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Evolution of Marine Noise Pollution Management

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Abstract

This paper will review landmarks in American and European marine noise science and management, reflecting a changing scientific and regulatory focus from acute, near-field effects on beaked whales to impacts on a wider range of species and their "acoustic habitat" over broader temporal and spatial scales. Increases in the scale of noise associated with human activities has led to greater levels of research and management. Although mitigation within the United States and Europe is principally aimed at reducing risk from acute effects of individual activities, regulators are moving in significant ways towards cumulative, multi-sectoral impact management. Solutions to be discussed include source-quieting methods and technologies for commercial shipping, pile driving, and seismic survey noise; spatial management through the use of programmatic and strategic environmental assessments, particularly for active sonar; and noise budget caps—for example, as a potential outcome of the European Union (EU) Marine Strategy Framework Directive. This paper also will identify the most pressing data needs for conservation management, including data on impacts (e.g., the impacts of offshore windfarm construction and operation on baleen whales), effective mitigation methods and technology (such as noise reduction standards for individual commercial ships), and cumulative effects (including impacts of chronic stress on cetacean morbidity, survival, and reproduction).

Key Words: noise pollution, cetacean, policy, legislation, MMPA, EU MSFD, U.S., Europe

Background and Introduction

Substantive reviews of the major sources of marine noise pollution and their associated impacts have been undertaken (e.g., Richardson et al., 1995; Gordon & Moscrop, 1996; National Research Council [NRC], 2003; Simmonds et al., 2004, 2014; Hildebrand, 2005; Jasny et al., 2005; Nowacek et al., 2007; Weilgart, 2007; OSPAR, 2009). Changes in animal communication systems are being observed in human-generated altered habitats (Rabin & Greene, 2002). There is an increasing recognition that lower-level but chronically present sound sources may significantly impact marine species, although through different mechanisms than seen with high power but intermittent or infrequent sound sources (Southall & Scholik-Schlomer, 2008). For example, masking can result in the disruption of breeding in animals that use sound during mating and reproduction, and of foraging in animals that use sound to detect prey. In addition, noise can mask important acoustic environmental cues that animals use to navigate or sense their surroundings, including sounds that are used to detect predators (Clark et al., 2009). It has become apparent that acoustic communication for some species is already seriously compromised, including for the highly endangered North Atlantic right whale (*Eubalaena glacialis*) (McDonald et al., 2006; Parks et al., 2007, 2009; Clark et al., 2009; Hatch et al., 2012). Masking impacts on foraging, reproduction, and survival are likely to be important in certain areas and for certain species.

Strides have been made in understanding the effects of anthropogenic noise on marine mammals and, to a lesser degree, how to monitor and mitigate its effects (Fitch et al., 2011; Simmonds et al., 2014). With increasing scientific evidence and better management in legislation, we are seeing a shift from management focused on near-field source mitigation to wider, more holistic management that begins earlier in the planning process and is based on effective reduction of noise pollution in important habitats. On occasion, novel technologies are employed to this end.

In the early 1980s, there was very little field research investigating the impacts of human-introduced noise pollution on cetaceans other than a Beaufort Sea seismic study (Richardson et al., 1986). As noise pollution was largely unrecognised publicly or politically, it was largely unregulated under the U.S. Marine Mammal Protection Act (MMPA) and other statutes, nor was it regulated or managed within Europe. In 1995, Acoustic Thermometry of Ocean Climate (ATOC), a large-scale ocean-wide experiment to determine the precision with which acoustic methods could be used to measure large-scale changes in ocean temperature and heat content, was a catalyst for recognition of noise pollution as a potential source of concern for marine mammals (Frankel & Clark, 2000, 2002). In 1995, the U.S. set the first thresholds for levels of sound beyond which marine mammals should not be exposed to prevent "injury" or "behavioural harassment" under the MMPA. In more recent years, the MMPA's regulatory scheme has increasingly been applied to noise sources to the point where nearly all "incidental take" authorizations issued under the MMPA today are at least partly, and in many cases primarily, focused on acoustic impacts (Roman et al., 2013).

The Joint Nature Conservation Committee (JNCC) produced its first iteration of UK seismic guidelines in 1995. Guidelines were gradually replicated, to various degrees, by numerous countries around the world (e.g., see Weir & Dolman, 2007; Dolman et al., 2009a). Following the Greek beaked whale stranding in 1996 (Frantzis, 1998), The Bahamas stranding in 2000 (Balcomb & Claridge, 2001), and other mixed species strandings, subsequent pathologies became the focus of noise pollution efforts (see the case study on military sonar below for details). These mixed species strandings helped to increase concern for the range of species impacted by noise and no doubt influenced the development of new noise exposure criteria provided by Southall et al. (2007). This process is complex and has taken a decade to complete. Criteria for injurious harassment, as defined by the MMPA, will come out before those for behavioural harassment as the latter are far more difficult to define empirically.

A shift has occurred from concerns about injury as a threshold for management towards behavioural and sublethal physiological impacts, including the relationship between the stressor and the stress response. Impacts may be species, situation, and context specific. For example, low-frequency ship noise may be associated with chronic stress in endangered North Atlantic right whales in heavy ship traffic areas (Rolland et al., 2012). As monitoring methods and technologies have become more sophisticated and a greater diversity of species are examined, papers have increasingly demonstrated susceptibility to hearing loss and behavioural reactivity to noise beyond what earlier studies had indicated (e.g., Lucke et al., 2009; Miller et al., 2009, 2012; Moretti et al., 2010; McCarthy et al., 2011; Miller, 2011; Popov et al., 2011a, 2011b; Tyack et al., 2011; Melcon et al., 2012; Pirotta et al., 2012; Goldbogen et al., 2013; also see Wright, 2014, for a wider discussion). Data increasingly indicate concern for a variety of taxa at the population level due to noise pollution (Hatch et al., 2012; Claridge, 2013; Moore & Barlow, 2013; Thompson et al., 2013). This evolving understanding of noise and the potential for impacts have resulted in a shift from addressing only the acute effects of noise on hearing and behaviour (Ellison et al., 2011).

Recognising the extensive, varied, and often subtle effects of noise pollution, there is now substantial investment in improving understanding of the impacts of noise pollution, particularly by the U.S. Navy and the oil and gas industry, who invest more than $25 million/y, collectively (Roman et al., 2013). Such funding allows collaborative and coordinated research efforts, such as the Joint Industry Programme (JIP) and Bureau of Ocean Energy Management (BOEM) funded Behavioural Responses of Australian Humpback Whales (*Megaptera novaeangliae*) to Seismic Surveys (BRAHSS) (e.g., Cato et al., 2013) and the Population Consequences of Disturbance program, led by the U.S. Office of Naval Research, which is refining a population-impact model based on studies of several data-rich species. European research funding is also increasing, including through £3 million UK Offshore Renewables JIP, although the momentum appears to have slowed for marine mammal projects. A number of UK consents have been given, despite outstanding uncertainties surrounding noise impacts.

The value of using behavioural responses to infer more systemic impacts is unclear as observable reactions are highly context-dependent. Other consequences of noise exposure may occur without any outward indication from the animal affected, including physiological stress responses and masking (Wright, 2014). An expert panel in the U.S. stated that injury and behavioural harassment criteria "do not determine the overall level of impact [as] physiological stress and other factors also need to be considered" (Fitch et al., 2011). Permitting under the MMPA is required for any activity that has the potential to result in a take as defined by statute. Most Incidental Take Authorizations (ITAs) cover sound-generating activities, such as naval training (utilizing sonar or explosives), seismic surveys, or marine construction, because they have the potential to result in marine mammal harassment (Daly & Harrison, 2012). Typical acoustic-related impacts that the National Marine Fisheries Service (NMFS) has considered are auditory fatigue, behavioural reactions (e.g., avoidance; changes in travel, dive, reproduction, and foraging patterns), masking, and stress (Daly & Harrison, 2012). Yet, some significant gaps remain in permitting activity (Roman et al., 2013) such as in the Gulf of Mexico for seismic exploration and in waters outside domestic ranges for the U.S. Navy. Moreover, even where authorizations occur, the MMPA has not been successful at addressing aggregate sublethal effects from noise and disturbance for a variety of reasons, including lack of definition of the relevant statutory standards, lack of agency capacity, a mitigation focus on near-source effects rather than on minimizing sublethal effects over larger scales, and an agency interpretation of the statute that allows for segmented review (Roman et al., 2013). Currently, shipping remains unregulated with regard to noise pollution globally, but the International Maritime Organization (IMO) (2013) has issued voluntary guidelines for quieting underwater radiated noise from commercial ships, and a number of ship classification societies have developed notations for quiet vessels.

The EU first formally enshrined underwater noise in law for determination of Good Environmental Status (GES) under the Marine Strategy Framework Directive (MSFD; 2008/56/EC). Member States are required to monitor and may need to limit the amount of anthropogenic noise in European waters in determination of GES (see Van der Graaf et al., 2012). Two noise-related indicators are defined under the Directive: one for intense sounds of short duration such as sonar, seismic surveys, and pile driving (Indicator 11.1.1), and one for low-frequency ambient noise associated primarily with shipping (Indicator 11.2.1). The Centre for Environment, Fisheries and Aquaculture Science (Cefas) (2011) presented two possible targets for MSFD Indicator 11.1.1 in UK seas. These would be applicable to anthropogenic sound sources measured over the frequency band 10 Hz to 10 kHz that exceed the energy source level 183 dB re1 μPa^2 m^2 or the zero to peak source level of 22 4 dB re 1 μPa^2 m^2. Where these source levels are exceeded, "a decrease" or "no annual increase" in the proportion of days and distribution over areas of 10-min latitude by 12-min longitude (Department of Energy and Climate Change [DECC] oil and gas licensing blocks) and their spatial distribution would be required (in Hull et al., 2011). Dekeling et al. (2014) outline monitoring guidance with respect to these MSFD 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. The UK monitoring programme for cetaceans does not currently plan to go beyond existing measures and does not meet the monitoring requirements for adequate implementation, management, and enforcement of the MSFD (Joint Links, 2013).

The EU Habitats Directive, Environmental Impact Assessment (EIA) Directive, and Strategic Environmental Assessment Directive, as transposed by Member States, are important frameworks for noise impact assessment and management. Shortcomings have been identified in their application to the noise issue (e.g., see Green et al., 2012).

There is broad recognition of concerns about noise levels from various sources within the marine mammal scientific community and numerous conservation nongovernmental organizations (NGOs) engaged through efforts at the IMO, Convention on Migratory Species, Convention on Biological Diversity, and International Whaling Commission (IWC) and within national and federal systems such as the U.S. and Europe. Noise-related resolutions and statements of concern issued by various international bodies and agreements have become commonplace (Simmonds et al., 2014, review these in detail). There is scientific and public recognition of the potential impacts of the military sonar issue specifically (Cox et al., 2006; Dolman et al., 2011a, 2011b); seismic exploration also has raised substantial concern in some regions such as the mid-Atlantic and southeast Atlantic of the U.S., the Balearic Islands, the Canary Islands, and Trinidad and Tobago, for their potential impacts on marine mammals and fish. Sound sources that receive less public attention include drilling, dredging, and pipe- or cable-laying, as well as recreational vessels and fishing activities.

Herein, we review the overlap between the scientific, legal, and political processes in the emergence of marine noise pollution as a recognised threat to demonstrate the progress that has been made in recent decades to understand and better manage noise pollution. The limitations of existing management and mitigation are summarised. Examples for noise reduction methods in offshore windfarm development and commercial shipping as well as spatial management in military active sonar are identified as examples to highlight areas of progress. Management and mitigation solutions are suggested, including alternative sources and planning processes, and uncertainties are identified. A summary of research needs and recommendations towards comprehensive management of all underwater noise sources in the future are provided.

Limitations in Existing Management and Mitigation

The management of noise pollution impacts was once almost entirely focused on the elements of impact that could be reduced through specific acts of mitigation at the source within a "safety zone." Details of the limitations in existing management and mitigation have been summarised for various jurisdictions (Weir & Dolman, 2007; Dolman et al., 2009a, 2009b; Parsons et al., 2009; Herschel et al., 2013; Roman et al., 2013; Wright, 2014). With some specific notable exceptions (such as demand reduction; Wright, 2014), current mitigation measures (such as use of marine mammal observers) are generally ineffective at reducing the aggregate impact of noise on marine mammals. This is largely because they typically focus on limiting damage to hearing at very close range and ignore the more insidious consequences of noise exposure that can arise at lower levels of sound (Wright, 2014).

Perhaps most importantly, the ability of most standard mitigation tools to reduce underwater noise overall is also limited if they are applied on a case-by-case basis in the face of an increase in the overall amount of industrial activity (Wright, 2014). There is growing appreciation, in both the regulating and regulated communities, of the need to consider the wider effects of a given project or activity beyond those capable of being addressed through on-board mitigation, as well as the still wider consequences of interactions between impacts from different human activities known as cumulative impacts (Simmonds et al., 2014; Wright, 2014; discussed in more detail below).

Management and Mitigation Solutions

The application of Best Available Technology (BAT) and Best Environmental Practice (BEP) is a requirement under the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) to prevent and eliminate marine noise pollution; BAT and BEP are principles guiding environmental policy in other jurisdictions. Since noise is internationally recognised as pollution, the concept of BAT and BEP should be applied to offshore construction activities, commercial shipping, seismic exploration, and other sources of noise. The BAT and BEP for particular sources will change with progress in technology and scientific knowledge (Koschinski & Lüdemann, 2013).

As with other forms of pollution, reducing input at source is likely to be the most effective way of reducing impacts (Simmonds et al., 2014) and, therefore, is the best way to achieve BEP. While some sources intentionally use sound (e.g., mid-frequency active sonar [MFAS], seismic surveying), others generate sound as a byproduct (e.g., shipping, pile driving). Therefore, reducing input and the application of BAT will require consideration of both alternative methods and source quieting.

Alternative Methods and Source-Quieting

Technological developments that will reduce or eliminate the various sound sources can be achieved either through refining or replacing the equipment in question, or by eliminating the demand for the activity entirely (Wright, 2014). Devising methods to remove or reduce unneeded sound or sound components (such as unwanted frequency bands) from operations or engineering alternative sound sources may reduce the zone of potential influence and/or address biologically significant sound source characteristics once they are defined. As a result, developing alternative exploration sound sources and quieting technologies increases the effective mitigation options available.

Source-quieting methods and alternative technologies have the potential to significantly reduce or beneficially modify acoustic output for some of the leading sources of ocean noise such as for commercial shipping, pile driving, and seismic survey noise (Weilgart, 2010; CSA Ocean Sciences Inc., 2014; IMO, 2014). Different strategies are needed for those sources that produce noise incidental to operations, including shipping and pile driving, compared to those that produce sound for a particular purpose, for example, seismic surveying and military sonar (Fitch et al., 2011). The U.S. BOEM took a step towards source reduction by convening a major international workshop on quieting technologies (e.g., airguns, pile-drivers, and vessels) for offshore energy in February 2013. The workshop identified that coordination is key to further improvements in technology development, establishment of the regulatory framework and mechanisms, design of environmental monitoring and field testing, and discussion of concepts and regulations to determine a path forward (CSA Ocean Sciences Inc., 2014). A number of alternatives to pile driving were identified once they were economically and environmentally proven. Accomplishing quieting through technology for vessels is not straightforward, but techniques like speed reduction and regular maintenance can significantly reduce radiated noise without requiring retrofits (CSA Ocean Sciences Inc., 2014).

JIP produced a report on reducing all aspects of noise generated from oil and gas activities, not just those associated with seismic surveying (Spence et al., 2007). Viable alternatives to seismic surveying include, but are not restricted to, marine Vibroseis (Weilgart, 2010; CSA Ocean Sciences Inc., 2014). Hydraulic and electromagnetic marine vibrators are deployed and towed at the same configuration as airgun arrays but have fewer elements, better source characteristics in shallow water, lower source signal rise times, peak energies, and less energy above 100 Hz compared to airguns. Design modifications to seismic airguns might include changing the design or adding silencers to further reduce unnecessary noise and/or the introduction of sound into the water in the horizontal direction (see Spence et al., 2007; Weilgart, 2010); indeed, one company (Bolt) has announced the availability of an airgun with comparatively lower noise outputs at higher frequencies. Another approach, developed but not implemented by British Petroleum (Ross & Abma, 2012), would slightly stagger the firing sequence in large airgun arrays in order to put the signals slightly out of phase, reducing their effective source level.

Other source-quieting ideas suggested at a recent U.S. noise workshop included active sonar signal modification with lower intensity tradeoffs and developing bubble curtains and muffling (e.g., cofferdams and pile caps) for pile driving (Fitch et al., 2011). Workshop participants were particularly coherent in recommending focused-attention, fast-tracking research on quieting technologies, among several other priorities (Fitch et al., 2011).

Case Study I: Effective Mitigation of Pile Driving for Offshore Wind Farms in German Waters—Germany has 143 offshore wind farms in various stages of development. Five (3.49%) are currently generating power, the first of which became operational in 2004 (James, 2013). In Germany, temporary threshold shift (TTS, a type of potentially recoverable auditory damage) is categorised as injury in the sense of law (IWC, 2012). In 2003, the German Federal Maritime and Hydrographic Agency included noise target levels of 160 dB re 1 μPa (Sound Exposure Level [SEL] for a single strike) or 190 dB re 1 μPa (zero-peak) at a distance of 750 m in the licenses of offshore wind farms within the German EEZ (Bundesamt für Seeschifffahrt und Hydrographie [BSH], 2012).

For piled foundations, this sound level can only be met by applying noise mitigation measures (Koschinski & Lüdemann, 2013). As a result of this requirement, a rapid development in better methods and systems for reducing the noise propagated away from foundation installation occurred. Such precautionary management quickly led to noise reduction solutions in this rapidly growing offshore industry. In addition, this stimulated research programmes to design noise reduction technology that helps meet the criterion as well as research to investigate the success of the results, both technically and biologically (Koschinski & Lüdemann, 2013). This approach both limits impacts and also encourages technological developments to reduce source levels (Simmonds et al., 2014). Reductions in overall noise generated from pile-driving construction would reduce pressure on EU MSFD GES targets (Dolman et al., in press). Adoption of strong targets for GES that require Member States to take action to reduce noise would contribute considerably to overcoming issues related to injury and disturbance. They would also provide clarity to developers and regulators (Dolman et al., in press). European case law confirms that the precautionary principle is required for any assessment of effects on site integrity, and precautionary assumptions within the early licensing conditions have been recommended to ensure legal compliance (Macleod et al., 2010).

Case Study II: Reducing Commercial Shipping Noise Globally—The global merchant fleet is collectively the greatest contributor to the increase in background noise levels underwater in every decade over the last half-century (see Wright, 2008). The main causes of hydroacoustic noise radiating from a merchant ship are from the propeller (cavitation) and the machinery (IMO, 2013). For most merchant vessels, the noise generated by cavitation will dominate all other sources of noise from that vessel. The noisiest vessels are likely to suffer excessive cavitation and may be operating inefficiently.

In 2004, the National Oceanic and Atmospheric Administration (NOAA) hosted an initial meeting entitled "Shipping Noise and Marine Mammals: A Forum for Science, Management, and Technology," which essentially served as an introduction of this issue to industry representatives, conservation managers and scientists from various fields (Southall, 2005). The U.S. held a workshop on the application of vessel quieting technology in 2007 (Southall & Scholik-Schlomer, 2008). The "Hamburg Protocol" resulted from another workshop, attended by ship owners and engineers, to investigate the impacts and management of shipping noise; it 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). This target was subsequently endorsed by the Scientific Committee of the IWC (2009).

The EU has since adopted an indicator for GES for underwater noise in the MSFD based on ambient noise levels and trends within frequency bands centred at 63 and 125 Hz (European Commission, 2010). These frequency bands are dominated by noise from shipping, and achieving GES is likely to require reductions in shipping noise (Leaper et al., 2014).

Following a U.S. proposal, the IMO (2009) added "noise from commercial shipping and its adverse impacts on marine life" to the work of its Marine Environmental Protection Committee (MEPC) in 2008. Nonmandatory technical guidelines for reducing ship noise were adopted in 2014. The IMO (2014) guidelines list design considerations for building new ships and also technologies known to contribute to noise reduction for existing ships, including state-of-the-art propellers and wake conditioning devices. With release of the IMO guidelines, ship classification societies, NGOs, researchers, regulators, and industry are now focused on implementation. There remains a need to assess the effectiveness of different options in order to prioritise efforts most effectively and economically. These include design considerations for new builds, modifications to the noisiest existing vessels, and changes in operational practices. Additional research to help implement the IMO guidelines has been identified (Leaper et al., 2014). Ongoing data on noise levels from individual ships and from new propeller design concepts that offer improvement in fuel efficiency through reduced cavitation should help develop further practical and economic quieting technologies in addition to measures identified in the IMO guidelines (Leaper et al., 2014). Governments, industry, and others must work together to implement the IMO's noise guidelines and quieting technology. Mechanisms to drive implementation of quieting technologies include ship classification societies, green certification societies, port environmental compliance programs, and national regulation(s).

Planning Processes – Spatial Management

Improved, early, and transparent planning will help reduce the overlap between marine mammal and human activities that generate noise pollution. Spatial management includes the use of programmatic and strategic environmental assessments. Benefits of appropriate spatial management include more appropriate scope for cumulative impacts analysis, more appropriate scope for alternatives analysis and monitoring designed to address aggregate effects, potentially more data generated for legal compliance (e.g., with EU directives), more resources available for analysis, and economy of scale for regulators and potentially more predictability (e.g., for understanding risks) for those who are regulated.

Project-specific EIAs are an important tool whose flaws and improvements are being increasingly scrutinised and audited (e.g., Green, 2000; Wright et al., 2013a). In many jurisdictions, for example, in the UK, industries themselves are responsible for drafting EIAs, which may reduce impartiality (Wright et al., 2013a) and influence EIA conclusions. In contrast, a detailed series of elements for the responsible planning and execution of a seismic survey for geophysical exploration and a practical roadmap for planning, executing, evaluating, and improving the design of a responsible seismic survey are provided by Nowacek et al. (2013). The use of programmatic EIAs in capturing a greater number and variety of activities than typically covered in project-specific reviews can establish a more appropriate scope for assessment and mitigation of aggregate impacts.

NOAA has identified that one of the most effective methods for reducing noise exposure-related impacts to marine mammals is spatial or temporal limitation of the activity where practicable (Lubchenco, 2010; Daly & Harrison, 2012). Yet, NOAA prescribed virtually no spatial-temporal mitigation in the U.S. Navy's Pacific Fleet operating areas, despite having identified biologically important habitat (Van Parijs et al., 2015) in those areas for marine mammals (e.g., NOAA, 2013). NOAA did integrate habitat-based mitigation into its multi-year Ocean Noise Strategy, however, which is soon due for public release (NOAA, 2014). Management procedures have become more detailed and sophisticated in many countries, as dictated by legislation; however, the incorporation of any reported information into future planning is still largely lacking. Yet, neither this nor a lack of available scientific information prevents industrial activities from moving forward. Clearly, there is much potential for improvement across the entire management process (Wright, 2014). Ultimately, better management and conservation efforts should help streamline decision-making processes.

Habitat-Based Management

In addition to wide, (often) national-level spatial measures, marine protected areas (MPAs) can provide an effective method of reducing noise impacts in known areas of importance during sensitive periods (Dolman et al., 2009a, 2009b; Hoyt, 2011). Habitat-based solutions are widely accepted as being the most effective way to reduce the impacts of noise on marine mammals (Agardy et al., 2007; Dolman et al., 2009a, 2009b; Lubchenco, 2010; Fernández et al., 2013). Data on the local seasonal distribution of endangered

North Atlantic right whales in Stellwagen Bank National Marine Sanctuary (NMS) were used to reroute the shipping channel into Boston Harbour to reduce collisions between ships and baleen whales (Hatch et al., 2008). Management areas include speed-reduction measures and passive acoustic monitoring to help protect these whales and other marine mammals, with likely incidental benefits in terms of noise reduction. In addition, rerouting of an oil and gas pipeline was undertaken off Sakhalin Island (along with various other mitigation measures during seismic activities) in the critical feeding grounds of the endangered western grey whales (*Eschrichtius robustus*) (Spence et al., 2007), and prevention of seismic surveys off Abrolhos Bank and the wildlife reserve in Brazil in the humpback whales' breeding grounds (Engel et al., 2004).

Other designations were put in place for general protection but have resulted in noise pollution reduction. One such example is the Sable Gully, located at the edge of the Scotian shelf off northeastern Canada, which was designated an MPA in 2004. A 21%/y increase in Sowerby's beaked whale (*Mesoplodon bidens*) in the Gully is most plausibly explained by a reduction in anthropogenic disturbance (e.g., declines in fishing activities, seismic exploration, and supersonic flight) since the area became an MPA (Whitehead, 2013). Following a series of beaked whale strandings associated with navy sonar exposure in this area (Fernandez et al., 2004), the Spanish government imposed a 50 nmi moratorium on naval exercises in the waters of these islands in 2004 (Parsons et al., 2008). There have been no mass strandings on the Canary Islands since implementation of this moratorium (Fernández et al., 2013).

Case Study III: Habitat-Based Mitigation of Military Exercises—Beaked whales are clearly a priority species due to their potentially extreme sensitivity to MFAS (Cox et al., 2006). Summaries of existing mitigation and suggested "best practise" measures for active sonar and beaked whales have been provided previously (Dolman et al., 2009b, 2010, 2011b). Cuvier's beaked whales (*Ziphius cavirostris*) stopped normal feeding and swimming, moving rapidly and silently away in longer dives when exposed to received levels of 89 to 127 dB re 1 μPa, accruing substantial energetic costs and increasing stranding and decompression sickness risk (DeRuiter et al., 2013). Other occurrences were disruption of foraging behaviour and avoidance by Blainville's beaked whales (*Mesoplodon densirostris*) (McCarthy et al., 2011) to multi-day naval exercises involving tactical mid-frequency sonars and an experimental approach using playbacks of simulated sonar at AUTEC in The Bahamas at exposures well below those used by regulators to define disturbance (Tyack et al., 2011). The sensitivity of killer whales (*Orcinus orca*) was published, both in experimental context and through data resulting from actual navy exercises (Kuningas et al., 2013; Miller et al., 2014). Long-finned pilot whales (*Globicephala melas*) appear to be much less sensitive (Antunes et al., 2014).

A number of studies suggest population-level impacts from repeated exposures of beaked whales to naval activities. A Blainville's beaked whale population on the Navy's AUTEC naval range in The Bahamas had lower abundance and recruitment success (calf to female ratio) than another off-range Bahamas population, based on a 15-y field study (Claridge, 2013). Further, adult females showed high residency at the navy range, putting them at risk, especially when pregnant and lactating (Claridge, 2013). In California, Navy activities were proposed as one of two plausible hypotheses, along with ecosystem change, to explain a precipitous decline in beaked whale populations in the California Current ecosystem (Moore & Barlow, 2013).

Species other than beaked whales are also vulnerable to mid-frequency military sonar. For example, other species have been involved in multiple species stranding events that were synchronous with military active sonar use (Parsons et al., 2009). MFAS can induce temporary reduction of hearing ability in a bottlenose dolphin (*Tursiops truncatus*) (Mooney et al., 2009a, 2009b). Long-finned pilot whales changed the type of vocalisation in the presence of military sonar signals (Rendell & Gordon, 1999). Blue whales (*Balaenoptera musculus*) were less likely to produce calls when MFAS was present (Melcon et al., 2012) and ceased deep feeding on krill (Goldbogen et al., 2013).

In addition, the range of military activities linked with strandings and death at sea is not restricted to MFAS. More than 50 short-beaked common dolphins (*Delphinus delphis*) stranded in Cornwall, UK, during a military exercise involving aerial activities (Jepson et al., 2013); at least 85 harbour porpoises (*Phocoena phocoena*) were bycaught following military exercising on the northwest coast of Denmark (Wright et al., 2013b); and pilot whales in the north of Scotland stranded following multiple high-order detonations (Brownlow et al., 2014). Conducting strategic assessment enables identification of important marine mammal habitats and implementation of adequate management measures.

Most naval activities within the U.S. territorial sea and the exclusive economic zone (EEZ) are now the subject of programmatic regulations (Roman et al., 2013), although, as noted above, spatial-temporal mitigation is not prescribed in many U.S. Navy MMPA authorizations. In contrast, other than an EIA before implementation of UK Sonar 2087, the UK Ministry of Defence has not conducted a strategic environmental assessment of the range of its activities, apparently with the approval of JNCC. As an example, Exercise Joint Warrior, a twice yearly event usually occurring for 2 or 3 wks in spring and autumn, which includes up to 30 ships, five submarines, and 85 aircraft, has never been subjected to full and transparent EIA (Dolman et al., 2009a; Dolman, 2012) despite routinely operating in some of the most sensitive marine habitats in northern Europe. A number of recommendations are made by Dolman (2012) towards effective management of the UK MODs activities, including the adoption of effective, long-term, and meaningful management measures in the planning stage, with full and transparent EIA as a starting point. A number of navies are active in funding and collaborating with marine mammal research, not least of all behavioural response studies on a wide range of vulnerable species to help discern thresholds of impact from sonar operations (e.g., Kvadsheim et al., 2012; Miller et al., 2012; DeRuiter et al., 2013; Baird et al., 2014; Benda-Beckmann et al., 2014).

Finally, efforts are also underway to understand the effectiveness of ramp up (also known as soft start). Benda-Beckmann et al. (2014) suggest that ramp-up protocols prior to sonar operations can be effective at reducing the number of marine mammals experiencing sound doses that are high enough to cause temporary or permanent threshold shifts. Effectiveness, however, may be strongly species- and context-dependent as marine mammals may not abandon important habitat, with the more vulnerable individuals less likely to leave. Both theory and observations refute the equation of noise tolerance with absence of impact (Barber et al., 2014). Tolerance can also have ecological costs; it can indicate more severe constraints on animal behaviour (Gill et al., 2001). For a fixed duration of sonar operation, reducing ship speed will further decrease the effect and increase the efficacy of ramp up. Spatial restrictions are increasingly used as a tool for managing military noise impacts. In addition to the Canary Islands' 50 nmi moratorium, the U.S. Navy (2005) relocated a major exercise to avoid DeSoto Canyon in the Gulf of Mexico, citing important sperm whale (*Physeter macrocephalus*) feeding habitat. The Greek Navy has said it will exclude exercises in future from southern Crete (A. Frantzis, pers. comm., 2014) after a 2014 beaked whale mass stranding closely timed with sonar use (Notarbartolo di Sciara et al., 2014). Other navies, such as those of Australia and Italy, have incorporated spatial management into their mitigation and planning procedures (for a review, see Dolman et al., 2009a), and the U.S. Navy (2008) has provided minimal spatial restrictions for sonar exercises in the western Atlantic, although their conservation benefits fall far short of the "reasonable alternatives" it identified in a 2008 programmatic environmental review.

Multi-Sector Cumulative Noise Impacts

Data increasingly indicate concern for cumulative impact of sublethal effects from a variety of sectors on a variety of taxa (e.g., Miller et al., 2009; Hatch et al., 2012; Claridge, 2013). Cumulative and synergistic effects have the potential to induce fitness consequences for individuals, which, in turn, can lead to consequences at the population level (Wright & Kyhn, 2012). Regulators face the considerable challenge of managing these accumulating and interacting impacts with little scientific guidance (Wright & Kyhn, 2012). The potential cumulative impact of multiple sound sources was demonstrated on the Mid-Atlantic Ridge. A large number of seismic surveys in combination with the good propagation of the low-frequency noise from these typically coastal surveys mean that surveys can be detected above natural background noise levels on 80 to 95% of days (Nieukirk et al., 2012). Further, the potential impacts of noise pollution in addition to more defined impacts such as bycatch in active or ghost fishing gear, other forms of pollution, and climate change need to be considered together. A number of new tools are being proposed and developed to help assess the overall impact of multiple threat exposures. The U.S. has developed a product called CetSound (http://cetsound.noaa.gov) to aid in the assessment and management of cumulative impacts. CetSound provides the best available distribution and density maps for every cetacean species, and maps additional biologically important areas (Van Parijs et al., 2015) for small resident populations and migratory species across the entire U.S. territorial sea and the EEZ. Through the CetMap process, NMFS is mapping noise levels from major chronic and intermittent sources across the entire U.S. waters. NOAA (2014) is currently preparing to release an Ocean Noise Strategy that will attempt to achieve multi-sectoral cumulative noise management using the mandates available under existing U.S. law.

The interim Population Consequences of Disturbance (PCOD) model (Harwood et al., 2014) provides a formal, mathematical structure that can be used to implement the conceptual framework for investigating PCOD that was funded by the U.S. Office of Naval Research and presented by the U.S. National Research Council's Committee on Characterizing Biologically Significant Marine Mammal Behaviour in its 2005 report (NRC, 2005). It can be used by regulators and developers to evaluate the potential effects of individual project proposals over the course of their construction and operation and to assess the cumulative impacts of multiple developments on marine mammal populations. The interim PCOD approach has been designed to be suitable for assessing the potential effects associated with the construction and operation of all types of marine renewable energy devices on populations of marine mammals in UK waters (Harwood et al., 2014). The assessments of the likely changes in abundance of any marine mammal population provided by the interim PCOD approach rely heavily on expert opinions and a number of strong assumptions (Harwood et al., 2014). These are clearly weaknesses.

The interim PCOD approach was also used to qualitatively determine the cumulative impacts of three proposed (unmitigated) port developments, in addition to existing tour boat operations, within the Moray Firth bottlenose dolphin Special Area of Conservation (SAC) in Scotland. Results demonstrated that, in combination, these activities may lead to significant impacts under the EU Habitats Directive (Lusseau, 2013). A number of assumptions and uncertainties were provided; however, these are not yet available as functioning management tools, and all require considerable data that are not available in most cases. Despite this, managers in various parts of the world are mandated to find some way to identify, quantify, and ultimately mitigate these cumulative impacts (Wright & Kyhn, 2012).

Knowledge of the expected long-term cumulative effects on species would help industry and regulators understand the context of sound issues and assess risk as offshore regions are developed. It would also allow regulators to design the appropriate mitigation measures for that area and for the species of concern.

Uncertainties

There are key uncertainties around determining biological significance at the individual and population levels: poor population estimates, structure and range (resulting in inappropriate management units), and changes in the reproductive success of individuals. Conservatively, accounting for uncertainty and sensitivity in impact models is necessary in situations in which current take models are based on relatively few data points and are often highly sensitive. Auditory criteria are also subject to enormous uncertainty. For example, a proposed NMFS (2013) weighting system for all odontocete species other than sperm whales was based on data from two bottlenose dolphin; yet, we do not know where these dolphins fall within the distribution of hearing sensitivity within their own species, let alone with odontocetes as a whole. All of these uncertainties will inhibit appropriate management unless a precautionary approach is adopted.

Data Requirements

There has been a relatively rapid evolution of applied research to investigate auditory and non-auditory abilities and the range of resulting noise pollution impacts, and of our knowledge limitations (including how noise contributes to cumulative impacts), as discussed in detail elsewhere (e.g., Wright, 2014). In 2009, the Joint Subcommittee on Ocean Science & Technology (JSOST) provided an integrated research plan on noise pollution for U.S. federal agencies (Southall et al., 2009). A recent noise pollution workshop report provides a useful summary of stakeholders' current priorities, including current and future research topics related to impacts (Fitch et al., 2011). A key issue resulting from the workshop was the requirement to formalise frameworks to strengthen links between data needs, especially baseline data, and application of data in management contexts (Fitch et al., 2011).

Baseline

There is a high probability of not detecting a precipitous decline in cetacean populations given present surveillance effort (Taylor et al., 2007). The establishment of detailed baseline data of animal population parameters, distribution, movement, and habitat utilization for areas of activity would allow improved risk assessments. This would also allow for improved interpretation of changes to animal populations and a better assessment of effects resulting from activities.

Basic life history data; social, acoustic, and behavioural ecology; as well as distribution and abundance data are all essential baseline data, required to make informed management decisions. Systematic effort is needed to define important marine mammal habitats, including "high-density areas" (defined through predictive modeling); foraging, calving, and higher-density migratory routes for migratory species; and habitat for small, resident populations in most parts of the world. Data should be obtained over sufficient time and space to understand seasonal movement patterns and changes that may occur as a function of climate change and human influences (Fitch et al., 2011). An explicit and regularly assessed plan is needed to prioritise, program, and execute the studies necessary to fill these data gaps (Fitch et al., 2011).

Reporting, Housing, and Sharing Data

A formal procedure for review and inclusion of data to inform regulatory decisions in an adaptive process, conducted within an appropriate time frame to ensure the science is up to date, as well as to ensure compliance and enforcement of required mitigation measures, is needed (as detailed in Weir & Dolman, 2007; Dolman et al., 2009a; Wright, 2014). A data repository, including ambient noise data (Dekeling et al., 2014), would assist with effective adaptive management. Standardised protocols, recording, and reporting would facilitate such an archive. Although JNCC guidelines are flawed in a number of aspects (Weir & Dolman, 2007; Parsons et al., 2009; Stone, 2015b), the resulting impact reports that are periodically produced are useful and should be replicated (Stone, 1997, 1998, 2000, 2001, 2003a, 2003b, 2006, 2015a; Stone & Tasker, 2006).

Focusing Noise Research

We may need to prioritise populations and research objectives based on conservation status, vulnerability of individuals or populations, and other factors such as region (i.e., Arctic, coastal, and other noisy areas). In addition, conservation efforts should prioritise populations already heavily impacted by multiple stressors and/or where the effects of masking are particularly strong given communication, behaviour, or ambient noise (e.g., chronically low SNR) (Fitch et al., 2011). Where data or density models exist, we can use quantitative impact analysis to show relative exposure risk. PCOD modeling efforts may be useful in developing scientific understanding of biologically significant impacts and associated management. A cooperative, interdisciplinary approach to hierarchically ordering research needs and then designing methodologies for data collection and analysis will be critical to understanding cumulative impacts (Fitch et al., 2011). The conservation status of each species and stressors other than sound exposure, in addition to noise (e.g., cumulative impacts), should be considered in predicting risk tolerance (Fitch et al., 2011).

There is a particular data gap on the impacts of offshore windfarm construction (particularly pile driving) and operation on baleen whales (Dolman et al., in press). Much of what is currently known about the impacts of offshore wind on marine mammals is derived from studies based in Europe and is limited to two cetacean species (harbour porpoise [e.g., Tougaard et al., 2009; Thompson et al., 2010; Brandt et al., 2011, 2012; Scheidat et al., 2011] and bottlenose dolphin [Bailey et al., 2010]). However, mysticetes have been reported to avoid other impulsive sounds and alter their vocalizations in response to their introduction (e.g., airguns; Stone & Tasker, 2006; Stone, 2015). Similarly, minke whales (*Balaenoptera acutorostrata*) have been observed to rapidly flee from military sonar exposures (e.g., Kvadsheim et al., 2012) and are present in much lower numbers during naval activity (Parsons et al., 2000). Mysticetes are a particular priority because of overlap between their expected low-frequency sensitivity and sounds generated during offshore windfarm construction (particularly pile driving) and operation. This lends support to the use of a more cautious lower value of sound exposure level to ensure that no animal is "injured" as a consequence of human noise exposures (Gedamke et al., 2011).

Developing Quieter Alternatives

Ideas generated from a recent U.S. noise workshop included establishing a research framework for supporting quieting technologies; developing incentive programs to advance this branch of research and development; and considering noise budget banking (e.g., cap and trade) for which user fees could fund research. Additional ideas included measures to reduce ship noise and cap ambient anthropogenic noise (Fitch et al., 2011). In Europe, progress is being made towards floating offshore wind farms that would be tethered to the seabed, which may reduce pile-driving noise.

Policy Application

Where applied research intercepts with policy, there has been less progress to date. A requirement for acoustic criteria for behavioural harassment has been established, and a matrix framework that incorporates contextual factors by categorising species, activities, and geographic areas to develop a series of step functions based on available literature documenting behavioural links was suggested (Fitch et al., 2011). Underwater noise is a trans-boundary issue, and international cooperation and coordination should be further stimulated. An enhanced understanding of impacts requires exposure levels and impacts of all noise-producing activities to be carefully monitored over suitable time frames and spatial scales (Simmonds et al., 2014).

Funding Future Research

An idea presented at a recent U.S. noise workshop was the introduction of a statutory user fee system on noise producers that would fund research and development (Fitch et al., 2011). U.S. agencies are presently considering various funding mechanisms for region-specific research on the impacts of seismic exploration, including user consortiums, as has been done for the Beaufort and Chukchi Seas, and prescription of research as a condition of permits and authorizations under various laws (e.g., CSA Ocean Sciences Inc., 2014).

Recommendations

These recommendations are not extensive and are intended to complement those recently provided by Wright (2014), which identify short-, medium-, and long-term solutions for reducing noise pollution from oil and gas, shipping, pile driving, and military sonar, as well as those previously identified (Weir & Dolman, 2007; Dolman et al., 2009a, 2009b; Simmonds et al., 2014). We make the following recommendations:

- As with other forms of pollution, reduction at source is the most effective approach to reducing impacts. Our main recommendation, therefore, is that the continuing development and use of quieter, alternative technologies and noise-reducing techniques should be prioritised, and that their mandatory use should be codified in regulations (Simmonds et al., 2014). Governments should accelerate development and use of these technologies through both R&D funding and regulatory engagement.

- Governments should make concerted and proactive efforts to fast-track and require source reduction technologies, including for current developments that are in the planning system. Providing funding is likely to encourage this.

- Governments, industry, and others must work to implement the IMO's noise guidelines and quieting technology. Mechanisms to drive implementation of quieting technologies include ship classification societies, green certification societies, port environmental compliance programs, and national regulation.

- Regulators should move towards better planning, including using spatial management.

- Governments and other responsible authorities around the world should phase in increasingly strict noise-level standards for all noise-producing activities (including through precautionary implementation of the EU MSFD) (Wright, 2014).

- Governments, industry, and environmental organizations should seek ways to address and reduce the underlying demand for noise-producing activities so that their occurrence can be reduced to the greatest extent possible (Wright, 2014), and duplicative activities should be eliminated such as by requiring data sharing in oil and gas exploration.

- Conservation targets (e.g., keeping X% of primary habitat in acoustically healthy condition or maintaining present baseline for acoustic habitat) should be set (Agardy et al., 2007).

- Longer-term studies are required to identify and assess the ultimate individual and population-level consequences of the numerous emerging noise-related issues.

- Environmental reviews must conservatively account for the substantial uncertainty and sensitivity in existing impact models by, for example, providing sensitivity analyses or modeling under a range of assumptions about species density, sound propagation, and other factors.

- Prepare programmatic/strategic EIAs in all sectors wherever possible.

- All navies should conduct full and transparent Environmental Assessments to include realistic impacts, appropriate precaution, and more effective mitigation, particularly by excluding high-intensity sonar use from important marine mammal habitats.

- Given the emphasis placed on the requirement for early planning and to account for certainty in a precautionary way, more strategic collection of field data and its subsequent availability is required as much emphasis should be given to understanding shifting baselines as to understanding impacts.

- Noise criteria need to be continually revised to ensure that they are up to date, precautionary, and take into account masking effects and other potential lower-level sublethal impacts to individuals and populations.

- In the meantime, measurement of noise budget, such as those under consideration under the EU Marine Strategy Framework Directive (Tasker et al., 2010), could lead to limits on the source levels that are introduced on a regional scale. The application of such a measure would be particularly useful in areas where noise pollution is increasing and is bordered by multiple countries—for example, in the North Sea.

- In the immediate term, studies to investigate the effectiveness of existing "best practise" on-board mitigation measures—namely, safety zone and ramp-up procedures—continue to be required, although some progress is acknowledged—for example, the Behavioural Response of Australian Humpback Whales to Seismic Surveys (BRAHSS) project (Cato et al., 2013). Advances in quieting technology, such as noise reduction standards for individual commercial ships, should be prioritised.

- Regulators and project proponents should establish communication with conservation organisations and other stakeholders to fully understand concerns early in the planning process.

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