Vol. 39: 247–254, 2019
https://doi.org/10.3354/esr00968

ENDANGERED SPECIES RESEARCH
Endang Species Res

Published July 25

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

B. W. Elliott[1,*], A. J. Read[1], B. J. Godley[2], S. E. Nelms[2,3], D. P. Nowacek[1,4]

[1]Duke University Marine Laboratory, Nicholas School of the Environment, 135 Duke Marine Lab Rd, Beaufort, NC 28516, USA
[2]Centre for Ecology and Conservation, University of Exeter, Cornwall Campus, Penryn TR10 9EZ, UK
[3]Plymouth Marine Laboratory, Prospect Place, Plymouth PL1 3DH, UK
[4]Duke University Pratt School of Engineering, 305 Teer Building Box 90271, Durham, NC 27708, USA

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-

*Corresponding author: brianna.elliott@duke.edu

Publisher: Inter-Research · www.int-res.com

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 (Gregr 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*.

Acknowledgements. S.E.N. was funded by the Natural Environment Research Council (NE/L002434/1).

LITERATURE CITED

Ahonen H, Stafford KM, de Steur L, Lydersen C, Wiig O, Kovacs KM (2017) The underwater soundscape in western Fram Strait: breeding ground of Spitsbergen's endangered bowhead whales. Mar Pollut Bull 123: 97–112

Becker EA, Forney KA, Foley DG, Smith RC, Moore TJ, Barlow J (2014) Predicting seasonal density patterns of California cetaceans based on habitat models. Endang Species Res 23:1–22

Blackwell SB, Nations CS, McDonald TL, Thode AM and others (2015) Effects of airgun sounds on bowhead whale calling rates: evidence for two behavioral thresholds. PLOS ONE 10:e0125720

Bröker K, Gailey G, Muir J, Racca R (2015) Monitoring and impact mitigation during a 4D seismic survey near a population of gray whales off Sakhalin Island, Russia. Endang Species Res 28:187–208

Bruce B, Bradford R, Foster S, Lee K, Cooper S, Przeslawski R (2018) Quantifying fish behavior and commercial catch rates in relation to a marine seismic survey. Mar Environ Res 140:18–30

Caldwell J, Dragoset W (2000) A brief overview of seismic air-gun arrays. Leading Edge (Tulsa Okla) 19:898–902
Carroll AG, Przeslawski P, Duncan A, Gunning M, Bruce B (2017) A critical review of the potential impacts of marine seismic surveys on fish and invertebrates. Mar Pollut Bull 114:9–24
Castellote M, Clark CW, Lammers MO (2012) Acoustic and behavioural changes by fin whales (*Balaenoptera physalus*) in response to shipping and airgun noise. Biol Conserv 147:115–122
Cerchio S, Strindberg S, Collins T, Bennett C, Rosenbaum H (2014) Seismic surveys negatively affect humpback whale singing activity off Northern Angola. PLOS ONE 9:e86464
CGG (2015) CGG begins new multi-client Broadseis survey in Norway. www.cgg.com/en/Investors/Press-Releases/2015/05/New-Multi-Client-BroadSeis-Survey-in-Norway (accessed 5 September 2016)
Cholewiak D, Clark CW, Ponirakis D, Frankel A and others (2018) Communicating amidst the noise: modeling the aggregate influence of ambient and vessel noise on baleen whale communication space in a national marine sanctuary. Endang Species Res 36:59–75
Christie KS, Gilbert SL, Brown CL, Hatfield M, Hanson L (2016) Unmanned aircraft systems in wildlife research: current and future applications of a transformative technology. Front Ecol Environ 14:241–251
Clark CW, Ellison WT, Southall BL, Hatch L and others (2009) Acoustic masking in marine ecosystems: intuitions, analysis, and implication. Mar Ecol Prog Ser 395:201–222
Compton R, Goodwin L, Handy R, Abbot V (2007) A critical examination of worldwide guidelines for minimizing the disturbance to marine mammals during seismic surveys. Mar Policy 32:255–262
Dahlheim M, Castellote M (2016) Changes in the acoustic behavior of gray whales *Eschrichtius robustus* in response to noise. Endang Species Res 31:227–242
DeRuiter SL, Doukara KL (2012) Loggerhead turtles dive in response to airgun sound exposure. Endang Species Res 16:55–63
Di Iorio L, Clark CW (2009) Exposure to seismic survey alters blue whale acoustic communication. Biol Lett 6: 20090651
Duncan AJ, Weilgart LS, Leaper R, Jasny M, Livermore S (2017) A modelling comparison between received sound levels produced by a marine vibroseis array and those from an airgun array for some typical seismic survey scenarios. Mar Pollut Bull 119:277–288
Dunlop RA, Noad MJ, McCauley RD, Scott-Hayward L and others (2017) Determining the behavioural dose–response relationship of marine mammals to air gun noise and source proximity. J Exp Biol 220:2878–2886
Ellison WT, Racca R, Clark CW, Streever B and others (2016) Modeling the aggregated exposure and responses of bowhead whales *Balaena mysticetus* to multiple sources of anthropogenic underwater sound. Endang Species Res 30:95–108
Ellison WT, Southall BL, Frankel AS, Vigness-Raposa K, Clark CW (2018) An acoustic scene perspective on spatial, temporal, and spectral aspects of marine mammal behavior responses to noise. Aquat Mamm 44:239–243
Estabrook BJ, Ponirakis DW, Clark CW, Rice AN (2016) Widespread spatial and temporal extent of anthropogenic noise across the northeastern Gulf of Mexico shelf ecosystem. Endang Species Res 30:267–282
Forney KA, Becker EA, Foley DG, Barlow J, Oleson EM (2015) Habitat-based models of cetacean density and distribution in the Central North Pacific. Endang Species Res 27:1–20
Forney KA, Southall BL, Slooten E, Dawson S and others (2017) Nowhere to go: noise impact assessments for marine mammal populations with high site fidelity. Endang Species Res 32:391–413
Fossati C, Mussi B, Tizzi R, Pavan G, Pace DS (2018) Italy introduces pre and post operation monitoring phases for offshore seismic exploration activities. Mar Pollut Bull 120:376–378
Frankel AS, Gabriele CM (2017) Predicting the acoustic exposure of humpback whales from cruise and tour vessel noise in Glacier Bay, Alaska, under different management strategies. Endang Species Res 34:397–415
Gedamke J, Harrison J, Hatch L, Angliss R and others (2016) Ocean noise strategy roadmap. NOAA, Silver Spring, MD. http://cetsound.noaa.gov/Assets/cetsound/documents/Roadmap/ONS_Roadmap_Final_Complete.pdf (accessed 15 September 2016)
Gordon J, Gillespie D, Potter J, Frantzis A, Simmonds MP, Swift R, Thompson D (2003) A review of the effects of seismic survey on marine mammals. Mar Technol Soc J 37:16–34
Gregr EJ, Baumgartner MF, Laidre KL, Palacios DM (2013) Marine mammal habitat models come of age: the emergence of ecological and management relevance. Endang Species Res 22:205–212
Harfoot MBJ, Tittensor DP, Knight S, Arnell AP and others (2017) Present and future biodiversity risks from fossil fuel exploitation. Conserv Lett 11:e12448
Harris RE, Miller GW, Richardson WJ (2001) Seal responses to airgun sounds during summer seismic surveys in the Alaskan Beaufort Sea. Mar Mamm Sci 17:795–812
Hatch LT, Clark CW, Van Parijs SM, Frankel AS, Ponirakis DW (2012) Quantifying loss of acoustic communication space for right whales in and around a U.S. National Marine Sanctuary. Conserv Biol 26:983–984
Hatch LT, Wahle CM, Gedamke J, Harrison J and others (2016) Can you hear me here? Managing acoustic habitat in US waters. Endang Species Res 30:171–186
Hawkins AD, Popper AN (2017) A sound approach to assessing the impact of underwater noise on marine fishes and invertebrates. ICES J Mar Sci 74:635–651
Hildebrand JA (2005) Impacts of anthropogenic sound. In: Reynolds JE, Perrin WF, Reeves RR, Montgomery S, Ragen TJ (eds) Marine mammal research: conservation beyond crisis. Johns Hopkins University Press, Baltimore, MD, p 101–124
Hildebrand JA (2009) Anthropogenic and natural sources of ambient noise in the ocean. Mar Ecol Prog Ser 395:5–20
Holles S, Simpson SD, Radford AN, Beten L, Lucchini D (2013) Boat noise disrupts orientation behavior in a coral reef fish. Mar Ecol Prog Ser 485:295–300
Larsen SB, Ashby W (2017) TGS. TGS and PGS announce fourth 3D seismic project offshore Eastern Canada. http://koreabizwire.com/tgs-and-pgs-announce-fourth-3d-seismic-project-offshore-eastern-canada/84224 (accessed 1 June 2017)
Lee KM, Wilson PS (2013) Attenuation of sound in water through collections of very large bubbles with elastic shells. Proc Meet Acoust 19:075048
Lee KM, Wochner MS, Wilson PS (2012a) Mitigation of low-frequency underwater noise generated by rotating machi-

nery of a mobile work barge using large tethered encapsulated bubbles. J Acoust Soc Am 131:3507
Lee KM, Wochner MS, Wilson PS (2012b) Mitigation of underwater radiated noise from a vibrating work barge using an encapsulated bubble curtain. J Acoust Soc Am 132:2056
Lee KM, McNeese AR, Wochner MS, Wilson PS (2012c) Reduction of underwater sound from continuous and impulsive noise sources. J Acoust Soc Am 132:2062
Løkkeborg S, Ona E, Vold A, Salthaug A (2012) Sounds from seismic air guns: gear- and species-specific effects on catch rates and fish distribution. Can J Fish Aquat Sci 69: 1278–1291
McCauley RD, Fewtrell J, Duncan AJ, Jenner C and others (2000) Marine seismic surveys — a study of environmental implications. APPEA J 40:692–708
McCauley RD, Day RD, Swadling KM, Fitzgibbon QP, Watson RA, Semmens JM (2017) Widely used marine seismic survey air gun operations negatively impact zooplankton. Nat Ecol Evol 1:0195
McKenna MF, Shannon G, Fristrup K (2016) Characterizing anthropogenic noise to improve understanding and management of impacts to wildlife. Endang Species Res 31: 279–291
Miller PJO, Johnson MP, Madsen P, Biassoni N and others (2009) Using at-sea experiments to study the effects of airguns on the foraging behavior of sperm whales in the Gulf of Mexico. Deep Sea Res I 56:1168–1181
Muir JE, Ainsworth L, Joy R, Racca R and others (2015) Distance from shore as an indicator of disturbance of gray whales during a seismic survey off Sakhalin Island, Russia. Endang Species Res 29:161–178
Muir JE, Ainsworth L, Racca R, Bychkov Y and others (2016) Gray whale densities during a seismic survey off Sakhalin Island, Russia. Endang Species Res 29:211–227
National Marine Fisheries Service (2016) Technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing: underwater acoustic thresholds for onset of permanent and temporary threshold shifts. NOAA Tech Memo NMFS-OPR-55. NOAA, Silver Spring, MD
National Research Council (2003) Ocean noise and marine mammals. National Academies Press, Washington, DC
Nelms SE, Piniak WED, Weir CR, Godley BJ (2016) Seismic surveys and marine turtles: an underestimated global threat? Biol Conserv 193:49–65
Nieukirk SL, Mellinger DK, Moore SE, Klinck K, Dziak RP, Goslin J (2012) Sounds from airguns and fin whales recorded in the mid-Atlantic Ocean, 1999–2000. J Acoust Soc Am 131:1102–1112
National Marine Fisheries Service (2018) Takes of marine mammals incidental to specified activities; taking marine mammals incidental to geophysical surveys in the Atlantic Ocean [83 FR 63268]. Fed Regist 83:63268–63381 (accessed 2 February 2019)
Nowacek DP, Southall BL (2016) Effective planning strategies for managing environmental risk associated with geophysical and other imaging surveys. IUCN, Gland
Nowacek DP, Thorne LH, Johnston DW, Tyack PL (2007) Responses of cetaceans to anthropogenic noise. Mammal Rev 37:81–115
Nowacek DP, Clark CW, Mann D, Miller PJO and others (2015) Marine seismic surveys and ocean noise: time for coordinated and prudent planning. Front Ecol Environ 13:378–386
Nowacek DP, Christiansen F, Bejder L, Goldbogen JA, Friedlaender AS (2016) Studying cetacean behaviour: new technological approaches and conservation applications. Anim Behav 120:235–244
Parsons EC, Dolman SJ, Jasny M, Rose NA, Simmonds MP, Wright AJ (2009) A critique of the UK's JNCC seismic survey guidelines for minimising acoustic disturbance to marine mammals: best practise? Mar Pollut Bull 58: 643–651
Paxton AB, Taylor JC, Nowacek DP, Dale J, Cole E, Voss CM, Peterson CH (2017) Seismic survey noise disrupted fish use of a temperate reef. Mar Policy 78:68–73
Pikesley SK, Agamboue PD, Bayet JP, Bibang JN and others (2018) A novel approach to estimate the distribution, density and at-sea risks of a centrally-placed mobile marine vertebrate. Biol Conserv 221:246–256
Popper AN, Hastings MC (2009) The effects of human-generated sound on fish. Integr Zool 4:43–52
Przeslawski R, Brooke B, Carroll AG, Fellows M (2018) An integrated approach to assessing marine seismic impacts: lessons learnt from the Gippsland Marine Environmental Monitoring project. Ocean Coast Manage 160:117–123
Radford AN, Kerridge E, Simpson SD (2014) Acoustic communication in a noisy world: Can fish compete with anthropogenic noise? Behav Ecol 25:1022–1030
Redfern JV, Hatch LT, Caldow C, DeAngelis ML and others (2017) Assessing the risk of chronic shipping noise to baleen whales off Southern California, USA. Endang Species Res 32:153–167
Rees AF, Avens L, Ballorain K, Bevan E and others (2018) The potential of unmanned aerial systems for sea turtle research and conservation: a review and future directions. Endang Species Res 35:81–100
Richardson WJ, Miller GW (1999) Displacement of migrating bowhead whales by sounds from seismic surveys in shallow waters of the Beaufort Sea. J Acoust Soc Am 106: 2281
Rivera JM, Glover DC, Kocovsky PM, Garvey JE and others (2018) Water guns affect abundance and behavior of bigheaded carp and native fish differently. Biol Invasions 20: 1243–1255
Robertson FC, Koski WR, Thomas TA, Richardson WJ, Würsig B, Trites AW (2013) Seismic operations have variable effects on dive-cycle behavior of bowhead whales in the Beaufort Sea. Endang Species Res 21:143–160
Robertson F, Koski WR, Trites AW (2016) Behavioral responses affect distribution analyses of bowhead whales in the vicinity of seismic operations. Mar Ecol Prog Ser 549:243–262
Rolland RM, Parks SE, Hunt KE, Castellote M and others (2012) Evidence that ship noise increases stress in right whales. Proc R Soc B 279:2363–2368
Romano TA, Keogh MJ, Kelly C, Finneran JJ (2004) Anthropogenic sound and marine mammal health: measures of the nervous and immune systems before and after intense sound exposure. Can J Fish Aquat Sci 61: 1124–1134
Simpson SD, Radford AN, Tickle EJ, Meekan MG, Jeffs AG (2011) Adaptive avoidance of reef noise. PLOS ONE 6: e16625
Simpson SD, Purser J, Radford AN (2015) Anthropogenic noise compromises antipredator behaviour in European eels. Glob Change Biol 21:586–593
Slabbekoorn H, Bouton N, van Opzeeland I, Coers A, ten

Cate C, Popper AN (2010) A noisy spring: the impact of globally rising underwater sound levels on fish. Trends Ecol Evol 25:419–427
Slotte A, Hansen K, Dalen J, Ona E (2004) Acoustic mapping of pelagic fish distribution and abundance in relation to a seismic shooting area off the Norwegian west coast. Fish Res 67:143–150
Small RJ, Brost B, Hooten M, Castellote M, Mondragon J (2017) Potential for spatial displacement of Cook Inlet beluga whales by anthropogenic noise in critical habitat. Endang Species Res 32:43–57
Southall BL, Bowles AE, Ellison WT, Finneran JJ and others (2007) Marine mammal noise exposure criteria: initial scientific recommendations. Aquat Mamm 33(Spec Issue):411–521
Stone CJ, Tasker ML (2006) The effects of seismic airguns on cetaceans in UK waters. J Cetacean Res Manag 8:255–263
Tyack PL (2008) Implications for marine mammals of large-scale changes in the marine acoustic environment. J Mammal 89:549–558
Tyson RB, Piniak WED, Domit C, Mann D, Hall M, Nowacek DP, Fuentes MMPB (2017) Novel bio-logging tool for studying fine-scale behaviors of marine turtles in response to sound. Front Mar Sci 4:219
Vallina SM, Follows MJ, Dutkiewicz S, Montoya JM, Cermeno P, Loreau M (2014) Global relationship between phytoplankton diversity and productivity in the ocean. Nat Commun 5:4299
Verfuss UK, Gillespe D, Gordon J, Marques TA and others (2018) Comparing methods suitable for monitoring marine mammals in low visibility conditions during seismic surveys. Mar Pollut Bull 126:1–18
Videsen SKA, Bejder L, Johnson M, Madsen PT (2017) High suckling rates and acoustic crypsis of humpback whale neonates maximise potential for mother–calf energy transfer. Funct Ecol 31:1561–1573
Vilardo C, Barbosa AF (2018) Can you hear the noise? Environmental licensing of seismic surveys in Brazil faces uncertain future after 18 years protecting biodiversity. Perspect Ecol Conserv 16:54–59
Weilgart LS (2007) A brief review of known effects of noise on marine mammals. Int J Comp Psychol 20:159–168
Weir CR (2008) Short-finned pilot whales (*Globicephala macrorhynchus*) respond to an airgun ramp-up procedure off Gabon. Aquat Mamm 34:349–354
Weir CR, Dolman SJ (2007) Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. J Int Wildl Law Policy 10: 1–27
Weir CR, Pierce GJ (2012) A review of the human activities impacting cetaceans in the eastern tropical Atlantic. Mammal Rev 43:258–274
Wikgren B, Kite-Powell H, Kraus S (2014) Modeling the distribution of the North Atlantic right whale *Eubalaena glacialis* off coastal Maine by areal co-kriging. Endang Species Res 24:21–31
Williams W, Wright AJ, Ashe E, Blight LK and others (2015) Impacts of anthropogenic noise on marine life: publication patterns, new discoveries, and future directions in research and management. Ocean Coast Manage 115: 17–24
Wochner MS, Wilson PS, Lee KM (2013) Protection of a receiving area from underwater pile driving noise using large encapsulated bubbles. In: Proc IEEE/OES Acoust Underwat Geosci Symp (Rio de Janeiro) 2013:6683986. IEEE, Piscataway, NJ
Wochner MS, Lee KM, McNeese AR, Wilson PS (2014) Attenuation of low frequency underwater noise using arrays of air-filled resonators. In: Proc 43rd Int Congr Noise Control Eng (Internoise 2014, Melbourne): paper 595. Australian Acoustical Society, Toowong
Yazvenko SB, McDonald TL, Blokhin SA, Johnson SR and others (2007) Distribution and abundance of western gray whales during a seismic survey near Sakhalin Island, Russia. Environ Monit Assess 134:45–73

Editorial responsibility: Sascha Hooker, St. Andrews, UK

Submitted: September 12, 2018; Accepted: May 27, 2019
Proofs received from author(s): July 16, 2019