THE EFFECTS OF SEISMIC SURVEYS ON MARINE ORGANISMS

Background

Seismic surveys involve projecting a long series of intense sound pulses to collect data about the ocean's bottom layers (Przeslawski et al. 2018). They are used for many purposes, including oil and gas exploration. Seismic surveys of the Outer Continental Shelf off the Mid-and South Atlantic coasts have not been conducted since the 1980s. However, in 2017 the federal Bureau of Ocean Energy Management (BOEM) proposed issuing five permits authorizing the use of seismic surveys within the Mid- and South-Atlantic Planning areas in support of oil- and gas exploratory activities (Figure 1).

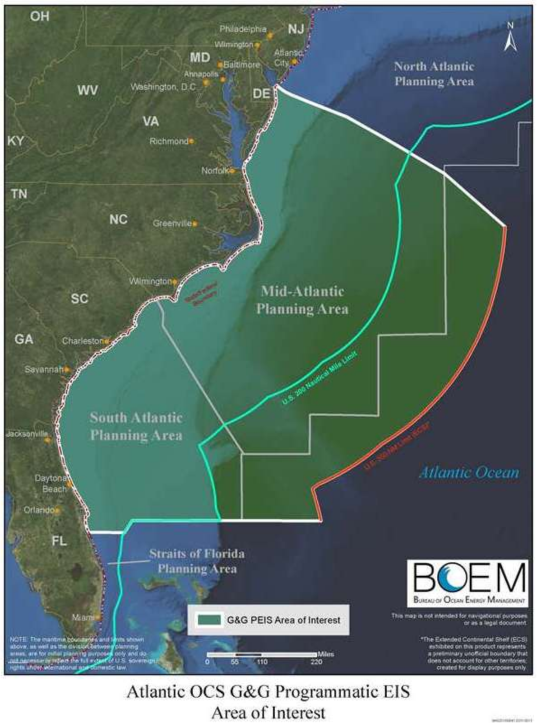


Figure 1. Mid- and South-Atlantic Planning Areas. Source: BOEM.gov

The National Marine and Fisheries Service (NMFS) published a Biological Opinion in 2018 that evaluated the potential impact the proposed seismic surveys might have on endangered species and designated critical habitat (NMFS 2018). They concluded that the surveys would potentially have adverse effects on some species and habitat, while others were unlikely to be negatively affected (Table 1). Species and critical habitat likely to be impacted included several species of whales, including the North Atlantic right whale, and several species of sea turtles, including the Green Sea Turtle and Loggerhead Sea Turtle, all of which are listed as species of concern by the Georgia Department of Natural Resources (DNR SWAP 2015).

Table 1. Endangered species and designated critical habitats evaluated in the biological opinion

Species *likely* to be affected by the Action	**Species *not likely* to be affected by the Action**	**Critical Habitat *not likely* to be affected by the Action**
Blue Whale	Atlantic Sturgeon	Atlantic Sturgeon
Fin Whale	Giant Manta Ray	Loggerhead turtle (NW Atlantic Population)
North Atlantic Right Whale	Hawksbill Sea Turtle	North Atlantic Right Whale
Sei Whale	Oceanic Whitetip Shark	
Sperm Whale		
Green Sea Turtle (North Atlantic Ocean population)		
Kemp's Ridley Sea Turtle		
Leatherback Sea Turtle		
Loggerhead Sea Turtle (NW Atlantic population)		

Adapted from NMFS (2018)

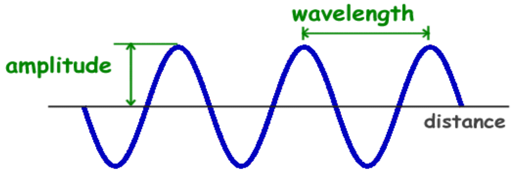
The NMFS Biological Opinion was informed by an extensive scientific literature review included in the 2014 BOEM Programmatic Environmental Impact Statement (PEIS). However, research conducted subsequent to the PEIS provides further information on the possible effects of seismic testing on marine organisms that was not available at the time the Biological Opinion was compiled. The purpose of this report is to review and summarize research conducted during the six years since the publication of the PEIS. It is primarily focused on marine organisms (zooplankton, fishes, sea turtles, and whales) found off the Georgia coast. However, we also included relevant studies of nonindigenous species, as in many cases information on native species was not available.

The report that follows is divided into three sections. Part One is an overview of natural and anthropogenic sounds in the ocean and a description of the seismic surveying process. Part Two summarizes literature on the potential physical, behavioral, and physiological effects seismic surveying may have on zooplankton, fishes, sea turtles, and whales. Part Three provides information on data gaps and further research needs.

Part One - Sounds in the Marine Environment

Because sound does not travel well between water and land, the marine environment may seem relatively quiet to the human ear. However, many marine organisms have adapted to using sound as their principal mode of interacting with their environment, as sound travels farther and faster in water than in air and also moves faster than light through water (Carr 2019). Sound travels in waves, which can be characterized by their frequency, velocity, wavelength, and amplitude. Frequency is the number of pressure waves that pass by a reference point per unit of time and is measured in hertz (Hz), or cycles per second. Lower frequency sounds have longer wavelengths than higher frequency sounds, and typically persist longer and travel farther. Amplitude is the height of the wave, or the "loudness" of a sound, and is usually measured in decibels (dB) (Figure 2). The velocity of a wave is the distance that it travels per unit time.

Figure 2. Relationship between wavelength and amplitude.



Source: https://www.ducksters.com/science/physics/properties_of_waves.php

Natural sources of sound

Sounds in the ocean come from both natural and anthropogenic sources. Natural sounds can be further subdivided as either abiotic or biotic in origin. Abiotic sounds are produced by the physical environment itself and include rain, lightning strikes, wind, breaking surface waves, the movement of ice, water, or sediments, and natural seismic activity such as volcanic eruptions or earthquakes. Biotic sources of sound include signals made by fish, seabirds, marine mammals, invertebrates, or any other organism in the marine environment (Gedamke et al. 2016). These sounds vary in frequency (Table 2) and amplitude. For example, wind, surface waves, and precipitation range in frequency from approximately 0.1 to 50 kHz whereas fish and baleen whale sounds usually range from 0.1 to 1 kHz, but can exceed 2 kHz (Estabrook et al. 2016). Marine organisms use sound for a wide variety of life sustaining activities including feeding, mating, predator avoidance, communication, and navigation.

Table 2. Frequency of typical sources of natural ocean sound

Sound source	Frequency (Hz)
Fish vocalizations	50 - 2000 (most often 100 - 500)
Breaking waves	500 - 50,000
Shrimp snapping	2000 – 5000
Heavy rain	100 - >20,000

Adapted from Hildebrand (2009); Ocean noise variability and noise budgets, URI & Inner Space Center

Anthropogenic sources of sound

Anthropogenic sounds are produced from human activities taking place in the marine environment. These include sounds produced by ships, boats and other transportation vessels, fishing activities, construction and dredging activities, oil and gas drilling, military sonar activities, and underwater explosions (Table 3). Geophysical surveys (including seismic surveys for oil and gas) also fall into this category. These vary in both amplitude and frequency, and overlap with the ranges of natural sources of sound (compare Table 2 with Table 3). Sounds from anthropogenic sources have only been present since the beginning of the Industrial Revolution and are rapidly increasing (Gedamke et al. 2016).

Table 3. Amplitude and frequency of typical sources of anthropogenic ocean sound

Sound source	Source level (dB at 1m)	Frequency (Hz)
Air-gun array	260	5-300
Pile driver hammer	237	100-1000
Cargo vessel	192	40-100
Small boat outboard engine	160	1000-5000

Adapted from Hildebrand (2009)

Sound from seismic surveys

Marine seismic surveys are used to obtain data about the structure, composition, and dynamics of the ocean's bottom layers (Przeslawski et al. 2018). They involve intense pulses of sound that reflect off the seabed and can be used for oil and gas exploration. Seismic surveys can be 2D, 3D, and, most recently, 4D. This discussion is limited to 2D surveys, as that is what is being considered in the BOEM proposal for the Mid- and South-Atlantic Planning Areas (NMFS 2018).

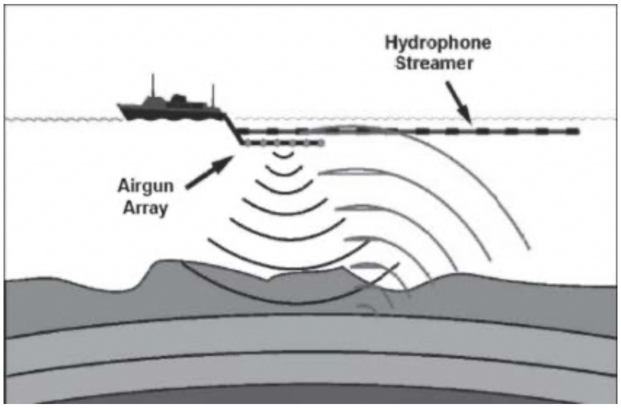


Figure 3: Seismic vessel towing airgun array and hydrophone streamer (NMFS 2018).

2D seismic surveys generally involve a single vessel that tows an array of airguns as well as a hydrophone (Figure 3). The five proposed actions in the BOEM proposal would use 24 to 48 airguns depending on the permittee (NMFS 2018). The airguns are towed at 4–10 m under the water surface (Przeslawski et al. 2018). They generate sound by releasing a bubble of compressed air that rapidly expands and collapses, forming a pulse of sound that penetrates the seafloor. The sound the airguns produce is omnidirectional, with the greatest energy at low frequencies (20–50 Hz) and declining energy above 200 Hz (Hawkins et al. 2015). The hydrophone streamer, which can be 3,000–12,000 m in length, is towed at a depth of 6–8 m behind the vessel and measures the reflected and refracted sound waves. This information is used to produce a 2D image of the substructure of the ocean floor (Elliot et al. 2019).

The airgun array usually generates a seismic pulse every 10 s, which results in a sounding every 25 m when the vessel speed is about 5 knots (2.6 m/s), but this rate may vary (Slabbekoorn et al. 2019). Lower frequencies undergo little damping as they travel through the water and can spread across large distances (Elliot et al. 2019). Although the vessel's movement prevents peak sound levels from occurring at the same spot for long periods, the contribution of airgun noise to the overall ambient sound levels, averaged over time, can be considerable and may result in high cumulative exposures (Slabbekoorn et al. 2019). For example, Estabrook and others (2016) found that seismic airgun noise dominated the ambient sound environment below 500 Hz throughout their study area in the northern Gulf of Mexico. Their results showed that in many instances there was a series of multiple arrivals of the same resounded pulse immediately following the original, thus reducing the time between pulses and inundating the soundscape with near-continuous elevated noise levels. They also found that the seismic airgun sound propagated over several hundred kilometers, thus exposing a large area and a wide range of species and habitats to chronically elevated noise levels. The authors noted that current U.S. regulations do not account for the chronic sound characteristics of reverberated and reflected airgun impulses over many tens of kilometers or more (Estabrook et al. 2016).

Part Two – Effects of Seismic Sound on Organisms

The effects of exposure to sound on marine animals may include physical injury (mortality, tissue trauma), behavioral modifications (altered communications, startle response), and physiological effects (increased stress hormones). Physical injury is most likely to occur in animals that are in close proximity to a sound source, whereas sources that are farther away are more liable to result in behavioral and physiological stress responses (Normandeau 2012). Behavioral effects are particularly difficult to evaluate, since they are highly dependent on context and reactions may not be proportional to the received sound level (Faulkner et al. 2016). The immediate response to seismic sound may be relatively short-term and limited to a small area (e.g., alarm response), resulting in more easily detectable behavioral changes. Increases in background noise lasting for months over large areas may lead to chronic effects (e.g., reduced prey avoidance) that are more difficult to measure (Gedamke et al. 2016). Physiological responses include increases in stress hormone levels and decreased immune responses and are most directly determined by metabolic rate, which can be measured through respiration, oxygen consumption, excretion, or food consumption rates (Cockrem

2014). It is important to remember that any direct effects of seismic sound on individual marine animals, if severe enough (e.g., mortality, feeding interference), can result in indirect negative effects on animal populations (Gedamke et al. 2016), particularly when combined with impacts from other stressors.

The sections below describe the physical, behavioral, and physiological effects of seismic survey sound on zooplankton, fishes, whales, and sea turtles, to the extent that information is available. The discussion of whales is focused on research on baleen whales, which includes right and humpback whales. Note that the North Atlantic right whale is the primary marine mammal in Georgia and is critically endangered.

Physical Effects

Noise from seismic surveys can result in physical injuries to the body. If these are severe enough, they may directly result in death of the organism. Indirect mortality may occur in cases where injuries, although not directly fatal (e.g. organ damage and loss of sensory hair cells), interfere with the animal's ability to feed or escape predators (Popper et al. 2014).

Zooplankton

Very little is known about the physical effects of seismic activity on zooplankton despite their importance in marine food webs. The juvenile stages of many recreationally and commercially important fish species rely on zooplankton as a food source, as does the North Atlantic right whale. Reductions in the abundance of zooplankton across large areas could disrupt the oceanic food web and result in decreased numbers of fishes and whales (Fields et al. 2019).

Changes in Abundance and Mortality

Although very few studies have been conducted on seismic noise and zooplankton, two recent reports show that airgun sounds can have negative effects on these organisms. McCauley and others (2017) found significant reductions in zooplankton populations off the southeastern coast of Tasmania after experimental airgun blasts. The exposed populations had a median decrease of 64% in abundance compared to controls (pre-blast), with 58% of the 34 individual taxa identified showing at least a 50% decrease in abundance. There was also a 2- to 3-fold increase in the percentage of dead organisms (measured by vital stains), and evidence for a sonar "hole" in the range of plankton backscatter. The authors speculated that the sound from the airgun blast most likely damaged the sensitive hair-like receptors that zooplankton use to navigate possibly resulting in lower abundances and eventual mortality. Calculated impact ranges for mortality were more than two orders of magnitude greater within 1.2 km of the blast than previous research suggested. Subsequent modeling based on McCauley's findings suggest that at a distance of 15 km from an airgun blast, zooplankton may experience a 14% decrease in abundance (Richardson et al. 2017).

In a later study by Fields and others (2019) copepods were collected and transferred to experimental bags that were positioned at different depths and distances from seismic airguns. Immediate mortality was measured by counting the number of dead individuals 1 hour after exposure. Dead individuals were counted and removed every day for 7 days to measure cumulative mortality. Results indicated that immediate mortality was significantly different from controls at distances of 5 m or less from the airguns. One week after the airgun blast, mortality of zooplankton placed 10 m from the airgun blast was 9% higher than that of controls, but was not significantly different for samples located 20 m from the blast. The increase in mortality, relative to controls, did not exceed 30% at any distance from the airgun blast. In contrast to McCauley et al. (2017), the authors suggest that seismic blasts have limited effects on the mortality of copepods within 10 m of the blast and no measurable impact at greater distances (Fields et al. 2019).

Fishes

Fishes detect particle motion by three pairs of otolith organs, which consist of the otolith itself and the sensory hair cells. The hair cells act as transducers, converting the mechanical stimulus of the particle motion into an electrical signal that can be processed by the central nervous system. Fishes are approximately the same density as water, whereas the boney otolith is about 3–4 times denser than the fish’s body and responds to sound with a differential amplitude and phase. As a consequence, the hair cells that are in contact with the otolith undergo a shearing displacement, which they convert into the neurological responses that are perceived as sound (Slabbekoorn et al. 2019).

Temporary Threshold Shift

Hearing threshold shifts (hearing loss) can be caused by exposure to intense sound. Threshold shifts can be temporary (TTS) or permanent (PTS) and result from physical damage to the sensory hair cells within the auditory system. TTS itself is not considered to be an injury in fishes as sensory hair cells are constantly added and also replaced when damaged. The period of time required for hearing to return to normal after termination of a sound that causes TTS is variable and depends on many factors, including the intensity and duration of sound exposure. While experiencing TTS, individual fish may be of increased risk of mortality due to interference with the ability to communicate, avoid predators, or find prey (Popper et al. 2014). However, the effects and significance of various levels of TTS on free-living fishes have not been examined (Carroll et al. 2017).

Barotrauma

Injuries caused by very high sound level exposure and increased air or water pressure are collectively referred to as barotrauma. Fishes with swim bladders are more likely susceptible to physical injury from underwater sound exposure than those that lack swim bladders because sound waves cause the swim bladder to expand and contract with the fluctuating pressures, which can result in trauma when the swim bladder hits against internal organs (Gedamke et al. 2016).

Much of the research on fish barotrauma due to low-frequency sound has focused on pile driving, which, on the lower end of its range, generates similar acute, high-intensity, low-frequency sound as airguns in seismic surveys. A 2017 literature review by Carroll and others (2017) found that exposure of freshwater fishes to pile driving resulted in substantial damage to internal organs including the swim bladder, liver, kidney, and gonads of fishes. Fish species with enclosed swim bladders appeared to be more susceptible to barotrauma from pile driving than fishes with swim bladders connected to the gut. Larger fish were more likely to be injured than smaller fish, perhaps due to the difference in swim bladder resonance, although smaller fish showed delayed onset of injuries and experienced longer recovery times (Carroll et al. 2017).

Whales

Estimates of audible frequency ranges for baleen whales, including the North Atlantic right whale, are derived from vocalization frequencies, anatomical modeling, and limited anecdotal observations of spontaneous responses to tonal signals in free-ranging animals. They indicate that baleen whales belong to a discrete, low frequency-oriented hearing group (Southhall et al. 2019) with a generalized hearing range of 7 Hz to 35 kHz (Gedamke et al. 2016).

Temporary Threshold Shift

Currently, TTS data only exist for four species of cetaceans (bottlenose dolphins, belugas, harbor porpoises, and Yangtze finless porpoises) and three species of pinnipeds (Northern elephant seal, harbor seal, and California sea lion) exposed to a limited number of sound sources (i.e., mostly tones and octave-band noise) in laboratory settings (Finneran 2015). There are no data available on sound-induced hearing loss for baleen whales as there are as yet no direct measurements of hearing for any of these species (Southhall et al. 2019).

Sea turtles

Few studies have examined the physical effects of seismic airgun activity on sea turtles. It is possible that seismic airgun exposure would mortally injure sea turtles that are in very close proximity to the sound source (e.g., underwater explosions) (Popper et al. 2014). Another potential physical impact on sea turtles from seismic surveys is entanglement in equipment, either towed by a vessel or deployed on the seabed. While no peer-reviewed literature documenting such incidences was found in a review by Nelms and others (2015), the authors received unpublished anecdotal reports of turtle entrapments in tail buoys and airgun strings during several offshore seismic surveys off the west coast of Africa. There was also an incident where eight olive Kemp ridely turtles became entangled in ocean bottom cable gear off Gabon (Nelms et al. 2015).

Mortality

A literature review by Nelms and others (2015) found only one study that looked specifically for evidence of sea turtle mortality due to seismic surveys. A marine and terrestrial monitoring program that was part of a seismic survey operation recorded observations of 16 turtles over an 11-day period. Eight live turtles were sighted at sea, and eight dead turtles were found, four of which were in the ocean and four of which were stranded on land. Of the dead turtles, five showed signs of interactions with fishing activities/human consumption of turtle meat. The authors do not suggest what may have caused the deaths of the remaining three nor do they specify whether further investigation into the cause of death occurred. No link with the seismic survey was confirmed (Nelms et al. 2015).

Temporary Threshold Shift

Studies measuring hearing sensitivity in sea turtles have found that all species investigated (loggerhead, green, leatherback and Kemp's ridley) are capable of detecting low frequency sounds, indicating that their hearing ranges overlap with the type of low frequency sound emitted by seismic airguns. However, due to a lack of research, it is not known what frequencies of sound exposure would cause permanent or temporary hearing loss or what effect this might have on sea turtle fitness or survival. TTS could potentially lead to habitat exclusion and disruption of behaviors necessary for life functions (e.g., breeding, foraging, basking), and physiological stress responses, which may result in changes to swim speed, dive depth and duration, and restricted access to surface breathing. Such negative changes in individual fitness could have possible detrimental effects on an entire population (Nelms et al. 2015).

Behavioral Effects

Elevated sound levels can elicit various types of behavioral responses in marine organisms, from short-term (e.g. brief startle response) to longer-term responses with potentially severe implications (e.g. reduced rate of foraging or predator avoidance) (Carroll et al. 2017). One effect of elevated sound levels, whether from natural or anthropogenic sources, is the reduction in area over which animals are able to acoustically communicate. This is called masking and may result in interference with intraspecific communication and social interactions, prey detection, predator avoidance, and navigation (Gedamke et al. 2016).

Behavioral effects are more likely to occur at lower frequencies than physical and physiological effects. However, behavioral effects are more difficult to monitor in the field and many studies on the effects of airguns on behavior are therefore conducted in labs or using caged individuals (Carroll et al. 2017). It is important to keep in mind that the results obtained from such research may not be indicative of the behavior of wild subjects.

Zooplankton

Predator avoidance

Field and others (2019) examined the behavior of copepods for the presence of sublethal effects, specifically changes in predator avoidance, following exposure to seismic airgun blasts. The zooplankton were removed from experimental bags following exposure to the airgun blasts at distances of 0, 0.7, 1.5, 3.0, 5.0, 20, and 25 m and transferred to a transparent tank for observations of escape reactions. The exposed copepods showed no significant change in the threshold stimulus needed to initiate an escape reaction or in the distance or speed of the escape response compared to the control group. These results suggest that airgun blasts have no effects on the predator avoidance response of copepods (Field et al. 2019).

Fishes

Alarm response/avoidance

There is evidence that some fish species may avoid reef sites and aggregate in lower densities following exposure to sound from seismic surveys. A study on the inner continental shelf of North Carolina by Paxton and others (2017) found a 78% decline in snapper grouper complex species abundance at a reef habitat site after seismic testing. Based on observations conducted by video cameras, fish occupation during the three days before the seismic survey exhibited a daily pattern of increased abundance during the evening, as opposed to morning and afternoon. This use pattern did not occur on the day following the airgun blasts, even though the research site was located about 8 km from the seismic survey track. The authors concluded that fishes detect and respond to seismic noise, reducing aggregation at reef habitats and potentially disrupting important life functions including foraging and mating.

An extensive literature review by Carroll et al (2017) found that investigations of the possible effects of seismic surveys on the distribution and abundance of numerous fish species have yielded various responses. One study of pelagic fish (blue whiting and mesopelagic species) showed that, although there were insignificant short-term horizontal distribution effects from airgun sound, the observed populations occurred in deeper waters during seismic exposure compared to their pre-exposure distribution. Free-ranging marine fish (juvenile saithe and cod, and adult pollock and mackerel) inhabiting a small inshore reef system off the coast of Scotland exposed to sound from three airguns exhibited startle responses to all received sound levels, but no avoidance behaviors were observed. (Carroll et al. 2017). In a study in Bass Strait, Australia, Przeslawski and others (2018) observed minor effects in acoustically tagged tiger flathead, which increased their swimming speed during a 2D seismic survey and changed their daily movement patterns after completion of the survey. However, the fishes showed no significant displacement.

Potential habituation to repeated airgun exposure has been demonstrated for some fishes. Behavioral observations of three coral reef fish species in field enclosures before, during and after exposure to airguns showed that repeated exposure resulted in increasingly less obvious startle responses (Carroll et al. 2017). Similarly, temporary habituation to airgun blasts was observed in whiting schools when they returned to pre-exposure depth following one hour of continual exposure to airgun sound, however, they descended to greater depths upon resumption of airgun discharges (Carroll et al. 2017).

Whales

Whales produce complex and variable sounds which are associated with many behavioral responses including communication, navigation, prey detection, and others. Sound from seismic surveys may adversely impact these behaviors, with the extent of impact depending on factors such as proximity to the sound source and the life stage of the individual animal (i.e., older whales are less sensitive to higher frequencies) (Elliot et al. 2019).

Sound avoidance

The effect of sound sources on the behavior of whales can often be characterized as a dose–response relationship, where the probability of an animal responding to the sound by avoidance increases with the 'dose' or received level of sound. Quantifying this response is difficult as there is the potential that the animal is avoiding not only the sound source but also the vessel operating the source (Dunlop et al. 2017). The behavioral responses of migrating humpback whales (baleen whales) to a single airgun, a small clustered seismic array, and a commercial array were used by Dunlop and others (2018) to develop a dose-response model that would allow avoidance responses to be measured in terms of received sound level and source proximity (Table 4).

Table 4. Details of seismic treatments including the average and range of the received sound exposure levels and the source vessel proximities to the subject whales.

Treatment	**Received SEL (dB)**	**Proximity (km)**
20 in^3 single airgun	130 (104-156)	5.4 (0.5–12.9)
Control for 20 in^3 airgun	N/A	3.9 (0.3–12.5)
Small cluster array (140 in^3)	135 (108-166)	6.3 (0.6–13.1)
Control for small array	N/A	6.8 (0.9–12.6)
Full commercial array (3130 in^3)	135 (101-166)	6.8 (0.6–14.7)
Control for full array	N/A	6.6 (0.9–16.0)

Adapted from Dunlop et al. 2018

The results indicated that whale groups were more likely to increase their distance from the source when they were within 4 km and the received sound level was over 130 dB. The 50% probability of response occurred when the whales were within 2.5 km of the source and the received levels were 150–155 dB. Interestingly, a small number of whales swimming close to the source vessel did not exhibit an avoidance response at the highest received levels (160–170 dB). The study found no correlation between whale response and the size of the sound source (full commercial array vs. smaller array vs. single air gun). Rather, the response was a function of the combination of received sound level and proximity to the air gun source (Dunlop et al. 2018).

Avoidance behavior may be more complex than simply moving directly away from a source. An individual animal may modify its responses based on the characteristics of its immediate environment, the circumstances of the interaction, and its behavioral state (Dunlop et al. 2017). For example, Gomez and others (2016) analyzed the results of 41 papers that examined the behavioral responses of baleen whales to airgun sound and found that responses were observed starting at approximately 110 dB. However, high-severity behavioral responses were equally likely as low- and moderate-level behavioral reactions at these received sound levels. The authors concluded that even when comparing one cetacean functional hearing group (low frequency baleen whales) with one type of sound (seismic airguns), the severity of behavioral response still did not vary in relation with sound level (Gomez et al. 2016).

Masking

Whales are heavily dependent on sound as their primary sensory system. For example, the North Atlantic right whale's 'up-call' signal functions as a contact call between individuals, whereas their 'gunshot' sounds may act in part as a male display behavior (Cholewiak et al. 2018). The calls of right whales and other baleen whale signals are low broadband signals with frequencies ranging from 10 Hz to over 200 kHz, making these species more likely to be subjected to higher levels of communication masking from vessel sounds, which are mostly below 200 kHz (Hatch et al. 2012).

Two studies of right whales in the Stellwagen Bank National Marine Sanctuary show that whales in this area have experienced communication disruptions due to acoustic masking by shipping vessels. Hatch and others (2012) compared ambient sound conditions measured in 2012 to a reference sound level that was 10 dB lower, which they used as a proxy for ocean sound levels in the mid 20th century, a period within the lifetimes of many existing North Atlantic right whales. They calculated that contact-calling right whales lost an average of 63% of the communication opportunities estimated to have been available to them in the mid 20th century. During the passage of commercial vessels, the lost communication space (i.e., area available to whales to exchange information or hear important environmental cues) increased to 67% (Hatch et al. 2012). Similarly, Cholewiak and others (2018) evaluated relative levels of masking for four baleen whale species, including right whales, from the combination of current ambient noise conditions and noise from commercial ships, local fishing vessels, and local whale-watching vessels. They found that the combination of current ambient sound conditions with the addition of vessel sounds led to a reduction in communication range of 16 km^2 and a median communication masking index of 5% for right whale gunshot sounds.

Whales can also react to increased noise by amplifying their calls. An analysis of whale upcalls (n=120) recorded from 12 acoustically tagged North Atlantic right whales in the Bay of Fundy, Canada, found that the amplitude of whale calls linearly increased in response to the presence of increased ambient ocean sound (Parks et al. 2011). Another study, also in the Bay of Fundy, investigated the potential effects of point-source noise from a passing container ship on right whale upcalls. Tennessen (2016) found that increases in the whales' upcall amplitude and frequency increased detection range and reduced transmission loss in the presence of the point-source noise. Although these findings demonstrated that amplitude compensation is an effective way to improve the detection range of upcalls, the authors concluded that this response may not be a sustainable solution if ocean noise levels continue to rise.

Sea turtles

Very little recent data exist on the behavioral responses of sea turtles to seismic sound, and the results from older studies conducted on loggerhead or green sea turtles were inconclusive (Gedamke et al. 2016). Difficulties in studying sea turtles in the wild include problems with identifying individuals in sea conditions and the relatively short period of time they spend on the surface breathing. Another challenge with interpreting avoidance behaviors is the difficulty of determining whether the diving response is caused by sound from an airgun or the presence of a vessel (Nelms et al. 2015).

Alarm response/sound avoidance

As with whales, Nelms and others (2015) conducted a literature review of studies that evaluated the relationship of seismic surveys and behavioral responses in sea turtles. They found eight publications that included captive and wild turtles. These studies are of limited value however, due to a variety of problems including small sample size, lack of controls, and confined settings (laboratory). One study found that loggerhead turtles exposed to low frequency sound in a tank responded by swimming to the surface and remaining there or staying slightly submerged, possibly because received sound levels were lower at the surface. Other investigators observed that caged green and loggerhead turtles exposed to increasing levels of airgun sound swam noticeably faster when airgun levels exceeded 166 dB. At sound levels above 175 dB, their behavior became more inconsistent, a possible indication of discomfort or confusion. However, these results may not be representative of real, open-water situations where the propagation of sound differs and the turtle is able to move away (Nelms et al. 2015).

Physiological Effects

The physiological effects of chronic stress can be evidenced by neuroendocrine response, alteration of metabolic pathways, and changes in an individual’s activity and performance. One individual’s physiological response patterns may vary considerably from those of others within the same population (Slabbekoorn et al. 2019). Studies on the impacts of chronic stress effects such as immune suppression, inhibition of other hormonal systems, and the disruption of reproductive function within marine systems remain rare. There has been very little study of the physiological effects of seismic surveys on fishes and marine mammals and no such research on sea turtles.

Fishes

Endocrinological stress

For fishes, there is some evidence to suggest that seismic sounds may elicit endocrinological stress. In a literature review, Carroll and others (2017) found one study showing that experimental seismic noise (underwater explosions in laboratory conditions) affected primary stress hormones (adrenaline and cortisol) in Atlantic salmon. In another study, European seabass had elevated ventilation rates in response to recordings of pile-driving and seismic surveys in a lab setting. These fishes did not exhibit such stress when recordings of passing ships were played. This study also found that fishes exposed to recordings of pile-driving or seismic noise for 12 weeks no longer responded with an elevated ventilation rate to the same sound type, and showed no differences in stress, growth or mortality compared to fishes reared with exposure to recordings of ambient noise. However, there are several limitations to tank-based playback experiments, and therefore the relevance of these findings to actual airgun exposure in open-water conditions is uncertain (Carroll et al. 2017).

Whales

Endocrinological stress

A study of North Atlantic right whales in Canada found a correlation between reduced ship traffic and decreased baseline levels of stress-related glucocorticoids. Rolland and others (2012) found that reduced ship traffic in the Bay of Fundy, following the events of September 11, 2001, resulted in a 6 dB decrease in underwater noise, with a significant reduction in sounds below 150 Hz. This sound reduction was associated with decreased baseline levels of stress-related fecal hormone metabolites (i.e., glucocorticoids) in North Atlantic right whales. This finding provides preliminary evidence that exposure to low-frequency noise may be associated with chronic stress in right whales.

Part Three – Knowledge Gaps and Research Needs

Seismic surveying is known to have many types of effects on marine organisms. These can range in severity from short-term physical startle reactions to long-term behavioral changes such as abandonment of feeding habitat to mortality. Physiological stress responses to seismic sound on individuals can indirectly impact entire populations and exert cumulative pressures on already stressed species. However, there is much that is unknown. Below we compile information on knowledge gaps and research needs that were identified in the literature.

Recent reports and workshops that have focused on the effects of anthropogenic noise on marine organisms and associated data gaps include the 2012 BOEM Environmental Studies Program Effects of Noise on Fish, Fisheries, and Invertebrates in the U.S. Atlantic and Arctic from Energy Industry Sound-Generating Activities Workshop (Normandeau 2012) and the 2016 NOAA Ocean Noise Strategy Roadmap (Gedamke et al. 2016).

The proceedings of both workshops (Gedamke et al. 2016, Normandeau (2012) provided general lists of priority information needs for noise assessments to measure and minimize anthropomorphic sound impacts. These included:

1. Determination of the abundance, density, and distribution mapping of protected species.
2. Increased understanding of species' use of sound, auditory thresholds and hearing mechanisms.
3. Increased understanding of sound levels that cause hearing loss and other physical injuries.
4. Increased understanding of behavioral sensitivity and responses to sound, including masking.
5. Identification of times, areas or species of particular concern for risk assessment, e.g.: species particularly susceptible to anthropogenic noise.
6. Collection of baseline stress-marker datasets for comparison to field measurements.
7. Increased understanding of the effects of masking on all taxa and the consequences of reduced communication space.
8. Soundscape characterization including long-term background noise in frequencies relative to marine species hearing range.
9. Understanding the effects of aggregate noise sources and cumulative effects of noise on individual animals and species populations.

The BOEM Workshop also identified the need for development of a common terminology for sound measurement and exposure among researchers, acousticians, and regulators, as well as standardization of data collection methods and outputs from different sound sources. Additionally, the Workshop recommended that existing published standards concerning the measurement of ambient sound must be updated using currently available data and that differences in standards between the two main standard organizations (American National Standards Institute, International Organization for Standardization) should be resolved (Normandeau 2012).

Many of the studies we evaluated also identified data gaps specific to zooplankton, fish, whales, and sea turtles. Many of these are quite broad and basic. For example, despite the importance of zooplankton as a food source for numerous species of marine fishes and mammals there are very few published studies of how they might be affected by seismic sound. Likewise, the potential effects of seismic sound on sea turtles remain largely unstudied despite the endangered status of most species of this group. There are also no direct measurements of underwater hearing available for any baleen whales, including the North Atlantic right whale.

As we synthesized information for this report we found a limited number of papers specifically focused on seismic survey effects on marine organisms in the Southeast, forcing us to rely on research from Australia, Canada, Maine, Massachusetts, and elsewhere. This is most likely due to the historical lack of interest in conducting offshore oil and gas activities within this area. Moreover, the research we identified was highly focused on airgun sound effects on fish and whales as opposed to zooplankton and sea turtles. Within these studies, physical and behavioral effects were more heavily examined. While the majority of projects included in the report were field studies, laboratory experiments were also included, particularly for sea turtles. Although in some cases results from such research may be extrapolated to wild populations, it is important to keep in mind the limitations of these studies. For example, experiments on captive fish, whether in laboratory tanks or sea cages, are unlikely to yield valid results because fish behavior changes and their behavioral range constricts in captivity (Normandeau 2012).

Below is a list of additional knowledge gaps identified in the literature that are specific to the organisms included in this report:

Zooplankton

- ⇒ Determine which zooplankton groups are most at risk from exposure to seismic sound, what the potential impacts of such exposure may be, and possible mitigation methods (Normandeau 2012).

Fish

- ⇒ Determine the potential displacement of marine fishes in the water column due to seismic sounds, the extent and duration of any shift, and the sound level necessary to cause this movement (e.g. duration, geographic distance) (Paxton et al. 2017).
- ⇒ Identify potential short- and long-term physiological impacts resulting from seismic sound exposure (Castellote et al. 2012).
- ⇒ Quantify the potential impacts of acoustic masking, including the sound levels at which different fish species exhibit masking and its biological consequences (Elliot et al. 2019).
- ⇒ Examine the effects of seismic sound on particle motion, which many species of fish use to interpret sound in the marine environment, in sound impact studies (Elliot et al. 2019).

Whales

- ⇒ Identify how whales use sound to carry out their life functions and respond to communication masking (Cholewiak et al. 2018).
- ⇒ Quantify long-term responses to masking over large areas of whale habitat (Hatch et al. 2012).
- ⇒ Determine the sound levels, duration, and biological conditions that lead to avoidance behavior in whales and their potential exclusion from important habitats. Examine how these variables change with an individual whale's development stage (i.e., age) and subsequent fitness (Dunlop et al. 2017).
- ⇒ Quantify long- and short-term negative physiological impacts and stress responses from prolonged exposure to seismic sound (Castellote et al. 2012).

Sea Turtles

- ⇒ Identify the effects of exposure to seismic sounds on hearing loss in sea turtles.
- ⇒ Determine whether such exposure causes sea turtles to lose the hair cells in the basilar papilla or if these cells can be recovered (Popper et al. 2014).
- ⇒ Characterize short- and long-term behavioral responses, such as changes to diving, foraging, migration patterns, distribution and abundance, and nesting behavior of sea turtles (Elliot et al. 2019).
- ⇒ Measure the physiological responses of wild sea turtles, including stress hormone levels, in response to seismic surveying (Elliot et al. 2019).

The effects of anthropogenic noise on marine organisms has attracted a great deal of attention in recent years and this is likely to increase given the current level of interest in expanding offshore oil and gas drilling. Identifying and exploiting oil and gas reserves involves increasing vessel traffic and seismic surveying, which add more sound to an already noisy marine acoustic environment. The marine organisms on which a healthy ocean habitat depends are being impacted by these sounds in ways we are only beginning to appreciate, and there are multiple data gaps on this topic.

Literature Cited

Carr, Sarah (2019). It's Not Just About Marine Mammals Anymore: How Ocean Noise Can Harm Marine Ecosystems. *The Skimmer on Marine Ecosystems and Management* (September 24, 2019).

Carroll, A.G., R. Przewlawski, A. Duncan, M. Gunning, and B. Bruce (2017). A critical review of the potential impacts of marine seismic surveys on fish & invertebrates. *Marine Pollution Bulletin,* 114: 9-24.

Castellote, M., C.W. Clark, M.O. Lammers (2012). Acoustic and behavioural changes by fin whales (*Balaenoptera physalus*) in response to shipping and airgun noise. *Biol. Conserv*., 147: 115–122.

Cholewiak, D., C.W. Clark, D. Ponitakis, A. Frankel, 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.

Cockrem, J. (2014) Review of stress and the measurement of stress in marine mammals.

Dunlop, R.A., M.J. Noad, R.D. McCauley, E. Kniest, R. Slade, D. Paton, and O.H. Cato (2018). A behavioural dose-response model for migrating humpback whales and seismic air gun noise. *Marine Pollution Bulletin,* 133: 506-516.

Dunlop, R.A., M.J. Noad, R.D. McCauley, L. Scott-Hayward, 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.

Elliott, B.W., A.J. Read, B.J. Godley, S.E. Nelms, D.P. Nowacek (2019). Critical information gaps remain in understanding impacts of industrial seismic surveys on marine vertebrates. *Endangered Species Research,* 39: 247-254.

Estabrook, B.J., D.W. Ponirakis, C.W. Clark, and A.N. Rice (2016). Widespread spatial and temporal extent of anthropogenic noise across the northeastern Gulf of Mexico shelf ecosystem. *Endang Species Res,* 30: 267-282.

Faulkner, Rebecca C., Adrian Farcas, and Nathan D. Merchant (2018). Guiding principles for assessing the impact of underwater noise. *Journal of Applied Ecology,* 55: 2531-2536.

Fields, D.M., N.O. Handegard, J. Dalen, C. Eichner, K. Malde, O. Karlsen, A.B. Skiftesvik, C.M.F. Durif, and H.I. Browman (2019). Airgun blasts used in marine seismic surveys have limited effects on mortality and no sublethal effects on behavior or gene expression, in the copepod *Calanus finmarhicus*. ICES *Journal of Marine Science,* 76(7): 2033-2044.

Finneran, J. J. (2015). Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015. *The Journal of the Acoustical Society of America*, *138*(3): 1702-1726.

Gedamke, J., J. Harrison, L. Hatch, R. Angliss, and others (2016). *Ocean noise strategy roadmap*. NOAA, https://cetsound.noaa.gov/Assets/cetsound/documents/Roadmap/ONS_Roadmap_Final_Complete.pdf

Georgia Department of Natural Resources (2015). *Georgia State Wildlife Action Plan*. Social Circle, GA: Georgia Department of Natural Resources.

Gomez, C., L.W. Lawson, A.J. Wright, A.D. Buren, D. Tollit, and V. Lesage (2016). A systematic review on the behavioural responses of wild marine mammals to noise. The disparity between science and policy. *Canadian Journal of Zoology,* 94(12): 801-819.

Hatch, L.T., C.W. Clark, S.M. Van Parijs, A.S. Frankel, D.W. Ponirakis (2012). Quantifying loss of acoustic communication space for right whales in and around a U.S. National Marine Sanctuary. *Conserv Biol*, 26: 983-984.

Hawkins, A.D., Craig Johnson, and Arthur N. Popper (2020). How to set sound exposure criteria for fishes. *Journal of the Acoustical Society of America,* 147(3): 1762-1777.

Hildebrand, John A. (2009). Anthropogenic and natural sources of ambient noise in the ocean. *Marine Ecology Progress Series*, 395: 5-20.

McCauley, R.D., R.D. Day, K.M. Swadling, Q.P. Fitzgibbon, R.A. Watson, and J.M. Semmens (2017). Widely used marine seismic survey air gun operations negatively impact zooplankton. *Nature ecology and evolution*, 1(7): 0195.

National Marine Fisheries Service, NOAA (2018). Biological Opinion on the Bureau of Ocean Energy Management's Issuance of Five Oil and Gas Permits for Geological and Geophysical Seismic Surveys off the Atlantic Coast of the United States, and the National Marine Fisheries Services' Issuance of Associated Incidental Harassment Authorizations. ESA Section 7 Consultation.

Nelms, S.E., W.E. Piniak, C.R. Weir, and B.J. Godley (2016). Seismic surveys and marine turtles: An underestimated global threat? *Biological conservation*, 193: 49-65.

Normandeau Associates, Inc. (2012). Effects of noise on fish, fisheries, and invertebrates in the US Atlantic and Arctic from energy industry sound-generating activities. A Workshop Report for the U.S. Dept. of the Interior, Bureau of Ocean Energy Management. Contract # M11PC00031. 72 pp. plus Appendices.

Paxton, A.B., J.C. Taylor, D.P. Nowacek, J. Dale, E. Cole, C.M. Voss, and C.H. Peterson (2017). Seismic survey noise disrupted fish use of a temperate reef. *Mar Policy,* 78: 68-73.

Parks, S., E. Johnson, D. Nowacek, and P. Tyack (2011). Individual right whales call louder in increased environmental noise. *Biol. Lett*., 7(1): 33–35.

Popper, A., A.D. Hawkins, R.R. Fay, and others (2014). *Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report* Prepared by ANSI-Accredited Standards Committee S3/SC1 and Registered with ANSL 978-3-319-06658-5, Springer International Publishing.

Przeslawski, Rachel, Brendan Brooke, Andrew G. Carroll, and Melissa Fellows (2018). An integrated approach to assessing marine seismic impacts: Lessons learnt from the Gippsland Marine Environmental Monitoring project. *Ocean and Coastal Management,* 160: 117-123.

Richardson, A.J., R.J. Matear, A. Lenton (2017). Potential impacts on zooplankton of seismic surveys. CSIRO, Australia. 34 pp.

Rolland R.M., S.E. Parks, K.E. Hunt, M. Castellote, and others (2012). Evidence that ship noise increases stress in right whales. *Proc Biol Sci,* 279: 2363-2368.

Slabbekoorn, H., J. Dalen, D. de Haan, H.V. Winter, C. Radford, and others (2019). Population-level consequences of seismic surveys on fishes: An interdisciplinary challenge. *Fish and Fisheries*, 20(4): 653-685.

Southall, B.L., J.J. Finneran, C. Reichmuth, P.E. Nachtigall, D.R. Ketten, A.E. Bowles, W.T. Ellison, D.P. Nowacek, and P.L. Tyack (2019). Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. *Aquatic Mammals*, 45(2): 125-232.

Tennessen, J.B. and S.E. Parks (2016). Acoustic propagation modeling indicates vocal compensation in noise improves communication range for North Atlantic right whales. *Endangered Species Research*, 30: 225-237.