From Documented Impacts to Cross-Taxa Perspectives: Towards a Framework for Assessing Vulnerability to Underwater Noise

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Abstract

The escalating threat of aquatic noise to marine life underscores the urgency of setting scientifically grounded underwater noise limits. The Marine Strategy Framework Directive (MSFD) Descriptor 11 provides a policy lever to mitigate pressures arising from underwater noise. Achieving this goal requires that underwater radiated noise (URN) management shifts from a primarily pressure-based approach, focused on quantifying environmental sound pressure, towards a risk-based, ecosystem-oriented framework. This approach requires the selection of indicator species to relate noise vulnerability to impacts on populations. As part of the Interreg North Sea DEMASK project, the need for a multi-criteria framework for selecting indicator species from multiple taxa is introduced, with the overarching goal of assessing vulnerability to URN. The framework should combine a range of attributes related to the sound sensitivity and production of the animal, documented impacts of URN, and attributes describing the species' general vulnerability related to life-history traits and socio-ecological status. Here, an overview of documented impacts of URN on mammals, fish, and invertebrates in the North Sea is presented, with the aim of motivating a multi-criteria, cross-taxa framework in selecting indicator species to support an adaptive and impact-focused vulnerability assessment.

Keywords

Impact · Ecosystem-based assessment · Sensitivity · Auditory mechanism · Marine Strategy Framework Directive (MSFD) · DEMASK

Introduction

The continued global expansion of human activities in the marine environment is coupled with growing evidence of the adverse effects of anthropogenic noise on aquatic life (Duarte et al. 2021). To achieve Good Environmental Status (GES), the EU Marine Strategy Framework Directive (MSFD) Descriptor 11 requires that "*the introduction of energy into the marine environment is at levels that do not adversely affect the marine environment.*" The implementation of the MSFD Descriptor 11 provides a policy lever to mitigate these pressures by underscoring the urgent need to establish scientifically grounded underwater noise limit values (UNLVs) to address the escalating threat of aquatic noise on marine life.

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Effectively achieving this goal compels a shift in underwater radiated noise (URN) management from a primarily pressure-based approach, focused on quantifying environmental sound pressure, towards a risk-based, ecosystem-oriented framework (Sigray et al. 2025). This approach requires the selection of indicator species to relate UNLV to the percentage of exposed habitats and its population-level implications. UNLVs must be based on empirical evidence of physiological and behavioral responses to assess the proportion of habitats that is impacted, thereby determining the GES of a marine unit.

The Technical Group on underwater noise (TG Noise; Borsani et al. 2023) introduced the Level of Onset of Biologically Adverse Effects (LOBE) to determine the affected area. This implies that the percentage of area exceeding LOBE should be less than the threshold value—or the maximum permitted percentage area affected by URN, which is currently up to 20% of a given marine area (EC Directorate-General for Environment 2022). SATURN Acoustical Terminology Standard explained some difficulties with defining LOBE and introduced the concept of UNLV to take its place. UNLV is defined by SATURN as the "*value of a specified underwater noise metric (UNM), as determined by an appropriate authority, above which management action is considered*" (Ainslie et al. 2024). In this chapter, the authors use UNLV in preference to LOBE.

Setting regional UNLVs is complex as it involves measurements of multiple sources of URN in different environments and varying sensitivities (and reactions) of a wide range of receptive animals. While studies of acoustic sensitivities of marine mammals have dominated bioacoustics research, work on acoustic sensitivity of fish and invertebrates to URN has only significantly progressed in recent decades. Marine mammals can hear sounds in the frequency range of 7 Hz to 165 kHz, depending on the species (National Marine Fisheries Service 2024), while fish and invertebrates can generally detect within lower frequency ranges (<1 kHz, except for a few known species; Popper and Hawkins 2019; Solé et al. 2023; Lucke et al. 2024) and are sensitive to particle motion, and in some cases to sound pressure. With an impact-based assessment, however, indicator species must be selected not solely for their demonstrated sensitivity to URN but also for their vulnerability to impacts of noise pollution and their spatio-temporal distribution. Beyond species-specific hearing ranges and detection mechanisms (auditory receptors/organs, pressure vs. particle motion), noise vulnerability, and environmental variability, effective management must also coordinate across jurisdictions, given the transboundary nature of URN.

Considering a multi-taxa perspective on the assessment of URN vulnerability is foundational to an ecosystem-based strategy to URN management. Although data remains scarce for many fish and invertebrate species, these gaps should not hamper the implementation of regional UNLVs. As part of the Interreg North Sea DEMASK (Development and evaluation of noise management strategies to keep the North Sea healthy) project, the objectives of this chapter are: (1) to give an overview of documented impacts of URN on marine mammals, fish, and invertebrates in the North Sea and (2) to highlight the need for a multi-criteria approach in selecting indicator species from multiple taxa for an ecosystem-based approach to URN management.

Overview of Documented Noise Impacts

Marine Mammals

Impulsive and continuous noise can affect marine mammals by altering their behavior, through acoustic interference (including impaired hearing sensitivity and masking of acoustic signals) and by inducing physiological stress (Erbe et al. 2018). Although the effects of URN have been studied more extensively in marine mammals than in other taxa, research efforts remain imbalanced across species. Most studies to date have focused on a few well-studied species and on short-term, individual-level responses. By contrast, cumulative and long-term impacts, particularly how individual disturbances may scale up to the populational level, remain poorly understood (Erbe et al. 2018).

In the North Sea, the harbor porpoise (*Phocoena phocoena*) is the most extensively studied species with respect to noise impacts. Documented responses include deterrence and displacement, alterations in diving and foraging behavior, and both temporary and permanent reductions in hearing sensitivity. These effects have been observed in relation to diverse noise-making activities, such as pile-driving, seismic surveys, and shipping, and have been tested in both controlled settings (e.g., captive exposure experiments) and in free-ranging animals using tagging and passive acoustic monitoring (see Impact Table 1 for references: https://urn-impact-table.netlify.app/).

While the harbor porpoise has been studied intensively over decades, considerably less is known about the effects of URN on other marine mammal species in the North Sea. Behavioral responses have been reported for white-beaked dolphins (*Lagenorhynchus albirostris*), bottlenose dolphins (*Tursiops truncatus*), and common minke whales (*Balaenoptera a. acutorostrata*), with hearing impairment additionally documented in grey seals (*Halichoerus grypus*) and harbor seals (*Phoca vitulina vitulina*; see impact table for references). Even less information is available for killer whales (*Orcinus orca*) and white-sided dolphins (*Lagenorhynchus acutus*). However, the limited number of studies should not be interpreted as evidence of low vulnerability. Instead, assessments of vulnerability to noise should consider documented impacts of URN alongside species-specific ecological and life-history traits and population-level factors.

Fishes

A considerably wide range of literature has documented both physiological and behavioral responses of North Sea fish species to both continuous and impulsive noise. Although audiograms only exist for a few species, significant responses at certain sound pressure levels (SPL) and frequency ranges have been reported for several species.

The anatomical variation among fish taxa corresponds to diversity in auditory mechanisms (Ladich and Schulz-Mirbach 2016). The presence of a gas bladder and the proximity and connection of the ear to the bladder primarily determine the sensitivity of a fish to particle motion and sound pressure. Fish with bladders that are mechanically linked to the ear, such as herring (*Clupea harengus*) and sprat (*Sprattus sprattus*), are primarily sensitive to sound pressure, while fish without a swim bladder, such as flatfish, skates, and rays, are only sensitive to particle motion and a narrow band of frequencies (Popper and Hawkins 2019; Lucke et al. 2024).

Reported physiological and behavioral responses of fish to URN have been documented in both tank and field experiments, with the distance between the animals and sound sources during observations ranging from under 1 m to 50 km. Commonly reported behavioral responses to vessel noise were reduced predator inspection behavior and changes in swimming behavior (see Impact Table 2 for references: https://urn-impact-table.netlify.app/). Moreover, acoustic masking from vessel traffic has been shown to reduce the effective communication range for some species such as cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*), with implications for their reproductive success (Stanley et al. 2017). Likewise, a laboratory experiment showed that acoustic communication between gobies (*Pomatoschistus pictus* and *Gobiusculus flavescens*), vital for spawning success, can be negatively affected by noise (De Jong et al. 2018). Collectively, these findings suggest that the reliance of fish on acoustic cues for survival and reproduction is compromised when continuous anthropogenic noise masks biologically relevant signals.

More physiological responses such as changes in ventilation rate and biochemical stress responses were reported by experiments on impacts of impulsive noise such as seismic airguns and pile-driving (see Impact Table 2: https://urn-impact-table.netlify.app/). Fish possessing a physoclistous swim bladder, i.e., fish that do not have a gut connection to adjust the volume of gas in response to sound pressure, were shown to be more susceptible to barotrauma injuries when exposed to impulsive pile-driving sounds (Halvorsen et al. 2012). However, numerous behavioral reactions to impulsive noise have also been observed, some resembling those elicited from continuous noise exposure. These include altered swimming direction, vertical movement, dispersion, reduced feeding motivation, freezing response, and diminished predator inspection (see Impact Table 2: https://urn-impact-table.netlify.app/).

Invertebrates

The impact of URN on invertebrates has been accentuated more recently compared to mammals, and despite their abundance and significant importance to ecosystem structure and function, invertebrates have hitherto been largely overlooked in environmental risk assessments, mainly due to lack of data. Still, there is today a considerable amount of literature documenting negative effects on a wide range of invertebrate species (Duarte et al. 2021; Solé et al. 2023). These represent different taxonomic groups, although research efforts are imbalanced, focusing mainly on commercial crustaceans, bivalves, and cephalopods (such as lobsters, mussels, and cuttlefish), while only very limited data exist for several taxa and species.

Impacts of both impulsive noise from, e.g., pile driving or seismic airgun shots, and continuous URN from shipping, motorboats, or drilling have been shown for a range of invertebrate species and taxa from the North Sea, with effects demonstrated on different life stages and at different levels of biological organization (e.g., behavioral, physiological, and cellular effects; see Impact Table 3 for references: https://urn-impact-table.netlify.app/). Effects range from mortality in crustacean zooplankton after exposure to shots from seismic airguns, at >1 km distance (McCauley et al. 2017; Vereide et al. 2023), to masking of sounds used for communication in the European lobster (*Homarus gammarus*), implied by an increased number of agonistic, low-frequency buzzing sounds produced by males in areas with high levels of vessel noise (Jezequel et al. 2021). After exposure to both continuous and impulsive noise, a wide range of behavioral effects have been documented, including impaired feeding activity, anti-predator responses, changes in movement patterns, digging behavior, settlement, and mating. Physiological, cellular, and genetic stress responses, such as effects on growth, respiration, induced stress protein levels, and oxidative stress, have been demonstrated in a range of species and taxa. Furthermore, disrupted early-life development, such as reduced egg hatching, larval growth, survival, and metamorphosis, but also stimulated larval growth and settlement, reduced settlement selectivity, and accelerated metamorphosis have been demonstrated in, e.g., the great scallop (*Pecten maximus*), Pacific oyster (*Magallana gigas*), Norway lobster (*Nephrops norvegicus*), and different cephalopods (see Impact Table 3 for references: https://urn-impact-table.netlify.app/). Reduced camouflage ability was found in juvenile shore crabs (*Carcinus maenas*) after exposure to playback of ship noise (Carter et al. 2020), and clear signs of physical damage to statocysts and neurons of the auditory system have been demonstrated in adults, juveniles, and eggs of cephalopods (e.g., *Sepia officinalis*) at high exposure to sinusoidal wave sweeps (at 50–400 Hz) and playback of pile driving and drilling (André et al. 2011; Solé et al. 2018; see Impact Table 3 for references: https://urn-impact-table.netlify.app/).

The impacts exhibited may disrupt biological processes, with implications for survival and fitness and indirect consequences on the populations, potentially affecting the structure and function of the ecosystem. However, most invertebrate studies demonstrate short-term, individual-level responses, while cumulative, long-term impacts on population level, and indirect consequences for other species and taxa remain largely unknown. Moreover, most studies on invertebrates have been conducted in laboratory tanks without precise and accurate control of noise exposure and therefore unrealistic noise environments. As for other taxa, threshold (lowest-detectable) effect level and dose-response relationship describing the magnitude of a response as a function of exposure levels have seldom been established. Based on present knowledge, invertebrates are mainly sensitive to particle motion; however, research quantifying particle motion impacts is limited, and most studies report impacts at certain SPL. Still, the great amount of evidence of negative consequences of URN on invertebrates advocates their inclusion in future environmental risk assessments.

The Complexity of Defining "Vulnerability to Noise"

Documented noise impacts that vary over a broad range of species from marine mammals to fish and invertebrates call for a multi-taxa approach to addressing underwater noise. While research has largely emphasized species-level sensitivity to different sources of underwater noise, the vulnerability of the marine ecosystem as a whole has been insufficiently addressed. An ecosystem-based approach should draw not only from these documented sensitivities and noise impacts but assess species' vulnerability considering their habitats and populations. In addition, it should recognize that research efforts have been highly uneven across species, with some taxa being well studied while others remain largely unexamined, as highlighted through this review on documented impacts of noise. This disparity should be accounted for when assessing vulnerability.

Sensitivity and vulnerability represent distinct concepts: here, sensitivity refers to the capacity of a species to detect and/or respond to acoustic stimuli, whereas vulnerability denotes the degree to which a species is susceptible to, or unable to cope with, URN, a concept involving exposure (e.g., frequency, intensity, duration, spatial overlap, timing), as well as intrinsic factors related to an organism's susceptibility and adaptive capacity (sensu IPCC 2007). A species may exhibit high sensitivity yet display low vulnerability to URN if it experiences limited exposure to the stressor or demonstrates sufficient adaptive capacity. Identifying the species that are most impacted by URN is complex, as objectively comparing impacts on behavior, physiology, and other lower levels of biological organization in terms of their detrimental impact at the population level, considering the variability in responses among individuals, is not straightforward. However, evaluating species through the broader lens of vulnerability provides a more comprehensive perspective, aligning with an ecosystem-based approach to addressing the issue.

URN vulnerability should integrate factors considering the species' exposure and general adaptive capacity, such as the species' life-history traits and socio-ecological status. Species that depend on specific habitat features, have seasonally high energy requirements, or exhibit relatively long generation lengths, low fecundity, and limited mobility are likely to be more vulnerable to stressors such as URN, as these traits limit their capacity to escape or compensate for disturbances. Species with populations that are threatened, in decline, or are subject to high commercial fishing pressure should be considered highly vulnerable. Moreover, priority should be given to keystone species—those that play a critical ecological role, with their abundance or activity significantly influencing biodiversity (Paine 1966; Valls et al. 2015).

A multi-criteria approach (Fig. 1) for determining the most vulnerable species, composed of attribute categories such as the hearing (or sound sensitivity) and sound production of the animal, documented impacts of noise and socio-ecological status, must be tailored to each taxon to address differences in auditory mechanisms, URN exposure, and susceptibility. A framework for noise vulnerability assessment taking these different attribute categories into account is developed as part of the Interreg North Sea project DEMASK (A. Calonge et al., manuscript in preparation, October 21, 2025). Each category can be composed of different specific attributes tailored for

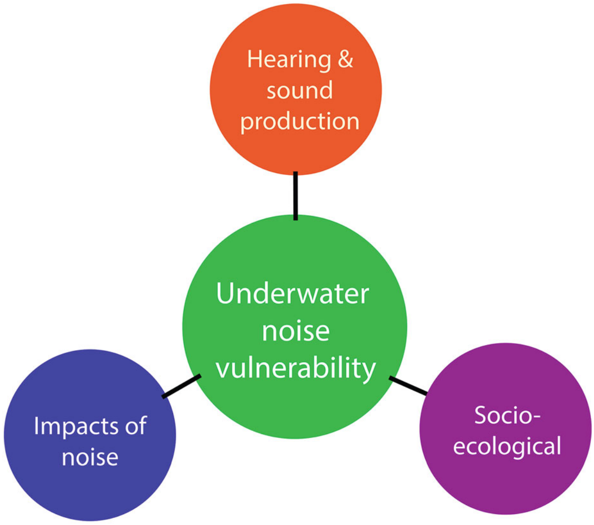

Fig. 1 A holistic, impact-based approach to underwater radiated noise vulnerability is composed of multiple attribute categories—hearing (or sound sensitivity) and sound production, impacts of noise, and socio-ecological status. Each category can be composed of different specific attributes tailored to each taxon

each taxon. For instance, for the hearing and sound production category, the hearing adaptation attribute, i.e., depending on whether the species has anatomical structures mechanically linking the swim bladder to its ear, applies specifically to fish, but not to the other taxa. Similarly, commercial value, an attribute related to the species' socio-ecological status, is a relevant consideration for fishes and invertebrates, but not for mammals in EU marine areas. These taxon-specific attributes collectively determine species-level vulnerability to underwater noise. While the framework can be implemented in other regions, the specific indicator species selected for the North Sea and related UNLVs for the assessment of proportion of habitats affected would not be necessarily applicable in other regions.

Assessing every North Sea species is not feasible, but many commercially and/or ecologically important taxa have been studied, allowing several indicator species to be selected from those with documented sensitivity and/or impacts to underwater noise. Selection should consider not only vulnerability but also the strength and completeness of the evidence base. Ideal candidates are species that rank high in terms of vulnerability to URN, supported by robust data, with well-documented noise impacts and clear habitat associations that will enable a reliable assessment and monitoring of threshold values related to proportion of areas impacted by URN.

An integrated, ecosystem-based approach to URN assessment should be adaptive, impact-focused, and comprehensive. Addressing URN requires a multi-taxa perspective, drawing on evidence of its impacts on critical ecological processes such as foraging, predation/predator avoidance, reproduction, communication, and migration. The vulnerability framework must remain adaptive, continuously updated with findings from experimental research and noise-monitoring programs. Regional UNLVs should be reviewed regularly and revised when necessary. Ultimately, a comprehensive ecosystem-based approach must account for population-level impacts and holistically evaluate URN in conjunction with other anthropogenic stressors affecting vulnerable species.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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