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Contribution to the Theme Section 'Marine pollution and endangered species'



OPINION PIECE

Critical information gaps remain in understanding impacts of industrial seismic surveys on marine vertebrates

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ABSTRACT: Anthropogenic noise is increasing throughout the world's oceans. One major contributor is industrial seismic surveys—a process typically undertaken to locate and estimate the quantity of oil and gas deposits beneath the seafloor—which, in recent years, has increased in magnitude and scope in some regions. Regulators permit this activity despite widespread uncertainties regarding the potential ecological impacts of seismic surveys and gaps in baseline information on some key species of conservation concern. Research to date suggests that impacts vary, from displacement to direct mortality, but these effects remain poorly understood for most species. Here, we summarize potential effects of seismic surveys, describe key knowledge gaps, and recommend broad-scale research priorities for 3 impacted taxonomic groups: fish, marine mammals, and sea turtles. We also suggest further technological advances, improved mitigation measures, and better policy and management structures to minimize the ecological impacts of seismic surveys in light of scientific uncertainty.

KEY WORDS: Seismic airguns · Marine vertebrates · Marine mammals · Marine turtles · Turtles · Ocean noise · Chronic stress

1. BACKGROUND

Anthropogenic noise is altering marine soundscapes globally (Hildebrand 2009, Williams et al. 2015, Ellison et al. 2016, Estabrook et al. 2016, Hatch et al. 2016, Cholewiak et al. 2018). In particular, seismic airguns are one of the loudest and most pervasive anthropogenic sources of sound in the ocean (National Research Council 2003, Bröker et al. 2015). Used primarily in oil and gas exploration and reservoir monitoring—and sometimes in research—seismic surveys release highly compressed air from an array of airguns towed behind a survey vessel, though survey

designs vary widely (National Research Council 2003, Hildebrand 2009). These air pockets expand and collapse rapidly to form a pulse of sound that penetrates the seafloor, and the reflecting and refracting sound waves provide an image of the substructure, including potential oil and gas deposits (Caldwell & Dragoset 2000). Noise from airguns is dominated by low frequencies, thus undergoing little attenuation and propagating across vast distances; the distance traveled and intensity vary by region, survey characteristics, and environmental factors (Hildebrand 2009).

Sound is the primary sensory modality for many marine vertebrates, vital for communication, orienta-

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tion, and foraging (Compton et al. 2007, Nowacek et al. 2007, Videsen et al. 2017). There is growing concern that seismic surveys may have adverse impacts on marine life, ranging from physiological to behavioral impacts. Broadly, these include disruption of communication (Cerchio et al. 2014, Dahlheim & Castellote 2016), temporary displacement from habitat (Yazvenko et al. 2007, Castellote et al. 2012), and potential mortality (Gordon et al. 2003, Hildebrand 2005). Of particular concern are the effects of chronic noise on animals, such as stress (Nowacek et al. 2007, Tyack 2008, Rolland et al. 2012) and hearing damage, especially from accumulated exposure (Weilgart 2007). The extent of impact depends on factors such as proximity to the sound source, life stage, and other biological and physical factors—a complicated and contextual mix of factors that are difficult to study in field settings (Dunlop et al. 2017, Ellison et al. 2018). Wider ecosystem effects may impact vertebrates indirectly, such as through prey shifts (Gordon et al. 2003). It has been found that adult and larval zooplankton abundance decreased within an hour of experimental airgun exposure (McCauley et al. 2017).

In recent decades, the potential effects of seismic surveys and general anthropogenic noise on marine species have received increased attention in both the policy and scientific contexts (Forney et al. 2017, Harfoot et al. 2017, Vilardo & Barbosa 2018). The international policy field is gradually recognizing the need to better understand and manage ocean noise (e.g. the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic area [ACCOBAMS] contains a resolution on addressing ocean noise), but regulatory actions and mitigation designs fall short of the actions needed to effectively reduce impacts. Despite this growing attention, the impacts of seismic surveys specifically on marine vertebrates—fish, turtles, and marine mammals—remain poorly understood as seismic surveys continue and expand into new areas (Nelms et al. 2016, Carroll et al. 2017).

2. OVERVIEW OF KNOWLEDGE GAPS

Most research has focused on the effects of a specific sound source on one species in a single location (e.g. Richardson & Miller 1999, Di Iorio & Clark 2009, Miller et al. 2009). Ocean noise, however, can propagate swiftly across vast distances—especially the low frequencies employed in seismic surveys (Nieukirk et al. 2012)—and therefore can affect a range of species (Hildebrand 2009, Nowacek et al. 2015). Additionally,

the aggregate impact of noise from multiple sources (e.g. commercial shipping and seismic surveys) needs to be considered and modeled, especially in key habitats (Dunlop et al. 2017, Frankel & Gabriele 2017, Redfern et al. 2017, Small et al. 2017).

Regulatory bodies sometimes permit surveys without baseline information about potentially affected species, including accurate data on distribution and abundance, and instead extrapolate potential impacts from studies in other areas. This makes it nearly impossible to assess basic individual- and/or population-level impacts (Stone & Tasker 2006, Weir & Pierce 2012, Przeslawski et al. 2018). Very few marine vertebrate species have received adequate attention, and most remain unstudied. For example, from 1983 to 2013, only 29 studies (including some in the grey literature) on sea turtles and seismic surveys were published, while 187 papers were published on fish, and 414 were published on marine mammals (Nelms et al. 2016).

Consequently, further targeted research is needed on the effects of seismic surveys (McKenna et al. 2016, Hawkins & Popper 2017). This includes impacts on short- and long-term physiological responses, important fitness parameters (e.g. breeding, foraging, predator avoidance), and distribution and movement at various spatio-temporal scales in both field and laboratory settings. We recommend the following broad research priorities for the 3 main taxonomic groups:

2.1. Fish

2.1.1. Research potential displacement in the water column, and physiological impacts. The extent and duration of displacement, as well as the thresholds of received sound levels that lead to such movement (e.g. duration, geographic distance), are poorly understood (Slotte et al. 2004, Paxton et al. 2017). Such displacement not only carries ecological implications, but could also impact fisheries (Løkkeborg et al. 2012, Carroll et al. 2017).

2.1.2. Better understand potential impacts of masking with acoustically active fish species. Many fish rely on sound to communicate, breed, and find key habitat, but little is understood about how anthropogenic noise may disrupt these activities (Popper & Hastings 2009, Slabbekoorn et al. 2010, Holles et al. 2013, Radford et al. 2014, Simpson et al. 2015).

2.1.3. Assess potential for avoidance of essential habitat areas, including reefs or other spawning, mating, or foraging sites. Recent evidence shows that

some fish may avoid reef sites, aggregate in lower densities (Simpson et al. 2011, Paxton et al. 2017), or their distribution (Bruce et al. 2018) and abundance (Rivera et al. 2018) may be affected after exposure to elevated noise levels. Studies of impacts on key habitat areas, such as monitoring utilization of key spawning grounds before and after surveys, can help delineate population-level consequences.

2.2. Marine mammals

2.2.1. Understand how marine mammals respond to potential masking caused by seismic surveys, and subsequent implications for fitness. There is widespread concern that seismic surveys will lead to masking of important acoustic signals vital to communication in marine mammals, particularly in baleen whales (Clark et al. 2009, Di Iorio & Clark 2009, Hatch et al. 2012). Dedicated research is needed to understand the received sound levels at which different species exhibit masking, as well as the response to, and biological consequences of, masking.

2.2.2. Examine the extent and duration of avoidance behavior, and how it varies with ontogeny and subsequent implications for fitness. Marine mammals exercise avoidance behavior when exposed to certain low-frequency sound sources (McCauley et al. 2000, Harris et al. 2001, Weilgart 2007), potentially resulting in exclusion from important habitats, such as feeding and breeding areas. More information is needed on the received sound levels, duration, and biological states that lead to avoidance (Dunlop et al. 2017).

2.2.3. Conduct studies to assess stress and physiological consequences in marine mammals, particularly from long-term, chronic seismic exposure. One of the main potential impacts from seismic exploration is stress (Romano et al. 2004, Rolland et al. 2012), which can affect reproduction, immune systems, growth, health, and other important life functions. The impacts on marine mammal hearing, survival, and reproduction could be examined by comparing populations with and without such exposure, or by conducting health assessments before and after a survey. For example, targeted studies to examine pathology of stranded animals in areas with/without seismic activities could lend insights into physiological impacts of animals exposed to sound. All of these types of studies could be conducted in areas of recurring surveys, such as around Sakhalin Island, Russia (Bröker et al. 2015, Muir et al. 2015, 2016), West

Africa (DeRuiter & Doukara 2012), and the Beaufort Sea (Richardson & Miller 2013, Robertson et al. 2013, 2016), to name just a few places. Ideally, this type of information would be collected at an individual- and population-level setting to determine demographic consequences from surveys.

2.3. Sea turtles

2.3.1. Measure and observe physiological responses of sea turtles to airguns, including stress hormone levels, in a field setting. These studies should be conducted with control and experimental groups of turtles, assessed before, during, and after surveys. The physiological responses should be analyzed in repeat surveys to assess long-term physiological impacts, rather than just immediate impacts.

2.3.2. Monitor short- and long-term behavioral responses, including changes to diving, foraging, migration patterns, and nesting behavior. Of these, impacts on migratory corridors and nesting behavior should be prioritized. Behavioral impacts are easier to assess than physiological responses, because such impacts can be assessed using readily available methods, such as satellite-linked telemetry and other biologging devices (Tyson et al. 2017). Research to date has noted some dive response to seismic surveys (DeRuiter & Doukara 2012), but implications of this behavior are poorly understood.

2.3.3. Conduct studies of the impact of airguns on sea turtle distribution and abundance at sea. Both density models and actual measurements of density before and after surveys could be used to assess impacts (e.g. using biologging devices, unmanned aerial devices, etc.). Not only will such studies help reveal impacts of seismic surveys on marine turtle distribution and abundance, but they may reveal insight into displacement vs. habituation/tolerance in marine turtles. Recent studies demonstrate progress on methodological approaches to the study of sea turtle distribution and abundance in the context of anthropogenic activity (Pikesley et al. 2018).

3. KNOWLEDGE GAPS SURROUNDING MITIGATION MEASURES

Globally, and sometimes even within waters of the same country (e.g. the United States), no single minimum standard of mitigation measures exists (Verfuss et al. 2018). In countries where mitigation measures are recommended, the standards are often

guidelines rather than requirements (Compton et al. 2007, Parsons et al. 2009, Nowacek et al. 2015). The standards are designed to mitigate impacts on marine mammals, with no current set of standards or guidelines for sea turtles and fish. Within the patchwork of mitigation measures, little is known about the efficacy of mitigation in protecting marine vertebrates from the sounds of airguns (Weir & Dolman 2007, Weir 2008, Parsons et al. 2009). Furthermore, without baseline information on species before surveys (Ahonen et al. 2017), it is challenging to conduct management and assess the efficacy of these standards during or after surveys.

In areas where mitigation measures are used, several procedures are commonly employed: ramp-up (or soft start) — where airguns build sound over time to reach full amplitude — which is intended to alert animals to the sound source and allows them to leave the area (Weir & Dolman 2007); visual monitoring by protected-species observers; and exclusion zones, which define a radius where surveys are required to shut down if animals are detected (Compton et al. 2007, Weir & Dolman 2007). Important issues exist with these standards, such as the ineffectiveness of visual monitoring in poor visibility conditions (e.g. low light, fog) and the practicability of exclusion zones due to difficulties detecting animals below the ocean's surface, in rough seas, or as a result of observer bias (Compton et al. 2007, Weir & Dolman 2007). Passive acoustic monitoring can be used to detect the presence of vocalizing cetaceans near airguns (Weir & Dolman 2007); however, cessation of vocalization is one of the documented responses to airguns (Blackwell et al. 2015).

Many nations have established 'safe' sound exposure levels for marine mammals exposed to seismic surveys, which are typically applied uniformly to all species (Compton et al. 2007, Southall et al. 2007, Nelms et al. 2016). Most of these mitigation measures were created for marine mammals based on published hearing thresholds, but are then applied to other taxa (i.e. sea turtles; Nelms et al. 2016, Hawkins & Popper 2017) and/or to species or groups for which no hearing data exist (e.g. baleen whales). It is also often unclear what impacts these measures intend to mitigate — such as hearing loss, basic behavioral disruption, injury, or death.

4. INNOVATIVE APPROACHES TO SEISMIC SURVEYS

We encourage a holistic approach to reducing impacts from the process, involving research, policy,

and technology fields. In addition to a lack of policy and regulatory consensus on mitigation standards described above, the permitting process for seismic surveys is often extremely haphazard (Nowacek et al. 2015). For example, in the United States, duplicative surveys are permitted in the same area, which increases the potential for cumulative effects from the noise of multiple surveys. If only a single survey were permitted in a particular lease area, total noise levels would decrease. In the same vein, governments could commission surveys to one party, and then sell the data to generate revenue. Likewise, as employed by Norway and several other nations, governments could consider multi-client surveys (CGG 2015, Larsen & Ashby 2017), where interested parties can purchase seismic data rather than conduct repetitive surveys. Lastly, regulatory bodies should consider requiring seismic companies to use the smallest array and survey the smallest area necessary to further reduce total noise introduced into the environment.

Additionally, quieter, less invasive technologies exist. Vibroseis, for example, offers continuous, lower peak sound with a narrower frequency response than a typical airgun array (Nowacek & Southall 2016, Duncan et al. 2017). Other alternative sources include: gravity gradiometry, which is used by oil and mineral prospectors to measure the density of the subsurface, as well as the E-Bolt airgun, designed to reduce the high-frequency components that have potential for causing disturbance to some marine life while retaining the low-frequency components critical to seismic exploration (www.teledynemarine.com/eSource).

Technological advances also now exist to augment mitigation measures, such as drone technology for direct monitoring (Christie et al. 2016, Nowacek et al. 2016, Rees et al. 2018), enhanced species distribution modeling (Gregg et al. 2013, Becker et al. 2014, Wilkgren et al. 2014, Forney et al. 2015), and acoustic telemetry for fish and sea turtles (Przeslawski et al. 2018). Technological advances also include methods for reducing the amount of seismic survey noise that spreads away from the array. Bubble curtains using arrays of large tethered encapsulated bubbles can attenuate underwater sound in the 50 to 1000 Hz frequency band from a variety of continuous and impulsive sources by as much as 50 dB (Lee et al. 2012a,b,c, Lee & Wilson 2013, Wochner et al. 2013). Air-filled resonators, similar to Helmholtz resonators, have been demonstrated as effective in abating the noise from a sound source by as much as 30 dB (Wochner et al. 2014). Without economic or regulatory incentives to use this technology, however, industry is not prioritizing this technology in surveys.

Thus, regulators should consider requiring a shift towards quieter and mitigation-focused technology, which could be considered to be part of a mitigation package.

5. PROGRESS TO DATE

We applaud recent progress to mitigate the impacts of seismic surveys. In September 2016, for example, the International Union for Conservation of Nature (IUCN) released guidelines for best practices during seismic survey planning, execution, and monitoring (Nowacek & Southall 2016). Concerning ocean noise pollution more generally, several non-governmental organizations and collaborators made a voluntary commitment at the United Nations Ocean Conference to prevent and reduce ocean noise pollution in June 2017, indicating they will develop a 'noise inventory' of the main global ocean noise sources, as well as form working groups under this commitment. The ACCOBAMS agreement has a 2010 resolution to address anthropogenic noise in the Black Sea and Mediterranean waters, which encourages signatories to the ACCOBAMS to consider noise in management plans and reduce noise where applicable.

Some countries are taking important steps to address the potential effects of seismic surveys. In the vein of a more regulatory approach to addressing seismic surveys, the Italian Environmental Impact Assessment Commission, the body that regulates permits for oil and gas activity in Italy's waters within Italy's Ministry of the Environment and Protection of Land and Sea, implemented a requirement in 2015 for studies to be conducted 60 d before and after a seismic survey to determine marine mammal density and abundance (Fossati et al. 2018). The United States has made recent progress in addressing ocean noise more generally. In 2016, the National Oceanic and Atmospheric Administration (NOAA)—the agency tasked with regulating the marine environment in the USA—released their first Ocean Noise Strategy Roadmap, which addresses seismic surveys at the federal policy level (Gedamke et al. 2016). NOAA also published technical acoustic guidelines for determining thresholds at which noise levels could impact marine mammal hearing sensitivity (National Marine Fisheries Service 2016). At the same time, however, the USA is at a critical juncture in regulating seismic surveys and marine mammals, with NOAA recently permitting marine mammal take incidental to seismic surveys in the US Atlantic

Ocean for the first time (National Marine Fisheries Service 2018). At the time of writing, regulatory bodies are not requiring any advanced studies, testing of mitigation measures, or requiring the use of alternative technology, while the scope of potential seismic activity represents a precedent-setting opportunity to do so.

6. CONCLUSION

Much remains to be learned about the impact of seismic surveys on marine vertebrates. So far, most research has focused on the impacts on individual organisms or species, with little attention on population-level impacts over large spatial and temporal scales. In addition to the studies referenced in Section 2 above, we encourage governments to revisit their permitting processes and consider more effective governance methods. A more prudent approach to the scale and number of surveys, as well as critical consideration of enhanced mitigation measures, is needed to avoid undermining conservation gains made with marine megafauna over the past decades. Regulatory bodies are at a critical juncture to address this issue, particularly when managing sensitive species that are in decline and highly vulnerable to ocean noise, such as North Atlantic right whales *Eubalaena glacialis*.

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