (Levin *et al.* 2009). The problem can be conceptualized as a cascade from high-level goals into more specific objectives, and finally into operational targets (Figure 1). For underwater noise, relevant policy exists both as high-level ecosystem-based goals (e.g., EU MSFD, EU MSP Directive, NOAA Ocean Noise Strategy, Canadian Ocean Protection Plan), and as requirements at species level (e.g., Canadian Species at Risk Act, U.S. Marine Mammal Protection Act). However, the final step of setting operational targets for underwater noise is presently lacking.

A major difficulty in formulating operational targets is the uncertainty over how much noise pollution is sustainable for a population or ecosystem. Noise exposure elicits a range of physiological and behavioral responses in individual animals, the consequences of which are challenging to quantify at the population and ecosys-

tem levels (King *et al.* 2015). One solution is to take a risk-based approach, and assume that the risk of adverse consequences increases with increased exposure to noise pollution. Species-level objectives can then be based on managing noise exposure (Figure 1). The task then becomes how to quantify the risk posed by noise exposure in a way that is ecologically relevant, and which enables the setting of operational targets despite uncertainty.

A recipe for risk-based cumulative noise indicators

The approach we propose defines quantitative indicators of risk as illustrated in Figure 2. The reasoning behind each step is outlined in the subsections below. Technical details are provided in Appendix S1.

Define management area for indicator species

Two possible paradigms for managing noise pollution are *place-based* and *ecosystem-based* approaches. For example, a place-based approach might measure the area of (possibly designated) habitat degraded by noise pollution, while an ecosystem-based approach might consider the noise exposure of a population regardless of political boundaries. Each perspective has its limitations: designated areas and political jurisdictions do not necessarily have ecological relevance (Agardy *et al.* 2011), while managing transboundary populations presents practical and political

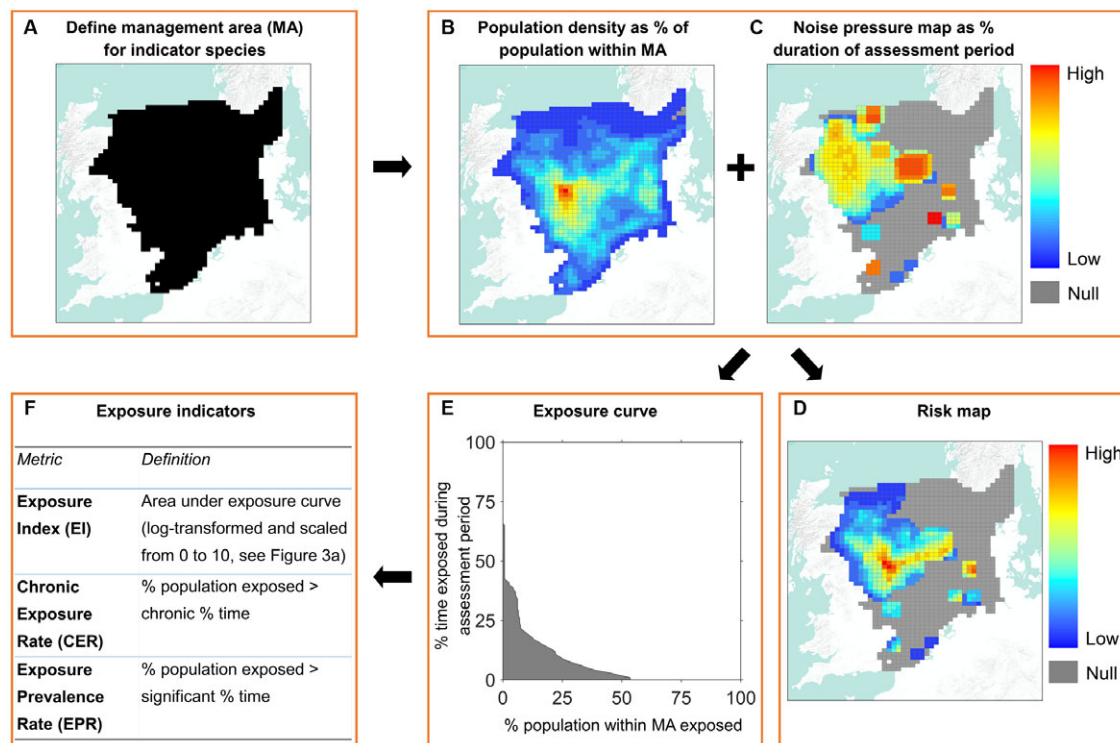


Figure 2 Workflow for mapping risk and calculating exposure indicators. Example population density (B) is modeled North Sea harbor porpoise density during fall (Sep.-Nov.), from Gilles *et al.* (2016). Noise pressure map (C) is based on impulsive noise data reported for the OSPAR maritime area in Sep.-Nov. 2015.

challenges (c.f. fisheries management). The method proposed is compatible with either approach, and requires a management area (MA) to be specified for the indicator species (Figure 2A): either a defined habitat, such as a marine protected area (MPA) or spawning area, or a management unit—a spatial boundary for a population at an ecologically relevant scale. This demarcation allows the indicators to be defined based on percentages of the area or population exposed.

Indicator species are selected according to: (1) acoustic sensitivity and (2) conservation, ecological, or economic importance. They may also be considered representative (or precautionary) exemplars of broader taxa.

Population density of indicator species as a percentage of population within MA

The risk of impact from a noise source depends on the density of acoustically sensitive species in the affected area at the time. Population densities should therefore be incorporated into noise management where possible, preferably including temporal variability. Here, we normalize the population density to be a percentage of the population within the MA (Figure 2B), meaning that rel-

ative or absolute population densities can be used. Where population density is not available, area can instead be used (see herring spawning example below). Throughout the article, we use “population” and “population density” interchangeably: for highly mobile species, it may be more appropriate to interpret “population” as the population’s habitat, scaled by habitat use.

Noise pressure map as percentage duration of assessment period

The next step is to quantify levels of noise pollution within the MA. One option is to use acoustic models to predict noise levels; however, this approach raises practical and scientific difficulties. From a practical perspective, modeling requires acoustics expertise and highly detailed data on proposed activities (Farcas *et al.* 2016), placing considerable time and resource expectations on managers and industry. Scientifically, risk assessment based on noise levels is problematic, since received noise level is a poor predictor of marine mammal behavioral responses (DeRuiter *et al.* 2013; Brandt *et al.* 2016; Gomez *et al.* 2016) and fish displacement (Handegard *et al.* 2013). The approach taken here builds on Handegard *et al.*

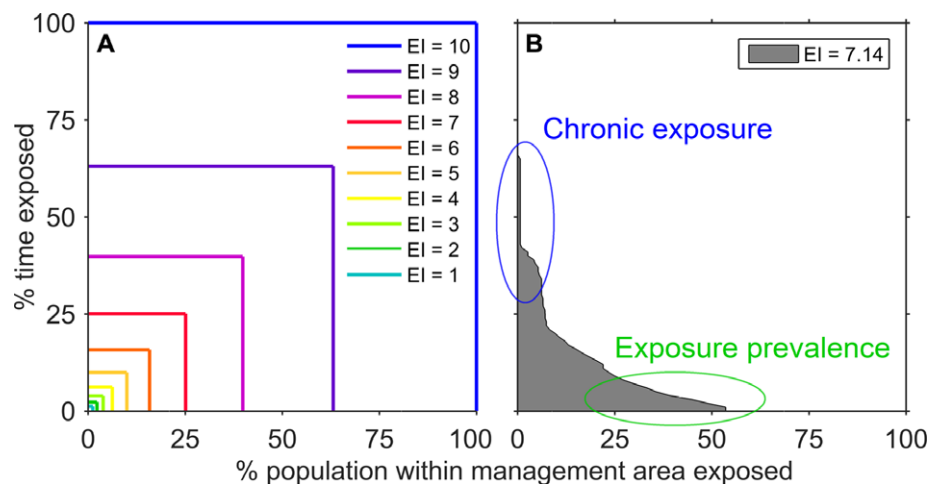


Figure 3 Interpreting exposure curves (A) illustrative scaling of EI (B) regions of the exposure curve corresponding to exposure prevalence and chronic exposure.

(2013) and a systematic review of marine mammal responses (Gomez *et al.* 2016) to quantify noise pollution based on the area affected (using the “distance of effect”; Brandt *et al.* 2016; Gomez *et al.* 2016) and the associated duration (Figure 2C).

Risk map

The population density and noise pressure maps are then combined to produce a risk map (Figure 2D), following the methodology used in Maxwell *et al.* (2013) for cumulative effects assessment. The risk map shows the greatest cooccurrence of population density and noise pressure, enabling managers to prioritize mitigation measures where they have the greatest capacity to reduce risk (in combination with the quantitative indicators described below).

Exposure curve

The noise exposure curves introduced here plot the percentage of time that a given percentage of the population (or area) is exposed (Figure 2E). The curves are generally characterized by a decay as exposure time increases, with a decreasing percentage of the population exposed for greater exposure durations (Figure 2E). The exposure curves provide a quantitative basis for the definition of indicators which track exposure levels.

Exposure indicators

While the risk maps (Figure 2D) and exposure curves (Figure 2E) can inform decision-making, they are intermediate steps in deriving indicators. Here, we reserve the

term “indicator” for metrics which can be expressed as a single number for target setting purposes. Indicators are proposed based on the overall exposure—the exposure index (EI)—and on specific threshold criteria (Figure 2F).

EI expresses the overall exposure of the population based on the area under the exposure curve. This area is log transformed and scaled from 0 to 10, as illustrated in Figure 3(A).

Although it is useful to express overall exposure as a single number, this does not indicate the distribution of exposure. For example, a small percentage of the population may be exposed for a large percentage of time (chronic exposure), or vice versa (prevalent exposure). This can be derived from the exposure curve (Figure 3b), but to capture these differences for target setting, further indicators can be formulated. For example, chronic exposure rate defines the percentage of the population exposed $\geq x\%$ of the time, above which exposure is considered chronic. Similarly, exposure prevalence rate describes how widespread exposure is across the population density, according to the percentage population exposed for $\geq y\%$ of the time, above which exposure is considered non-negligible. Such indicators can target specific management concerns more effectively than EI.

Target setting

These indicators make quantifying and managing the risk of impact from cumulative noise exposure possible. However, the task of setting operational targets will ultimately fall to policy makers. Several strategies could be adopted for target setting, for example: (1) “no net increase” or “net reduction” in risk; (2) scientific consensus around sustainable levels of risk; and (3) evidence-based

approach relying on suitable data to predict population-level impact. In principle, options (1) or (2) can already be implemented in practice (see below). However, option (3) may not be viable in the near term, since data that explicitly link noise exposure to population level effects may take many years to emerge due to the complexity of compounding factors that affect population growth.

Implementation

The transboundary nature of underwater noise and at-risk populations require that cumulative noise management be implemented at a regional level (though some migratory species may require global governance). Some regions (e.g., Northeast Atlantic, Baltic Sea, Mediterranean Sea) are already reporting impulsive noise activity (pile driving, seismic surveys, explosions, and some sonar activity) to regional noise registries, and further registries are planned (e.g., in the United States; Hatch *et al.* 2016). These registries could now be adapted for use as planning tools to manage cumulative noise exposure from these sources based on operational targets agreed at regional level. The case studies below draw on data from one such registry to demonstrate how these indicators work in practice.

Two case studies in the North Sea

Two case studies are presented which apply these methods to: (1) a population for which seasonal population density data are available (harbor porpoise) and (2) recognized seasonal habitat during a key life stage (herring spawning). These species were selected for their acoustic sensitivity and importance to management. Further details on the methods and input data are provided in Appendix S1.

Gridded data were used to map population density (or habitat) and noise exposure, similarly to studies of cumulative effects (Halpern *et al.* 2008; Maxwell *et al.* 2013). The noise pressure map was based on data reported for 2015 to the OSPAR Impulsive Noise Registry, which records data on pile driving, seismic air guns, explosions, and some military sonar activity in the Northeast Atlantic. These noise data are known to be incomplete, and the case studies should be interpreted as illustrative. The data were mapped in *pulse block days*: the number of calendar days in which one or more impulsive noise sources occurred within a grid cell.

North Sea harbor porpoise

Harbor porpoise in the North Sea have been displaced from impulsive noise sources by up to ~20 km (Tougaard

et al. 2009), and the noise pressure map was adjusted to reflect this distance of effect. Seasonal estimates of population density were based on modeled maps (Gilles *et al.* 2016) derived from field surveys (Hammond *et al.* 2013).

Risk maps and exposure curves for spring, summer, and fall are shown in Figure 4. The EI (Figure 3a) indicates that overall exposure increased with each season (Figure 4d). The exposure curves show that exposure prevalence (Figure 3b) was markedly lower in spring, with <25% of the population density exposed (Figure 4d), yet by some measures chronic exposure was higher, with spring showing the greatest proportion exposed for >20–30% of the time. Figure 4 also highlights the importance of the Dogger Bank (the high-risk area at ~55°N, ~2°E evident in Figure 4b) as a high-risk area, indicating that targeted mitigation measures to reduce exposure in this region would substantially reduce risk for the overall population. In considering such place-based restrictions, these indicators allow the comparative risk reduction of prospective management scenarios to be evaluated.

North Sea herring spawning areas

Herring are particularly sensitive to sound, and maps of herring spawning areas are used to manage the risk of impact at this key life stage. Decreases in herring abundance have occurred at up to ~37 km around seismic surveys (Slotte *et al.* 2004). Using this distance of effect, we produced a noise pressure map using the noise data described above. We then selected three seasonal spawning areas (Figure 5a) from a map used for risk assessment by U.K. regulators (Coull *et al.* 1998), and combined these with the noise pressure map to produce a risk map (Figure 5b) which indicates the percentage of the corresponding spawning season in which noise exposure occurred.

The resulting exposure curves and exposure indices (Figure 5c) reveal striking differences in exposure among the three spawning areas. While the English Channel/southern North Sea (SNS) area had zero reported exposure, the SNS and northern North Sea (NNS) areas had EI values of 7.54 and 7.62, respectively. The exposure prevalence was particularly high for SNS, with 84% of the area exposed at some point during the spawning season. Chronic exposure was marginally higher for NNS, with 10% of the area exposed for >30% of the spawning season. This example demonstrates how the indicators can highlight periods and areas with higher cumulative risk where population density data may be lacking or not considered appropriate. This area-based approach could also be applied to MPA management, and to understand the sensitivity of multispecies indicators (Dempsey *et al.* 2017) to noise exposure.

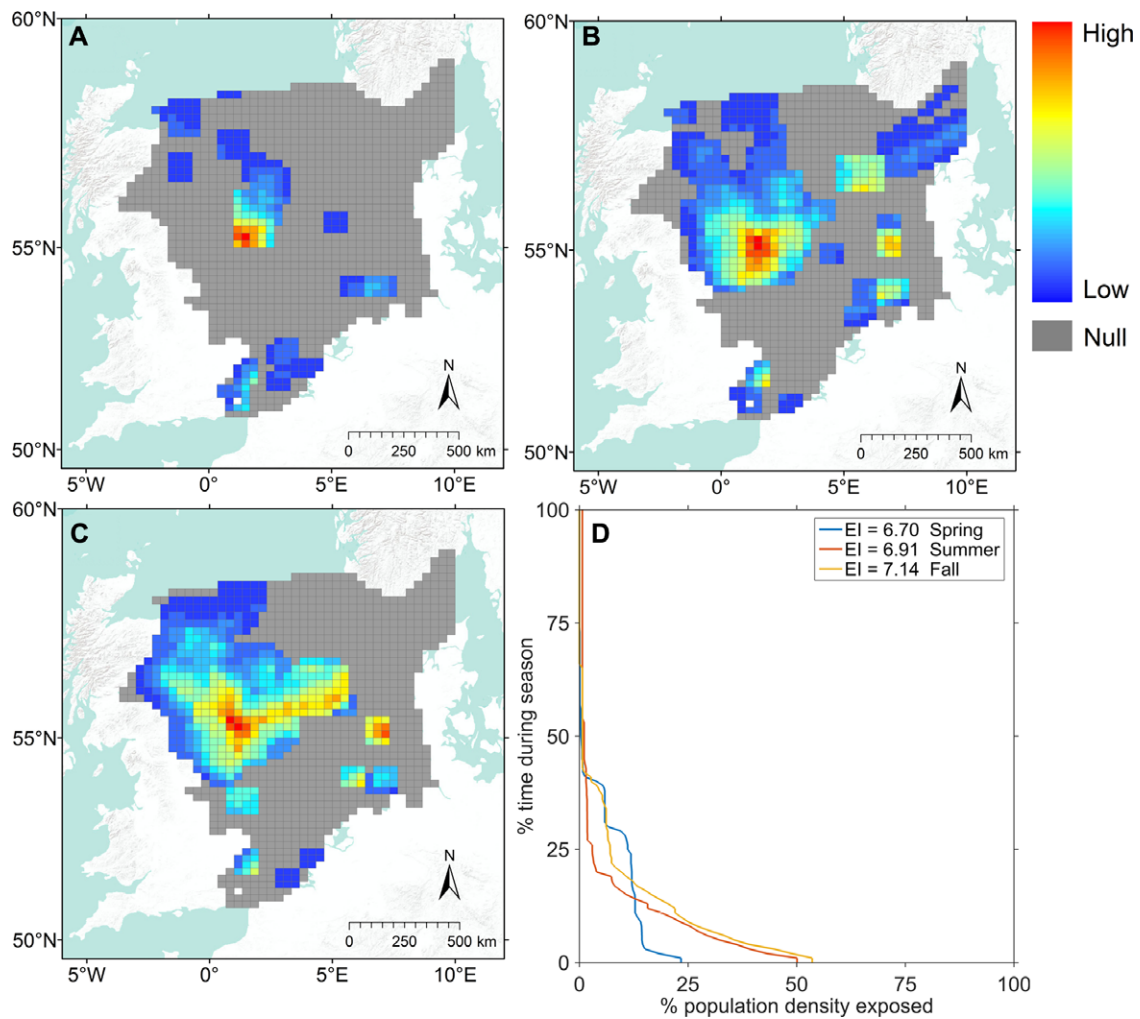


Figure 4 Illustrative seasonal risk maps (A-C) and exposure curves (D) for North Sea harbor porpoise during 2015 (A) spring (Mar.-May) (B) summer (Jun.-Aug.) (C) fall (Sep.-Nov.) (D) exposure curves and exposure indices. Risk maps incorporate harbor porpoise density data from Gilles *et al.* (2016).

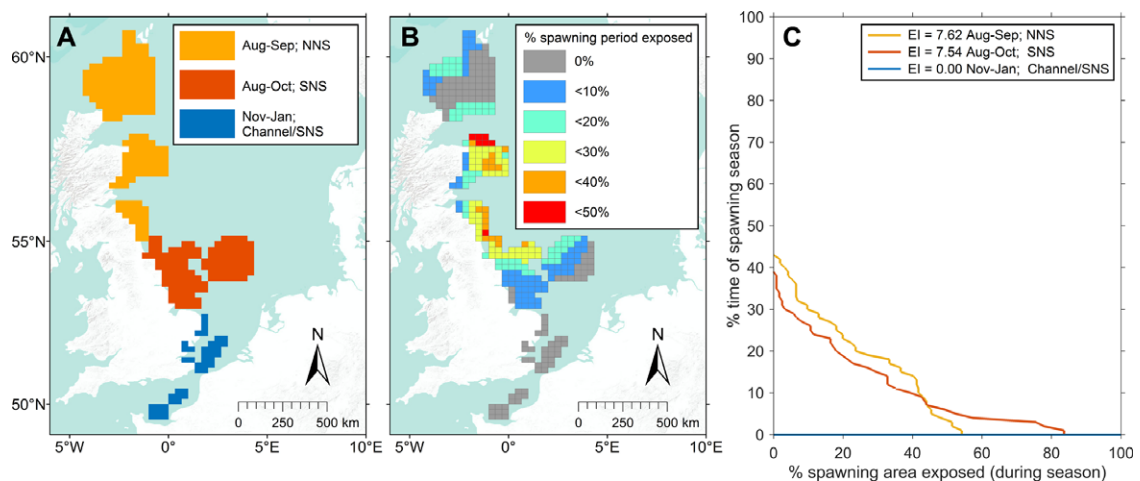


Figure 5 (A) Selected herring spawning areas in the NNS, SNS, and English Channel/SNS (B) percent of each spawning period exposed to noise (C) exposure curves and indices.

Improving risk estimates

Numerous refinements could be made to the risk estimation in these case studies. For example, including the effect of displacement after the activity has ended (residual disturbance; Verfuss *et al.* 2016), and increasing the spatial resolution (or using non-gridded data). Effects other than displacement can also be evaluated, and it is important to emphasize that the impact on animals that do not respond overtly should not be interpreted as neutral (Bejder *et al.* 2009): this risk is reflected in the methodology since all animals within the distance of effect are considered to be exposed. Comparing the density-based (Figure 4) and area-based (Figure 5) approach for the same species would inform the interpretation of different approaches and show the degree to which anthropogenic pressure is focused on animal hotspots. While risk-based approaches already imply uncertainty, this can also be incorporated explicitly into the exposure curves and indices by propagating through uncertainties in the population density and noise pressure data. These case studies broadly demonstrate how the approach works in practice; implementation will require bespoke adjustments to be made according to scientific and regulatory specificities.

The future of marine noise management

Marine noise management is still in its infancy. This presents an opportunity to integrate noise pollution into existing and emerging marine management practices from the outset. The approach presented here has been developed accordingly, and has the flexibility to map and quantify risk at the population level (e.g., harbor porpoise study; Figure 4) or to be applied in place-based management (e.g., in MPAs or recognized habitat; Figure 5). The methodology also borrows from and is compatible with risk mapping approaches used in cumulative effects assessment (Halpern *et al.* 2008; Maxwell *et al.* 2013), enabling noise to be incorporated as a stressor in such assessments.

As our understanding of the large-scale effects of underwater noise on marine ecosystems improves, the uncertainty inherent in target setting will diminish. This prospect need not defer pragmatic action to set targets in the near term. Such action could draw on instructive precedents for developing quantitative criteria in the context of uncertainty through scientific consensus (Southall *et al.* 2007) and by expert elicitation (King *et al.* 2015). In some regions and for some noise sources, the reporting and assessment structures necessary to manage cumulative noise pollution are already in place,

and uptake of a risk-based management approach could proceed immediately.

Regardless of future policy targets, the surest way of avoiding adverse ecological consequences is to minimize the exposure of acoustically sensitive species to anthropogenic noise (Wright & Kyhn 2015). The indicators presented here allow managers to quantify such measures, and will reflect risk reduction achieved, for example, by reducing the amount of activity, moving activities to lower risk periods and locations, and applying noise abatement measures which reduce the distance of effect (e.g., noise reduction technologies for pile driving activity; Brandt *et al.* 2016; or shipping; IMO 2014).

Conclusions

Responsible management of underwater noise pollution will require pragmatism and resolve in the face of considerable scientific uncertainty. The flexible, risk-based approach advocated here provides a basis for such management, enabling targets to be formulated at relevant management scales and cascaded to regulatory decision-makers. Scientific understanding of the impacts of underwater noise is rapidly evolving, and the adaptability of the approach allows for the assimilation of new knowledge while meeting the demands of expediency often required in decision-making. As reporting and assessment of noise-generating activities become ever more embedded, such approaches provide a mechanism to implement existing and future policy commitments to manage cumulative noise pollution.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Figure S1 Example of ecosystem-based management implementation.

Appendix S1 Materials and methods.

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