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MARINE NOISE POLLUTION – INCREASING RECOGNITION BUT NEED FOR MORE PRACTICAL ACTION

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ABSTRACT

Over the last two decades, marine noise pollution has become increasingly recognized as an issue of major significance. The issue has become a primary focus of marine mammal research, but is also of concern to the public and policy makers. The result has been efforts involving a variety of disciplines, and relevant legislation and associated guidance are now in place in many parts of the world. Most current mitigation efforts are directed at reducing the risk of injury from exposure to intense noise, although the effectiveness of such mitigation measures in terms of risk reduction has rarely been quantified. Longer-term chronic impacts of noise including disturbance or masking of sounds critical for feeding and reproduction have received substantially less attention in management. New technologies are being developed for a number of activities which can substantially reduce noise inputs into the marine environment. As with other forms of pollution, reducing input at source is likely to be the most effective way of reducing impacts. We recommend as a priority the implementation of noise quieting technologies and the spatial and temporal exclusion of noise to minimize contact with marine life.

KEYWORDS

Marine noise; Cetaceans; Whales; Marine renewable energy; Mitigation; Management

INTRODUCTION

Marine mammals and other marine animals live in a medium through which sound propagates extremely well and light does not. This explains the heavy reliance of many marine animals on acoustics for navigation, hunting, reproduction and communication. It also helps to explain the increasing use of sound underwater by humans in our attempts to efficiently navigate, explore and exploit the seas and what lies beneath them. Whales and dolphins (collectively known as cetaceans) are highly adapted physiologically and behaviourally to use sound [Tyack and Miller, 2002]. Cetacean conservation and welfare and human-produced sounds in the oceans may sometimes be in conflict, and this includes both sound generated as an acoustic tool and that produced incidentally to other activities, notably shipping noise. Various substantive reviews have considered this topic in recent years (for example, [Richardson et al., 1995; Gordon and Moscrop, 1996; National Research Council of the National Academies, 2003; Simmonds et al., 2004; Hildebrand, 2005; Jasny, 2005; Weilgart, 2007; and Wright and Highfill, 2007]). In summary, these reviews consider the available evidence showing how noise can reduce communication ranges and obscure sounds of interest (known as masking), disrupt reproductive behaviours (including by causing cessation of singing and possibly also mother-calf separations), affect energetic budgets through interference with foraging and increased travel, exclude animals long term from certain important habitats, induce chronic stress responses, cause temporary or permanent loss of hearing sensitivity, induce physical injury and, in extreme cases, cause animals to die. While marine species may have evolved to cope with and indeed use the many natural sounds in the marine environment, human activities are now a major source of noise, particularly low-frequency noise, throughout many parts of the world's oceans and are exposing animals to many more very high-level and chronic (usually lower-level) sounds. While animals have exhibited some coping strategies, these are limited and in any case likely carry other physiological or behavioural costs. Moreover, long-lived animals such as cetaceans are unable to evolve adaptations in time to these new incursions into their habitat [Rabin and Greene, 2002].

The 2003 US National Research Council report on underwater noise and marine mammals, and an associated in-depth review [Hildebrand, 2005], identified the major marine noise sources and their general acoustic characteristics. These lists include commercial shipping (with sound emissions greatest in the main shipping routes, coastal and port areas); seismic airgun arrays for oil and gas exploration (increasingly in deep water, but with emphasis on the continental shelf); naval sonars (variable below 70º latitude and with emphasis in coastal areas); fisheries sonars (primarily coastal and over the continental shelf); unknown research sonars; and acoustic deterrent and harassment devices used predominantly to deter predators by fisheries and aquaculture facilities (again mainly in the coastal zone). Acoustic deterrent devices are now also used in some instances to try to keep wildlife away from loud noise sources. Most recently, offshore construction, especially of wind farms, has been added to this list of notable sources, with pile driving a particularly substantial contributor [Simmonds and Brown, 2010].

MILESTONES IN THE EMERGENCE OF MARINE NOISE POLLUTION AS A RECOGNIZED THREAT

In 1971, Payne and Webb [1971] alerted the world to the importance of sound for baleen whales and then, in the 1980s and 1990s, marine noise pollution emerged as a significant environmental issue that required regulation and management. There were various drivers for this emergence. For example, Simmonds and Lopez-Jurado [1991] connected a largely unprecedented series of beaked whale live mixed-species strandings between 1982 and 1989 in the Canary Islands to military exercises. Van Bree and Kristensen [1974] had earlier suggested military exercises might have been involved in a beaked whales mass stranding in the Caribbean, and Frantzis [1998] similarly later raised concerns about a single beaked whale stranding that coincided with the use of military sonar in Greece in 1996. A high-profile stranding event in the Bahamas in 2000 after a military exercise was swiftly investigated leading to the US government acknowledging the likely contribution of sonar exposures [Balcomb and Claridge, 2001; Evans and England, 2001; Parsons et al., 2008]. These and other similar events eventually led the International Whaling Commission's (IWC) Scientific Committee to note that "there is now compelling evidence implicating military sonar as a direct impact on beaked whales in particular" ([IWC, 2004]; see also [Moore and Barlow, 2013]).

The use of loud noise in an effort to measure ocean temperatures across entire ocean basins in the Acoustic Thermometry of Ocean Climate (ATOC) experiment and its predecessor (the Heard Island Feasibility Test) was another issue that caused considerable concern and gained public attention (e.g., [Simmonds, 1992; McCarthy, 2004; Anon, 2013]). These experiments also set precedent for the requirement for formal environmental impact assessments to be made for noise-making activities. In 1995, the Scripps Institution of Oceanography and the US Navy reached an agreement with several plaintiffs (including Natural Resources Defence Council) to conduct a more extensive, multi-year Marine Mammal Research Program together with the ATOC experiment. A year later, many of these same plaintiffs came to an agreement with the US Navy to establish a research program to examine the potential effects of Low Frequency Active Sonar on some whale species [Jasny, 2005].

In the last years of the 20th century and the early years of the 21st, several international and regional conventions came to acknowledge the significance of marine noise pollution. For example, IWC Resolutions 1997-7 and 1998-5 directed the IWC's Scientific Committee to provide regular updates on environmental matters that affect cetaceans, including noise pollution, and the Scientific Committee has now had noise pollution as a standing agenda item since 1999 [Simmonds and Dolman, 2000]. (The IWC Scientific Committee also regularly makes expert assessment of unusual cetacean mortality events.)

In 2004, the United States Congress directed the US Marine Mammal Commission (MMC) to “fund an international conference or series of conferences to share findings, survey acoustic ‘threats’ to marine mammals, and develop means of reducing those threats while maintaining the oceans as a global highway of international commerce.” The MMC duly convened an Advisory Committee on Acoustic Impacts on Marine Mammals and sponsored a series of meetings to prepare a regrettably non-consensual report, issued to Congress in March 2007 [MMC, 2007]. Among the Commission’s recommendations were: (i) the establishment of a coordinated national research program on the effects of anthropogenic sound on marine mammals and the marine environment; (ii) the establishment of consistent standards for the regulation of sound in the marine environment; and (iii) the promotion of US leadership in international matters related to anthropogenic sound in the marine environment.

In a publication associated with the MMC’s workshops, Cox et al. [2006] confirmed the plausibility of a newly-identified mechanism, known as “gas and fat embolic syndrome,” behind the noise-related mortalities of beaked whales [Cox et al., 2006]. This mechanism was consistent with pathologies seen in sonar-stranded beaked whales, such as hemorrhaging around the brain and lesions in vital organ tissues derived from gas and fat embolism [Jepson et al., 2003; Fernández et al., 2005]. The finding had significant implications for both research and management. For research, it opened up several lines of investigation into marine mammal diving physiology and the susceptibility of marine mammals to decompression sickness. For management, it raised profound questions about the effectiveness of near-source mitigation to prevent injury and death, since gas-bubble injury, probably being behaviourally mediated, could occur at much lower exposure levels and hence much greater distances than those associated with direct acoustic trauma.

Several intergovernmental organizations with competence over the marine environment or marine industry began to engage with underwater noise issues in the 2000s. The Agreement on the Conservation of Small Cetaceans in the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS) and the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic area (ACCOBAMS) have considered marine noise [Dolman et al., 2010]. Relevant resolutions included the 2007 ACCOBAMS “Guidelines to address the impact of anthropogenic noise on marine mammals in the ACCOBAMS area” and Resolution 4 which requested parties and range states to develop mitigation, conduct research and “develop and implement procedures to assess the effectiveness of any guidelines or management measures introduced.” Likewise, the International Maritime Organization (IMO) added “noise from commercial shipping and its adverse impacts on marine life” to the work of its Marine Environmental Protection Committee (MEPC) in 2008 [IMO, 2009], and the European Cetacean Society passed a resolution on the “urgent need” for mitigation of sonar activities at its 2009 annual general meeting [Dolman et al., 2011]. In the same year, OSPAR (the Convention for the Protection of the Marine Environment of the North East Atlantic) produced a review [Götz et al., 2009] and the Convention on Biological Diversity produced its synthesis of the noise literature in 2012 [CBD, 2012a; 2012b].

Most recently, in 2013, the IWC Scientific Committee made a statement encouraging time/area closures and new quieting technologies to address noise pollution [IWC, 2013] and encouraged further scientific investigations to evaluate mitigation measures, and the effects of noise on cetaceans and their habitats.

Generally, the efforts of these agreements' resolutions and statements have focused on improving understanding of impacts through increased and coordinated research, critically examining existing management measures, and the developing, implementing, and reporting of mitigation measures. However, the recent Marine Strategy Framework Directive (2008/56/EC) of the European Union explicitly requires consideration of underwater noise in determination of Good Environmental Status (GES). Thus member states must monitor and ultimately limit the amount of anthropogenic noise in European waters (see [Van der Graaf et al., 2012]). Two noise-related indicators have been defined in the Directive: one for intense sounds of short duration such as sonar, seismic surveys and pile driving, and one for low-frequency noise associated primarily with shipping. Dekeling et al. [2013] outline monitoring guidance with respect to these indicators including establishing registers of intense noise sources and monitoring programs for ambient noise. Member states are required to establish these monitoring programs by 2014 such that management measures can be implemented by 2016 in order to achieve GES by 2020. We also note that the European Commission Habitats Directive (92/43/EEC), which came into force in 1992, requires EU member states to protect harbour porpoises and bottlenose dolphins via the establishment of Special Areas of Conservation and that the Directive intends that all cetaceans are strictly protected throughout their entire range in EU waters [Ross et al., 2011].

Similarly, in the US the National Oceanic and Atmospheric Administration (NOAA) 1995 Acoustic Guidelines initially established what constitutes a "take" of marine mammals under the US Marine Mammal Protection Act (MMPA) and Endangered Species Act. In more recent years, the MMPA's regulatory scheme has increasingly been applied to noise sources, to the point where most "incidental take" authorizations issued under the Act are at least partly, and in many cases are primarily, focused on acoustic impacts [Roman et al., 2013]. For example, although some important gaps remain, most naval activities within the US territorial sea and Exclusive Economic Zone (EEZ) are now the subject of programmatic rule makings. Furthermore, in the oil and gas sector, operators regularly apply for MMPA incidental harassment authorizations as a condition of their geophysical exploration permits.

To help managers address the implications of the MMPA as mediated through acoustic thresholds defined by the National Marine Fisheries Service (NMFS), Southall et al. [2007] reviewed the available literature and offered initial scientific guidance regarding avoiding injurious exposure – i.e., Temporary Threshold Shift and Permanent Threshold Shift (TTS/PTS) – to the different groups of marine mammals. They specifically avoided providing suggestions for specific threshold criteria for behavioural responses, despite a thorough review and discussion, primarily given the contextual complications where responses depend on what the animals are doing (partly addressed in [Ellison et al., 2011]). Their guidance on behavioural responses was unrelated to their suggested TTS/PTS thresholds.

The Southall et al. [2007] guidance has become widely used by regulators and industries around the world but included cautions regarding its use, and more recent findings on auditory impacts or effects on behaviour (or both) have confirmed that the thresholds were not sufficiently protective, and that the guidelines should be updated. Work is in progress to revisit these criteria [Tougaard et al., 2013] and US regulators have recently released a draft of updated acoustic criteria for Level A Harassment, or "injury." Other countries have also developed voluntary guidelines for the mitigation of impacts by seismic survey noise on marine mammals and some, for example New Zealand's, have recently been updated [New Zealand Government, 2012].

Also important to the issue's development was the series of five workshops supported by *Okeanos-Foundation for the Sea* on critical and emergent topics: (1) spatio-temporal management [Agardy et al., 2007]; (2) the interaction between noise and stress responses [Wright and Highfill, 2007]; (3) the impacts and management of shipping noise [Wright, 2008]; (4) the management of cumulative impacts [Wright, 2009]; and (5) alternatives to airguns in seismic surveys [Weilgart, 2010]. These workshops were characterized by extremely productive, multi-disciplinary discussions. Perhaps their most notable outcome was the "Hamburg Protocol," which called for a "reduction in the contributions of shipping to ambient noise energy in the 10-300 Hz band by 3 dB in 10 years and by 10 dB in 30 years relative to current levels" [Wright, 2008]. The statement from all participants of the shipping workshop, including ship owners and engineers, contributed significantly to motivating the current IMO process for the development of voluntary guidelines for quieter commercial vessels ([IMO, 2013]; and see below).

Commercial shipping has not been the only sector to respond to these issues. Key responses from military sources have included the establishment of the NATO SOLMAR program in 1999 [Anon, 2014], and there have been several US Navy Office of Naval Research research programs related to the impacts of noise on marine mammals and fish. Finally, we note a major petroleum industry program of research in the Exploration and Production (E&P) Sound and Marine Life Programme established in 2005, which has mostly supported work on source characterization and theoretical hearing work [E&P, 2014].

Research Development

For some time, much of the research on noise impacts has focused on physical impacts on cetaceans, especially damage to their hearing and ears, and also the causes of atypical strandings. Emphasis has been given to introduced sounds within the frequency ranges that cetaceans use to vocalize but recent research has shown that sounds outside of this range may also be important (e.g., [Melcón et al., 2012]).

The focus of concerns has also now moved to a wider range of potential effects. For example, increased risk of fisheries by-catch through distraction has been suggested (e.g., [Nielsen et al., 2012; Wright et al., 2013]). Similarly, the potential for the acoustic startle reflex to generate fear conditioning has also been considered [Götz and Janik, 2011]. Whales may suffer a greater risk of ice entrapment due to avoidance of noise [Heide-Jørgensen et al., 2013]. Noise-induced stress responses have also been considered, with their importance supported by the discovery that cortisol levels were reduced in right whales during the period following the attacks on the USA on September 11, 2001, where the level of maritime traffic and associated ambient noise levels substantially dropped [Rolland et al., 2012]. There is increasing awareness and concern in the scientific and regulatory communities that noise can alter or undermine various important biological processes (e.g., [Wright and Highfill, 2007]).

Additionally, the complexity of assessing the consequences of noise exposure for hearing and its compensatory mechanisms is being realized. For example, there have been subjective loudness measurements in bottlenose dolphins (*Tursiops truncatus*, [Finneran and Schlundt, 2011]); the discovery of automatic gain control and flexible auditory brainstem responses in harbour porpoises (*Phocoena phocoena*, [Linnenschmidt et al., 2012]); and the mechanism for differentiation between outgoing and returning clicks in harbour porpoises [Linnenschmidt and Beedholm, 2012]. Other relevant work includes that by Parks et al. [2007; 2009] on North Atlantic right whales (*Eubalaena glacialis*), Di Iorio and Clark [2010] on blue whales (*Balaenoptera musculus*), Castellote et al. [2012] on fin whales (*B. physalus*), and Nachtigall and Supin [2013] on false killer whales (*Pseudorca crassidens*). These, and other, revelations challenge the M-weighted hearing functions proposed by Southall et al. [2007] and complicate key issues such as masking and the onset of TTS and PTS.

In-field Behavioural Response Studies are increasingly underway to study diving behaviour and sound production of key noise-affected cetaceans in response to a variety of purposely-introduced anthropogenic noise stimuli (for example, [Southall et al., 2012]). Such studies have limitations, but are intended to explore certain key concerns and provide results that will inform management decisions. For example, recent studies using information from actual naval exercises over hydrophone-instrumented naval ranges and/or sonar playbacks to whales with acoustic tags have revealed potentially problematic responses at much lower received levels than present impact thresholds would assume [DeRuiter et al., 2013; Goldbogen et al., 2013; McCarthy et al., 2011; Miller et al., 2012; Moretti et al., 2010; Pirotta et al., 2012; Tyack et al., 2011]. This has caused reassessment of the presumption that the mere presence of whales in a frequently disturbed environment, such as a naval training range, means they suffer no considerable impacts. Indeed, for the first time, population impacts in beaked whales have been clearly indicated due to noise from naval exercises/sonar based on two separate lines of evidence from a 15-year study: lower abundance and fewer births of Blainville's beaked whales on a naval range vs. an area 170 km away in the Bahamas [Claridge, 2013].

Degradation of the acoustic environment is also increasingly seen as an important perspective deserving consideration. Considerable reduction in a whale's "communication space" through masking by noise (see [Møhl, 1980; 1981]) has now been recognized as a serious concern for these species [Clark et al., 2009; Hatch et al., 2012].

Finally, new tools are under development to assess overall noise exposure for populations. For example, the NMFS has produced cumulative noise and cetacean distribution maps covering, in varying degrees of resolution, the entire US EEZ, and Roman et al. [2013] suggested that these maps would become an important tool for the management of noise in relation to cetaceans.

Mitigation Development

There is general consensus that reducing noise exposure levels is likely to be the most effective available means of reducing impacts on marine mammals. This can be achieved by reducing noise levels at source, reducing noise propagation, or avoiding noisy activities at times and in places where sensitive species are present. Limiting noise input reduces impacts on all vulnerable species, whereas spatial and temporal restrictions will only protect species with consistent and predictable distribution patterns.

Technologies exist to restrict input of noise incidental to shipping [IMO, 2013] and offshore construction using pile driving [Koschinski and Lüdemann, 2013], and will shortly be available for deliberate sounds such as those created by high-energy seismic surveys (see below discussion of marine vibroseis). In some cases, these technologies can be applied with little or no economic cost, while in other cases there may be sizable costs to industry. Time-area closures can provide a way of keeping noise sources away from vulnerable species, but rely on sufficiently detailed temporal and spatial knowledge of distribution patterns combined with the ability to avoid generating noise in the area at those times.

Other measures that attempt to reduce noise impacts associated with physical injuries rather than masking or disturbance include increasing loud noises slowly (e.g., "soft-start," otherwise known as "ramp-up," procedures for seismic surveys and pile driving) or shutting down or reducing intense noise sources when vulnerable species come within a specified range of the source. Soft-starts or ramping up assume that animals will move away before being exposed to levels that may cause injury, but there are few data on which to test this assumption and so remains speculative [Parsons et al., 2009]. Cetaceans may be detected by visual means or passive acoustics but both methods will only detect a proportion of the animals within an area. For less easily detected species or in low-visibility conditions (e.g., at night or during rain) it may be extremely low [Parsons et al., 2009]. For example, the Navy's ability to visually detect beaked whales during sonar training exercises through the use of ship-board monitoring was estimated to be only 2% within 1 km (e.g., [Barlow and Gisiner, 2006]). New thermal technology holds promise as an additional means of detection, but given its high false positive rate, is currently valuable only as a supplement to visual monitoring efforts [Zitterbart et al., 2013].

Since starting to work on the issue of underwater noise from ships in 2008, the IMO has been developing voluntary technical guidelines for ship quieting technologies. The draft guidelines agreed by the Design and Equipment Subcommittee will be considered for adoption by the full Marine MEPC in April 2014. The draft guidelines note that "radiated noise from commercial ships may have both short- and long-term negative consequences on marine life, especially marine mammals" and describe ways in which radiated noise can be reduced with particular emphasis on reducing propeller cavitation [IMO, 2013]. Implementing the noise reduction measures described in the guidelines will require engagement by shipping companies, ship builders, and designers. Further encouragement may come from port authorities, ship classification, or green certification societies. The IMO has also considered operational measures to reduce noise. Operating vessels at slower than previous cruising speeds has been a way of saving costs in response to rising fuel prices, but slow steaming also has environmental benefits, including potentially substantial reductions in noise [Leaper and Renilson, 2012; Leaper et al., 2014].

Significant efforts are also underway to reduce underwater noise from other marine industries. The 2013 US Bureau of Ocean Energy Management (BOEM) workshop on quieting technologies for seismic surveys, pile driving, and shipping held in Silver Spring, Maryland, was an example of the high profile that this issue now has and demonstrates that technological approaches are being sought [BOEM, 2013]. In Europe, major progress in quieting technology has been made for pile driving, led in particular by Germany, which has set an action-forcing standard for the development of better systems [BOEM, 2013]. From 2003, the German Federal Maritime and Hydrographic Agency has included in the licenses of offshore wind farms within the German EEZ noise target levels of 160 dB (Sound Exposure Level – SEL) or 190 dB (peak) at a distance of 750 m [Koschinski and Lüdemann, 2013]. This is based on research showing sensitivity to seismic and pile driving noise by harbour porpoises (e.g., [Brandt et al., 2011; Lucke et al., 2009; Scheidat et al., 2011]). For seismic exploration, an important alternative technology potentially exists in the marine vibroseis technique, a controlled sound source for oil and gas exploration, that can significantly lower peak pressure by spreading acoustic energy over time, remove the sharp rise time, and largely eliminate noise output above 100 Hz, which is wasted energy unused by geophysicists [Weilgart, 2010; 2012; BOEM, 2013]. Hence marine vibroseis has considerable potential to reduce both peak and total sound energy levels, but this will depend on the specification of the system that is used. The implications of a continuous source also need to be investigated further. Several companies are now developing marine vibroseis systems, with at least one on schedule to produce a commercially available array in the near future [BOEM, 2013]. Accelerating the development and use of these technologies will require the engagement of regulators [Weilgart, 2010; 2012].

In recent decades, we have also seen the emergence of marine protected areas and, more recently, marine spatial planning and ocean zoning to help manage potentially damaging activities at sea. These approaches are usually twinned with environmental impact assessment, which increasingly encompasses consideration of noise and disturbance. There has also been an increase in investment by industry in the development of noise reduction and alternative technologies [Roman et al., 2013]. In general, however, regulators remain heavily reliant on the use of safety zones – a measure whose limitations are widely acknowledged (e.g., [Barlow and Gisiner, 2006; Weir and Dolman, 2007; Parsons et al., 2009; Lubchenco, 2010; Wright, 2014] – as their primary current means of noise mitigation.

For at least some noise sources, there is a general consensus that time-area closures represent one of the most effective available means of reducing impacts on marine mammals (e.g., [Agardy et al., 2007; Dolman, 2007; OSPAR, 2009; Lubchenco, 2010]. Such closures have been successfully enacted for some areas. For example, there have been no mass strandings on the Canary Islands since the Spanish government imposed a moratorium on naval exercises in the waters of these islands in 2004 [Fernandez et al., 2013]. Another example is provided by the rerouting of the shipping channel around the most important whale habitats on Stellwagen Bank to reduce collisions with humpback and endangered right whales, which also had noise-related benefits [Roman et al., 2013]. As noted above, reducing speed typically reduces noise, and any measure that keeps shipping and whales apart will also reduce noise exposure.

CONCLUSIONS

In 2004, Simmonds commented that "over the course of the last couple of decades, scientists and conservationists have become increasingly aware of threats to biodiversity that are diffuse and hard to assess but are, nonetheless, of great concern." His examples were climate change, chemical pollution, and marine noise pollution. Of these, he suggested chemical pollution had received the greatest attention, with response mechanisms already incorporated in a host of national and international legislation. By contrast, at that time marine noise pollution was "an emerging, but undoubtedly serious, concern," where "its implications are less well understood than other global threats." He suggested that it was at the same stage that had been reached with chemical pollution some thirty years earlier [Simmonds, 2004]. Our assessment here is that significant progress has been made since these comments. Marine noise pollution can now be seen as a significant, mainstream issue that is witnessing rapid development in research, mitigation, technology development, and monitoring. Such initiatives are also supported by improving knowledge of species and populations, as underpinned by the International Union for Conservation of Nature and Natural Resources Red List.

In the US in particular marine mammal research has seen an "explosion of investment in the issue," often driven by litigation, non-governmental organizations, public pressure, and regulatory requirements [Roman et al., 2013; Zirbel et al., 2011a; 2011b]. The US Navy and the oil and gas industry now commendably annually fund more than US$25 million in related research, including baseline research on marine mammal distribution, abundance, and ecology. Elsewhere, directives binding on EU nations seek to protect listed species from factors including "disturbance," and targets are required to be set for noise in order to achieve GES.

In making these positive observations, we do not mean to indicate that everything is progressing as well or as quickly as it should. There have been limited practical steps that have actually reduced noise exposures but, in many cases, the exposures of vulnerable populations to noise sources have increased, noting in particular the growing concerns linked to increasing industrial activities in the Arctic [Moore et al., 2012; Reeves et al., 2012]. In addition, while cumulative sub-lethal impacts and degradation of acoustic habitat are now recognized – by both researchers and regulators in the US and Europe – as critical issues requiring management (e.g., [US Government, 2008; Clark et al., 2009; Wright, 2009; Lubchenco, 2010; CBD 2012a; Hatch et al., 2012; Van der Graaf et al., 2012; Goldbogen et al., 2013; Dolman et al., in press]), little as yet has been done to directly address these problems on a management level, even though guidance exists (e.g., [Wright and Kyhn, 2012]).

Concerns have also been raised about the conflict of interest and resulting loss of credibility of research funded directly by noise producers [Wade et al., 2010]. Despite the recommendation (which we support) that having an independent, non-aligned commission to design research and distribute funds from noise producers would remedy this issue, little progress has been made.

Recommendations

As with other forms of pollution, reduction at source is the most effective approach to reducing impacts. Our main recommendation is therefore that the continuing development and use of quieter, alternative technologies and noise-reducing techniques should be prioritized, and that this should be codified in regulations. Where currently available technologies are insufficient to reduce noise for a particular type of activity, then decision makers should acknowledge this and operational noise reduction should be the priority area for management and research. The approach used by Germany of setting noise action-forcing limits for offshore pile driving should be applied more broadly to other noise-producing activities. This approach both limits impacts and also encourages technological developments to reduce source levels.

Alongside reducing noise levels at source, impacts on sensitive species can also be reduced by temporal or spatial separation. Modelling combined with field research will continue to help in the identification of concentrations of noise-sensitive species. Such research should be prioritized, as should the identification of small, range-limited populations. The presence of such populations should trigger time-area closures for activities that generate high levels of noise.

Application of noise-reduction methods need not be economically costly. For example, Leaper and Renilson [2012] suggest that reducing ship noise may even save money in the long run by increasing energy efficiency. For shipping and other industries there is still a need for further development of cost-effective noise reduction solutions. These developments will be encouraged and facilitated by a better understanding of the problem coupled with legislation that prevents unnecessary noise. Some sectors may be largely unaware that they are generating harmful noise. For example, echo sounders for pleasure craft are only needed in a limited number of situations yet frequently remain switched on the whole time. Such devices can also be designed to work at higher frequencies (>150 kHz) that are less likely to be audible to marine life. There are promising developments for seismic surveys using marine vibroseis which could replace at least some, and perhaps eventually all, airguns, which generate high noise levels over a much wider range of frequencies than is needed. However, this change will need to be driven by regulation. Noise levels from military sonar remain a serious concern, and it may not be considered acceptable from an operational perspective to reduce source levels. If exercises using such equipment are deemed to be essential, then they should only occur in areas with the least marine life.

Cumulative and synergistic effects from all noise sources and other threats should be taken into account. Underwater noise is a transboundary issue, and international cooperation and coordination should be further stimulated. An improved understanding of impacts requires exposure levels and impacts of all noise-producing activities to be carefully monitored over suitable time-frames and spatial scales.

In addition, it would be helpful if the various existing demonstration projects for marine renewable energy devices were assessed for their noise characteristics and potential impact on marine mammals. The push in many countries towards more sustainable energy sources should proceed with the appropriate caution, while not being unduly delayed. Reducing habitat degradation arising from noise pollution could provide more resilience to the myriad other threats that marine mammals, and the marine environment, face.

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