Noisy oceans: How anthropogenic sounds are threatening marine vertebrates and their conservation

**Abstract**

Conserving marine vertebrates maintains marine ecosystem functions and reduces biodiversity declines. Anthropogenic noise is an important, yet relatively recent, source of pollution affecting marine vertebrates at all stages of their lifecycle. In water animals rely on sound for communication, during mating, antagonistic displays, foraging, and as settlement cues. Marine vertebrate physiology, behavior, and social structure are therefore heavily influenced by acoustic reception and production and are vulnerable to noise interference. Here we explore the sources of noise pollution in coastal and pelagic habitats, and how they impact marine vertebrate taxa, potentially at population levels. Threats of varying intensity expose a complex relationship with noise while emphasizing the necessity for stricter regulations, which currently only exist at regional levels.

**Key words**

Soundscape, marine vertebrates, biophony, anthrophony, masking, stress

**The rise of sound as a marine pollutant**

Conservation of marine ecosystems remains a challenge in the current biodiversity crisis despite global targets to protect 30% of the ocean by 2030 [1]. Marine vertebrates are present throughout the ocean, occupy various trophic levels, play integral roles in nutrient cycling and ecosystem functioning, and are important sources of nutrition and income for coastal communities [2]. However, their varied ecosystem roles and distributions result in substantial challenges for their conservation, as multiple stressors compound and threaten animals at individual, population, and ecosystem levels. One important stressor that has only recently come under the spotlight is noise pollution, which includes the sounds produced by human activities [3]. Anthropogenic noise, or anthrophony, has been on the rise since the industrial revolution, especially in the sea where increases in shipping have been linked to global economic growth. It is estimated that from 1950 to 2007 there has been a decadal 3.3 decibel (dB) increase in ocean sound levels [4]. Elevated noise levels across marine ecosystems have been flagged as a major threat to marine animals and the soundscapes they rely on.

Soundscapes are “the entire sonic energy produced by a landscape”, combining biophony, geological (geophony), and anthrophony [3,5]. Underwater, sound travels four times faster than in air which results in less transmission loss over long distances [6,7]. Senses such as sight and the use of chemoreception are limited in the ocean, as light and chemicals cannot propagate over long vertical or horizontal distances, making sound an essential form of information transmission [7]. Biological sounds differ in their resonant frequencies (generally ranging from 0.01 to 20 kHz) and amplitude (dB), depending on the species, population, and sometimes individual animal [3].

Anthropogenic noise has diverse sources and effects, but its population-wide impacts remain poorly understood. The majority of research is reliant on species-specific models and controlledexperiments, but a wider scope of noise effects across species needs to be monitored[8]. In this review we identify the primary sources of noise pollution in coastal and pelagic zones, and their effects on different groups of marine vertebrates inhabiting these areas at any point in their life-history. We evaluate the behavioral, physiological, and ecosystem-wide impacts to identify current and proposed solutions to mitigate the effects of noise pollution on marine vertebrates.

**Coastal and shallow water noise pollution**

In coastal ecosystems both land and water activities contribute to the soundscape. Land and offshore construction and development, traffic, harbours, beaches, and small recreational boats dominate the anthrophony (see **Table 1**) [9,10]. Amphibious species, such as seabirds, are particularly susceptible to terrestrial sound disturbances during breeding or molting seasons on land, with some studies showing individuals abandoning their nests or increasing stress levels [11,12]. Sound transmission also occurs between terrestrial and aquatic realms. In the Brazilian carnival of Salvador, noise levels underwater significantly increased and led to reductions in the feeding and fleeing behavior of reef fish [9].

Directly in shallow waters, studies along the Danish coast found that recreational boats without Automatic Identification Systems (AIS) had higher occurrences and increased noise centered around 0.125, 2, and 16 kHz [13]. In New Zealand a study found that small recreational boats dominating low frequency bands (0.1 kHz – 0.8 kHz) in shallow habitats daily, regardless of protection status [14]. Coastal noise pollution is complex, as sound particle motion is affected by topography and other structures which can change the absorption, reflection, and refraction [15]. Thus, noise from land may propagate much further than anticipated [10].

**Anthropogenic noise in the open ocean**

Sound pollution in the open ocean can travel further without the same obstructions as coastal seascapes. Noise sources consist of, but are not limited to, large shipping vessels, explosions, sonar, seismic explorations, dredging and pile-driving, and offshore wind farms, ranging in amplitude and consistency (**Table 1**). Shipping is the greatest contributor in low frequency ranges, with noise originating from propellers and increasing with vessel size [16]. In areas with lucrative petroleum and gas reservoirs, seismic surveys are used to detect these geological features. In the Gulf of Mexico, seismic surveys have been shown to chronically elevate noise levels in low frequency bands [3,17]. Many of the pelagic activities listed in **Table 1** indicate more low frequency sources, ranging from constant to high intensity. However, these activities are essential to economic and military growth, as well as promoting clean energy (ie. Offshore windfarms), which implies their persistence in the ocean.

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**Table 1: Anthropogenic noise sources**. Dominant frequency bands are labeled as low (0.01 kHz - 0.1 kHz), mid (0.1 kHz – 10 kHz), and high (> 10 kHz). Sound sources and resonant frequencies are collated from Duarte *et al*. (2021) and Chahouri *et al.* (2022) [3,15].

**How do marine vertebrates use and produce sound?**

Sound in marine vertebrates is used for communication, social behavior during mating and breeding, foraging, predator avoidance and navigation [3,18]. These sounds can be percussive or emitted as frequency and/or amplitude modulated vocalizations with unique contours. The varied repertoire of sound use is influenced by diverse evolutionary pathways in hearing and vocalizing mechanisms, which occupy different frequency bands and avoid overlaps among many species (see **Figure 1**) [3,19]. Cetaceans are known for their complex acoustic behaviors which allow for their intricate social structures: signature whistles in dolphins allow them to identify each other and changes in contour, harmonics, repetition, or duration can communicate emotion [20]. Many odontocetes also use broadband clicks to echolocate during hunting, therefore their auditory systems are sensitive to a wide range of frequencies. Even in cetacean species that lead more solitary lives, such as humpback whales, male individuals produce unique songs during mating [21]. Like other baleen whales, their vocalizations, and therefore also hearing ranges are primarily sensitive to low frequency bands.

Amphibious marine vertebrates, such as sea-turtles, sea-birds, and pinnipeds are adapted to hear and vocalize underwater and on land through frequency modulated vocalizations sometime reaching ultrasonic frequencies (Weddell Seal) and percussive sounds [22]. However, many are more sensitive to noise in water rather than air, especially in deep diving species [23–25]. All fish are capable of sensing the particle displacement from sound energy, however, there is limited evidence of active sound production in elasmobranchs [26–28]. Many teleost species also vocalize in unison to create conspicuous choruses during mating or spawning aggregations which are characteristic components of some habitat soundscapes [29]. While not all marine vertebrate species vocalize, most have evolved auditory systems to sense acoustic energy. Even when not directly communicating, they listen to surrounding soundscapes to gather information about ecosystem health, which provides migratory and settlement cues. [3,30]. However, it also makes them vulnerable to noise interference within their hearing and vocalizing ranges (**Figure 1)**.

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**Figure 1: Overlapping Anthrophony and Biophony.** Combined hearing and vocalization frequency ranges for main taxonomic groups of marine vertebrates and anthropogenic noise sources adapted from Figure 2B in Duarte *et al*. (2021) [3]. Information on Sirenian hearing and vocalizations were taken from Moore *et al.* (2021) [31].

**Noise interference and animal responses**

Animal responses to anthropogenic noise are categorized as behavioral, acoustic, or physiological [32]. The point at which individuals experience a permanent or temporary effect from noise is determined by their sound threshold, which has thus far relied on hearing models and controlled experiment to find critical signal-to-noise ratios (SNL) [6,8]. Attempting to avoiding these negative effects is one way in which behavioral changes can occur. For example, some odontocetes use auditory gain control, a strategy whereby hearing sensitivity is intentionally lowered in response to a sound cue that warns of incoming loud noise [33]. However, the ability to maneuver around the presence of loud noises is not always possible.

For marine vertebrates that rely on acoustics for direct communication ‘auditory masking’ has become a concern. It occurs when noise interferes with a signal, preventing it from being heard or recognized by the listener [34]. In a study by Branstetter and Sills (2022), critical ratios of SNL for signal detection were evaluated for marine mammals, indicating that some species may be better adapted to hear through background noise. There was evidence that individuals employed anti-masking strategies, such as changing the sound level of vocalizations (Lombard Effect), spatial relocation, and increasing elements or duration of signals. In this study [34], lower frequency tones were better at masking high frequency tones, which has implications for animals using high frequency vocalizations in the open ocean where low-frequency shipping noise is dominant (**Figure 1**).

Physiological damage from loud noises has also been observed, both in tissue damage and increased stress levels. Greater stress can create an imbalance in bodily functions, including hormonal changes which may decrease reproductive success [35]. During high intensity noise exposure, for example the use of naval sonar, subsequent behavioral and physiological damage linked to mass strandings have occurred (**Text Box I**) [16,36,37]. Combined, these effects highlight potential for population-wide damage caused by anthropogenic noise.

**TEXT BOX I**

Case Study: Mass strandings of beaked whales

A group of seals on a flatbed

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Figure 6.1 in Boelens *et al.* (2016) [18]

Mass strandings are where two or more individuals from the same species are stranded on land [6, 37]. These events increased after the development of submarine military sonar in the 1960s. In 2002 14 beaked whales stranded on a beach in the Canary Islands fter a nearby NATO naval exercise using sonar. Post-mortem studies have shown gas emboli to be the most plausible cause of death following changes in diving and foraging activity. Symptoms common among stranded cetaceans resemble stress cardiomyopathy (CM) [38]. In 2004 the Spanish government implemented a moratorium on underwater naval exercises within a 50 km radius of the islands, and there have not been mass strandings since [6].

**Current regulations and noise reductions**

Sound propagation underwater is omnidirectional and travels long distances, making it hard to identify sources or predict the extent of their impact. Furthermore, given the economic importance of activities at sea and the vast extent of oceans that lie beyond areas of national jurisdiction , limiting anthropogenic noise is challenging [7]. International recommendations and guidelines have been described, however, formal regulations only exist at regional levels [6]. In North America, the National Oceanic and Atmospheric Association (NOAA) leads the Ocean Noise Strategy and in Canada “slow-down” zones for boats and quieting technologies have been implemented [6,10]. In the EU, there is a Marine Strategy Framework Directive (MSFD) containing a technical group tasked with identifying and setting thresholds for noise sources. This data is used to temporally and spatially regulate noise where animal populations are most vulnerable and inform protected area planning through other regional bodies, such as ACCOBAMS (Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area) [6,38].

Unintentionally, the recent COVID pandemic greatly reduced noise pollution around the world in an “anthropause” [39]. In a study by Stevens *et al*. (2023), dolphins dishabituated from anthropogenic sound and their responses to anthropogenic sound increased after the anthropause, suggesting higher attentiveness. This implies that species may recover after potentially damaging noise exposure. While there are clear adverse effects of noise pollution on marine vertebrates, there are also cases where animals become tolerant to noise when residing in areas where human activity is higher [39,40]. However, this tolerance may still result in vocalization or hearing sensitivity changes, which could impede communication and the ability of animals to process acoustic information from their soundscape.

**Concluding remarks**

Vocalization and sound reception drive biological and ecological functions necessary for the survival of marine vertebrates. Anthropogenic activities are infiltrating pelagic and coastal soundscapes across all frequencies used in biological vocalizations and auditory reception (**Figure 1**). As the oceans get noisier, some species may be able to adjust their use of acoustics, however, short and long-term effects of noise exposure at threshold levels have the potential to incur individual and population-wide damage [11]. As soundscapes change, movement and foraging ecologies may also be affected and propagate to ecosystem-wide effects. Monitoring efforts, such as those directed through MFAS, should be expanded globally to understand the full extent of noise pollution impacts, identify habitats used by animals at vulnerable life-history stages, and promote the expansion of quieting zones and boat technologies. Protecting soundscapes is essential to preserving the acoustic environment vital for the survival of marine vertebrates.

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