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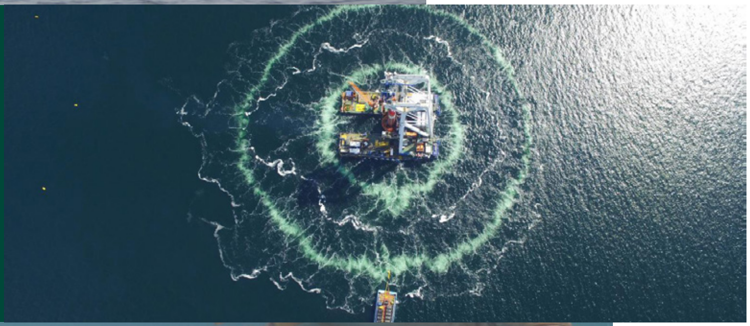
99

REVIEW OF THE IMPACTS OF ANTHROPOGENIC UNDERWATER NOISE ON MARINE BIODIVERSITY AND APPROACHES TO MANAGE AND MITIGATE THEM



UN environment programme

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Review of the Impacts of Anthropogenic Underwater Noise on Marine Biodiversity and Approaches to Manage and Mitigate them

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Foreword

During the spring of 2020, when an earlier draft version of this report was being prepared to be circulated for peer review, the world was gripped by the first wave of the Covid-19 pandemic. Activities at sea, as on land, including shipping, offshore construction, hydrocarbon exploration and extraction, seismic surveys, research, military exercises and tourism, slowed to a near halt, resulting in a precipitous drop in the volume of anthropogenic ocean noise.

The quieting of the ocean was a sudden, yet temporary, reversal in a trend now many decades old, which has seen an increase in anthropogenic noise-producing activities in our oceans. And these activities are reaching further into remote areas, including the polar regions, that had previously remained largely silent.

Thanks to the many studies conducted over the last few decades, we now know that underwater noise caused by human activities can cause adverse physical, perceptual and behavioural effects — direct, indirect and cumulative—for some species of marine mammals, marine reptiles, fishes, diving birds and invertebrates. These impacts have been an issue of concern to researchers for several decades, and while recent research has increased our understanding of impacts, this is a complex area of study, and uncertainties remain—including regarding the extent of effects and the impacts on some marine taxa.

In response to the increased knowledge and understanding of these impacts, several regional and international agreements and processes have been put in place to regulate, mitigate and manage underwater noise. Indeed, the Parties to the Convention on Biological Diversity first discussed the potential adverse impacts of anthropogenic noise on marine and coastal biodiversity in 2010, when they requested the Executive Secretary to produce a scientific synthesis report on the subject. Several iterations of this report have since been prepared, culminating in a call to take measures to avoid, minimize and mitigate these adverse impacts (decision XII/23) and to report back to the CBD on efforts to do so. Based on this work, a draft updated version of this report was prepared and circulated for peer review in September 2020.

The response, both enthusiastic and informative, highlighted the timeliness of the initiative. Input was received from more than 40 Parties and other Governments, organizations/entities and individual experts, many of whom emphasized the need to further update the report, in view of the enormous quantity of research findings and technological developments since the last version of the document was prepared. The version you now have before you was revised in response to these comments. I take this opportunity to thank the reviewers for their input, which has led to a vastly improved treatment of this rapidly developing field of study.

This scientific synthesis report is intended to provide an overview of the important research that has been undertaken on the potential impacts of anthropogenic underwater sound generation on marine and coastal biodiversity and habitats, and to advise Parties and other relevant stakeholders on appropriate measures to minimize and mitigate these impacts. While it synthesizes the best available knowledge in this rapidly developing area of study, it also highlights the gaps in knowledge. Importantly, this report also highlights recent technological improvements and other mitigation strategies aimed at attenuating anthropogenic sound.

Levels of anthropogenic sound in the marine environment have increased substantially in many regions in the past century and will likely continue to grow, further stressing oceanic biota that is already facing numerous threats, including from climate change, overexploitation and pollution. However, unlike other threats, the effects of which will linger long after the source is abated, the effects of noise reduction will be felt instantly. I hope that this report will provide governments and other stakeholders with the information needed to take appropriate action to "build back quieter" as we "build back better", contributing to a future where the ocean is healthy and productive.

I would like to express my appreciation to Mr. Simon Harding and Mr. Neil Cousins, who contributed their knowledge and expertise to the development of this report, and to the European Union, for its generous financial support.

Elizabeth Maruma Mrema
Executive Secretary, Convention on Biological Diversity

Executive Summary

In the context of the Convention on Biological Diversity (CBD), the need to address issues relating to impacts that may arise from anthropogenic underwater noise emerged in 2010, at the tenth meeting of the Conference of the Parties (COP 10). At that time, nascent research was shedding light on the potential impacts of anthropogenic underwater noise on marine biodiversity. Evidence was increasingly demonstrating that anthropogenic underwater noise can cause physical, perceptual, and behavioural effects for some marine species, including marine mammals, marine reptiles, fishes, diving birds and invertebrates. Indeed, its effects on marine biodiversity had received increasing attention at the international level, with recognition by several global and regional bodies and organizations.

Significant advancements in research and knowledge on this complex issue have taken place since 2010 and various policy processes at the national, regional and global levels have increased their attention on this issue, including under the CBD. This report seeks to review the broad range of knowledge on this issue, building upon the previous syntheses of information under the CBD. It is intended to provide high-level information to support the understanding of potential impacts and to guide Parties and other relevant stakeholders to take appropriate measures to mitigate the potential significant adverse effects of anthropogenic underwater sound.

The main findings of the report are as follows:

The characteristics and trends of underwater sound

1. **Marine animals produce and rely on sounds for many functions, including communication, navigation, foraging, reproduction and territorial interactions**

   The marine underwater soundscape consists of sounds produced by the physical environment (e.g., wind, waves, ice activity), marine fauna (e.g., marine mammals, fishes and invertebrates) and human activities (e.g., shipping, geophysical surveys and piling). Underwater sound provides many marine animals with sensory information about the surrounding environment in three dimensions, even providing information from distances beyond visual ranges. Sound travels almost five times faster through water than through air. Underwater sound can travel hundreds of kilometres under certain conditions and thus can enable animals to communicate over long distances. Underwater sound pressure propagation is primarily affected by the sound frequency, water depth, and density differences within the water column. Vibrations, however, can travel more slowly than sound pressure and may extend over long distances depending on the source.

2. **The marine soundscape is changing due to decreasing biodiversity, altered geophysical sound sources because of climate change, and increasing anthropogenic underwater sound**

   Research indicates that changes such as decreasing abundance of marine sound-producing wildlife, alterations to species distributions, degradation of marine habitats, and geophysical sounds such as sea ice or storms being altered because of climate change, have implications for how marine animals use sound and their sensitivity to anthropogenic underwater sound. Since the Industrial Revolution, there has been a rapid rise in underwater sound from anthropogenic activities, altering the marine soundscape across a broad range of frequencies, within the hearing range of marine animals. In some areas across the globe, low-frequency ambient sound has increased by at least 20 dB from pre-industrial conditions to 2009. In the North Pacific and Indian Ocean, low-frequency underwater sound has been increasing primarily due to commercial shipping, while reportedly decreasing in areas such as the Northeast Pacific, Equatorial Pacific and South Atlantic Ocean. Some have reported that vessels have become the most common source of anthropogenic underwater sound in the oceans, due to increasing levels of fishing, recreational use, and commercial shipping. Activities relating to research, military exercises, shipping and hydrocarbon extraction have intensified in historically untouched regions (e.g., the Arctic and Antarctic), and may further increase in the future.

The varying sources and types of anthropogenic underwater noise

3. **Anthropogenic sound in the environment can be categorized as impulsive (pulse) or non-impulsive (continuous)**

   Impulsive sounds are short bursts of energy occurring for a finite duration, for example those produced by explosions, seismic airguns, or pile-driving strikes. Non-impulsive sounds occur when acoustic energy is spread over time, for example those produced by vessels, drilling, vibropilling and vibrations associated with some offshore renewable energy operations. Marine animals may be impacted by the sound pressure that is produced and by changes to particle motion.

4. **The main sources of anthropogenic underwater noise include explosives, industrial activities, seismic surveys, military and civilian sonars, ships and smaller vessels**

   Underwater explosions are one of the strongest sources of anthropogenic underwater noise, capable of propagating equally in all directions and detectable across ocean basins. Pile driving for construction of coastal and marine facilities is known to cause the highest levels of sound pressure production in comparison to other industrial development activities, such as dredging, drilling or nearshore mining. Future deep-seabed mining, if permitted, has the potential to generate greater underwater noise than nearshore mining. The energy of seismic surveys, used for oil and gas exploration and other research purposes, penetrates several metres below the sea surface and can extend up to 100 km into the ocean floor. Sound signals from seismic airgun surveys have been received thousands of kilometres away from the source when spread in a sound channel. Sonar can also be a major contributor to underwater sound, with sound extending hundreds of kilometres from source. Vessels can significantly contribute to the level of underwater sounds in some areas. The level of sound is generally dependent upon their size (and load), speed, operational mode and any implemented sound-reduction measures.

5. **Other anthropogenic sources include acoustic harassment and deterrent devices, research sound, icebreakers, acoustic telemetry, and activities above water**

   A range of other activities contribute to the level of underwater sound in some environments. The intensity and extent of sound depends upon the activity. Acoustic and harassment and deterrent devices can generate high levels of sound to displace animals. A variety of different sound sources are used to investigate the physical structure of the ocean, for example, seismic airgun arrays and multibeam echosounders. Ice-breaking ships are a source of sound in polar regions and typically have a higher source level than more common vessel activity due to the act of breaking the ice by ramming into it, specialized equipment used to break the ice and unique propeller cavitation. Underwater sound can also be generated by acoustic telemetry that is used for underwater communications, remote vehicle command and control, diver communications, underwater monitoring and data logging, trawl net monitoring and other industrial and research applications requiring underwater wireless communications. Sound that is generated above water can also transmit to the marine environment, e.g., from coastal vehicle movements and aircraft.

Impacts of anthropogenic underwater noise on marine wildlife

6. **Anthropogenic underwater noise has a variety of direct, indirect and cumulative impacts on marine species**

   Direct adverse impacts can be generally divided into three categories: direct physical effects (hearing loss, injury and stress); masking (of communication signals and other biologically significant sounds), and behavioural disturbance. In extreme cases, intense noise can lead to mortality for some species. Marine wildlife can be sensitive to sound pressure and particle motion. Impacts from changes to particle motion are of greatest note for fishes and invertebrates. In addition to direct effects, marine wildlife could potentially be indirectly affected by changes to food resources that result from underwater noise impacts. This may relate to impacts on productivity and areas that may support key life-cycle functions. Cumulative impacts may relate to sound from multiple sources, the combination of sound with other stressors, and from long-term chronic exposure.

7. **Exposure criteria or acoustic thresholds have been developed for some taxonomic groups to predict the noise exposure levels above which adverse physical or behavioural effects are expected**

   Exposure criteria exist for sound pressure and have been only developed for marine mammals, fishes and marine turtles. The criteria mainly relate to onset thresholds where there is potential for injury, including hearing loss. Hearing losses can reduce the range for communication, affect the ability to forage, increase vulnerability to predators, and induce stranding. The criteria are intended as guidance and are often estimated under laboratory conditions. They are to be used as one tool to evaluate the effects of sound. There are gaps in knowledge to clearly understand the potential for sound pressure impacts across all sensitive groups, particularly for fishes and marine turtles. A significant gap for some groups is that sound exposure criteria do not relate to changes in particle motion, which is of note for determining the effect of underwater sound generation on fishes. There are also limitations in the thresholds for understanding behavioural responses under different contexts.

8. **Underwater sound can cause direct physical effects**

   Mortality of marine mammals has been recorded with respect to explosions. Explosives can result in a pressure drop which may cause air-filled organs to rupture. Research has suggested links between high-intensity sonar (e.g., used for military exercises) to stress responses and lethal effects for marine mammals (i.e., mass stranding events). Levels of intense sound produced during seismic activities or pile driving may be strong enough to cause noise-induced hearing loss in some species when referring to sound exposure criteria. However, there is no proven evidence of such effects in the wild, although associations with aberrant behaviour and seismic activities have been drawn. Hearing damage in marine mammals from noise generated by shipping is thought to be unlikely to occur from the passage of a single vessel. However, some modelled research under specific conditions suggests that there may be potential for permanent damage to hearing from sustained and/or repeated exposure to noise generated by shipping over long periods.

   Marine fishes exposed to intense noise (such as from explosions or pile driving) can experience temporary hearing loss and tissue damage, but the level of impact depends on the species and the sound source. Sound could also have an impact on the eggs and larvae of marine fishes such as decreased egg viability, increased embryonic mortality, or decreased larval growth.

   Research suggests that marine invertebrates are susceptible to underwater noise. There is growing evidence to understand the potential for physical effects across species, but cause-effect associations have been made with respect to stranding of giant squid and laboratory studies have shown physical effects on cephalopods. Other research has shown the potential for physical effects on invertebrate larvae, scallops, zooplankton, and lobster. There is limited information to determine the potential for injury to other marine groups, including marine turtles and seabirds. Research suggests that temporary thresholds shifts can occur to a certain high level of sound for marine turtles under laboratory conditions. Diving seabirds can be exposed to underwater noise when feeding but there are limited studies of the physical effects of noise on the hearing of seabirds.

9. **Underwater sound may cause the direct masking of biologically significant sounds, such as communication signals**

   Increased level of background or ambient sound, such as sound produced by vessels, can reduce an animal's ability to receive acoustic signals. Communication masking is of concern for marine mammals that communicate using low frequencies (e.g., whales, seals), and as a result in some instances compensate for the masking by changing the frequency, source level or timing of their signal. Fishes can be impacted by an interference with acoustic communication and through the masking of important environmental auditory cues. This can affect the fishes' ability to, for example, find prey, avoid predators, undergo courtship interactions, and aggregate for spawning. Anthropogenic-induced degradation of marine ecosystems such as coral reefs may also indirectly influence larval orientation and recruitment to habitats by changing the acoustic profile of these habitats. Many invertebrates, including species of polychaete worms, barnacles, amphipods, shrimp, crabs, lobsters, mantis shrimps, sea urchins and squid, are also capable of producing sounds. Low frequency anthropogenic noise may be masking acoustic communication in marine invertebrates such as crustaceans or the detection of prey or predators by cuttlefish. Masking of important acoustic cues used by invertebrates during larval orientation and settlement may also be a factor in the coastal zone and could lead to maladaptive behaviour that reduces successful recruitment.

10. **Underwater sound may cause direct behavioural and physiological effects**

A wide range of anthropogenic noise sources are known to elicit changes in behaviour in marine mammals, and the responses elicited can be highly complex, variable and context specific. Behavioural responses may range from changes in surfacing rates and breathing patterns to active avoidance or escape from the region of highest noise levels. Responses may also be conditioned by certain factors such as auditory sensitivity, behavioural state (e.g., resting, feeding, migrating), nutritional or reproductive condition, habituation, sensitization, prior experience, age, sex, presence of young, proximity to exposure and distance from the coast. Behavioural disturbance responses of marine mammals have been documented in relation to noise from recreational boats, industrial maritime traffic, seismic surveys, oceanographic tests, sonar, acoustic hardware, airplanes and explosions. In some instances, repeated short-term changes in behaviour may lead to long-term impacts through continual avoidance leading to habitat displacement. In some cases, animals who have been displaced for several years only return once the noise-generating activities have ceased. Exclusion from important feeding, breeding or nursery habitats likely has an adverse impact on survival and growth.

Adverse physiological effects of underwater noise on marine fishes may not be immediately obvious and are varied. They may include changes in stress levels, metabolism, resistance to disease, reduced energy reserves (for feeding, migration and reproduction) and reduced fertility. Highly stressed fish may also be more susceptible to predation and other environmental effects. Many of the studies of physiological impacts on fishes completed to date have been on captive individuals in enclosed areas where the fishes could not avoid the sounds, possibly also affecting the stress response. There have been a range of studies to determine the potential effects of anthropogenic noise on the behaviour of marine fishes but very little is known about the long-term effects of exposure to sound or about the effects of cumulative exposure to loud sounds. The responses of fishes are also, like marine mammals, context-specific and may vary with their age and condition, as well as under different environmental conditions. Behavioural responses can vary between different sound sources, or with the same sound when the level of sound received by the animal differs. Responses to noise by fishes can range from no change in behaviour, to mild awareness of the sound or a startle response, to small temporary movements for the duration of the sound, to larger movements that might displace fish from their usual locations for short or long periods of time. The most serious impacts are reportedly on survival and reproduction.

There is growing research that demonstrates both physiological and behavioural impacts of particle motion and seabed vibration on marine invertebrates. Across different species, research indicates that underwater sound can alter biochemical responses, growth rates, reproduction rates, feeding behaviour, and antipredator behaviour. There is limited information to determine the potential for injury to other marine groups, including marine turtles and seabirds. Laboratory-based research, however, shows behavioural responses to sound, including strong initial avoidance. There are currently no reported studies of the long-term effects of altered behaviour in marine turtles. Likewise, to marine turtles, there are limited data for impacts on diving seabirds, although behavioural reactions to underwater sound of some species have been reported in research.

Approaches to mitigate and manage the impacts of anthropogenic underwater noise

11. **The increased understanding of, and attention on, underwater noise impacts has led to the development of a range of mitigation and monitoring approaches, which include avoidance and minimization strategies**

    Mitigation measures can be mainly characterized in terms of spatio-temporal approaches (avoidance) and physical, operational and abatement controls (minimization). The type of mitigation and management depends on the source and activity characteristics, such as the type of sound, duration and location, and the receptors that may be affected. The full understanding of the usefulness of some mitigation measures, especially minimization techniques, is at times hindered by the complexities of the marine environment and uncertainties in baseline information, the impacts that occur and the effectiveness of mitigation approaches. Due to these uncertainties, some suggest the adoption of precautionary approaches. These should be proportionate and founded within a robust process of scientific evaluation and judgement as part of an informed risk-based approach, using existing evidence, expert input, and quantified approaches wherever possible. Additionally, the "mitigation hierarchy" is generally considered as a best practice framework to manage risks and impacts to biodiversity, outlining preventative and remediative measures. This hierarchy also provides a mechanism to manage uncertainties through the prioritization of avoidance strategies, especially where significant impacts may occur.

12. **Several guidelines have been developed that outline mitigation measures to reduce the impact of noise on marine wildlife**

    Detailed guidelines have been created by various entities, including industry, governments, intergovernmental organizations, or as part of multilateral environmental agreements. They mainly relate to marine mammals, but in some cases also relate to marine turtles, fishes and seabirds. The guidelines provide various measures depending on the source of sound (geophysical/seismic surveys, pile driving, sonars, explosives and shipping) and can be location specific (e.g., Gulf of Mexico, Canadian guidelines). The guidelines generally provide planning and operation measures to apply both avoidance and minimization strategies; and they share some commonalities in terms of the recommendations that are made.

13. **Geographical and seasonal restrictions (avoidance) are regarded as a highly successful mitigation measure**

    These measures relate to the scheduling of underwater sound-generating activities to avoid times or locations that are used for activities such as breeding, spawning, resting, feeding or migration, and locations with rich marine life or sensitive species. Spatio-temporal approaches further require advanced planning and often need to be informed by robust baseline environmental and biological data of the concerned ecosystem. Monitoring over multiple seasons or years prior to operations is required for sensitive areas, such as those with threatened or endangered species. In situations where avoidance may not be possible, additional planning, mitigation, monitoring and the analysis of potential effects is needed.

14. **Operational controls (minimization) primarily provide approaches to reduce risks of injury, but do not provide robust mitigation for other impacts such as behavioural, perceptual, or stress-related**

    Such operational controls include pre-shoot watches, soft-start/ramp-up procedures, establishing mitigation zones, soft-start delay, shut-down upon sighting, operational stoppages, and guidelines for conducting activities in periods of poor visibility and darkness. However, the potential effectiveness of these approaches needs to be considered and fully understood, such as limitations associated with the probability of observation or detection using visual monitoring and Passive Acoustic Monitoring (PAM) approaches. While they primarily relate to marine mammals, they may also reduce risks to other marine species but their effectiveness in this regard is uncertain, and as such, other approaches may be more appropriate.

15. **Alternative technologies to limit impulsive sound production exist, although some are still in development or not widely deployed**

    Progress has been made in developing alternatives to pile driving for offshore wind turbines. Alternative technologies to replace airguns in seismic surveys have been under development for some time, but there is a potential to reduce the amount of seismic survey activity required using existing complementary technologies, such as low-frequency passive seismic methods, electromagnetic and gravity surveys, or fibre optic receivers. Additionally, several abatement technologies have been developed to reduce noise levels that mainly relate to piling activities.

16. **Continuous noise from vessels can be reduced through design and operational measures**

    The main sound sources from ships are those caused by the propeller, by machinery, including sea-connected systems (e.g., pumps), and by the movement of the hull through the water. Propeller cavitation is usually the dominant source for large commercial vessels. Noise reduction that can be achieved through design include measures such as altering propeller design, wake flow modification, machinery improvements and treatments, engine selection (including alternative fuels), hull treatments (including air bubble abatement) and use of wind propulsion (e.g., kite sails). Operational mitigation measures are mainly concerned with travelling at slower speeds or ensuring there is routine maintenance of equipment such as propellers. The slowing of vessel speeds, regulating vessel routing and scheduling has been adopted in many areas.

17. **Acoustic monitoring and modelling/mapping are also essential elements of noise mitigation in the marine realm**

    These are particularly used for the assessment of sound levels and for predicting or determining the presence of marine species close to noise generating activities. Mapping tools are used to describe average human-induced noise fields over extended periods of time or for large areas of coastline or open ocean. They are also used to define and demonstrate risk-based noise-exposure indicators that can be used by managers to quantify and reduce the exposure of a population to noise pollution. Habitat modelling techniques are also able to predict species densities at fine spatial scales to match the size of operational area. Tools have also been developed to measure communication masking in the marine environment. Monitoring tools include visual observations, PAM, Active Acoustic Monitoring (AAM) and real-time marine mammal detection. Other monitoring techniques include, for example, the use of thermal imaging, especially for detection at night. Acoustic, species distribution and habitat mapping can provide effective visualizations of low frequency contributions from anthropogenic sound sources, and important information for risk assessment and marine spatial planning. PAM can be used for real-time mitigation and monitoring, and is used to detect cetaceans, although with some limitations. AAM is more applicable for fishes, turtles and invertebrates, and non-vocalizing marine mammals. However, AAM systems can often only detect animals at closer ranges than passive monitoring but are able to estimate the range of targets more easily.

18. **A variety of management frameworks, agreements and processes that deal with underwater noise pollution have been developed**

    Different management frameworks exist to manage underwater noise, particularly spatio-temporal restrictions as part of a wider marine spatial planning approach, and impact or risk assessment frameworks. Numerous international agreements and processes have been developed that provide information on regulating, mitigating and managing underwater noise pollution at the regional and international levels. This includes text within international agreements that countries are party to or special resolutions, the undertaking of focused meetings, development of working groups, and the production of focused reports and guidance. In addition to international agreements, various international organizations have supported research (including for specific geographical areas) and produced material to inform policy makers and industry approaches.

19. **Efforts have been made to set global standards, limits and guidelines for acoustic measurements of anthropogenic underwater noise at the national and international levels**

    International standards have been developed for environmental impact assessments (EIAs) and for mitigation measures to be used by governments or industry. There are several voluntary industry standards set by the International Standards Organization (ISO) focusing on underwater acoustics. Other forms of standards for mitigation and management of underwater noise have been proposed as well.

Future research needs

20. **Anthropogenic underwater noise represents a known and increasing pressure on the marine environment, yet significant knowledge gaps and uncertainties remain**

    Whilst underwater sound is of concern to many marine wildlife taxa, current knowledge is limited in some areas, including for understanding impacts on fishes, marine turtles, seabirds and invertebrates. There has been considerably more research for cetaceans and, to a lesser extent, other marine mammals, such as pinnipeds, but there are still many knowledge gaps that need addressing. There is also a need to better understand impacts in the wild, and to improve the consideration of particle motion impacts in addition to sound pressure. Detailed research programmes on the effects of anthropogenic underwater noise on individuals, species, populations, habitats and ecosystems as well as cumulative effects with other stressors need to be put in place or consolidated where they already exist. Research should focus on developing a better understanding of biodiversity values, risks (including cumulative), and how these are mitigated and managed. Such research may be supported by regional programmes to promote monitoring, learning and adaptive management. These programmes may seek to take standardized approaches to support understanding across a range of taxa and environments and develop approaches to share information.

    Existing or proposed management frameworks also need to be tested and refined accordingly in a range of scenarios. Based on the available literature, a range of research needs as well as research areas of priority have been identified. Underwater noise and properties of emitted sound in a changing marine environment need further characterization. Mitigation procedures and measures need more assessment of their effectiveness through an independent peer-reviewed process, and improvement, due to vast remaining uncertainties. Commonly applied measures also need to be tested at the species level. If not effective, they should be replaced by proven approaches, for example, the prioritization of avoidance where uncertainties remain or in areas where high-value biodiversity may be affected. There is also a need for better standardization. Protecting marine life from the increasing threat of human-induced underwater sound will also require more effective governance of the activities producing noise, which depends on a combination of greater understanding of the impacts and increased awareness of the issue by decision-makers, on a global, regional and national scale, to implement adequate regulatory and management measures.

1. INTRODUCTION

BACKGROUND

This report seeks to provide a review of current knowledge of adverse impacts that occur from underwater noise generated by anthropogenic activities and provides an outline of the status of management and mitigation approaches to address these impacts. It also highlights and discusses the uncertainties in current knowledge.

The marine environment is filled with a range of sound sources, which includes biotic and abiotic natural sources and sound derived from anthropogenic activities. Sound can be classified in terms of the pressure and the particle motion that is produced from the source. Not all sound has negative consequences, and indeed natural sound has a range of important functions for some marine wildlife, including for communication, navigation, orientation, feeding and the detection of predators and hazards. The presence of an anthropogenic sound therefore does not necessarily mean that an animal will be harmed or affected in a detrimental way. Underwater "noise" is a type of unwanted sound for the receiver that interferes with the detection of other sounds of interest.[1] The opposite of noise is a "signal", i.e., a sound that contains some useful or desirable information. A particular sound can therefore be noise to one receiver and a signal to others.[2,3] In addition, some sounds can have negative effects whilst others will be neutral. Therefore, underwater sound that is generated by anthropogenic activities that leads to negative consequences for marine biodiversity is of greatest concern for the protection and conservation of marine biodiversity. The terms "sound" and "noise" are often used interchangeably, however in this report the term "noise" is generally used, to refer sound with a negative impact or mitigation of such impacts.

Underwater sound derived from anthropogenic activities has increased over the last century in some areas as the use of the oceans has expanded and diversified.[4,5,6,7,8] Long-term measurements of ocean ambient sound indicate that low frequency anthropogenic sound has generally increased in certain areas over the last 50 years. There are, however, spatial and temporal variations between different places where most intensive sound generation has taken place.[9] The United Nations General Assembly (UNGA, 2018)[10] reported that coastal areas and areas where a higher degree of human activity takes place, including shipping lanes with high levels of traffic, are the most impacted by anthropogenic underwater noise. However, there is evidence of increased ambient underwater sound across broader oceans basins in some regions.[11]

Evaluating underwater noise in the marine environment is highly complex; there is a need to address a range of technical disciplines and a wide range of variabilities in perceptions and responses of marine wildlife. There are spatial variations in the propagation of sound related to complex physical and environmental relationships. There are also variables with respect to sensitivity and vulnerability of marine biodiversity receptors, including between individuals within the same populations. The consequence of underwater noise also varies spatially and temporally as areas become subject to ever-increasing cumulative exposure and where underwater noise expands into regions that have historically seen lower levels of exposure (e.g., the Arctic and Antarctic regions).[12,13,14,15]

Simmonds et al. (2014)[16] provided a historical timeframe for the growing concern associated with the adverse impacts of underwater noise on marine wildlife that required regulation. Initial concerns were raised in connection with military exercises and whale stranding events in the 1970s[17,18], 1980s[19] and 1990s.[20] Other concerns were raised as a result of the Acoustic Thermometry of Ocean Climate (ATOC) experiment,[21,22] which set precedent for formal environmental impact assessments to be conducted for activities that generate underwater noise.[23] Over recent decades, extensive research and reviews have been undertaken regarding the negative impacts on marine wildlife that arise from anthropogenic noise. Most of the research has focused on sound derived from underwater sources, but some research has also provided evidence of adverse impacts resulting from sound generated on land and in the air. Historically, studies have focused on marine mammals, marine turtles, fishes and invertebrates, but in recent years, the level of research on other trophic organisms has increased, including a small number of studies concerning diving birds and marine snakes.

The adverse impact of anthropogenic underwater noise on marine wildlife has been an issue of concern over many decades, and research is shedding ever increasing light on the potential consequences. This report seeks to provide an overview of the important research that has been undertaken to inform the understanding of potential impacts from anthropogenic underwater noise. Research has determined that sound is important to a wide range of marine wildlife. The many studies that have been undertaken over the last few decades have provided evidence to demonstrate that underwater noise can cause physical, perceptual and behavioural effects for some marine species, including marine mammals, marine reptiles, fishes, diving birds and invertebrates. Adverse impacts may be short-lived or lead to long term effects associated with chronic exposure and injury. In some instances, some types high intensity underwater noise present a mortality risk for some species. The evidence-base varies across groups related to the extent and type of research that has been undertaken across the different groups but is also associated with the full understanding of what impacts may occur in the wild.

Although there is significant evidence that there are impacts associated with underwater noise generation, many gaps in knowledge remain. These gaps relate to data paucity on baseline conditions (including populations, behaviours and ecological connectivity/ wide-ranging movements) and difficulty in determining the spatial scales at which impacts occur (including the potential for impacts, especially indirect impacts, to occur over large areas).[24] They also relate to uncertainties in understanding sensitivities across all taxa. Even where there is evidence of potential adverse impacts among some wildlife groups, research does not cover all species that may be affected. There are also gaps in our understanding of the consequence of subtle effects, linking short-term effects with long-term effects, effects on populations, etc. There is a particular problem in the limited ability to observe impacts (including lethal effects), and there is potential to under- or over-estimate non-lethal effects.[25] Accurate quantification of impacts is also, at times, limited by data paucity on baseline and difficulty in determining the spatial scales at which impacts occur (including the potential for impacts to occur over large areas due to ecological connectivity, especially indirect effects),[26] absence of long-term ecological baseline and exposure monitoring and the absence of integrated cumulative assessments at local and regional scales in many regions. The impacts that arise from underwater noise occur at a range of temporal and spatial scales with variable sensitivities among different marine wildlife groups and sometimes for individuals that are exposed within the same groups. The behaviour of sound also varies geographically depending upon the conditions that exist where sound is generated and extends. In addition, some research has been undertaken with inherent limitations resulting in uncertainties in outcomes, such as translating experiments in controlled lab-based environments with real-life assessments in the natural environment. The understanding of the impacts of underwater noise is therefore complex and can be hampered by existing limitations. Uncertainties may also exist with respect to the effectiveness of mitigation measures that are used to minimize impacts.[27,28,29] These gaps in knowledge also affect the selection of appropriate mitigation strategies. These uncertainties are explored where appropriate throughout the report, and recommendations are made to help manage them.

The issue of anthropogenic underwater noise and its effects on marine biodiversity has received significant attention at the international level, with recognition by several regional and international bodies. For example, the United Nations General Assembly, the International Maritime Organization (IMO), the International Whaling Commission (IWC), the European Parliament and European Union, the Baltic Marine Environment Protection Commission (HELCOM), the North Atlantic Marine Mammal Commission (NAMMCO), the Food and Agriculture Organization (FAO), and the International Union for Conservation of Nature (IUCN), as well as bodies under the Convention on the Conservation of Migratory Species of Wild Animals (CMS), the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR), the Agreement on the Conservation of Cetaceans in the Black Sea Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS) and the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS) have all considered the negative effects of anthropogenic underwater noise through the adoption of resolutions or recognition of the issue for the marine environment; these will be explored in chapter 5.

THE ISSUE OF ANTHROPOGENIC UNDERWATER NOISE WITHIN THE CONVENTION ON BIOLOGICAL DIVERSITY AND THE PURPOSE OF THIS REPORT

The need to address issues relating to adverse impacts that may arise from anthropogenic underwater noise emerged in the context of the Convention on Biological Diversity (CBD) in 2010, at the tenth meeting of the Conference of the Parties (COP 10). At this meeting, the COP, in decision X/29 (paragraph 12), requested the Secretariat of the CBD to produce a scientific synthesis report on the impacts of anthropogenic underwater sound generation on marine and coastal biodiversity and habitats, as well as tools and approaches to minimize and mitigate these impacts.

The draft report was made available as an information document at the 16th meeting of the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA 16) in Montreal in May 2012 and was welcomed later that year by the eleventh meeting of the Conference of the Parties to the CBD. In 2014, on the basis of a request from COP decision XI/18, an expert workshop on underwater noise and its impacts on marine and coastal biodiversity was convened in London in 2014. The above-noted synthesis provided a basis for background documentation to inform this workshop. The workshop informed the development of COP decision XII/23, in which COP encouraged Parties and other Governments as well as indigenous and local communities and other relevant stakeholders, to take specific appropriate measures to avoid, minimize and mitigate the potential significant adverse impacts of anthropogenic underwater noise on marine and coastal biodiversity. In the same decision, and in subsequent decisions, the COP requested the Secretariat to compile and share information related to the activities to minimize and mitigate the impacts of anthropogenic underwater noise. The Secretariat prepared numerous information documents synthesizing such information, on the basis of submissions from Parties, Other Governments and relevant stakeholders, which were made available to meetings of the Subsidiary Body on Scientific, Technical and Technological Advice.

A draft version of this report was developed on the basis of this previous work and was circulated, in September 2020, for peer review via CBD notification 2020-070. The present version of the report reflects revisions made in response to comments received through the peer-review and aims to inform Parties, other Governments and relevant organizations in their efforts to address the impacts of anthropogenic underwater sound on marine and coastal biodiversity and habitats.

Research into the adverse impacts of underwater noise and how to manage them is an extensive and complex topic that is continually developing. Therefore, whilst the report seeks to provide a synthesis of information at the time of writing, it does not seek to provide a technical scientific review of all information available or provide a critical academic examination of research undertaken. The review is intended to provide high-level information to support the understanding of potential impacts and to guide Parties and other relevant stakeholders to take appropriate measures to mitigate the potential significant adverse effects of anthropogenic underwater noise. This document seeks to address the following key requirements identified by the Conference of the Parties in paragraphs 2 and 3 of decision XII/23:

- Provide information on when significant impacts may occur, characterizing by source.
- Refer to best practice assessment approaches in existing guidance.
- Identify current knowledge gaps and recommend areas of further research, using recommendations in existing literature as a basis.
- Provide information on thresholds where they exist for some species and outlining the relevance for their application, including referring to available metrics.
- Explore the use of strategic management approaches to help mitigate impacts, including mapping of sensitivities, and for predicting impacts and for informing protection and conservation of certain areas.
- Identify mitigation options for avoiding and minimizing impacts.
- Provide a platform to support the engagement of industry and other sectors and to encourage collaboration between relevant international bodies.

Notes

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2. UNDERWATER SOUND: CHARACTERISTICS, RELEVANCE AND TRENDS

OVERVIEW OF UNDERWATER SOUND

Sound is a mechanical disturbance that travels through an elastic medium (e.g., air, water or solids).[1] The way that sound travels is dependent upon the medium in which it travels. Water is an excellent medium for sound transmission as liquid molecules bond together in a relatively tight formation resulting in a higher elasticity.[2] Sound travels almost five times faster through sea water than through air (about 1500 vs. 300 ms^{-1}).[3,4] At low frequencies, underwater sound has been known to travel hundreds of kilometres under certain conditions[5] with little loss in energy.[6] The distance that sound can travel can enable long distance communication of animals, but also potentially, far-field impacts.[7] Sound pressure propagation in the marine environment is affected by three main factors: the frequency of the sound, water depth, and density differences within the water column, which vary with temperature and pressure.[8] Other factors that may affect the transmission of underwater sound include seabed morphology and substrate type. In general, acoustic power will be lost from the source due to spreading, absorption and scattering.[9] Some activities can also lead to low-frequency vibrations through the seabed substrate, which can create particle motion in the water column.[10,11,12,13] Activities such as dredging, pile driving and drilling on the seabed all directly add to the level of vibration, while other marine-based activities operating in the water column (e.g., shipping, seismic surveys, and sonar) have the potential to add vibration indirectly through propagation. Vibrations can travel more slowly than sound pressure and may also extend over long distances depending upon the source. Therefore, the behaviour of underwater sound is complex and is dependent upon the environmental conditions in the area where sound is generated, the type of activities that create sound and its propagation, all of which can vary significantly.

All sources of underwater sound are made up of both sound pressure (fluctuations in the medium above and below the local hydrostatic pressure) and particle motion.[14,15,16,17] The hearing of marine species may involve the detection of pressure and/or particle motion, and therefore, they may be impacted by both. Most marine mammals are sensitive to sound pressure, and there is some evidence to suggest that they may be sensitive to changes to particle motion. For instance, Mooney et al. (2016)[18] reported that whales could potentially use particle motion to determine the distance of signalling animals. Fishes and invertebrates are sensitive to particle motion, and some fishes are also sensitive to sound pressure (those with morphological specializations that use the swimbladder as a pressure-to-particle motion converter).[19,20,21,22,23,24,25] Particle motion perception differs from pressure perception.[26] The differences include the limiting of the detectable frequency range to a few hundred hertz, restricting the detectable sound intensities to higher levels and shortening distances over which sounds can be perceived.[27,28] Particle motion has been explained as the back-and-forth motion of the component particles of the medium, measured as the particle displacement, velocity or acceleration.[29,30] Hawkins et al. (2020)[31] reported that distant from the sound source, at a depth that is not affected by the seabed, particle motion is proportional to sound pressure. However, they reported that close to source the particle motion is higher for a given sound pressure. Also, they reported that close to the seabed the amplitude of particle velocity may be reduced. In addition, as mentioned above, the particle motion component of an underwater sound may propagate not only via the water column, but also by the seabed. Hawkins and Popper (2017)[32] reported that whilst it has become commonplace to estimate particle velocity from the measurement of sound pressure using simple models, these are only valid in environments that are distant from reflecting boundaries and other acoustic discontinuities. Therefore, detecting particle motion requires specific monitoring to measure this factor directly.[33,34] This information demonstrates the difficulty in the use of sound pressure levels to understand the impact of changes in particle motion.

The unit for measuring the frequency of underwater sound is Hertz (Hz). The pascal (Pa) is the standard measure for sound pressure. The reference pressure for underwater sound is 1 micropascal (1 µPa).[35] There are different measurements and metrics used to quantify the amplitude and energy of the sound pressure level.[36,37,38,39,40] These include:

- **Peak sound pressure (p_{max}):** the maximum absolute value of the instantaneous sound pressure during a specified time interval expressed in Pa.
- **Peak-to-peak sound pressure ($p_{pk\text{-}pk}$):** the difference in pressure between the maximum positive pressure and the maximum negative pressure in a sound wave.
- **Mean-squared pressure (RMS):** the average of the squared pressure over time.
- **Sound pressure level (SPL):** a decibel (dB) measure of the pressure metrics defined above referenced to 1µPa.
- **Source level (SL)**: the received level measured or estimated 1 m from the source.[41]
- **Sound exposure level (SEL):** a measure of the total energy contained within a sound signature; it depends on both amplitude of the sound and duration. This is often normalized to 1 second and is reported as 1 μPa^2s. For pulses and transient sounds, the acoustic energy flux density enables sound exposures of differing duration to be related to one another for purposes of assessing exposure risk. Further definitions have been made for types of SEL:
  - Sound Exposure Level – single strike (SEL_{SS}) – an index of energy used in pile driving studies for when the pile is struck once.
  - Cumulative Sound Exposure Level (SEL_{cum}): the linear summation of the individual sound events over the time period of interest.
- **Frequency weighting:** The hearing of different species is frequency-dependent. Therefore, received sound pressures can be weighted by the frequency response of hearing for the animal.

IMPULSIVE AND NON-IMPULSIVE SOUND

Anthropogenic sounds in the environment can be categorized as impulsive (pulse) or non-impulsive (intermittent or continuous).

Impulsive sounds are short bursts of energy that occur for a finite duration. Examples of pulsed sound are those produced by explosions, seismic airguns and pile-driving strikes. These sounds are all characterized by a relatively rapid rise from ambient pressure to a maximal pressure value followed by a decay period that may include a period of diminishing, oscillating maximal and minimal pressures.[42] Pulse sounds contain a wide frequency range, which is commonly referred to as broadband.[43] They can either be a single event or are repetitive and sometimes as a complex pattern. Impulsive sounds may be expressed as peak levels. However, peak (and RMS) is not sufficient for characterizing the energy in short sounds that start and stop. SEL is therefore often used as the metric for these sound sources. The SEL_{cum} metric is used to reflect that sound may not be from exposure to a single source but to accumulated energy from exposure to multiple sounds.[44] Hawkins and Popper (2017)[45] reported that whilst SEL_{cum} is an important metric and is often used to regulate activities against sound exposure criteria, the SEL_{ss} and the number of impulses are also important and that the reliance on the SEL_{cum} metric alone may be inappropriate. Popper et al. (2014)[46] also reported that the SEL metric becomes less useful, and possibly misleading, at longer exposure durations.

Non-impulsive (continuous) sounds occur when acoustic energy is spread over time. Signals can be broadband or more tonal (containing one or few frequencies), brief or prolonged, continuous or intermittent, and do not have the rapid rise time (typically only small fluctuations in amplitude) characteristic of impulsive signals.[47] The amplitude of sound may vary through the duration, but it does not fall to zero for a specific period of time. Examples of sources producing non-impulsive sounds include vessels, drilling, vibropiling and vibrations associated with some offshore renewable operations. The duration of such sounds, as received at a distance, can be greatly extended in highly reverberant environments.[48] RMS SPL is the commonly used metric for non-impulsive sounds in the marine environment.

It is important to note that the metrics referred to above relate to sound pressure and are not directly related to the measurement of particle motion. Additional approaches are therefore required for the measurement and monitoring of particle motion impacts on marine wildlife.[49,50]

THE MARINE SOUNDSCAPE

The marine underwater "soundscape" comprises the collection of biological, geophysical and anthropogenic sounds present in a particular location and time.[51,52] The different components include:[53]

- Geophony – sounds produced by the physical environment (e.g., wind, waves, tidal actions, ice, lightning strikes, earthquakes)
- Biophony – sounds produced by non-human organisms (e.g., fishes, marine mammals, invertebrates)
- Anthrophony – sounds that result from human activity (or produced by humans)

Marine soundscapes will therefore be affected by changes to these different components. Duarte et al. (2021)[54] reported that "ocean soundscapes are rapidly changing because of massive declines in the abundance of sound-producing animals, increases in anthropogenic underwater sound, and altered contributions of geophysical sources, such as sea ice and storms, owing to climate change". This has implications for how marine animals use sound and their sensitivity to underwater sound being produced by anthropogenic activities.

Natural (non-anthropogenic) underwater sound

There are a range of natural sound sources in the marine environment, which can be of physical or biological origin. Natural physical phenomena that contribute to underwater ambient sound include wind, waves and swell patterns; bubbles; currents and turbulence; earthquakes and sub-sea volcanic eruptions; lightning strikes; and precipitation, ice cover and ice activity (movement of ice sheets or icebergs that cause the release of energy as sound).[55,56] Wind-driven waves are the dominant natural physical sound source in the marine environment. In the absence of anthropogenic and biological sound, ambient sound is wind dependent over an extremely broad frequency band from below 1 Hz to at least 100 kHz.[57] In the open ocean, underwater sound levels can be increased by more than 20 dB (10 Hz to 10 kHz band) by spilling and plunging breakers,[58] while precipitation can raise ambient sound levels by up to 35 dB across a broad band of frequencies (100 Hz to more than 20 kHz).[59] Closer to shore, sounds from pack ice cracking may increase underwater sound levels by as much as 30 dB. Seismic waves from undersea earthquakes can be up to 30–40 dB above ambient sound levels, with a sharp onset, and can last from a few seconds to several minutes.[60]

A range of marine taxa, including marine mammals, many fishes and some invertebrates, have developed special organs and mechanisms for detecting and emitting underwater sound. Animals produce sound ranging from infrasonic (<20 Hz) to ultrasonic, although most are emitted between 10 Hz and 20 kHz, and these sounds are audible to a wide range of marine taxa.[61] Animals produce sounds for a wide variety of functions, including navigation, foraging, agonistic displays, territorial defence, mate attraction and reproductive courtship.

Marine mammals (cetaceans and pinnipeds) produce sounds that are used for communication, orientation, navigation and foraging. Sounds range from the 10 Hz low-frequency calls of blue whales to the ultrasonic clicks exceeding 200 kHz in certain offshore dolphins.[62] Source levels of click sounds used by sperm whales in navigation and foraging can be as high as 235 dB re 1μPa peak-to-peak.[63] However, these sounds are focused within a very narrow field[64] in comparison to anthropogenic sources. Baleen whales are thought to use low frequency sound for communication,[65,66,67,68] including sound that travels over ocean basins.[69,70,71] Most toothed whales (odontocetes) emit three main types of sound: tonal whistles and bursts of broadband pulses that sound to the human ear like cries, grunts or barks, all used for communication, and short duration pulses used for echolocation.[72] Some species also produce codas for social interaction.[73,74,75] Odontocete echolocation clicks are highly directional forward-projecting pulsed sounds of high intensity and frequency. Some species of seal produce strong underwater sounds that may propagate for great distances.[76] Many marine fish species produce sound for communication.[77] The low frequency sounds created by fishes can make a significant contribution to ambient sound.[78] Fishes can produce sounds as individuals, but also in choruses,[79] and the increase in low-frequency sound can be as much as 20–30 dB in the presence of chorusing fishes.[80] A dominant source of ambient sound in tropical and sub-tropical waters is snapping shrimp, which can increase ambient levels by 20 dB in the mid-frequency band.[81] In addition to shrimp, other invertebrates contribute to ambient reef sound, including squid,[82] crabs,[83] lobsters[84] and urchins,[85] with the latter producing dawn and dusk choruses of feeding sounds that are amplified by their skeletons.

Duarte et al. (2021)[86] reported on the effects of climate change on biophony through degradation of marine habitats and alterations to species distributions. In addition, they reported on the change in physical parameters that affects the behaviour of sound in the marine environment.

The importance of sound for marine organisms

Sound is an important sensory modality for many marine animals.[87] The distinctive properties of underwater sound mentioned previously and the limitations of other senses, such as vision, taste and smell, in the marine environment in terms of range and speed of signal transmission, mean that sound is the preferential sensory medium for a large proportion of marine animals. As a result, marine animals have evolved a wide range of receptors to detect and use sound.[88] Underwater sound around marine species can be called their "soundscape" and provides animals with sensory information about the surrounding marine environment in three dimensions. Almost all marine vertebrates rely on sound for a wide range of biological functions, including the detection of predators and prey, communication and navigation.[89,90] Sound is particularly important as it provides information from distances well beyond visual ranges. The ability to use information about the soundscape also requires that an organism is able to discriminate among acoustic signals, determine the location of the sound source (localization), and perceive biologically important sounds in the presence of "masking sounds". The soundscape is therefore of great importance for many species.

To maximize the use of the underwater acoustic environment, marine mammals have developed broader hearing frequency ranges than are typically found in terrestrial mammals.[91] Marine mammals can be organized in generalized hearing groups.[92,93] Baleen whales are low-frequency cetaceans; dolphins, toothed whales, beaked whales, bottlenose whales are mid-frequency cetaceans; and true porpoises, *Kogia* spp., river dolphins, *cephalorhynchid* and *Lagenorhynchus* spp are high-frequency cetaceans. Pinnipeds and sirenians have best hearing capabilities at low frequencies.[94,95,96] Marine mammals use sound as a primary means for underwater communication and sensing.[97] They can emit sound to detect and communicate the presence of a conspecific or other animal, and to communicate their own position, identity and reproductive or territorial status.[98] There is also some evidence to indicate potential communication of some humpback whale groups during foraging.[99] Odontocete cetaceans have developed sophisticated echolocation systems to detect, localize, and characterize underwater objects and prey, and use communication signals to coordinate movement.[100]

Data on hearing by marine turtles is limited,[101] but some research has identified hearing sensitivity at low frequencies.[102,103,104,105,106,107,108,109,110,111] Some researchers have examined the possible role that hearing plays in aiding the perception of acoustic signals to some support functions and for communication.[112,113,114,115,116] However, data and knowledge in this regard are limited. With respect to other marine reptiles, Chapius et al. (2019)[117] reported on hearing sensitivity for sea snakes. Their data suggest that sea snakes are sensitive to low-frequency sounds but have relatively low sensitivity compared with bony fishes and marine turtles. They concluded that further studies are required to understand the role of sound in sea snake life history and further assess these species' vulnerability to anthropogenic sound.

There is a significant body of research into the hearing capabilities of fishes.[118,119,120,121,122,123,124,125,126,127,128,129,130] Fishes only hear low-frequency sounds, and they are able to discriminate between sounds of different amplitude and frequency, and between calls that differ in their temporal characteristics.[131] Their hearing range and sensitivity are known to vary considerably between species.[132] As already discussed, fishes receive sound through particle motion and, in some instances, sound pressure. All fishes detect and use particle motion, which is integral to hearing and is used to locate the direction of the source.[133] Some species with a swimbladder (and other gas-filled cavities) also detect sound pressure. For such fishes, gas is compressible and changes in volume in response to sound pressures. This results in the swimbladder translating sound pressure into particle motion and transferring higher levels of particle motion to the inner ear. Having a gas bubble or swimbladder close to, or connected to, the ear enhances the hearing ability of fishes in response to sound pressure.[134] The contribution of sound pressure in hearing varies across species that have these morphological characteristics and can vary at different sound frequencies.[135] In addition, some fish species that have a swimbladder only detect particle motion.[136] Fishes can use cues to seek out the location of a sound source, and sounds may play a role in navigation, foraging for prey, detection of predators, and communication of reproductive state, and some marine species may use sound for habitat selection.[137,138,139,140,141,142,143,144,145,146] Many fish species also produce sounds for a variety of functions, such as feeding, reproduction and fighting.[147,148]

There is expanding research on the hearing of marine invertebrates and the potential impacts of anthropogenic underwater noise, but it remains one of the least-studied groups.[149,150,151,152,153,154,155,156,157,158,159,160,161,162,163,164,165,166,167,168] Studies confirm the detection of sound by invertebrates and that they detect sound at low frequencies through sensitivities to particle motion (including seabed substrate vibration).[169,170,171,172,173,174,175,176,177,178,179,180,181,182,183] Some crustaceans, echinoderms and bivalves are known to produce sounds for various contexts, including conspecific territorial interactions, warning signals, prey stunning and predator deterrence, or as a by-product of foraging.[184,185,186,187]

ANTHROPOGENIC UNDERWATER SOUND

Duarte et al. (2021)[188] reported on a rapid rise in underwater sound from anthropogenic activities since the Industrial Revolution. Before this time, soundscapes largely comprised geological and biological sources. Human activity has altered the marine soundscape across a broad range of frequencies within the hearing range of marine animals.[189]

Increased underwater sound from anthropogenic activities includes the deliberate use of sound for research (e.g., seabed mapping from seismic activities) and also as by-products from activities such as vessel movements (e.g., commercial, recreational and fishing), trawling gear, drilling and piling of structures, exploration of hydrocarbon resources, dredging, use of explosives for fishing, controlled explosions of discarded bombs, and the transfer of sound from land and air activities (e.g., aircraft and traffic), and ice-breaking in Arctic and Antarctic regions. Other activities, such as seabed mining, may also contribute sound to the marine environment in the future. There has also been an expansion of activities in historically untouched regions, such as the Arctic and Antarctic, relating to research, military exercises, shipping and hydrocarbon exploration,[190,191,192] which may increase further in the future.[193] Some of these sources are infrequent, but some activities, such as shipping, have led to longer term and broad scale effects with a concentration of sound generation in coastal areas and along wider shipping lanes – see Figure 1.[194] In some areas, activities cannot be considered in isolation and lead to cumulative effects where sound generated from different sources combine.

Vessels are reported as being responsible for the continual and steady rise of underwater sound at low frequencies (10–100 Hz) in many ocean regions at a rate as high as 3 dB/decade.[195,196,197,198,199,200] Erbe et al. (2019b)[201] reported that vessels have become the most ubiquitous and pervasive source of anthropogenic underwater sound in the oceans. Sound produced by vessels is increasing due to fishing, recreation use and higher levels of commercial shipment of goods. In addition, the increased size (and load) and speed of some watercraft has led to higher levels of sound generation.[202,203,204] Erbe et al.(2019b)[205] reported there have been significant increases in the use of small boats around the world, which has led to increased underwater sound in coastal areas. They provided examples of increases in small vessel registrations in some regions, including 1 per cent per annum between 1980 and 2017 in the United States and 3 per cent per annum in Australia between 1999 and 2009. Most of these vessels also use high-frequency sonar for navigation and fish-finding. Sound at these higher frequencies is of concern to some coastal odontocete species.[206] Over the past 50 years, increased shipping has contributed an estimated 32-fold increase in the low-frequency sound present along major shipping routes.[207]

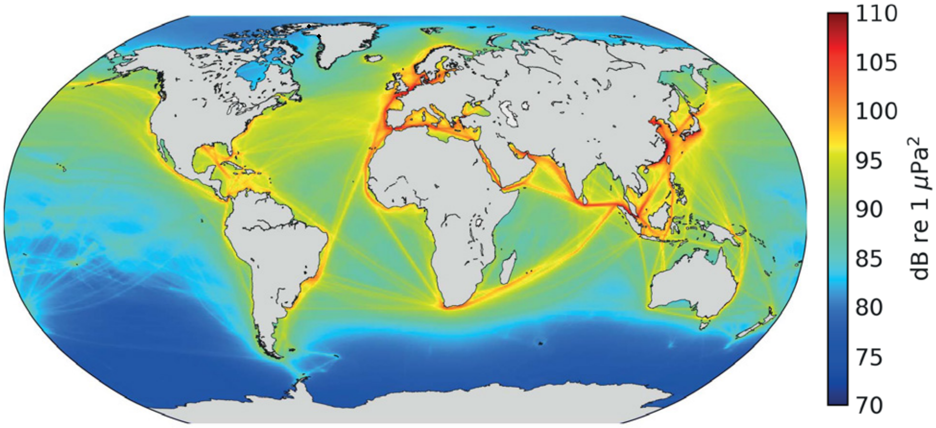

Figure 1. Average sound level estimated globally from marine traffic (at 100 Hz), based on average shipping activity directed from automatic identification system (AIS) data for 2014 (Source: image extracted from Duarte et al., 2021).[208]

Long-term measurements of ocean ambient sound have been undertaken in the North Pacific and Indian Ocean. These studies have revealed that low-frequency anthropogenic underwater sound has been increasing in these oceans, primarily due to sound produced by commercial shipping.[209,210,211] It is reported that, globally, low-frequency ambient sound has increased by at least 20 dB from pre-industrial conditions to 2009,[212,213] although the rate of increase has slowed in some regions in the last decade.[214] Decreases in low-frequency sound levels have been reported in other areas, such as the Northeast Pacific, Equatorial Pacific and South Atlantic Ocean.[215] Therefore, changes to the underwater sound levels across the globe are not uniform. Variations that have been found in studies primarily relate to the extent of vessel movements, but also technological improvements and other mitigation strategies to quieten ships in some places over time.[216]

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3. SOURCES AND TYPES OF UNDERWATER ANTHROPOGENIC NOISE

Many studies have considered, and in some instances quantified, the extent of anthropogenic noise production in the marine environment from various sources.[1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41]

Such research has provided information that relates to field measurements, nominal levels and back-calculations, as well as specific baseline conditions where measurements have been taken. Figure 2 and Table 1 use information provided in recent literature to provide a general indicative guide for ranges and peak levels of sound pressures that are generated from anthropogenic sources. Such information provides a useful guide to provide a comparison of sound pressure levels with ambient conditions, noise exposure criteria and frequency overlap with the frequency hearing ranges of marine animals.

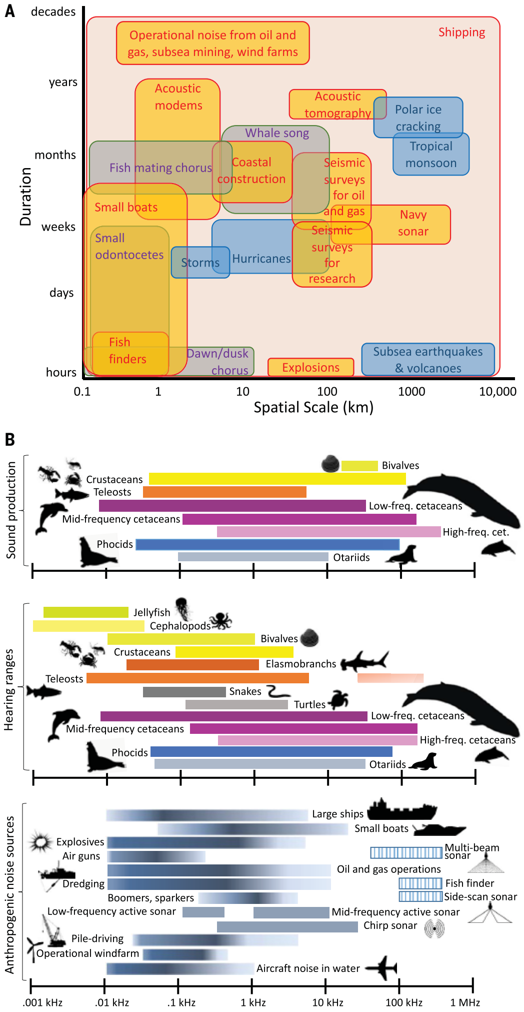

Figure 2. Anthropogenic sound and overlap with hearing and sound production for marine wildlife (Source: Duarte et al., 2021).[42] (A) showing the spatial extent and duration of different sound sources and (B) showing the approximate sound production and hearing ranges of selected anthropogenic sound sources.

Table 1. Main sources of anthropogenic sound in the marine environment and indicative values (Source: Prideaux, 2017).[43]

Sound	Sound Intensity Level (dB re1 µPa)	Bandwidth	Major Amplitude	Duration	Directionality
Military					
Military low-frequency active sonar	240 Peak @ 1m	<1kHz- 1khz	[unknown]	600-1,000ms	Horizontally focused
Military mid-frequency active sonar	235 Peak @ 1m	1-5kHz	[unknown]	1-2s	Horizontally focused (3 degrees down)
Continuous active sonar	182 Peak @ 1m	500Hz – 3kHz	[unknown]	18 seconds	Horizontally focused
Military mine counter measures sonar	[unknown]	100kHz-500kHz	[unknown]	[unknown]	[unknown]
Seismic Surveys					
Seismic surveys	260-262 Peak to Peak @ 1m	10Hz-150kHz	10-120Hz also 120dB up to 100kHz	30-60ms	Vertically focused
Civil High-Power Sonar					
Single beam sounders	240 Peak @ 1m	12kHz-700kHz depending on the application	[unknown]	0.1ms	Vertically focused
Sidescan sonar	240 Peak @ 1m	12kHz-700kHz depending on the application	[unknown]	0.1ms	Vertically focused fan spread
Multibeam echosounders	240 Peak @ 1m	12kHz-30kHz, 70kHz-200kHz, 300kHz-500kHz depending on the application	[unknown]	0.1ms	Vertically focused fan spread
Sparkers and boomers	204-220$_{\text{rms}}$ @ 1m	80Hz-10kHz	[unknown]	0.2ms	[unknown]
Chirps	210-230 Peak @ 1m	20Hz-20kHz	[unknown]	250ms	[unknown]
Coastal and Offshore Construction Works					
Explosions, TNT 1-100lbs	272-287 Peak @ 1m	2Hz-~1,000Hz	6-21Hz	<1-10ms	Omnidirectional
Pile driving	248-257 Peak to Peak @ 1m	20Hz-20kHz	100Hz-500Hz	50ms	Omnidirectional
Dredging	168-186 $_{\text{rms}}$ @ 1m	20Hz-1kHz	500Hz	Continuous	Omnidirectional
Offshore Platforms					
Platform drilling	150 $_{\text{rms}}$ @1m	30Hz-40Hz	[unknown]	Continuous	Omnidirectional
Drill ships (including maintenance)	190 $_{\text{rms}}$ @ 1m	10Hz-10kHz	[unknown]	Continuous	Omnidirectional
Positioning transponders	100 $_{\text{rms}}$ @ 2km	20kHz – 35kHz	[unknown]	Continuous	Omnidirectional

Table continues on next page

Sound	Sound Intensity Level (dB re1 µPa)	Bandwidth	Major Amplitude	Duration	Directionality
Playback and Sound Exposure Experiments					
Ocean tomography	165-220 Peak @ 1m	50Hz-200Hz	[unknown]	[unknown]	Omnidirectional
Shipping and Vessel Traffic					
Small vessels	160-180 $_{\text{rms}}$ @ 1m	20Hz-10kHz	[unknown]	Continuous	Omnidirectional
Medium vessels	165-180 $_{\text{rms}}$ @1m	Below 1kHz	[unknown]	Continuous	Omnidirectional
Large vessels	Low Frequency 180-190 $_{\text{rms}}$ @ 1m High Frequency 136 $_{\text{rms}}$ @ 700m	Low Frequency a few hundred Hz High Frequency 0.354khz-44.8khz	[unknown]	Continuous	Omnidirectional
Pingers					
Acoustic navigation beacons	160-190 Peak @ 1m	8kHz-16kHz	[unknown]	[unknown]	Omnidirectional
Acoustic deterrent devices	130-135 Peak @ 1m	9kHz-15kHz	[unknown]	100-300ms	Omnidirectional
Acoustic harassment devices	190 Peak @ 1m	5khz-20kHz, 30kHz-160kHz depending on the application	[unknown]	[unknown]	Omnidirectional
Other Sound-generating Activities					
Acoustic data transmission	185-196 @ 1m	18kHz-40kHz	[unknown]	[unknown]	Omnidirectional
Offshore tidal and wave energy turbines	165-175 $_{\text{rms}}$ @ 1m	10Hz-50kHz	[unknown]	Continuous	Omnidirectional
Wind turbines	90-112 $_{\text{rms}}$ @ 110m	50Hz-20kHz	[unknown]	Continuous	Omnidirectional

EXPLOSIVES

Explosives are used for several purposes in the marine environment, including construction, the removal of unwanted structures, military ship shock trials that test how ships handle undersea explosions, military warfare or practice, and, although now illegal in many regions, the small-scale use of charges to deter marine mammals (seal bombs), catch fish (blast fishing) or for coral mining.[44] Underwater explosions are one of the strongest point sources of anthropogenic noise in the marine environment.[45,46] For example, the large number of explosives used in naval ship shock trials can produce a total source level (SL) of more than 300 dB. Noise from explosions propagates equally in all directions and can be detected over great distances, including across ocean basins.[47,48] Underwater transmission of explosions is complex, with an initial shock pulse followed by a succession of oscillating bubble pulses. Source levels can vary with the type and number of explosives used and the water depth at which the explosion occurs, and usually range from 272 to 287 dB re 1 µPa zero to peak at 1 m distance (1–100 lb. TNT) with a frequency range of 2- ~1000Hz for a duration of <1-10ms. The core energy is between 6-21Hz.[49,50,51]

INDUSTRIAL ACTIVITIES

Industrial activities include pile driving for construction of coastal and marine facilities; dredging (to maintain shipping lanes, extract geological resources, such as sand and gravel, and to route seafloor pipelines, and lay submarine cables); drilling (for pile installation and hydrocarbon exploration); nearshore mining; and the construction and operation of offshore renewable energy and hydrocarbon production facilities.[52] In the future, deep-water seabed mining has the potential to generate greater underwater noise than nearshore mining,[53] and sound will arise from support vessels on the sea surface and from machinery on the seabed, such as remotely operated vehicles.[54] Some activities are planned to operate on a non-stop basis, which will substantially increase ambient sound levels,[55] but actual sound characteristics of the mining equipment in operation at depth are not known at this time.[56]

The industrial activities provide both impulsive and non-impulsive sound sources. They typically produce underwater sound that has the most energy at low frequencies (20 – 1000 Hz).[57] As well as sound pressure, many industrial sources of anthropogenic sound also likely cause vibration within the seabed by direct means (e.g., contact with the sediment) or indirectly (propagation via the water column),[58] leading to particle motion impacts, as previously mentioned.

Of these activities, impact piling is known to lead to the highest levels of sound pressure production, but other activities can also generate relatively high levels of sound that lead to adverse impacts on marine wildlife. Pile driving is used for a variety of nearshore and offshore developments, including for example, port and harbour works, bridge construction, oil and gas platform installations, and in the construction of offshore wind farm foundations. Source levels can vary depending on the diameter of the pile, the method of pile driving (impact piling driven by hammer or vibratory installation, known as vibropiling),[59] and site-specific influencing factors (e.g., sediment resistance and water depth).[60] Impact driving and larger pile sizes will generally lead to higher levels of sound. Vibropiling also produces continuous signals whereas impact piling is impulsive. Monitoring studies have been completed to determine the level of underwater sound generated from the piling of offshore wind farm structures. Degraer et al. (2012)[61] reported that the piling of 5 m monopiles at Bligh Bank produced sound levels of 179-194 dB re 1µPa as measures and normalized distance of 750 m from the piling location. Sound pressure levels from piling have been reported to reach around 250 dB re 1 µPa peak to peak at 1m.[62] The frequency spectrum ranges from less than 20 Hz to more than 20 kHz with most energy around 100–200 Hz.[63]

Drilling is done from natural or built islands, platforms and drilling vessels (semi-submersibles and drilling ships), producing almost continuous sound. Underwater sound levels from natural or built islands have been reported to be moderate (SL ~ 145 dB re 1 µPa at 1 m or less)[64] with the main frequency content below 100 Hz.[65] Sound from fixed drilling platforms is slightly lower, e.g., 115–117 dB re 1 µPa at 405 and 125 metres, respectively.[66] Drilling from drill-ships produces the highest levels of sound pressure, with a maximum broadband source level of about 190 dB re 1 µPa rms at 1 m (10 Hz–10 kHz).[67] The ships use thrusters to remain in position, resulting in a mixture of propeller and drilling sounds.[68] Jimenez-Arranz et al. (2019)[69] reported sound generated by a Mobile Offshore Drilling Unit (MODU) in deep waters of the North Atlantic. Results showed that the MODU is a primarily low-frequency source (90 per cent of the emitted acoustic energy concentrated below 250 Hz) with tonal components in the kHz range and an average broadband sound level of 118 dB re µPa within 1 km. In another study, well head (choke valves) were recorded as producing continuous sound levels of 159 dB re 1 µPa @ 1m $_{\text{rms}}$ from the source.[70,71]

Dredging in the marine environment is undertaken to maintain shipping lanes, extract geological resources, such as sand and gravel, and to route seafloor pipelines. The activity emits continuous broadband sound during operations, mostly in the lower frequencies. One study estimated source levels ranged from 168 to 186 dB re 1 µPa at 1 m $_{\text{rms}}$ (maximum ~ 100 Hz) with a bandwidth between 20 Hz and 1 kHz.[72,73] Measurements of the sound spectrum levels emitted by an aggregate dredger show that most energy was below 500 Hz.[74] Grab dredging has been recorded as producing 124 dB re 1µPa @150m[75] and trailing suction hopper dredging (THSD) at 139 dB re 1µPa @ 430m, 142 dB re 1µPa at 930 m, 131 dB re 1µPa @ 1500 m and 144 dB re 1µPa @ 250 m.[76,77] Measurement of source levels of a TSHD dredger operating on the Hastings Shingle Bank[78] calculated the broadband source level at 186 dB re 1 µPa at 1 m, which is consistent with the source levels reported by Richardson et al. (1995)[79] and Greene (1987).[80] Thomsen et al. (2009)[81] reported that a source level 187 dB re 1 µPa at 1 m when determining the effects of THSD dredging is appropriate. Greene (1987)[82] calculates the underwater sound generated from a cutter suction dredger (CSD) as between 168 and 178 dB re 1µPa. Clarke et al. (2002)[83] reported a sound level of 112 dB µPa at 500 m for an operating CSD.

Offshore wind farms also create low source levels of sound during their operation.[84,85] Operational source levels of offshore wind farms depend on the foundation type, size, environmental conditions (i.e., depth, topography, sediment structure, hydrography), wind speed and probably also the size of the wind farm.[86] Underwater sound during operation originates from moving mechanical parts in the nacelle emitted at low frequency levels below 1 kHz.[87] Other sources of sound may also include wind induced vibration of the tower. Tougaard et al. (2020)[88] provided sound pressure level measurements at different distances from the source. The highest level of sound reported was 137 dB re 1µ Pa at 40 m, and most measurements were between 100 and 130 140 dB re 1µ Pa at 10-200 m from the source.

Tougaard et al.[89] also provided a summary of sound sources from other offshore renewables, which is summarized here. Offshore tidal and wave energy turbines are a relatively recent technological development that can also contribute to the soundscape where they are developed.[90] Monitoring of a tidal turbine (axial-flow, high solidity) operated by OpenHydro in the English Channel (Brittany, France) at distances between 100 and 2400 m identified a maximum source level of 152 dB re 1 µPa at 1 m in the 128 Hz decidecade band, and all other decidecade source levels fell below 137 dB re 1 µPa at 1 m.[91] The frequency of sound emitted was 40 Hz to 8 kHz. Other measurements on tidal turbines have identified a SPLs of <110 dB re 1 µPa at a frequency of approximately 300 Hz.[92] Monitoring of a wave energy device in Falmouth Bay (England) determined that sound generated from the device was undetectable at a 200 m distance.[93] At the same site, another study reported that at 100m SPLs were centred around 115 dB re 1µPa and ranged from 105 to 125 dB re 1 µPa.[94] Risch et al. (2020)[95] measured underwater sound transmission from a tidal stream turbine in the Pentland Firth (Scotland). They reported that most sound was concentrated in the lower frequencies, ranging from 50 to 1000 Hz; within 20 m of the turbine sound pressure levels were elevated by up to 40 dB, and at 2300 m, sound pressure levels were over 5 dB higher than ambient sound levels.

SEISMIC SURVEYS

Marine seismic surveys are primarily used by the oil and gas industry for exploration but are also used for other types of research purposes. Seismic surveys involve directing a high energy sound pulse into the sea floor and measuring the pattern of reflected sound waves. The energy penetrates several metres below the surface and can extend up to 100 km into the ocean floor.[96] A range of sound sources may be used depending on, amongst other things, the depth of penetration required. These include airguns, sparkers, boomers, pingers and "compressed high-intensity radiated pulse (CHIRP) sonar".[97] The main sound-producing elements used in oil exploration are airgun arrays, which are towed from marine vessels.[98] Airguns release a volume of air under high pressure, creating a sound wave from the expansion and contraction of the released air bubble.[99] To yield high acoustic intensities, multiple air guns (typically 12 to 48) are fired with precise timing to produce a coherent pulse of sound. During a survey, guns are fired at regular intervals (e.g., every 10 to 15 seconds), as the towing source vessel moves ahead. The duration of activities depends on the specific needs for acquiring data, but can be days, weeks, or months.[100] Seismic airguns generate low-frequency sound pulses. Most of the energy from airgun arrays occurs in the frequency range of 10–100 Hz, although the source spectrum typically extends to over 2200 Hz.[101] The low-frequency energy (10 to 120 Hz) is mainly focused vertically downwards, but higher frequency components are also radiated horizontally. Sound signals from seismic airgun surveys can be received thousands of kilometres away from the source if spread in a sound channel. Autonomous acoustic seafloor recording systems on the central mid-Atlantic Ridge showed year-round recordings of airgun pulses from seismic surveys conducted more than 3000 km away.[102] Moore et al. (2012)[103] also reported sounds in Fram Strait, off northeastern Greenland, year-round, even during the winter when the area was ice covered and no seismic exploration was being conducted locally. These sounds were, however, recorded under specific environmental conditions. Low-frequency energy can also travel long distances through bottom sediments, re-entering the water far from the source.[104] The nominal source level of an airgun array can reach up to 260-262 dB (p-p) re 1 µPa @ 1m.[105,106]

Sparkers and boomers are high-frequency devices that are generally used to determine shallow features in sediments. These devices may also be towed behind a survey vessel, with their signals penetrating several hundred (sparker) or tens (boomer) of metres of sediment due to their relatively higher frequency spectrum and lower transmitted power. Typical source levels can be 204–210 dB (rms) re 1 μPa @ 1 m.[107] Chirp sonars also produce sound in the upper frequency range of seismic devices (approx. 0.5 to 12 kHz). The peak source levels from these techniques are lower than nominal values for air gun arrays. However, these techniques still create relatively high sound levels. The peak source level for these devices is about 210 – 230 dB re 1 μPa @ 1 m.[108]

SONAR

The use of acoustic energy for locating and surveying is described as active sonar. Sonar was the first anthropogenic sound to be deliberately introduced into the oceans on a wide scale. There are a variety of types of sonars that are used for both civilian and military purposes. They can occur across all sound frequencies and are divided in this section into low- (<1 kHz), mid- (1 to 10 kHz) and high-frequency (>10 kHz). Military sonars use all frequencies while civilian sonar uses some mid- but mostly high-frequencies (although broadband acoustics systems are becoming increasingly common for civilian systems). Except for military sonar, most types of sonar operate at one frequency of sound, but generate other unwanted frequencies (e.g., harmonics of the fundamental frequency due to non-linear processes). These extraneous lower intensity frequencies are rarely described in detail but are thought to possibly have wider effects than the main frequency used, especially if they are at low frequencies, which propagate further underwater.[109]

Low-frequency sonar

Low-frequency active (LFA) sonars are used for broad-scale military surveillance, designed to provide the sound source over scales of hundreds of kilometres for other passive listening platforms to detect submarines.[110] Specialized support ships are used to deploy LFA sonars, which consist of arrays of source elements suspended vertically below the ship. For example, the United States Navy's Surveillance Towed Array Sensor System (SURTASS) LFA sonar uses an array of up to 18 projectors operating in the frequency range from 100 to 500 Hz, with a 215 dB re 1 μPa @ 1 m source level for each projector.[111] These systems are designed to project beams of energy in a horizontal direction, with a vertical beam width that can be steered above or below the horizontal. The signal includes both constant-frequency (CF) and frequency-modulated (FM) components with bandwidths of approximately 30 Hz.[112] The signal consists of various waveforms that vary in frequency and duration. A ping sequence (a continuous sequences of waveforms) can last 6 to 100 seconds with an average length of 60 seconds, but the duration of continuous sound transmission in each sequence is 10 seconds. The time difference between ping sequences is 6 to 15 minutes and a typical duty cycle of 10 per cent. Signal transmissions are emitted in patterned sequences that may last for days or weeks. As of September 2018, there were four ships operating LFA sonar systems in the U.S. military: one with the original LFA system and three vessels with the compact LFA system (CLFA).[113]

Mid-frequency sonar

Military mid-frequency sonars at high source levels are used for detecting submarines at moderate range (<10 km). For example, a US Navy hull-mounted system (AN/SQS-53C) sonar system uses pulses in the 2 – 10 kHz range (normally 3.5 kHz) and usually operated at source levels of 235 dB re 1 μPa @ 1m, although higher levels were recorded for a short period. Another US Navy system (AN/SQS-56) uses this same frequency band but with lower source levels (223 dB re 1 μPa @ 1m).[114] These systems are used in offshore waters, but also scan shallower inshore environments to detect submarines that can operate closer to shore.[115]

Some non-military sonars also operate in the mid-frequency band. Bathymetric sonars use these frequencies for wide-area, low resolution surveys. For example, the Fugro Seafloor survey model SYS09 uses both 9 and 10 kHz transducers operated at 230 dB re 1 μPa at 1m.[116] Sub-bottom profilers produce a mid-frequency (3 to 7 kHz) and high source level (230 dB re 1 μPa at 1 m) pulse, to map seafloor sediment layers and buried objects.[117]

High-frequency sonar

Military high-frequency sonars are used in attacking or defending systems and are designed to work over hundreds of metres to a few kilometres.[118] These sonars use a wide range of modes, signal types and strengths. As with other military sonars, their reported usage is generally within exercise areas, but they are also used outside of these areas. Scanning sonars and synthetic aperture sonars are used for harbour defence, underwater search and recovery,[119] and high intensity seabed mapping (side-scan sonar). Frequencies between 85 and 100 kHz are used for human diver/swimmer detection, while 100 kHz is optimal for obtaining a high resolution of seabed features, including benthic cover. Hydroacoustic sonars are used to detect the presence of living organisms and particles in oceans, lakes, and rivers.[120] By transmitting sound at high frequencies (20 to 1000 kHz), hydroacoustic sonars can detect individual objects or aggregates, such as schools of fish, in the water column.[121]

Civilian and commercial sonars operating at high frequencies are used for detection, localization and classification of various underwater targets (e.g., the seabed, plankton, fish, divers).[122] These sonars generally produce sound at lower source levels with narrower beam patterns and shorter pulse lengths than military sonars but are more widespread due to the large number of commercial and recreational vessels that are equipped with sonar.[123] Such vessels operate mostly in shallow shelf-seas, and sonar usage occurs continuously throughout the year, both during the day and at night. Most of the systems focus sound downwards, though some horizontal fish finders are available. Fish-finding sonars typically operate at frequencies between 24 and 200 kHz. Some horizontally acting fish- finding sonars are thought to be relatively powerful. For example, the Furuno FSV-24 sonar operates at 24 kHz and can detect and track shoals of tuna up to 5 km away.[124] Bathymetric mapping sonars use frequencies ranging from 12 kHz for deep-water systems to 70-100 kHz for shallow-water mapping systems.[125] Multibeam sonars operate at high source levels (e.g., 245 dB re 1 µPa at 1 m) but have highly directional beams.[126]

Continuous active sonar

Recent advances in naval sonar and signal processing technologies allow for simultaneous transmission and listening (continuous active sonar, CAS).[127] CAS has lower source-level amplitudes than traditional pulsed active sonar), but potentially with greater cumulative sound energy as it allows for greater duty cycle (percentage of time with active transmission) leading to near-continuous illumination of a target and therefore more detection opportunities.[128,129] CAS operates between the 500Hz to 3KHz range with sound intensity levels typically 182 dB in water at 1m, peak value, (182 dB re 1µPa @ 1m peak) with a signal duration of 18 seconds.[130]

SHIPS AND SMALLER VESSELS

Large commercial vessels (greater than 100 m in length, e.g., container/cargo ships, super-tankers, cruise liners)

Large commercial vessels produce relatively loud and predominately low-frequency sounds. Source levels are generally in the 180–195 dB (re: 1µPa) range with peak levels in the 10 – 50 Hz frequency band.[131,132,133] The propulsion systems of large commercial ships are a dominant source of radiated underwater sound at frequencies <200 Hz.[134] Individual vessels produce unique acoustic signatures, although these signatures may change with ship speed, vessel load, operational mode and any implemented sound-reduction measures.[135,136]

Most of the acoustic field surrounding large vessels is created by propeller cavitation (when vacuum bubbles created by the motion of propellers collapse), causing ships at their service speed to emit low-frequency tonal sounds and (high-frequency) sound spectra up to tens of kHz quite close to vessels.[137] Smaller, but potentially significant, amounts of radiated sound can arise from on-board machinery (engine room and auxiliary equipment).[138] Hydrodynamic flow over the ship's hull and hull attachments is an important broadband sound-generating mechanism, especially at higher speeds.[139] There are also significant depth and aspect-related elements of radiated vessel sound fields as a function of shadowing and the Lloyd's Mirror effect (LME, where the air/water interface reflects the sound wave, and the reflection has an opposite polarity of the original wave) near the surface of the water.[140] Source (propeller) depth is also important in terms of long-range propagation. Large vessels are near-field sources in both offshore (in shipping routes and corridors) and coastal waters (mainly in traffic lanes, waterways/canals, or ports). Due to their loud, low-frequency signatures, large vessels dominate low-frequency background sound in many marine environments worldwide.[141,142] Modern cargo ships can also radiate sound at high frequencies, with source levels over 150 dB re 1µPa at 1m around 30 kHz.[143] Vessel sound from a range of different ship types recorded at four locations in Danish waters in 2012 elevated ambient sound levels across the entire recording band from 0.025 to 160 kHz at ranges between 60 and 1000m.[144]

Medium-sized vessels (length 50–100 m, e.g., support and supply ships, many research vessels)

Tugboats, crew boats, supply ships and many research vessels in the medium-sized category typically have large, complex propulsion systems, often including bow-thrusters.[145] Many fishing vessels also fall within this category. Typical broadband source levels for small- to mid-size vessels are generally in the 165–180 dB (re: 1µPa) range.[146,147] Most medium-sized ships are like large vessels in that most of the sound energy is low-frequency band (<1 kHz). While broadband source levels are usually slightly lower for medium-sized vessels than for the larger commercial vessels, there are some exceptions (e.g., as a function of age or maintenance of the ship), and medium-sized ships can produce sounds of sufficient level and frequency to contribute to marine ambient sound in some areas.[148] Mid-sized vessels spend most of their operational time in coastal or continental shelf waters and overlap in time and space with marine animals.

Small vessels (length up to 50 m, e.g., recreational craft, jet skis, speed boats, operational work boats)

Small boats with outboard or inboard engines produce sound that is generally highest in the mid-frequency (1 to 5 kHz) range with source levels of 150 to 180 dB re 1 µPa @ 1 m), although the output characteristics can be highly dependent on speed.[149,150,151] Source spectra for small craft and boats include tonal harmonics at the resonant vibrational frequencies of propeller blades, engines, or gearboxes below about 1 kHz, as well as significant energy resulting from propeller cavitation extending up to and above 10 kHz. Due to the generally higher acoustic frequency and near-shore operation, sound from smaller vessels is regarded as having more geographically limited environmental impacts in that it does not extend far from the source. Small craft and boats can dominate some coastal acoustic environments at certain times, particularly partially enclosed bays, harbours and/or estuaries.[152] In fact, recreational vessels have been identified as the most important contributor to mid-frequency ambient sound in some coastal habitats.[153]

ACOUSTIC HARASSMENT AND DETERRENT DEVICES

Acoustic harassment devices (AHDs) have historically been deployed to prevent pinniped predation on finfish farms, fisheries or salmon runs through the production of high source level acoustic signals.[154] Within marine aquaculture, AHDs are attached to cages and can be set to run continuously. Due to their relatively high source level and often broadband characteristics, AHDs can potentially be a significant source of underwater sound in areas of dense fish farming and can be widely detected above ambient conditions.[155] AHDs can also be used during offshore wind farm foundation piling as a mitigation tool. A variety of AHD types exist, and they differ significantly in their acoustic characteristics (e.g., frequency range, amplitude, and duty cycle). ADDs generate high and intensive sounds in the range of 2 to 40 kHz, with source levels ≥185 dB re 1 µPa @ 1 m RMS.[156]

Acoustic deterrent devices (ADDs) are generally used to displace marine animals or to deter small cetaceans from bottom-set gillnets or other fisheries to reduce bycatch and incidental mortality. ADDs operate at lower source levels than AHDs—usually 130 to 150 dB re 1 µPa.[157] The frequencies range from 9-15kHz for a duration 100-300ms every 3-4 seconds.[158] Acoustic characteristics of ADDs differ from AHDs particularly with respect to randomization of pulse intervals and pulse duration. However, the signal structure and source levels of pingers can be relatively consistent when they must comply with national or regional guidelines (e.g., EU Council Regulation (EC) No 812/2004). Devices falling under this regulation are known to produce either 10 kHz tones or wide-band sweeps covering a frequency range from 20 to 160 kHz. Such ADDs that are based on analogue signal generation emit tones (10 kHz) at source levels (broadband) between 130 and 150 dB re 1 μPa, while digital devices can either have the same specifications or produce wideband sweeps at broadband source levels of 145 dB 1 μPa.[159]

Fish deterrent devices (FDDs) are mainly used in coastal or riverine habitats to temporarily displace fish from areas of potential harm (e.g., guiding them away from water intakes of power plants).[160] There is considerable variation between devices in terms of the frequency range which depends on the fish species to be targeted. If the device needs to be effective against a broad range of species, relatively low or infrasonic frequencies are generally used. For example, some devices produce infrasound at frequencies of about 10 Hz[161] or between 20 and 600 Hz.[162] Other devices produce primarily ultrasonic frequencies and are specifically designed to deter high-frequency hearing specialists. FDDs for clupeid species, some of which have ultrasonic hearing, operate at frequencies between 120 kHz and 130 kHz, with source levels up to 190 dB.[163] FDDs generally produce sequences of short pulses (e.g., 100–1000 ms^{-1}) at intervals of one to several seconds and duty cycles up to 50 per cent.[164]

OTHER ANTHROPOGENIC SOURCES

Research sound

Ocean science studies use a variety of different sound sources to investigate the physical structure of the ocean, for example, seismic airgun arrays and multibeam echosounders. Ocean tomography studies measure the physical properties of the ocean using sound sources with frequencies between 50 and 200 Hz and high source levels (165–220 dB re 1 μPa). The "Heard Island Feasibility Test" projected signals with centre frequencies of 57 Hz in the 'SOFAR channel' (175 m depth) at source levels up to 220 re 1 μPa.[165] The signals could be detected across ocean basins with received levels up to 160 dB re 1 μPa at 1 km distance. The subsequent "Acoustic Thermometry of Ocean Climate" (ATOC) research programme was initiated in the early 1990s to study ocean warming across the Pacific basin.[166] The ATOC sound source emitted coded signals at four-hour intervals at source levels of 195 dB re 1 μPa for up to 20 minutes with a 5-minute ramp-up period.[167] The mobile Ocean Acoustic Waveguide Remote Sensing (OAWRS) experiment in the Gulf of Maine was used to image fish shoals over a 100 km diameter area. It has been reported that sound from this experiment was recorded more than 200 km away.[168]

Research projects also use sound to estimate current speed and direction by using drifting sources called SOFAR floats.[169] These devices drift at depth and periodically emit a high-intensity tone (195 dB re 1 μPa at 1 m) between 185 and 310 Hz. The sounds are detected by distant receivers. and their timing is used to determine the float location and therefore the distance drifted as a proxy for deep currents.[170]

Icebreakers

Ice-breaking ships are a source of sound in polar regions and typically have a higher source level than more common vessel activity due to the act of breaking the ice by ramming into it, specialized equipment used to break the ice and unique propeller cavitation.[171,172,173]. Some ships are equipped with bubbler systems that blow high-pressure air into the water around the ship to push floating ice away. The sound is continuous while the bubbler system is operating, with a broadband spectrum below 5 kHz. A source level of 192 dB re 1 μPa at 1 m has been reported for bubbler system sound. Icebreaker propeller cavitation sound is generated due to the episodic nature of breaking ice, which often involves manoeuvres such as backing-and-ramming into the ice.[174] The spectrum of propeller cavitation sound is broadband up to at least 20 kHz and has a source level of 197 dB re 1 μPa at 1 m.[175,176] As documented by PAME (2019),[177] some studies have been undertaken to measure underwater sound levels from ice-breaking activities. Erbe and Farmer (2000)[178] measured high source levels from an ice breaker in the Beaufort Sea, ranging between 189 and 205 dB (based on different percentiles and ice-breaking activities) between 100 Hz and 20 kHz. Roth et al. (2013)[179] measured the source level of an icebreaker in the Arctic Ocean far north of Alaska, and measured source levels between 190 and 200 dB_{rms} in the octave bands centred on 10, 50 and 100 Hz. One other Arctic study measured the source level of one research vessel in the eastern Beaufort Sea,[180] and the source level between 63 Hz and 20 kHz was 176 dB_{rms}. Geyer et al. (2016)[181] found that propeller cavitation and ice breaking activity from 100 km away elevated ambient levels by 10 to 28 dB between 5 and 1950 Hz.

Acoustic telemetry

Acoustic telemetry is used for underwater communications, remote vehicle command and control, diver communications, underwater monitoring and data logging, trawl net monitoring and other industrial and research applications requiring underwater wireless communications.[182] For seafloor monitoring, acoustic modems are used as an interface for subsurface data transmissions, sending data using modulated acoustic signals between seafloor instruments and surface buoys. Long-range systems can operate over distances of up to 10 km using frequencies of 7 to 45 kHz, at source levels of up to 190 dB re 1 μPa @ 1 m. An integrated communications project is the "Acoustic Communication Network for Monitoring of Underwater Environment in Coastal Areas (ACME)". This system uses chirps of continuously varying frequencies and frequency-shift keying sound covering a frequency range of 5–15 kHz.[183]

Activities above water

Sound that is generated above water can also transmit to the marine environment, e.g., from coastal vehicle movements and aircraft. Leon-Lopez (2021)[184] reported measured levels of sound in a coastal lagoon near a popular tourism location in Mexico. They reported that low-frequency sound corresponded with vehicle traffic during different periods, and that this sound was most likely from roadway sound, both structure-borne and air- borne (band 10–2000Hz). Levels of around 108 dB were recorded, as were reductions with reduced traffic movements because of confinement during the COVID-19 pandemic. Aircraft produce sound in the air; however, sound can transmit into water directly below.[185] This includes low-flying aircraft (such as that used for research) and commercial aircraft at higher altitudes. Erbe et al. (2018)[186] reported on the potential for sound generated by aircraft to be transmitted to the underwater soundscape. They reported that commercial passenger airplanes were recorded in a coastal underwater soundscape exhibiting broadband received levels of 84–132 dB re 1 μPa rms; and that power spectral density levels of underwater sound from aircraft exceeded ambient levels between 12 Hz and 2 or 10 kHz (depending on site) by up to 36 dB, sometimes exceeding 120 dB re 1 μPa (broadband, root-mean-square).

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4. KNOWN AND POTENTIAL IMPACTS OF ANTHROPOGENIC UNDERWATER NOISE

INTRODUCTION

This report does not seek to provide detailed advice on how to undertake environmental impact assessments or strategic environmental assessments that may be required to assess the effects of anthropogenic underwater noise. Detailed guidance for such assessments can be found in other guidance documents, such as Faulkner et al. (2018),[1] Prideaux (2015[2], 2017[3]), Nowacek and Southall (2016),[4] NOPSEMA (2020),[5] and IOGP/IPIECA (2020).[6] Farcas et al. (2016)[7] and Prideaux (2019)[8] have also provided guidance for underwater noise modelling for environmental impact assessments. This chapter focuses on providing an overview of current understanding of what impacts may arise from anthropogenic underwater noise.

Anthropogenic underwater noise is known to have a variety of direct, indirect and cumulative impacts on marine species, ranging from exposures that cause no adverse impacts, to significant behavioural disturbances, hearing loss and possible mortality. The potential effects depend on a number of factors, including the duration, nature and frequency of the noise, the received level (sound level at the animal), the overlap in space and time with the organism and noise source, and the context of exposure (i.e., animals may be more sensitive to noise during critical times, like feeding, breeding, spawning, or nursing/rearing young, and could have varying responses associated with multiple stressors or due to health).[9,10] Creating a synthesis of potential impacts is also complicated due to the variability in auditory capabilities across marine taxa. As already note in chapter 1, there remain uncertainties in the understanding of impacts. These may be associated with research gaps for some marine taxa and accurate quantification of extent of effects. However, despite these challenges, evidence has emerged to determine that underwater noise from anthropogenic activities leads to a range of adverse impacts on marine wildlife.

As previously noted, marine animals can be impacted by instantaneous high pressure sound waves and from the generation of particle motion. For sound pressure, the potential damage from instantaneous high pressure waves increases in a non-linear fashion with total acoustic energy received for a given type of stimulus.[11] Adverse impacts can be broadly divided into three categories: masking, behavioural disturbance and physical effects (hearing loss, injury and stress)[12] although there is some overlap between these categories. In extreme cases, intense noise can lead to mortality for some species, although this is limited across some marine taxa. The chronic and cumulative effects of anthropogenic noise on marine species and populations also requires attention.[13] The degree of cumulative effects will also depend on the mobility of marine organisms (and the noise sources). Highly mobile species may be able to avoid stationary noise, while more sedentary or sessile species will not be able to move away from a stationary noise source. Displacement may lead to both direct and indirect effects on the individuals affected and the habitat to which they are displaced. Issues associated with displacement are discussed in more detail below.

There have been several extensive reviews of the impacts of anthropogenic noise on marine organisms since concerns have been identified.[14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37, 38,39,40,41,42,43,44,45,46] The literature exploring the potential implications of underwater noise for all marine wildlife is vast and continually expanding. As such, knowledge continues to mature and evolve. The following sections provide a high-level overview of potential impacts reported for marine wildlife, along with key references for each group, as appropriate.

Shannon et al. (2016)[47] provided a synthesis of scientific literature that has examined the potential impacts from anthropogenic underwater noise (at that time). Of the 242 studies they reviewed, 88 per cent reported a statistically measured response to underwater noise exposure. Most of these studies found evidence of responses in vocal behaviour, movement and physiology. During the same period, Williams et al. (2015)[48] also reported on a review of literature that studied the impact of underwater noise. They reported that marine mammals were the most frequently considered group, with studies on invertebrates and marine turtles being less represented. Duarte et al.

(2021)[49] have reported on more recent advances in knowledge of impacts. They examined the robustness and consistency of the evidence of literature assessing the impacts of underwater noise on marine wildlife. Results from their research are presented in Figure 3, which shows that many studies identified the potential for significant adverse impacts on marine mammals, fishes and invertebrates, including impacts associated with animal behaviour, injury, mortality and productivity. The authors do not, however, explain how they defined what is considered "significant" in this context. Behavioural impacts were most reported in the literature they reviewed. Likewise, to Williams et al. (2015),[50] they reported that impacts on marine mammals were most studied, there was a paucity of quantitative assessments for marine reptiles and diving seabirds, and only a limited number of studies on pinnipeds and sirenians. They also reported that evidence was limited to support conclusions that changes in biophony resulting from habitat degradation reduce the settlement of marine larvae on preferred habitats. The evidence for impacts on animals exposed to multiple sources of anthropogenic noise was also small, limiting the understanding of cumulative impacts.

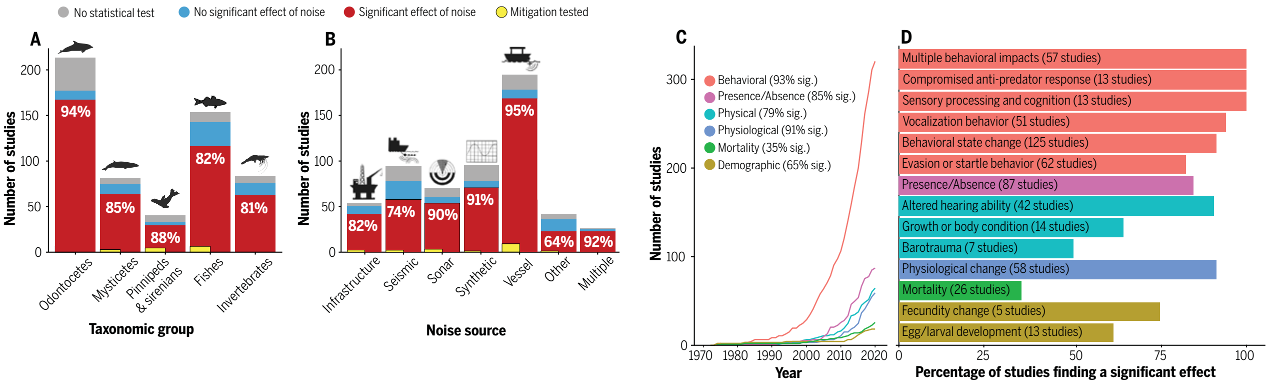

Figure 3. Synthesis of adverse impacts from anthropogenic underwater noise on marine mammals, fishes, and invertebrates (Source: Duarte et al., 2021).[51] (A and B) show the number of studies found spilt by taxa and underwater sound source; and red indicates a significant negative effect, blue indicates no significant effect, gey indicate no statistical test. (C) shows cumulative frequency curves over time of all studies. (D) shows the percentage of studies that found a significant effect of underwater noise for each subcategory.

NOISE EXPOSURE CRITERIA

One way to assess the impact from underwater sound generation resulting from anthropogenic activities is to set criteria for noise exposure that should not be exceeded. Exposure criteria or acoustic thresholds have been developed to predict the noise exposure levels above which adverse physical effects (i.e., injury) or behavioural harassment are expected. These criteria relate to sound pressure and have only been developed for marine mammals, fishes and marine turtles. The inherent limitations that are discussed above also have consequences for the development and utilization of these criteria. As previously discussed, many marine wildlife species are sensitive to particle motion, but there are no criteria to address such effects.[52] There is an urgent need to define noise exposure criteria for fishes and invertebrates in terms of particle motion as well as sound pressure, as it will be particle motion that they respond to in most instances.[53] Hawkins and Popper (2017)[54] set out a strong case for the use of criteria as part of the risk assessment process and for assessment against criteria to be used by governments to establish regulations, policies and guidance that specify those levels that are acceptable and those which should not be exceeded. They reported that "in practice, the sound exposure criteria selected in environmental impact assessments are often largely speculative and both the scientific and legal framework for establishing them is poorly defined." Further information on how regulatory frameworks may be improved can be found in papers produced by Lewandowski and Staaterman (2020)[55] and Colbert (2020).[56]

For marine mammals, noise exposure criteria relate to onset thresholds where there is potential for injury, including noise-induced hearing loss associated with either temporary or permanent auditory threshold shifts (TTS or PTS) in the sensitivity of an animal to all or part of its sonic frequencies, and levels that elicit behavioural responses.[57,58,59] For fishes and marine turtles, criteria were developed in 2014.[60] PTS results from non-recoverable damage to hair cell bodies or to their mechano-sensory cilia.[61] With the onset of TTS there is no long-term damage to hearing, but damage may occur that is recoverable. Increasing the exposure sound pressure level (SPL) and/or the sound duration results in greater levels of TTS until, at some level of exposure, a sufficiently severe shift in threshold occurs, which results in an incomplete hearing recovery.[62] Sometimes the shift from TTS to PTS can occur suddenly and unpredictably even when the experimental test sound stimulus is gradually increased, with unrecoverable PTS resulting.[63] Hearing losses can reduce the range for communication, interfere with the ability to forage, increase vulnerability to predators, and may cause erratic behaviour with respect to migration and mating, and could induce stranding.[64]

Threshold criteria for marine mammals

Initial scientific recommendations for marine mammals were published by the US National Marine Fisheries Service (NMFS) in 1995,[65] when precautionary exposure for levels of harassment from impulsive noise were presented. In 2007, exposure criteria were released based on assessment methods similar to those applied for humans.[66,67,68] Taxon were split into five categories according to the functional hearing abilities of different marine mammal groups. Criteria suggestions were only provided for injurious exposure and not for behavioural responses of marine mammals, although a qualitative, 10-step index for the severity of behavioural response was proposed. However, when the severity index was compared to reports of behavioural observations relative to the received sound level, the exposure sound level (e.g., dose-response approach) failed to reliably predict the probability of identified behavioural responses.[69,70] Southall et al. (2007)[71] recognized the limitations of their approach given data limitations, and the focus was on species under the jurisdiction of NMFS, which led to the exclusion of some species.

Following the evolution of knowledge for marine mammals, including the classification of species into hearing groups, further exposure criteria were developed by the US Navy in 2012 and the National Oceanic and Atmospheric Administration (NOAA).[72] In 2016, NOAA released technical guidance for assessing the effects of anthropogenic noise on marine mammals, including a revised set of acoustic threshold levels for the onset of permanent and temporary threshold shifts (PTS and TTS).[73] The exposure criteria were derived from quantitative methods reported by Finneran (2016)[74] using frequency weightings. The 2016 guidelines were subsequently updated with revisions in 2018.[75] The NOAA guidance identifies the received levels above which individual marine mammals are predicted to experience changes in their hearing sensitivity (either temporary or permanent) for all underwater anthropogenic noise. The guidance includes:

- A protocol for estimating Permanent Auditory Threshold Shift and Temporary Auditory Threshold Shift onset levels for impulsive and non-impulsive sources
- The formation of marine mammal functional hearing groups (a modified version of the groups recommended in 2007): low-, mid-, and high-frequency cetaceans, otariid and phocid pinnipeds
- The incorporation of marine mammal auditory weighting functions into the calculation of thresholds

No studies to determine PTS in marine mammals have been published. Most studies on injurious effects of underwater noise have been undertaken in laboratory experiments to uncover underwater noise characteristics that elicit TTS, and upon which PTS levels are extrapolated using growth rates.[76,77] PTS onset levels are therefore estimated rather than measured.

Southall et al. (2019)[78] provided updated recommendations for marine mammal exposure criteria in a peer-reviewed publication. This paper presented estimated audiograms, weighting functions and underwater noise exposure criteria for temporary and permanent auditory effects of noise for six species groupings, including all marine mammal species. The exposure criteria developed by Southall et al. (2019)[79] are identical to the latest NOAA guidance,[80] but there are notable distinctions. This includes a modified nomenclature for marine mammal hearing groups and phocid seals, and all other marine carnivores are now considered separately in terms of both underwater and aerial hearing. Southall et al. (2019)[81] also provided exposure criteria for sirenians (manatee and dugongs) based on a comprehensive review of all available data on direct measures of hearing, auditory anatomy and emitted noise characteristics for all marine mammal species.

The criteria provided by NOAA (2018)[82] and Southall et al. (2019)[83] for impulsive noise are provided using frequency weighted sound exposure level (SEL) and unweighted peak SPL, which can be used when considering SEL over time or absolute maximum SPL. Exceedance of either threshold is considered sufficient to result in the predicted TTS or PTS onset. For non-impulsive sources, NOAA (2018)[84] and Southall et al. (2019)[85] provided TTS onset thresholds using frequency weighted SEL criteria. Southall et al. (2019)[86] reasoned that is because non-impulsive sources are typically of relatively long duration and given the very high peak SPL values required to induce TTS/PTS, there are virtually no scenarios for which the SEL criterion would not be met prior to an exposure exceeding what would be the associated dual-metric peak SPL criteria. It is assumed that the SEL values will be calculated over the entire duration of a discrete exposure and/or will be cumulative over multiple repeated exposures that occur in sufficiently rapid succession. NOAA (2018)[87] provide weighted SEL_{cum} thresholds related to a cumulative exposure over the duration of an activity within a 24-hour period. Southall et al.[88] reported that although 24-hour intermittency period has been proposed to "reset" the SEL accumulation as a precautionary approach, in some instances, a shorter interval would be more appropriate in terms of considering multiple exposures as discrete events rather than continuing to accumulate sound energy.

The SEL metrics reported by NOAA (2018)[89] and Southall et al.(2019)[90] only account for the cumulative exposure to one source in the hearing range of an individual. They do not consider the cumulative or aggregate effect of multiple sources. NOAA (2018)[91] provided advice on how to combine multiple datasets and determine appropriate surrogates when little or no data exists.

Southall et al. (2019)[92] stated some important assumptions and limitations for the PTS and TTS thresholds that are proposed. They reported that the TTS and PTS thresholds are derived using median values of available data in several areas. However, they reported that impacts may relate to variability in susceptibility of individuals and the context of exposure scenarios. As such, single threshold criteria underestimate potential effects for some or in some scenarios and overestimate effects for others, the extent of each potential outcome depending on the degree of individual variability as well as key contextual aspects of exposure. The exposure criteria should therefore be used as a guide to predict the potential for PTS and TSS, but not used as an absolute. NOAA (2018)[93] also reported that thresholds do not represent the entirety of an effects analysis, but rather serve as one tool to help evaluate the effects of noise produced during a proposed action on a marine mammal. Other aspects that should be considered within an overall assessment of risk include behavioural impact thresholds, auditory masking assessments and evaluations to help understand the ultimate effects of an impact on an individual's fitness and on populations.

Threshold criteria for fishes and marine turtles

Interim exposure criteria for physical effects on marine fishes from pile driving were developed on the west coast of the United States of America over several years by the fisheries hydroacoustic working group (FHWG), as established by the California Department of Transport, and were published in 2008. Prior to this, NOAA used peak SPL to assess the risk of injury to fishes, but this metric did not consider the injury risk to non-auditory tissues in fishes with swim bladders.[94] Exposure guidelines for fishes and marine turtles from different sound sources were published in 2014.[95] A working group initiated by NOAA divided possible effects into three categories: mortal and potentially mortal effects, impairment (including recoverable injury, TTS, and masking) and behavioural changes. Exposure guidelines for effects are based on six different "animal" groups:

- Fishes lacking swim bladders that are sensitive only to sound particle motion and show sensitivity to only a narrow band of frequencies (e.g., flatfishes—Pleuronectiformes—and sharks skates and rays—Chondrichthyes)
- Fishes with a swim bladder where that organ does not appear to play a role in hearing. These fish are sensitive only to particle motion and show sensitivity to only a narrow band of frequencies. This group

includes salmonids (Salmonidae) and some tunas and mackerel (Scombridae), but many other species are likely to fit into this category as well.

- Fishes with swim bladders that are close, but not intimately connected, to the ear. These fishes are sensitive to both particle motion and sound pressure and show a more extended frequency range than groups 1 or 2, extending up to about 500 Hz. This group includes codfishes (Gadidae), eels (Anguillidae), some drums and croakers (Sciaenidae), and perhaps other fishes.
- Fishes that have special structures mechanically linking the swim bladder to the ear. These fishes are primarily sensitive to sound pressure, although they also detect particle motion. They have a wider frequency range, extending to several kHz and generally show higher sensitivity to sound pressure than do fishes in groups 1, 2, or 3. The group includes some of the squirrelfishes (Holocentridae), drums and croakers (Sciaenidae), herrings (Clupeidae), and the large group of Otophysan fishes
- Fish eggs and larvae
- Marine turtles

Whilst these interim criteria exist, Hawkins et al. (2020)[96] reported that until gaps in knowledge on some impacts are filled it is difficult to establish reasonable criteria that set out the levels of sound from different sources that could possibly adversely affect fishes. Popper et al. (2019a)[97] reported that determining sound exposure criteria for fishes is difficult as the levels of hearing loss will vary due to numerous factors, perhaps most important of which is the hearing sensitivity of fish, as well as the characteristics of the anthropogenic sound (duration, intensity, rise time, spectrum). They also reported that for TTS to occur, the level of the anthropogenic sound must be substantially above the hearing threshold of a fish for some extended period of time. Popper et al. (2019a)[98] reported that the 2014 guidelines provide conservative levels of sound, but they must be taken as extremely tentative because they are based on data from only three species, while TTS could not be induced in other species even with very high sound levels. Although limitations exist, Hawkins et al. (2020)[99] reported that a recent comprehensive review undertaken by Popper et al. (2019a)[100] concluded that there is nothing in the literature since 2014 that would markedly change the 2014 criteria. They concluded that the interim criteria proposed in the 2014 guidelines should be adopted until more data become available to update them. They reported on key limitations associated with behavioural responses under different contexts, the applicability of existing sound propagation models and how they quantify changes in particle motion levels, and a need to consider transmission along the substrate, taking account of differences in the type of substrate.

IMPACTS ON MARINE MAMMALS

The possible effects on marine mammals have been placed into the following zones of influence that depend on the sound level and distance:[101]

- Physical (including physiological) effects: to include mortality, damage to body tissues, gross damage to hearing organs, and chronic stress effects that may lead to reduced viability. Injurious impacts can be referenced with PTS and TTS criteria values discussed above.
- Perceptual effects: including masking of biologically significant sounds (e.g., communication signals, echolocation, and sounds associated with orientation, finding prey, or avoiding natural or manmade threats).
- Behavioural effects: including disruption of foraging, avoidance of areas, altered dive and respiratory patterns, and disruption of mating systems.
- Indirect effects: including reduced prey availability resulting in reduced foraging resource.

Boyd et al. (2008)[102] provided a summary of the types of anthropogenic noise sources that could affect marine mammals and their responses. Table 2 provides a summary of effects from a range of sources, including from vessels.

Table 2. Types of anthropogenic noise sources that could affect marine mammals (Source: Boyd et al., 2008).[103]

Source	Effects of greatest concern
Vessels	• Masking • Habitat displacement
Airguns	• Masking • Physical trauma • Hearing loss • Behavioural change • Habitat displacement • Behaviourally-mediated effects
Intense low- or mid-frequency sonar	• Physical trauma • Hearing loss • Behavioural change • Behaviourally-mediated effects
Pile driving	• Physical trauma • Hearing loss • Behavioural change • Behaviourally-mediated effects
Other sonars (depth sounders, fish finders)	• Masking • Hearing loss • Behavioural change • Behaviourally-mediated effects
Dredges	• Behavioural change • Behaviourally-mediated effects • Habitat displacement
Drills	• Hearing loss • Behavioural change • Behaviourally-mediated effects
Bottom towed fishing gear	• Behavioural change • Behaviourally-mediated effects • Habitat displacement
Explosions	• Physical trauma • Hearing loss • Behavioural change • Behaviourally-mediated effects
Recreational vessels	• Masking • Behavioural change • Behaviourally-mediated effects
Acoustic deterrents	• Behaviourally-mediated effects
Over flying aircraft (including sonic booms)	• Behaviourally-mediated effects

Prideaux (2017)[104] provides a list of activities that should be considered in terms their effects on marine mammal groups. These include seismic surveys, civil high-power sonar, coastal and offshore construction works, offshore platforms, vessel traffic, pingers and other sound-generating activities.

Prideaux (2017)[105] also provided an excellent synopsis of potential impacts of underwater noise on marine mammal groups. In addition to presenting a discussion of potential effects and relevance of sound exposure criteria (using thresholds in NOAA, 2016),[106] they provided assessment criteria for determining potential impacts, including sufficient understanding of population stock structure, habitat use (including displacement areas), the indirect effects associated with displacement and information gaps, to promote precautionary approaches (including avoidance strategies).

Physical effects

Marine mammals are known to be susceptible to a range of physiological effects and injuries that have been attributed to anthropogenic noise. A synopsis of current information on potential effects is provided below.

Biotrauma in marine mammals has been recorded related to explosions.[107] The death of two humpback whales has also been attributed to acoustic trauma caused by a 5000 kg explosion through severe injury to the temporal bones.[108] Underwater detonations as part of military exercises resulted in the death of three (possibly four) long-beaked common dolphins that had sustained typical mammalian blast injuries.[109] Explosives can result in a dramatic pressure drop, which may cause air-filled organs to rupture.[110]

Sonar has also been linked to stress responses that may have lethal effects for marine mammals. Lethal effects can occur when underwater noise elicits behaviours that alter normal functioning of physiological mechanisms required to survive.[111] This includes the reporting of whales with gas/fat emboli. Such issues have been identified in beaked whale strandings.[112] Other issues relate to such effects as "fight or flight" responses and decompression sickness,[113,114,115] which have been linked to mass stranding events. As already noted, concerns have been raised about the association of mass stranding events with military exercises in the 1970s,[116,117] 1980s[118] and 1990s.[119] Various studies have concluded that mass stranding events coincide with high- intensity sonar systems (including naval activities).[120,121,122,123,124,125,126,127,128,129,130,131,132,133,134,135,136,137] Parsons (2017)[138] reported that an analysis of atypical mass strandings of beaked whales found enough evidence for a statistically significant correlation between mass stranding events and naval exercises in the Caribbean and Mediterranean. Necropsies of beaked whales stranded in the Bahamas in 2000 clearly revealed that the animals had suffered acoustic trauma resulting in haemorrhaging around the brain, in the inner ears and in the acoustic fats (fats located in the head that are involved in sound reception).[139] The official interim report for the mass stranding event concluded that an acoustic or impulse injury caused the animals to strand, and that mid-frequency active sonar used by the navy while transiting was the most plausible source of the acoustic trauma or impulse.[140] Analysis of subsequent mass stranded beaked whales found acute systemic micro-haemorrhages and gas and fat emboli in individuals that mass-stranded during a naval exercise in the Canary Islands in 2002.[141,142] Similarly, four species of stranded cetacean (one beaked whale, two dolphin and one porpoise species) had acute and chronic lesions in liver, kidney and lymphoid tissue (lymph nodes and spleen) associated with intravascular gas bubbles (emboli).[143] Southall et al. (2013)[144] investigated the potential cause of long-term displacement and mass stranding of melon-headed whales (*Peponocephala electra*) in Madagascar. They identified the likely cause as a high-power multi-beam echosounder system, rather than a seismic airgun survey, which was speculated as playing a role. Several other (non-beaked) species, such as minke whales and pygmy sperm whales, have stranded concurrently with beaked whales in sonar-related stranding events, while other species, including long-finned pilot whales, melon-headed whales, dwarf sperm whales, common dolphins, and harbour porpoises, have stranded in noise-related events.[145,146,147,148] Whilst there is a lot of research linking mortality and mass stranding events, these may be underestimated if based solely on stranded individuals, as affected cetaceans are also highly likely to die at sea[149] and may not be washed up or detected.[150,151]

Although seismic activities have sometimes been associated with mass stranding events, the links have not been proven (i.e., Southall et al. 2013).[152] However, Gray and Waerebeek (2011)[153] reported on aberrant behaviour of a pantropical spotted dolphin in proximity to an airgun array during 3D seismic explorations off Liberia. A cause-effect relationship with the seismic survey was suggested, but not proven. There is little additional evidence available to confirm any potential injurious effects for seismic activities, although sound generated could be injurious when compared to estimated sound exposure criteria (see above).

There is no documented case of injury to marine mammals caused by pile driving at sea, and there remains uncertainty on the injurious effects that may occur from this activity. Levels of intense sound produced during pile driving may be strong enough to cause noise-induced hearing loss in some species when referring to sound exposure criteria (see above). Research indicates that sound from pile driving has the potential to induce hearing loss in marine mammals if they remain within a certain distance of the source.[154,155,156]

Sound from acoustic deterrent devices (ADDs) may result in TTS or PTS of hearing sensitivity for marine mammals (pinnipeds and cetaceans), particularly if they remain in the vicinity of the ADD location for extended time periods (hours)[157] or are exposed to multiple ADDs with overlapping signals.[158]

Hearing damage in marine mammals from noise generated by shipping has not been widely reported and is thought to be unlikely to occur from the passage of a single vessel.[159] However, there is the potential for permanent damage to hearing from sustained and/or repeated exposure to noise generated by shipping over long periods.[160] Increasing collision rates between sperm whales and high-speed ferries in the Canary Islands were thought to be linked to hearing damage. Inner ear analysis of two whales killed in collisions revealed low frequency inner ear damage and auditory nerve degeneration leading to the suggestion that low frequency noise could be considered a marine hearing hazard.[161] Erbe et al. (2019b)[162] reported upon the effects of shipping on marine mammals. They reported that whilst underwater noise produced by vessels is of primary concern related to perceptual and behavioural effects, consideration should also be given to the potential for TTS onset in some situations where relatively high levels of noise are produced. As an example, they reported on the potential for cumulative sound exposure levels to exceed TTS onset exposure criteria predicted by Southall et al. (2019)[163] using modelled data from research in the Moray Firth, Scotland.

Perceptual effects

The term "masking" refers to what happens when increased levels of background or ambient sound reduces an animal's ability to receive acoustic signals (i.e., for communication, social interaction, foraging or navigation).[164,165,166] Erbe et al. (2016)[167] provided a detailed review of communication masking for marine mammals that is a key reference for providing an overview of masking effects. If the anthropogenic sound is strong enough relative to the received signal, then the signal may be "masked".[168] If features within the signal convey information, it may be important to receive the full signal with an adequate signal-to-sound ratio to recognize the signal and identify the essential features.[169] As ambient sound or transmission range increases, information will be lost at the receiver, ranging from inability to detect subtle features of the signal to complete failure to detect the signal.[170] Consequently, the active space in which animals can detect the signal of a conspecific[171] or other acoustic cue will decrease with increased masking sound. Masking does not happen at the source. Rather, masking is a phenomenon that occurs at the receiver, some distance away from the source.[172]

Masking in the marine environment is regarded as a key concern for marine mammals,[173] especially for those that communicate using low frequencies, such as baleen whales, seals and sea lions, and some of the of vocalizations of toothed whales.[174] There is therefore strong evidence that, in some instances, cetaceans are compensating for the masking effects from underwater noise by changing the frequency, source level, redundancy or timing of their signal.[175,176,177,178,179,180,181,182] This phenomenon suggests that the anthropogenic noise levels in the marine environment are clearly interfering with communication in marine mammals.[183] Temporary changes in signalling may enable animals to cope with different levels.[184] Changes in signal parameters may adequately compensate for small increases in masking sound and are not likely to have any adverse effects during short periods of time but may not be sufficient to compensate for more severe levels of masking.[185] The energetic and functional costs of making changes to vocalizations for individuals or populations are currently unknown.[186]

As previously noted, the principal constituent of low-frequency (5–500 Hz) ambient sound levels in the world's oceans are acoustic emissions from commercial shipping.[187,188] Masking can also occur at higher frequencies (1–25 kHz) when vessels are near an animal and exposed to cavitation sound from propellers. Concerns regarding the impacts of noise from large vessels have focused mainly on marine animals that use low frequencies for hearing and communication. Vessel noise in higher frequency bands has the potential to interfere (over relatively short ranges) with the communication signals of many marine mammals, including toothed whales.[189] Masking of harbour porpoise communication and echolocation at close range (up to 500 m) by high-speed ferries and other large vessels has been highlighted as a cause for concern in shallow waters of high traffic coastal areas.[190] More localized masking in the coastal and inshore zone is a growing cause for concern, as the number and speed of smaller motorized vessels increase dramatically in many regions.[191] There have been numerous studies of the effects of masking from vessel noise on marine mammals, including baleen whales,[192] beluga whales,[193,194] bottlenose dolphins,[195,196,197] short-finned pilot whales,[198] killer whales,[199,200] gray whales,[201,202,203,204] humpback whales,[205,206,207] North Atlantic right whales,[208,209,210,211] narwhals[212] and beaked whales.[213,214] Some of these have estimated or modelled the extent to which low-frequency noise from shipping or other vessels can dramatically reduce communication ranges for marine animals.[215,216,217,218,219,220] For example, the noise of an icebreaker vessel was predicted to mask beluga calls up to 40 km from the vessel,[221] while pilot whales in deep water habitat could suffer a 58 per cent reduction in communication range caused by the masking effect of small vessels in the coastal zone.[222] Underwater noise is also reported to mask the underdeveloped calls of newborn beluga whales, reducing the distance that a newborn call can be heard by conspecifics to only a few tens of metres.[223] Using a metric to measure "communication masking" the acoustic communication space for the highly endangered North Atlantic right whale has shown to be seriously compromised by noise from commercial shipping traffic.[224] An important social call for right whales, the gunshot, was also found to be susceptible to masking by vessel noise.[225] Erbe et al. (2019b)[226] reported that there are fewer studies on the effects of smaller vessels on communication of marine mammals. They reported on a study by Dunlop (2016a)[227] that looked at changes to social calls from humpback whales, but no changes were observed at received levels of 91–124 dB re 1 μPa rms from a recreation fishing vessel.[228] Miller et al. (2015)[229] also reported a sharp decline in echolocation-based foraging of northern bottlenose whales from naval sonar activities.

Masking effects on marine mammals have also been suggested for other anthropogenic noise sources, including low-frequency sonar on humpback whale,[230,231] pile-driving noise on bottlenose dolphins,[232] low-frequency wind turbine noise on harbour seals and harbour porpoises,[233,234] low frequency noise from dredging on baleen whales and seals,[235] and airgun pulses on narwhals.[236] There is also the potential for certain AHDs to mask the communication signals of some species of Delphinid cetaceans or seals.[237] Low-frequency noise produced by fish deterrent devices or tidal turbines have the potential to mask baleen whale communication or the vocalizations of some seal species.[238]

Behavioural (and stress) effects

A wide range of anthropogenic noise sources are known to elicit changes in behaviour in marine mammals, and the responses elicited can be highly complex, variable and context specific. Behavioural responses may range from changes in surfacing rates and breathing patterns to active avoidance or escape from the region of highest noise levels. Responses may also be conditioned by certain factors such as auditory sensitivity, behavioural state (e.g., resting, feeding, migrating), nutritional or reproductive condition, habituation, sensitization, prior experience, age, sex, presence of young, proximity to exposure and distance from the coast.[239,240] Götz and Janik (2011)[241] reported that repeated exposure and response leads to desensitization and induces fear conditioning. Therefore, the extent of behavioural disturbance for any given acoustic signal can vary both within a population as well as within the same individual.[242,243]

The subjects of vocal plasticity and mass strandings have been covered previously in sections for masking and physiological effects of anthropogenic noise, respectively. This section provides information on three broad areas of behavioural change in marine mammals (disturbance responses, interruption of normal activity and permanent/temporary habitat displacement), and leads onto a discussion of potential population effects, physiological responses and chronic effects.

There is extensive information documenting the disturbance responses of marine mammals to anthropogenic noise such as recreational boat noise, industrial maritime traffic activities, seismic surveys, oceanographic tests, sonar, acoustic hardware, airplanes and explosions.[244,245,246,247,248,249,250,251,252,253] Short-term reactions of cetaceans to anthropogenic noise include sudden dives, moving away from sources, vocal behavioural change, shorter surfacing intervals with increased respiration, attempts to protect their young, increased swim speed and abandonment of the polluted area.

Erbe et al. (2019b)[254] and Southall et al. (2017)[255] reported on several studies that have researched behavioural responses to underwater noise generated by vessels. Erbe et al (2019b)[256] reported upon the effects of small vessel movements on bowhead whales in the Arctic (citing Richardson et al., 1982[257]; Greene, 1985[258]; Richardson et al., 1985[259]; Johnson et al., 1986[260]), humpback whales moving away from large vessels[261] or ceasing foraging activities.[262] Vessel activity has been reported to reduce foraging success in killer whales[263] and dolphins.[264,265] Vessel noise also influenced the foraging behaviour of Blainville's beaked whale up to at least 5 km away from the source.[266] Sound levels generated by nearby vessels may be impairing the ability to forage using echolocation by masking echolocation signals.[267] Other examples include killer whales and dolphins, which are known to change their motor behaviour in response to small vessel presence and noise,[268,269] while blue and fin whales have similarly responded to shipping movements and noise.[270] Manatees have been shown to respond to approaching vessels by changing fluke rate, heading and dive depth.[271] In contrast, Erbe et al. (2019b)[272] also reported on studies that have shown no response to vessel movements of North Atlantic right whales[273] and humpback whales.[274]

Degraer et al. (2013)[275] reported upon the disturbance of harbour porpoise (*Phocoena phocoena*) occurring up to at least 20 km during a piling event for an offshore wind farm development in Belgian waters. Miller et al. (2015)[276] reported upon the effect of sonar on northern bottlenose whales. They reported that at a received SPL of 107 dB re 1 μPa, an individual whale began moving in an unusually straight course and then made a near 180^o turn away from the source and performed the longest and deepest dive (94 min, 2339 m) recorded for this species. Animal movement parameters differed significantly from baseline for more than 7 h until the tag fell off 33–36 km away.

Sonar-induced disruption of feeding and displacement from high-quality prey patches could have significant and previously undocumented impacts on baleen whale foraging ecology, individual fitness and population health,[277] particularly for endangered species.[278] Wensveen et al. (2019)[279] also reported avoidance and cessation of feeding of beaked whales associated with sonar exposure. The use of airgun arrays during seismic surveys and their impact on marine mammal behaviour has been thoroughly assessed in terms of behavioural responses. A range of conclusions has been drawn with respect to behavioural reactions to seismic surveys. However, many types of marine mammals have reacted strongly to the intense noise of seismic surveys. Several species of baleen whale show avoidance behaviour,[280] as do pinniped species.[281,282] As assessment of cetacean responses to 201 seismic surveys resulted in the suggestion that odontocetes may adopt a strategy of moving out of the affected area entirely, while slower moving mysticetes move away from the seismic survey to increase the distance from the source, but do not leave the area completely.[283] A causal connection between seismic surveys and ice entrapment events leading to narwhal mortality has been proposed along with a call for research on the effects of airgun use on narwhals.[284] Observations of sperm whales that were resident in an area with seismic surveys occurring over many years did not record any avoidance behaviour, which may indicate habituation. The observations did, however, show more subtle changes in foraging behaviour at sound levels that were considerably below the threshold level used to predict a disruption of behaviour.[285] These subtle changes were picked up because of a rigorous experimental design. Dunlop et al. (2017a),[286] recorded no abnormal behavioural responses of migrating humpback whales to a full seismic airgun array in Australia. However, the whales displayed changes in behaviour, including a slowed progression southwards in response to the active treatments, for some cohorts, that was below typical migratory speeds. This response was more likely to occur within 4 km from the array at received levels over 135 dB re 1 mPa^{2}s. Erbe et al. (2019b)[287] reported upon the trials that were reported by Dunlop et al. (2015[288], 2016b[289], 2017a[290]b[291], 2018[292]). They found that while no behavioural change was seen in some trials, others revealed a decrease in dive duration, travel speed and the number of breaches.

Long-term in-depth studies are also important to detect subtle effects. For instance, on study showed that the apparent habituation of a dolphin population to noise produced by vessels was a result of more sensitive individuals avoiding the affected area whilst the less sensitive ones remained.[293] Subtle behavioural responses to ship noise have also been documented for killer whales.[294] It is also important to consider that animals that are most vulnerable to a disturbing stimulus may not be the most responsive, in that the most stressed animals may have less capacity to alter their behaviour.[295] For example, a starving animal may choose to keep feeding when exposed to a disturbing stimulus rather than stop feeding and move away.[296] Such trade-offs may influence activity budgets, potentially affecting fecundity, survival[297] and population health.[298]

It is thought that, in some instances, repeated short-term changes in behaviour may lead to long-term impacts at the population level through continual avoidance leading to habitat displacement[299,300] or by reducing energy acquisition in terms of lost feeding opportunities.[301] It is also possible for migratory species to be subjected to multiple noise sources along their migration route or be impacted in areas of aggregation that support important functions. Often, impact assessments consider the potential for temporary displacement of species as a response that reduces the potential for injury, and thus minimizing the significance of impacts. However, this assumes that all animals do readily displace, and this may not be the case for all groups. The consequences of displacement are poorly understood but could lead to increased stress and impact on behaviours (e.g., reproduction and foraging).[302] However, the displacement of numerous cetacean species has been well documented in the scientific literature[303,304] and, in some cases, individuals have been displaced for several years, only returning when the activities causing the anthropogenic noise ceased.[305] If the displacement results in the animals being excluded from important feeding, breeding, or nursery habitats then this is likely to have a deleterious impact on survival and growth of the population group.[306] Similarly, a prolonged disruption in normal behaviour can reduce foraging time and efficiency. Furthermore, displacement may not be possible for species with high site fidelity.[307] Although there is some uncertainty in this regard, such issues should be considered, especially if displacement is considered as a desirable response to limit impacts. A lack of observed response may not mean that there are no fitness costs;[308] and therefore, a lack of response should not be automatically determined as showing a lack of adverse impacts.[309] The apparent tolerance of disturbance may have subtle effects that lead to consequences, which may include population-level effects.[310]

Stress responses that lead to the alteration of normal functions may lead to lethal effects (i.e., mass stranding).[311] Chronic stress has also been raised as an issue of concern in marine mammals through the prolonged or repeated activation of the physiological stress response,[312] as well as the life-saving combination of systems and events that maximizes the ability of an animal to kill or avoid being killed.[313] The goal of this stress response is to enable the animal to survive the perceived immediate threat. Prolonged disturbance of marine mammals to intermittent or continuous anthropogenic noise has the potential to induce a state of chronic stress if the exposures are of sufficient intensity, duration and frequency. The stress response may be triggered repeatedly either through a direct response to noise (e.g., small vessel noise) or indirectly via one or more noise-related impacts (e.g., shipping noise masking communication, navigation, or foraging abilities).[314] Chronic stress is known to have adverse health consequences for populations of terrestrial animals by affecting fertility, mortality and growth rates. Moreover, it is known that a range of biological systems and processes in animals are impacted by exposure to noise: the neuroendocrine system, reproduction and development, metabolism, cardio-vascular health, cognition and sleep, audition and cochlear morphology, the immune system, and DNA integrity and genes.[315] It could therefore be inferred that noise-induced chronic stress has the potential to detrimentally alter similar critical life history parameters in marine mammals (e.g., disease susceptibility, reproductive rates, mortality rates), that may have long-term consequences for populations. North Atlantic right whales, for instance, showed lower levels of stress-related faecal glucocorticoids after a period of decreased shipping in the wake of the terrorist attacks on the United States on 11 September 2001, with an attendant 6 dB decrease in shipping noise.[316] Kastelein et al. (2015)[317] reported increased respiration rates and jumps when a captive harbour porpoise was exposed to playbacks of pile-driving pulses in a controlled experiment. The population-level effect of individual sources of noise will depend on their context and cumulative impacts. One way to better understand this issue is qualitatively mapping the overlap between the distribution of risk (presence, intensity, and frequency of noise from individual sources) and the species density and vulnerability. Integrating this information in a visual risk map can help to identify whether risks from cumulative noise sources warrant management action in a particular area, as well as inform the prioritization of research and conservation actions. For example, risk maps for different noise sources have been produced for harbour porpoises in the North Atlantic.[318]

The potential impacts of noise also need to be considered in a wider context through addressing the consequences of acoustic disturbance on populations in conjunction with other stressors, including bycatch mortality, overfishing leading to reduced prey availability and other forms of pollution, such as persistent organic pollutants.[319,320] These various stressors may also act synergistically or cumulatively. For example, underwater noise could interact with bycatch or ship strikes in that the individual is less able to detect the presence of fishing nets or nearby vessels.[321] Multiple sources of anthropogenic noise may also interact cumulatively or synergistically such as when naval sonar emissions from multiple vessels produce confusing sound fields.[322]

Few studies have found a population-level change in marine mammals caused by exposure to anthropogenic underwater noise, though it is listed as a contributing factor to the decline or lack of recovery of several regional whale populations (e.g., western North Pacific gray whales[323,324,325] and "southern resident" killer whales in the eastern North Pacific[326]). An example of where population effects have been reported relates to a review of the recruitment of Blainville's beaked whales in the Bahamas following military sonar exercises in 2000.[327] Chronic shipping traffic has also been reported as one of the main contributors to population declines of beluga whales in the St. Lawrence Estuary.[328] Another reported example relates to the use of ADDs over large areas and extended time periods; they may represent a source of chronic underwater noise pollution, which may negatively affect animals' individual fitness, potentially with long-term population consequences.[329] In contrast, a detailed review found little response by cetacean populations to human acoustic disturbance in four case study areas.[330] Some of the potential explanations for this were hypothesized, including the lack of accurate population estimates for marine mammal species and the ability of individuals to adapt and compensate for negative effects.[331] Limitations inherent in studies and the complexity of animal behaviour and context means that it is not always possible to infer direct cause and effect relationships.[332]

Pirotta et al. (2018)[333]determined that behavioural responses from anthropogenic disturbance are related to different life-cycle activities and functions. It is therefore important to investigate behavioural responses to disturbance and, particularly, the context in which these responses may change. The process by which impacts on behaviour could lead to long-term population-level consequences can be addressed using models, including the Population Consequences of Disturbance (PCoD) framework.[334] DEPONS is another model available for assessing population-size effects of underwater sound generation on marine mammals. This model is currently focused on assessing population consequences for harbour porpoises.[335]

Indirect effects

In addition to direct effects, marine mammals could potentially be indirectly affected by changes to foraging resources that result from underwater noise impacts. This may relate to impacts on fishes and invertebrates and are especially important in areas that may support key life-cycle functions. The potential effects on such resources are discussed below.

EFFECTS ON MARINE FISHES

Notable reviews of the effects of noise on fishes have been produced, and these should be referred to as key sources to understand the current status of knowledge.[336,337,338,339,340,341,342,343,344,345,346,347,348,349,350] The following provides a synopsis of some of the key information contained within these sources.

As previously noted in this report, all fishes are sensitive to change in particle motion, and some fishes are also sensitive to changes in sound pressure.

Most assessments of the potential effects of underwater noise have not paid attention to particle motion, however, and therefore there is limited evidence to demonstrate impacts.[351] This is especially an issue as it means that the actual hearing sensitivity of most fish species is not really known.[352] It is therefore very important that particle motion be considered in studies that seek to assess the impacts of anthropogenic underwater noise.[353,354] Popper et al. (2019b)[355] provide an overview of methods to measure particle motion. The following section therefore provides an overview of effects on fishes, but the level of understanding is limited by the paucity of information on the effects of particle motion. Other limitations include the fact that many experiments to determine hearing thresholds and capabilities have been conducted in laboratory environments using tanks under than less than satisfactory conditions.[356]

Hawkins and Popper (2018)[357] outlined the effects (potential measurable changes that could lead to adverse impacts) that may arise on fishes from exposure to underwater sound. They reported that exposure to underwater noise can have:

- Physical effects (including death, permanent injury or recoverable injury);
- Physiological (including changes in stress levels, metabolism and immune system; reduced energy reserves and fertility; and temporarily impaired auditory function); and
- Behavioural effects (including impairment of communication, startle or avoidance responses, displacement, disruption to life-cycle functions, reduced foraging efficiency, increased energy expenditure, changes to schools and groupings, and impaired detection).

Popper et al. (2019a)[358] stated that fishes from different "hearing groups" not only vary in their hearing abilities, but also in their susceptibility to hearing loss, physical injury and physiological damage from exposure to noise. They may also vary in their behavioural responses to noise, although these are often influenced by other factors.

Hawkins and Popper (2017)[359] reported that effects can range from mild short-term to long-term severe. Examples of mild effects relate to short-lasting startle responses to noise that rapidly diminish with repeated presentation or that do not change the overall behaviour of the animals. These were considered unlikely to affect key life functions or result in changes to vital functions and do not translate into long-term consequences. More significant effects may influence key life functions, including recruitment, growth, reproduction and survival, which may lead to potentially damaging affects for populations. With respect to acute effects from short-term exposures, these may include death, injury, permanent or temporary hearing impairment or those behavioural responses that may disrupt important life functions. With longer exposure, chronic effects may occur, including developmental deficiencies and physiological stress. Hawkins and Popper (2017)[360] also reported that there are deficiencies in current approaches to quantify population-level effects, and that impact assessments generally form conclusions based on the potential significance of effects without presenting direct evidence of population changes.

Physical effects

Popper et al. (2019b)[361] reported that hearing loss may result from exposure to intense noise, but there is no evidence of PTS in fishes. Fish- can replace lost or damaged hair cells, which limits the potential permanent hearing loss,[362,363] but evidence suggests that recovery takes a long time for some species under some circumstances, as discussed below.[364] It is possible for damage to occur to the swim bladder or other organs involved in the detection of sounds that may result in permanent changes to the hearing abilities of some fishes, although this would not be called PTS.[365] There is, however, evidence of TTS in fishes. Popper et al. (2019b)[366] reported that there is evidence that TTS in fishes only occurs when the potentially damaging sound is at a certain (as yet undefined) level above the auditory threshold at the frequency of exposure. Popper et al. (2014)[367] defined onset of TTS in fishes as any reduction in hearing of 6 dB (change of 50 per cent) or greater that persists for 24 hours or longer. Termination of a TTS-inducing sound leads to the return of normal hearing ability. Temporary hearing loss may affect the ability of a fish to avoid predators, capture prey or communicate with other individual mates.[368] There is variability in both the level of impact and the recovery time caused by differences in sound exposure (level and duration) and in the sensitivity of the species at the frequencies of the exposure.[369,370,371] For fishes that detect sound pressure, based on data from Smith et al. (2006[372], 2011[373]), Popper et al. (2019b)[374] reported that a signal needs to be at least 60 dB above the auditory threshold for an extended period of time (hours) to induce TTS. Popper et al. (2019b)[375] also reported that the despite the evidence of hearing damage in fishes, there are substantial issues regarding the assessment of TTS. Of note, they reported that most studies that have demonstrated TTS have involved species that have an adaptation that enhances hearing sensitivity (fishes that have special structures mechanically linking the swim bladder to the ear), and that studies on species without these specializations generally showed less hearing loss or no hearing loss at all.[376] They also reported that for species that are primarily particle motion detectors, TTS is likely related to the direct stimulation of the ear by the particle motion rather than sound pressure. They reported that whether particle motion leads to TTS depends upon the level of particle motion at the position of the fish, the time over which the fish is exposed to the particle motion, and the level of particle motion above hearing threshold needed to produce TTS. Finally, they reported that the received particle motion signal must be well above the particle motion threshold for particle motion to induce TTS in fishes that only detect that component of the sound signal.[377]

Research undertaken in the 1980s and 1990s showed that high-intensity pure tones presented for several hours may cause damage to the ears of some fish species.[378,379] The ears of caged pink snapper individuals were extensively damaged by a seismic airgun towed from a start-up position 400–800 m away to 5–15 m at closest approach to the cage.[380] The airgun had a source level at 1 m of 222.6 dB re 1 μPa peak to peak, or 203.6 dB re 1 μPa mean squared pressure. The most extensive damage was seen in the group that was sacrificed for analysis 58 days after exposure; at this time, damage was more extensive than at 18 hours. They reported that the equivalent highest levels (at closest approach) for a large seismic array would be experienced within 500 m. Caveats were presented for this study in that fish were caged and could not swim away, and evidence suggests that fish would have moved away from the source. Weilgart (2018)[381] cited Popper (1977)[382] in suggesting that the snapper ear is apparently typical of other marine species such as tuna, cod and haddock. In contrast to this study, recovery of 6–20 dB after TTS has been observed in freshwater species within 24 h.[383] A study of hearing loss in four coral reef fish species during a seismic survey did not find any loss of hearing up to 193 dB re 1 μPa.[384] Exposure of two fish species (hybrid striped bass and Mozambique tilapia) to intense pile driving sound between 210 – 216 dB re 1 μPa s $\mathrm{SEL_{cum}}$ resulted in damage to a significant number of sensory hair cells in the inner ear of hybrid striped bass at the highest sound level but no damage at the lower levels.[385] Hearing impairment, namely TTS, associated with long-term, continuous exposure (2 hours), and masked hearing thresholds have been reported for fishes exposed to simulated noise (playback) of small boats and ferries.[386,387] However, these studies were conducted in conditions with questionable sound fields. As reported by Weilgart (2018),[388] Scholik & Yan (2002)[389] found that the fathead minnow showed significant decreased hearing sensitivity after one hour of white noise exposure at 142 dB re 1μPa, and slow recovery after exposure. Smith et al. (2004)[390] reported that goldfish exposed to 160-170 dB re 1μPa exhibited significant loss of hearing after 10 minutes, with exposure worsening linearly over 24 hours and not fully recovering for 18 days.[391] Weilgart (2018)[392] also reported on the research undertaken by Amoser and Ladich (2003)[393] where white noise at 158 dB re 1μPa was played back to goldfish and catfish for 12- and 24-hours duration, Hearing loss was recorded in both species, but variations were found in hearing loss and recovery time between the species exposed to the same acoustic stimuli.. Popper et al. (2007)[394] reported temporary hearing impairment at one frequency when rainbow trout were exposed to low-frequency active sonar to a maximum received level of 193 dB rms re 1 $\mu\mathrm{Pa}^2$ for 324 or 648 seconds, and they reported differences in effects on hearing for different groups of rainbow trout.[395] No other impacts were recorded during this study.[396] Song et al. (2008)[397] recorded no damage to the ears of three freshwater species exposed to 5-20 shots from a very small (730 cu. in.) seismic airgun array at received levels of 205- 209 dB peak re 1μPa.[398] Casper et al. (2013)[399] demonstrated that for hybrid striped bass damage to sensory hair cells only occurred for sound exposure levels that were substantially above the levels that resulted in damage to other body tissues.[400]

It has been suggested that fishes may be susceptible to two types of tissue damage when exposed to intense sound.[401] Firstly, sufficiently high sound levels are known to cause the formation of micro-bubbles in the blood and fat tissue.[402] Growth of these bubbles by rectified diffusion[403] at low frequencies could create an embolism and either burst small capillaries, causing superficial or internal bleeding, or cause damage to fish eyes where tissue may have high gas saturation.[404] Secondly, exposure to transient high-level sound may cause traumatic brain injury. The swim bladder of a fish is a gas-filled structure that can be susceptible to damage by high intensity, particularly impulsive sound. Gas oscillations induced by high SPLs can potentially cause the swim bladder to tear or rupture.[405,406] In addition, sounds from an impulsive source can cause gas organs, such as the swim bladder and lung, to oscillate and push on the surrounding tissues. Rapid expansion and contraction of the swim bladder can damage proximate organs including the liver, kidney and gonads and the swim bladder itself.[407,408] Ruptured swim bladders have been reported in fishes exposed to explosions[409,410,411] and to pile-driving sound.[412,413,414] Fishes that do not possess swim bladders, such as flatfish, are less susceptible to damage from explosions[415] and pile-driving[416] sound.

There is limited information available on mortality of fish from noise exposure, and it relates only to impulsive sound sources such as pile driving and explosions, especially in terms of acoustic data. "Blast fishing" explosions on tropical coral reefs are known to kill and injure fishes and invertebrates but also cause extensive damage to reef habitat.[417] Blasts occurring during the decommissioning of oil and gas platforms can also cause fish mortality.[418] Exposure of fishes to seismic airguns[419] or high intensity sonar (both low- and mid-frequency types)[420,421] did not result in mortality. The threshold for the onset of injury from pile-driving sound in juvenile Chinook salmon (*Oncorhynchus tshawytscha*) has been defined as an SEL_{cum} of 210 dB re 1 µPa^2 s.[422] There is a general correlation between the extent of tissue damage and the cumulative level of sound energy to which a fish is exposed.[423] However, the degree of effect also depends on a combination of the energy within single pile-driving strikes (SEL_{SS}) and the number of strikes but is not predictable from just knowing the cumulative energy.[424,425] A series of studies using pile-driving sound have quantified the physical effects of sound exposure on various types of tissue,[426] which have been used to develop interim sound exposure criteria for fishes.[427,428] Exposure to very high-intensity continuous sound with no impulsive components did not result in tissue damage in five species of fish.[429,430,431,432] Full recovery from tissue damage has been observed for Chinook salmon and striped bass within ten days after exposure to sounds up to 213 dB re 1 µPa^{2}s.[433,434] However, whilst injured, fishes may be more susceptible to infection and have reduced ability to feed or evade predators.[435] The very limited data available for the effects of sonar on fishes show no evidence of tissue damage or mortality to adults.[436,437] Studies focused on larval and juvenile fishes exposed to mid-frequency sonar recorded significant mortality (20-30 per cent) of juvenile herring in two out of 42 experiments,[438] which was estimated in a "worst-case" scenario to be equivalent to a lower mortality rate than would occur due to natural causes in the wild.[439] However, there is a need to repeat these experiments, as the sound level was only tested once, and so it is unknown if the increased mortality was due to the level of the test signal or to other unknown factors.[440]

Studies on the effect of impulsive noise (seismic air guns) on the eggs and larvae of marine fishes observed decreased egg viability, increased embryonic mortality, or decreased larval growth when exposed to sound levels of 120 dB re 1 µPa.[441,442] However, the veracity of these experimental studies has been questioned regarding the stated and actual acoustic conditions. Turbot (*Scophthalmus maximus)* larvae suffered damage to brain cells and to neuromasts of the lateral line.[443] The neuromasts are thought to play an important role in escape reactions for many fish larvae and thus their ability to avoid predators.[444] Injuries and increased mortality from air guns occurred at distances less than 5 m from the sound source. The most frequent and serious injuries occur within 1.5 m, and fishes in the early stages of life are most vulnerable.[445] It has been suggested that juveniles and fry have less inertial resistance to the motion of a passing sound wave and are potentially more at risk for non-auditory tissue damage than adult fishes.[446] A study that exposed larvae of the common sole to high levels of pile-driving sound in carefully controlled experimental conditions did not record any significant differences in larval mortality between exposure and control groups.[447] The highest cumulative sound exposure level used was 206 dB re 1µPa^2 s, which is more than the interim criteria for non-auditory tissue damage in fishes.[448] Juvenile European sea bass exposed in situ to pile-driving sounds resulting in an estimated cumulative sound exposure of between 215 and 222 dB re 1µPa^2 s did not differ in immediate mortality compared to controls.[449] There were also no differences in delayed mortality up to 14 days after exposure.

Physiological effects

Weilgart (2018)[450] reported that although fish may remain in noisy areas this does not mean that they are not affected, as adverse effects are not necessarily overt and obvious. Aguilar de Soto and Kight (2016)[451] reported that sublethal effects from stress are varied and can influence growth and condition of individuals affected. Stress is known to affect health and well-being in terrestrial vertebrates by influencing processes such as growth and reproduction. Highly stressed fish may also be more susceptible to predation or other environmental effects than non-stressed fish.[452] Of note, Weilgart (2018)[453] reported that the stress hormone cortisol can negatively affect growth, sexual maturation, reproduction, immunity and survival, and that changes in metabolic rates could cut into the fish's energy budget, leaving less energy for feeding, migration and reproduction.

Aguilar de Soto and Kight (2016)[454] reported on a range of research investigating stress impacts on fishes, including high plasma cortisol and glucose levels in goldfish when kept in conditions of high noise exposure (white noise, 160–170 dB re 1 μPa) in comparison with a control group kept at 110–125 dB re 1 μPa (although cortisol levels dropped to control levels after one hour of noise exposure),[455] stress responses in captive fish[456] and anxiety in pink snapper and jack/trevally from airgun exposure.[457] Weilgart (2018)[458] reviewed studies that looked at the stress of fishes in response to sound exposure, including research done by Nichols et al. (2015)[459] where increased cortisol levels were recorded when juvenile kelpfish were exposed to intermittent sound in tanks. They reported that the predictability in the timing of the sound may have mattered — with lower predictability causing more stress. In addition, the review considered research undertaken by Buscaino et al. (2010)[460] and Celi et al. (2016)[461] who reported biochemical changes in blood or plasma of fishes in response to sound that produced by vessel traffic. Studies of captive freshwater fishes exposed to simulated boat noise for 30 minutes increased the level of cortisol in the blood.[462] Underwater sound-related increases in heart rate, muscle metabolism and metabolic rates have also been reported for captive fish.[463,464,465] Analysis of biochemical and haematological parameters, stress indexes and growth rate for farmed fish exposed to different types of background noise showed that fish exposed to noise from onshore facilities were more stressed than those exposed to background noise from offshore aquaculture.[466] Although data are lacking for wild fishes in terms of noise-related stress effects, these studies at least suggest that anthropogenic noise could be a stressor in natural water bodies.[467] The issue of noise-related stress in marine fishes is clearly in need of investigation in the natural environment, which may involve developing new analytical techniques to accurately measure stress levels in situ. It is also important to mention that studies completed to date have been on captive animals in enclosed areas where the fish could not avoid the sounds.[468] It is therefore possible that the stress response could be related to the inability to move away from a noise rather than just the sound itself.

Behavioural effects

There has been a range of studies to determine the potential effects of anthropogenic noisse on the behaviour of marine fish but very little is known about the long-term effects of exposure to sound or about the effects of cumulative exposure to loud sounds. Fish behaviour is also often observed in a cage or tank. This can provide some useful information regarding the initial response to a sound[469] but is not representative of behaviour when exposed to the same sound in the wild, for example in a spawning or feeding ground.[470] Animals in captivity also behave differently when compared to those in the wild whose movements are unrestricted.[471] It is also important to recognize that the responses of fish are context-specific and may vary with their age and condition, as well as under different environmental conditions.[472] Behavioural responses can vary between different sound sources, or with the same sound when the level of sound received by the animal differs.[473,474]

The response to noise by fish can range from no change in behaviour to mild "awareness" of the sound or a startle response (but otherwise no change in behaviour), to small temporary movements for the duration of the sound, to larger movements that might displace fish from their normal locations for short or long periods of time.[475] Weilgart (2018)[476] reported that the most serious impacts are on survival and reproduction.

Avoidance of vessels, vertically or horizontally in the water column, has been reported for cod and herring, and was attributed to the underwater sound generated.[477,478] Vessel activity can also alter schooling behaviour and swimming speed of fish.[479] A review of fish avoidance of research vessels indicates that simple behavioural models based on sound pressure levels are insufficient to explain how fish react to survey vessels, and that research is needed into the stimuli that fish perceive from approaching vessels, particularly low-frequency infrasound.[480] Weilgart (2018)[481] cited research that showed impaired parental behaviour and offspring survival and heightened aggression and defensive behaviour of spiny chromis fish exposed to vessel noise.[482]

In a field-based study with reliable acoustic data, schools of two species of wild pelagic fishes, sprats (*Sprattus sprattus*) and mackerel (*Scomber scombrus*), in a quiet coastal location mainly responded to simulated pile driving sound by dispersing and changing depth respectively.[483] Recent tank-based studies, where acoustic conditions were less reliable, did show that the shoaling behaviour of groups of juvenile seabass (*Dicentrarchus labrax*) was affected by playbacks of pile driving.[484] The groups exposed to pile-driving sounds were less cohesive, less directionally ordered and less correlated in speed and directional changes compared to those exposed to ambient sound playbacks. The research demonstrated that sound can influence the spatial and directional organizational characteristics of fish shoals, which likely has functional consequences, including effects on the benefits of group living, such as reduced predation risk and transmission of social information.[485]

There has been concern regarding the effect of impulsive noise on migratory fishes where pile driving was conducted in a narrow strait used by salmon during the migration season.[486] The recorded sound exposure level of 190 dB 1 μPa s at 28 m from the pile was deemed high enough to block migration and potentially cause hearing damage to fish passing close to the pile. Modelling of pile driving effects on migrating European sea bass using experimental behavioural data predicted that they would take significantly longer to arrive at their spawning site, which could have important implications at a population level.[487] The temporal structure of sound can also affect behaviour. Sea bass exposed to both intermittent and continuous sound showed significantly slower recovery from the former compared to the latter.[488] It was suggested that intermittent sound (e.g., pile driving) may have stronger behavioural impacts on some fishes than continuous sounds (e.g., drilling) although further research is required to verify this for other species. Responses may also vary for the same species depending on the age / size and condition of the fish.[489] Popper et al. (2019b)[490] reviewed recent studies that have considered the impact of pile driving on the behaviour of fishes, some of which have reported impacts, while others have not.[491,492,493,494,495,496,497,498,499,500,501,502]

As reported by Popper et al. (2019b),[503] the behavioural and physiological effects of exposure to airguns have been reviewed by several investigators.[504,505,506,507,508,509,510] Bruce et al. (2018)[511] reported on research to quantify field-based fish behaviour in response to a 2D seismic survey in Australia. They reported that fishes that were found in abundance prior to the survey were reduced by 65-70 per cent two days after tagging, suggesting movement outside of the study area, although various tagged individuals returned sporadically during seismic survey activities. They also reported tiger flathead showed behaviour consistent with responses to seismic activities. Gillnet catches of redfish (*Sebastes norvegicus*) and Greenland halibut (*Reinhardtius hippoglossoides*) doubled during seismic shooting, although longline catches of haddock and Greenland halibut dropped, compared to pre-shooting levels.[512] Pelagic species such as blue whiting (*Micromesistius poutassou*) reacted to air guns by diving to greater depths but also by an increased abundance of individuals 30–50 km away from the affected area, suggesting that migrating fishes would not enter the zone of seismic activity.[513] Conversely, a study using direct video observation showed that temperate reef fishes remained close to their territories after exposure to air-gun arrays with only minor behavioural responses observed.[514] However, it was suggested that responses were because the reef is their familiar home territory and that airguns were not approaching. Schools of herring (*Clupea harengus*) did not react to a full-scale 3D seismic survey, which was attributed to a strong motivation for feeding, a lack of suddenness of the air gun stimulus (use of ramp up procedures) and an increased level of tolerance to the seismic survey.[515] Mid-frequency active sonar did not elicit a significant behavioural response in herring in terms of vertical or horizontal escape reactions.[516] Similarly, herring did not react significantly to low-frequency sonar signals from a passing vessel but did show a reaction to the sound of a two-stroke engine at a much lower SPL.[517] ADDs (or pingers), which produce frequencies lower than 10 kHz and have a source level above 130 dB re 1 μPa, are likely to have a significant influence on the behaviour of fish.[518] Although the responses of fishes to commercially available acoustic harassment devices (AHDs) have not been thoroughly tested, it is thought that AHDs, which produce substantial energy in the ultrasonic range, may cause some behavioural avoidance responses in fish species with good ultrasonic hearing but only close to the device (within 20 m).[519] A tank-based study of foraging performance in three-spined sticklebacks (*Gasterosteus aculeatus*) exposed to acoustic noise found that the addition of noise resulted in decreased foraging efficiency, with more attacks needed to consume the same number of prey items.[520] Acoustic noise increased food-handling errors and reduced discrimination between food and non-food items, results that are consistent with a shift in attention. In this case, noise may have attracted the attention of the fish, thus preventing them from focusing fully on foraging. A similar study involving the same species and the European minnow (*Phoxinus phoxinus*) found that both species foraged less efficiently but their foraging behaviour was altered in different ways, with the minnow feeding less often whilst the stickleback fed at the normal rate but made more mistakes.[521] A significant modification in foraging habits has also been reported for Mediterranean damselfish (*Chromis chromis*) due to recreational boat noise.[522]

Elasmobranchs do not have a swim bladder or any other air-filled cavity, meaning that they are incapable of detecting sound pressure. Therefore, particle motion is assumed to be the only sound stimulus that can be detected. There are a limited number of studies that have investigated the effects of anthropogenic noise exposure on elasmobranchs. Some experiments exploring behavioural responses to sound in sharks (but not skates or rays) have been undertaken.[523] Studies of acoustic attraction in 18 species of coastal and oceanic sharks found that individuals would approach underwater speakers broadcasting low-frequency, erratically pulsed sounds from several hundred metres.[524] A few studies investigating avoidance behaviour, found that sudden loud sounds (20-30 dB above ambient noise levels) played when a shark approached a location would startle the shark and cause it to turn away from the area. In most cases involving attraction and repulsion, the sharks would habituate to the stimuli after a few trials.[525] Chapius et al. (2019)[526] reported on the effect of recorded underwater sound stimuli (using an artificial sound and orca calls) for seven reef and coastal shark species in Australia and white sharks in South Africa. Some behavioural responses were recorded for the different groups, although species-specific differences in sensitivity and/or reactivity were noted. Anthropogenic noise sources that have the potential to affect elasmobranchs are thought to be pile driving, wind turbines and boat noise.[527] Elasmobranchs have been reported to aggregate around coastal and offshore built structures.[528]

Reproductive success of fishes may be sensitive to anthropogenic underwater noise, potentially reducing fitness.[529,530] In aquarium experiments the courtship behaviour and spawning success of two closely related species of marine goby (two-spotted, *Gobiusculus flavescens*, and painted, *Pomatoschistus pictus*) were assessed when subjected to continuous noise. Reduced acoustic courtship by males was recorded in noise treatments for both species while less visual courtship was also shown for one species (painted goby). Female painted gobies were also less likely to spawn in the noise treatment. Overall, the study provides experimental evidence of the negative effects of noise on acoustic communication for reproduction and spawning success.[531] Experimental evidence of disruption to reproductive success in natural conditions has also been reported. Weilgart (2018)[532] provides a review of research showing impaired parental behaviour of spiny chromis fish,[533] altered courtship behaviour of the two-spotted goby and painted goby[534] and reproductive activities of toadfish.[535] From such studies, Weilgart (2018)[536] and Popper et al. (2019b)[537] also reported on increased aggression, hiding, flight reactions, decreased anti-predator defence, feeding, spawning, disturbance to migrations and home ranges, amongst other behavioural responses to underwater noise.

Masking effects

Masking by anthropogenic noise can affect fishes in two main ways: by interfering with acoustic communication or through the masking of important environmental auditory cues.

As reported by Popper et al. (2019b),[538] there is considerable concern about how much the presence of anthropogenic sounds may mask sounds that are important to fishes (including the acoustic scene) and hearing sensitivity, including decreasing the range at which biologically important sounds can be detected, thereby preventing fishes from, for example, hearing an oncoming predator or finding distant prey. Fishes are known to produce sounds during territorial fighting, when competing for food or when being attacked by a predator.[539] Acoustic communication can also be extremely important for courtship interactions[540] and in spawning aggregations.[541] There is some evidence that acoustic communication can affect the survival and reproductive success of fishes[542,543] and that communication and spawning success can be negatively affected by continuous noise.[544] However, it is not known whether the masking of the sounds produced by fishes for mate detection and recognition, or for aggregating reproductive groups have any significant fitness consequences for individuals or populations in the wild. It has been suggested that fishes offer a more feasible opportunity than marine mammals to investigate the effects of anthropogenic noise on acoustic communication to determine the impact on individual fitness and population viability.[545]

A study in the Mediterranean Sea revealed that recreational boat noise can significantly increase detection threshold levels for conspecific sounds in brown meagre drums (*Sciaena umbra*) and Mediterranean damselfish (*Chromis*

chromis). It was inferred that passing vessels were reducing detection distances in this environment by up to 100 times.[546] Signals may also be detected but not fully understood as some of the required information in the signal is lost. Although not reported in marine fishes to date, a reduction in detection distance that influenced mate attraction was reported in birds,[547] while sexual signals for mate selection in frogs[548] have been masked in noisy conditions. Numerous studies on birds show that critical ratios can be used to predict the masked thresholds for pure tones when maskers consist of complex anthropogenic and natural sounds.[549] The general principles that hold for birds are very likely to hold for fishes.[550] Some fish communities that are in busy shipping lanes or noisy coastal areas may be restricted in their ability to detect and respond to acoustic signals. The noise of large ferries masked the sound of Atlantic croaker calls, restricting communication.[551] On the Stellwagen Bank in Massachusetts Bay, commercial shipping activity elevates the amount of low frequency sound to near constant high levels. This is thought to reduce the communication space for Atlantic cod and haddock, raising concerns that communication between conspecifics may be compromised during critical biological periods, such as spawning,[552] and therefore affect reproductive success. Underwater noise generated by vessels also reduced the communication space of the bigeye (*Pempheris adspersa*), a nocturnal fish species that uses contact calls to maintain group cohesion while foraging, by up to 62 per cent with the passage of one large vessel less than 10 km from the listening station, and reduced communication space by 99 per cent compared to the ambient soundscape .[553] These results suggest that vessel noise may have chronic effects on some fish populations through the reduction of communication space.

Changes in fish acoustic behaviour in noisy environments have been found in a few cases. The mean pulse rate of sounds produced by brown meagres (*Sciaena umbra*) increased following repeated boat passes compared to ambient conditions, which was assumed to be caused by boat noise.[554] However, it was not known whether the increase in vocal activity was caused by an increased density of callers or by an increased acoustic output by those individuals already calling. More recently, evidence for the Lombard effect[555] in fishes has been reported for a freshwater fish, the blacktail shiner (*Cyprinella venusta*).[556] This species increased its call amplitude in the presence of elevated background noise levels in experimental conditions by increasing the spectral levels of acoustic signals. The capacity of fishes to exhibit the Lombard effect[557] is thought to be constrained by body size and the energetic costs of producing louder sounds. Changes in call frequencies in response to abiotic noise sources[558] or to tidal state[559] have also been reported in fishes but only for individual species. Further research is required in both laboratory and field conditions to determine whether the Lombard effect and other changes in vocal behaviour (see Radford et al., 2014 for potential ways) occur for many other fish species.

Anthropogenic underwater noise may also interfere with prey or predator detection in marine fishes.[560] Predator avoidance by fishes may depend on species hearing or localizing specific sounds.[561,562] Some herring species (Clupeidae) of the genus *Alosa* can detect ultrasound (up to 180 kHz), which could allow them to detect and avoid echo-locating whales.[563] Studies on European eels and juvenile salmonids revealed that they can detect and avoid infrasound (<20 Hz), which may allow them to sense the hydrodynamic sound generated by closely approaching predators.[564,565] It has been suggested that predators that use sound for hunting (e.g., in dark or turbid environments) can be restricted by noisy conditions through lower availability of suitable foraging areas and a lower catching efficiency.[566] The latter has also recently been shown for predatory fishes that rely on vision to catch prey and was attributed to the noise interfering with the attention span of the fish, distracting it from feeding.[567]

Antipredator behaviour has recently been shown to be compromised by anthropogenic underwater noise in some fish species for laboratory-based studies, but not for others. In playback experiments juvenile European eels were significantly less likely to be startled by an "ambush predator" and caught more than twice as quickly by a "pursuit predator".[568] It was suggested that acoustic disturbance could have important physiological and behavioural impacts on animals, compromising life-or-death responses. Antipredator behaviour in two species of sympatric fish was not compromised when exposed to additional sound, with one species having a faster antipredator response, which could be caused by increased vigilance.[569] More recently, studies of juvenile damselfish placed in 80 ml plastic jars in a natural shallow water (2 m) sand patch have shown that motorboat noise from two-stroke outboard engines compromised antipredator behaviour by changing the way the fish assess risk, which can reduce individual fitness and survival.[570]

Anthropogenic masking of natural acoustic cues that are important for the orientation of marine fishes may also be occurring in coastal environments. The noise generated by temperate or tropical (coral) reef communities is one of the cues that may be used by the pelagic larval stages of reef fishes for orientation prior to settlement.[571,572,573] Fish larvae have also been shown to return to their natal reef.[574,575] Studies of reef noise indicate that habitats within coral reefs produce different acoustic profiles[576] that are used by some species of juvenile reef fishes for nocturnal orientation.[577] It has also been found that reef fish larvae, after several hours of exposure, can become attracted to artificial sounds that would normally be avoided.[578] It has been suggested that increased levels of noise may inhibit orientation/settlement of fish larvae on coral reefs by masking the necessary acoustic cues received by larval fish,[579] although the importance of acoustic cues compared to chemical ones has not been determined. Orientation of cardinalfish (Apogonidae) larvae was affected by boat noise in a choice chamber experiment, with significant directional responses recorded for reef+boat playback compared to reef only,[580] although the acoustic properties of this type of tank-based experiment have been questioned. It does appear that anthropogenic noise has the potential to negatively influence the recruitment of fish larvae onto temperate or tropical reef systems, but this needs further verification. Underwater noise produced by ship engines has also been shown to attract settlement of mussel larvae, causing biofouling of ship hulls.[581]

Anthropogenic-induced degradation of marine habitats such as coral reefs may also indirectly influence larval orientation and recruitment to habitats by changing the acoustic profile of these habitats. Quieter habitats combined with increasing anthropogenic sound may have an impact on larval recruitment through reduced settlement.[582]

Conclusions

Although our knowledge of the potential effects of anthropogenic sound on marine fishes has increased considerably over the past two decades, there remain large gaps in our understanding that require attention.[583] Many studies have been conducted on captive fishes under laboratory conditions, rather than on free-living fishes in the wild,[584] partly due to the greater difficulty in undertaking acoustic studies on fishes in their natural environment. Further work with more refined experimental designs should be able to verify these studies and determine the actual acoustic conditions experienced by the animal in question. There is also a lack of information on the responses of fishes to particle motion, rather than sound pressure.[585] More understanding of behavioural effects of anthropogenic noise on fishes and the potential for masking biologically important sounds is regarded as a critical research need given that the potential for these effects can extend for hundreds to thousands of metres from a sound source.[586]

IMPACTS ON OTHER MARINE ORGANISMS

Marine turtles

There is limited information available for the effects of anthropogenic noise on marine turtles at the present time. Marine turtles are sensitive to low frequency sounds within the range of 100 to 1000 Hz with greatest sensitivity between 100 and 400 Hz,[587,588] which overlaps with the peak amplitude low frequency sound emitted by seismic airguns (10 – 500 Hz).[589] Juvenile green turtles are sensitive to a broader and higher frequency range of 50 – 1600 Hz.[590] Hearing in marine turtles allows them to perceive biological signals, and hearing damage may lead to a reduced ability to avoid natural and anthropogenic threats, such as fisheries by-catch and vessel collisions, which are major sources of turtle mortality[591].

Only studies involving air-gun arrays and their effect on marine turtles have been completed to date. These studies are either experimental where enclosed individuals are exposed to air guns or are part of monitoring assessments conducted during seismic surveys from the survey vessel.[592] Most experimental studies to assess short-term responses have demonstrated a strong initial avoidance response in marine turtles to air-gun arrays[593,594,595] at a strength of 175 dB re 1μPa rms or greater. Enclosed turtles also responded less to successive air-gun shots, which may have been caused by reduced hearing sensitivity (TTS). For example, one turtle out of the 25 studied experienced a TTS of 15dB and recovered two weeks later.[596] It was estimated in one study that a typical air-gun array operating in 100–120 m water depth could cause behavioural changes at ~2 km and avoidance at around 1 km for marine turtles.[597] A recent monitoring assessment recorded that 51 per cent of loggerhead turtles dived at or before their closest point of approach to the air-gun array.[598] Conversely, olive ridley turtles did not react to air gun shots.[599]

Long-term exposure to high levels of low frequency anthropogenic noise in coastal areas that are also vital habitat may affect turtle behaviour and ecology.[600] Acoustic disturbance could potentially lead to interruption of key behaviours such as for breeding, foraging, or basking (thermoregulation) or changes in behaviour that compromise energy budgets.[601] Avoidance behaviour may result in significant changes in turtle distribution with potential consequences for individuals or populations if displaced from their preferred feeding habitat.[602] At lower sound levels turtles that remain in an affected area may show abnormal behaviour that reduces their foraging efficiency. However, there are currently no reported studies of the long-term effects of altered behaviour in marine turtles. Further research is needed to understand both physical and behavioural effects of anthropogenic underwater sound generation on individuals and populations.

Marine invertebrates

Invertebrates have mechanoreceptors facilitating the detection of particle motion in the surrounding medium.[603] All cephalopods and some bivalves, echinoderms and crustaceans have a sac-like structure called a statocyst which contains a statolith and associated sensory hairs.[604] Statoliths are thought to allow an organism to detect particle motion. Epidermal hair cells (cephalopods) and sensory setae (crustaceans) also help to detect particle motion in their immediate vicinity. Crustaceans appear to be most sensitive to sounds of less than 1 kHz[605] but some species are able to detect up to 3 kHz.[606] Cephalopods are sensitive to water movement stimuli in a range between <20 and 1500 Hz.[607,608] There have been several reviews on particle motion and vibration in relation to invertebrates with detailed information on assessment approaches, sensory mechanisms and potential effects, including behavioural responses.[609,610,611]

Research suggests that marine invertebrates are susceptible to underwater noise. The impacts of underwater noise have been investigated in terms of physical and behavioural reactions, and for stress responses and effects on larvae.[612,613],[614] Filiciotto et al. (2018)[615] reported on the physical, behavioural and biochemical responses of a semi-terrestrial crab (*Neohelice granulata*) to lab-generated sound. The results of this study showed significant changes in the number of signals emitted, locomotor behaviours and plasma parameters, such as haemolymph total haemocyte count and glucose, lactate and total protein concentrations. Brown shrimp exposed to increased background noise for up to three months demonstrated significant decreases in both growth and reproductive rates.[616] Shrimps were also more aggressive in the noisy treatments with increased mortality and decreased food intake. These are often regarded as symptoms of stress in vertebrates. Exposing red swamp crayfish (*Procambarus clarkii*) to low frequency sound also produced significant variations in haemato-immunological parameters.[617] Hubert et al. (2018)[618] reported on controlled in-field experimental studies to determine changes to foraging behaviour of shore crabs (*Carcinus maenas*) and common shrimps (*Crangon crangon*) to broadband artificial sound. They found that aggregations around a fixed food item were reduced when there was sound exposure. However, Hubert et al. (2021)[619] reported that food-finding shore crabs in a T-maze did not respond to boat sound playbacks. A study has also assessed the effects of low-frequency sound on cnidarians, with injuries observed to the statocyst sensory epithelium of two species of jellyfish (Scyphozoa) that are consistent with acoustic trauma observed in other species.[620]

Effects on marine invertebrate larvae from anthropogenic underwater noise have been demonstrated from experimental studies. Almost half (46 per cent) of scallop larvae (*Pecten novaezelandiae*) exposed to playbacks of seismic pulses in tanks developed body abnormalities, and significant developmental delays were also evident.[621] Enclosed sea hare embryos (*Stylocheilus striatus*) that were exposed to in-field playbacks of underwater noise generated by vessels also experienced delayed development and increased mortality of recently hatched larvae.[622] In laboratory experiments using water baths, exposure to continuous noise from tidal or offshore wind turbines significantly delayed megalopae metamorphosis in two species of brachyuran crab when compared to development in natural habitat sound.[623]

Several physiological and behavioural responses to underwater noise generated by shipping have been reported. Murchy et al. (2020)[624] reported that during their systematic review of literature that the effects from vessel-induced noise were most widely studied. Foraging and antipredator behaviour of shore crabs (*Carcinus maenas*) was negatively affected by playback of ship noise in controlled tank-based experiments, suggesting an increased risk of starvation or predation.[625] Underwater noise produced by vessels also increased the settlement rate of green-lipped mussel larvae (*Perna canaliculus*),[626] which may have connotations for ship fouling by mussels. A study of noise-related effects on cuttlefish behaviour indicates that interference of the acoustic sensory channel affected signalling in another (visual) sensory channel, i.e., anthropogenic underwater noise has a marked effect on the behaviour of a species that does not rely on acoustic communication.[627] All sensory channels should therefore be considered when trying to understand the overall effects of anthropogenic stressors such as noise on animal behaviour. For invertebrates living in sediment, two functionally important species, a clam (*Ruditapes philippinarium*) and a decapod (*Nephrops norvegicus*) showed behavioural changes and stress response when exposed to underwater broadband sound fields that resembled offshore shipping and construction activity, which altered their contributions to fluid and particle transport, both key processes in mediating benthic nutrient cycling.[628] The study provides evidence that exposing coastal environments to anthropogenic sound fields is likely to have much wider ecosystem consequences than are presently acknowledged. Stress responses to playbacks of shipping noise have been reported for several marine crustaceans. Components of the haemato-immunological system of the Mediterranean spiny lobster (*Panulirus elephas*) were altered,[629] while the metabolic rate of the shore crab (*Carcinus maenas*) increased for crabs experiencing ship-noise playbacks compared to ambient noise.[630] Wale et al. (2019)[631] also reported on the effects of underwater noise on the blue mussel (*Mytilus edulis*) in controlled laboratory experiments using ship noise playbacks. They reported evidence of noise-induced changes in DNA integrity and oxidative stress, as well as physiological and behavioural changes.

Marine invertebrates have also been reported to be affected by underwater noise generated by seismic surveys. Direct observation of squid exposed to airgun noise showed a strong startle response involving ink ejection and rapid swimming at 174 dB re 1µPa rms and avoidance behaviour.[632] A significant increase in the strandings of giant squid in Spain during 2001 and 2003 coincided with the proximity of seismic survey vessels conducting air-gun arrays.[633] Pathological analysis of stranded squid showed the presence of lesions in tissues and organs leading to the suggestion that they were caused by excessive noise exposure from air guns.[634] Secondly, an experimental study showed that moderately intense low frequency noise was responsible for the severe acoustic trauma and mortality in four species of cephalopod.[635] Lesions in the sensory and lining epithelia of the statocysts, and damaged sensory hair cells and nerve fibres were reported in each species.[636] In particular, massive lesions were found in cuttlefish for all noise exposed individuals.[637] The number of lesions also increased with greater exposure to low frequency noise. Regeneration of statocyst sensory epithelium was also tentatively identified but requires further study for verification. As relatively low levels of low-frequency noise and short exposure had induced severe acoustic trauma in these cephalopods, it was suggested that there may be considerable effects of similar noise sources on these species in natural conditions over longer time periods.[638] McCauley et al. (2017)[639] reported on the effects of experiment airgun signal exposure on zooplankton. Their results showed that exposure caused a two- to threefold increase in dead adult and larval zooplankton with impacts observed out to the maximum 1.2 km range sampled. Day et al. (2017)[640] reported on field-based experimental exposure of seismic signals on the scallop (*Pecten fumatus*). Their results showed that exposure had significant impacts, including on mortality, behaviour and physiology. They observed that the impacts may have resulted from high seabed ground accelerations. Day et al. (2019)[641] investigated the impact of seismic surveys on the righting reflex and statocyst morphology of the rock lobster (*Jasus edwardsii*) using field-based exposure to signals. Their results showed impaired righting and significant damage to the sensory hairs of the statocyst, with impacts persisting over the course of the experiments up to 365 days post-exposure, which did not improve following moulting. Fitzgibbon et al. (2017)[642] assessed the impact of seismic air gun exposure from controlled field experiments on the haemolymph physiology and nutritional condition of the same species. Their results indicated that haemolymph physiology is reasonably resilient to seismic acoustic signals, however, air gun exposure may negatively influence nutritional condition and immunological capacity.

As well as being receptive to sound, many invertebrates, including species of polychaete worms, barnacles, amphipods, shrimp, crabs, lobsters, mantis shrimps, sea urchins and squid, are also capable of producing sounds.[643,644,645,646] In some species, the sounds emitted are thought to be ecologically important in terms of acoustic communication between conspecifics[647]. It has been suggested that acoustic communication and perception in invertebrates might be related to as many functions as in marine vertebrates.[648] Low frequency anthropogenic noise may be masking acoustic communication in marine invertebrates such as crustaceans[649] or the detection of prey or predators by cuttlefish.[650] Masking of important acoustic cues used by invertebrates during larval orientation and settlement may also be a factor in the coastal zone and could lead to maladaptive behaviour that reduces successful recruitment.[651]

Research has also been undertaken to assess the effects of seabed vibration in relation to effects on invertebrates in the marine and coastal environment, particularly with regard to the epibenthos,[652] but also sediment-dwelling taxa.[653] Solan et al. (2016) [654] showed that both impulsive and continuous broadband affected burying, bioirrigation and movement in the Norway lobster. They also reported stress responses in the Manila clam, with impacts on feeding. Weilgart (2018)[655] reported that this study showed that responses to underwater noise can be subtle and may take long periods of time to become detectable at the population or ecosystem level. Another study used modelling to estimate the impact range of pile driving on the American lobster, at up to 500 m from the source.[656] Further studies investigated the sensitivity and behavioural responses of blue mussels and hermit crabs to sediment vibration, which indicated that these species showed responses up to 300 m from blasting and 220 m from backhoe dredging.[657,658,659]

Although the number of scientific studies of the effects of anthropogenic underwater noise on marine invertebrates is growing, there are still uncertainties in our knowledge. Further research is therefore needed, including improvements to the understanding of adverse impacts on individuals' ability to survive and linked population implications, and the role of chronic and cumulative exposure.[660]

Seabirds

More than 800 species of birds live on or near water, many of whom dive when foraging for food,[661] including cormorants, grebes, auks, murres, sea ducks and penguins. Diving seabirds can be exposed to underwater noise when feeding but there are limited studies of the effects of noise on the hearing of seabirds.[662,663] Hansen et al. (2020)[664] reported that in contrast to in-air hearing, underwater hearing has only been measured in two species of aquatic birds, the lesser scaup (*Aythya affinis*) and the great cormorant (*Phalacrocorax carbo*). Both species are sensitive to underwater noise, with thresholds not substantially different from that of odontocetes and pinnipeds at low frequencies. The studies on great cormorant by Larsen et al. (2020)[665] reported that this species has in-air hearing abilities comparable to those of similar-sized diving birds, and that their underwater hearing sensitivity is at least as good as their aerial sensitivity. They concluded that this species may have anatomical and physiological adaptations for amphibious hearing.

Noise-induced damage to hair cells has been measured in terrestrial birds although as a group, birds are considered more resilient to auditory damage than mammals as they can replace hair cells of the cochlea and vestibular system.[666] Severe non-auditory damage of seabirds exposed to intense noise in the form of explosions has been reported for western grebes following an underwater detonation from military training activities.[667] Birds attracted to fish kills after initial detonations were subsequently impacted by further blasts, leading to 70 individuals washed up on a nearby beach. Necropsy of 10 birds confirmed that the blast injuries sustained by the grebes were the cause of death. Diving seabirds are likely to be at greater risk of a noise impact if they are attracted to feed on dead or disorientated fish in the vicinity of impulsive sources such as seismic arrays, pile driving or explosives.[668] Hansen et al. (2020)[669] investigated the behavioural responses of two diving common murres (*Uria aalge*) from experiments using naval mid-frequency active sonar at various intensity levels in a quiet pool at sound pressure levels ranging from 110 to 137 dB re 1μPa. Their results showed that animals presented clear reactions to both types of underwater noise. Underwater playback of chase-boat engines has successfully been used to scare diving birds and reduce predation of farmed mussels by eider ducks, long-tailed ducks and common scoters.[670,671] Playbacks of underwater noise were also used to scare African penguins out of an area where blasting was planned.[672] Strong behavioural reactions to sudden or loud airborne sounds have been documented for seabirds such as king penguins[673] and crested terns.[674]

If diving seabirds and penguins are vulnerable to anthropogenic underwater noise, a behavioural change could lead to reduced foraging or avoidance of a feeding area, with possible implications for survival and fitness. This is especially applicable to penguins as they spend long periods in the water foraging and diving.[675] A recent study of African penguins revealed a strong avoidance of preferred foraging areas during seismic surveys.[676] The penguins foraged significantly further from the source vessel when in operation, increased their overall foraging effort and then resumed normal behaviour when the surveys ceased.

The lack of information available about the hearing of diving seabirds in water and the impacts that may arise from anthropogenic underwater noise strongly supports the need for a detailed programme of research. Further comparative anatomical studies of diving birds' middle and inner ears are required, along with behavioural studies of hearing in air and in water.[677] Secondly, behavioural studies of these birds in their natural habitats are needed to determine whether or how sound is used for communication, foraging, predator avoidance or other behaviour.[678]

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5. MITIGATION AND MANAGEMENT APPROACHES

This chapter reviews existing measures and procedures available to mitigate the effects of anthropogenic underwater noise on marine biodiversity. It highlights examples of avoidance and minimization approaches and covers advances in monitoring and mapping tools to support mitigation. It also reviews relevant international agreements, management frameworks and international standards.

The increased understanding of underwater noise impacts has led to the development of a range of mitigation and monitoring approaches, which include avoidance and minimization strategies. Similarly, to the consideration of impacts, developments in mitigation and the understanding of the effectiveness of measures proposed and implemented is fast-moving. Again, the full understanding of the usefulness of some mitigation measures, especially minimization techniques, is at times hindered by the complexities of the marine environment and the uncertainties that have been previously discussed. Uncertainties may also exist with respect the effectiveness of mitigation. Acknowledging uncertainty is important to explain the level of confidence in impact assessment results, to drive further research, and to inform the selection and advancement of appropriate mitigation strategies, including the adoption of programmes that embed monitoring and adaptive management approaches. One solution to managing these issues is to adopt precautionary approaches, an embedded principle in international best practice for biodiversity assessments, such as leading safeguard standards produced by International Finance Institutions, e.g., the International Finance Corporation (IFC) Performance Standard 6 (PS 6) and its Guidance Note 6 (GN 6).[1,2,3] Such standards suggest that precautionary approaches should be taken when determining biodiversity values, assessing project impacts and developing mitigation strategies (including adaptive management). For biodiversity, the precautionary approach has been widely applied in global biodiversity policy such as Principle 15 of the Rio Declaration on Environment and Development (1992) and the Convention on Biological Diversity. Merchant (2019)[4] emphasized the need for precautionary approaches to be adopted under conditions of scientific uncertainty.

Popper et al. (2020)[5] reported that in many cases data are too incomplete to regulate or adjust industry action in a meaningful way; they acknowledge, however, that, given that there is evidence of effects on marine wildlife, it is not appropriate to wait for further evidence to be collected (especially as this takes time). They made some recommendations to address these issues, including the need for a substantial increase in research and that the focus of this research should be to answer the questions that are most critical for understanding the issues and for developing mitigation measures and regulations. They also recommend some standardization of the research questions being asked and how they are asked, especially to enable comparisons to be made. They also reported that mitigation should only be applied where adverse impacts are evident and may be significant. They argue that an "over-precautionary approach, such as changes to the noise source simply for the sake of mitigation, has a high chance of being ineffective, unless one knows whether and how marine animals are impacted by anthropogenic noise from that source". Finally, they recommend that until further evidence is available, regulators must use a comprehensive risk-based approach using analytical methods that help separate where effects are important and where they are not. In 2000, The European Commission reported that the "implementation of an approach based on the precautionary principle should start with a scientific evaluation, as complete as possible, and where possible, identifying at each stage the degree of scientific uncertainty" (Science for Environment Policy, 2017).[6] Therefore, whilst uncertainty does require the adoption of precaution, such approaches should be supported by robust scientific judgement related to predictable outcomes of impacts and mitigation effectiveness as part of an informed risk-based approach, using existing evidence, expert inputs, and quantified approaches wherever possible.

The "mitigation hierarchy" provides a best practice framework to manage risks and impacts to biodiversity and is an important principle embedded within international biodiversity safeguard standards. It is defined by CSBI (2013)[7] as the sequence of actions to anticipate and avoid impacts on biodiversity and ecosystem services; and where avoidance is not possible, minimize; and where impacts occur, rehabilitate or restore; and where significant residual impacts remain, offset. Avoidance and minimization are seen as preventative measures; restoration and offset are seen as remediative measures.[8] The mitigation hierarchy seeks to prioritize the earlier steps of the hierarchy, i.e., avoidance of impacts can be emphasized where there is potential for significant impacts and/or where projects may affect natural habitat and features of conservation note, e.g., legally protected and internationally recognized areas, threatened ecosystems, and significant populations of endangered/critically endangered, migratory and congretatory and endemic species (see IFC 2012,[9] 2019[10]). As such, this framework may help to address uncertainties and adopt precaution through the avoidance of impacts where this appropriate to values that may be affected and project risks. The mitigation hierarchy also places emphasis on minimization, and precautionary approaches can also apply to these measures. The adoption of precautionary mitigation requires an understanding of what measures exist and how effective they may be, as well as how they are proportionally balanced with risks. Measures therefore need to be proportionate. Mitigation approaches discussed in this chapter are therefore related to the relevant early components in the hierarchy. No reference is made in this chapter to restoration and offset approaches. CSBI (2015)[11] provides further detailed reading on the mitigation hierarchy.

Mitigation measures for impacts arising from anthropogenic underwater noise can be mainly characterized in terms of spatio-temporal approaches (avoidance) and physical, operational and abatement controls (minimization). The type of mitigation and management depends on the source and activity characteristics, i.e., the type of sound (impulsive or non-impulsive), duration and location (fixed or transient); and also, the receptors that may be affected.

Geographical and seasonal restrictions to avoid the ensonification of species and habitats are widely regarded as a highly successful mitigation measure.[12,13] In general, and as outlined in the guidance above, the underwater sound-generating activity should be scheduled to avoid times or locations that are used for activities such as breeding/spawning, feeding or migration. As an example, the Agence Nationale des Parcs Nationaux (ANPN) guidelines for the planning and operation of offshore seismic exploration within the national parks of Gabon prohibit seismic activities during the period of humpback whale migrations and the breeding and nesting seasons for marine turtles. Australian national policy also restricts seismic surveys during whale breeding, calving, resting, feeding and migrations.[14] As discussed below, the guidelines that exist for mitigating impacts from underwater noise make recommendations for spatio-temporal avoidance. It is important to note that spatio-temporal approaches require advanced planning and robust baseline studies to be completed. The Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA), IUCN, New Zealand and CMS guidelines make recommendations for avoiding sensitive times of the year and avoiding overlapping activities with reproductive periods and important areas with rich marine life or sensitive species (including marine mammals, turtles, fishes and invertebrates). A review of the Canadian guidelines, which dated from 2008, further recommends avoiding areas with critical and/or important habitats of marine mammals and turtles, during mating, feeding, breeding and resting.[15] The IUCN guidelines provide the sort of information needed to collect baseline environmental and biological data, both biotic and abiotic features of the concerned ecosystem. Prior-to-operations monitoring taking place over multiple seasons or years is particularly needed for sensitive areas (e.g., with threatened or endangered species). CMS guidelines further specify that good quality and statistically meaningful baseline studies of biological abundance and distribution must take place at least a year, but ideally two, prior to seismic surveys. However, in some cases, complete avoidance of an area during a particular temporal window may not be possible and additional mitigation will be required. For example, at high latitudes where sea ice occurs there can be an overlap between the time available for seismic surveys and the presence of sensitive species of marine mammals, such as gray whales.[16] In such situations, particular attention should be paid to planning, mitigation and monitoring and the analysis of potential effects. Also, the effectiveness and limitations of such measures must be fully understood.

Minimization measures that have been primarily designed to reduce the risk of injury to marine mammals (which are also used for marine turtles in some places) are widely applied, although application may vary based on legal instruments in place requiring their implementation, capacity, etc. Many of these procedures are also applicable to other marine taxa, although mitigation measures may not be (e.g., the use of visual observers to determine species presence and proximity to a sound-generating activity), whilst the effectiveness of others is not known (e.g., soft-start procedures for marine fishes). Limitations of these guidelines and practices are not discussed in detail here as these have been thoroughly reviewed elsewhere.[17,18,19,20,21,22] Abatement measures that seek to reduce the noise at source may provide general minimization of effects across taxonomic groups. Mitigation measures do not tend to focus on addressing particle motion, although measures that mitigate impacts on sound pressure may also mitigate some of these effects.

Mitigation measures require regular updating to keep in touch with changes in acoustic technology, results from monitoring of their effectiveness, the latest scientific knowledge relating to acoustic sensitivity and population ecology, as well as changing species behaviours (e.g., in response to other wider impacts or climate change). This report reflects current status and knowledge. The intention is not to provide a detailed discussion of all measures available across industries, but rather to provide an overview of key guidance and measures.

GUIDELINES

Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic area Guidance (2019)

A methodological guide has been produced to provide mitigation guidance for impulsive and continuous sound in the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic area (ACCOBAMS) region.[23] The guidance provides an overview of design avoidance through use of alternative technologies that that may be adopted to mitigate impacts from impulsive activities. This includes the use of drilling, vibro-drilling and alternative foundations (concrete gravity and bucket) as an alternative to driven piling, as well as the use of marine vibroseis (MV) and Low-level Acoustic Combustion Source (LACS) as alternatives to seismic surveys using airguns (see discussion of such techniques below). The guidance also provides information on the application of different mitigation techniques and the level of sound reduction that may be experienced through their implementation. This includes technologies available to minimize impulsive sound, including bubble curtains (big and small), hydro sound dampers (HSD), cofferdams, IHC noise mitigation system (IHC-NMS), BEKA shells and tuneable resonator system. The guidance provides information on the noise reductions that may be achieved through application of these technologies.

For each of main sources of impulsive sound, a mitigation framework is required that consists of three main stages: a planning phase, real-time mitigation and a post-activity phase. For the planning phase, recommendations for each type of impulsive sound source include the need to collect baseline information, selecting periods for activities when there is low sensitivity for marine biodiversity, using quantified methods (i.e., modelling) to define exclusion zones (to inform the deployment of operational controls), and selecting technologies and techniques that reduce the level of sound that may be produced. Recommended real-time operational controls include the use of acoustic mitigation devices use of soft-start protocols, and the use of visual monitoring and passive acoustic monitoring (PAM) protocols. The guidance also covers the use of infrared camera technology to support visual monitoring approaches. Post-activity recommendations relate to the reporting of monitoring.

Regarding continuous sound from shipping, the guidance provides a range of measures for mitigating impacts, including design and operational measures. These measures are informed by guidelines for minimizing underwater sound from commercial ships that were developed by the International Maritime Organization's (IMO) Design and Equipment Subcommittee.[24] Such measures are discussed in more detail below with reference to other more recent literature.

The guidance also provides a range of tools to support the implementation of mitigation measures, such as identification of spatial areas of biodiversity concern, underwater sound hotspots, and reference to a common register for the Mediterranean basin for the monitoring of impulsive sound (INR-MED).

Joint Nature Conservation Committee Guidelines (2010 & 2017)

The Joint Nature Conservation Committee (JNCC) published guidelines to minimize the risk of injury to marine mammals from using explosives (2010a),[25] piling noise (2010b)[26] and geophysical surveys (2017).[27] The guidelines outline mitigation measures for activities on the United Kingdom Continental Shelf (UKCS) but are used globally as an example of good practice. They pertain primarily to marine mammals. They identify the potential applicability of the guidance to marine turtles as well as basking sharks – although they state that the appropriate mitigation may need investigation for these species. All three guides provide a clear overview of the recommended activities to be undertaken at the planning stage, during activities and post operation.

Planning

The guidelines for the different activities provide recommendations for the planning phase prior to undertaking operations. In general, all the Guidelines require that studies are undertaken to assess the presence of marine species (including protected species) and periods of high sensitivity or when restrictions could apply (i.e., migration, breeding, calving, or pupping, spawning or periods of aggregation). Other spatio-temporal recommendations include the need to assess the available mitigation measures that could be applied to minimize the risk, e.g., plan activities during daylight and good visibility, and in periods with low likelihood of encountering marine mammals.

The guidelines also recommend the establishment of mitigation zones for minimizing risks of injury. For the use of explosives, the default zone is 1 km. For piling and geophysical surveys, the mitigation zone should be at least 500 m. If variations to these zones are proposed they should be supported by clear rationale, including risk assessment that is potentially supported by modelling. Other recommendations include the need to demonstrate that Best Available Technique (BAT) is being used and that trained observers and PAM operators are used. The Guidelines for geophysical surveys provide most detail in this regard. All the Guidelines provide recommendations for minimizing impacts using soft-start (ramp up) approaches. The Guidelines for geophysical surveys also present recommendations for further minimization approaches, including using the lowest practicable power levels as well as the need for consultations and additional mitigation requirements in areas of important habitat for marine mammal species, which may include, in the United Kingdom of Great Britain and Northern Ireland, Special Areas of Conservation (SAC), Marine Conservation Zones (MCZs), or Nature Conservation Marine Protected Areas (NCMPAs).

Operation

During operation, visual monitoring by trained Marine Mammal Observers (MMOs) is recommended, along with guidance on protocols, roles, and responsibilities. To supplement visual observations, such as in poor visibility or darkness and rough sea states (above Sea State 4), PAM should be utilised. The limitations of PAM are also recognized.

All the Guidelines require a search prior to operations commencing. For the use of explosives, this search should be for at least 60 minutes, and for piling at least 30 minutes. For geophysical surveys (airgun and high-resolution surveys), the timing of the search is provided for waters depths of <200 m and >200 m. For the former a search of 30 minutes is required, and for the latter, 60 minutes is required. During this period all the Guidelines recommend a 20-minute delay from the time of last detection within the mitigation zone before the commencement of operations. Guidelines for the use of explosives also recommend a post-detonation search, which should be at least 15 minutes after the last detonation.

As mentioned above, all the Guidelines recommend soft-start approaches. For the use of explosives, this includes the use of sequencing so that smaller charges are detonated first. For piling and geophysical surveys, the approaches and timings for soft-start processes are provided; recommendations are also made for breaks in activity, including requirements for undertaking soft-starts and searches for marine mammals. Further recommendations are made in the Guidelines for geophysical surveys for line changes, airgun testing and undershoot operations. It is also noted that mini airguns require a pre-shooting search but not a soft start. These Guidelines also provide some different requirements for airgun shooting and high-resolution surveys. This includes the possibility that soft-starts may not be possible for some sub-bottom profiling equipment, and that if several types of high resolution survey equipment are to be started sequentially or interchanged during the operation, only one pre-shooting search is required prior to the start of acoustic output, only if there are no gaps in data acquisition of greater than 10 minutes. For multi-beam surveys in deep waters (>200 m) utilising frequencies of <100Khz, a risk assessment should be completed.

The Guidelines for the use of explosives and piling provide recommendations for the use of ADDs, which should only be used alongside MMOs and/or PAM, and for a short period of time. However, the use of these devices should consider their effectiveness and the impacts may arise from their use.

All of the JNCC Guidelines for the different sound sources also provide recommendations for reporting following the completion of operations.

Brazilian Institute of Environment and Renewable Natural Resources Guidelines (2018)

National Guidelines for monitoring and mitigating the impact of seismic surveys on marine mammals and marine turtles in Brazilian waters are outlined by the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA, 2018).[28] The Guidelines describe mandatory procedures required for the issuance of the Seismic Survey Licenses (LPS). General precautions to reduce the risk are explained for the planning stage and during the seismic surveys, as described below. The Guidelines provide further details on line-change procedures, criteria for the number of MMOs and PAM operators required, their training, background, experience, and language skills, including standardized and detailed guidance on how to perform the observation, detection and recording of marine biota.

Planning

In general, the guidelines require the noise impacts to be reduced as much as possible, e.g., by investing in technologies or operational alternatives. At the planning stage, it is required to be aware of the presence of marine mammals and marine turtles in the area, as well as the areas or periods of feeding, mating, nursing, migration or spawning. Survey activities should avoid these areas and should not overlap with the restricted areas and periods outlined by the Joint Normative Instructions IBAMA/ICMBio 01/2011 and 02/2011. Furthermore, stakeholders must be made aware of any other seismic surveys being conducted in the area at the same time, avoiding spatio-temporal overlap. If avoidance is impossible, special operating arrangements and additional mitigation and monitoring measures may be required. Furthermore, qualified and well-equipped MMOs and PAM operators should be hired to implement the IBAMA procedures. Finally, airgun arrays must:

- Have the lowest energy output
- Minimize the horizontal emission of acoustic energy
- Minimize sound emission at higher frequencies than those required for data acquisition

Operation

During the seismic surveys, it is generally required to use only the necessary amount of the seismic source and minimize their use for tests and equipment calibration. A direct communication channel must be established between MMOs/PAM operators and the seismic crew, and the former needs to be consulted 30 minutes prior to the start of ramp-up (soft-start). When acquiring geometries that require more than one vessel (e.g., bottom cable techniques), MMOs and PAM systems must be located on the source vessel. If more than one source is employed simultaneously, MMOs and PAM systems must be on all source vessels. Further operational procedures are the following:

- Pre-watch scanning (combined visual observation with PAM) of at least 30 minutes of the exclusion (mitigation zone), which should be less than 1 km
- If no marine mammal/chelonian is detected, ramp-up procedures may begin. If there is a sighting, activation of the seismic source is delayed until no sightings have occurred for at least 30 minutes
- Ramp-up is always implemented prior to the activation of seismic sources, starting with the array smallest sound source, and should last at least 20 minutes until full power is reached, but not more than 40 minutes

- Immediate shutdown of any seismic sources is necessary whenever a marine mammal/chelonian is detected in the exclusion zone. Ramp-up is restarted after 30 minutes of no sightings
- If seismic sources are interrupted for any reason at any point for more than 5 minutes, pre-watch scanning must be re-initiated, followed by ramp-up procedures
- If interrupted for less than 5 minutes, the activity may resume with the same power, provided that no sightings have occurred in the meantime, otherwise scanning and ramp-up must be restarted
- In general, onboard observation must occur in daylight and good visual conditions, throughout all operations, e.g., line change, navigation
- At night or in poor visual conditions, seismic survey activities are only allowed with the use of PAM (the Guidelines provide full details on the operational procedures under these circumstances)
- For seismic source tests, the above guidelines apply, unless the sound pulses are at minimum power, whereby pre-watch scanning is necessary but not ramp-up

The Guidelines further mention the mandatory use of PAM in marine seismic surveys in Brazil, to be used alongside visual observation, and describe the necessary equipment, as well as the procedures for PAM operation and register. They also provide instructions for the marine biota monitoring report following the completion of the seismic survey activity.

Bureau of Ocean Energy Management Guidelines (2012)

The United States Department of the Interior Bureau of Ocean Energy Management (BOEM, 2012)[29] has published guidelines for seismic survey mitigation measures and its protected species observer program. These Guidelines apply to borehole and surface seismic survey activities conducted in waters below 200 m in the whole of Gulf of Mexico, and regardless of water depth in the Gulf of Mexico waters east of 88.0° W. longitude. They establish operational procedures for ramp-up (soft-start) and visual observation to minimize the risk to marine mammals (emphasizing whales) and marine turtles during seismic surveys, whilst using airgun or airgun arrays. The exclusion (mitigation) zone is set at 500 m. The ramp-up procedures for surface seismic surveys include the following:

- Visual observation of the exclusion zone and surrounding areas for at least 30 minutes prior to ramp-up procedures. If no marine mammals/turtles are detected, ramp-up may begin.
- Ramp-up should not be initiated at night or under poor visual conditions
- Ramp-up is initiated by firing a single, the smallest airgun, with gradually activating the others for at least 20 minutes, but less than 40 minutes
- All airgun operations are shut down as soon as a marine mammal/turtle is detected. Re-initiation may proceed after visual inspection of at least 30 minutes if there has been no sighting
- Any shut-down for other reasons (e.g., mechanical failure) for longer than 20 minutes, full ramp-up procedures must be re-initiated
- Short periods of airgun silence for less than 20 minutes do not require subsequent ramp-up (if visual observations continue and there have been no sightings).
- If a minimum source level of the airgun array of 160 dB re 1 µPa-m (rms) is maintained, the 30-minute visual clearance of the exclusion zone before ramping up to full output is not required (the Guidelines explain further conditions for this procedure)

The above-noted guidance is largely similar for borehole seismic surveys, except for the following:

- When visual observations are performed and it is daylight, ramp-up is not required for shutdowns of 30 minutes or less, provided there has been no sighting. If marine mammals/turtles are sighted, ramp-up is required and may begin only after visual observation with no sightings for 30 minutes.
- At night or under poor visual conditions, ramp-up is allowed only when PAM is used
- At night or when visual observation is not possible, ramp-up is not required for shutdowns of 20 minutes or less. If PAM is used at night or in poor visibility, ramp-up is not required for shutdowns of 30 minutes or less

The Guidelines proceed with outlining the conditions for the protected species observer program. This includes the roles and responsibilities for visual observers who have completed the associated training program and who must be present on all seismic vessels conducting operations in water depths greater than 200 m throughout the Gulf of Mexico. Additionally, it is strongly recommended to include PAM as part of the program. However, PAM does not replace any of the mentioned mitigations, except for when it is used at times of reduced visibility when visual observation is not possible. Finally, the Guidelines explain the reporting requirements of the results of the mitigation measures following the operations.

Canadian Guidelines (2008)

National seismic survey guidelines for operations in Canadian waters are set out in a "Statement of Canadian Practise with respect to the Mitigation of Seismic Sound in the Marine Environment".[30] This statement both formalizes and standardizes mitigation measures in Canada for seismic operations and was developed using the best available and internationally recognized mitigation techniques. It considers not only marine mammals, but also marine turtles and fishes, and any other marine species at the population-level. At the planning stage, seismic surveys must be planned to avoid:

- A significant adverse effect on individual marine mammals or marine turtles that are listed as endangered or threatened on Schedule 1 of the Species at Risk Act;
- A significant adverse population-level effect for any other marine species;
- Displacing individuals of endangered or threatened species of marine mammal or turtle from breeding, feeding or nursing;
- Diverting migrating individuals of endangered or threatened species of marine mammal or turtle from a known migration route or corridor;
- Dispersing aggregations of spawning fishes from a known spawning area;
- Displacing a group of breeding, feeding, or nursing marine mammals, if it is known there are no alternate areas available to those marine mammals for those activities, or that if by using those alternate areas, those marine mammals would incur significant adverse effects; and
- Diverting aggregations of fish or groups of marine mammals from known migration routes or corridors if it is known there are no alternate routes or corridors, or if the fish aggregations or marine mammal groups incur significant adverse effects if they use an alternate migration route or corridor.

To avoid the seismic operation having any of the effects mentioned above will require extensive background knowledge of the area to be surveyed in terms of marine fauna distribution, migration and critical habitats and seasons for feeding, breeding/spawning, and nursing.

Once there is sufficient baseline information for an area of proposed activity, it is possible to draw up a set of spatio-temporal restrictions, so that the species or taxa of concern are not affected or that disturbance is kept to a minimum.

It is important to note that Moulton et al. (2020)[31] have reviewed the Canadian guidelines. They conducted a literature review and an analysis of recent available science as well as of other Canadian and international processes and guidelines. They suggested 29 recommendations to modify the 2008 guidelines, which concern both practices for planning seismic surveys and operational mitigation measures and monitoring and are concisely outlined in a table in the appendix of DFO (2020).[32] For planning procedures, it is recommended to consider using lower power air source alternatives to standard air source arrays, as well as using new technologies to replace air source arrays, e.g., eSource™ and marine vibrators. Furthermore, as there is a lack of seasonal, georeferenced baseline data on the distribution of mammals, marine turtles and fishes in many offshore areas in Canada, research effort is needed prior to survey activities to determine species occurrence to apply effective spatio-temporal measures. Spatio-temporal avoidance should be applied in areas where SARA-listed (Species at Risk Act) cetaceans are expected to be present, as well as in other critical and/or important habitats (e.g., used for mating, feeding, breeding, resting) of marine mammals and turtles, including non-SARA-listed species. Additionally, areas identified by indigenous peoples and local communities as important for subsistence harvesting of marine mammals and fish should be avoided before or during harvesting. For operational mitigation measures and monitoring, there are recommendations on modifications regarding the safety zone and start-up procedures, shut-down of air source arrays, line changes and maintenance shut-downs, operations in low visibility, additional mitigation measures and modification, and operations in and near ice-covered waters.

Greenlandic Guidelines (2015)

National guidelines[33] have been published that outline good environmental practices both for planning for and conducting offshore seismic surveys in Greenland to reduce impacts on marine mammals. The document also advises on the preparation of environmental impact assessments (EIAs) and environmental mitigation assessments (EMAs) of seismic activities. Seismic surveys are usually conducted from mid-June through November, but if they are to be carried outside these seasons or in the ice-covered waters off North Greenland, EIA is then required.

Planning

Efforts must be taken to evaluate methods to reduce and/or baffle high frequency noise, produced by the airguns, and the lowest power levels to achieve the objectives of the seismic survey must be chosen. Evaluations must further include which marine mammals are likely present in the area, and whether there are any seasonal or habitat aspects to be considered, e.g., breeding, calving, pupping, and migration. The Guidelines further describe protection areas for marine mammals in relation to seismic surveys: areas of concern and closed areas. For the former, regulation and further mitigation may apply, whilst seismic surveys are generally not allowed in the latter, although limited seismic surveys may be allowed. A list of sensitive species and maps to showcase the areas of concern and closed areas are provided. No regulation of seismic surveys applies in relation to fish and fisheries, however maps of the most important fishery grounds are also included in the guide to potentially avoid overlap with seismic surveys. Additionally, operators need to be aware of other planned seismic surveys in nearby licensing areas in Greenland and Canada and other disturbing activities in the area.

Operation

If marine mammals are likely to be present in the area, seismic activities should be conducted only when visibility is good, if possible, to allow for visual observation using marine mammal and seabird observers (MMSOs). The Guidelines provide specific advice on the role and responsibilities of the MMSOs. Additionally, PAM is required during periods of darkness, low visibility, or when the sea state is not conducive to visual mitigation. However, the guidance highlights its limitations regarding accuracy, thus infra-red detection systems shall be an alternative in the future. The exclusion zone is set at 500 m, with the following operational procedures:

- Pre-shooting search by the MMSOs or PAM operators (if used) is required for 30 minutes in shallower waters (<200 m), and for 60 minutes in deep waters (>200 m). That applies for both airguns and mini-airguns.
- If a marine mammal is detected during the search, ramp-up (soft-start) is delayed until it has been 20 minutes since the last sighting and the animal has left the exclusion zone (ramp up delay is not necessary for polar bears on ice, but if they jump into the water, the guidelines apply)
- If a marine mammal is detected (even on ice) during ramp-up, firing must be reduced to the smallest airgun in the array (mitigation gun). Ramp-up is re-initiated when the animal is outside the exclusion zone and 20 minutes have passed.
- Same applies for when a marine mammal is detected (even on ice) while firing the airguns at full power. Upon reducing to mitigation gun, full power is re-initiated when the animal is outside the exclusion zone.
- Ramp-up is necessary every time firing of the airguns is initiated (except when using 'mini-airgun'), and should not take significantly longer than 20 minutes (over 40 minutes is considered excessive)
- If airguns stop for less than 5 minutes, they can restart at full power

- If airguns stop for between 5-10 minutes, a visual scan is performed in the exclusion zone: airguns may restart at full power if there is no sighting, but if there is one, mitigation gun is used until 20 minutes after the animal is outside the exclusion zone, and new ramp-up is initiated
- If airguns stop for longer than 10 minutes, pre-shooting search and ramp-up are required as explained above, except for when MMSOs can attest that there have been no sightings before and during the break, then pre-shooting search is not necessary
- For airgun testing, a 20-minute ramp-up is required if all airguns are to be tested at full power. Ramp-up is not required if a single airgun is to be tested at low power (further guidance is provided on this matter)
- Further guidance is presented for the procedures for line changes

New Zealand Code of Conduct (2013)

The New Zealand Government's Department of Conservation 2013 Code of Conduct for Minimising Acoustic Disturbance to Marine Mammals from Seismic Survey Operations[34] is subject to a thorough review process every three years. In 2015, feedback collected from experts[35] was addressed through several technical working groups.[36] Based on the advice from the technical working groups, a series of technical reports were produced, and a revised code of conduct was produced in 2017. The revised code also incorporated feedback from stakeholder workshops, such as increasing the flexibility of operators to use emerging technologies.[37] However, this latest draft guidance has not been implemented. In addition, the Government of New Zealand has prohibited future oil and gas exploration and associated seismic activities, although other seismic activities are expected to be subject to regulation using the 2013 code of conduct.

The code of conduct provides detailed guidance for operators on their legal requirements to minimize noise levels and the potential for disturbance to marine mammals in New Zealand waters. Whilst the code is primarily concerned with the protection of marine mammals, proponents are strongly encouraged to adopt whatever means are available to avoid or mitigate negative effects on other key species (such as turtles, penguins, and seabirds) or key habitats identified in the planning stage as being potentially impacted.

The code splits seismic surveys into three main types based on the airgun capacity:

- Level 1 (>427 cubic inches) – large-scale geophysical investigations with dedicated seismic survey vessels or other studies with high powered acoustic sources. This level has the most stringent requirements for marine mammal protection.
- Level 2 (151-426 cubic inches) – lower scale seismic investigations often associated with scientific research. Smaller platforms using moderate power or smaller source arrays with less risk and therefore less stringent mitigation measures.
- Level 3 (<150 cubic inches) – all other small-scale survey technologies that are of such low impact and risk that they are not subject to the provisions of the code.

Planning

For Level 1 and Level 2 surveys, the guidance requires that a marine mammal impact assessment (MMIA) is completed. As part of the planning phase, particular attention is required to minimize effects on defined areas ecological importance, including the use of spatio-temporal avoidance approaches. In addition, it is required that operations use the lowest practicable power levels for the acoustic source array.

Operation

The code also provides clear instructions on the specific roles and responsibilities of MMOs and PAM operators during operations and sets out procedures in the form of operation flowcharts that are practical and easy to use. The requirements for operational controls relate to each level of survey, with Level 1 and Level 2 surveys requiring the most stringent operational controls. This includes requirements for pre-start observations, soft-starts, approaches to be undertaken in poor sighting conditions, delayed start and shutdowns, and line turns. Pre-start observation periods for Level 1 and 2 surveys require that no marine mammals have been observed in the relevant mitigation zone for at least 30 minutes. In addition, for Level 1 surveys, no fur seals should be observed in the relevant mitigation zones for at least 10 minutes. For delayed starts and shutdowns, the mitigation zones vary based on the level of survey and the status of concern of the species observed. The maximum mitigation zone is 1.5 km for species of concern for Level 1 surveys, and the minimum zone is 200 m for species that are not of special concern (for Level 1 and 2 surveys). For species of concern, the time for delayed starts and shutdown is 30 minutes, and, for other species, in the 200 m zone only it is 10 minutes.

International Union for Conservation of Nature Geophysical Guidelines (2016)

The International Union for Conservation of Nature (IUCN) has produced a guide[38] for the planning of offshore geophysical surveys (using large-scale airguns) and other methods of environmental imaging (e.g., multi-beam sonar systems). The guidelines primarily focus on marine mammals, however its content is noted to be applicable and adaptable to any protected and sensitive species (PSS), e.g., fishes, marine turtles, seabirds. Following a pre-survey screening, the document outlines four necessary practices: (i) assessment and evaluation of the environment in the area, (ii) risk evaluation and plans development, (iii) implementation of mitigation and monitoring of operations, and (iv) evaluation and improvement.

Planning

In general, prior to survey activities, risk assessment of the activity and an analysis of environmental features and affected species in the survey area should occur. Existing data should be assessed on the occurrence and distribution of protected or sensitive species (PSS), physical/biological environment, and current and future human activities (in addition to survey activities). To determine the extent of risk, it is important to consider whether the present species/populations are threatened or endangered, whether they are resident or transient during the survey activity, whether the activity is planned to occur during biologically important periods, e.g., breeding, feeding, calving, mating, and the hearing capabilities and sensitivity to the sound sources.

Practice (i) involves the collection of baseline environmental and biological data (biotic and abiotic features of the ecosystem). The guide explains in full detail how to complete a robust evaluation of potential effects from a survey. In-situ measurements of the biological environment and natural variability patterns are necessary. Furthermore, the guide identifies how to determine the actions and alternatives for seismic surveys to reduce the noise impacts, followed by an emphasis on stakeholder engagement. Under practice (ii), the Guidelines provide information on how to conduct a structured evaluation of risks of proposed actions and alternatives (including the direct physical and behavioural responses by the species), develop a monitoring strategy and methods to be followed before, during and after the activities, and identify the appropriate mitigation actions, which may include the following:

- Plan activities during non-sensitive seasons/periods
- Minimize the use of the loudest noise sources during periods of low visibility
- Identify maximum allowable exposure levels for protected species and more vulnerable types of individuals (e.g., mother-calf pairs), as well as any other species
- Based on the maximum allowable exposure levels, determine the shut-down criteria
- Identify additional mitigation requirements
- Develop operational protocols for the detection of PSS: visual monitoring; real-time passive and/or active acoustic monitoring; aerial visual surveys; infrared, night-vision, or other technologies
- Use experienced and well-trained personnel, and designate an effective and integrated command chain

Operation

Practice (iii) deals with operational implementation of the mitigation measures mentioned above, implementation of real-time mitigation as well as of monitoring protocols. Implementation of mitigation measures requires written protocols, based on anticipated scenarios, that are understood and practiced by responsible parties in advance, and the guidelines provide a list of such protocols. Furthermore, implementation of real-time mitigation during operations may also include the following:

- Clear communication systems must be set up to ensure effective implementation of the mitigation measures
- It is recommended not to conduct operations at night or during low-visibility conditions, although it is acknowledged that not surveying at night may increase the overall duration of the survey
- Monitoring is a fundamental aspect of operation, and in the case of PSS or sensitive areas, there should be an independent observer to ensure objective reporting on the performance and efficacy of monitoring and mitigation
- Personnel responsible for implementing mitigation are trained, competent and not overly burdened with other responsibilities
- Such personnel are given rest in between observation periods to increase effectivity
- Operations do not resume until an all-clear is given by the central coordinator based on the protocols
- The central coordinator ensures that the reporting of observations for mitigation are being properly reported, archived and backed-up

Furthermore, the guidance includes advice on the implementation of monitoring protocols with data validation and archiving, which include real-time and archival monitoring systems, and require advance preparation, implementation with evaluation, and post-survey integration and reporting. Finally, there is advice on the assessment and evaluation procedures following the end of the operations (practice (iv)).

Convention on Migratory Species Guidelines (2019)

The Convention on Migratory Species (CMS) has published a report[39] on Best Available Technology (BAT) and Best Environmental Practice (BEP) to reduce or mitigate underwater sound from shipping, seismic airgun surveys and pile driving. The Guidelines stipulate that the most effective way to manage the threat of underwater sound is by using a precautionary approach, i.e., quieting. For seismic airgun surveys, this includes using quieting technologies, e.g., marine vibroseis, instead of airguns. For pile driving, the document outlines many new quieting technologies and quieter alternatives, e.g., gravity-based foundations, vibropiling, BLUE piling.

Planning

The BEP for underwater noise generated by shipping provides advice on spatio-temporal avoidance approaches. This includes re-routing shipping lanes around areas with important habitats and avoiding times and areas of high sound propagation as sound may travel further under certain conditions. Thus, ships should avoid or reduce the amount of time travelling parallel to the continental slope or shelf, and if they must travel across, they should do so at right angles. They should further avoid or reduce time at colder and higher latitude waters, and generally operate in the warmer months.

The BEP for seismic airgun survey sound generation mentions the two most effective mitigation measures: (i) avoid conducting activities in the areas rich in marine life and sensitive species, and (ii) quieting, i.e., lowering the source level. Baseline studies of biological abundance and distribution of marine life are necessary at least once a year (preferably twice), to identify the biodiversity-rich areas, and must be of sufficient quality and statistical power. Sensitive and important areas/seasons for activities such as spawning, breeding, feeding and migration should be avoided, not only for marine mammals but also marine turtles, fishes and invertebrates. Furthermore, acoustic refuges of still quiet habitat should be established, and marine protected areas (MPAs) should include acoustic buffer zones around them. Additionally, for pile-driving sound, activities with noise levels that could injure or harass marine mammals cannot occur during periods of highest risk for priority species.

Operation

For sound generated by shipping, the document primarily highlights slow steaming or reducing ship speed, which reduce both underwater sound levels as well as greenhouse gas emissions. Furthermore, the practice of cold ironing, better maintenance, minimizing cavitation, optimizing the propeller design to the hull and to usual operating conditions, and focusing quieting on the 10-15 per cent of the noisiest container and cargo ships are additional measures to reduce the impacts of shipping noise.

For underwater sound generated by seismic airgun surveys, the exclusion (mitigation) zone should be dynamically set based on oceanographic features but should be at minimum 500 m. However, a minimum pre-clearance zone (pre-ramp up watch zone) should be 1 km from the outer perimeter of the airgun array. Activities should occur only in daylight and good visual as well as weather conditions. Activities at night or in poor visibility are allowed only if PAM is proven to be as effective as PAM together with MMOs. PAM is recommended to be used alongside MMOs, but it is stated that these may be inadequate if animals are not vocal or easily heard. During operations, a pre-watch by well-trained MMOs and PAM operators is necessary for at least 30 minutes prior to commencement of ramp-up (soft start). In deep waters where beaked whales may be expected, the pre-watch should be at least 120 minutes. If sensitive species are detected in the exclusion zone or approaching it, ramp-up is delayed and may not begin until 30 minutes after the sighting; this rises to 120 minutes in case of beaked whales. An immediate shutdown should occur if a sensitive or vulnerable species enters the exclusion zone. The Guidelines further emphasize monitoring and reporting protocols, data sharing and conducting biological survey after the seismic survey is finished to verify any changes in the abundance of distribution of species.

For sound generated by pile-driving, the guidelines recommend using Acoustic Deterrent Devices, which may purposely displace marine species at the start of pile driving. Additionally, pile driving should include similar procedures for ramp up (soft start) as well as MMOs and PAM operators as for seismic surveys. Visual and acoustic monitoring should take place 24 hours a day, and pile driving should not be allowed at night or in poor visual conditions.

International Association of Oil & Gas Producers and International Association of Geophysical Contractors Guidelines (2017)

The International Association of Oil & Gas Producers (IOGP) and International Association of Geophysical Contractors (IAGC) have produced recommendations for monitoring and mitigation measures for cetaceans (whales, dolphins, and porpoises) during seismic surveys that use compressed air source arrays.[40] The Guidelines are similar to the other guidance mentioned previously, outlining an exclusion zone of 500 m, visual observation for at least 30 minutes prior to operation, with a delay in soft-start procedure until at least 20 minutes after last sighting. Soft-start begins with the smallest volume element in the array, and it should last at least 20 minutes but not longer than 40 minutes, as stipulated in other guidelines. Soft-start does not have to be reinitiated if seismic sources have been silent for less than 20 minutes. Contrary to some of the other guidance, activities may proceed (beginning with the soft-start procedure) in poor visibility or darkness but the use of PAM should be considered in such cases.

CONCLUSIONS

The above guidelines outline mitigation measures to reduce the impact of noise on marine mammals, and in some cases on marine turtles, fishes or seabirds, from the use of geophysical/seismic surveys, pile driving, sonars, explosives and shipping. Geophysical/seismic surveys are covered by ACCOBAMS, JNCC, IBAMA, BOEM, CMS, IUCN, IOGP/IAGC, Canadian, New Zealand and Greenland guidelines, pile driving by JNCC, ACCOBAMS and CMS guidelines, sonars by ACCOBAMS, explosives by ACCOBAMS and JNCC, and shipping by CMS. Some of the guidance applies regionally (ACCOBAMS, Gulf of Mexico), some nationally (United Kingdom of Great Britain and Northern Ireland, Canada, Brazil, Greenland, New Zealand). Other guidelines are more generalized for their spatial consideration (guidelines of IUCN, CMS, IOGP and IAGC). In general, most of the guidance outlines specific measures for avoidance and minimization of the noise risk associated with the above activities, including spatio-temporal restrictions and operational controls, as further described below. However, some tend to focus more on one or the other, for example the US BOEM guidelines, which primarily outline measures for minimization but do not deal with avoidance. Further to that, some guidelines emphasize the importance of assessments and evaluation of the area environment and of the associated risk, as well as proper planning, monitoring and evaluation procedures, such as the IUCN guidelines. The Greenland guidelines further outline the procedures for EIA and EMA. While many of the guidelines recommend the same or similar tools and procedures, sometimes they may differ in the details and implementation aspects of the protocols.

MITIGATING IMPULSIVE SOUND

Operational controls

Detailed guidelines for noise-generating activities that include such protocols are included in the guidelines discussed above. In general, existing guidelines cover the following:

- *Pre-shoot watches* – All guidelines recommend pre-shoot watches to search for any animals within the mitigation zone by the MMOs or PAM operators, however they tend to differ in the time required. For seismic surveys, it is generally 30 minutes, but JNCC and Greenland guidelines further specify that this time period applies to water depths <200 m, and in depths >200 m pre-shoot watch should last 60 minutes; the New Zealand Code provides a shorter time period for fur seals. As per CMS guidelines, in deeper waters where beaked whales are expected, it is 120 minutes. As for explosives and piling, pre-shoot watches should last 60 and 30 minutes, respectively.
- *Soft-start/ramp-up* – All guidelines require the implementation of soft-start procedures after the pre-shoot watches, except when using mini-airguns. Many guidelines stipulate that they should last for at least 20 minutes, and no longer than 40 minutes. JNCC guidelines for seismic surveys further outline soft-start of at least 15 minutes, and no longer than 25 minutes if maximum airgun volume is <180 cubic inches. JNCC guidelines for piling and Canadian guidelines do not provide the maximum duration. The Moulton et al. (2020)[41] review, however, mentioned that maximum duration must always be provided and may vary depending on the number of vessels and array size, thus it cannot be standardized.
- *Mitigation/exclusion/safety zone* – While all guidelines stipulate that a mitigation zone must be established, they tend to differ regarding the distance of the zone—500 m is suggested for piling and seismic surveys by JNCC, BOEM, Canadian and Greenland guidelines, whereas 1 km is suggested by JNCC for explosives and by IBAMA for seismic surveys. The New Zealand guidelines provide a range of zones depending upon the species of concern and level of survey, with 1.5 km being the maximum and 200 m the minimum. The CMS guidelines recommend at least a 500 m mitigation zone, and a 1 km pre-ramp up watch zone.
- *Soft-start delay* – The guidelines recommend a delay to soft-start if an animal has been sighted within the mitigation zone during pre-shoot watch, however they differ in the period of time for the delay. JNCC and Greenland guidelines suggest a delay of 20 minutes since last detection. The IBAMA, BOEM and CMS guidelines suggest a delay of 30 minutes, but in the case of beaked whales the CMS guidelines further recommend a delay of 120 minutes. The New Zealand guidelines also recommend delayed starts of 30 minutes for most marine mammal species across mitigation zones, except for fur seals, which is set at 10 minutes within a 200 m mitigation zone.
- *Shut-down* – CMS, IBAMA, BOEM and New Zealand guidelines recommend an immediate shut-down when an animal is sighted within the mitigation zone. Greenland guidelines indicate that if there is a detection during ramp-up or at full power, firing should be reduced to mitigation gun, and full power may be re-initiated when the animal is gone and 20 minutes have passed.
- *Operational stoppages* (i.e., for maintenance) – Most of the guidelines address the steps for operational stoppages, but they tend to differ. BOEM and IOGP/IAGC guidelines suggest that breaks of less than 20 minutes do not have to be followed by ramp-up procedures (for borehole seismic surveys this applies to breaks of less than 30 minutes). IBAMA and Greenland guidelines recommend that operations may fully resume after breaks of less than 5 minutes. Greenland guidelines further state that breaks of between 5 and10 minutes require a visual scan for any sightings, and over 10 minutes full pre-shoot watch and ramp-up procedures. The Canadian guidelines do not specify how long the air sources can be stopped for before a ramp-up is required.
- *Activities in periods of poor visibility and darkness* – Most guidelines recommend conducting activities during daylight or when visibility is good, otherwise the use of PAM is highly recommended. IBAMA and Greenland guidelines, however, require the use of PAM in the dark or when visibility is poor. Furthermore, CMS guidelines allow activities at night or in poor visibility only if PAM is proven to be as effective as PAM together with MMOs.

These operational controls primarily provide approaches to reduce risks of injury to marine mammals. The measures proposed also present opportunity to reduce risks to other taxon (e.g., marine turtles and fishes), but their effectiveness in this regard is largely unproven. These measures do not provide robust mitigation for other impacts that may occur, such as behavioural, stress or perceptual effects. To support the implementation of operational controls, the guidelines discussed above provide guidance on monitoring approaches, which generally including the undertaking of visual observations and PAM.

These approaches are widely undertaken for offshore development activities. However, some authors have questioned the potential effectiveness of these approaches. Leaper et al. (2015)[42] reported upon the limitation of visual observations to mitigate impacts, including the fact that visual detectors will only detect a proportion of marine mammals that are within a mitigation/ exclusion / safety zone. They reported that in many cases the use of visual observers will result in a very small risk reduction. Although PAM is often used in conjunction with visual observations, they reported that there is limited data on the probability of detection associated with PAM, and that acoustic detection probability is strongly associated with underwater sound levels and vocal behaviour. Nelms et al. (2016)[43] provided a detailed review of the operational controls that are adopted for marine turtles for seismic activities. They reported upon limitations, including issues associated with the detection of marine turtles in darkness or when visibility is poor, as well as in conditions above Beaufort 1 wind scale. The approaches taken also do not detect individuals below the surface, and therefore, detection rates are low; detection rates decrease at distance and the mitigation/exclusion/safety zones are too extensive for detections to be viable; and the appropriateness of these zones and approaches to minimize risk to marine turtles is unknown. They recommended that for real-time mitigation measures to be effective, an ability to locate individuals is essential. Given the issues with respect to visual observation and in the absence of other proven techniques, they recommended the use of spatio-temporal restrictions as a priority, especially in areas where important life functions occur.

Alternative technologies to limit impulsive sound production

A summary of alternative noise-quietening technologies for impulsive-sound-generating activities relating to seismic surveys and offshore construction is provided in Table 3, with information provided on their known effectiveness and state of development. Information was mainly derived from reviews in existing literature,[44,45,46,47,48] where considerable further detail can be found on the technologies, and from some existing guidelines.

Alternative acoustic source technologies are those that have the potential to replace existing commonly used technologies in certain conditions. Many of the alternative technologies are in various stages of development and are currently not commercially available for use, although considerable progress has been made in recent years, especially in the development of alternatives to pile driving for offshore wind turbines[49] (Table 3a). There are several alternative foundation types in existence or currently being developed, including vibratory pile driving, foundation drilling, floating wind turbines and gravity-based or bucket foundations. Underwater sound measurements during installation are only available for a few of these technologies but many reduce or eliminate the emission of impulsive sound generated by pile driving. Some alternative approaches may emit continuous sound, though at lower levels. The use of alternative approaches requires a case-by-case assessment of the techniques that are proposed, their technical feasibility and baseline characteristics.[50]

Alternative technologies to replace airguns in seismic surveys have been under development for some time and include marine vibroseis (MV), the low-level acoustic combination source (LACS) and a low impact seismic array (LISA) (Table 3b). Most of these technologies are still under development or testing. MV prototypes are currently being tested but are not yet commercially available.[51] A LACS system is commercially available for shallow penetration of sediments, towed streamer seismic surveys or vertical seismic profiling. A modelling comparison of received sound levels produced from an MV array and an airgun array showed that, overall, MV produced lower broadband SELs, particularly at long range, and lower peak pressure, especially at short-range, than airguns.[52]

Table 3. Summary of alternative technologies available for pile driving (3a) and seismic surveys (3b) and their development status

3a: Marine Construction – Pile Driving (Sources: Koschinki and Lüdemann, 2013[53], 2020[54]; ACCOBAMS, 2019[55]; CSA Ocean Sciences Inc., 2013[56], and references therein)

Technology	Description	Emissions	Development Status / Comments
Vibropiling	Vertical oscillation of the pile at a specific low frequency (10-60 Hz) using rotating weights. Often used in combination with impact pile driving	Lower peak pressure levels than impact driving, 10-20 dB. Some broadband sound emitted at higher frequencies between 500 Hz and several KHz.	Proven technology. Routinely used on smaller piles. Total energy imparted can be comparable to impact pile driving as more time is required for installation. Technology for larger piles and deeper water have been developed
Drilling **(and cast-in-place concrete piles)**	Drill head is clamped to the pile base and drills a cavity into which the pile sinks. Various technologies currently being developed. The drive-drill-drive method combines impact piling or vibropiling with drilling – when resistance is met, the material inside the pile is drilled out.	In shallow water emitted sound levels are much lower than impact pile driving, and continuous levels are lower than those from large vessels	Proven technology for several offshore deep foundation applications but some technologies still under development. Sound levels have not been fully documented in offshore conditions.
Vibro-drilling	Combination of a vibrator tandem PVE and a drill head in one unit. Pile is driven into the seabed by vibration, drilling is applied when there is resistance to vibration	<130 dB @ 750 m (estimated, not field tested)	Development stage not known
Press-in-piles	Use of hydraulic rams to push piles into the ground. Self-contained units that use static forces to install piles. Designed for urban areas but also used in shallow waters	Underwater sound measurements not available but sound levels are expected to be very low	Not known for offshore developments
Gravity-based foundations	Steel-reinforced concrete structures held in place by their weight and supplementary ballast. Excavation of the seabed required by suction hopper dredging for most designs.	No specific sound measurements available but impact pile driving / impulsive noise is eliminated. Main emissions are sounds from ships and dredging	Proven technology in shallow waters (<20 m depth). Very limited use in deeper waters but developments are planned for up to 45 m. One design, the crane-free gravity foundation, is self-installing and does not require dredging or levelling of the seabed. This currently needs testing at the full-scale prototype stage.

Technology	Description	Emissions	Development Status / Comments
Floating foundations	Three main types: spar, tension leg platform and semi-submersible platforms. Aimed at expanding wind farms into greater depths. Can involve pile driving to fix anchor points or use gravity base or suction anchors	No specific sound measurements available but no reduction in emissions expected if pile driving is used for anchor installation. For other anchoring systems emissions from gravity base and suction anchors are expected to be similar to gravity and bucket foundation installation respectively.	Mainly at prototype stage but often based on proven technology from the oil and gas industry. Semi-submersibles and SPAR buoys have been most thoroughly tested.
Bucket or suction-based foundations	A large steel caisson that is embedded into the seabed by suction pumps. Water is pumped out of the cavity underneath the caisson – the vacuum in combination with the hydrostatic pressure enables the caisson to penetrate the seabed	No specific sound measurements available but noise levels thought to be negligible as impact pile driving / impulsive sound is eliminated. Sound sources are support ships and the suction pump	A proven technology in the oil and gas industry. Designs for wind farms are currently at the full-scale prototype and demonstration project stage.

3b: Seismic Surveys (Sources: ACCOBAMS, 2019[57]; CSA Ocean Sciences Inc., 2013[58] and references therein)

Technology	Description	Emissions	Development Status / Comments
Marine vibroseis	Hydraulic and electromechanical MVs can be towed in the same configuration as airgun arrays or operated in a stationary mode. MVs have lower source signal rise times, lower peak pressures and less energy above 100 Hz. Electromechanical systems have several technical and logistical advantages over hydraulic ones.	Source level: 203 dB re 1μPa; 6-100 Hz. Auditory masking is likely to be more of a problem than with using airguns as signals are for a longer duration and will have a higher duty cycle (per cent time "on"). The masking issue may be overcome by using a sweep as signal.	MV prototypes still being tested, but are not yet commercially available (Weilgart, 2018b)[59]. Previous hydraulic systems successfully field tested but not cost-effective due to expense to retrofit vessels. New "seavibe" prototype is reliable and more efficient than airguns.
Low Level Acoustic Combination Source (LACS)	The LACS system is a combustion engine producing long sequences of acoustic pulses at a rate of 11 shots/second with low intensity at non-seismic (>100 Hz) frequencies.	Source level: 218 dB re 1μPa at 1 m (peak to peak)	One system is market available and suitable for shallow penetration, towed streamer seismic surveys or vertical seismic profiling. Second system for deeper penetration is under development and needs field testing once built.
eSource	eSource is a tunable, flexible seismic source that reduces the high frequency emissions. The key principle behind eSource is the gradual release of air at a predetermined rate and as a function of time. By controlling the way the air is released, the spectral content of the pressure signal can be tuned.	Unknown.	Commercially available and tested.

Complementary technologies for seismic surveys

As well as developing alternatives to airguns to conduct seismic surveys, there is some potential to reduce the amount of seismic survey activity required using existing complementary technologies or methods to investigate subsurface geology.[60] These include low-frequency passive seismic methods, electromagnetic surveys, gravity and gravity gradiometry surveys, and the use of fibre optic receivers.

Low-frequency passive seismic methods use natural sounds (natural seismicity, ocean waves and microseism surface waves) to image the subsurface and have been studied in academia and industry to identify and delineate hydrocarbon reservoirs.[61] Of the three natural sounds that are recorded, the use of microseism surface waves is still at an early stage of development, the ocean waves method requires further testing, and measuring natural seismicity takes longer to collect sufficient data to produce results than the other two.[62] However, all three ways are regarded as promising and worthy of further investigation and development.

Electromagnetic (EM) surveys are often used in conjunction with seismic surveys, and there are currently two techniques that have been used as an exploration tool in the last decade: controlled source electromagnetic (CSEM) and magnetotelluric (MT) surveys. The CSEM technique involves the transmission of very low frequency (< 1 Hz) EM signals into the upper layer of the seafloor. The environmental impacts of CSEM are expected to be negligible as the CSEM source uses extremely low spatial and temporal frequencies with a small region of potential influence to marine life.[63] MT surveys are a passive measurement of the Earth's EM fields by detecting the natural electrical and magnetic fields present.[64] Both methods are often used in combination for subsurface mapping. At the present time, these methods do not have the resolution or penetration to replace seismic surveys, but broader application of EM methods does have the potential to reduce the level of 3D seismic surveying required.[65]

Gravity and gravity gradiometry surveys are passive remote-sensing methods that measure variations in the naturally occurring gravity field. Both technologies have been used by mining and petrochemical industries for decades.[66] Gravity gradiometry involves measuring the Earth's gravity gradient and provides better resolution than gravity surveys but also requires more complex and expensive equipment. The techniques are not applicable in all geological settings but have the potential to reduce the amount of seismic survey effort required.[67]

Fibre optic receivers are sensors that incorporate optical fibres to transmit the received acoustic signal as light.[68] They are mainly used for seismic permanent reservoir monitoring, but the technology is not currently available for towed streamer surveys. However, several key characteristics have been identified that could lead to sound reduction during airgun surveys:[69]

- Reduced amplitude – fibre optic receivers on the seafloor have greater sensitivity and achieve a better signal-to-sound ratio than towed conventional sensors which are subject to additional sound in the water column. This allows the use of smaller airgun sources for 4D surveys
- Reduced airgun volume – fibre optic receivers have better low-frequency performance meaning that the requirement for large airgun volumes may be reduced
- Reduced survey duration – as the receivers are permanently deployed, total survey time is reduced compared to towed streamer surveys because no infill is needed, and weather downtime is minimized.

The technology is particularly suited to future use with alternative seismic sources that produce less high frequency output. To accommodate conventional airgun sources, the sensors require a large dynamic range at higher frequencies to avoid sensor saturation,[70] and these sensors are currently expensive. Combining fibre optic receivers with techniques that emit less high-frequency sound, such as marine vibroseis, will eliminate the need to use the more expensive sensors.[71]

Abatement technologies

Several mitigation techniques have been developed to attenuate noise from activities that generate impulsive sound in the marine environment (Table 4). This section focusses on techniques designed to reduce noise levels from marine construction activities, particularly pile driving (Table 4a) and seismic surveys (Table 4b). Information sources used to compile the tables were primarily two reviews of noise mitigation techniques produced by the Governments of the United States of America[72] and Germany,[73,74] with additional information from ACCOBAMS,[75] OSPAR[76] and Bellman et al. (2020).[77] It is important to note that systems work at varying distances from source.

Table 4. Summary of noise abatement techniques for pile driving (4a) and seismic surveys (4b) and their development status

4a. Pile driving and associated marine construction activities (dredging and drilling)

Mitigation Technology	Description	Emission Reduction	Development Status* / Comments
Big air bubble curtain	A large bubble curtain that usually consists of a pipe with drilled holes placed on the seabed around the whole foundation or structure. Compressed air escaping from the holes forms the bubble screen, shielding the environment from the noise source.	Single bubble curtain: 11-15 dB (SEL), 8-14 dB (peak)** Double bubble curtain: 17 dB (SEL), 21 dB (peak)	Proven technology and potential for optimization in terms of handling and system effectiveness (air supply, bubble sizes and distance from source). Double screens reduce emissions more than single ones and are most effective when two separate bubble curtains form. Seismic path propagation may be reduced due to the large diameter of the system.
Little air bubble curtain (several variations)	More customized smaller curtain that is placed around the noise source in a close fit. Can consist of a rigid frame placed around the source but several designs are possible: -Layered ring system – multiple layers of perforated pipes that surround the source in a ring-shaped arrangement; -Confined bubble curtain – additional casing around the area of rising bubbles. Casing can consist of plastic, fabric or a rigid pipe and does not affect the mitigating properties of the system; -Little bubble curtain of vertical hoses – vertical arrangement of several perforated pipes or hoses around the source.	Layered ring system: 11-15 dB (SEL), 14 dB (peak) Confined little bubble curtain: 4-5 dB (SEL) Little bubble curtain with vertical hoses: 14 dB (SEL), 20 dB (peak)	Pilot stage with full-scale tests completed. Practical application possible. Tidal currents can cause bubble drift and sound leakage, but effect can be minimized in more recent designs. Confined bubble curtains initially designed for shallow waters with strong tidal flow. All designs do not affect seismic path propagation. Vertical hose design prevents sound leakages as there are no horizontal gaps between the hoses.
Hydro Sound Damper (HSD)	HSD consists of fishing nets embedded with small latex balloons filled with gas and foam that surround the source. The resonance frequency of the balloons is adjustable, even to low-frequency ranges.	10-13 dB (SEL) at 750 m; >20dB at 100-800 Hz and)	HSD have been successfully applied with >340 piles in various commercial offshore windfarms at water depths up to 45 m and pile diameters up to 8 m with a very low rate of malfunction.
'encapsulated bubbles'	Same principle as HSD - balloons of 6-12 cm diameter used to reduce low-frequency components of pile driving noise.	Up to 18 dB (singular third octave bands)	Currently under development with a few "proof of concept" field experiments completed.

Table continues on next page

Mitigation Technology	Description	Emission Reduction	Development Status* / Comments
Dewatered cofferdams	Rigid steel tube that surrounds the pile from seabed to surface, with the water pumped out between the tube and pile. The air space between the pile and the water column attenuates sound – acoustic decoupling of the pile driving noise within the cofferdam.	Up to 22 dB (SEL), 18 dB (peak) Generally expected to match bubble curtains in terms of noise mitigation	Practical application in many commercial projects in shallow waters (<15 m). Currently at the pilot stage for deeper offshore waters and proposed for depths of at least 45 m. Further developments for offshore underway (e.g., free standing system, telescopic system). Installation likely to require more time than lined barriers or bubble curtains, and specialist equipment is needed for offshore developments.
Pile-in-Pipe Piling	Particular type of cofferdam where the cofferdams are the four legs of a foundation. Pile driving occurs above the sea level so that acoustic decoupling is enabled by the construction itself. Requires considerably more material than conventional cofferdams.	27–43 dB (SEL) – modelled High noise reduction expected	Validated concept stage but is a variation on a proven technique. Complete dewatering of cofferdams will be crucial Cofferdams are not reusable as they are part of the foundation.
IHC Noise Mitigation System (NMS)	Double-layered screen filled with air and a multi-level and multi size confined bubble curtain between the pile and the screen.	5-17 dB (SEL)** Noise reduction by NMS predicted to exceed that of a bubble curtain	Applied in over 450 pile installations for pile diameters of up to 8 m with a very low rate of malfunction
BEKA Shells	Double steel casing with a polymer filling combined with an inner and outer bubble curtain and acoustic decoupling (vibration absorber). Multiple layers create shielding, reflection, and absorption effects.	6-8 dB (SEL)* Predicted to have the highest noise reduction potential of all techniques presented	Lower end penetrates the seabed to decouple sound transmission along the seismic path. *Available emission reduction data collected in specific problematic circumstances (ESRa Project). Pilot stage completed. Requires full-scale testing in offshore field conditions.
Prolongation of pulse duration	Prolonging the pulse duration of a pile strike will reduce the corresponding sound emission which in principle can be achieved by having an elastic piling cushion between the hammer and pile. Disadvantage of a loss of piling force with the use of cushions increasing the total number of strikes.	Models: 4-11 dB (SEL), 7-13 dB (peak)** Piling cushions (various materials): 4-8 dB (SEL)**	Modelling and experimental stage for large pile diameters but proven technology for small pile diameters. In tests, Micarta (Bakelite) was identified as the best option for piling cushion material.
Modification of piling hammer	Not specified	Not available	Experimental stage – research results pending
AdBm Noise Abatement System	Uses large arrays of Helmholtz resonators, tuned to specific frequencies, to capture and mitigate noise from various noise sources	Not available	Proven to water depths of 40 m, and capable of operating to >100 m

* With regard to North Sea offshore conditions and water depths to 40 m.

** Data from several developments or field tests combined

4b. Seismic surveys

Technology	Description	Emission Reduction	Development Status / Comments
Bubble curtains	Evaluation of deploying towed air bubble hoses to reduce lateral noise propagation (BOEM sponsored study).	Initial evaluation; at least 20 dB Second evaluation: bubble curtains were not able to produce the required noise reduction.	Not practical for deep water and does not block sound when there is a direct line of sight to the source.
Parabolic reflectors	Evaluation of the potential to make airgun arrays more vertically directional by towing a parabolic reflector over the array.	Potential for large reductions in sound, especially at vertical angles > 70°.	Not recommended for further investigation in 2009 due to several limitations (elevated risk in towing and deployment, not effective in shallow water because of bottom reflections).
Airgun silencer	Consists of acoustically absorptive foam rubber on metal plates mounted radially around the airgun.	Tests: 0-6 dB (SPL) above 700 Hz but overall increase in SPL of 3 dB due to an increase in sound near 100 Hz.	Modest reduction achieved in tests but thought to have potential to improve. Regarded as a "proof of concept" that would require further development in 2007 but later, in 2009, as "impractical".

The information provided here is an overview of existing and developing noise reduction techniques; the information sources mentioned above should be consulted for more detailed information. In addition, one of the main sources of information used[78] was compiled as an information synthesis background document for a workshop on quieting technologies for seismic surveying and pile driving, organized by the Bureau of Ocean Energy Management (BOEM) of the Government of the United States.[79] The final summary report describes the discussions, conclusions and recommendations of this workshop.

Techniques to reduce noise from pile driving mainly consist of placing a barrier around the pile to attenuate sound from hammering. The barrier can be a solid casing that is drained or filled with a layer of bubbles or other absorptive materials, or a curtain of bubbles. There has been considerable progress in the development of a range of methods to mitigate pile-driving noise. The most commonly used techniques are cofferdams and bubble curtains. Techniques that alter the duration of the noise pulse and the design of the piling hammer are also at the early stages of development (Table 4a).

There have been numerous studies of the effectiveness of bubble curtains for wind turbine foundations, docks and other coastal construction projects and pile driving activities (See CSA Ocean Sciences Inc., 2013[80] for a list of published studies). Big bubble curtains (BBCs) are currently regarded as the best-tested and most proven noise mitigation technique for the foundations of offshore wind farms.[81] Their suitability has been shown through modelling, field testing and practical application. Additionally, using a double layer of bubbles can be considerably more effective for noise mitigation than a single bubble curtain. Little bubble curtains (LBCs) also have considerable potential, and more recent designs involving the use of a ring of vertical hoses or casings can prevent bubble drift in tidal currents.[82] Of the three designs mentioned (Table 4a), the curtain of vertical hoses is at the most advanced stage of development. LBCs have the potential to be applied in commercial offshore settings once the components are adapted to offshore conditions.[83] To date, bubble curtains have been shown to result in noise reductions that can meet regulatory noise criteria,[84] reduce behavioural disturbance of marine mammals[85] and avoid fish kills.[86]

Hydro Sound Dampers (HSD) use a net embedded with small elastic, gas-filled balloons and foam to enclose the pile. By varying the balloon size, the HSD can be adjusted to achieve maximum noise reduction at particular frequencies. Other advantages over bubble curtains are that the HSD system is very flexible in terms of assembly design to suit different applications and does not rely on compressed air.[87]

The known effectiveness and current development status of two recent designs for complex isolation casings (IHC Noise Mitigation System and BEKA Shells) are summarized in Table 4a. These combine the effects of a reflective casing and confined bubble curtains with the principle of cofferdams to reduce noise by absorption, scattering and dissipation.[88] Both systems have been designed primarily for piling activities and in theory will achieve greater noise reduction than bubble curtains or cofferdams individually. However, both systems require further testing in an offshore setting to provide actual emission reduction data that can confirm the modelling predictions.

The potential for technical noise mitigation from pile driving is currently limited by the multipath transmission of the emitted sound waves. Modelling of the relative contribution of propagation pathways (air, water, and seismic paths) indicates that the water path propagates the greatest amount of noise, and mitigation techniques have therefore focused on reducing the sound radiation into the water.[89] However, the seismic contribution through the seabed is usually the limiting factor for the effectiveness of mitigating the water path[90] as a considerable amount of sound energy can re-enter the water column via the seismic path. The seismic contribution to overall sound transmission in water is 10-30 dB less than the three paths combined.[91] Therefore, the maximum achievable noise reduction for current mitigation techniques is limited to 30 dB unless the seismic path is also attenuated.[92]

Damping of the seismic path from the embedded section of the pile is currently difficult[93] but needs to be considered if noise mitigation systems are to be improved further.[94] The application of BBCs may enable noise reduction from the seismic path as the large diameter of the mitigation system can extend beyond the distance where seismic path noise re-enters the water column. BEKA shells are also designed to mitigate the noise propagated through the seismic path by penetrating the seabed and decoupling the sound transmission via this route.[95]

Verfuss et al. (2019)[96] have undertaken a review of abatement technologies for the construction of offshore wind farms. Their review found that numerous systems are deployed, including BBCs, NMS, HSD and vibrohammers. They reported that for BBCs, NMS and HSD, broadband sound levels can be reduced by at least 10 dB, and reductions of up to 20 dB have been demonstrated—more when combining two approaches. They also concluded that abatement approaches are generally more effective at reducing the risk of noise impact on marine mammals and fish sensitive to higher frequencies.

Noise mitigation techniques for seismic surveys Several techniques to reduce lateral noise emissions from airguns have been investigated including the use of bubble curtains and parabolic reflectors, and the development of an airgun silencer or re-designed quieter airguns (Table 4b). Both bubble curtains and parabolic reflectors were regarded as impractical and ineffective after initial evaluation. Airgun silencers were first thought to have potential, as modest levels of noise reduction were measured during tests,[97] but then were also later considered to be impractical.[98] Efforts to re-design airguns for the reduction of high-frequency emissions have made more progress and are commercially available.

Mitigation of continuous noise from vessels

The main sound sources from ships are those caused by the propeller, by machinery, including sea-connected systems (e.g., pumps), and by the movement of the hull through the water.[99,100,101] Propeller cavitation is usually the dominant source for large commercial vessels.[102]

Guidelines for minimizing underwater noise from commercial ships have been developed by the Design and Equipment Subcommittee of the International Maritime Organization (IMO).[103] The guidelines mainly focus on considering noise in the design of propellers and hulls, and in the selection of on-board machinery. They also encourage model testing during the design phase and maintenance during operation. The draft guidelines were adopted by the IMO's Marine Environment Protection Committee in 2014. The guidelines are voluntary and are intended to provide general advice about the reduction of underwater noise to designers, shipbuilders and ship operators. The adoption of these guidelines is said to have represented acknowledgement of the severity of the issue and were considered a big step forward in reducing ship noise.[104] Guidelines for commercial shipping have also been developed by the AQUO and SONIC projects in Europe.[105]

Reducing noise production by ships can be achieved through design or operational solutions, and a wide range of these are available.[106,107,108] Many of the alterations are designed to improve the propulsive efficiency of the ship. It is thought that existing technology can be used to quieten the noisiest ships, which are also currently operating at sub-optimal efficiencies.[109] The main techniques available are improving propeller design to reduce cavitation and match actual operating conditions and improving the wake flow into the propeller for existing ships or for new vessels. The latter is achievable with relatively little additional cost to the overall price of a vessel[110] and reduces the cost compared to retrofitting;[111,112] it may also result in lower running costs once operational.[113] Retro-fitting existing ships to improve wake flow is also relatively cheap compared to other more substantial design changes. Gassman et al. (2017)[114] reported that retrofitted design modifications to improve energy efficiency may also lead to reduced underwater noise. Sound generation can also be reduced by making machines run more quietly through improving balance, tightening tolerances, changing geartooth profiles, etc. [115] Vard Marine (2019)[116] have produced a technology matrix for a range of design mitigation approaches. This matrix includes a review of measures, their advantages and disadvantages, readiness, cost implication, whether they apply to new builds or retrofitting, and their effectiveness. Other less recent reviews have been produced to summarize available design measures.[117,118] These reviews are extensive and are not repeated here. They include measures such as altering propeller design, wake flow modification, machinery improvements and treatments, engine selection (including alternative fuels), hull treatments (including air bubble abatement) and use of wind propulsion (e.g., kite sails). Vard Marine (2019)[119] also provide a summary of methods to predict the level of underwater sound generation. Due to the time lags associated with implementing design measures to global shipping, the most effective approaches in the short to medium term would be to target actions for the noisiest vessels.[120]

Transport Canada (2019)[121] reported on the proceedings of an international technical workshop it hosted at IMO Headquarters in London from 30 January to 1 February 2019. They reported on a range of approaches for quieting ships and provided a range of recommendations for actions and future work, including the bodies that could implement them. The recommendations are not repeated here, but included the production of a new quiet ship design guide, development of thresholds and measurement methodologies, development of noise monitoring in at least one major port in each of the largest shipping nations, developing a publicly accessible database, developing designs for abatement approaches (such air bubble systems), and a range of policy options (e.g., providing economic incentives, regulatory limits and compulsory monitoring of shipping sound).

Operational procedures to reduce noise emissions are mainly concerned with travelling at slower speeds or ensuring there is routine maintenance of equipment such as propellers. Ship speed can affect the level of sound produced by some vessels,[122,123] but the relationship may be weak or non-existent, particularly for vessels with controllable pitch propellers.[124] Trounce (2018)[125] reported on a trial of voluntary vessel slowdowns in Haro Strait, Canada in 2017 as part of the Vancouver Fraser Port Authority's (VFPA) Enhancing Cetacean Habitat and Observation (ECHO) Program. Joy et al. (2019)[126] also reported on the benefit of slowdowns from the ECHO Program on resident orca whales in the Salish Sea. These studies demonstrated that slower speeds resulted in the reduced generation of underwater sound and behavioural impacts. Faber et al. (2017)[127] considered a range of speed restrictions on global shipping economics. They reported that if idle ships were brought back into service, in 2017 vessels speeds could be reduced by 8 per cent to mitigate slower shipment of goods. Leaper (2019[128], 2014[129]) also reported that the fuel savings from slower speeds were usually higher than cost of operating extra vessels. In addition, the growth of fleet tonnage and increases in capacity could allow speed reductions as high as 20-30 per cent for most ship types.[130,131] McKenna et al. (2013)[132] reported that an optimal trade-off between duration and intensity of shipping may be achieved at around 8 knots.

As part of the ECHO Program, vessel design characteristics have been correlated with underwater sound generated by vessels.[133] This research determined that vessel length had the strongest correlation with the level of sound produced. This was followed by main engine RPM, main engine power, auxiliary engine power and design speed, which were also correlated with underwater radiated noise; the relative strengths of these correlations were not always consistent between vessel categories. However, none of these individual design characteristics were found to be associated with those vessels having the lowest noise emissions. Instead, specific vessel operating conditions, including reduced speed through water and reduced draft, were most strongly associated with the lowest noise emissions. It is important to note that ECHO Program incorporated consideration of changes to ambient underwater sound levels from other factors, such as currents, water temperature, weather and biological components, which supported the evaluation of mitigation measures.

Regulating vessel routing and scheduling[134] may also achieve reductions in ambient underwater sound levels by reducing the density of shipping traffic in certain areas and/or times, such as sensitive habitats or seasons for marine taxa.[135,136] Re-routing vessels has been suggested to avoid operation in environments that favour long-range transmission[137] such as locations where sound will propagate into the deep sound channel.[138] These locations are where the sound channel intersects bathymetric features such as the continental slope or at high latitudes where it is very close to the surface.[139] Avoiding such areas can be achieved by vessels moving further offshore in some cases but such re-routing will need careful consideration if there is an associated increase in speed or distance travelled[140] (and fuel usage).

MONITORING AND MAPPING TOOLS

This section outlines the monitoring and mapping tools that enable the production of acoustic maps and marine species population maps for a given area. Data needs and the current availability of acoustic and mapping tools are discussed. Monitoring tools include PAM, habitat models for marine mammals and real-time marine mammal detection. New monitoring techniques such as the use of thermal imaging are also highlighted.

Acoustic monitoring and modelling are essential elements of noise mitigation for the marine environment both for the assessment of impulsive and continuous sound levels in an area and for predicting and determining the presence of marine species in the vicinity of noise generating activities.

Acoustic and species distribution mapping

The development of acoustic mapping tools has made considerable progress in recent years, with several tools currently being developed/used by researchers, mainly for government agencies. These tools are being put together to describe average human-induced noise fields over extended periods of time or over large areas of coastline or open ocean. They can provide powerful visualizations of low frequency contributions from anthropogenic sources and their extent and begin to address the scales at which many marine animals operate. In combination with tools to characterize the distribution and density of marine animals as well as important management jurisdictions, they can provide important information for risk assessment and for understanding what tools are available to address those risks.[141]

Two important tools developed in the United States are “SoundMap” and “CetMap” by two working groups convened by NOAA: the underwater sound-field mapping working group and the cetacean density and distribution mapping working group. SoundMap aims to create mapping methods to depict the temporal, spatial and spectral characteristics of underwater noise. The specific objective of CetMap is to create regional cetacean density maps that are time- and species-specific for waters of the United States using survey and models that estimate density using predictive environmental factors. CetMap is also identifying known areas of specific importance for cetaceans, such as feeding and reproductive areas, migratory corridors and areas in which small or residential populations are concentrated.[142] The SoundMap product will enable predicted chronic noise levels to be mapped for an area over a specific timeframe and facilitate the management of cumulative noise impacts for cetaceans and other taxa. Mapping of more transient and localised noise events from acute sources such as military sonar or seismic surveys can also be undertaken.

Both tools were presented to a range of stakeholders from government and industry as well as research scientists, environmental consultancies, and conservation advocacy groups at a symposium in 2012.[143] Discussions at the meeting provided feedback for the working groups on the utility of the products to support planning and management, and suggested ways to improve the tools such as integrating them with other mapping products to assess risk from multiple stressors and determine cumulative impacts. The use of equivalent, unweighted sound pressures levels (L_{eq}), which are averages of aggregated sound levels, was also questioned in that it does not provide sufficient detail to show the acoustic conditions experienced by individual animals.[144] However, it was generally agreed that the products were a useful first step in developing practical tools to map both noise and cetaceans in the marine environment and have great potential as they are further improved. Regular updates of the products are also required to keep them up to date and usable.

In Europe, acoustic mapping approaches are also being developed to define and demonstrate risk-based noise-exposure indicators that can be used by managers to quantify and reduce the exposure of a population to noise pollution.[145] Two case studies of cumulative impulsive noise activity in the North Sea and the associated risk of effects on herring spawning and the harbour porpoise have been published.[146] The approach has the flexibility to map and quantify risk at the population level or be applied in place-based management for specific habitats or managed areas, such as MPAs. The methodology is also compatible with risk mapping approaches used in cumulative assessment,[147] which enables noise to be incorporated as a stressor in such assessments.[148] In addition, visual maps quantifying risk from various sources of noise for the different assessment units of harbour porpoises in the North Atlantic have recently been generated to inform place-based management.[149] In the Mediterranean Sea region, within the framework of the European project QUIETMED2, a methodology based on a habitat approach has been proposed. It applies habitat models to quantify the potentially usable habitat area for multiple species and produces risk maps using exposed habitat area index, constructed by superimposing this habitat area for each one of the representative species with the noise pressure map. The proposed methodology is potentially open to other species for which suitable habitat can be predicted.[150]

The European Union project called "Achieve Quieter Oceans by shipping noise footprint reduction" (AQUO) was a four-year programme between 2012 and 2015.[151] It brought together experts on shipbuilding, underwater acoustics and bioacoustics using a multidisciplinary approach to develop guidelines for controlling the underwater radiated noise (URN) from commercial shipping. Both technical and operational solutions were evaluated by considering the impact on marine life, feasibility in terms of ship design, and cost-effectiveness, including fuel efficiency.[152] For impacts on marine life, three species were selected for assessment: the harbour porpoise, Atlantic cod and the common cuttlefish. For two of these species, scenarios related to masking by shipping noise were used: masking of communication signals of male cod during spawning and masking of killer whale predator sounds for a harbour porpoise. The corresponding risk using adapted zones of influence concept[153] was calculated and mapped spatially. With sufficient computational power, it is also possible to run the predictive model in real time, using AIS[154] information, to provide the capability for real time underwater noise monitoring and ship traffic management.[155]

Another product that was developed for Europe was the Subsea Environmental Acoustic Noise Assessment Tool (SEANAT), which provides a range of tools for modelling sound fields associated with underwater noise sources.[156] SEANAT has been developed by the Centre for Marine Science and Technology at Curtin University for use in Economic Exclusion Zone (EEZ) of Germany. The product can configure model scenarios, run underwater sound propagation models in realistic acoustic environments, compute received levels and visualize the resulting sound fields. Sound propagation modelling uses two models: RAMGeo, a modified version of the Range-dependent Acoustic Model (RAM), is used for lower frequencies up to 2 kHz, whereas for higher frequencies (>2 kHz), the Bellhop model is used.

Habitat modelling of cetaceans can also help to inform marine spatial management and planning. Cetacean modelling has considerably advanced in recent decades and near real-time forecasts of distribution[157] are now possible providing highly useful information that can assist in the planning of anthropogenic noise-generating activities. Cetacean habitat modelling techniques are also able to predict cetacean densities at fine spatial scales to match the size of operational areas.[158] Densities are estimated as continuous functions of habitat variables, such as sea surface temperature, seafloor depth, distance from shore or prey density.[159] Model results have also been collaboratively incorporated into an online mapping portal that uses OBIS-SEAMAP geo-datasets and a spatial decision support system (SDSS) that allows for easy navigation of models by taxon, region, or season.[160] The

SDSS displays model outputs as colour-coded maps of cetacean density for an area of interest along with a table of densities and measures of precision. This user-friendly online system enables the application of these habitat models to real world conservation and management issues.[161]

There are also considerations to develop confirmatory or mechanistic models that will provide more robust and accurate predictions of species distributions that are based on greater ecological understanding.[162] However, mechanistic models do currently have several limitations,[163] and an incremental iterative process from simple to complex formulations is recommended before spatially explicit models of marine mammal population dynamics incorporating prey abundance and environmental variability can be successfully built.[164]

Mapping the distributions of marine mammals other than cetaceans is required as well as important species from other taxa such as fishes, turtles and invertebrates. Fisheries data is a key source of information to produce species distribution and habitat maps for many marine fishes. These data should be combined with products such as SoundMap to enable spatio-temporal risk assessments that can feed into the marine spatial planning process. Ecosystem-level modelling frameworks for the marine environment that permit the inclusion of human activities should also be considered.[165]

Continuous noise pollution has the potential to mask the vocalizations or hearing of marine animals during important activities such as navigating, feeding or breeding. These chronic effects may be more substantial than short-term acute effects over the spatial and temporal extents relevant to marine animals that rely on acoustic communication.[166] There is increasing recognition that sub-lethal impacts such as communication masking or behavioural responses from chronic exposure to noise are perhaps one of the most important considerations for populations.[167] Communication masking is particularly an issue for baleen whales that rely on low-frequency sounds for major life functions as their communication frequencies overlap with most chronic noise producing activities, particularly from large commercial vessels. It is therefore important to be able to measure chronic noise levels and determine the extent of communication masking for marine fauna such as baleen whales.

Studies in the Mediterranean Sea of Cuvier's beaked whale distribution indicate that modelling tools can be employed for a preliminary risk assessment of "unsurveyed" areas.[168] *A priori* predictions of beaked whale presence in the Alboran Sea were evaluated using models developed in the Ligurian Sea that use bathymetric and chlorophyll features as predictors. The accuracy of predictions was found to be adequate, suggesting that the habitat model was transferable for use in an area different from the calibration site.[169] This study indicates that initial risk assessments may be feasible in data-poor areas if a regional habitat model for a particular species is available for transfer into the unsurveyed site.

Tools have been developed to measure communication masking in the marine environment. One example is the assessment of communication space and masking for the endangered North Atlantic right whales in an ecologically relevant area during their peak feeding season on the east coast of the United States.[170,171] Modelling techniques were used to predict received sound levels from vessel and whale sound sources for the area within the frequency band that contains most of the sound energy in whale contact calls. As well as providing techniques to measure and predict the degree of communication masking, the tools can be used to support the development of management guidelines, as they provide a method for integrating different quantitative evaluations into a management framework.

Further development of tools to assess masking in other marine taxa such as fishes is required. The potential for communication masking in marine fishes is considerable,[172] which overlaps with low frequency shipping noise. There is a need to develop techniques to translate the effects of masking on ecosystem services[173] for marine taxa, especially marine mammals and fishes. Integration of masking effects into assessments of cumulative impacts from multiple stressors is also required.

Passive and active acoustic monitoring

PAM is used as a tool for cetacean detection, although there are limitations associated with its use, as explained above. PAM is also a useful tool for the collection of baseline data before a project starts and once operations have been completed to monitor long-term patterns of cetacean distribution in the project area. PAM can be used for real-time operational mitigation and monitoring, and for studies that seek to determine conditions over time. PAM has become a fundamental tool, not only for researching the behaviour of whales, but for designing real-time mitigation protocols that may minimize the potential impacts of anthropogenic activities.[174]

The ability to conduct detailed real-time mitigation and monitoring has improved considerably in recent years with the availability of GIS-based data collection tools such as PAMGUARD,[175] SEAPRO and PAM Workstation,[176] LOGGER[177] and WILD.[178] Further information on these PAM tools has been summarized in a report by the ACCOBAMS/ASCOBANS joint noise working group (Table 19).[179] Most PAM systems still require human operators to assess incoming sounds, although automated detection systems also exist. Advances in electronics, computers and numerical analysis have made PAM technology more accessible and affordable to researchers.[180] Various systems are in use, including radio-linked systems, drifting buoys, and arrays of autonomous recorders for versatile and long-term deployments. However, PAM does have several limitations,[181,182] although some of these can be addressed.[183] Specifically, PAM is unable to:

- Accurately measure animal abundance as passive acoustics cannot independently verify the number of animals from which vocalizations originate. Several techniques have been used by field-based researchers to accommodate for this;
- Identify to the species level in some cases – especially for odontocetes. This can be overcome by collecting simultaneous visual observations;
- Determine whether a lack of acoustic communication is associated with the absence of animals that might otherwise be vocalizing. Visual observers can confirm the presence of marine mammals in favourable conditions. At night or in adverse weather conditions, marine mammal presence may be detected by thermal imaging of blows.[184]

In addition, subtle variations in marine mammal sounds produced between different populations of the same species can reduce the accuracy of automated detection systems.[185] The orientation of the sound-producing animal in relation to the PAM system can also influence the levels received and therefore the estimated distance to the animal.[186] Fixed PAM sensors can also be used to estimate animal density from a variety of approaches.

The correct use of PAM is important so that acoustic detection is as accurate and effective as possible. In the past, there was a lack of guidance for PAM implementation and a lack of training programmes for its use.[187] As PAM use has become more widespread, accredited training programmes have been developed for industry. Detailed guidance on the qualifications, training standards and conduct of PAM operators and MMOs is available as a series of Marine Mammal Observer Association (MMOA) position statements.[188] High quality standardized training of MMOs/PAM is offered by ACCOBAMS through the ACCOBAMS school with accredited trainer organisations.[189] National governing bodies have also approved MMO/PAM training courses offered by private contractors, for example the Joint Nature Conservation Committee in the United Kingdom[190] or the Department of Conservation in New Zealand.[191]

The use of PAM to detect non-mammal marine fauna is questionable as vocalizations by fishes and invertebrates are quieter than those of marine mammals. Specific PAM systems used in noise mitigation procedures that can detect the presence of fishes have not yet been developed,[192] although the use of passive acoustics for fisheries monitoring and assessment is an active and growing research field.[193,194]

Active acoustic monitoring (AAM) techniques are more applicable for non-vocalizing marine fauna such as fish, turtles, and invertebrates and for non-vocalizing marine mammals. However, AAM systems can often only detect animals at closer ranges than passive monitoring but is able to estimate the range of targets more easily. The use of active acoustic systems will, however, add sound energy to the marine environment, which may have behavioural effects on some taxa, particularly marine mammals, and increase the occurrence of stress and masking responses. The use of AAM is not recommended for marine mammals, except in the case of mitigating single loud sounds such as explosives where they can be used simultaneously as an alarming device.[195] The potential effects of AAM on other marine taxa also need to be investigated.

Large-scale real-time passive monitoring of the marine acoustic environment can provide information on both continuous and impulsive noise production as well as detecting the presence and location of vocalizing marine taxa such as marine mammals. "Listening to the Deep Ocean Environment" (LIDO) is an international project that can monitor marine ambient noise in real-time over large spatial and temporal scales.[196] Acoustic information is collected at cabled deep-sea platforms and moored stations in multiple sites associated with national or regional observatories. The software has several dedicated modules for noise assessment, detection, classification and localization.[197] Data are processed to produce outputs that can characterize an acoustic event as well as spectrograms for quick visualization and compressed audio. The outputs are publicly available via a website[198] and can be viewed with a specific application. The main approach is to divide the recording bandwidth into frequency bands that cover the acoustic niche of most cetacean species and apply a set of detectors and classifiers. This information is then used by localization and tracking algorithms to monitor the presence and activity of cetaceans. This acoustic detection, classification, and localization (DCL) system has the potential to be used as a mitigation tool for some offshore noise generating activities and has the advantage of being a fully automated system that can operate in all conditions (sea state, day/night) with no specialist operators required. The technology has been adapted to offer internet-based tools to ocean users, such as oil and gas and renewable energy (windfarm) companies.[199]

Another example of long-term monitoring is the ECHO Program, which installed an underwater listening station in the Strait of Georgia in 2015 to monitor real-time underwater noise source levels from large commercial vessels (deep-sea ships, ferries, tugs), as well as marine mammal presence and total ambient underwater noise. The underwater listening station operated for more than two and a half years and was successful in providing near real-time analysis of vessel source levels for over 5,100 vessel transits (ONC, 2018).

MANAGEMENT FRAMEWORKS AND INTERNATIONAL AGREEMENTS

This section provides information on a range of management frameworks currently in use or proposed to manage underwater noise pollution. These include the use of spatio-temporal restrictions (STRs) to protect marine fauna from noise pollution as part of a wider marine spatial planning approach and the use of impact or risk assessment frameworks. The progress made under various agreements and processes at the regional and international level (e.g., ACCOBAMS/ASCOBANS/CMS, OSPAR, HELCOM, EU MSFD, IMO and the UN) to address underwater noise pollution is also summarized.

As previously discussed, spatio-temporal restrictions, including marine protected areas, are regarded as one of the most effective ways of protecting cetaceans and their habitat from the cumulative and synergistic effects of noise and other anthropogenic stressors.[200,201] Avoiding noise production when vulnerable marine fishes or invertebrates are present has also been recommended.[202] The use of spatio-temporal restrictions (STRs) to protect marine mammals and other taxa from noise pollution and other stressors has been strongly endorsed with the proposal of a conceptual framework for STR implementation.[203] However, the size of marine areas to be protected from noise is a major concern as sound can propagate great distances in the marine environment, especially at low frequencies.[204] For example, for intense mid-frequency sounds to be excluded from areas tens of kilometres away from critical cetacean habitats would require an STR of 100-1000 km^2 while protection from intense low frequency sounds could require distances of hundreds of kilometres and STR areas of at least 10 000 to 100 000 km^2.[205] The use of noise-based STRs as part of marine spatial planning frameworks requires that managers have a certain level of background information for the species of concern and their preferred habitats for activities such as breeding/spawning or feeding. Information on the timing, location, type and intensity of proposed noise-generating activities is also needed to evaluate the level of risk to marine fauna in the region if spatial restrictions are not permanent.

Management frameworks

Management frameworks for the marine environment include underwater noise management and mitigation as part of a broader approach to control the impacts of anthropogenic stressors on marine biodiversity, often within an ecosystem-based management approach. These frameworks include marine spatial planning approaches and assessments of the level of risk or impact for species. Risk and impact assessments are also moving to estimating effects on species at the population level. Since effects on the individual level can be the first indications of effects at the population level, they must also be considered.

A framework for the systematic prioritization of noise mitigation for cetaceans was developed and proposed during a global scientific workshop on spatio-temporal management of noise[206] (Table 5). The framework consists of six steps and draws heavily on the general principles identified in the conservation planning and adaptive management literature.[207] Although published in 2007, it is still valid for use in noise mitigation today and contains some similar recommendations for mitigation practices provided in recent publications.[208] The six-step process could also be tailored to suit other marine taxa such as vulnerable species of fishes, turtles or invertebrates.

Table 5. A framework for systematic prioritization of noise mitigation (for cetaceans) (Source: adapted from Agardy et al., 2007).[209]

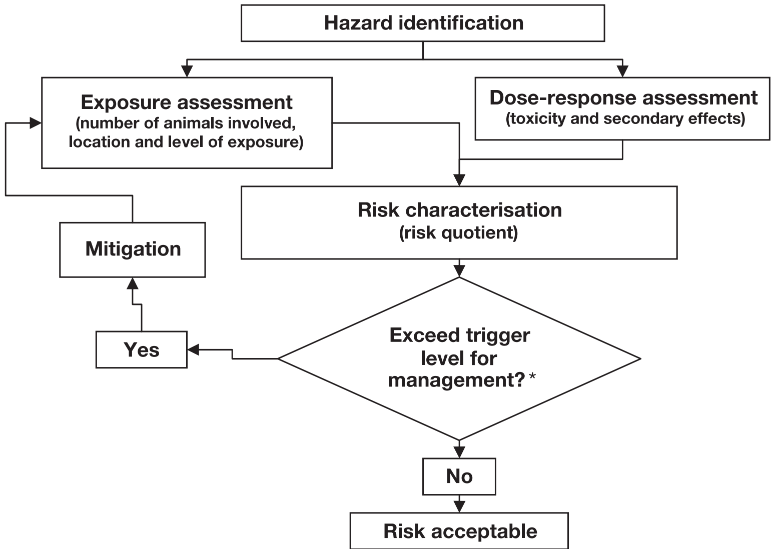
Step	Notes
1. Define the goal(s), constraints and geographic scope of the planning process	Key requirements of the goal on which prioritization can be structured are: clear geographic scope, a measurable conservation target, the desired degree of confidence, and a measure of social opportunity costs. Crucial to the transparency of the project and helps engage all stakeholders.
2. Identify relevant data and data gaps	Spatial information on species habitat distributions, threats (e.g., areas of seismic exploration) and socio-economic information (e.g., current jurisdictional boundaries). Sufficient data is seldom available for all species and all social aspects). Urgent data collection may be needed but usually preferable to proceed with data that is available and use expertise and modelling to make decisions.
3. Synthesize habitat and threat data to generate exposure ranking maps	Identify areas of overlap between biodiversity value and threats to those values e.g., Threat maps may be species-specific or general. Weighting of species of concern or interest can be applied.
4. Generate map of mitigation priority areas	Integrate exposure maps from 3. With spatial data on existing opportunities and impediments, opportunity costs and any other relevant spatial information. Commonly associated with systematic conservation planning algorithms that can be used to produce an "optimal" solution e.g., the most effective protection for a species or habitat for the least cost. Committee processes (Delphi methods) can be used instead of algorithms for less complicated situations.
5. Identify and prioritize actions for priority conservation zones	Action prioritization is necessary as conservation budgets are finite. Use a coherent and transparent approach with a respected prioritization protocol that incorporates the concepts of conservation benefit, feasibility and cost efficiency, to prioritize actions.
6. Implement and monitor	Ensure that monitoring data is integrated back into the decision-making process to enable adaptive management. This requires good coordination between managers and scientists. Monitoring is central to the success of the adaptive prioritization framework. Design monitoring programme in advance to allow monitoring prior to implementation.

To inform marine spatial planning and other processes, such as environmental impact assessments, several national-scale systems were developed, including Ocean.Data.Gov and the NOAA CMSP Data Registry. The Ocean.Data.Gov system is dedicated to coastal and marine scientific data and aims to build capacity in the development of spatial data, data standards, mapping products and decision support tools. These information platforms feed into NOAA's Integrated Ecosystem Assessment (IEA) framework, which is regarded as a promising approach to ecosystem-based management and a leading example of a comprehensive ecosystem-based assessment.[210] The IEA framework consists of five components: 1. Scoping, 2. Identifying indicators and reference levels, 3. Performing risk analyses, 4. Evaluating management strategies, and 5. Monitoring and evaluating progress towards management goals. The framework has been widely implemented in U.S. waters[211] and in the North Sea.[212]

Undertaking risk or impact assessments is a key part of ecosystem-based management and conservation planning. Quantitative risk assessment techniques that could be applicable for the assessment of underwater noise effects in combination with other impacts include the use of population viability analysis (PVA). This technique is commonly used to quantify the probability that a species will decline to an unacceptably low population size within a particular timeframe.[213] To date, PVA has not been widely used to assess noise impacts and the viability of populations of marine fauna under a range of management scenarios.

A framework to assess risk to indicator species in coastal ecosystems has been tested in Puget Sound, in the U.S. state of Washington.[214] The framework can identify land- or sea-based activities that pose the greatest risk to key species of marine ecosystems, including marine mammals, fishes and invertebrates. Ecosystem-based risk is scored according to two main factors: the exposure of a population to an activity and the sensitivity of the population to that activity, given a particular level of exposure. The framework is scalable, transparent and repeatable, and can be used to facilitate the implementation of EBM, including integrated ecosystem assessments and coastal and marine spatial planning.[215] In the Puget Sound case study, the combined effects of four human activities – coastal development, industry, fishing,and residential land use – were assessed for seven indicator species: two marine mammals, four fishes and one invertebrate. The framework offers a rigorous yet straightforward way to describe how the exposure of marine species to human stressors interacts with their potential to respond under current and future management scenarios.[216] The applicability of this framework to assess the risk of noise effects for marine species requires consideration.

A risk assessment framework specifically addressing underwater noise impacts for marine mammals is also available[217] and could be adapted for other marine taxa. The framework consists of a four-step analytical process: 1. Hazard Identification, 2. Dose-response assessment, 3. Exposure assessment, and 4. Risk characterization. A fifth step, risk management, involves the design and application of mitigation measures to reduce, eliminate or rectify risks.[218] A decision flow and information pathway for the framework is presented in Figure 4. The decision pathway contains a feedback loop involving mitigation when the risk exceeds the trigger level, indicating that an adaptive approach to managing risk is taken.



* Trigger level defined by legislation, value judgement or biological significance

Figure 4. The information flow and decision pathway for a risk assessment process (Source: Boyd et al., 2008).[219]

An example of an assessment framework to explore the long-term impact of a noise generating activity on a marine mammal[220] is summarized in Figure 5. In this case, it is the impact of pile-driving from wind farm construction on a harbour seal population within a Special Area of Conservation (SAC) under the EC Habitats Directive. Spatial patterns of seal distribution and received noise levels were integrated with available data on the potential impacts of noise to predict the number of individuals that would be displaced or experience auditory injury. Then expert judgement was used to link these impacts to changes in vital rates (fecundity and survival) and applied to population models that compare population changes under baseline and construction scenarios over a 25-year period.[221] A schematic of the approach taken is provided below (Figure 5).

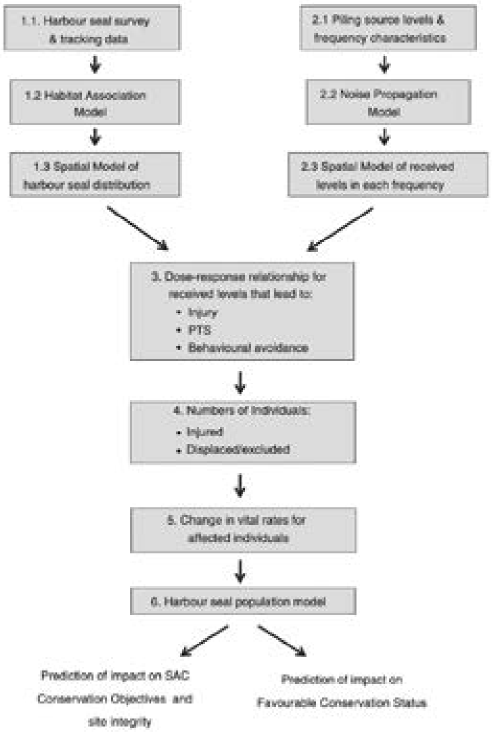


Figure 5. Schematic of the approach used to assess the impact of wind farm construction on the harbour seal in a Special Area of Conservation (SAC) and with Favourable Conservation Status (FCS). (Source: Thompson et al., 2013)[222]

The framework can be used to provide preliminary guidance on how developers should assess the population consequences of acoustic disturbance from construction activities in the marine environment. There was considerable uncertainty for some parts of the analysis, particularly for the number of animals that were displaced from the area or experienced Permanent Threshold Shift (PTS) and how this affected individual fitness.[223] The latter was completely dependent on expert judgement. It was deemed most appropriate to use expert judgement in the short-term for certain parameters, but in the long-term, use of the Population Consequences of Acoustic Disturbance (PCAD) framework[224] is recommended as more information becomes available and uncertainty is reduced. Development of the framework relied heavily on the availability of detailed information on harbour seal populations in the locality, which also makes the case study a suitable opportunity to develop detailed PCAD studies in the future.[225]

The modelling framework could also be suitable for use on other less studied harbour seal populations, although it may be necessary to "borrow" data, such as fecundity estimates, from better studied populations or possibly other seal species.[226] It is important to recognize that, due to the level of uncertainty and the use of conservative estimates for some individual parameters, this assessment framework is assessing worst-case impacts. Conservatism accumulates through the framework, leading to more significant short-term impacts than is thought to be likely.[227] However, the framework does offer an alternative interim approach that can provide regulators with confidence that proposed developments will not significantly affect the long-term integrity of marine mammal populations, in this case the harbour seal. The use of mitigation and management frameworks over the whole lifetime of a proposed noise-generating activity was discussed previously.

The Enhancing Cetacean Habitat and Observation (ECHO) Program, referred to above, was developed to better understand and reduce the cumulative effects of shipping on at-risk whales throughout the southern coast of British Columbia, Canada. The ECHO Program, launched in 2014, involves the transboundary voluntary collaboration of marine transportation industries, conservation groups, scientists, indigenous peoples and local communities, and Governments of Canada and the United States, including representatives from Fisheries and Oceans Canada, Transport Canada, the National Oceanic and Atmospheric Administration (NOAA) and the Coast Guards of both Canada and the United States. With a goal to develop measures that lead to a quantifiable reduction in threats to whales as a result of shipping activities, the ECHO Program, in collaboration with its many partners, has undertaken numerous research projects to assess underwater shipping noise and its potential impacts and has developed and tested numerous operational measures (e.g., voluntary vessel slowdowns, voluntary vessel lateral displacement zones, real time acoustic measurement system for vessels) and tools (e.g., port incentives for quieter vessels, whale notification system for mariners, whale awareness training tutorial for mariners) for reducing underwater noise.

International agreements and processes

This section provides an overview of progress on the regulation, mitigation and management of underwater noise by several regional and international agreements.

Convention on the Conservation of Migratory Species of Wild Animals (CMS)

CMS Parties first addressed anthropogenic ocean noise in 2008 through a dedicated resolution. At that time, the focus was mostly on whales and dolphins, even though it was recognized that other species might also be affected. In the years since, scientific studies have increasingly demonstrated that impacts may be far more severe and wide-ranging than previously thought, affecting not only migratory species, but also their prey, and thereby the entire marine food web. In recognition of this, and given the transboundary nature of the threat, CMS Parties have repeatedly agreed to strong guidance on how to address this issue in a precautionary way.

Several times, Parties to CMS have called for noise-related considerations to figure in the early planning stages of activities, especially by making effective use of EIAs. However, they have acknowledged that applying this emerging knowledge in local and national decision-making is a challenge. Therefore, they requested the development of a set of guidelines for those entrusted with granting approvals and permits for activities in the marine environment, outlining ways of assessing in advance what the impact on marine life will be.

In CMS Resolution 12.14, Adverse Impacts of Anthropogenic Noise on Cetaceans and Other Migratory Species, CMS Parties endorsed Guidelines on Environmental Impact Assessments for Marine Noise-generating Activities, which detail the requirements for EIAs that allow managers to make informed decisions. These Guidelines cover the following industries or underwater sound sources:

- Military and civil high-powered sonar
- Shipping and vessel traffic
- Seismic surveys (air gun and alternative technologies)
- Construction works
- Offshore platforms
- Playback and sound exposure experiments
- Pingers (acoustic deterrent/harassment devices, navigation)
- Other noise-generating activities (acoustic data transmission; wind, tidal and wave turbines; future technologies)

The Guidelines are accompanied by detailed Technical Support Information,[228] which explains to policy- and decision-makers how underwater noise works, how it affects marine life, and what the specific vulnerability of different groups of species is. In this, CMS focuses not only on protected species, but also on their prey. A new module, Advisory Note: Further guidance on independent, scientific modelling of noise propagation (UNEP/CMS/COP13/Inf.8), was added in 2020 at the thirteenth meeting of the Conference of the Parties to CMS, when decision 12.43 set out the need for voluntary guidelines that would contribute to meeting the recommendation in Resolution 12.14. In response, in 2019, "Best Available Techniques (BAT) and Best Environmental Practice (BEP) for Three Noise Sources: Shipping, Seismic Airgun Surveys, and Pile Driving" was produced.

Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS)

ASCOBANS Parties have long recognized underwater anthropogenic underwater sound as a major threat to small cetaceans in the Agreement Area. The first resolutions that included noise were adopted in 2000. The Conservation and Management Plan annexed to the Agreement stipulates that ASCOBANS work towards "the prevention of other significant disturbance, especially of an acoustic nature".[229] ASCOBANS working group on underwater noise was established in 2009. In 2012, the noise working groups serving the ACCOBAMS and ASCOBANS Agreements were merged, and in 2014, CMS was also included. Reports of the working group can be found on the ASCOBANS website.

In 2008, an Intersessional Working Group on the Assessment of Acoustic Disturbance was formed to examine and evaluate human activities causing noise disturbance and related best practices in noise management in relation to the work of ASCOBANS. Their report[230], (ASCOBANS/AC17/Doc.4-08), which includes guidelines for best practice mitigation measures, focuses on three main anthropogenic activities: use of naval sonar, seismic surveys and pile-driving.

The harbour porpoise is particularly susceptible to impacts from a vast frequency range of underwater noise because of its very acute hearing, wide hearing range and high responsiveness to sounds (ASCOBANS 2016[231]). Three regional ASCOBANS action plans for the harbour porpoise all address the issue of noise:

- Recovery Plan for Baltic Harbour Porpoises (adopted through Resolution 8.3 and Resolution 6.1)
- Conservation Plan for the Harbour Porpoise Population in the Western Baltic, the Belt Sea and the Kattegat (adopted through Resolution 7.1)
- Conservation Plan for Harbour Porpoises (*Phocoena phocoena L.*) in the North Sea (adopted through Resolution 6.1)

Resolution 6.2 focusing on noise from offshore construction activities for renewable energy production was adopted in 2009. Other extant noise resolutions include Resolution 5.4 Adverse Effects of Sound, Vessel and Other Forms of Disturbance on Small Cetaceans (2006), and Resolution 8.11 (Rev.MOP9) CMS Family Guidelines on Environmental Impact Assessment for Marine Noise-generating Activities (2020), which adopts the guidelines and encourages Parties to take into account the Action Plan resulting from the ACCOBAMS Workshop on sonar and cetacean interaction.

Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS)

Monitoring noise-producing activities in the ACCOBAMS Area and mitigating noise impacts on cetaceans are recognized as being of high priority by Parties for achieving the ACCOBAMS objectives. To assist countries in noise monitoring, some tools have been developed, such as the "ACCOBAMS Guidelines to address the impact of anthropogenic noise on cetaceans in the ACCOBAMS area" and the Methodological Guide: "Guidance on underwater noise mitigation measures".

Since 2012, with the support of the Joint CMS/ACCOBAMS/ASCOBANS Noise Working Group (see below), ACCOBAMS has developed a basin-wide strategy for ocean noise monitoring in the Mediterranean, identified the noise hot spots in the Mediterranean Sea and developed a Regional Noise Register Demonstrator for impulsive noise.

To pursue these efforts, the ACCOBAMS Permanent Secretariat has committed to assisting the UNEP/MAP – Barcelona Convention in formulating a regional Mediterranean strategy, by developing indicators on ocean noise to be monitored to assess the status of the marine environment and ecosystems under the Ecosystem Approach (EcAp) of the Barcelona Convention; the two entities collaborate closely on this issue. In May 2019, some Guidance Factsheets for indicators related to underwater noise were presented by ACCOBAMS. The need for further collaboration on noise was pointed out, to gather relevant knowledge, prior to incorporating them into the "Integrated Monitoring and Assessment Programme".

Moreover, in the framework of the EU-funded quietMEd project, the ACCOBAMS Permanent Secretariat, in collaboration with specific experts, contributed to several activities. The main outputs of the project address methodologies and best practices for monitoring impulsive and continuous underwater noise. The project also included the development of a common register for the Mediterranean basin for the monitoring of impulsive noise (INR-MED): http://80.73.144.60/CTN_Geoportal/home/.

ACCOBAMS is involved in a new EU project "QUIETMED2". It is also funded by the DG Environment and aims to enhance cooperation among Member States in the Mediterranean Sea Region for achieving a good environmental status (GES) assessment on Descriptor 11: noise in the Mediterranean. This project will assess the conditions for developing new functionalities in the INR-MED.

In 2018, the ACCOBAMS Permanent Secretariat, with the assistance of the ACCOBAMS MMO/PAM Courses Committee, finalized the standard high-level course material. To date, five training courses have been conducted by ACCOBAMS trainers in the ACCOBAMS Area.

In 2019, ACCOBAMS organized a workshop on "sonars and cetacean interactions", which aimed to improve dialogue and cooperation of national navies with ACCOBAMS, especially regarding military activities.

In November 2019, ACCOBAMS Parties adopted a new Resolution on this issue: Resolution 7.13 "Anthropogenic Noise", which contained two annexes: Annex 1, The Action Plan resulting from the workshop on sonars and cetacean interactions, and Annex 2, the revised detailed Guidelines to address the impacts of anthropogenic noise on cetaceans in the ACCOBAMS Area.

Joint CMS/ASCOBANS/ACCOBAMS Noise Working Group

The Joint CMS/ASCOBANS/ACCOBAMS Noise Working Group (Joint NWG) consists of members and observers of the scientific and advisory bodies of CMS, ACCOBAMS and ASCOBANS. External experts also participate in the Joint NWG to ensure the best possible advice can be generated for Parties.

The Joint NWG presents reports on progress and new information to each meeting of the CMS Scientific Council, ACCOBAMS Scientific Committee and ASCOBANS Advisory Committee. It addresses the mandates of relevant resolutions for all three organisations.

In 2013, the Joint NWG produced three main reports as part of its 2012–2014 work programme:

1. Anthropogenic noise and marine mammals. Review of the effort in addressing the impact of underwater noise in the European Union
2. Implementation of underwater noise mitigation measures by industries: operational and economical constraints
3. Guidance on Underwater Noise Mitigation Measures

Since 2013, the Joint NWG has been addressing the development of guidance for the whole duration of impulsive noise generating operations (pre-operation assessment and planning, implementation, and post-operation evaluation) with an emphasis on seismic surveys and the need for a more rigorous assessment stage as part of EIAs or SEAs.

In 2014, the Joint NWG worked with the ACCOBANS Secretariat to: a) identify anthropogenic noise/cetacean interaction hot spots in the ACCOBANS area and to map and develop monitoring of ambient noise, particularly in critical habitats; and b) develop monitoring guidance on marine noise for Ecological Objective (EO)11. In late 2014, the Joint NWG developed a Statement of Concern relating to activities in the Adriatic Sea. Guidelines for offshore exploration activities in the Adriatic Sea were also developed in early 2015. Also, that year the Joint NWG began to identify further area statements, modelled on the Adriatic Statement, which were then developed in 2015/2016.

In 2016, the Joint NWG, along with CMS Scientific Councillors and members of working groups, ACCOBAMS Scientific Committee Members and ASCOBANS Advisory Committee Members, CMS, ACCOBAMS and ASCOBANS Focal Points, several IUCN Species Specialist Groups as well as the CMS, ASCOBANS and ACCOBAMS Secretariats, reviewed and provided comments on the draft CMS Family Guidelines on Environmental Impact Assessments for Marine Noise-generating Activities. These Guidelines were subsequently endorsed by CMSCOP12, their implementation invited by ACCOBAMS MOP7, and adopted by ASCOBANS MOP9.

In 2017, the Joint NWG developed an advisory statement on offshore exploration activities in sensitive areas of the Mediterranean Sea. The statement overlays information about the current ecologically or biologically significant marine areas (EBSAs) in the Mediterranean Sea with ACCOBAMS science vulnerability and provides recommendations for offshore exploration activities. Also in 2017, the Joint NWG contributed to the "Overview of the noise hotspots in the ACCOBAMS area" project. This produced a first inventory of noise-producing human activities, identified areas where such activities are carried out, obtained cumulative maps of noise-producing human activities, and proposed a first identification of noise-cetacean interaction hotspots.

The Joint NWG also contributed to an ACCOBAMS investigation into the Mediterranean noise monitoring strategy, based on the European Marine Strategy Framework Directive (MSFD) TG-Noise guidance for Descriptor 11. Two indicators have been proposed, one for impulsive noise and one for ambient noise.

OSPAR Commission

The Convention for the Protection of the Marine Environment of the North-East Atlantic (the OSPAR Convention) has set up an Intersessional Correspondence Group on Noise (ICG Noise) under the OSPAR Environmental Impacts of Human Activities Committee. The ICG Noise initially focused on the monitoring of impulsive and ambient noise but also on primary and secondary noise mitigation measures. For the latter, the group has developed is currently developing an inventory of noise mitigation measures initially on for with priority given to pile driving and seismic activities and explosions. Other sources and activities that will be considered within the inventory are high frequency impulsive noise from echosounders, explosions, dredging activities, sonar and shipping. The inventory will provide an overview of the effectiveness and feasibility of mitigation options and help to support OSPAR EU member states in establishing programmes of measures in relation to underwater noise under the MSFD.

OSPAR adopted an Ambient Noise Monitoring Strategy in 2015. The approach for monitoring of underwater noise uses sound maps, generated from a combination of models and measurements. Models should be used to place measurement equipment and to extrapolate from measurements to generate estimates for entire region. In 2017, OSPAR undertook its first regional assessment of the pressure from impulsive noise as part of the Intermediate Assessment of the state of the North-East Atlantic. That assessment was updated in 2019, allowing for a first multi-year assessment. Impulsive noises are generally regulated through national marine licensing therefore an Impulsive Noise Registry was developed to hold the information and produce a regional assessment based on pulse block days. In 2021 OSPAR agreed on an impulsive noise risk of impact indicator aimed at assessing the impact of that pressure on specific indicator species. For its 2023 Quality Status Report, OSPAR will produce an updated indicator assessment on pressure from impulsive noise and first assessments on ambient noise and risk of impact from impulsive noise in the North Sea. These results and other information, for example on measures and impacts, will be brought together in a thematic assessment on underwater noise.

OSPAR's North-East Atlantic Environment Strategy 2030, adopted in October 2021, sets a new strategic objective to reduce anthropogenic underwater noise to levels that do not adversely affect the marine environment and commits OSPAR to producing, by 2025, a regional action plan setting out a series of national and collective actions and, as appropriate, OSPAR measures to reduce noise pollution.

Convention on the Protection of the Marine Environment of the Baltic Sea Area

The Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention or HELCOM) stipulates (under Regulation 2 of Annex VI) that Parties must use the best available technology and best environmental practice to prevent and eliminate pollution, including noise, from offshore activities.

At the HELCOM Ministerial Meeting in Moscow in 2010, Parties agreed to "develop common methodologies and appropriate indicators to facilitate national and coordinated monitoring of noise and identification of sources of noise and to further investigate the potential harmful impacts to wildlife from noise".[232]

In its capacity as the coordinating platform for the regional implementation of the EU MSFD in the Baltic Sea for those Contracting Parties that are also EU members, HELCOM initiated work to develop HELCOM core indicators, which are harmonized with MSFD Descriptors under the HELCOM-CORESET project.

In 2013, at the HELCOM Ministerial Meeting in Copenhagen[233] Contracting Parties agreed that "the level of ambient and distribution of impulsive sounds in the Baltic Sea should not have negative impact on marine life and that human activities that are assessed to result in negative impacts on marine life should be carried out only if relevant mitigation measures are in place."

This commitment resulted in the development and implementation of the Regional Baltic Underwater Noise Roadmap 2015-2017[234], which included the establishment of a joint HELCOM/OSPAR registry of licenced impulsive noise events[235] in 2015 and development of a regional monitoring programme for continuous noise[236], which was approved in 2018. The programme includes annual minor (at nationally prioritized locations) measurements with occasional major (acoustic sensors in a range of environments) measurement campaigns. Production of soundscape maps by modelling is included, as well as data arrangements to compile and visualize regional monitoring data. HELCOM regional monitoring guidelines for continuous noise[237] were also adopted in 2018 and updated in 2021. More recently, a HELCOM continuous noise database[238] was set up to host national data as contemplated in the monitoring programme.

HELCOM published a report in 2017 presenting the rationale for selecting Baltic species with the potential to be impacted by noise, together with a preliminary identification of biologically sensitive areas. The report includes a prioritized list of seven noise-sensitive species: harbour porpoise, harbour seal, ringed seal, grey seal, cod, herring and sprat. The report was updated in 2019[239] based on available knowledge and lessons learned. HELCOM has also produced an overview report of underwater noise mitigation measures in the Baltic Sea region. Based on the new knowledge and information gathered, HELCOM included a qualitative assessment on underwater noise in its second holistic assessment 2011-2016, the *State of the Baltic Sea report*[240]. Preparations for the third Holistic assessment (HOLAS III) are underway, as well as further development of indicators on underwater noise, supported by the HELCOM Expert Network on Underwater Noise supported by the EU co-financed HELCOM BLUES project, as well as the State and Conservation Working Group.

Furthermore, in the HELCOM Brussels Ministerial Declaration in 2018 it was agreed to:

- Develop an action plan, preferably by 2021, and regionally coordinated actions on underwater noise; and
- Continue fruitful cooperation between European Regional Seas Conventions, and in particular OSPAR, in close coordination with work undertaken by Contracting Parties in other relevant fora, including the UNEP Regional Seas Programme.

HELCOM's work to continue the operationalization of underwater noise indicators is included in several actions under the HELCOM Recommendation on the Regional Action Plan on Underwater Noise, adopted in 2021, following the 2018 Ministerial Meeting commitment. The indicators will enable the evaluation of progress towards the goal of achieving good status with respect to underwater noise in the Baltic Sea. The work has mainly focused on pressure indicators. Further research is needed to close knowledge gaps on the impact of anthropogenic noise on sensitive species at the population level.

EU Marine Strategy Framework Directive (MSFD)

The Marine Strategy Framework Directive (MSFD; Directive 2008/56/EC), adopted in 2008, aims to achieve good environmental status in European marine waters, and in this regard, it identifies anthropogenic inputs of substance and energy into the maritime environment, such as human-induced marine underwater noise, as pollution. It also dedicates one of the specific 11 qualitative descriptors to define good environmental status on this issue.

To implement these requirements, European Commission Decision (EU) 2017/848 of 2017 defines good environmental status of marine waters, and lays down criteria, specifications and standardized methods for their monitoring and assessment. It sets out how to assess the extent to which good environmental status is being achieved for anthropogenic (i) impulsive and (ii) continuous low-frequency sound, based on two criteria defined for descriptor 11, described as follows:

(i) The spatial distribution, temporal extent and levels of anthropogenic impulsive sound sources do not exceed levels that adversely affect population of marine animals.
(ii) The spatial distribution, temporal extent and levels of anthropogenic continuous low-frequency sound sources do not exceed levels that adversely affect population of marine animals.

In both cases, EU Member States are to establish threshold values for these levels through regional cooperation. A technical group on underwater noise (“TG Noise”) was set up in 2011 to steer this work and advise EU Member States on the operational implementation of this descriptor.

So far, the work implemented at EU and regional levels through TG Noise has focused on monitoring issues and has been closely related to activities undertaken in regional seas conventions (RSC, see below). Such work has included the publishing of monitoring guidance for underwater noise in European Seas,[241] the setting up of a register of loud impulsive noise, and the development of a joint monitoring programme for continuous noise. TG Noise is now focusing on the assessments of impacts of noise and the development of thresholds in relation to the indicators developed in the framework of the MSFD, as described above.

As part of their marine strategies, required under the MSFD, EU Member States have implemented various measures aimed at maintaining noise at levels that do not cause harm to marine ecosystems. These include defining specific areas for both impulsive and continuous noise, developing eco-friendly ships, raising awareness, carrying out research and developing guidelines for noise assessments.

Other relevant European laws contribute to the reduction of underwater noise:

- Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment (as amended by Directive 2014/52/EU) requires the environmental effects of such projects likely to have significant effects on the environment to be assessed before the projects are authorized.
- The EU’s Habitats and Birds Directives (Directives 92/43/EEC and 2009/147/EC) are also relevant. Natura 2000 sites designated to protect features such as marine animal species listed in the Habitats Directive require measures to avoid any significant disturbance of those species. Human activities that are likely to have a significant effect on these sites need to be assessed and authorized in accordance with the Directive. In addition, the Commission guidance document on ‘establishing Natura 2000 sites in the marine environment’ contains a specific section on noise pollution.

With regard to noise-related data, the EU’s European Marine Observation and Data Network (EMODnet) provides open access to data and digital maps of underwater noise that are helping analysts determine its sources and level in order to develop measures for reducing its impact.

The MSFD is also implemented through European RSCs such as OSPAR for the North-East Atlantic, HELCOM for the Baltic and the Barcelona Convention for the Mediterranean Sea. The Directive requires EU Member States to coordinate their actions on marine waters in these regions and their sub-regions using relevant mechanisms and structures of RSCs and other relevant international forums. Making use of the experiences and existing cooperation in monitoring, RSCs have played an essential role in developing and starting joint programmes to monitor underwater sound.

Several projects and actions are taken at the European, regional or national level. Completed projects and initiatives in European marine waters include:

- BIAS - Baltic Sea Information on the Acoustic Soundscape (2013-2016)[242]
- AQUO - Achieve Quieter Oceans by shipping noise footprint reduction (2012-2015)[243]
- MaRVEN - Environmental Impacts of Noise, Vibrations and Electromagnetic Emissions from Marine Renewable Energy (2013-2015)[244]
- Baltic BOOST - "Best Practices for Action Plans to Develop Integrated, Regional Monitoring Programmes, Coordinated Programmes of Measures and Addressing Data and Knowledge Gaps in Coastal and Marine Waters" (2015-2016)[245]
- BONUS SHEBA - Sustainable shipping and environment of the Baltic Sea region (2015-2018)[246]
- QUIETMED - Joint programme on noise for the implementation of the Second Cycle of the MSFD in the Mediterranean Sea (2016-2018)[247]

Ongoing and new European initiatives include:

- JONAS - Joint programme for Ocean Noise in the Atlantic Seas (2019-2021)[248]
- JOMOPANS - Joint Monitoring Programme for Ambient Noise North Sea (2018-2020)[249]
- Soundscape - Soundscapes in the North Adriatic Sea (2019-2021)[250]
- QUIETMED2 - Joint programme for good environmental assessment on Descriptor 11-noise in the Mediterranean Marine Region (2019 – 2021)[251]
- CeNoBS - Support MSFD implementation in the Black Sea through establishing a regional monitoring system of cetaceans and noise monitoring (2019-2021)[252]
- LIFE-PIAQUO - Making the seas less noisy (2019-2022)[253]
- RAGES - Risk-based Approaches to Good Environmental Status with case study on non-indigenous species and underwater noise[254]

An updated report published in 2020 summarizes these projects.[255]

United Nations General Assembly

The United Nations General Assembly, in its annual resolution on oceans and the law of the sea, has repeatedly noted that ocean noise has potential significant adverse impacts on living marine resources, affirmed the importance of robust scientific studies in addressing this matter, encouraged further research, studies and consideration of the impacts of ocean noise on living marine resources and noted the work of States and competent international organizations in that regard.[256] It has also called upon States to consider appropriate cost-effective measures and approaches to assess and address the potential socioeconomic and environmental impacts of anthropogenic underwater noise, considering the precautionary approach and ecosystem approaches and the best available scientific information, as appropriate.[257]

The annual General Assembly resolution on sustainable fisheries has also regularly contained language on anthropogenic underwater noise, for example, calling upon States to consider the potential environmental and socioeconomic impacts of anthropogenic underwater noise from different activities in the marine environment and to address and mitigate such impacts, taking into account the best available scientific information, the precautionary approach and ecosystem approaches, as appropriate (resolution 74/18, para. 40).

In paragraph 107 of resolution 61/222, the General Assembly asked the Division for Ocean Affairs and the Law of the Sea to compile the peer-reviewed scientific studies on the issue of ocean noise it receives from Member States and to make them available on its website. This mandate was extended through resolution 64/71 to include intergovernmental organizations, and the request has been renewed annually.[258] The studies received are available on the website of the Division.[259]

The first World Ocean Assessment, published in 2016 as the outcome of the first cycle of the Regular Process for Global Reporting and Assessment of the State of the Marine Environment, including Socioeconomic Aspects (Regular Process), addressed the issue of anthropogenic underwater noise particularly in the context of shipping, ports, submarine cables and pipelines and offshore mining industries.[260] The Second World Ocean Assessment, published in 2021, contains a stand-alone chapter (chapter 20) on trends in inputs of anthropogenic noise to the marine environment, including key region-specific changes and consequences.[261]

Pursuant to resolution 71/257, as recalled in resolution 72/73, the nineteenth meeting of the United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea, held in June 2018, focused its discussions on the topic "Anthropogenic underwater noise" and was informed by a report of the Secretary-General on the topic.[262] During the discussions, many delegations expressed concern over potential social, economic, and environmental impacts of anthropogenic underwater noise.[263] In December 2018, resolution 73/124 on Oceans and Law of the Sea was adopted by the General Assembly, which notes the discussion of the Informal Consultative process with respect to impacts arising from anthropogenic underwater noise.

In June 2017, the United Nations Conference to Support the Implementation of Sustainable Development Goal 14: Conserve and sustainably use the oceans, seas, and marine resources for sustainable development (United Nations Ocean Conference), convened pursuant to resolutions 70/226 and 70/303, adopted the declaration "Our ocean, our future: call for action", including a specific reference to addressing underwater noise".[264] The Global Alliance for Managing Ocean Noise (GAMEON) was launched as part of a voluntary commitment to the Ocean Conference in 2017, with progress recorded in October 2019, and is well placed to identify practical global indicators for a monitoring element related to ocean noise (see UN Ocean Conference, 2019).[265]

In 2018, UNICPOLOS (United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea) devoted its 19th meeting, held at United Nations Headquarters from 18 to 22 June 2018, to the focus topic of "Anthropogenic underwater noise".[266]

International Maritime Organization

In 2004, in response to the growing body of research that was emerging on the issue, the Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO) commenced discussions on the harmful impacts on marine life of underwater noise from ships. In 2008, MEPC agreed to initiate the development of non-mandatory technical guidelines recognizing that underwater noise associated with shipping was an issue that could be mitigated and addressing concerns about its short- and long-term negative impacts on marine life, especially marine mammals. As a result of this work, in 2014, MEPC approved guidelines for commercial ships on ways to reduce underwater noise. This non-mandatory instrument, entitled Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life (MEPC.1/Circ.833) is intended to provide general advice on the matter to designers, shipbuilders and ship operators. The Guidelines focus on primary sources of underwater noise, namely on propellers, hull form, on-board machinery, and various operational and maintenance recommendations, such as hull cleaning. MEPC has subsequently considered a range of documents that relate to underwater noise generation from shipping, including providing a response within MEPC 74/17/3 in 2019 on "Advancing international collaboration for quiet ship design and technologies to protect the marine environment" (MEPC 74/17/2). MEPC 74/INF.28 (2019) also highlighted the results of a recent review of underwater radiated noise mitigation measures from ships. MEPC 74/INF.36 (2019) highlights the recommendations and outcomes from the Quieting Ships to Protect the Marine Environment Workshop, hosted by Transport Canada at IMO Headquarters in London in early 2019.

In 2021, at its 76th session, MEPC agreed to commence further work on underwater noise from ships and agreed to include a new output on the review of the 2014 Guidelines and identification of next steps (MEPC 76/15). The Sub-Committee on Ship Design and Construction has been assigned to coordinate the work, since the review of the Guidelines mainly relates to technical issues. The work is likely to include identifying: barriers to uptake and implementation of the Guidelines; measures to further prevent and reduce underwater noise from ships, including options to integrate new and advancing technologies and/or vessel design solutions; areas that require further assessment and research; an acceptable means of measuring existing ship noise profiles following ISO or international standards; and develop a proposal for a programme of action and/or next steps to further prevent and reduce underwater radiated-noise based on the findings of the review. The target completion year for the work is 2023.

Furthermore, in 2021, IMO submitted a proposal to the Global Environment Facility (GEF) regarding the potential funding of a global underwater vessel noise project (GloNoise) to assist developing countries and regions to raise awareness, to build capacity and to collect information to assist the policy dialogue on the mitigation of anthropogenic underwater noise from shipping.

The issue of underwater noise and its effects on marine life is also considered through IMO-designated "Particularly Sensitive Sea Areas" (PSSAs). These are areas considered to deserve special protection due to their recognized ecological or socio-economic or scientific significance, and which may be vulnerable to damage by ships. Through the establishment of these areas, specific measures to protect the environment are applied to international shipping. The 2005 revised guidelines for the identification and designation of PSSAs (resolution A.982(24), as amended by resolution MEPC.267(68)), recognizes that noise from ships can adversely affect the marine environment and living resources of the sea.

International Union for Conservation of Nature

International Union for Conservation of Nature (IUCN) Resolutions 3.068 (Bangkok, 2004) and 5.81 (Jeju, 2012) set out requirements to address underwater noise pollution. As discussed above, in 2016, the IUCN developed a practical guide for environmentally responsible and effective planning of offshore geophysical surveys and other forms of environmental imaging, particularly with respect to marine mammals, though the principles and practices can be applied to any protected and sensitive species.[267]

International Whaling Commission

The International Whaling Commission (IWC) has been conducting scientific research and informing policy makers on underwater noise for several decades.[268] The IWC Scientific Committee has examined the impacts of underwater noise on cetacean behaviour, communication, feeding, reproduction and migratory patterns. The Committee has also examined the distribution of cetaceans in relation to the characteristics of, and predicted sound levels from, anthropogenic sources, in order to assess expected impacts and evaluate possible mitigation measures. The IWC's Conservation Committee includes anthropogenic sound as a priority threat in its Strategic Plan[269] and Work Plan.[270]

At its biennial meeting in 2018, the IWC adopted Resolution 2018-4, which addresses the impacts of underwater noise on cetaceans. In this Resolution, the Commission agreed that, in line with the precautionary approach, the lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to address the effects of anthropogenic underwater noise. The Resolution included several recommendations to IWC contracting governments and a call for the Secretariat to share its scientific and conservation information with the IMO and other bodies to encourage action and promote cooperation in addressing these impacts on cetaceans.

As directed by the Commission, much of the IWC's work is carried out in collaboration with the IMO, which has jurisdiction over global shipping. IWC contributed to the development of IMO's Guidelines for the Reduction of Underwater Noise from Commercial Shipping (MEPC.1/Circ.833), and has subsequently provided updates to IMO on more recent developments and scientific findings.

An IWC Scientific Committee workshop on Advancing Efforts to Address Underwater Noise from Shipping provided further scientific evidence of the impacts of noise and focused on ambient sound, noise budgets and indicators. A second workshop is planned in 2022 to develop the Conservation Committee Anthropogenic Underwater Noise (AUN) workplan.

The AUN intersessional group will be reviewing existing recommendations on seismic exploration in the IWC as well as in other international for a.

Arctic Council

The Protection of the Arctic Marine Environment (PAME) addresses marine policy measures in response to environmental change from both land- and sea-based activities. PAME develops and coordinates strategic plans, programmes, assessments and guidelines, complementing existing legal arrangements aimed at protection of the Arctic marine environment. As referenced above, in 2019, PAME produced *Underwater Noise in the Arctic: A State of Knowledge Report.*[271] The report was produced to provide a baseline understanding of underwater noise in Arctic regions, including ambient sound levels, underwater sound created by anthropogenic activities, and impacts of underwater noise on marine life, including marine mammals, fishes, and invertebrates. In 2021, PAME also produced a report titled *Underwater Noise Pollution from Shipping in the Arctic.*[272]

SETTING STANDARDS AND GUIDELINES AT THE NATIONAL / INTERNATIONAL LEVEL

This section provides information on the status of efforts to set global standards (ISO) for acoustic measurements of anthropogenic noise in the marine environment. The need for standards, limits and guidelines for a range of noise-related procedures that concern the marine environment is also highlighted. These include the setting of international standards for EIAs and for mitigation procedures undertaken by Government and/or industry regarding noise-generating activities, such as seismic surveys or naval sonar. International harmonization of ways to define underwater noise exposure criteria is also included.

National and international standards

In 2009, a voluntary consensus standard for the measurement of underwater noise from ships was developed by the American National Standards Institute (ANSI) and the Acoustical Society of America (ASA). The standard describes measurement procedures and data analysis methods to quantify the underwater-radiated noise level from a vessel referenced to a normalized distance of 1m. Three different standards are specified according to the level of precision needed.

In December 2011, The International Standards Organization's (ISO) Technical Management Board established a new subcommittee: TC 43/SC 3, underwater acoustics. The Secretariat of the subcommittee is provided by the ASA acting on behalf of the ANSI. The scope of the subcommittee is:

> Standardization in the field of underwater acoustics (including natural, biological, and anthropogenic sound), including methods of measurement and assessment of the generation, propagation and reception of underwater sound and its reflection and scattering in the underwater environment including the seabed, sea surface and biological organisms, and including all aspects of the effects of underwater sound on the underwater environment, humans and aquatic life.

ISO standards are of a voluntary nature for use by industry as appropriate and developed based on the demand of industry. The ISO underwater acoustics subcommittee contains three working groups (WG) that are predominantly working on the following subjects:

- WG1 Measurement of noise from ships
- WG2 Underwater acoustic terminology
- WG3 Measurement of radiated noise from marine pile driving

Under a separate subcommittee ISO TC8/SC2, Marine Environment Protection, the standard ISO 16554 – Ship and marine technology – Measurement and reporting of underwater sound radiated from merchant ships – deep-water measurement, was published in 2013. The standard provides shipyards, ship owners and ship surveyors with an easy-to-use and technically sound measurement method for underwater sound radiated from merchant ships for use at the final delivery stage of ships. The measurement method should be carried out without delay (within a few hours), possibly during the official sea trial of the target ship after the completion of construction and before delivery. Classification societies may issue a notation on the underwater sound level radiated from the ship under survey using the measurement results conducted according to ISO 16554.

A “sister” standard, ISO 16554-2 Ship, and marine technology – Measurement and reporting of underwater sound radiated from merchant ships – shallow-water measurement, is currently under development.

The ISO underwater acoustics subcommittee has also developed the standard ISO 17208-1:2016, Acoustics – Quantities and procedures for description and measurement of underwater sound from ships – Part 1: Requirements for precision measurements in deep water used for comparison purposes. ISO 17208-1:2016 describes the general measurement systems, procedures and methodologies to be used to measure underwater sound pressure levels from ships at a prescribed operating condition. Two “sister” standards are in development:

(i) ISO/DIS 17208-2 Underwater acoustics – Quantities and procedures for description and measurement of underwater noise from ships – Part 2: Determination of source levels from deep water measurements; and
(ii) ISO/NP 17208-3 Underwater acoustics – Quantities and procedures for description and measurement of underwater noise from ships – Part 3: Requirements for measurements in shallow water.

Other standards that are under the direct responsibility of the acoustics subcommittee are ISO 18405, Underwater acoustics – Terminology, and ISO 18406, Underwater acoustics – Measurement of radiated noise from marine impact pile driving. Both standards were published in 2017. Also published that year was ISO 20154:2017: Ships and marine technology – Guidelines on vibration isolation design methods for shipboard auxiliary machinery. The purpose of ISO 20154:2017 is to provide general guidelines on the design of ship vibration isolation based on the basic methodology of vibration isolation for shipboard machinery. A well-designed vibration isolation system can significantly reduce the vibration transmission from shipboard machinery to ship structures, lowering the noise level onboard the ship or the underwater noise radiated from the ship.

Several other subjects have been discussed by the acoustics subcommittee, including a standard for measuring ambient noise, measurement standards for explosions or air gun pulses, and other potential future work items, including the measurement of underwater sound from active sonars, underwater sound propagation modelling, measurement of the underwater sound field and underwater noise mapping.

Work on the development of acoustic standards has been carried out in Europe with a focus on acoustic monitoring in relation to the environmental impact of offshore wind farms in the North Sea. European countries that border this sea collaborated to develop standards and definitions of quantities and units related to underwater sound.[273] These metrics were then used for the development of standardized measurement and reporting procedures, aimed specifically at acquiring the relevant acoustic data for assessing the impact of the construction, operation and decommissioning of offshore wind farms on marine life.[274]

Setting other forms of standards for the mitigation and management of underwater noise has been proposed. These include the:

- Mandatory use of comprehensive EIA (or SEA) for any proposed impulsive noise-generating activity in the marine environment following best practice guidance (see guidance stated in chapter 4);
- Setting of measurement standards for particle motion, of sound in the near field, and of ground transmission of sound;[275]
- Standardization of the design of behavioural data collection to make results comparable;[276]
- Standardization of monitoring data formats to improve data quality and robustness for use in research and evaluation;[277]
- Generic standardization of the main phases of impulsive noise-generating activities – pre-operation planning and assessment, implementation and mitigation, post-operation evaluation and reporting;
- International standardization of mitigation procedures and measures for naval exercises using active sonar;[278]

- Use of training standards for operational activities e.g., MMOs or PAM operators;[279]
- Setting of regional standards for cumulative noise mapping and marine spatial planning;[280]
- Uptake of transparency and accountability standards by noise-generating operators to ensure best practice is followed and that information that is not commercially sensitive is made available to inform management;[281]
- Setting of data-sharing standards for online data banks of acoustic, environmental and ecological information.[282]

SUMMARY

Considerable progress has been made to mitigate the effects of anthropogenic underwater noise produced by industry, particularly for seismic surveys and offshore construction techniques such as pile driving, and shipping. Detailed mitigation measures and procedures, which are largely designed to protect marine mammals, have been developed for use by these industries. Examples of best practice are the mitigation and monitoring plans and procedures implemented to protect gray whales from the effects of seismic surveys[283] and the use of mandatory exposure levels for pile driving in Germany which catalyzed the production of new mitigation technologies by the offshore energy industry.[284,285]

Although best practice exists, in some instances it can be non-mandatory and not used to a standard level by industry or the military. For example, although mitigation measures for active sonar are taken during exercises by navies, in some cases, no measures apart from MMO and PAM protocols are taken in strategic exercises.[286] The debate between national security needs versus the welfare and security of vulnerable marine fauna continues. There is a need for a minimum level of mitigation by navies on all military exercises that can be verified by independent observers.

Noise exposure thresholds and management measures are moving away from a reliance on received level (RL) thresholds to a broader ecosystem-level assessment of the cumulative impacts of both multiple impulsive noise sources and increased levels of ambient noise. However, most mitigation measures are not very effective in reducing the aggregate impact of underwater noise on marine mammals,[287] let alone on other marine taxa. Further development of techniques to assess cumulative impacts of underwater noise is required and this "overall noise impact" also needs to be considered alongside other multiple stressors affecting marine taxa.[288]

There have been some advances made in considering how anthropogenic underwater noise affects animal behaviour and whether a proposed noise-generating activity will have an impact on a population. Researchers, working together with regulators and industry, are developing and testing new monitoring and mitigation practices that take into consideration some of the more obvious behavioural effects on marine mammals, such as displacement. Considerable data-gathering is needed, particularly for the measurement and recognition of behavioural effects on marine taxa and the determination of noise impacts at the population level. In particular, a far greater understanding of the more subtle behavioural effects (e.g., communication masking, stress responses, cognitive bias, fear conditioning, and attention and distraction) on marine taxa and how these influence populations are needed.[289] Such knowledge can then feed into the development of improved mitigation practices to minimize or prevent chronic impacts on marine fauna at the population level.

Improvements in technology and processing capacity have enabled substantial advances in real-time mitigation and monitoring procedures for impulsive noise-generating activities, mainly for marine mammals, although this has also highlighted the need for meticulous planning and implementation of mitigation practices facilitated by clear and practical communications protocols. Mapping tools to show acoustic characteristics of a particular area or the presence and distribution of species of concern are becoming more available to assist in marine spatial planning and the development of mitigation frameworks.

Spatio-temporal management of underwater noise at the regional level should focus on eliminating harmful levels of anthropogenic noise from locations and times that are critically important to marine fauna, such as feeding, spawning and nursery grounds. If a noise-generating activity is permitted within range of a sensitive area, then mitigation practices of the highest standard[290] are required to ensure disturbance to the species of concern is prevented or kept to an acceptable level.

For many of the advances made for improving mitigation there is a focus on a limited number of marine taxa, notably marine mammals and particularly cetaceans. This can be justified to a certain extent given their often-vulnerable conservation status and high sensitivity. However, other taxa, such as marine fishes, reptiles and many invertebrate groups, all require greater attention in terms of fundamental research on the effects on individuals and populations and the development of specific mitigation measures and procedures. This is especially required for keystone species within marine ecosystems and for those that significantly contribute to providing ecosystem services. Identifying key species that are sensitive and vulnerable to underwater noise and developing best practice to mitigate the impacts of noise for these taxa should be prioritized.

A review of mitigation for cetaceans provides a range of recommendations for both the main activities that produce unwanted noise emissions and for regulatory bodies responsible for managing the marine environment.[291,292] These are summarized in Table 6, and their applicability to other marine taxa is highlighted. Numerous recommendations were also made by the ACCOBAMS/ASCOBANS joint noise working group,[293] and these have also been incorporated.

The recommendations include specific mitigation measures for the main noise-generating activities in the marine environment, acoustic and biological research priorities, and measures to improve the sharing of information to facilitate best practice for mitigation planning and implementation. Most of the recommendations are applicable to marine taxa other than mammals. However, in some cases, there is insufficient knowledge to effectively implement a particular measure, even though it is likely to reduce noise levels for species of marine fishes or invertebrates. Further research is required to determine if acceptable levels for many non-mammal species for both impulsive and continuous noise exist, and if so, what these are.

Table 6. Recommendations to improve the mitigation and management of underwater noise for marine mammals, but also relevant for other marine taxa (adapted from Wright, 2014[294]; Maglio, 2013[295]).

Domain	Recommendation / Action	Applicable to Non-Mammal taxa?
General	Implement proactive area-based management efforts where sufficient data is available (e.g., time-area closures, MPA establishment)	Yes
	Include environmental considerations at the very early stages of project planning	Yes
	Prioritize the collection of necessary biological data to support area-based determinations in data-deficient regions.	Yes
	Noise-generating activities in data-deficient areas are to be undertaken with extreme caution	Yes
	Implement buffer zones around established protected areas to ensure noise levels with these areas do not go beyond acceptable levels	Yes
	Address cumulative impacts from multiple stressors through appropriate cumulative impact assessment and management	Yes
	Adopt protocols that encourage cooperation within industry in the preparation of cumulative impact assessments so that all potential impacts are known in advance	Yes
	Identify ways to limit the combined impacts of human activity on marine mammal populations to prevent population decline	Yes
	Incorporate the level of uncertainty into any established legal noise thresholds	Yes
	Identify and quantify understudied noise sources such as high-powered active transducers (echosounders, various sonars)	Yes
	Improve knowledge of acoustic biology and of the distribution, abundance and life history of marine mammal species, especially endangered and data-deficient species	Yes
	Quantify effects of noise on marine mammals at the population level	Yes
	Establish or enhance direct linkages between the scientific community and the private sector to exchange information on best available practices and technologies and the effectiveness of mitigation measures during operations	Yes
Oil and gas industry (seismic surveys and other activities)	Implement technology-forcing, scientifically based noise limits for all types of oil and gas activities (e.g., exploration, extraction, and decommissioning) that can be phased in over a period of not more than 10 years. Set noise limits according to area characteristics e.g., lower limits for biologically sensitive areas	Yes
	Determine the effectiveness of soft start / ramp-up procedures for marine mammal species in "real world" conditions	Yes
	Conduct research into the long-term effects of exposure to seismic activity on marine mammals, such as non-injurious impacts that may occur outside the prescribed safety zone	Yes
	Assess the noise-related impacts of other aspects of the industry – drilling rigs, drill ships, offshore terminals etc. – and conduct research to reduce their noise levels	Yes
	Use risk assessment software tools to improve mitigation measures during an operation	Yes – if available
	Promote the use of national, regional or global public web platforms to industry that contain data/maps on species presence/abundance and distribution and the location of maritime protection zones, biologically important areas, etc.	Yes

Table continues on next page

Domain	Recommendation / Action	Applicable to Non-Mammal taxa?
Shipping	Encourage port authorities to develop regional port partnerships and adopt noise-related certification standards for low noise propulsion technologies and/or operational mitigation measures	Yes
	"Green" certification programmes to include noise-related criteria in their standards	Yes
	Governments to actively support the efforts of the International Maritime Organization to address noise from ships	Yes
	Regulators to mandate and incentivize compliance with the pending IMO guidelines	Yes
	Assess the feasibility of operational measures for shipping such as route and speed management	Yes
	Develop indicators for quantifying ship noise and use on-board monitoring systems to indicate the need for maintenance or repair	Yes
	Encourage port authorities to provide noise reduction incentives such as discounted harbour fees	Yes
Pile driving and other coastal offshore operations	Determine acoustic emissions during the installation of gravity-based or suction foundations and of vibratory pile drivers	Yes
	Encourage the adaptation of screw pile technology for use in offshore settings (low noise emissions)	Yes
	Recognize the limitations of noise mitigating measures for pile driving and gradually introduce more restrictive standards	Yes
	Include a shutdown safety zone appropriate to the noise source which is monitored by visual observers and/or PAM	Yes- turtles (visual)
	Improve the knowledge and understanding of cumulative impacts of noise generated by construction activities	Yes
	Further test the effectiveness of source-based and target-based technologies	Yes (source-based)
Naval activities	Take efforts over the long-term to refine military sonars to produce signals that are less damaging to marine mammals	Yes
	Encourage the use of risk assessment software by all navies	Yes
	Encourage the use of national, regional, or global public web platforms by navies, that contain data/maps on species presence/abundance and distribution and the location of maritime protection zones, biologically important areas, etc.	Yes – if available
	Avoid conducting sonar exercises in locations with topographical characteristics thought to lead to strandings	No
	Use of pre-survey scans, safety zones, ramp-ups and the lowest possible source levels	Yes (lowest source)
	Include lower-level pings between sonar pulses if modelling shows that there is time for animals to approach too close to the source	No
	Restrict sonar exercises to daylight hours and use experienced MMOs instead of lookouts	No

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6. FUTURE RESEARCH NEEDS

This assessment of anthropogenic underwater noise and its effects on marine organisms has highlighted the extent of knowledge gaps and uncertainties. Uncertainties need to be addressed in a systematic manner to fully understand the potential effects of increased noise from human activities in the marine environment. There are a suite of research needs that must be addressed to both better characterize and quantify anthropogenic noise in the marine environment and the impact it has on marine organisms. However, the extensive knowledge gaps also mean that prioritization will be required. Detailed research programmes on the effects of anthropogenic underwater noise on species, populations, habitats and ecosystems as well as cumulative effects with other stressors need to be put in place or consolidated where they already exist. Current knowledge for some faunal groups, such as elasmobranch fishes, marine turtles, seabirds, and invertebrates, is particularly lacking. Other priorities for acoustic research are endangered or threatened marine species and critical habitats they depend upon for important activities such as foraging or spawning. Marine species that support commercial or subsistence fisheries should also be assessed for susceptibility to noise pollution and the issue of anthropogenic noise considered for fisheries management plans. Existing or proposed management frameworks also need to be tested and refined accordingly in a range of scenarios. Several current or proposed large-scale research programmes are addressing a range of issues with a focus on marine mammals. However, there is a need to scale up the level of research and management efforts to significantly improve our understanding of the issue and minimize the impact of noise on marine biodiversity.

The literature that has been reviewed to inform the development of this document includes a range of research needs. These set out important recommendations for marine mammals,[1,2,3,4,5] specific research needs for other taxa,[6,7,8,9,10,11,12,13,14,15,16,17] recommendations across all marine wildlife groups,[18,19] and also region-specific recommendations.[20,21] The main research priorities recommended by these reviews are summarized in Table 7. Details of these recommendations are incorporated into the following sections as appropriate.

Research needs can be split into four main areas:

- Further characterization of underwater noise and properties of emitted sound in a changing marine environment;
- Baseline data on the biology, distribution, abundance and behaviour of marine species;
- Detailed information on the impacts of noise on marine animals at the individual, population and ecosystem level;
- Assessment and improvement of mitigation procedures and measures.

Several research areas that should be highly prioritized:[22]

- Describing soundscapes;
- Impacts of particular sound sources;
- Effects of anthropogenic noise on marine animals;
- Mitigation of effects;
- Measurement and description of noise and the conduct of acoustic experiments.

ANTHROPOGENIC SOURCES AND AMBIENT SOUND

Although there has been considerable previous investment in the collection of underwater sound data for commercial, military or research purposes, our knowledge of anthropogenic sound fields in the marine environment is incomplete.[23] The seas and oceans are also becoming noisier as marine-based human activities increase in diversity and intensity, particularly in coastal and shelf waters. Ambient noise levels for mid and high frequencies are increasing with the greater use of sonar and increased small boat traffic.[24] Anthropogenic noise sources are also often distributed heterogeneously in time and space, which contributes to the complexity of underwater "soundscapes" that marine organisms inhabit.[25] In addition, the different components of anthropogenic sound attenuate at different rates depending on their frequency and environmental conditions, further increasing complexity and making it difficult to predict the actual sound levels received by marine organisms.[26] The type of sound is also important in terms of whether it is a continuous emission over a long period or a series of short intermittent pulses causing different chronic or acute effects even though the power of the sound emitted is the same.

Further quantification of the underwater acoustic environment is therefore required. Increased levels of passive (or active) acoustic monitoring is needed to detect and characterize both natural and anthropogenic sound sources and collect ambient noise information for key areas. Anthropogenic sources considered to be of the highest concern (in the United States) are certain military sonars, ice-breaking, seismic air guns and new classes of large vessels closely followed by wide-azimuth seismic surveys, pile driving, as well as oil drilling and production.[27] Priorities for action are likely to change somewhat at the national level depending on the key activities and sound sources present or planned within areas under national jurisdiction. Regional or ocean-wide priorities for acoustic research will need to be considered and agreed through regional or global bodies.

Passive acoustic monitoring can also provide real-time information to characterize ambient sound fields and feed into models to predict future trends. To model ambient noise levels, a better understanding of the signal characteristics of anthropogenic sources is needed.[28] With improved source profiles and a more precise understanding of how the level of activity contributes to the resulting ambient noise profile, researchers can extend noise modelling so that better predictions can be made for regions with known anthropogenic activities that are currently lacking in acoustic information.[29]

More detailed information on the location and distribution of anthropogenic noise sources in the oceans can contribute to real-time estimates of regional or global noise levels as part of large-scale ocean monitoring systems. For example, the geographic position of commercial vessels or the tracklines for seismic profiling could be used in models along with data on environmental variables (bathymetry, sound speed profiles, wind and wave noise spectra) to provide a more accurate assessment of the relative contribution of natural and anthropogenic noise sources.[30] Establishing sound monitoring stations and programmes to survey different types of underwater soundscapes is required to build up a greater understanding of the underwater acoustic environment and how this is changing. A long-term aim should be the development of underwater anthropogenic acoustic thresholds for marine ecosystems to determine the amount of anthropogenic sound an ecosystem can tolerate without its status being altered,[31] or whether this can be practically determined, especially with respect to cumulative impacts.

There is also a need for further research to predict the effects on declining ocean pH on the properties of underwater sound. As ocean acidity increases, there is a corresponding reduction in the absorption of low frequency sound (100 Hz–10 kHz);[32] [33] the mechanism for this chemical relaxation-based acoustic energy loss is well known.[34] More than 50 per cent reduction in the absorption of sound at 200 Hz has been predicted in high latitudes (e.g., North Atlantic) by 2100,[35] although these predictions have been disputed by subsequent modelling studies.[36] If the former predictions are the more likely scenario, then there is the potential that marine organisms sensitive to low-frequency sound (e.g., baleen whales) will be more susceptible, particularly in acoustic hotspots where high levels of anthropogenic noise (e.g., shipping) coincide with the greatest drop in absorption.

Research programmes, such as the International Quiet Ocean Experiment (IQOE)[37] and the LIDO project,[38] are important elements in improving our understanding of underwater sound and anthropogenic noise in our oceans and need to be supported over the long-term.

BASELINE BIOLOGICAL INFORMATION

To understand how anthropogenic noise is having an impact on marine biodiversity it is important that considerably more biological and ecological information for a particular species is available, including its presence and behaviours. Information for species and populations is incomplete for many marine animals, particularly for invertebrates but also for many marine fishes and mammals (e.g., beaked whales). In addition, data can be scarcer in some regions than others, e.g., within developing countries, the Arctic and Antarctic.[39,40] The scale of this task suggests that a system of prioritization is needed. Marine species that are known or highly likely to be susceptible to the effects of anthropogenic noise but are also threatened by other stressors, such as overexploitation, habitat loss or other forms of pollution, are among the highest priorities. In addition, there is a lack of basic biological information regarding underwater acoustics for many threatened species to. For example, elasmobranch fishes are recognized as highly threatened taxa[41] but very little is known about their sense of hearing, with data available for only a few species.[42] Research is therefore required for species that are data deficient in terms of auditory biology, hearing sensitivity and how they use sound for communication or for key life processes such as feeding or predator avoidance. Again, due to the number of species involved, research could focus on representative[43] species as surrogates for less-common or more-difficult-to-test species[44] or on a wide range of morphologically and taxonomically diverse species of interest.[45] Representative species could be selected according to trophic group, lifestyle (e.g., pelagic, or demersal/benthic) or life history stage. In addition to an improved understanding of the importance of sound to marine organisms it is equally important to collect detailed information on the distribution, behaviour and population size of selected species. Knowing what constitutes normal behaviour and which habitats are preferred by marine species at particular times will enable more effective management and mitigation measures to be made.

Another priority is the use of all reliable biological information currently available for species from a range of sources (e.g., fisheries data for stocks and distribution, marine mammal monitoring data, tagging studies for marine turtles, teleost fishes or elasmobranchs) to help build up a more coherent picture of the life history traits for that organism. The development and maintenance of standardized online databases has been highly prioritized for marine mammals[46] and could be applied to other groups of marine vertebrates, such as teleost and elasmobranch fishes and marine turtles.

IMPACTS OF NOISE ON MARINE BIODIVERSITY

The high level of uncertainty for many species also applies to our current knowledge of the impacts of anthropogenic noise. Again, prioritization of marine species for research will be required, and the same criteria mentioned previously for selection should apply. High priority research areas are listed in Table 7 and include the effects of anthropogenic noise on individuals in terms of physical damage, physiology and behaviour but also the long-term effects on populations and the cumulative effects of noise in combination with other stressors.[47,48] Studies at the population, community and ecosystem level are all required[49] and should be linked to the provision of ecosystem services by marine fauna. Population-level effects can be predicted from individual responses if there is adequate data on energy budgets, the effect of disturbance and other aspects, such as predator-prey dynamics in relation to anthropogenic noise.[50]

The effects of anthropogenic noise on marine mammals are considerably better known than on other taxa, although even within this group some species have been studied more than others, and significant uncertainties remain. For instance, Erbe et al. (2019b)[51] reported that the impacts from sound produced by vessels have not been studied for most marine mammal species and studies on subtle changes are more limited than other responses, such as avoidance.

There is a need to increase the knowledge base for data-deficient groups (e.g., marine fishes, marine turtles, and invertebrates). Hawkins et al. (2020),[52] Popper and Hawkins (2019),[53] Popper et al. (2019a[54], b[55], 2020[56]) reported a range of research needs for fishes and invertebrates, which includes broadening of studies across species, measuring sensitivity to agreed standards (including a focus on particle motion), better understanding of the sound pressure and particle motion that elicit behavioural responses (in the wild), development or better use of models to assess particle motion, improvement of approaches to measure and assess particle motion (including approaches for monitoring), better understanding of detrimental changes to physiology and masking, development of exposure and response data, improved data on hearing sensitivity, development for the measurement and use of particle motion in regulatory activities, and a better understanding of fitness consequences. Weilgart (2018)[57] also reported a range of recommendations for these groups, which align with those previously stated and a need to better understand cumulative effects, develop reliable indicators of harmful stress, focus of field research in areas have seen a reduction in sound levels (i.e., as a consequence of mitigation approaches). Nelms et al. (2016)[58] have also outlined research needs for marine turtles, including the need to improve the understanding of injury risks and behavioural responses.

Collection of field-based data for behavioural (and other) long-term responses of individuals to anthropogenic noise is needed. This is particularly required for teleost fishes where it is not possible to extrapolate from studies of caged fishes to wild animals.[59] For non-behavioural research, new technology may have to be developed to monitor the effects of anthropogenic underwater noise in situ via devices such as smart tags, e.g., for measurements of hearing loss, metabolism and the production of stress hormones.

The chronic and cumulative effects of anthropogenic noise on marine organisms and populations have received some attention in recent years, particularly for marine mammals,[60,61] but need thorough assessment for other taxa (e.g., teleost and elasmobranch fishes, marine turtles and invertebrates). It is known that chronic disturbance in the coastal environment can lead to reduced reproductive success in some cases[62] and further research studies are required to investigate whether this is also the case for other marine fauna. Reproductive success may also be compromised by changes in behaviour (e.g., avoidance of spawning sites) or masking of communication between potential mates.[63]

Increasing levels of ambient noise in marine and coastal environments have led to concerns of masking of important biological signals either received or emitted by marine organisms. Although this has theoretically been demonstrated for marine mammals,[64] there is little evidence to confirm masking in other marine taxa. Research must also be continued on the anti-masking strategies adopted by various marine mammals, and these require study of how different species alter their vocalizations in response to increasing levels of background noise.[65] Teleost fishes are one group where acoustic reception and communication can be highly important for survival or reproduction.[66] Masking of important orientation cues may also occur for both fishes and invertebrate larvae prior to settlement.[67,68] The potential for masking in a range of marine taxa is apparent, and the risk of an impact is likely to increase as anthropogenic noise levels rise in shallow seas. This should be regarded as a high priority research need as it has the potential to affect multiple species simultaneously with long-term consequences for populations and communities.

Extensive research on particle motion and seabed vibration is particularly required to better understand effects on several taxa. Vibration through the substrate is also receiving greater attention, with research needs for this subject becoming more apparent, especially for invertebrate fauna living on or in the seabed[69] and their roles in ecosystem functioning.[70]

Thus far, the socio-economic consequences of noise-induced impacts on marine populations have not been substantially considered by the research community, although the subject is receiving attention in some regions.[71] Avoidance of noisy areas or reduced population success may have a significant effect on catches of commercial fishes or invertebrate species. Seismic surveys have previously been linked to short-term reductions in catch levels.[72]

Reviews have also highlighted methodological issues in experimental design and the need for proper controls and pathology (where applicable) as well as careful measurement of sound sources and signals and the use of proper sound metrics.[73,74,75,76] Early experimental work in the sea confirmed the importance of working under appropriate acoustic conditions.[77] For laboratory-based work investigating anthropogenic noise effects on marine taxa, it is extremely important that the experimental acoustic conditions accurately depict either natural conditions found in the sea or the sound properties of anthropogenic sources. For example, considerable research has been carried out in small tanks where the acoustic field is considerably different to that found in the natural environment.[78] The tanks themselves can alter the acoustic field in certain conditions, making the determination of meaningful results difficult. Care must also be taken when comparing different types of audiograms used to estimate hearing thresholds.[79] Standardization in research studies will help to both define the sound field received but also allow for comparisons of source signals of different types.[80]

As reported by Popper et al. (2020)[81] research should focus on answering questions that are most critical for understanding the issues and for developing mitigation measures and regulations, and there is a need for standardization of research questions being asked and how they are asked. This is especially important to compare results between different types of research and species.

MITIGATION AND MANAGEMENT

The mitigation and management of anthropogenic noise in the marine environment has been extensively covered in the previous chapter. Research needs are mentioned there (e.g., Table 6) with further points provided in Table 7. Several issues were highlighted that currently exist with commercial and government approved mitigation procedures for marine activities emitting underwater noise. There is a need to critically assess the effectiveness of such mitigation procedures[82] through an independent peer-reviewed process. Some progress has been made for seismic surveys such as the Behavioural Response of Australian Humpback whales to Seismic Surveys (BRAHSS) project.[83] Measuring the efficacy of mitigation measures such as "soft start" in naval sonar exercises is also required. Recommendations can then be made to improve existing guidelines for the relevant practitioners. The long-term aim is the production of global standards that nations (and their military, for sonar operations) can sign up to, and considerable progress has been made to achieve this for marine mammals.[84,85]

It is also important to assess the overall noise budgets for the marine environment at a range of scales and how the cumulative effects of multiple sources of anthropogenic noise can be minimized spatially or temporally. Noise budgets are a key part of the EU's MSFD and are in development[86] but require further research to be applicable to a wider range of taxa and geographic regions. There is also a need to investigate the effectiveness of mitigation measures in terms of their ecological benefit and the recovery of individuals or populations from chronic noise exposure,[87] especially in relation to cumulative stressors.

As well as improving mitigation procedures and measures, it is important that industry is encouraged to improve existing mitigation tools, such as the mechanisms of noise emission, by developing quieter noise sources through engineering modifications (e.g., shorter duration, narrower directionality or eliminating unnecessary frequencies).[88,89,90] The development of PAM systems or other remote sensing techniques to detect a range of marine taxa is an important step for improving mitigation.[91] For example, PAM will become more successful as a mitigation tool if it is able to accurately detect a significant number of vocalizing marine mammal species within exclusion zones, identify each marine mammal species and provide a reliable range measurement to the animal.[92]

Table 7. Priority research needs for anthropogenic noise and its impact on marine biodiversity (adapted from Boyd et al., 2008[93]; Southall et al., 2009[94]; Tasker et al., 2010[95]; Hawkins et al., 2015[96])

Subject Area(s)	Research Priorities	Biodiversity Conservation Priorities
Marine acoustics and monitoring	Long-term biological and ambient noise measurements in high-priority areas (e.g., protected areas, critical habitats, commerce hubs,) and more widely at the ocean basin level to record trends. Establish sound monitoring stations and programmes to survey different underwater soundscapes that involve real-time monitoring and storage of raw data.	Migratory corridors; foraging, mating/spawning and nursery habitats. Identification of remaining quiet areas and ambient noise hotspots.
	Determine the characteristics, distribution, and abundance of anthropogenic sound sources in the marine environment. Improve knowledge of the propagation of sound (both sound pressure and particle motion). Describe and fully evaluate the effects of sound fields produced by anthropogenic sound sources. Establish a central data repository and standards/protocols for data collection.	Identify "noise hotspots" where multiple sources occur or are likely to occur. Propagation of sound and vibration through the seabed – especially relevant to benthic fishes and invertebrates.
	Develop new technologies (e.g., acoustic monitoring) to detect, identify, locate and track marine vertebrates, to increase the effectiveness of detection and mitigation. Determine ecological thresholds for anthropogenic sounds – how much an environment can tolerate without its ecological status being changed.	Monitoring of susceptible groups (e.g., beaked whales) and non-vocal vertebrates (e.g., teleost fishes, elasmobranchs, turtles). Prioritize development of tools for particle motion monitoring.
Baseline biological information	Biological research on: Structure and function of acoustic sensory organ • Use of sound by marine organisms; • Species-specific communication maximum ranges; • Basic information on hearing ability, especially for low-frequency and high-frequency species; • Modelling of the auditory system (to reduce dose response experimental exposure to sound); • Developing new tools to identify unknown biological sound sources and document associated behaviours. • Critical habitats, migration routes and reproductive periods Establish a library of sounds for marine animals to facilitate the use of passive acoustic tools.	Data deficient taxa: teleost fishes, elasmobranchs, marine turtles, invertebrates. Marine species that are endangered and/or highly susceptible to multiple stressors (or surrogates for endangered spp.). Taxa that rely on particle motion to detect sounds. Accurate measurement of hearing in field conditions, especially for fishes and invertebrates.
	Expand/improve distribution, abundance, behavioural and habitat data for marine species particularly susceptible to anthropogenic sound.	Beaked whales, threatened cetaceans.
	Expand/improve distribution, abundance, behavioural and habitat data for marine species with high potential susceptibility to anthropogenic sound.	Teleost fishes, invertebrates (Cephalopods).
Baseline biological information and monitoring	Support the development, standardization and integration of online data archives of marine vertebrate distribution, abundance and movement for use in assessing potential risk to marine vertebrates from sound-producing activities.	
	Standardize data-collection, reporting and archive requirements of marine vertebrate monitoring programmes.	Marine mammals, marine turtles, selected fishes (apex predators, threatened keystone species), selected invertebrates.

Subject Area(s)	Research Priorities	Biodiversity Conservation Priorities
Effects of noise on marine organisms	Data collection, involving controlled exposure experiments, for key species of concern and/or for data-deficient taxa for the effects of noise (where applicable) on: • Hearing loss (TTS/PTS) and auditory damage (e.g., sensory hair cells); • Physiology(e.g., stress effects); • Behaviour – e.g., avoidance / displacement or disruption of normal activity; • Non-auditory injury – barotrauma, embolism, decompression sickness; • Masking – communication and orientation; • Survival and reproductive success; • Particle motion effects on all of the above. Accurate measurement of the effects of noise in experiments that adequately replicate the sound characteristics of anthropogenic sources. Characteristics of sound that make them more likely to be harmful to fishes and invertebrates.	Key concerns: baleen whales, beaked whales, Arctic and endangered species of marine mammal. Data-deficient taxa: teleost fishes, elasmobranchs, marine turtles, invertebrates. Prioritize fishes and invertebrates of the greatest ecological and commercial/ nutritional importance.
	Investigate cumulative and aggregate effects of noise and stressors on marine organisms for both: • multiple exposures to sound (anthropogenic and natural) • sound in combination with other stressors	Identify noise exposure criteria for cumulative effects. Determine which metrics are most appropriate for expressing the accumulation of sound energy.
	Improve ability to identify and understand biologically significant effects of sound exposure to improve effectiveness and efficiency of efforts to mitigate risk.	
Effects of noise on marine populations and communities	Measure changes in vital rates, e.g., fecundity, survival for populations. Measure changes in community composition.	Endangered species with small populations and limited distribution or mobility.
Measurement and description of sounds	Adoption of relevant and universally acceptable metrics that describe sound appropriately and enable comparison of the effects of sound on different sound types and taxa. Development of a common terminology for sound measurement and exposure understandable to the whole community. Developing inexpensive "non-specialist" instrumentation for underwater sound measurement in the laboratory and in the field.	Required for both sound pressure and particle motion. Measurement of particle motion is particularly needed for teleost fishes and invertebrates.
The conduct of acoustic experiments	Development of special acoustic facilities to enable investigators to present sounds to animals with full specification of the signals presented both in the laboratory and in the field, and for both sound pressure and particle motion.	

Table continues on next page

Subject Area(s)	Research Priorities	Biodiversity Conservation Priorities
Mitigation	Promote strategies that seek to implement the mitigation hierarchy, with particular emphasis on avoidance, especially in areas important to the conservation of habitats and species	
	Develop and improve noise-exposure criteria and policy guidelines based on periodic reviews of best available science to better predict and regulate potential impacts.	
	Develop and validate mitigation measures to minimize demonstrated adverse effects from anthropogenic noise.	
	Test/validate mitigating technologies to minimize sound output and/or explore alternatives to sound sources with adverse effects (e.g., alternative sonar waveforms).	
	Efficacy of ramp-up, soft start and other aversive techniques for marine turtles, fishes and invertebrates.	
	Application of acoustic monitoring to detect the presence of fishes and invertebrates.	
	Support the development of regional programmes to deliver mitigation strategies using existing good practice models (e.g., the ECHO Program).	

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7. CONCLUSIONS

The level of anthropogenic noise in the marine environment has increased substantially in the last century[1] as human activities in coastal and oceanic waters have expanded and diversified. The underwater world is subject to a wide array of anthropogenic noise from activities such as commercial shipping, oil and gas exploration and the use of various types of sonar.[2] The level of activity is also predicted to rise over the coming decades as maritime transportation and the exploration and extraction of marine resources continue to grow.[3]

Sound is extremely important to many marine animals and plays a key role in communication, navigation, orientation, feeding and the detection of predators.[4] From invertebrate larvae[5] to the largest animals on the planet,[6] the detection and recognition of underwater sound is crucial. The use of sound underwater is particularly important to many marine mammals such as cetaceans and especially the toothed whales, which have highly specialized echolocation abilities. Many other marine taxa also rely on sound on a regular basis, including teleost fishes and invertebrates such as decapod crustaceans. The importance of sound for many marine taxa is still rather poorly understood and in need of considerable further investigation.

Concerns about the impacts of anthropogenic noise on marine animals have grown steadily over the last four decades. The levels of introduced noise in the marine environment are now considered to be a global issue and a significant stressor for marine life. Noise is listed as one of the impacts that can result in a substantial loss of biodiversity over time in sensitive marine habitats.[7] In combination with other stressors, underwater noise pollution is likely to contribute to marine defaunation, which is predicted to increase as human use of the oceans industrializes.[8]

A wide range of effects of increased levels of noise on marine fauna have been documented both in laboratory and field conditions. Low levels of sound can be inconsequential for many animals. However, as sound levels increase the elevated background noise can disrupt normal behaviour patterns, leading to less efficient feeding, for example. Masking of important acoustic signals or cues can reduce communication between conspecifics[9] and may interfere with larval orientation, which could have implications for recruitment. Some marine mammals have tried to compensate for the elevated background noise levels by making changes in their vocalizations.[10]

Intense levels of noise exposure have caused physical damage to tissues and organs of marine animals,[11,12] and even moderate levels of noise can lead to mortality, with lethal injuries of cetaceans documented in stranded individuals caught up in atypical stranding events.[13] Noise has been shown to cause permanent or temporary loss of hearing in marine mammals and fishes. Behavioural responses such as strong avoidance of the sound source can lead to habitat displacement.[14] Some marine animals, such as beaked whales, are particularly susceptible to anthropogenic noise, and some populations have experienced declines for years after a sonar-induced stranding event.[15] Short-term effects have been observed in several marine mammals and fishes but the long-term consequences of chronic noise pollution for individuals and populations are still mainly unknown. Potential long-term impacts of reduced fitness and increased stress leading to health issues have been suggested.[16] There is also growing concern about the cumulative effects of anthropogenic noise and other stressors and how they can affect populations and communities.[17]

Research has particularly focused on cetaceans and, to a lesser extent, other marine mammals, such as pinnipeds, but there are still many knowledge gaps that need addressing. Acoustic research for marine fishes and invertebrates is still very much in its infancy and requires considerable investment to set up systematic studies of the effects of marine noise on these animals. Consequently, many noise-induced impacts for less well-studied taxa are currently predicted effects, some of which have been inferred from studies of other faunal groups. Many of the less-studied groups rely on particle motion for sensing their acoustic environment, and our understanding of this is very limited although gaining more attention. Substantial further research is required to better understand the impacts of anthropogenic noise on marine biodiversity. Uncertainties must be acknowledged to drive improvements in research and to understand the confidence in assessments being made. Robust risk-assessment approaches need to be implemented to consider and address these uncertainties and precautionary approaches taken where they are appropriate.

There is also need to a better focus on answering the key questions of concern to effectively regulate activities that may cause harm. A system of prioritization will also be needed to focus on species that are already highly threatened or endangered through a combination of multiple stressors and intrinsic characteristics, but also representative groups of understudied taxa such as marine fishes and invertebrates, as well as ecologically or commercially important taxa. There is also a need for better standardization across the board. Some regional programmes have developed best practice approaches (e.g., the ECHO Program) that can be rolled elsewhere to provide field-based understanding, especially in areas where significant effects may be possible or in danger of increased exposure relating to expanding activities. Such research needs to focus on developing a better understanding of biodiversity values, risks (including cumulative), and how these are mitigated and managed. Programmes may seek to take standardized approaches to support understanding across a range of taxa and environments and develop approaches to share information. Indeed, locations for linked global programme development may be agreed amongst Parties in a way that seeks to provide a much understanding as possible using various pre-determined criteria.

There are also additional global factors to consider when assessing the potential of anthropogenic noise to affect marine species. It is known that low-frequency sound absorption decreases with increasing acidity in seawater. Modelling of projected changes in acidity caused by ocean acidification has suggested that particularly noisy regions that are also prone to reduced sound absorption should be recognized as hotspots where mitigation and management is probably most needed. Further work is required to verify or refute these predictions.

Studies have shown an expansion of activities in historically untouched areas, such as within the Arctic and Antarctic regions,[18,19,20] and risks in these areas may increase in the future due to expansion of such activities.[21] The Arctic and Antarctic are also where populations that have not been exposed to noise are likely to occur. These have been highlighted as key sources of baseline information that can be used in mechanistic models to predict impacts before they occur and potentially get ahead of the curve of rapid industrialization of the ocean.[22] The most quiet sites should be subject to precautionary measures so that they become either acoustic refuges or experimental control sites to improve our understanding of the ecological impact of ocean ensonification.[23]

Long-term strategic recommendations have been made regarding the mitigation of anthropogenic underwater noise.[24] Ways should be found to address and reduce the underlying demand for noise-producing activities, switching to quieter technologies and improving inefficiencies. Avoidance of impacts should be prioritized where significant impacts may occur, in line with the adoption of the mitigation hierarchy. It is worth remembering that sound is a form of energy that has the potential to be transferred, converted or stored for later use.[25] Much of the anthropogenic noise in the oceans (e.g., from propulsion systems) is due to inefficiency and has been regarded as wasted energy that could be used more productively.[26] Also, the increasingly strict noise level standards for all noise-producing activities are phased in by regulatory bodies to drive innovation to reduce noise at the source. This has been evident in Germany where mandatory noise exposure standards for wind farm installation have fuelled technical innovation and the development of mitigation techniques to meet the standards.[27] Setting lower noise level standards will help to address behavioural and other non-injurious effects of noise on marine fauna, both in proximity to acute sources and at greater distances.

As our use of the oceans increases and becomes more industrialized, anthropogenic noise in the marine environment is an issue that is likely to increase in significance over the next few decades, which could have both short- and long-term negative consequences for marine animals. The increase in the uncontrolled introduction of noise is likely to add significant stress to already-stressed oceanic biota,[28] which will likely contribute to marine biodiversity loss,[29] if not tackled in combination with other anthropogenic drivers. Protecting marine life from this growing threat will require more effective control of the activities producing noise, which depends on a combination of greater understanding of the impacts and increased awareness of the issue by decision-makers, on a global, regional and national scale, to implement adequate regulatory and management measures.

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