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Literature Synthesis on the Effects of Oil- and Gas-related Noise on Marine Life

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List of Abbreviations and Acronyms

AINJ	auditory injury
AUV	autonomous underwater vehicle
BOEM	Bureau of Ocean Energy Management
CPT	Cone Penetrometer Test
dB	decibel(s)
dB re	decibels relative to
DP	dynamic positioning
DTH	down-the-hole
ESA	Endangered Species Act
ft	foot (feet)
GOA	Gulf of America
HiPAP	High Precision Acoustic Positioning
hr	hour(s)
HRG	high-resolution geophysical
Hz	Hertz
in	inch(es)
IPN	Integrated Projector Node
J	joules
L_{pk}	peak sound level
L_{pk-pk}	peak-to-peak sound level
µPa	micropascal(s) (equal to 10^{-6} pascals or 10^{-11} bar)
m	meter(s)
MBES	multibeam echosounder
MMPA	Marine Mammal Protection Act
MODU	mobile offshore drilling unit
MV	marine vibroseis
NMFS	National Marine Fisheries Service
OCS	Outer Continental Shelf
Pa	pascal(s)
PTS	permanent threshold shift
RMS	root mean square
s	second(s)
SBP	sub-bottom profiler
SEL	sound exposure level
SPL	sound pressure level
SVL	particle velocity level
TTS	temporary threshold shift
USGS	U.S. Geological Survey

1 Introduction

Many activities related to oil and gas development on the Outer Continental Shelf (OCS) add noise to the marine environment but the extent to which these additional noises affect marine life is driven by a complex interaction of physical and biological factors. The Bureau of Ocean Energy Management (BOEM) is the primary regulator of oil and gas development in U.S. OCS waters. BOEM's Center for Marine Acoustics has compiled the relevant literature on this evolving and nuanced topic for use in environmental reviews (e.g., National Environmental Policy Act analyses, Endangered Species Act [ESA] and Marine Mammal Protection Act [MMPA] consultations, and related studies). This document summarizes the state of knowledge as of summer 2026 and is expected to be updated approximately yearly.

2 Sources of Underwater Sound

Ocean sounds originate from a variety of sources. Some come from non-biological sources, such as wind and waves, while others come from the movements or vocalizations of marine life (Hildebrand 2009). In addition, humans introduce sound into the marine environment through activities like oil and gas exploration, construction, military sonars, and vessel traffic (Hildebrand 2009). The acoustic environment or “soundscape” of a given ecosystem comprises all such sounds—biological, geophysical, and anthropogenic (Pijanowski et al. 2011). Soundscapes are highly variable across space, time, and water depth, among other factors, and dependent on the properties of sound transmission and the types of sound sources present in each area. A soundscape is sometimes called the “acoustic habitat,” as it can be a vital attribute of a given area where an animal may live (i.e., habitat) (Hatch et al. 2016).

2.1 Physics of Underwater Sound

Sounds are created by the vibration of an object within its medium (**Figure 1**). When an object’s vibration is coupled to the medium (e.g., water, in the case of underwater sound), that vibration travels as a propagating wave away from the sound source (**Figure 1**). As this wave moves through the water, the water particles undergo tiny back-and-forth movements (i.e., particle motion), essentially oscillating in roughly the same location. When the particle motion results in more particles in one location (depicted as the area of compression in **Figure 1**), that location has relatively higher pressure. Particles are then accelerated away from the higher-pressure region, causing the particles to transfer their energy to surrounding particles and propagate the wave. Acoustic pressure is a non-directional (scalar) quantity, whereas particle motion is an inherently directional quantity (a vector). The total energy of the sound wave includes the potential energy associated with the sound pressure and the kinetic energy from particle motion.

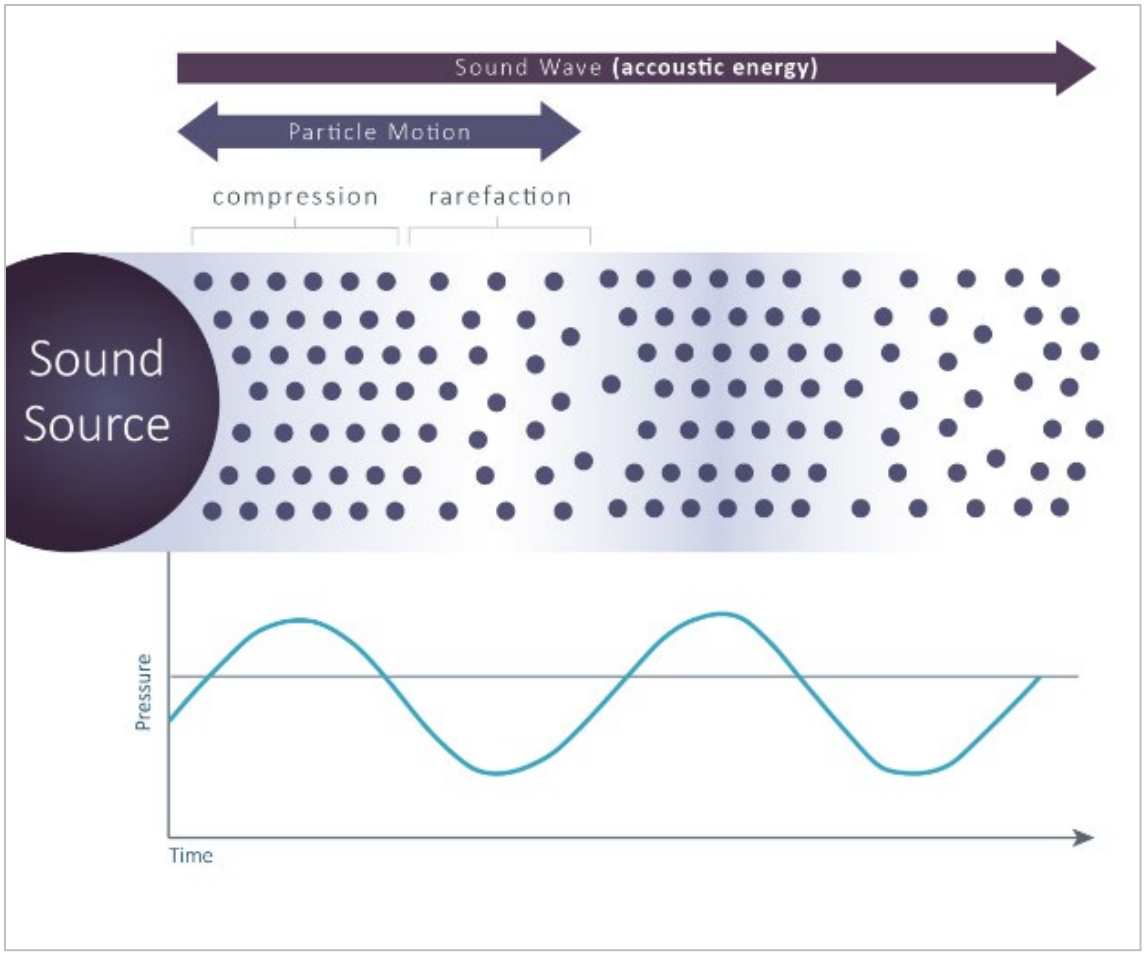

Figure 1. Basic mechanics of a sound wave
Credit: BOEM

2.2 Units of Measurement

Sound can be quantified and characterized based on several physical parameters. A complete description of the units can be found in ISO 18405:2017 (International Organization for Standardization 2017). Some of the major parameters and their SI units (in parentheses) are described below.

Acoustic pressure (pascal, Pa): The values used to describe the acoustic (or sound) pressure are peak pressure, peak-to-peak pressure, and root mean square (RMS) pressure deviation. The peak sound pressure is defined as the maximum absolute sound pressure deviation within a defined period and is considered an instantaneous value (**Figure 2**). The peak-to-peak pressure is the range of pressure changes from the most negative to the most positive-pressure amplitude of a signal (**Figure 2**). RMS sound pressure represents a time-averaged pressure and is calculated as the square root of the mean (average) of the time-varying sound pressure squared over a given period (**Figure 2**). The peak level (L_{pk}), peak-to-peak level ($L_{pk\text{-}pk}$), and sound pressure level (L_{rms} or SPL) are computed by multiplying the logarithm of the ratio of the peak or RMS pressures to a reference

pressure (1 micropascal [µPa] in water) by a factor of 20; these values are reported in decibels (dB; see ***Sound Levels*** below).

Sound exposure (pascal-squared second, or Pa²s): Sound exposure is proportional to the acoustic energy of a sound. It is the time-integrated squared sound pressure over a stated period or acoustic event (**Figure 2**). Unlike sound pressure, which provides an instantaneous or time-averaged value of acoustic pressure, sound exposure is cumulative over a period of time.

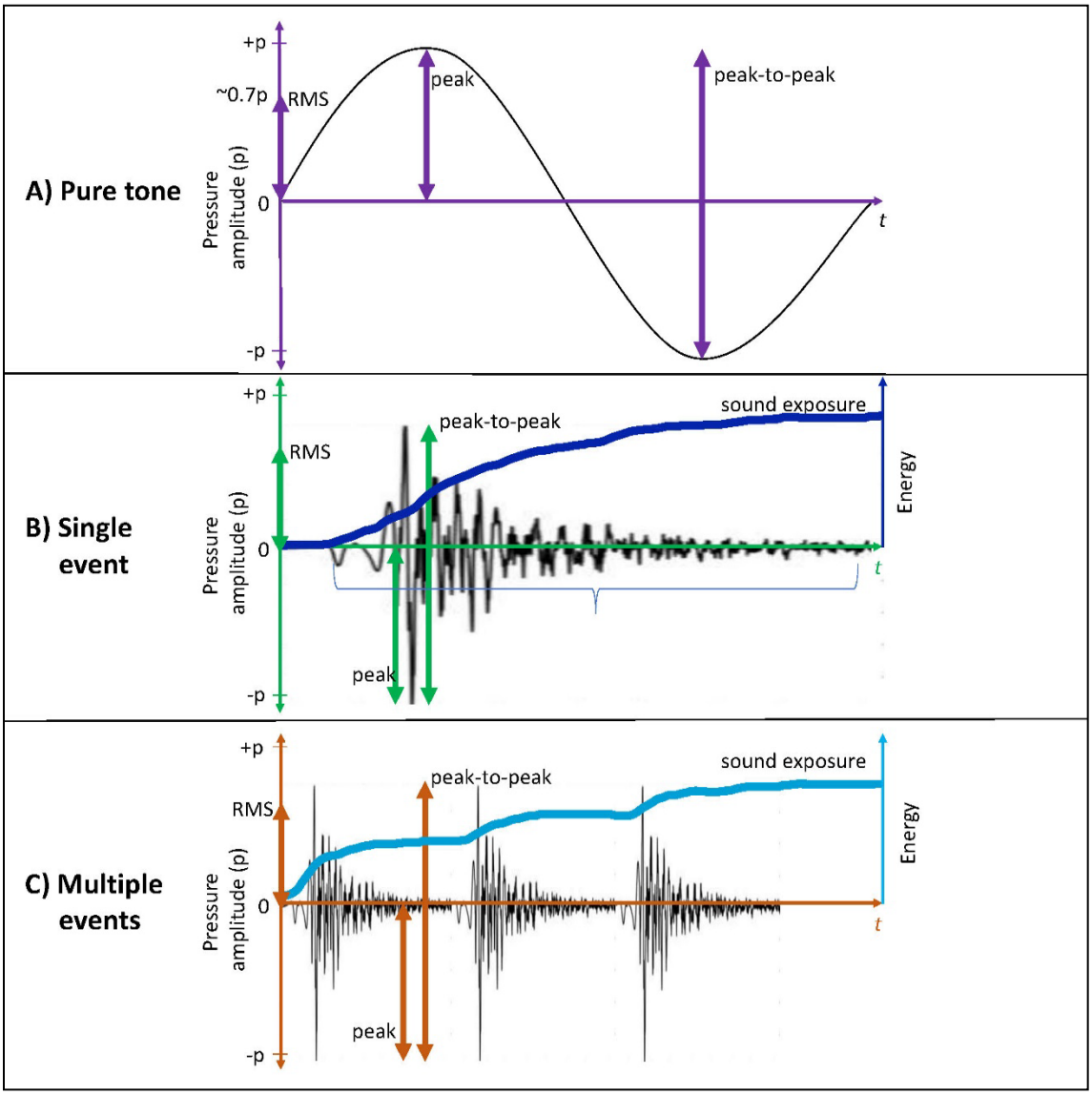

Figure 2. Sound pressure wave representations of three sound types, illustrating four acoustic metrics: RMS, peak, peak-to-peak, and sound exposure.

A) A sine wave of a pure tonal signal with equal positive and negative peaks, so peak-to-peak is exactly twice the peak, and RMS is approximately 0.7 x peak. B) A single impulsive event has one large positive pulse and a large negative pulse that is not necessarily the same magnitude. In this example, the negative pulse is more extreme and is thus the reported peak (zero-to-peak) value; peak-to-peak is less than double the zero-to-peak metric. Sound exposure is shown as it accumulates across the time window. The ending sound exposure would be considered the "single-shot" exposure, and the RMS value is that value divided by the duration of the pulse. C) Three consecutive impulsive events with zero-to-peak

and peak-to-peak assessed the same way as in panel B. Sound exposure is shown accumulating across all three strikes, and RMS is the total sound exposure divided by the entire time window shown. The cumulative sound exposure for this series of signals is the total energy from all three pile strikes. Figure credit: BOEM.

Particle velocity (meter per second, m/s): Particle velocity describes the rate of change in position of an oscillating particle about its origin with respect to time. Similar to sound pressure, particle velocity is dynamic and changes as the particles move back and forth. Therefore, peak particle velocity and RMS particle velocity can be used to describe this physical quantity. One major difference between sound pressure and particle velocity is that the former is a scalar (i.e., without a directional component), and the latter is a vector (i.e., includes both magnitude and direction). Particle acceleration also can be used to describe particle motion and is defined as the rate of change of velocity of a particle with respect to time. It is measured in units of meters per second squared, or m/s^2.

Acoustic intensity (watts per square meter, or W/m^2): Acoustic or sound intensity is the amount of acoustic energy that passes through a unit area perpendicular to the direction of propagation per second. It is the product of the sound pressure and the sound velocity. With an idealized constant source, pressure and particle velocity will vary in proportion to each other at a given location, but intensity will remain constant.

Sound Levels: There is an extremely wide dynamic range of values when measuring acoustic pressure in pascals, so it is customary to use a logarithmic scale to compress the range of values. Aside from the ease it creates for comparing a wide range of values, animals (including humans) perceive sound on a logarithmic scale. These logarithmic acoustic quantities are known as sound levels and are expressed in decibels (dB), which is the logarithm of the ratio between a measured acoustic quantity (such as pressure or intensity) and a standardized reference value. Underwater acoustic SPLs are referenced to a pressure of 1 µPa (equal to 10^{-6} pascals [Pa] or 10^{-11} bar). (Note that airborne SPLs have a different reference pressure of 20 µPa.)

These metrics (sound pressure, particle velocity, sound exposure, and intensity) are described in the following ways when described as levels:

- RMS sound pressure level (L_{rms} or SPL, in dB re 1 µPa)
- Peak pressure level (L_{pk}, in dB re 1 µPa)
- Peak-to-peak pressure level ($L_{pk\text{-}pk}$, in dB re 1 µPa)
- Sound exposure level (SEL, in dB re 1 μPa^2s)
- Particle velocity level (SVL, in dB re 1 nm/s)

There are a few commonly used time periods used for SEL, including a 24-hour period (SEL_{24}, used in the United States for the regulation of noise impacts to marine mammals) or the duration of a single event, such as a single pile-driving strike or airgun pulse, called the single-strike SEL (SEL_{ss}). A sound exposure for some other period, such as the entire installation of a pile, may be written without a subscript (SEL), but to be meaningful should always denote the event duration.

Source Level: Source level represents the amount of acoustic power radiated from a sound source. It describes how loud a particular source is in a way that can inform expected received levels at various ranges. It can be conceptualized as the product of the acoustic pressure at a specific point and distance from that point to a spherical (omnidirectional) source, assuming an ideal, infinite, lossless medium. The source level is the sum of the received level and the propagation loss to that receiver. It is commonly described in terms of the received level at a distance of 1 m from the source; however, this approach can be misleading because taking an actual measurement at 1 m is often impractical or impossible for large or non-spherical sources. The most common type of source level is an SPL source level in units of dB re 1 µPa · m, though in some circumstances an SEL source level may be expressed (in dB re 1 $\mu Pa^2 s \cdot m^2$); peak source level (in units of dB re 1 µPa · m) may also be appropriate for some sources.

2.3 Propagation of Sound in the Ocean

Underwater sound can be described through a source-path-receiver model. An acoustic source emits sound energy, which radiates outward and travels through the water and the seafloor. The sound level decreases as the sound travels through the environment away from the source. The amount by which the sound levels decrease between the theoretical source level and a receiver is called propagation loss. Among other things, the amount of propagation loss that occurs depends on the source-receiver separation, geometry of the environment the sound is propagating through, frequency of the sound, properties of the water column, and properties of the seafloor and sea surface.

As sound waves travel through the ocean, they often encounter areas with varying physical properties, which can alter the sound propagation pathway compared to propagation in a homogenous, boundary-free medium. For example, near the ocean's surface, water temperature is usually higher, resulting in relatively fast sound speeds. As temperature decreases with increasing depth, sound speed also decreases. Sounds bend toward areas with lower speeds (Urick 1983). Ocean sound speeds are often slowest at mid-latitude depths of about 1,000 m; because of sound's preference for lower speeds, sound waves above and below this "deep sound channel" often bend towards it. Sounds originating in this layer can travel great distances. Sounds can also be trapped in the mixed layer near the ocean's surface (Urick 1983). Latitude, weather, and local circulation patterns influence the depth of the mixed layer, and the propagation of sounds near the surface is highly variable and difficult to predict.

At the boundaries near the sea surface and the sea floor, acoustic energy can be scattered, reflected, or attenuated depending on the properties at the surface (e.g., roughness, presence of wave activity, or bubbles) or seafloor (e.g., bathymetric features, substrate heterogeneity; Urick 1983). For example, fine-grain sediments tend to absorb sounds well, while hard bottom substrates reflect much of the acoustic energy back into the water column. The presence of ice on the ocean's surface also can affect sound propagation. For example, the presence of solid ice may dampen sound levels by scattering incident sounds. The effect also will depend on the thickness and roughness of the ice, among many other factors related to the ambient conditions.

As a sound wave moves from a source to a receiver (i.e., an animal), it may travel on multiple pathways that may be direct, reflected, and refracted, or a combination of these mechanisms, creating a complex pattern of transmission across range and depth. The patterns may become even more complicated in shallow waters due to repeated interactions with the surface and the bottom, frequency-specific propagation, and more heterogenous seafloor properties. All these variables contribute to the difficulty in reliably predicting the sound field in each marine environment at any given time.

2.4 Sound Source Classification

In the current regulatory context, anthropogenic sound sources are categorized as impulsive or non-impulsive, and as continuous or intermittent, based on their physical qualities and because these characteristics can influence the manner and extent to which these sounds affect marine life (NMFS 2018). These categories were originally developed for considering impacts to marine mammals but are now used more broadly across taxa to evaluate risks of injury, behavioral disturbance, and acoustic masking, which is when noise interferes with an animal's ability to detect or interpret important sounds. In general, impulsive and non-impulsive distinctions are used to assess hearing impacts, while continuous and intermittent distinctions are used to describe behavioral effects and masking potential

Impulsive noises are characterized as having the following characteristics (American National Standards Institute 2010):

- Broadband frequency content
- Fast rise times and rapid decay times
- Short durations (i.e., < 1 second)
- High peak sound pressures

Non-impulsive sound sources are less resolved and may have the following characteristics:

- Variable in spectral composition, i.e., broadband, narrowband, or tonal
- Longer rise times and decay times, and longer total durations compared to impulsive sound
- Continuous (e.g., vessel engine radiated noise) or intermittent (e.g., echosounder pulses)

This binary classification framework provides a conservative basis for predicting potential auditory impacts because sources are classified based on the characteristics at the source, but they can change during propagation through the water. For example, sounds that are impulsive at the source may become less impulsive (and therefore less damaging) as they travel through the water column (Martin et al. 2020).

In addition, animals will encounter many signals in their environment, or complex sounds, which may contain many of or all these sound types. Evidence—particularly from studies on terrestrial mammals (Hamernik and Hsueh 1991)—suggests that complex sounds may cause more damage than continuous sounds of the same energy, but regulatory frameworks currently do not recognize complex sounds as a distinct category.

One approach that has gained attention for assessing the impulsiveness of a sound is calculating its *kurtosis*. Kurtosis describes the prevalence of extreme values within a distribution of observations as a way to characterize the "peakiness" of a signal. A sound with high kurtosis is characterized as having sharp peaks in its waveform and produces more hearing damage than exposure to an equivalent-energy sound with low kurtosis, which has a more uniform waveform and very few, if any, peaks. A kurtosis value of 3 is considered Gaussian (i.e., normally distributed) noise, while a kurtosis value of > 40 is considered fully impulsive (Martin et al. 2020). A distribution of sound level observations from a time series with a kurtosis value between 3 and 40 would be considered a complex sound. The underwater bioacoustics community has proposed the use of kurtosis to more accurately classify the impulsivity of a sound transmitting through the environment for marine mammal exposures (Martin et al. 2020; Zeddies et al. 2024).

The National Marine Fisheries Service (NMFS) has expressed that there is value in understanding kurtosis and the potential use of this metric in the future to more accurately characterize real-life sounds (NMFS 2024). Kurtosis-corrected SEL has been recommended as a reliable way to predict the onset of auditory injury in humans (Zhao et al. 2010; Goley et al. 2011) and terrestrial mammals (Hamernik and Qiu 2001; Hamernik et al. 2003). However, at present, the information needed to apply this concept to marine mammals, fish, sea turtles and other taxa is lacking. For example, what kurtosis value correlates with hearing damage in each of these species groups? Over what duration should kurtosis be evaluated? Although research has begun to provide insight (Muller et al. 2020; von Benda-Beckmann et al. 2022), there remain information gaps preventing the practical application of kurtosis in marine life acoustic impact regulations.

Impulsive sounds associated with oil and gas development include seismic airguns, explosions, sparkers, and boomers; it is generally accepted that impulsive sources have a greater likelihood of causing hearing damage than non-impulsive sources (explosions are further considered for non-auditory injury in **Section 2.4.3**). At close distances to impulsive sounds, animals are likely to experience physiological effects, including a brief decrease in hearing sensitivity (temporary threshold shift [TTS]) and auditory injury, which includes but is not limited to irreversible hearing loss (permanent threshold shift [PTS]). These effects are also possible after exposure to non-impulsive sounds if the duration of exposure is long enough.

For behavioral effects of anthropogenic sound on marine mammals, NMFS classifies sound sources as either intermittent or continuous (NMFS 2018). Continuous sounds, such as drilling or vibratory pile driving, remain "on" (i.e., producing sound over a given period); however, this classification is not well-defined. An intermittent sound typically consists of bursts or pulses of sound on a regular on-off pattern, also called the duty cycle. Examples of intermittent sounds are those from scientific echosounders, sub-bottom profilers (SBPs), and impact pile driving. It is important to recognize that these delineations are not always practical in application, as a continuous, moving sound source (such as a vessel passing over a fixed receiver) could be considered intermittent from the perspective of the receiver.

2.5 Sound Sources Related to Oil and Gas Development

2.5.1 Seismic Surveys (Airguns)

Seismic surveys are used to locate oil and gas resources below the seafloor. Seismic airguns are steel cylinders that are towed behind a source vessel and are connected to shipboard air compressors. The chamber is filled with compressed air (usually 2,000 psi), which is rapidly released to create an impulsive sound. Depending on the need of the survey, airguns can be deployed as single elements or as part of an airgun array comprising dozens of individual elements. Geophysical surveys may span a single day, weeks, or months.

Surveys that use single airguns (or small arrays of four or fewer airguns) are typically intended to image the uppermost section of the seafloor (up to a depth of 1 km) with source frequencies primarily between 10–200 Hz (Jiménez-Arranz et al. 2020). The time interval between single airgun "shots" is usually less than 6 s, and the reflected signals are received by a single hydrophone streamer of several hundred meters in length to create 2D reflection profiles. Typical industry surveys that use single airguns are likely to cover only one OCS lease block, which is usually 4.8 km on a side. Including vessel turns at the end of lines, the time required to survey one OCS lease block is approximately 36 hours.

Deep-penetration 2D and 3D seismic surveys, which are conducted by the hydrocarbon exploration industry, typically cover areas off existing leases or multiple lease areas. For 2D seismic surveys, a single streamer is towed behind the survey vessel, together with a single source or airgun array. Seismic vessels generally follow a systematic pattern during a survey, typically a simple grid pattern for 2D work, with lines more widely spaced, typically no closer than 0.5 km. In simplified terms, 3D surveys collect a very large number of 2D slices, with minimum line separations of only 25–30 m. A 3D survey may take many months to complete (e.g., 3 to 18 months) and involves multiple passes to cover a given survey area, thus providing a substantial increase in resolution. A series of 3D surveys collected over time (commonly referred to as 4D surveying) is used for reservoir monitoring and management. Wide azimuth survey configurations involve multiple vessels operating concurrently in a variety of geometries between the source vessel and acquisition vessel. Several source vessels (usually two to four) are used in coordination with single- or dual-receiver vessels, either in a parallel or rectangular arrangement with a typical 1,200-m vessel spacing to maximize the azimuthal quality of data acquired. Finally, vertical seismic profiles involve placing seismic sensors inside a well at varying depths, recording both direct-arriving and reflection energy from the acoustic source. Usually a smaller total airgun volume (and therefore lower acoustic energy) is required for vertical seismic profiles than for towed-streamer surveys.

Seismic surveys (both 2D and 3D) can use large arrays of as many as several dozen airguns, and total airgun volumes can be several thousand cubic inches. The airguns are discharged at regular time intervals, typically every 10 seconds (International Association of Oil & Gas Producers 2011). Most of the energy produced by airgun arrays are below 250 Hz (with 90% of the energy between 70–140 Hz), but there may be additional energy up to 20 kHz (Madsen et al. 2006; Jiménez-Arranz et

al. 2020). SPL source levels of single airguns (40–70 in^3) are typically between 200–230 dB re 1 µPa · m, while source levels of arrays (~400–3,000 in^3) range from 230–260 dB re 1 µPa · m (BOEM 2023). Low-frequency sounds propagate very well in the ocean, and sounds from seismic airguns can ensonify large areas and be detectable above ambient noise more than 100 km from the source (Hynes et al. 2025; Wiggins et al. 2025).

Airgun arrays have important advantages as a seismic source compared to single airguns. Large "tuned" arrays use airguns of varying chamber volumes to reduce the bubble pulse of the array source signature and increase the resolution of the source signal. A horizontally distributed array of airguns produces a downward-focused source signal. In addition, the number of airguns in an array is a much more important factor in determining the peak output level of the source than total airgun volume. Peak-to-peak amplitude of an airgun array increases linearly with the number of airguns but only increases by the cube root of total air volume (Caldwell and Dragoset 2000; Jiménez-Arranz et al. 2020).

Additional detail on seismic surveys can be found in Jiménez-Arranz et al. (2020) and BOEM (2023).

2.5.2 Airgun Alternatives

Several alternative seismic technologies have reached technological and market readiness and may be able to supplant airguns in seismic surveys. These technologies are expected to reduce both the intensity and spatial extent of underwater noise exposure, offering a more environmentally responsible approach to seismic exploration. Collectively, these technologies reflect a shift toward more environmentally considerate seismic survey methods, aimed at minimizing behavioral or physiological disturbances to marine species. Currently, there are three categories of sources that could be used in lieu of airguns.

The first category can be considered an airgun "modification" and not a true "alternative" to an airgun. Bluepulse and E-source are two examples currently on the market. Both use specially shaped internal chambers and a throttled shuttle mechanism that slows the flow of air out of the chamber. This longer rise time means that there is a reduction in high-frequency noise and peak pressure compared to a traditional airgun. While it is indeed beneficial to the environment to reduce extraneous high-frequency noise, these airgun modifications offer no geophysical advantage—the data quality obtained is identical to that of a traditional airgun. Of the three categories, this source type offers the least benefit to both industry and marine species.

The second category is Ultra-Low Frequency pneumatic sources, which are entirely new technologies on the market. They release very high volumes of air at once, which improves low-frequency bandwidth for sub-salt and sub-basalt imaging and also reduces potential environmental impacts (Chelminski et al. 2019; Large et al. 2022). These systems include the Tuned Pulse Source™, Gemini Source™, and Harmony™, which are characterized by bubble resonance frequencies below 7 Hz. These sources typically contain peak energy below 10 Hz, with reduced signal amplitude above ~60–90 Hz. Ultra-Low Frequency systems are considered impulsive, intermittent sources; however, they are designed to provide two primary advantages

over conventional airguns. First, they provide deeper subsurface penetration and improved imaging of complex geology due to the concentrated low-frequency energy. Second, the reduced signal amplitude at higher frequencies may lower sound exposure for marine mammals and other taxa whose hearing ranges overlap with the higher-frequency components of conventional airgun pulses.

Finally, marine vibroseis (MV) differs significantly from the previous two categories because it does not release air at all. Rather, MV units essentially function like underwater loudspeakers; they use electromechanical or hydraulic actuators towed from a vessel or mounted on the seafloor to produce controlled, continuous, or swept acoustic signals. This allows MV systems to emit energy over a broader range of frequencies with a more gradual onset and lower peak sound pressure levels, which can improve subsurface imaging (especially for high-resolution and full-waveform inversion applications) and potentially reduce disturbance to marine life compared to impulsive sources like conventional airguns. MV systems also offer precise control over signal characteristics including frequency content and signal duration, which enables optimization for specific geological targets and survey objectives. However, their deployment and operational logistics differ from conventional towed arrays.

2.5.3 High-Resolution Geophysical Surveys

High-resolution geophysical (HRG) surveys are conducted to characterize the bathymetry, sediment type, and benthic habitat characteristics of the marine environment and to identify archaeological resources or obstacles on the seafloor. These surveys differ from deep-penetration seismic surveys because they only intend to image the seafloor or shallow subsurface. The suite of sources that may be used in HRG surveys includes side-scan sonars, multibeam echosounders (MBESs), magnetometers and gradiometers, parametric SBPs, compressed high-intensity radiated pulse (CHIRP) SBPs, boomers, and sparkers. These HRG sources may be towed behind a ship, mounted on a ship's hull, or deployed from remotely operated vehicles or autonomous underwater vehicles (AUVs). In deepwater environments, sources are usually deployed from AUVs about 5–10 m off the seafloor; this means the ensonified area is smaller than if a source was deployed on a ship at the surface.

Many HRG sources are active acoustic sources, meaning they produce sound deliberately to obtain information about the environment. Except for some MBESs and side-scan sonars, these sources produce sounds below 180 kHz and thus may be audible to some marine species. Source levels vary widely depending on source type and operational power level used, from ~145 dB re 1 µPa·m for towed SBPs up to 245 dB re 1 µPa·m for some MBESs (Crocker and Fratantonio 2016). While sparkers are omnidirectional, most other HRG sources have narrower beamwidths (e.g., MBES: up to 6°, parametric SBPs: 30°, boomers: 30–90°; Crocker and Fratantonio 2016).

Generally speaking, sources that emit sound in narrow beams directed at the seafloor are less likely to affect marine species because they ensonify a smaller portion of the water column (Ruppel et al. 2022). Most HRG sources emit short pulses of sound, with periods of silence in between. This

means that only several "pings" emitted from a vessel towing an active acoustic source would reach an animal below, even if the animal was stationary (Ruppel et al. 2022).

Further detail on HRG sources can be found in BOEM (2023) and Crocker and Fratantonio (2016).

2.5.4 Geotechnical Surveys

Geotechnical surveys (e.g., the collection of sediment cores) are conducted to determine the physical and mechanical properties of sediments and the structure of the sediment layers. These surveys typically rely on on-site measurements of physical properties or acquiring actual specimens for testing in the laboratory. There are some systems that generate and use acoustic signals to acquire this data (e.g., acoustic corers); however, with many of these methods, noise is produced as an unintended by-product of the mechanical process of acquiring the sample. Generally, the noise produced is low level and low frequency (< 2,000 Hz).

Special geotechnical drillships are required when conducting geotechnical surveys in water that are too deep for jack-up rigs or semi-submersibles. Modern drillships use dynamic positioning (DP) systems to hold them in place, which often introduces more noise into the marine environment than the geotechnical sampling itself. For more information on DP system noise, see **Section 2.5.7**.

Shallow test wells, which are used to evaluate subsurface properties, are actively drilled using an engine from a drilling barge, jack-up rig, or semi-submersible. "Shallow test drilling" refers to drilling into the seabed at depths less than those in a deep stratigraphic test, i.e., less than 500 ft.

Standard penetration testing is a method in which a sample tube is driven into the seabed at the bottom of a borehole; the number of blows required to penetrate the seabed provides an indication of the density of the substrate and is termed the "standard penetration resistance." Erbe et al. (2017) measured sounds from a jack-up rig during standard penetration testing and back-calculated SPL source levels to be 160 dB re 1 µPa·m, with most of the energy below 3 kHz.

Another type of geotechnical drilling is called standard rotary coring. Two or three tubes (each with a core liner, holder, and drill bit) are used in conjunction to obtain cores longer than 30 m and up to several hundred meters into seafloor. They are typically powered by diesel or gas engines, using air or muds for cooling the drill bits. Erbe et al. (2017) found that, when using an 8.3-cm drillbit to penetrate 4–20 m into the seafloor, SPL source levels were around 145 dB re 1 µPa·m, with most of the energy in the 30–400 Hz range. Tetra Tech reported sound levels measured at 150-m distance while drilling 4.5-in diameter bores into clay and mud (Tetra Tech Inc. 2014). The depth of the bore was not reported. SPLs varied from 95–108 dB re 1 µPa while drilling was taking place, but this is comparable to ambient noise measurements taken before drilling commenced (Tetra Tech Inc. 2014).

A deep stratigraphic test (also known as a Continental Offshore Stratigraphic Test well) is a borehole drilled not to encounter hydrocarbons, but to provide information about regional stratigraphy, ground truth geophysical data, estimate the age of sediments from collected

microfossils, and evaluate the potential quality of source rocks (BOEM 2017). A deep stratigraphic test is defined in 30 CFR 251 as "drilling that involves the penetration into the sea bottom of more than 500 feet (152 meters)."

Finally, Cone Penetrometer Tests (CPT) provide a precise stratigraphy of the sampled core. A CPT is a pointed steel pipe that is forced into the seafloor; penetration is achieved through a hydraulic jacking mechanism. In waters less than 30 m, floating or jack-up barges typically are used; in deeper water (> 30 m), the CPT can be placed on seafloor. Chorney et al. (2011) measured sound levels from a Mini-CPT while DP thrusters were operational, and the measured 1/3 octave band levels while the Mini-CPT was operational were virtually identical to periods when only the DP thrusters were in use. Therefore, the use of CPTs did not significantly increase underwater sound levels beyond contributions from the DP thrusters and are therefore expected to be relatively quiet. For more information on DP system noise, see **Section 2.5.7**.

2.5.5 Dredging

Dredging removes and transports sediment from the seafloor elsewhere. Dredging may be used to increase the width of shipping lanes, open new areas for construction, extract valuable metals, remediate contaminated sediments, or collect sediment for beach renourishment.

Dredging produces distinct sounds during each specific phase of operation: excavation, transport, and placement of dredged material (Central Dredging Association 2011; Jiménez-Arranz et al. 2020). Engines, pumps, and support vessels used throughout all phases may introduce low-level, continuous noise into the marine environment. The sounds produced during excavation vary depending on the sediment type; denser and more consolidated sediment requires the equipment to exert more force, increasing the produced sound levels (Robinson et al. 2011). Hydraulic dredges, such as cutterhead suction dredges or trailing suction hopper dredges with cutterheads or drag arms in continuous contact with the seabed, typically generate nearly continuous and relatively high-level sounds during excavation, especially in coarser sediments (McQueen et al. 2018; Jiménez-Arranz et al. 2020). Mechanical dredges, including grab (clamshell) and backhoe dredges, tend to produce more intermittent sounds as the bucket or excavator arm is lowered, digs, and raised with a winch. During the sediment transport phase, factors such as load capacity, draft, and vessel speed influence the resulting sound levels (Reine et al. 2014b), and additional sounds are produced during pump-out operations when dredge plant pumps are operated (Central Dredging Association 2011).

Dredging activities generally produce low-frequency sounds; most energy is below 1 kHz, with peaks typically occurring between 150–300 Hz (McQueen et al. 2018). McQueen et al. (2018) summarized results from several studies that measured sounds during dredging operations. For cutterhead suction dredges, SPL source levels were 168–175 dB re 1 µPa·m (Greene Jr. 1987; Reine et al. 2012b; 2014a). Trailing suction hopper dredges were slightly louder, with SPL source levels ranging from 172–190 dB re 1 µPa·m (McQueen et al. 2018). Dickerson et al. (2001) recorded a maximum SPL of 124 dB re 1 µPa at 154 m during the moment when the grab (clamshell) dredge

bucket hit the seabed; during other phases of operation (e.g., raising and lowering of grab dredge, dumping sediment on barge), the received SPL was closer to ~110–115 dB re 1 µPa at 154 m. Finally, SPL source levels during backhoe dredge operations ranged from 163–179 dB re 1 µPa·m (Nedwell et al. 2008; Reine et al. 2012a). Additional detail and measurements of dredging sounds can be found in Jiménez-Arranz et al. (2020), McQueen et al. (2018), and Robinson et al. (2011).

2.5.6 Drilling and Production

A range of facilities may be used for offshore drilling and production, depending on water depth, duration of the planned activity, and other factors. Fixed platforms and jack-up rigs are limited to relatively shallow waters (up to 500 m), while mobile offshore drilling units (MODUs) are necessary in deeper waters. Drillships and semi-submersibles are two types of MODUs; both are held in place using DP systems which can add considerable levels of noise to the marine environment. For more information on DP system noise, see **Section 2.5.7**.

The noise produced during drilling is non-impulsive and nearly continuous in nature, though it may be highly variable depending on the type of substrate that is encountered (Richardson et al. 1995). There could be tonal sound generated by the drill bit, mechanical noise transferred through the ship's hull, and noise from the vessels and DP systems (MacDonnell 2017). The dominant energy from drilling noise is generally below 1,000 Hz, largely due to noise generated by the DP systems (Greene Jr. 1987; MacDonnell 2017).

The noise levels generated during drilling generally depend on the platform type and degree of coupling between these mechanical sources and the structure. Drillships and semi-submersibles are the loudest because there is a large degree of coupling between the machinery vibrations and the water. For example, measurements conducted during exploratory drilling from a drillship in 2,120-m water depth revealed that broadband SPL source levels (10 Hz–32 kHz) were between 185–188 dB re 1 µPa (MacDonnell 2017); at 2-km distance, this level diminished to 118.4 db. The authors concluded that noise from drilling itself was negligible compared to the noise generated by the DP systems and support vessels. Nonetheless, they found that there was no risk of auditory injury in marine mammals or fishes from exploratory drilling operations based on peak pressure measurements; TTS was expected to occur at smaller ranges than the shutdown zones (a designated radius around the source within which observation of a protected species requires the activity to stop until the animal leaves or is no longer detected), so TTS was also deemed unlikely. Another study examining exploratory drilling from a semi-submersible at two different water depths (300 m and 1,175 m) found that, in deeper waters, sounds propagated further, with received levels nearly 20 dB higher than ambient conditions at 5 km from drilling operations; broadband SPL source levels reached up to 191 dB µPa·m (Delarue et al. 2021). These measurements are consistent with earlier work by Nedwell and Edwards (2004), who measured underwater noise from a 250 m-long drillship and found SPL source levels to be 195 dB re 1 µPa · m

Generally, drilling from fixed platforms is quieter than from MODUs because the machinery is above the water line, there is a relatively small contact area between the legs of the structure and

the water, and no DP systems are used. For example, Gales (1982) measured drilling noise at 30-ft distance from a fixed platform and found SPLs in the frequency range of 50–500 Hz were around 130 dB re 1 µPa; McCauley (1998) reported that SPLs at 125 m from a moored platform in 110m of water could reach 117 dB re 1 µPa.

Similar to drilling noise, the level of production noise depends on the type of platform, the degree of coupling with the water, and whether DP systems are used. Gales (1982) examined production noise from fixed platforms and found that the dominant frequencies were below 500 Hz, and received levels at 100 m ranged from 110–130 dB re 1 µPa. Floating, production, storage, and offloading platforms use DP systems to maintain their position during offshore operations, particularly when transferring oil to tankers; this activity can generate sounds with broadband SPL source levels around 180 dB re 1 µPa · m (Erbe et al. 2013).

2.5.7 Vessels and DP Systems

Transiting vessels generate continuous sound from their engines, propeller cavitation, and onboard machinery, as well as from the hydrodynamics of water flow underneath a vessel (Ross 1976). The actual radiated sound usually has a combination of broadband and tonal sounds, and depends on several factors, including the type of machinery on the ship, the material conditions of the hull, how recently the hull has been cleaned, interactions with the sea surface, and the shielding from the hull, which physically blocks and attenuates machinery/propeller noise in some directions, making radiated noise directional and reducing sound levels in front of the ship.

In general, vessel noise increases with increases in ship size, power, speed, propeller blade size, number of blades, and rotations per minute. Small vessels, like those used for crew transport, typically produce higher-frequency sound than large container ships, with most energy concentrated in the 1–5 kHz range. Kipple and Gabriele (2003) measured underwater sound from vessels ranging from 14- to 65-ft long (25 to 420 horsepower) and back-calculated source levels to be 157–181 dB re 1 µPa·m. Large oil tankers (~200–380 m) tend to have source levels between 175–185 dB re 1 µPa·m (Jiménez-Arranz et al. 2020). During seismic or HRG surveys, vessels typically travel at slower speeds (typically 5 knots), which reduces underwater radiated noise. For example, recordings from a speed reduction program in the Port of Vancouver (210- to 250-m water depths) showed that reducing speeds to 11 knots reduced vessel source levels by 5.9–11.5 dB, depending on the vessel type (MacGillivray et al. 2019). For additional measurements of noise from support and crew vessels, tugs, inflatable rigid inflatable-hull boats, icebreakers, cargo ships, oil tankers, and more, see Jiménez-Arranz et al. (2020)

DP systems also produce continuous noise, but unlike transiting vessels, this source is usually stationary. DP systems use propellers and thrusters for vessel station-keeping (e.g., holding station over a specific seafloor location), docking, and other precise maneuvering during operations. DP uses input from gyrocompasses, motion sensors, GPS, active acoustic positioning systems, and wind sensors to determine relative movement and the environmental forces at work. Most of the noise generated by DP systems (which is low frequency and high amplitude) comes from the vessel

thrusters. As with propulsion, source levels during the use of DP vary greatly based on size and type of vessel, type of thruster, and operational conditions, including both weather and oceanographic conditions.

DP systems typically do not have a high peak sound pressure and rapid rise time compared to impulsive sounds but can still produce significant acoustic energy, most of which is below 1,000 Hz, with tones related to engine and propeller size and type (National Institute for Occupational Safety and Health 1998; Acoustical Society of America 2008). The sound also can vary directionally, and this directionality is much more pronounced at higher frequencies. Because this is a dynamic operation, the sound levels produced will vary based on the specific operation, the exact system used (e.g., jet or propeller rotation, versus a rudder or steering mechanism), and other factors—such as the blade rate, blade pitch and cavitation, and material condition of the system. Representative sound field measurements from the use of DP are difficult to obtain because the sound transmitted is often highly directional and context specific. Because DP thrusters change orientation and load to hold station, the dominant direction of radiated sound shifts accordingly.

There are few dedicated sound source characterizations of DP. Nedwell and Edwards (2004) reported that DP thrusters of the semi-submersible drill rig *Jack Bates* produced periodic noise (corresponding to the rate of the thruster blades), with most energy between 3–30 Hz. The received SPL measured at 100 m from the vessel was 188 dB re 1 µPa. Warner and McCrodan (2011) found that most DP-related sounds from the self-propelled drill ship, R/V *Fugro Synergy*, were in the 110–140 Hz range, with an estimated source level of 169 dB re 1 µPa · m. Sounds in this frequency range varied by 12 dB during DP, while the broadband levels, which also included diesel generators and other equipment sounds, varied by only 5 dB over the same time period (Warner and McCrodan 2011). All measurements of DP report high variability in levels with time, due in part to intermittent usage and relatively slow rotation rates of thrusters used in DP. Thus far, it has been difficult to provide a realistic range of source levels from the data because most reports do not identify the direction from which sound was measured relative to the vessel, and DP thrusters are highly directional systems. However, it is clear that when DP systems are used in conjunction with other operations (e.g., drilling, production), noise from DP tends to dominate.

The active acoustic positioning systems used in DP can be additional sources of high-frequency sound. These systems usually consist of a transducer mounted through the vessel's hull and one or more transponders affixed to the seabed. Kongsberg High Precision Acoustic Positioning (HiPAP) systems produce pings in the 10–32 kHz frequency range. The hull-mounted transducers have source levels of 188–206 dB re 1 µPa · m depending on adjustable power settings (Kongsberg Maritime AS 2013). The fixed transponders have maximum source levels of 186–206 dB re 1 µPa · m, depending on model and beam width settings from 15 to 90° (Jiménez-Arranz et al. 2020). These systems have high source levels; however, beyond 2 km, they generally are quieter than other components of the sound from DP vessels.

2.5.8 Trenching, Cable Laying, and Pipeline Laying

Trenching sleds dig the trenches for laying pipeline or cable by displacing the sediment with a water jet. Depending on the technique used, the cable may be laid directly into the trench as the trench is being cut, allowing the sediment to settle back into the trench and cover the cable, or a separate burying pass may be made after the cable is laid. Nedwell and Edwards (2004) measured sounds from a 130 m-long trenching vessel and found that sound levels were similar to those produced during pipeline laying in the same area (see below), except for a 20-kHz tonal sound, which they attributed to the vessel's DP thrusters. For more information on DP system noise, see **Section 2.5.7**.

Pipelines are installed by lay barges, which are either anchored or dynamically positioned while the pipeline is laid. Noise is also introduced into the water from the DP systems, movement of supply ships and tugs, and anchoring. Up to 10 ships may be operating in the same area during pipeline laying; barges with very heavy anchors continually move along the pipeline route. Certain joints of the pipeline must be welded into place while offshore, so a conventional lay barge with a welding station is required. Nedwell and Edwards (2004) measured noise from a pipeline-laying ship working in both shallow (< 50 m) and deeper (50–100 m) waters near the Shetland Islands in Scotland. In shallower areas, they found increased sound levels at distances up to 2.3 km at frequencies < 1 kHz; by 7.4 km from the source; sounds from pipeline laying had faded into ambient noise. Johansson and Andersson (2012) measured sounds during pipe laying operations in 40-m water depth; at 1.5-km distance, the SPL was 130.5 dB re 1 µPa. DP thrusters were active when the measurements were taken, so it is difficult to know sound levels from pipeline laying alone.

2.5.9 Pile Driving

Pile driving is used to install infrastructure on the seafloor. Fixed structures are secured to the sea floor with steel piles and generally can be installed in up to about 300-m water depths. For hydrocarbon production, pile driving may be used to install fixed platforms, caissons, well protectors, casing, wellheads, and conductors. Measurements of noise produced during impact pile driving have been taken during offshore wind development. However, the size of the steel pipes used for oil and gas infrastructure is significantly smaller than that used in offshore wind, so the levels of underwater noise are expected to be much lower.

Impact pile driving employs a hammer to strike the pile head and force the pile into the sediment; the typical hammer strike rate is approximately 30–50 strikes/minute. Typically, force is applied over a period of less than 20 ms, but the pile can generate sound for upwards of 0.5 seconds. Impact pile-driving noise is characterized as impulsive because of its high peak pressure, short duration, and rapid onset time. Underwater sound levels generated during pile driving depend on many factors, including the pile material and size, characteristics of the substrate, penetration of the pile in the seabed, hammer energy and size, and water depth. Larger pile diameters and harder substrates typically require higher hammer energy.

Jacket piles are commonly used for different types of offshore infrastructure. At the Block Island Wind Farm, Amaral et al. (2018) measured sound levels at various distances during pile driving of jacket foundations (50-in pile diameter, 30-m water depth). The authors reported SPL received levels between 150–160 dB re 1 µPa at approximately 750 m from the piles. Using measurements combined with acoustic modeling, the peak-to-peak source levels were estimated to be between 233 and 245 dB re 1 µPa · m (Amaral et al. 2018). Both caissons and well protectors, two common jacket-based platforms used in oil and gas development, have similar pile size, so sound levels are expected to be similar to those measured at Block Island Wind Farm by Amaral et al. (2018). Typical impact pile driving associated with oil and gas infrastructures operates at a rate of 15 to 60 blows per minute and requires 500 to 5,000 strikes to drive the pile into the seabed (Jiménez-Arranz et al. 2020).

Installing larger foundations is typically much louder than installing smaller jacket piles because larger foundations require very large hammers that use energy generally in the range of 2,500 to 4,000 kJ. At South Fork Wind Farm, where piles of 11-m in diameter were driven while using a double big bubble curtain, SPL received levels typically ranged from between 168–177 dB re 1 µPa measured outside the bubble curtain approximately 750 m from the piles (Küsel et al. 2024).

Vibratory hammers may be used as an alternative to impact pile driving, and the noise produced is non-impulsive and nearly continuous. The vibratory hammer continuously exerts vertical vibrations into the pile, which causes the sediment surrounding the pile to liquefy, allowing the pile to penetrate the substrate. The vibratory hammer typically oscillates at a frequency of 20–40 Hz (Matuschek and Betke 2009) and produces most of its acoustic energy below 2 kHz. For small piles potentially used in jacket foundations, source levels are expected to be similar to those measured by Buehler et al. (2015), who found measured received levels of 185 dB re 1 µPa at a 10-m distance from a 72-in steel pile.

Techniques that are quickly gaining use for installation of infrastructure in hard rock substrates are down-the-hole (DTH) systems (pile driving and drilling). These systems use a combination of percussive and drilling mechanisms, with a hammer acting directly on the rock to advance a hole into the rock while also advancing the pile into the hole (Guan et al. 2022; NMFS 2022). Noise characteristics for DTH pile driving include both impulsive and non-impulsive components. The impulsive component of the DTH pile driving is the result of a percussive hammer striking the bedrock, while the non-impulsive component is from drilling and air-lifting of cuttings and debris from the pile. While only limited studies have been conducted on DTH pile-driving noise, its characteristics strongly resemble those of impact pile driving but with a higher hammer strike rate, on the order of 10–12 strikes per second (Guan et al. 2022). Most of the acoustic energy from DTH pile driving is concentrated at frequencies below 2 kHz, similar to conventional impact pile driving. Due to the high rate of hammer striking, along with the sounds of drilling and debris clearing out, sound levels in between the pulses are much higher than conventional impact pile driving (Guan et al. 2022). Guan et al. (2022) report measurements from DTH pile drilling during the installation of 0.84-m shafts within 1.22-m steel piles: the single-strike SELs were 138–142 dB re 1 μPa^2s at 10 m.

2.5.10 Decommissioning

When oil and gas platforms become obsolete, they go through a decommissioning process, which may involve partial or complete removal of the platform structure using an explosive-severance technique or mechanical cutting. When using explosives under water, the underwater pressure signature of a detonation is composed of an initial shock wave (characterized by extreme changes in pressure, both positive and negative) followed by a succession of oscillating bubble pulses. This also is generally true for explosive severance of platforms, but the shock wave is modified by passage through the structure and the ocean sediment, while the oscillation bubble is mostly contained within the structure itself, often venting upward inside the structure's legs or conductors. This alters the acoustic energy that is ultimately released into the ocean.

Below-mud-line detonations are likely to produce lower pressure levels at the same propagation distances than open-water shock trial configurations due to absorption through the structure, attenuation of energy by sediments, and the confinement of the explosion within well casings and platform piles. The energy released to the ocean may be 30–70% of an explosion of equivalent weight in the open ocean, depending on the type and configuration of the explosives used; the thickness, age, and type of steel used in the structure; and the type of sediment present at the site. Data have shown that, at 400 ft from the detonation site, the shock wave parameters measured for below-mud-line detonations were less than 10% of the values expected for open-water detonations (BOEM 2016b). Additionally, as the depth of below-mud-line detonations increases, the impact zones for marine species decreases (Barkaszi et al. 2016; BOEM 2016b).

There generally has been a shift to using non-explosive methods (i.e., mechanical cutting) for removing oil and gas infrastructure; however, due to safety and other considerations, these methods may not always be a viable option. A recent study measured received sound levels during the mechanical cutting of well conductor casings on oil and gas platforms in California. The cutters operated at 60–72 RPM, and the cutting time varied widely between cuts (on the order of minutes to hours). At distances of 106–117 m from the cutting, received SPLs were 120–130 dB re 1 µPa, with most acoustic energy falling between 20 and 2,000 Hz (Fowler et al. 2022). This type of sound is considered non-impulsive and could be continuous while cuts are being made, with quieter periods between cuts.

2.5.11 Aircraft

Manned aircraft consist of propeller and jet engines, fixed-wing craft, as well as helicopters. Unmanned systems also exist. For jet engine aircraft, the engine is the primary source of sound. For propeller driven aircraft and helicopters, the propellors and rotors also produce noise. Aircraft, including both jet and propeller types, generally produce low-frequency sound below about 500 Hz (Richardson et al. 1995). Although aircraft noise can be substantial in air, penetration of aircraft noise into the water is limited because much of the noise is reflected off the water's surface (Richardson et al. 1995). The noise penetrates the water column at a critical incident angle or cone. With an idealized flat sea surface, the maximum critical incident angle is ~13 degrees (Urick 1983);

beyond this, sound is reflected off the surface. When the sea surface is not flat, there may be some additional penetration into the water column in areas outside of this 13-degree cone. Nonetheless, the extent of noise from passing aircraft is more localized in water than it is in air.

Richardson et al. (1995) report underwater received levels measured during controlled aircraft flights using hydrophones at 3–18 m depth. These measurements were subsequently compiled in a review by Jiménez-Arranz et al. (2020). Received levels included 124 dB re 1 µPa (dominant frequencies between 56–80 Hz) from a maritime patrol aircraft with an altitude of 76 m, 109 dB re 1 µPa (dominant frequency content below 22 Hz) from a medium utility helicopter (Bell 212) with an altitude of 152 m, and 107 dB re 1 µPa (tonal, 82 Hz) from a turbo prop utility aircraft (Twin Otter) with an altitude of 457 m. Recently published levels associated with unmanned aircraft (Christiansen et al. 2016; Erbe et al. 2017) indicate that source levels are around or below 100 dB re 1 µPa·m.

3 Marine Mammals—General Information on Hearing

3.1 Importance of Sound to Marine Mammals

Marine mammals are highly dependent on acoustic cues as a primary means of communicating and assessing their environment. Sound travels faster and farther in water (~1,500 m/s) than it does in air (~350 m/s), making this a reliable mode of information transfer across large distances and in dark environments, where visual cues are limited. Sound plays an essential role in critical activities like breeding, navigating, avoiding predators, foraging, and maintaining social structure. Marine mammals glean information from a range of acoustic signals, including ambient sounds produced on coral reefs, low-frequency rumbles associated with approaching storms, and vocalizations of other marine fauna. Additionally, toothed whales utilize echolocation clicks to navigate their surroundings and locate prey (Madsen and Surlykke 2013).

3.2 Hearing Anatomy

Like terrestrial mammals, the auditory anatomy of marine mammals generally includes the inner, middle, and outer ear (Ketten 1994). Not all marine mammals have an outer ear, but if it is present, it funnels sound into the auditory pathway. The middle ear acts as a transformer, filtering and amplifying the sound. The inner ear is where auditory reception takes place. The key structure in the inner ear responsible for auditory perception is the cochlea, a spiral-shaped structure containing the basilar membrane and lined with auditory hair cells. Specific areas of the basilar membrane vibrate in response to the frequencies of the acoustic stimulus, causing hair cells mapped to specific frequencies to be differentially stimulated and to send signals to the brain (Ketten 1994).

Although the cochlea and basiliar membrane are well conserved structures for all mammals, there are some key differences in the auditory anatomy of terrestrial mammals when compared with marine mammals. Marine mammals have the unique need to hear in aqueous environments. Amphibious marine mammals (including seals, sea otters, and sea lions) have evolved to hear both in air and under water, and all except phocid pinnipeds have external ear appendages. Cetaceans do not have external ears or air-filled external canals; they do have bony portions of the ear that are much denser than those of terrestrial mammals (Ketten 1994).

All marine mammals have binaural hearing and can extract directional information from sound. But the pathway that sound takes into the inner ear is not well understood for all cetaceans and may not be the same for all species. For example, in baleen whales, bone conduction through the lower jaw and skull is likely to play a role in hearing (Cranford and Krysl 2015) by transferring vibrations to the tympanic bullae, which each vibrate at different frequencies. This mechanism is believed to be the way in which baleen whales experience directional hearing (Morris et al. 2025). Odontocetes have a fat-filled portion of the lower jaw, which is thought to funnel sound towards the ear (Mooney et al. 2012). Hearing tests have been conducted on several species of odontocetes, while only two adolescent individuals of the same baleen whale species (minke whale) have ever been tested

(Houser et al. 2024). Therefore, most of our understanding of baleen whale hearing comes from examining the ears of deceased whales (Erbe et al. 2016; Houser et al. 2017).

Many marine mammal species produce sounds through vibrations in their larynx (Frankel 2002). In baleen whales, for example, air in the lungs and laryngeal sac expands and contracts, producing vibrations and sounds within the larynx (Frankel 2002). Baleen whales produce low-frequency sounds that can be used to communicate with other animals over great distances (Clark and Gagnon 2004). Differences in sound production among marine mammals varies, in part, with their use of the marine acoustic environment. Toothed whales hunt for their prey using relatively high-frequency (10s of kHz) echolocation signals. To produce these signals, they have a specialized structure called the "melon" in the top of their head, which is used for sound production. When air passes through the phonic lips, a vibration is produced, and the melon helps transmit the vibration from the phonic lips to the environment as a directed beam of sound (Frankel 2002). It is generally believed that if an animal produces and uses a sound at a certain frequency, its hearing sensitivity will overlap those frequencies. An animal's hearing range is likely much broader than their range of sound production, as they rely heavily on acoustic information—beyond the signals they produce themselves—to understand their environment.

3.3 Functional Hearing Groups

Marine mammal species have been classified into functional hearing groups based on similar anatomical auditory structures and frequency-specific hearing sensitivity obtained from hearing tests on a subset of species (Finneran 2016; NMFS 2018; Southall et al. 2019). For those species for which empirical measurements have not been made, species are grouped by phylogenetic and ecological characteristics. This concept of marine mammal functional hearing groups was first described in Southall et al. (2007). After a few updates based on newer studies, the science (Southall et al. 2019) and regulations (NMFS 2024) now recognize at least eight functional hearing groups: low-frequency cetaceans, high-frequency cetaceans, very high-frequency cetaceans, sirenians, phocids in air, phocids in water, other marine carnivores in air, and other marine carnivores in water (Southall et al. 2019) (**Table 1**).

NMFS has the regulatory authority over the protection of cetaceans and most pinnipeds species. The U.S. Fish and Wildlife Service oversees the protection of sirenians and other marine carnivores (i.e., polar bears, walruses, and sea otters).

Table 1. Marine Mammal Functional Hearing Groups from the NMFS 2024 technical guidance

Hearing Group	Generalized Hearing Range*
Low-frequency cetaceans (baleen whales)	7 Hz to 36 kHz
High-frequency cetaceans (dolphins, toothed whales, beaked whales, bottlenose whales)	150 Hz to 160 kHz
Very high-frequency cetaceans (true porpoises, *Kogia*, river dolphins, *cephalorhynchid*, *Lagenorhynchus cruciger & L. australis*)	200 Hz to 165 kHz

Hearing Group	Generalized Hearing Range*
Phocid pinnipeds in water (true seals)	40 Hz to 90 kHz
Otariid pinnipeds in water (sea lions, fur seals)	60 Hz to 68 kHz
Phocid pinnipeds in air (true seals)	42 Hz to 52 kHz
Otariid pinnipeds in air (sea lions and fur seals)	90 Hz to 40 kHz
Sirenians	250 Hz to 72 kHz

Notes: Represents the generalized hearing range for the entire group as a composite (i.e., all species within the group), where individual species' hearing ranges may not be as broad. Generalized hearing range chosen based on ~65 dB threshold from composite audiogram, previous analysis in NMFS (2018), Southall et al. (2007), and Southall et al. (2019). Additionally, animals can detect very loud sounds above and below that "generalized" hearing range.
Source: NMFS (2024)

After Southall et al. (2019), a formative study was conducted on hearing in baleen whales (Houser et al. 2024). In a bay off Norway, auditory brainstem response tests were performed in situ on two adolescent minke whales. The upper limit of their hearing range was determined to be between 45–90 kHz, substantially higher than previously thought. This study was conducted while NMFS was updating their 2024 technical guidance, and this information did not inform that guidance.

3.4 Potential Impacts of Underwater Sound on Marine Mammals

The effects of anthropogenic sound on marine life have been studied for more than half a century. In that time, it has become clear that this is a complex subject with many interacting factors and extreme variability in response from one sound source to another and from species to species—even within species (i.e., individuals may have markedly different responses to a similar exposure). But some general trends have emerged from this body of work. First, louder and more impulsive sounds are more likely to create adverse physiological effects, such as auditory injury or TTS. These impacts generally occur at relatively close distances to a source; in comparison, behavioral effects, masking, or increases in stress can occur wherever the sound can be heard. Second, the hearing sensitivity of an animal plays a major role in whether it will be affected by a sound or not, and there is a wide range of hearing sensitivities among marine mammal species. Regulations to protect marine life from anthropogenic sound have been based on these general concepts.

The importance of sound to marine mammals, consequently, means there is potential for adverse effects from unwanted sounds, such as anthropogenic noise. Depending on the level of exposure, context, and type of sound, potential impacts of underwater sound on marine mammals may include non-auditory injury, auditory injury (e.g., permanent hearing loss), temporary hearing loss, behavioral changes, acoustic masking, or increases in physiological stress (Götz et al. 2009). Each of these impacts is discussed below.

***Non-auditory Injury*:** Non-auditory physiological injury is possible for very intense sounds or blasts, such as explosions. This kind of impact is only possible during detonation of explosives in

decommissioning or in the rare occurrence of unexploded ordnances. Although many marine mammals can adapt to large changes in pressure—such as in a deep foraging dive—the shock waves produced by explosives expose the animal to rapid, large changes in pressure, which in turn causes a rapid expansion of air-filled cavities (e.g., the lungs). This expansion forces the surrounding tissue or bone to move beyond their limits, potentially leading to tears, breaks, or hemorrhaging. The extent and severity of injury depends on several factors, including the size of the air-filled cavities, ambient pressure, proximity to the blast, and size of the blast (U.S. Navy 2017). In extreme cases, lung damage can be so severe that it can directly kill the animal; a less severe lung injury may indirectly lead to death due to an increased vulnerability to predation or inability to complete foraging dives.

Auditory injury and Temporary Hearing Loss: An animal's auditory sensitivity to a sound depends on the spectral, temporal, and amplitude characteristics of the sound (Richardson et al. 1995). When exposed to sounds of significant duration and amplitude (typically within close range of a source), marine mammals may experience noise-induced threshold shifts and auditory injury, which includes, but is not limited to, PTS. PTS is an irreversible loss of hearing due to hair-cell loss or other structural damage to auditory tissues (Saunders et al. 1985; Henderson et al. 2008). TTS is a relatively short-term (e.g., within several hours or days), reversible loss of hearing following noise exposure (Southall et al. 2007; Finneran 2015), often resulting from hair-cell fatigue (Saunders et al. 1985; Yost 2000). During TTS, an animal's hearing threshold rises, meaning that a sound must be louder to be detected. Prolonged or repeated exposure to sounds at levels that are sufficient to induce TTS—without adequate recovery time—can lead to auditory injury, including PTS (Southall et al. 2007; Finneran 2015). Research suggests that some odontocete species may have mechanisms to selectively reduce their hearing sensitivity when provided with a precursory cue to signal that an intense sound is about to arrive, which may help them to protect themselves from auditory injury or TTS (Nachtigall and Supin 2013).

Behavioral Impacts: When exposed to underwater sound, marine mammals may show varying levels of behavioral disturbance ranging from no observable response to overt behavioral changes. They may flee from an area to avoid the noise source, change their vocal activity, stop or change foraging behaviors, or change their typical dive or social behavior, among other responses (National Research Council 2003). The implications of behavioral disturbance can range from temporary displacement of an individual to long-term consequences on a population, such as a reduction in fitness related to decreased foraging success.

Studies have shown that noise level alone often fails to reliably predict behavioral responses because several contextual factors play a role in whether and how an animal will respond (Richardson et al. 1995; Southall et al. 2007; Ellison et al. 2011; DeRuiter et al. 2013; Gomez et al. 2016). Some of these factors include the following:

- Exposure context (e.g., behavioral state of the animal, habitat characteristics)
- Biological relevance of the signal (e.g., whether the signal is audible, whether the signal sounds like a predator)

- Life stage of the animal (e.g., juvenile, mother, or calf)
- Prior experience of the animal (e.g., is it a novel sound source)
- Sound properties (e.g., duration of sound exposure, SPL, sound type, mobility or directionality of the source)
- Physical properties of the medium that may affect how the sound propagates (e.g., bathymetry, temperature, salinity) (Southall et al. 2021)

It is possible that marine mammals may become habituated (show a reduced response) or sensitized (show an increased response) when repeatedly exposed to sounds (Nisbet 2000; Bejder et al. 2009). Tolerance is defined as "the intensity of disturbance that an individual tolerates without responding in a defined way" (Nisbet 2000). Over the course of a habituation process, individual tolerance levels may increase; conversely, tolerance levels may decrease as individuals become sensitized to specific stimuli (Nisbet 2000; Bejder et al. 2009).

Variability exists across species and among individuals, resulting in variable thresholds of disturbance (Richardson et al. 1995; Gomez et al. 2016). Due to these many factors, behavioral impacts are challenging to both predict and measure, and this uncertainty remains an active field of study in marine mammal bioacoustics.

Auditory Masking: Auditory masking (also called acoustic masking) occurs when a sound signal that is of importance to a marine mammal (e.g., communication calls, echolocation, and environmental sound cues) is undetectable due to other noise present in the same frequency band. In other words, masking occurs when a noise source overlaps in time, space, and frequency with—thus obscuring—a signal of interest (Richardson et al. 1995; Clark et al. 2009). Auditory masking may occur over larger spatial scales than noise-induced threshold shift or behavioral disturbance. Masking can reduce an individual's "communication space" (the range at which it can effectively transmit and receive acoustic cues from conspecifics) or "listening space" (the range at which it can detect relevant acoustic cues from the environment). A growing body of research is building on the risk of masking from anthropogenic sources, ecological significance of masking, and anti-masking strategies used by marine mammals (Turnbull and Terhune 1993; Serrano and Terhune 2001; Scheifele et al. 2005; Clark et al. 2009; Holt et al. 2009; Erbe et al. 2016; Putland et al. 2017; Branstetter and Sills 2022). This understanding is essential to fully address auditory masking in regulations or mitigation approaches (Erbe et al. 2016). In the interim, most assessments only consider the overlap in frequency between the sound source and hearing range of marine mammals.

Physiological Stress: The presence of anthropogenic noise, even at low levels, can increase physiological stress in marine mammals (Wright et al. 2007; Kight and Swaddle 2011). For example, various hormone levels (including cortisol, corticosterone, aldosterone, catecholamines, reproductive hormones, thyroid hormones, among others) may change in response to stress (Watt et al. 2021); animals also may exhibit increased respiration rates, an increase or decrease in heart rate (Williams et al. 2022), or changes in other bodily functions. With prolonged stress from noise,

these physiological changes may be tied to lower reproductive rates, decreased fertility, compromised immune function (Rolland et al. 2012), or disrupted metabolic regulation—potentially leading to accelerated aging or slowed growth.

It can be difficult to observe or sample these responses in wild animals. Several methods have emerged that allow for reliable measurements in marine mammals (Hunt et al. 2014) and may include sampling through blood, saliva, blubber, feces, urine, or the blow produced by a whale, or tagging animals with heart rate monitors (Rolland et al. 2005). The impact of physiological stress on an individual or population can be exacerbated by other factors, such as the age or condition of the animal (e.g., undergoing stress during a critical life stage, such as reproduction, or while its health is already compromised) or its vulnerability from other stressors (e.g., food scarcity, habitat loss).

3.4.1 Thresholds for Auditory Injury

The MMPA)(16 U.S.C. § 1362) and ESA)are the most relevant statutes when considering potential harm from anthropogenic noise on marine mammals.

The MMPA prohibits the "take" of marine mammals, defined as the harassment, hunting, capturing, or killing—or attempt of any of those actions—of a marine mammal. This act requires that an incidental take authorization be obtained from the NMFS for the incidental take of marine mammals as a result of anthropogenic activities. The MMPA divides the effects on marine mammals that could result in a take into two levels, defined as follows:

- **Level A**: Any act of pursuit, torment, or annoyance that has the potential to injure a marine mammal or marine mammal stock in the wild.
- **Level B**: Any act of pursuit, torment, or annoyance that has the potential to disturb a marine mammal or marine mammal stock in the wild by causing a disruption of behavioral patterns including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering, but that does not have the potential to injure a marine mammal or marine mammal stock in the wild.

With respect to anthropogenic sounds, NMFS publishes acoustic thresholds, otherwise known as "Acoustic Guidance," to delineate the sound levels at which potential takes could occur. Level A takes comprise auditory injury, whereas Level B takes include behavioral effects as well as TTS. The current regulatory framework used by NMFS for evaluating an acoustic take of a marine mammal involves assessing whether the animal's received sound level exceeds a given threshold. For Level A, this threshold differs by functional hearing group; for Level B, the same threshold is used across all marine mammals.

The current NMFS (2024) injury (Level A) thresholds consist of dual criteria of L_{pk} and 24-hour, cumulative SEL thresholds for both impulsive and non-impulsive sources (**Table 2**). These criteria, along with information about source levels and sound propagation, are used to predict the potential distance from a sound source within which injury may occur. To be conservative, the

criterion that results in the largest distance is generally used. SEL thresholds are frequency-weighted, which means that the sound is filtered based on the frequency-specific hearing sensitivity of the functional hearing group, de-emphasizing the frequencies at which the animals are less sensitive; see **Section 2.2** for the frequency range of hearing for each group. The frequency weighting functions are described in detail in NMFS (2024).

Table 2. Acoustic thresholds for onset of auditory injury (AINJ) and temporary threshold shift (TTS) for marine mammals for both impulsive and non-impulsive sound sources

Marine Mammal Functional Hearing Group	Effect	Impulsive Source L_{pk} (dB re 1 µPa)	Impulsive Source Weighted SEL_{24h} (dB re 1 μPa^2s)	Non-Impulsive Source Weighted SEL_{24h} (dB re 1 μPa^2s)
Low-frequency cetaceans	AINJ	222	183	197
“	TTS	216	168	177
High-frequency cetaceans	AINJ	230	193	201
“	TTS	224	178	181
Very high-frequency cetaceans	AINJ	202	159	181
“	TTS	196	144	161
Phocid pinnipeds underwater	AINJ	223	183	195
“	TTS	217	168	175
Otariid pinnipeds underwater	AINJ	230	185	199
“	TTS	224	170	179
Phocid pinnipeds in air	AINJ	162	140	154
“	TTS	156	125	134
Otariid pinnipeds in air	AINJ	177	163	177
“	TTS	171	148	157
Sirenians	AINJ	225	186	200
“	TTS	219	171	180

Notes: L_{pk} values are unweighted within the generalized hearing range of marine mammals (i.e., 7 Hz to 160 kHz). SEL values use a 24-hour accumulation period unless stated otherwise and are weighted based on the relevant marine mammal functional hearing group (Accomando et al. 2025). Underwater thresholds are in dB re 1 µPa = decibels relative to 1 micropascal; dB re 1 μPa^2s = decibels relative to 1 micropascal squared second; thresholds in air are in dB re 20 µPa = decibels relative to 20 micropascal; dB re 20 μPa^2s = decibels relative to 20 micropascal squared second. Non-impulsive sources can also be compared to the L_{pk} criteria if there is a chance of exceedance. Source: NMFS (2024).

Auditory Injury from Explosives: The supersonic shock wave from an explosion transitions to a normal pressure wave at a range determined by the weight and type of the explosive used. Because the distances associated with TTS and auditory injury exceed this transition range, the standard impulsive TTS and auditory injury thresholds (**Table 2**) are appropriate for assessing potential auditory impacts (NMFS 2024).

3.4.2 Thresholds for Behavioral Disturbance

For behavioral disturbance (Level B), NMFS currently uses a threshold of 160 dB re 1 µPa SPL for non-explosive impulsive sounds (e.g., airguns and impact pile driving) and intermittent sound sources (e.g., scientific and non-tactical sonar), and 120 dB re 1 µPa SPL for continuous sounds (e.g., vibratory pile driving, drilling) (NMFS 2025). This "unweighted" criterion applies to all marine mammal species. In-air behavioral thresholds for harbor seals and non-harbor seal pinnipeds are 90 dB re 20 µPa SPL and 100 dB re 20 µPa SPL, respectively (NMFS 2025). In contrast with SEL-based thresholds, the accumulation of acoustic energy over time is not relevant for this criterion—meaning that a Level B take can occur even if an animal experiences a received SPL of 160 dB re 1 µPa very briefly in one instance.

Although the Level B criterion is typically applied as a binary threshold—assuming no effect below the threshold and consistent effects at or above it—individual responses to sound exposure can vary significantly. As previously noted, a range of factors influence whether an individual is affected, leading to considerable variability even under similar exposure conditions. The context in which a sound is received affects the nature and extent of response (Southall et al. 2007; Ellison et al. 2011).

To better account for this complexity, Wood et al. (2012) introduced a more nuanced, graduated step function for Level B harassment. This approach estimates the proportion of individuals likely to exhibit behavioral disturbance at varying received sound levels. These probabilistic thresholds incorporate observed sensitivities in certain species, particularly beaked whales and migrating mysticete whales (**Table 3**), and provide an alternative method for estimating Level B takes in these groups.

The M-weighting functions used in this model—originally developed by Southall et al. (2007) and used by Wood et al. (2012)—differ from the NMFS (2024) weighting functions. While M-weighting is intended to assess the likelihood of audibility, the NMFS (2024) functions are used to predict the likelihood of auditory injury.

Table 3. Probabilistic disturbance $L_{p,rms}$ thresholds (M-weighted) used to predict a behavioral response (in dB re 1 µPa)

Marine Mammal Group	120	140	160	180
Porpoises/beaked whales	50%	90%	-	-
Migrating mysticete whales	10%	50%	90%	-
All other species/behaviors	-	10%	50%	90%

Probabilities are not additive and reflect single points on a theoretical response curve. Source: Wood et al. (2012).

Behavioral Disturbance from Explosives: Because the duration is so short, NMFS does not anticipate that single blast events within a 24-hour period would induce behavioral effects, as long as the exposures are below the onset of TTS thresholds for frequency-weighted SEL and peak pressure level. Only short-term startle responses are expected for behavioral responses. For

multiple detonations, the threshold applied for behavioral effects is that same TTS threshold minus 5 dB; see **Table 2** for TTS threshold values.

3.4.3 Thresholds for Non-Auditory Injury

Shock waves associated with underwater detonations can induce non-auditory physiological effects, including mortality and direct tissue damage (i.e., severe lung injury, slight lung injury, and gastrointestinal tract injury). The magnitude of the acoustic impulse, measured in pascal-seconds (Pa-s), is the integral of the positive-pressure shock pulse over time and serves as the threshold to predict non-auditory lung injury and mortality. Because lung capacity or size is generally directly related to the size of an animal, body mass is one parameter used to predict the likelihood of lung injury. Additionally, the depth of the animal (which represents the ambient pressure conditions of the animal) is used as a scaling parameter for lung volume. Gastrointestinal tract injury potential is identified using the peak SPL and is considered to occur beginning at levels of 237 dB re 1 µPa.

The U.S. Navy established thresholds to assess the potential for mortality and slight lung injury from explosive sources based on a modified Goertner Equation (U.S. Navy 2017). This model is recommended by NMFS for predicting injury impacts to marine mammals from explosives.

Tables 4 and 5 list the equations used to calculate thresholds based on effects observed in 50% and 1% of animals, respectively.

Table 4. U.S. Navy impulse and peak pressure threshold equations for estimating numbers of marine mammals and turtles that may experience mortality or injury due to explosives

Impact Assessment Criterion	Threshold
Mortality – Impulse	$144M^{1/3}(1+ D/10.1)^{1/6}$ Pa-s
Injury – Impulse	$65.8M^{1/3}(1+ D/10.1)^{1/6}$ Pa-s
Injury – Peak Pressure	L_{pk} of 243 dB re 1 µPa

Notes: Where M is animal mass (kg) and D is animal depth (m). Source: U.S. Navy (2017)

Table 5. U.S. Navy impulse and peak pressure threshold equations for estimating distances to onset of potential effect for marine mammal and turtle mortality and slight lung injury due to explosives

Impact Assessment Criterion	Threshold
Onset Mortality – Impulse	$103M^{1/3}(1+ D/10.1)^{1/6}$ Pa-s
Onset Injury (Non-auditory) – Impulse	$47.5M^{1/3}(1+ D/10.1)^{1/6}$ Pa-s
Onset Injury (Non-auditory) – Peak Pressure	L_{pk} of 237 dB re 1 µPa

Notes: Where M is animal mass (kg) and D is animal depth (m). These thresholds are relevant for mitigation planning. Source: U.S. Navy (2017).

3.5 General Approach to Acoustic Exposure Modeling

To predict the number of individuals of a given species that may be exposed to harmful levels of sound from a specific activity, a series of modeling exercises are conducted. First, the sound field of a sound-generating activity is modeled based on characteristics of the source (e.g., source level, frequency, directionality, beamwidth, deployment depth, array characteristics) and the physical environment (e.g., sediment type, sediment layers, sound speed, bathymetry). From the sound field, the range to the U.S. regulatory acoustic threshold isopleths can be predicted. This approach is referred to as *acoustic modeling*. By overlaying the marine mammal density information for a certain species or population in the geographical area of the activity, the number of animals exposed within the acoustic isopleths is then predicted. This is called *exposure modeling* (**Figure 3**). Some models further incorporate animal movement to make more realistic predictions of exposure numbers. Animal movement models may incorporate behavioral parameters, including swim speeds, dive depths, course changes, or reactions to certain sound types. Exposure modeling may be conducted for a range of scenarios, including different seasons, energy (e.g., size of airgun array or pile-driving hammers), mitigation strategies (e.g., 6 dB versus 10 dB of attenuation), and levels of effort (e.g., size of the survey).

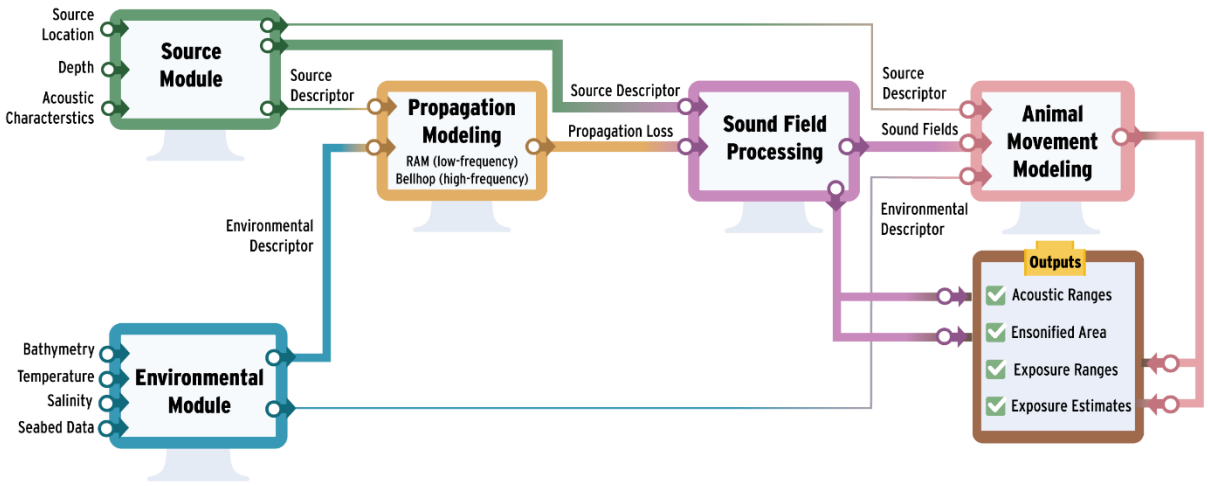

Figure 3. Overview of exposure modeling process
Figure credit: BOEM

4 Marine Mammals—Impacts of Underwater Sound

4.1 Potential Impacts of Non-BOEM Acoustic Sources

The underwater soundscape in many areas of the ocean contains sounds from anthropogenic activities. The largest contributors tend to be geophysical (seismic) exploration and commercial shipping. Where these activities occur in highly industrialized environments (like the Gulf of America [GOA]), ambient sound levels below 1 kHz typically are very high (Wiggins et al. 2016; Frasier et al. 2024). Other sources of anthropogenic activity in the ocean that produce sound include commercial and recreational fishing, dredging, coastal and offshore construction, mineral exploration in offshore areas, Navy sonar activity, and ocean research activities. A brief discussion of some of these sources, and their potential effects on marine mammals, are discussed below.

4.1.1 Navy Sonar

The U.S. Navy uses low (< 1 kHz) and mid-frequency (1–10 kHz) sonar to detect and track submarines, and to locate mines. Strandings may occur when sound disorients animals, causing them to change their normal dive behaviors, experience increased stress levels, or become unable to navigate or communicate effectively. There have been numerous cases of Navy sonar use linked to marine mammal strandings, primarily of beaked whales (D'Amico et al. 2009; U.S. Navy Marine Mammal Program 2017).

Historically, it has been difficult to assess why these strandings occurred. It was not until a stranding happened that researchers became aware of and could investigate a situation; often, by then, it was too late to understand the exact situation of the stranding. As a result, a robust research program now exists to better understand the effects of Navy sonar on marine mammals (McCarthy et al. 2011; Manzano-Roth et al. 2016; Harris et al. 2017); this research program largely focuses on behavioral effects. One consistent finding from these studies is that animals tend to cease their normal activity and leave the vicinity when Naval sonar is in use. One study found that the playback of killer whale calls elicited the same response as Naval sonar in beaked whales (Tyack et al. 2011); the animals stopped making foraging echolocation clicks and took an unusually long time to ascend from their deep foraging dives. The authors hypothesized that, due to the similarity in frequencies, the whales may have mistaken the sonar sound for those produced by a predator.

4.1.2 Vessel Noise

Vessel noise can be a dominant component of marine soundscapes near areas with heavy shipping traffic. Source levels for large container ships can range from 177 to 200 dB re 1 µPa·m, or more (McKenna et al. 2013), with most energy concentrated below 1 kHz. This low-frequency noise from merchant ships can travel extremely far distances and has been shown to be detectable at 125 km from the source (Aulanier et al. 2017). A recent assessment of the underwater soundscape in the GOA between 2018–2020 reported vessel traffic as the second major source of anthropogenic noise in the region (after airgun noise), with vessel activity being present between 10–100% of the

time, and a greater presence in the summer months (Amaral et al. 2022). Due to the chronic presence of vessel noise in the GOA, marine mammals may experience behavioral or acoustic changes, masking, and/or an increase in physiological stress.

Behavioral changes have been observed in marine mammals as a result of vessel-noise exposure. Reviews of the literature on marine mammals and vessel noise (Richardson et al. 1995; Erbe et al. 2019) revealed that changes in behavior vary widely across species. The wide range of responses includes flee responses at long ranges and longer, deeper dives in beluga whales (Finley 1990; Martin et al. 2023); disruption of resting behavior in harbor seals (Mikkelsen et al. 2019); increases in swim velocities in belugas (Finley 1990), humpbacks (Sprogis et al. 2020) and narwhals (Williams et al. 2022); longer inter-breath intervals in dolphins (Nowacek et al. 2001); increased breathing synchrony in dolphin pods (Hastie et al. 2003); and changes in respiration rates for humpback whales (Sprogis et al. 2020). Changes to foraging behavior, which can have a direct effect on an animal's fitness, have been observed in porpoises (Wisniewska et al. 2018) and killer whales (Holt et al. 2021) in response to vessel noise.

Some marine mammals may change their acoustic behaviors in response to vessel noise, either due to a sense of alarm or to avoid masking. For example, fin whales (Castellote et al. 2012) and belugas (Lesage et al. 1999) have altered the frequency characteristics of their calls in the presence of vessel noise. When vessels are present, bottlenose dolphins have increased the number of whistles (Buckstaff 2004; Guerra et al. 2014), and sperm whales decrease the number of clicks (Azzara et al. 2013); humpbacks and belugas have been seen to completely stop vocal activity (Finley 1990; Tsujii et al. 2018). Some species may change the duration of vocalizations—fin whales shorten their calls (Castellote et al. 2012) or increase call amplitude (killer whales; Holt et al. 2009) to avoid acoustic masking. Holt et al. (2015) found that, as bottlenose dolphins increased the amplitude of their calls, metabolic rates increased by 20–50%. Although this study was not tied directly to exposure to vessel noise, it provides insight about the potential energetic cost of vocal changes (i.e., increases in vocal effort such as louder, longer, or increased number of calls).

Understanding the scope of acoustic masking is difficult to observe directly, but several studies have modeled the potential decrease in "communication space" when vessels are present (Clark et al. 2009; Erbe et al. 2016; Putland et al. 2017). For example, Putland et al. (2017) showed that, during the closest point of approach (< 10 km) of a large commercial vessel, the potential communication space of Bryde's whales was reduced by 99% compared to ambient conditions.

Finally, several studies have demonstrated a correlation between low-frequency anthropogenic noise and physiological stress in baleen whales. Rolland et al. (2012) showed that fecal cortisol levels (an indicator of stress) in North Atlantic right whales decreased following the 9/11 terrorist attacks, when vessel activity was significantly reduced. Similar responses have been observed in humpback whales (Pallin et al. 2022) and narwals (Watt et al. 2021). On daily and monthly timescales, gray whales also have shown changes in adrenal stress depending on vessel activity (Lemos et al. 2022). Interestingly, North Atlantic right whales do not seem to avoid vessel noise nor

vessel presence (Nowacek et al. 2004), yet they may incur physiological effects (e.g., stress), as demonstrated by Rolland et al. (2012).

Understanding unobservable effects such as physiological changes is especially important in the absence of observable effects. In some cases, animals may stay in an area where they are exposed to a stressor like chronic vessel noise because the benefits (e.g., prey availability, habitat suitability) outweigh the costs to the animal (e.g., Nehls et al. 2024). In environments where vessel activity is present for substantial periods of time, vessel noise likely serves as a chronic stressor for many marine mammals.

4.2 Potential Impacts of BOEM-Related Sound Sources

4.2.1 Seismic Surveys (Airguns)

Seismic surveys can cover large swaths of the ocean as mobile sound sources that regularly emit high energy pulses into the marine environment. This can be particularly impactful for populations with high fidelity in a given area, especially during ecologically important times, such as feeding, mating, or calving.

Decades of research have been amassing since the 1980s on the potential effects of airgun noise on marine mammals (Richardson et al. 1986; Ljungblad et al. 1988; McCauley et al. 1998; Gordon et al. 2003; Johnson et al. 2007; Affatati and Camerlenghi 2023). The potential effects of airgun noise on marine mammals include physical injury, physiological effects, behavioral disruption, and acoustic masking. Depending on the specifics of the survey, behavioral effects and acoustic masking may occur on the scale of tens of kilometers from the survey vessel. Airgun noise also may harm marine mammals indirectly if there are changes to the distribution and abundance of their prey within key foraging grounds. See **Section 7** for information about impacts to prey species.

While auditory injury is possible, an animal must be very close to a seismic airgun survey to be exposed to injurious sound levels. Auditory injury thresholds vary with hearing group, so the scale at which it could occur ranges from several kilometers for low-frequency cetaceans to < 50 m for high-frequency and very high-frequency cetaceans. Because marine mammals are mobile, they are likely to move away from a sound before sufficient duration has passed to cause auditory injury or TTS. If mitigations (e.g., exclusion zones) are applied, potential effects are even less likely to occur.

Physiological responses are also possible and more likely than auditory injury. However, these responses are difficult to study in the wild. Williams et al. (2022) monitored the cardiovascular, respiratory, and locomotor responses of narwhal (n=2) during seismic survey activities. The animals' heart rate switched between bradycardia (excessively slow heart rate) and tachycardia (excessively fast heart rate) during exposure, while the animals simultaneously reduced their glide duration and increased their stroke frequency—all representing an energetic cost of more than double for a dive. Prolonged exposure can lead to more serious consequences, such as physiological instability and some of the injuries previously described.

The most likely and well-studied effects to marine mammals from seismic surveys are behavioral. Many studies have been conducted over the last 40 years—providing insight about the effects of airgun surveys on marine mammals—and are organized here by behavioral state. Based on the evidence available, which is summarized below, there is a wide range of behavioral responses by marine mammals to seismic surveys.

4.2.1.1 Gross Movement

Many early studies focused on assessing the potential for a gross change in behavior of marine mammals in response to seismic surveys. Baleen whales were documented initiating avoidance behaviors to full-scale seismic surveys at distances of less than 10 km (Richardson et al. 1986; Ljungblad et al. 1988; McCauley et al. 1998; Johnson et al. 2007) and as far away as 20 km (Richardson et al. 1999). Yazvenko et al. (2007b) found limited redistribution of gray whales during a full seismic survey (i.e., two to four fewer observed whales) when sound energy was highest. However, the total animals observed in the area remained stable throughout the survey period, with no sudden flight reaction from the animals to the seismic survey. In a different study, fin whales moved away from a seismic survey during the first 72 hours of a 10-day seismic survey, with the displacement persisting well beyond the seismic survey (Castellote et al. 2012). Another study noted that sperm whales in the GOA previously observed in an area being surveyed were found only on the periphery of the survey area after 2 days of survey; they were then observed at a range of only 60 km after 5 days of activity in the area (Mate et al. 1994). In an assessment of protected species observer data, Barkaszi and Kelly (2019) found no statistical differences in the closest point of approach of Rice's whales or beaked whales to airgun surveys operating at full power when compared to silent periods. However, at the closest point of approach of *Kogia* species, these very high-frequency cetaceans were significantly farther away during full-power operations than during minimum source power operations, ramp-up, or silent periods, indicating an avoidance response to the full-power operations.

Many of the aforementioned studies were opportunistic as opposed to experimentally controlled; therefore, confounding factors such as the presence or noise of the survey vessel or movement of prey were not necessarily observed or accounted for but may play a substantial role in the variability of response by the animals.

4.2.1.2 Migration

In a comprehensive series of behavioral response studies, Dunlop et al. (2016) evaluated the effects of a range of airgun arrays on the behavior of migrating humpback whales in order to develop a dose-response curve for humpback whale to seismic survey noise. In one study, the researchers found that, when the seismic vessel towing a 20 in^3 airgun was in the migratory path of the humpback whales, the animals decreased their dive time and speed of southward movement (Dunlop et al. 2015). Dunlop et al. (2016) found that ramping up the airgun made no difference in comparison to the full-power source, and that the animals avoided the survey vessel at greater distances than the mitigation zone. During seismic surveys with a 3,130 in^3 array, Dunlop et al. (2017a) found changes in respiration rate and southward migration speed when animals were

within 4 km of the survey vessel or a received SEL of 135 dB re 1 μPa^2s. The team conducted a series of dose-response assessments (Dunlop et al. 2017b) and found that—when including single airguns, small array, and commercial array data—there was a 50% probability of response at received levels of 150 dB re 1 μPa^2s when an animal was within 2.5 km of the airgun source (Dunlop et al. 2018). The overall conclusion from these studies was that changes in movement were small, temporary, and likely in part attributed to vessel presence.

However, there may be differences in vulnerability to underwater sound based on life stage. For example, a lactating female may suffer greater energy deficits from such disturbances during migration than other demographics. Kavanagh et al. (2016) remarked that observed behavioral responses were not always attributed to the exposure to the seismic surveys, and that water depth and other environmental conditions likely played a role in responses. McCauley et al. (2000b) also found that migrating humpback whales avoided a seismic survey vessel at 4 km, while resting humpbacks avoided the vessel at a distance of 7–12 km.

4.2.1.3 Social and Acoustic Behavior

Effects on humpback whale movement have been observed within 4 km of a survey, but Dunlop et al. (2020) also found changes in social behavior beyond 4 km, namely, a 50% reduction in joining behavior (i.e., joining in breeding vocalizations) at approximately 7.5 km and a reduction to 0–20% at 2 km from the vessel. There did not appear to be a relationship between the magnitude of response and airgun size or received level, and ramping up the airgun was not useful in mitigating the disruption to social behavior. Dunlop et al. (2020) speculated that these behavioral effects, observed at larger ranges than expected, were likely attributed in part to masking of communication signals.

Changes in vocalizations have been seen across several baleen whale species. In another study of humpback whales, Cerchio et al. (2014) found there was a significant decrease in the number of humpback whales singing (a breeding display) due to increasing received levels associated with a seismic survey. McDonald et al. (1995) observed that blue whales stopped singing within a 10-km radius of a seismic survey. In another set of studies, the call rates of bowhead whales during autumn migration were compared before, during, and after airgun use at sites near (45 km) and distant (> 104 km) to the activities. Call rates dropped at the nearby sites when received levels were between 116–129 dB re 1 µPa (10–450 Hz) but not at distant sites, where received levels were 99–108 dB re 1 µPa (Blackwell et al. 2013).

In a subsequent study to investigate whether the calls decreased due to a cessation of calling or because the animals moved away, vocalizations were recorded at five sites at varying distances from a seismic survey with a 3,147 in^3, 24-gun array (Blackwell et al. 2015). Bowhead whales increased their calling rates as the cumulative SEL increased up to around 94 dB re 1 μPa^2s (when call rates leveled off), decreased when cumulative SEL exceeded 127 dB re 1 µPa2s, and ceased altogether when sound levels were above 160 dB re 1 µPa2s. Thode et al. (2020) reported similar findings of cessation when sound levels were excessive. Blackwell et al. (2015) also found that calling rates were five to six times higher at the farthest recording site than at sites closer to the

survey, indicating that the animals decreased their call rates when in proximity to seismic operations. Of note, there was no significant change in calling rate for shallow hazard surveys utilizing an airgun with volumes up to 880 in^3 (Blackwell et al. 2015).

The risk for complete masking from airguns is low relative to continuous sounds (e.g., ship noise) due to the duty cycle of the airgun signal (approximately 6–10%, or a 1-second signal every 10–15 seconds). However, as evidenced here, it may cause animals to change their call or song characteristics to compensate for the partial loss of communication space.

4.2.1.4 Fine-scale Movement Behavior

To understand the potential effects of seismic airgun survey noise on the behavior of sperm whales, a multi-year (2002–2005), controlled exposure experiment monitored the diving, swimming, and vocalization behaviors of eight sperm whales using D-tags (Jochens et al. 2008). While emphasizing limited statistical power due to low sample size, the study documented that the sperm whales received sound levels up to 167 dB re 1 µPa peak-to-peak (or SPL of 147 dB re 1 µPa) and did not avoid airgun arrays during ramp ups (at a distance of 7.3–12.5 km) or full-power operations (at a distance of 1–12 km; Madsen et al. 2006; Jiménez-Arranz et al. 2020). Only one of eight tagged animals exhibited a change in their dive pattern behavior, resting at the surface for 4 hours during the survey (Miller et al. 2009). This discrepancy highlights the need to have a robust sample size to capture the inherent variability in marine mammal behavior. Swimming pitch during foraging dives was 6% lower during exposure, though not statistically significant (Miller et al. 2009). Jochens et al. (2008) concludes that there were no biologically significant effects of seismic activities on sperm whales; however, due to the limited sample size and exposure sound levels, this finding cannot be viewed as conclusive.

In another study, comprehensive visual and acoustic monitoring was conducted during a seismic survey, with three vessels each towing two 2,400 in^3 airgun arrays in order to minimize exposure of gray whales to sound levels exceeding the behavioral impact threshold (Aerts et al. 2022; Rutenko et al. 2022). Mitigations were implemented for the comprehensive real-time monitoring; however, behavioral and respiratory responses were not eliminated (Gailey et al. 2022). As cumulative SEL increased, respiration intervals decreased, dive times decreased, and animals spent less time at the surface. The movement of whales also changed with increasing cumulative SEL, with whales appearing to avoid the survey vessel by moving closer to shore, moving perpendicularly to the vessel, and changing their speed. It is worth noting, however, that the primary factors for predicting behavior and respiratory responses were animal behavioral state and depth, not the anthropogenic activity.

Baleen whales are not the only species observed moving closer to shore in response to a seismic survey. Heide-Jørgensen et al. (2021) observed narwhals moving toward the shore as sound levels increased at a range of 10–15 km. They also found that narwhals increased their horizontal speed by 30% up to 2 hours before the survey vessel was in sight, changing their swimming speed and direction at distances between 5 and 24 km. Avoidance reactions to the airgun were detected at a range of > 5 km and > 11 km from the seismic vessel for a 207 in^3 airgun and 1,040 in^3 airgun array,

respectively. Tagged harbor porpoises showed a range of fine-scale movement responses (i.e., rapid and directed movement away, shorter/shallower dives, no response) to 1 minute of pulses from a single 10 in^3 airgun at ranges of 420–690 m and received levels of 135–147 dB re 1 μPa^2s (van Beest et al. 2018). Movement returned to normal within 8 hours. This was a similar response seen after the animals were captured and tagged for the study.

4.2.1.5 Feeding

Researchers have observed the responses of feeding gray whales to a 100 in^3 airgun and found that there was a 50% probability that the whales would stop feeding and move away from the area when the received levels reached 173 dB re 1 µPa SPL (Malme et al. 1986). However, Yazvenko et al. (2007a) found no change in feeding activity of western gray whales off Sakhalin Island, Russia (< 50-m water depth) during a 3D seismic survey overlapping their foraging grounds. In a study of the impact of airgun noise on narwhals, Tervo et al. (2021) found a 50% reduction in narwhal buzz rates when an operational airgun vessel was 12 km from the whales, and foraging ceased altogether when animals were 7–8 km from the vessel. Miller et al. (2009) found sperm whale buzz rate—a proxy for capturing prey—was 19% lower during airgun surveys, though this finding was not statistically significant.

4.2.1.6 Overall Conclusions Regarding Airgun Effects on Marine Mammal Behavior

It is worth reiterating that the opportunistic nature of many of these studies presents confounding factors (e.g., presence of the survey vessel or the movement of prey) that cannot necessarily be ruled out as the potential cause (or at least a contributing factor) for the responses observed. In addition, there are environmental factors that appear to play a significant and potentially greater role (than the seismic activity) in the variable behavior observed in individuals. Lastly, there are many interacting contextual and animal-specific factors that play a role in the possible response of a marine mammal to airgun noise.

The high variability in marine mammal responses depends on the species, context, environmental conditions, and exposure scenario. Although there is not a clear correlation with received level, behavioral effects are consistently seen at much longer ranges than those predicted based on the NMFS behavioral threshold alone. Certain species groups (i.e., low-frequency cetaceans) appear to be more susceptible to low-frequency noise; however, based on the significant overlap in the frequency of the sound source and the frequency range of best hearing, numerous studies suggest that at least some species in all hearing groups appear vulnerable to behavioral disturbance from airgun noise. It is not clearly evident whether these effects will yield biologically meaningful impacts on an individual or population.

In addition, the response strategy may vary across taxa, with some species leaving a disturbed area, while others stay. In these cases, it is important to note that not all effects may be visible or audible, as an animal constantly exposed to noise may appear to behave normally but could be experiencing chronic stress. This potential phenomenon is not yet well understood, as stress

physiology studies are difficult to perform in the wild and may also be affected by sampling bias (i.e., the mere sampling of biomarkers may induce stress in an animal).

All other things being equal, disturbance may be more costly to an animal with a longer window of exposure (one that is resident or resting in an area) compared to an animal traveling through an area. Greater energetic costs also may be associated with disruptions to certain behaviors (such as migrating or foraging) or particular demographics (such as lactating or pregnant females).

4.2.2 Airgun Alternatives

As alternative seismic technologies are reaching market readiness, field studies are just beginning to take place. Often, these studies are focused on obtaining side-by-side comparisons of geophysical data compared to traditional airgun surveys or conducted to obtain a more accurate sense of source levels, which can then be used for more accurate modeling predictions. For example, the Sound and Marine Life Joint Industry Programme recently completed sea trials using the Integrated Projector Node (IPN) MV source (Alfaro et al. 2023; Li and Martin 2025). This study aimed to compute the effective far-field source levels of the MV source using 1-IPN and 2-IPN configurations. Results were used to estimate the distances at which marine mammal hearing groups may experience auditory injury and TTS. The expected maximum distances for auditory injury thresholds (for any marine mammal hearing group) were ≤ 57 m for 1-IPN and ≤ 69 m for 2-IPNs, and the maximum expected distances for TTS thresholds were ≤ 113 m for 1-IPN and ≤ 161 m for 2-IPNs. The expected distances for the 160 dB unweighted SPL behavioral thresholds were 132 m for 1-IPN and 178 m for 2-IPNs (Li and Martin 2025). The results indicate that it would be nearly impossible for a marine mammal to experience auditory injury from MV, and, given the very small ranges to the TTS and behavioral thresholds, it is highly unlikely they would experience TTS or behavioral harassment.

Results from a modeling study suggest that an array of 18 MV IPNs and a 4130 in^3 airgun array produced similar spectral levels below 100 Hz at all modeled distances, while the spectral levels at higher frequencies were much higher for the air gun array (Matthews et al. 2020). Furthermore, results showed that the MV signal above 200 Hz was below ambient levels at distances as short as 100 m, while spectral levels for the air gun array in the same frequency band remained above ambient levels for several kilometers (Matthews et al. 2020).

In 2024, a team conducted a field study with a 1-element MV to examine potential behavioral effects on blue and fin whales. While the full analysis is still underway at the time of this publication, the authors' preliminary results showed that there was a minimal response of the tagged whales, suggesting that this source has relatively low potential for behavioral effects (Southall et al. 2026).

4.2.3 HRG Surveys

Smaller-scale, higher-resolution geophysical surveys typically are not used to identify oil and gas resources, but rather to identify shallow-water hazards or image the immediate subsurface for the

purposes of offshore construction. BOEM and U.S. Geological Survey (USGS) characterized underwater sounds produced by HRG sources and their potential to result in incidental take of marine mammals (i.e., behavioral effects; Ruppel et al. 2022). Given several key physical characteristics of the sound sources—including source level, frequency range, duty cycle, and beamwidth—Ruppel et al. (2022) concluded that most HRG sources, even without mitigation, are unlikely to result in substantial behavioral disturbances, which is generally consistent with field observations.

Dedicated behavioral response studies have not been conducted for each type of HRG source; the majority of work has focused on single and multibeam echosounders. For example, Vires (2011) found no change in Blainville's beaked whale click durations before, during, and after a scientific survey with a 38 kHz EK-60 single beam echosounder. Quick et al. (2017) found that short-finned pilot whales did not change foraging behavior but did increase their heading variance during use of an EK-60. Cholewiak et al. (2017) found a decrease in beaked whale echolocation clicks during use of an EK-60. Kates Varghese et al. (2020) found no change in three of four beaked whale foraging behavior metrics (i.e., number of foraging clicks, foraging event duration, click rate) during two deepwater mapping surveys using a 12-kHz MBES. There was an increase in the number of foraging events during one of the mapping surveys, but this trend continued after the survey ended, suggesting that the change was more likely in response to another factor, such as prey availability, than to the mapping survey. During both multibeam mapping surveys, foraging continued in the survey area, and the animals did not leave the area (Kates Varghese et al. 2020; 2021).

For some of the higher-amplitude sources such as bubble guns, some boomers, and the highest-power sparkers, Ruppel et al. (2022) concluded that behavioral disturbance is possible but would be unlikely if mitigation measures such as clearance zones and shutdowns are applied.

4.2.4 Geotechnical Surveys

Geotechnical surveys may introduce low-level (i.e., < 160 dB re 1 µPa·m source level), intermittent, broadband noise into the marine environment. These sounds could result in acoustic masking in low- or mid-frequency cetaceans but are unlikely to result in behavioral disturbance given their low source levels and intermittent use. Behavioral disturbance or masking may occur in more sensitive species (such as beaked whales) and species with hearing ranges that directly overlap the sound sources (specifically, high and very high-frequency cetaceans).

4.2.5 Dredging

Todd et al. (2015) provide an extensive review of the impacts of dredging on marine mammals. Some studies, primarily on seals and sea lions, found no observable response (Gilmartin 2002; Blackwell et al. 2004; Ecologia Environment 2008), while several other studies showed temporary to long-term avoidance behavior for bowhead, gray, humpback, and minke whales (Richardson et al. 1990; Borggaard et al. 1999; Tyack 2008; Anderwald et al. 2013; Todd et al. 2015). For example, gray and humpback whales seem to avoid certain areas, even key breeding habitats, when dredging is occurring (Borggaard et al. 1999; Tyack 2008). Empirical studies suggest that some

high-frequency cetaceans may also avoid dredging activities. For example, Diederichs et al. (2010) found short-term avoidance of dredging activities by harbor porpoises near breeding and calving areas in the North Sea. Pirotta et al. (2013) found that, despite a documented tolerance of high vessel presence, as well as high availability of food, bottlenose dolphins spent less time in the area during dredging periods. The study also showed that, with increasing intensity in the activity, bottlenose dolphins avoided the area for longer durations (with one instance being as long as 5 weeks; Pirotta et al. 2013).

Given the low source levels and transitory nature of dredging sources, exceedance of auditory injury thresholds is unlikely, but TTS thresholds could be exceeded (Todd et al. 2015). For example, using measurements of the highest source level from multiple dredging vessel operations, Heinis et al. (2013) modeled harbor porpoise and seal exposure to a dredging operation. They found that TTS levels would not be exceeded for harbor porpoise at any distance and would only be exceeded for seals at distances within 90 m of the dredging vessel.

These studies suggest that dredging noise has the potential to cause temporary hearing impairment at close distances and behavioral disturbance at greater distances. Masking and behavioral effects may be more likely for baleen whales and pinnipeds due to the low-frequency nature of the sounds and the overlap with their hearing sensitivity. Nonetheless, in most cases, behavioral effects are expected to be relatively short term and of low intensity.

4.2.6 Drilling and Production

Marine mammal sensitivity to noise from offshore drilling varies widely among species, individuals, and behavioral contexts. Early studies on pinnipeds and small odontocetes indicated relatively high tolerance under many conditions. For example, ringed seals exposed to construction and drilling noise around Northstar Island showed no decline in haul-out density even when underwater and airborne noise exceeded ambient levels at distances of a few kilometers (Moulton et al. 2003); seals were frequently observed within tens of meters of construction activities with minimal reaction (Blackwell et al. 2004). Long-term passive acoustic monitoring around a North Sea jack-up rig demonstrated that harbor porpoises remained present year-round and regularly occurred within 200 m of drilling and production structures, with no evidence of displacement during routine drilling operations (Todd et al. 2009). Instead, porpoises showed nocturnal increases in echolocation activity consistent with feeding around platform-associated prey aggregations.

Modeling indicates that porpoises may only detect jack-up drilling noise within roughly 70 m under some conditions (Todd et al. 2020). Additional monitoring from fixed platforms in the North Sea found no decrease in porpoise presence during continuous drilling, although brief, localized declines occurred during impulsive conductor-ramming events (Bach et al. 2010). More recent studies in which DP was used during exploratory drilling show similar patterns: during operations in the Scotian Basin, baleen whales, odontocetes, and porpoises continued to be detected at 2–20 km from a MODU with no evidence of displacement, though masking of low-frequency baleen whale calls occurred intermittently near the rig (Martin et al. 2019). Overall, these studies indicate

that for many species, particularly seals and porpoises, routine drilling and DP-thruster dominated rig noise often result in limited or no measurable avoidance, with localized acoustic masking being the most consistent effect.

Baleen whale responses, particularly among bowhead whales in Arctic regions, tend to be stronger and more variable, influenced by migration context, ice cover, and received sound levels. Bowhead whales have been observed diverting migration paths by roughly 10 km around active drillships, with some individuals maintaining distances of 15–30 km (Richardson et al. 1995). Playback experiments of drilling and dredging noise elicited reactions such as reorientation, temporary cessation of feeding, and altered surfacing and diving patterns, with approximately half of individuals responding at received levels around 115 dB re 1 µPa (20–1,000 Hz) (Richardson et al. 1990). Yet substantial variability exists: during spring migration in heavy ice, some bowheads passed within 100–500 m of drilling noise without interruption, while others—particularly mothers with calves—showed avoidance at lower levels (Richardson et al. 1990). Blackwell et al. (2017) reported that bowhead whale calling rates were correlated with increasing levels of drilling noise, where calling rates initially increased, peaked, and then decreased. Contemporary monitoring in other regions has revealed mixed responses. During exploratory drilling in the Flemish Pass, detections of blue whales, fin whales, harbor porpoises, and pilot whales declined within 2–5 km of a MODU using DP (interpreted as short-range avoidance or reduced calling) and sound levels intermittently exceeded TTS thresholds for animals remaining within approximately 2 km (Delarue et al. 2021). However, detections at ≥ 32 km remained unchanged (Delarue et al. 2021). The authors concluded that drilling noise can cause localized avoidance, temporary hearing effects, and significant masking of low-frequency communication space within a few kilometers of the MODU, but did not find evidence for population-level displacement or long-term distribution changes at larger spatial scales (Delarue et al. 2021).

Acoustic modeling of exploratory drilling in East Asia similarly indicates low risk of hearing impairment beyond approximately 40 m but potential behavioral disturbance out to approximately 1.9 km, with reduced cetacean and pinniped communication space (Huang et al. 2023). Conversely, Shell's monitoring during 2012 exploratory drilling in the Chukchi and Beaufort Seas reported largely neutral or mild reactions from cetaceans and pinnipeds, with limited avoidance and no evidence of large-scale displacement despite persistent drilling and support-vessel noise (Bisson et al. 2013). Overall, these studies show that baleen whales can exhibit avoidance, reduced calling, or altered behavior within a few to tens of kilometers of drilling, particularly in quiet environments or during sensitive migratory periods, while broader-scale displacement has rarely been documented. Many individuals appear to tolerate or habituate to drilling noise when migration routes or foraging needs constrain movement. Behavioral responses to drilling are therefore best characterized as highly context-dependent, typically localized, and generally of short duration relative to the activity.

4.2.7 Vessels and DP Systems

Underwater radiated noise from small vessels (e.g., for crew transport) and larger vessels (e.g., oil tankers) may have impacts on marine mammals in the area. These mobile sound sources would temporarily ensonify an area as the vessel passes through. A summary of the general effects of vessel noise on marine mammals can be found in **Section 4.1.2**.

In addition, DP systems may be used to keep large vessels in place during construction, drilling, or production. These fixed sound sources would ensonify an area during the entire duration of the activity which could lead to auditory masking or behavioral disturbance for animals in the vicinity. Note that the specific effects of DP noise on marine mammals have not been studied. DP is typically used in conjunction with other operations, so a specific source level is difficult to identify. However, choosing a level that is within the range of previous measurements (185 dB re 1 µPa·m) and assuming spherical spreading, one would expect received levels to reach 120 dB re 1 µPa within about 1.6 km of the vessel. This means that, within 1.6 km of a vessel, the continuous noise threshold for behavioral disturbance of marine mammals could be exceeded while DP systems are active. Further research is needed to understand the type of behavioral effects that could occur due to exposure to DP noise; some are likely to be discountable while others could result in significant disturbance.

4.2.8 Trenching and Pipeline Laying

Preparing an area for pipeline laying or cable laying may require jetting, plowing, or removal of soft sediments. Installation vessels are likely to use DP systems while laying the cables or pipeline. The sound associated with DP generally dominates other sound sources present, especially in the situation of cable laying or pipeline laying. Although no research has explicitly examined the effects of pipeline- and cable-laying noise on marine mammals, impacts are expected to be relatively low due to the low-intensity and localized nature of the sound source.

4.2.9 Pile Driving

Impact pile driving is used to install ocean infrastructure. Pile-driving noise has the potential to affect all marine mammal functional hearing groups in the area. Based on the size of the piles typically associated with oil and gas infrastructure (much smaller than those used for offshore wind foundations), it is unlikely that noise would cause auditory injury or TTS, but there could be some behavioral effects or acoustic masking. The majority of research on pile-driving noise has focused on large piles (e.g., several meters in diameter) and high-frequency cetaceans, which are species of high conservation concern in European waters (Carstensen et al. 2006; Dähne et al. 2013; Haelters et al. 2014; Kastelein et al. 2018; Graham et al. 2019).

The most-observed behavioral effect of pile-driving activity on marine mammals has been short-term avoidance or displacement from the pile-driving site. Several studies have shown that vocalizations of harbor porpoise are markedly lower within approximately 10–12 km of the construction site, suggesting short-term displacement during construction; porpoise presence

seemed to increase again once pile driving has ceased (Brandt et al. 2011; 2016; Osiecka et al. 2020; Benhemma-Le Gall et al. 2021). Similar results were found with Indo-Pacific humpback dolphins (Würsig et al. 2000) and harbor seals (Russell et al. 2016). In addition to avoidance behaviors, harbor porpoise showed decreasing catch success (Kastelein et al. 2019). For gray seals (Hastie et al. 2021) and dolphins (Branstetter et al. 2018), foraging success during pile driving was related to prey density and an interaction between prey density and received level.

Currently, there is no data on the potential effects on baleen whales from pile-driving noise. However, given the overlap in frequency content with their vocalizations (mostly below 1 kHz), these species would be most susceptible to acoustic masking. Low-frequency sound propagates greater distances than high frequencies, so masking may occur over large distances. When masking cannot be avoided, increasing noise could interfere with locating and communicating with other individuals.

Overall, it is reasonable to assume that there would be greater impacts to low-frequency cetaceans (i.e., baleen whales) than other species groups, even though direct research on pile-driving noise on baleen whales is limited. Based on the evidence from the literature, high- and very high-frequency cetaceans are likely to avoid areas where pile driving is taking place. Mitigative measures can prevent or decrease the chance that a marine mammal would experience potential effects from pile driving.

4.2.10 Decommissioning

Underwater explosions create shock waves characterized by extreme changes in pressure, which can cause injury and mortality to animals, depending on how close it is to the blast.

To predict the potential impacts of underwater explosives on marine species, several models have been developed. Goertner (1982) developed a model for physical injuries to cetaceans at a range of depths, and a modified version of this model is recommended by NMFS for predicting injury impacts to marine mammals (NMFS 2024). The physical range at which injury or mortality could occur will vary based on the amount of explosive material, size of the animal, and location of the animal relative to the explosive. Injuries may include hemorrhage or damage to the lungs, liver, brain, or ears, as well as auditory impairment, such as PTS and TTS (Ketten 2004). Smaller animals generally are at a higher risk of blast injuries.

Behavioral effects are possible out to greater ranges; however, explosions are ephemeral, and behavioral effects are expected to be very short term, challenging to observe, and of less concern compared to potential injury and mortality effects. Todd et al. (1996) observed humpback whales near underwater explosions and did not note any overt behavioral changes (e.g., changing course, abrupt dive behavior, etc.) within 1.83 km from the blast, at received peak pressures of 123 dB re 1 µPa. The researchers observed no overall trend in humpback whale movements during the month when intermittent blasting was taking place.

Mitigative measures can prevent or decrease the chance that a marine mammal will be severely injured or killed from an explosion. For example, seasonal and time-of-day restrictions can be put in place to avoid times when marine mammals may be present, noise mitigation devices can be applied to reduce noise propagation from the detonation, and visual and passive acoustic monitoring of clearance zones can be used to make sure the detonation does not occur until there are no animals detected.

4.2.11 Aircraft

Offshore activities may employ helicopters and fixed-wing aircraft for transporting construction and maintenance crew. In general, marine mammal behavioral responses to aircraft have most commonly been observed at altitudes of less than 150 m from the aircraft (Patenaude et al. 2002; Smultea et al. 2008). Aircraft operations have resulted in temporary behavioral responses, including changes in dive behavior, breaching, and tail slapping (bowhead and beluga whales, percussive behaviors such as breaching and tail slapping, Patenaude et al. 2002; transient sperm whales, Richter et al. 2006; abrupt dives of sperm whales, Smultea et al. 2008). Responses appear to be heavily dependent on the behavioral state of the animal, with the strongest reactions seen in resting individuals (Würsig et al. 1998). In addition, based on the physics of sound propagation across different media (e.g., air and water), only a small portion of the acoustic energy from aircraft operations couples into the water.

BOEM requires all aircraft operations to comply with current approach regulations for unidentified large whales (50 CFR 222.32). These include the prohibition of aircraft from approaching within 1,500 ft, which would minimize the potential responses of marine mammals to aircraft noise. Federal Aviation Administration (2004) encourages pilots to maintain an altitude of higher than 2,000 ft over noise-sensitive areas. Corporate helicopter policy states that helicopters should maintain a minimum altitude of 750 ft while in transit offshore and 500 ft while working between platforms (Helicopter Safety Advisory Conference 2010).

5 Sea Turtles—General Information on Hearing

5.1 Importance of Sound to Sea Turtles

Compared to marine mammals, the general importance of sound to sea turtles is not well understood, but there is a growing body of knowledge suggesting that sea turtles use sound in a multitude of ways. Sea turtles may use sound to navigate, to locate prey or preferred habitat, for predator avoidance, and for general environmental awareness (Piniak et al. 2016). They occupy different ecological niches throughout their life cycle, each characterized by unique acoustic conditions.

There are few studies reporting sound production in sea turtles, despite their ability to hear sounds in both air and water. Cook and Forrest (2005) found that nesting leatherback sea turtles produce sound when breathing in air, but this work suggested the sound was a by-product of labored breathing rather than a communication signal. Sea turtle embryos and hatchlings have been reported to make airborne sounds, thought to be produced for synchronizing hatching and nest emergence (Ferrara et al. 2014a; 2014b; McKenna 2016; Ferrara et al. 2019; Monteiro et al. 2019). Charrier et al. (2022) noted the production of 10 different underwater sounds in juvenile green sea turtles, including those within and above the frequency range of hearing reported for this species.

A more comprehensive understanding of sound production and hearing is needed in sea turtles, but the growing information thus far suggests sound may be important to these animals.

5.2 Hearing Anatomy

In general, sea turtle auditory perception is thought to occur through a combination of both bone and water conduction rather than air conduction (Lenhardt et al. 1983; 1985). The outermost part of the sea turtle ear, or tympanum, is covered by a thick layer of skin over a fatty layer that conducts sound in water to the middle and inner ear. This ear structure is a distinguishing feature from terrestrial and semi-aquatic turtles. This thick outer layer makes it difficult for turtles to hear well in air, but it facilitates the transfer of sound from the aqueous environment into the ear (Ketten et al. 1999).

The middle ear has two components that are encased by bone, the columella and extracolumella, that provide the pathway for sound from the tympanum on the surface of the turtle head to the inner ear, consisting of the cochlea and basilar membrane. This arrangement enables sea turtles to hear low-frequency sounds while underwater. The middle ear also is connected to the throat by the Eustachian tube. Because there is air in the middle ear, it is generally believed that sea turtles can detect sound pressure. Vibrations can also be conducted through the bones of the carapace to reach the middle ear. Based on studies of semi-aquatic turtles, Christensen-Dalsgaard et al. (2012) speculated that the sea turtle ear may not be specialized for bone conduction, but rather that sound-induced pulsations may drive the tympanic disc if the middle ear cavity is air-filled. Although the functional pathway of sound detection and the context in which each pathway is used are still

areas of ongoing research, it is believed that sea turtles may be sensitive to both pressure and particle motion. A detailed description of sea turtle auditory anatomy and different hearing capabilities of each species are available in Section 3 in Reese et al. (2023).

Sea turtle hearing has been measured in electrophysiological and behavioral studies both in air and water, and on a limited number of life stages for each of the five species. In general, sea turtles hear best in water between 100–750 Hz, do not hear well above 1 kHz, and are generally less sensitive to sound than marine mammals (Papale et al. 2020; Reese et al. 2023). There is data on loggerhead hearing capabilities at the post-hatchling (Lavender et al. 2012; 2014), juvenile (Bartol et al. 1999; Lavender et al. 2012; 2014), and adult stages (Martin et al. 2012) (**Table 6**), though substantial data gaps still exist on hearing sensitivity across species and throughout ontogeny.

Table 6. Hearing capabilities of sea turtles

Sea Turtle Species	Life Stage	Range of Audibility (Hz)	Range of Highest Sensitivity (Hz)	Source
Green (*Chelonia mydas*)	Juvenile	50–1,600	200–400	Ridgway et al. (1969); Bartol and Ketten (2006); Piniak et al. (2012b); (2016)
Hawksbill (*Eretmochelys imbricata*)	Hatchling	50–1,600	400	Piniak (2012)
Kemp's ridley (*Lepidochelys kempii*)	Juvenile	50–800	100–500[a]	Bartol and Ketten (2006)[b]; Muirhead et al. (2026)
Leatherback (*Dermochelys coriacea*)	Hatchling	50–1,200	300	Piniak (2012); Piniak et al. (2012a)
Loggerhead (*Caretta caretta*)	Post-hatchling[b]	50–1,100	200	Bartol et al. (1999); Lenhardt (2002); Martin et al. (2012); Lavender et al. (2014)
Loggerhead	Juvenile	50–1,100	50–800	"
Loggerhead	Adult	35–1,131	100–400	"

Notes: Data adapted from Papale et al. (2020) and Reese et al. (2023) is based on highest and lowest frequency of underwater audibility that was reported for each species including both auditory evoked potential and behavioral studies.
[a] Only in-air measurements are available for Kemp's ridley sea turtles from Bartol and Ketten (2006). In-air measurements indicated the range of audibility and highest sensitivity was from 100–500 Hz (Bartol and Ketten 2006). Underwater measurements indicated the range of highest sensitivity was from 200–300 Hz (Muirhead et al. 2026).
[b] Post-hatchling refers to the size classification given to hatchlings when they reach a straight maximum length of 5 cm.

5.3 Potential Impacts of Underwater Sound on Sea Turtles

As with marine mammals, sea turtles may experience a range of impacts from underwater sound, including non-auditory injury, auditory injury, temporary hearing loss (TTS), behavioral changes, acoustic masking, or increases in physiological stress. The potential impacts will depend on the physical qualities of the sound source and the environment, as well as the physiological characteristics and the behavioral context of the species of interest.

Sound from activities such as pile driving, seismic surveys, and drilling could have impacts on sea turtles given the overlap between sea turtles' hearing range and the frequency range of these sound sources; however, there are extremely limited data on how their behavior and physiology are impacted. A comprehensive review of the potential impacts of noise on sea turtles can be found in Nelms et al. (2016) and Reese et al. (2023).

There is no direct evidence of PTS occurring in sea turtles, but evidence of underwater noise-induced TTS in freshwater turtle species has been recorded and suggests turtles may be more sensitive to sound than previously understood (Salas et al. 2023; Mannes et al. 2024). In red eared sliders, Mannes et al. (2024) and Salas et al. (2023) reported the mean predicted TTS onset was 160 dB re 1 μPa^2s. There was individual variation in the susceptibility to TTS, as well as the magnitude of threshold shift and recovery rate, which was non-monotonic and occurred on time scales ranging from < 1 h to > 2 days post-exposure (Salas et al. 2023; Mannes et al. 2024). TTS also has been demonstrated in red eared sliders based on a 24-hour exposure that resulted in an SEL of 160 dB re 1 μPa^2s, where all animals showed a decrease in hearing sensitivity immediately after exposure but a full recovery 3- to 5-hours after exposure (Salas et al. 2023; Mannes et al. 2024).

Salas et al. (2024) found that underwater noise pollution also can induce TTS in the hearing of Eastern painted turtles (*Chrysemys picta picta*), revealing their vulnerability to noise-induced hearing loss and the potential consequences for their survival and ecological roles. Exposure to band-limited continuous white noise resulted in significant TTS at frequencies of 400 and 600 Hz, with higher sensitivity and greater shifts observed at the latter frequency. This frequency-dependent reaction parallels the findings in other freshwater species, indicating that similar auditory sensitivities could be typical within the Emydidae family.

Additionally, research in marine mammals suggests that prolonged or repeated exposure to sound levels sufficient to induce TTS without recovery time can lead to auditory injury, including PTS, so the same could be true for turtles and other vertebrates (Southall et al. 2007). Few studies have looked at hair-cell damage in reptiles, and existing studies do not indicate precisely if sea turtles are able to regenerate injured sensory hair cells (Warchol 2011). Further research is necessary to explore TTS across additional turtle species and different types of sound sources to inform decision making and to mitigate the impacts of noise on both freshwater and marine turtles.

For behavioral responses, a recent study by Kastelein et al. (2023) found that sea turtles exposed to synthetic sounds (including Helicopter Long-Range Active Sonar and killer whale vocalizations) exhibited responses to high-amplitude, low-frequency sounds between 0.2 and 1 kHz; responses

included increased swimming speed and changes in swimming patterns. Responses were influenced by the sound's spectrum and frequency modulation, and the turtles' behavioral state—and the responses were particularly noticeable for sounds within the turtles' hearing range. Most notable reactions occurred at SPLs exceeding 151 dB re 1 µPa, suggesting that the radius of disturbance areas around most anthropogenic sound sources is smaller for turtles than for marine mammals (Kastelein et al. 2023).

Several studies have examined physiological responses of sea turtles to physically stressful events (e.g., incidental or directed capture in fishing nets, cold stunning, handling, transport). However, to date, no research has been published on potential stress responses in sea turtles to elevated environmental noise (Reese et al. 2023).

Stress response studies characterizing physiological (stress or hormone) responses to sound are being conducted to estimate potential acoustic impacts on sea turtles from industry sound sources. Elevated levels of corticosterone have been observed in Kemp's ridley sea turtles and green turtles in response to stressful stimuli such as ground transport for rehabilitation and disease (Aguirre et al. 1995; Hunt et al. 2016). Other physiological impacts due to chronic stress include immunosuppression (Milton and Lutz 2003). Samuel et al. (2005) demonstrated that anthropogenic sound levels from boating and recreational activity near Long Island, NY, were over two orders of magnitude greater than when compared with the periods of lowest human activity and suggested exposure to such levels could affect sea turtle behavior.

Chronic exposure to anthropogenic noise may result in increased stress responses in sea turtles, which could have direct consequences on individual fitness (Reese et al. 2023). The soundscapes noise impacts of soundscapes experienced by sea turtles in biologically important habitats—and their behavioral and physiological responses—may be variable and in general are still not well understood.

5.4 Regulatory Thresholds

5.4.1 Thresholds for Auditory Injury

There are few empirical data available to form regulatory thresholds for sea turtle sound exposure. For several years, the regulatory community accepted the recommendations of Popper et al. (2014), which, as a conservative approach, used thresholds developed for fishes without swim bladders as the best available proxy for sea turtles. In earlier phases of the U.S. Navy Acoustic Criteria and Thresholds Analysis, the U.S. Navy also agreed that, while still unsatisfactory, data from fish provided a better analogy due to similar hearing range and that the functioning basilar papilla in the turtle ear is dissimilar to the functioning cochlea in mammals (U.S. Navy 2017).

However, more recently the U.S. Navy has modified their criteria and thresholds based on data on TTS for freshwater turtles (Salas et al. 2023; 2024). There is no direct data for auditory injury in sea turtles; therefore, the difference between TTS onset and auditory injury onset criteria is based on trends seen in terrestrial mammal data. Incorporating the best available science, new criteria and

thresholds for the onset of TTS and auditory injury have been developed for Phase 4 (**Table 7**) (Accomando et al. 2025). As with marine mammals, dual criteria (L_{pk} and SEL) are used for auditory injury and TTS, along with auditory weighting functions published by Accomando et al. (2025).

Table 7. Sea turtle auditory injury thresholds from the Phase 4 Navy report for impulsive and non-impulsive sounds

Metric	Auditory Injury	TTS
Impulsive SEL (dB re 1 μPa^2s) (weighted)	184	169
Impulsive L_{pk} (dB re 1 µPa)	230	224
Non-impulsive SEL (dB re 1 μPa^2s) (weighted)	198	178

Source: Accomando et al. (2025); AINJ = auditory injury, TTS = temporary threshold shift

5.4.2 Thresholds for Behavioral Disturbance

Limited data are available on the behavioral responses of sea turtles to anthropogenic noise. Several publications have attempted to examine sea turtle's immediate behavioral responses to seismic airgun noise. McCauley et al. (2000b) observed that one green turtle and one loggerhead sea turtle in an open-water pen increased swimming behaviors in response to a single seismic airgun at received levels of 166 dB re 1 µPa and exhibited erratic behavior at received levels greater than 175 dB re 1 µPa. Other empirical work has shown a range of responses, but NMFS developed sea turtle behavioral criteria based on these studies by McCauley et al. (2000b). The sound level at which sea turtles are expected to exhibit a behavioral response to both impulsive and non-impulsive sound is a received SPL of 175 dB re 1 µPa (McCauley et al. 2000b; U.S. Navy 2017) (**Table 7**). These thresholds apply to all life stages.

Newly published research detailing the behavioral reactions of sea turtles to noise (Kastelein et al. 2023) has emerged; however, the SPL RMS thresholds established by NMFS for behavioral disturbance during Phase 3 remain unchanged in Phase 4 (**Table 8**). For instances involving single and multiple explosions, SEL-based thresholds exist that align with the thresholds used for assessing behavioral responses of marine mammals to similar explosive events.

Table 8. Sea turtle behavioral response thresholds from the Phase 4 Navy report

Source	SPL RMS (dB, unweighted)	SEL (dB, cumulative; weighted)
Airguns	175	-
Pile driving	175	-
Sonar ≤ 2kHz	175	-
Explosives	-	164

Notes: Weighted cumulative SEL thresholds in dB re 1 μPa^2s and unweighted SPL RMS thresholds in dB re 1 µPa. The RMS and SEL calculations are based on duration defined by 5% and 95% points along the cumulative energy curve and capture 90% of the cumulative energy in the impulse. Source: Accomando et al. (2025)

5.4.3 Thresholds for Non-Auditory Injury

For both turtles and mammals, NMFS adopted criteria used by the U.S. Navy to assess the potential for non-auditory injury from underwater explosive sources as presented in Accomando et al. (2025). The criteria include thresholds for the following non-auditory effects: mortality, lung injury, and gastrointestinal injury. The critical explosive parameter tied to these criteria are peak pressure (L_{pk}) and positive impulse (J_0), sometimes just referred to as impulse. Based on work by Goertner (1982) and Yelverton et al. (1973), the U.S. Navy has identified the similitudes in **Table 9** as the threshold for the occurrence of these impacts (Accomando et al. 2025), which was used here for impact calculations. Unlike auditory thresholds, these depend upon an animal's mass and depth.

Table 9. U.S. Navy impulse and peak pressure threshold equations for estimating mortality or injury due to explosives

Impact Assessment Criterion	Threshold
Onset Mortality—Impulse	$103M1^{/3}(1+ D/10.1)^{1/6}$ Pa-s
Onset Injury (Non-auditory)—Impulse	$47.5M^{1/3}(1+ D/10.1)^{1/6}$ Pa-s
Onset Injury (Non-auditory)—Peak Pressure	L_{pk} of 237 dB re 1 µPa

Notes: M is animal mass (kg), and D is animal depth (m). Source: Accomando et al. (2025)

6 Sea Turtles—Impacts of Underwater Sound

6.1 Potential Impacts of Non-BOEM Acoustic Sources

The most notable and widespread source of anthropogenic noise in many parts of the OCS is from vessels, due to the prevalence of commercial shipping, fishing, and recreational boating activities. Despite growing concerns about the impacts of vessel noise on marine ecosystems, comprehensive investigations focused on the effects to sea turtles are quite limited. Key areas lacking adequate research include the specific frequencies of shipping noise and DP that may cause behavioral changes in sea turtles, their responses to continuous versus intermittent noise, and the long-term impacts of noise exposure on their foraging, nesting, and migratory patterns. Additionally, there is a need for studies that evaluate the synergistic effects of shipping noise combined with other anthropogenic stressors, such as habitat degradation and climate change. Furthermore, most existing studies primarily concentrate on larger marine mammals, leaving a substantial gap in understanding how sea turtles—which have unique auditory capabilities and higher prevalence in nearshore areas—are impacted by the increasing presence of vessel operations on the OCS.

6.2 Potential Impacts of BOEM-Related Sound Sources

6.2.1 Seismic Surveys (Airguns)

Although little is known about the effects of anthropogenic noise on sea turtles, potential impacts of seismic surveys may include auditory effects (TTS or auditory injury) and behavioral disturbance. Research on responses to seismic airguns have shown a range of behavioral effects in sea turtles, including startle responses and rapid swimming (McCauley et al. 2000b), swimming toward the surface at the onset of the sound (Lenhardt 1994), and avoidance (O'Hara and Wilcox 1990; Moein et al. 1994; Bowles et al. 1999; McCauley et al. 2000b; Lenhardt 2002; Weir 2007; Southwood et al. 2008; DeRuiter and Doukara 2012). Moein et al. (1994) found that caged loggerheads exposed to airguns at received levels of 175–179 dB re 1 µPa SPL initially avoided the sound source but appeared to habituate with repeat exposures, even when the exposures were separated by several days. McCauley et al. (2000b) approached one green and one loggerhead turtle in cages with a single airgun and observed startle responses starting at received SPLs of 166 dB re 1 uPa. O'Hara and Wilcox (1990) observed nine turtles in a large enclosure within a canal and saw that turtles spent more time in the areas further from the airgun when the firing pressure was at 140 kg/cm^2 but not at 70 kg/cm^2 (received sound levels not reported).

Field studies with free-swimming animals generally are more appropriate for drawing conclusions, but the work thus far has observed variable behavioral responses. DeRuiter and Doukara (2012) observed that 57% of loggerhead sea turtles in the vicinity of a seismic survey exhibited a diving response after exposure to received levels between 175 and 191 dB re 1 µPa. Observations of multiple species during a 10-month seismic survey off Africa showed that the majority of turtles continued to bask at the surface as the vessel moved by (regardless of whether the airguns were

actively shooting; Weir 2007). Out of 180 turtles that the authors were able to observe both before and after exposure, only 20 initiated response dives, with no clear difference in whether the airguns were on or off; however, data were too limited to draw firm conclusions, and it was unclear if responses were to the airgun sound or vessel presence (Weir 2007).

Subadult and adult turtles are presumably more susceptible to seismic airgun noise compared to post-hatchlings, as they spend more time submerged and at depth. In contrast, post-hatchlings typically reside at or near the surface and may be less likely to experience injury from the sound field produced by an airgun array below. Seismic airgun surveys conducted in shallower areas are anticipated to affect a greater number of turtles than deepwater surveys, but deepwater surveys are more likely to impact leatherbacks, particularly in upwelling zones where these turtles may gather to feed. Additionally, surveys conducted during summer nesting periods may affect more adult turtles—particularly loggerhead, green, and leatherback turtles—compared to non-nesting periods (Popper et al. 2014).

In addition to changing behavior, exposure to anthropogenic noise may result in the displacement of individuals from important habitats used for foraging, resting, and reproducing (Reese et al. 2023). However, such disruptions are expected to be temporary and should not affect the overall survival and reproduction of individual turtles.

Based on the current understanding of sea turtle hearing capabilities, it remains uncertain whether sea turtles rely completely on sound for communication and navigation; therefore, they may be affected by auditory masking (Popper et al. 2014).

Taken together, the results of studies with sea turtles suggest that they exhibit short-term responses to airgun noise when relatively close to the source, and, though they may experience physiological stress during avoidance, this response is expected to dissipate once they are outside the affected area.

6.2.2 HRG Surveys

Only a subset of HRG sources (e.g., boomers, sparkers) are likely to be audible by sea turtles given the frequency range of the sounds and the hearing range of turtles (**Section 5.2**), but that subset may have some effects. PTS is highly unlikely given the intensity and short duration of signals generated by this equipment (Crocker and Fratantonio 2016). Recently, BOEM and USGS characterized the acoustic qualities of HRG sources and their potential to result in behavioral disturbance of marine species, including sea turtles (Ruppel et al. 2022). In addition to frequency range, other characteristics of the sources—like the source level, duty cycle, and beamwidth—make it very unlikely that these sources would result in behavioral disturbance of sea turtles, even without mitigation (Ruppel et al. 2022).

A recent study examined the behavior of free-swimming leatherback turtles in the vicinity of a stationary sparker (Patel et al. 2026). They found that the probability of turtle foraging decreased while peak received levels increased. While this observation suggests that sparker noise can affect

turtle behavior, it is important to consider that received levels of this magnitude would be encountered infrequently during real-world sparker surveys since both the turtle and source would be moving. Therefore, although temporary displacement or behavioral responses may occur, these disruptions likely would be limited in extent and short term in duration.

6.2.3 Geotechnical Surveys

There is a notable lack of studies specifically examining the effects of noise from geotechnical operations on sea turtles. Most existing research focuses on broader categories of underwater noise, leaving a critical gap in understanding how geotechnical activities uniquely impact sea turtles. While generally low in level, continuous noise from geotechnical sampling has the potential to disrupt normal sea turtle activities, such as foraging, nesting, and migration (Díaz et al. 2024; Basdeo et al. 2025). Prolonged exposure to the sounds associated with geotechnical surveys may also increase stress, resulting in changes to swimming patterns (Díaz et al. 2024), increased energy expenditure, and avoidance of areas with heightened noise levels. Low-frequency, continuous noise may also mask natural sounds that sea turtles depend on for communication and navigation, potentially impairing their ability to interact with their environment (Piniak et al. 2016; Chevallier et al. 2024; Muirhead et al. 2026).

6.2.4 Dredging

Like with many other sound sources, the response of sea turtles to dredging noise is not well researched and is poorly understood relative to marine mammals. Even right at the source, SELs from dredging are not expected to exceed the recommended sea turtle cumulative sound exposure threshold for TTS or PTS, and behavioral thresholds would be exceeded only at very small distances (i.e., tens of meters). For example, suction dredging may produce sounds up to an SPL of 190 dB re 1 µPa (Robinson et al. 2011; Todd et al. 2015), which exceeds the behavioral response threshold of 175 dB re 1 µPa.

Currently, there is no information on the effects of dredging noise on sea turtles (Popper et al. 2014). There is evidence, however, of potentially positive impacts of dredging to breeding flatback turtles, which exhibited increased use of a dredging area and made longer and deeper resting dives during dredging operations (Whittock et al. 2017). The most likely driver for the observed behavioral response was speculated to be the absence of predators, which were displaced by the noise from dredging operations.

Despite the presence of active dredge vessels (which can often pose a risk to turtles), no events of injury or mortality were recorded. This finding was attributed to control measures (e.g., drag head chains) in place, which seemed to be effective in preventing entrainment (Whittock et al. 2017).

6.2.5 Drilling and Production

There is very little information on the impacts of drilling and production noise on sea turtles. However, sea turtle hearing sensitivity is within the frequency range (100–1,000 Hz) of sound

produced by low-frequency sources such as marine drilling (Popper et al. 2014). Similar to dredging operations, is unlikely that sounds from drilling will reach injury thresholds, unless the sea turtle is within very close proximity to the drilling activity (McCauley et al. 2000a; Piniak et al. 2012a; U.S. Navy 2017), but these sounds may cause temporary avoidance or displacement of sea turtles. Studies of sea turtles in the proximity of platforms are not conclusive on whether turtles habituate to a continuous sound source. Further research is required; however, based on current data, the risk of significant impacts is expected to be low.

6.2.6 Vessels and DP Systems

Vessel noise may impact sea turtle behavior, leading to temporary startle responses, altered submergence patterns, masking of biologically relevant sounds, and physiological stress (Samuel et al. 2005; National Science Foundation 2011). Sea turtles may exhibit a startle reaction (such as diving or swimming away) and temporary stress responses by increasing submergence time, extending dive durations, or surfacing (O'Hara and Wilcox 1990; Lenhardt 1994; Samuel 2004; National Science Foundation 2011). Hazel et al. (2007) found that sea turtles typically respond behaviorally to vessels at approximately 10 m or closer, suggesting that their detection of approaching vessels relies more on visual than on acoustic cues. Similarly, Lester et al. (2013) showed that the diamondback terrapin did not alter its behavior in response to recorded boat noise. Díaz et al. (2024) found that traveling green sea turtles increased vigilance with increasing vessel noise. However, those resting on the seabed did not exhibit increased vigilance, suggesting that sea turtles may also respond differently when in different behavioral states.

Current evidence indicates that sea turtles respond to vessel noise at very close ranges, making population-level impacts unlikely. While behavioral responses do occur, attributing them specifically to noise rather than visual or other cues remains challenging. Reactions such as avoidance behavior may disrupt essential activities like feeding. Therefore, it is prudent to consider that noise from vessels could elicit behavioral changes, such as evasive maneuvers, potentially leading to short-term behavioral changes and auditory masking.

6.2.7 Trenching and Pipeline Laying

Preparing an area for pipeline laying may require jetting, plowing, or removal of soft sediments, as well as the excavation of rock and other material through various dredging methods. Pipeline and cable-laying installation vessels are likely to use DP systems while laying the cables. The sound associated with DP generally dominates over other sound sources present, especially compared to the sounds produced by the dredging, trenching, and cable or pipeline-laying activities themselves. Given the estimated source levels and transitory nature of these sources, exceedance of PTS and TTS sound levels are not likely for sea turtles (Heinis et al. 2013), and behavioral disturbances would likely be low intensity and localized.

6.2.8 Pile Driving

Noise from impact pile driving is generally low frequency, which means it overlaps with the hearing range of sea turtles. It is characterized as impulsive because of its high peak pressure, short duration, and rapid onset time. High levels of exposure to impulsive sounds can adversely affect sea turtles through auditory injury, impairment, and behavioral disturbance (Lenhardt 1994; DeRuiter and Doukara 2012). Vibratory pile driving may be used in addition to or instead of impact pile driving in some cases. Vibratory pile driving is expected to create nearly continuous, non-impulsive, low-frequency noise. Therefore, the most damaging elements of sound exposure (the rapid rise time) that are possible with impact pile driving do not pose a risk. To date, no studies have examined the impact of pile driving on sea turtles; however, if the sea turtles remain within an area where piling is occurring for long enough, they may experience TTS or acoustic masking due to the continuous nature of this sound source. Reduced hearing sensitivity because of pile driving could limit the ability to detect predators, prey, or potential mates and reduce the survival and fitness of affected individuals. However, the role and importance of sound in these biological functions for sea turtles remain poorly understood (Lavender et al. 2014). Mitigative measures can prevent or decrease the chance that a sea turtle would experience potential effects from pile driving.

6.2.9 Decommissioning

Decommissioning and removal of OCS structures can be performed using either explosive or non-explosive-severance methods. The shock and pressure waves associated with explosions may cause a number of impacts to sea turtles, including behavioral disturbances, hearing impacts, and physical injuries such as hemorrhages in the lungs, liver, or brain (Ketten et al. 2005; U.S. Navy 2017). Turtles that are recovering after exposure may be more vulnerable to infection and predation, so there also could be indirect increases in mortality (Popper et al. 2014). Like marine mammals, the physical range at which injury or mortality could occur for sea turtles will vary based on the amount of explosive material, size of the turtle, and location of the turtle relative to the explosive.

Noise associated with the explosive removal of oil and gas structures has been linked to mortality of a small number of sea turtles (Klima et al. 1988; Gitschlag and Herczeg 1994). Injuries also have been documented. For example, Duronslet et al. (1986) examined the physiological response of submerged and caged turtles placed at 750, 1,200, 1,800, and 3,000 ft to a detonation of 50 lb of nitromethane. The animals closest to the blast had the most severe physiological responses, including dilated blood vessels (loggerhead) and an everted cloaca (Kemp's ridley); all animals showed some degree of control loss of their vaso-constrictor control centers (sustained pink coloration on throat and flippers).

For the use of explosives in structure decommissioning, applicable mitigative measures are designed to identify the presence of sea turtles near a structure prior to the detonation of an explosive and to avoid or reduce exposure of sea turtles to the shock and pressure waves.

6.2.10 Aircraft

Noises generated by aircraft that are directly relevant to sea turtles include both airborne sounds for turtles nesting or on the sea surface, and underwater sounds from air-to-water transmission from passing aircraft. The dominant tones for both types of aircraft are generally below 500 Hz (Richardson et al. 1995) and are within the auditory range of all sea turtles. Given the frequency range and sound levels produced, when aircraft travel at relatively low altitude, aircraft noise has the potential to elicit stress or behavioral responses in turtles (e.g., diving or swimming away or altered dive patterns; Samuel et al. 2005; National Science Foundation 2011; BOEM 2016a). A specific altitude below which such responses are likely has not been established for sea turtles, as the limited available data on aerial disturbance are derived from small unmanned aircraft (Bevan et al. 2018) rather than crewed aircraft. Nevertheless, the potential for stress or behavioral disturbance increases as aircraft altitude decreases and received sound levels rise.

Sea turtle sensitivity to airborne noise is not well understood, and existing studies have yielded mixed results. For example, Balazs and Ross (1974) exposed postnatal green sea turtles in a transplanted nest to short-duration, high-intensity noise from aircraft engine testing. On numerous occasions, a sudden burst of activity was noted within the nest at the onset of engine noise and continued until the noise subsided (Balazs and Ross 1974). On the other hand, Bevan et al. (2018) observed no evidence of behavioral responses from three species of sea turtles (green, flatback, and hawksbill turtles) exposed to drones flown directly overhead at altitudes ranging from 50 to 102 ft.

Aircraft related to oil and gas operations likely would operate at altitudes below 1,500 ft, except when landing or departing from service vessels. Therefore, disturbance effects on sea turtles are likely to be minimal given the planned altitude and generally low frequency of flights.

7 Fish and Invertebrate Resources—General Information on Hearing

7.1 Importance of Sound to Fish and Invertebrates

Many fishes and invertebrates produce sounds for basic biological functions like attracting a mate and defending territory. Sound production in fishes has evolved at least 33 times throughout evolutionary time, and the majority of ray-finned fishes likely are capable of producing sounds (Rice et al. 2022). Fish may produce sounds through a variety of mechanisms, such as vibrating muscles near the swim bladder, rubbing parts of their skeleton together, or snapping their pectoral fin tendons (Ladich and Bass 2011; Rice et al. 2022). Similarly, many marine invertebrates produce sounds, ranging from the ubiquitous snapping shrimp (Alpheidae) "snaps" (Johnson et al. 1947) to spiny lobster (Palinuridae) "rasps" (Patek 2002) to mantis shrimp (Stomatopoda) "rumbles" (Staaterman et al. 2011). Some sounds are produced as a by-product of other activities, such as the scraping sound of urchins feeding (Radford et al. 2008a) and even a "coughing" sound made when scallops (Pectinidae) open and close their shells (Di Iorio et al. 2012). Some species do not appear to produce sounds but still have acute hearing (e.g., goldfish [*Carassius auratus*]), which may indicate that animals glean a great deal of information about their environment through acoustic cues, a process called "auditory scene analysis" (Fay 2009).

All sounds in a given environment—biological, geophysical, and anthropogenic—make up the "soundscape" (Pijanowski et al. 2011). Soundscapes naturally vary over space and time, and there is increasing evidence that some fish and invertebrate species can distinguish between soundscapes of different habitats (e.g., Radford et al. 2008b; McWilliam and Hawkins 2013; Kaplan et al. 2015). In fact, some pelagic larvae may use soundscapes as a cue to orient towards suitable settlement habitat (Simpson et al. 2005; Montgomery et al. 2006; Radford et al. 2007; Vermeij et al. 2010; Lillis et al. 2015) or to induce molting into their juvenile forms (Lillis et al. 2013; Stanley et al. 2015). The unique acoustic signatures of marine habitats provide vital information to the range of species that reside within and around them.

Compared to marine mammals, scientists have only scratched the surface in understanding the importance of sound to the vast number of extant fish and invertebrate species. However, there is sufficient data thus far to conclude that underwater sounds are vitally important to their basic life functions, such as finding a mate, deterring a predator, or defending territory (Popper and Hawkins 2018; 2019). Thus, these lower taxonomic groups must be able to detect components of marine soundscapes, and detectability could be adversely affected by the addition of noise from anthropogenic activity.

7.2 Hearing Anatomy

All fishes and invertebrates can sense the particle-motion component of a sound wave (**Section 1.1**). The inner ear of fishes is similar to that of all vertebrates. Each ear has three otolithic end organs, which contain a sensory epithelium lined with hair cells, as well as a dense structure called

an otolith (Popper et al. 2021). As the back-and-forth particle motion moves the body of the fish (which has a density similar to seawater), the denser otoliths lag behind, creating a shearing force on the hair cells, which sends a signal to the brain via the auditory nerve (Fay and Popper 2000).

Particle motion also can occur through substrate vibration, and sediment dwelling species, like the sand lance (*Ammodytes* spp.), are believed to be able to detect particle motion over a greater distance via the substrate, because vibrations propagate further in sediment than in water (Williams et al. 2021). Nonetheless, animals that can only detect particle motion or substrate vibration are likely to detect sounds only within a few wavelengths of a sound source, where the particle-motion component of a sound wave is dominant (Urick 1983; Kalmijn 1988; Popper and Hawkins 2018).

In addition to particle-motion detection (a shared trait across all fishes), some species (typically referred to as "hearing specialists") are also capable of detecting acoustic pressure (Fay and Popper 2000). Special adaptations of the swim bladder (e.g., anterior projections, additional gas bubbles, or bony parts) bring it in close proximity to the ear; as the swim bladder expands and contracts due to the change in pressure, particle motion within the body of the fish sends a signal to the ear (Popper et al. 2021).

Hearing specialization is not limited to features that enhance hearing sensitivity or bandwidth (frequency). It may include adaptations for better signal discrimination, sound localization, and detection of signals among masking sounds, among others. Most fish that are considered hearing specialists typically can detect a broader range of acoustic frequencies (up to 3–4 kHz; Wiernicki et al. 2020; Lucke et al. 2024) , but a few species can detect sounds beyond that range (Popper et al. 2021). A few species in the herring family (Clupeidae) can detect ultrasonic (> 20 kHz) sounds (Mann et al. 2001), but this ability is considered to be very rare among the bony fishes.

Another important distinction for species that possess swim bladders is whether the swim bladder is "open" or "closed." Species with open swim bladders can release pressure via a connection to the gut, while those with closed swim bladders can only release pressure very slowly, making them more prone to injury when experiencing rapid changes in pressure (Popper et al. 2019). It should also be noted that hearing sensitivity can change with age; in some species like black sea bass (*Centropristis striata*), the closer proximity between the ear and the swim bladder in smaller fish can mean that younger individuals are more sensitive to sound than older fish (Stanley et al. 2020). In other species, hearing sensitivity seems to improve with age (Kenyon 1996).

Invertebrate bioacoustics is a rapidly expanding field of research (Normandeau Associates Inc. 2012; Mooney et al. 2016; Popper and Hawkins 2018). Like elasmobranchs and other fishes considered to be hearing non-specialists, marine invertebrates lack a gas-filled bladder and are unable to detect the pressure changes associated with sound waves. However, all cephalopods—as well as some bivalves, echinoderms, and crustaceans—have a sac-like structure (called a statocyst) that develops during the larval stage and includes a mineralized mass (statolith) and associated sensory hairs (e.g., crustaceans in Edmonds et al. 2016). Statocysts, which are similar

to fish ears, act like accelerometers; a dense statolith sits within a body of hair cells, and when the animal is moved by particle motion, it results in a shearing force on the hair cells (Budelmann 1992; Mooney et al. 2010). In addition to statocysts, some invertebrates have epidermal hair cells that help them to detect particle motion in their immediate vicinity (Budelmann 1992; Kaifu et al. 2008), comparable to lateral lines in fish (McCormick 2011). Similarly, decapods have sensory setae on their body (Popper et al. 2001), including on their antennae, which may be used to detect low-frequency vibrations (Montgomery et al. 2006).

The research thus far shows that the primary hearing range of most particle-motion-sensitive fish and invertebrates is below 1 kHz (Popper et al. 2021).

7.3 Hearing Groups

Although there is a wide variety in hearing anatomy and sensitivity among fishes and invertebrates, Popper et al. (2014) proposed three categories to describe fish hearing, and these categories have been accepted by the scientific community (**Table 10**). However, Lucke et al. (2024) recently proposed sub-categories within each of these groups to further delineate relative sensitivity across taxa; the authors also proposed rudimentary weighting functions. It is still unclear whether (or when) the regulatory community will adopt these new hearing groups.

Table 10. Fish and invertebrate groupings based on hearing anatomy

Group	Hearing Anatomy	Example Species[1]	Sensitivity to Underwater Sound
1	Fishes with no swim bladder or other gas chamber, invertebrates, eggs and larvae	Flatfish, Atlantic mackerel, sharks, rays, cephalopods, crustaceans, bivalves	Detect particle motion but not acoustic pressure, sensitive to sound over relatively small spatial scales, not susceptible to barotrauma. Generally capable of detecting sounds up to 1 kHz.
2[#]	Fishes with swim bladders in which hearing does not involve the swim bladder or other gas volume	Bluefish, snapper, some tunas, Atlantic salmon, European seabass, lake sturgeon, drum, black sea bass	Detect particle motion but not acoustic pressure. May be susceptible to barotrauma due to the presence of a swim bladder. May be sensitive to sounds up to ~3 kHz.
3[#*]	Fishes in which hearing involves a swim bladder or other gas volume	Cod, European eel, squirrelfish, croaker, Atlantic herring, goldfish	Detect particle motion and acoustic pressure. May be susceptible to barotrauma. Sounds can be detected over larger spatial scales and are generally considered to be the most sensitive to impacts from anthropogenic sound. May be able to detect sounds up to 5 kHz, and in some rare cases (e.g., herring) > 20 kHz.

Notes: Nomenclature based on classification in Popper et al. (2014). Example species and frequency ranges from Wiernicki et al. (2020).
[#] There is no distinction within Groups 2 and 3 between fishes with open vs. closed swim bladders, though some evidence suggests that this distinction could be important when considering susceptibility to barotrauma (Popper et al. 2019).
* Wiernicki et al. (2020) further divide Group 3 into two subgroups: 1) fishes with anterior projections of the swim bladder,

which bring it in closer proximity to the ear and enhances hearing; and 2) fishes with Weberian ossicles (special bones that connect the swim bladder to the ear) representing the most sensitive of all fishes.
[1] Scientific names for example species, by group. Group 1: flatfish (order Pleuronectiformes), Atlantic mackerel (*Scomber scombrus*), sharks and rays (subclass Elasmobranchii), cephalopods (class Cephalopoda), crustaceans (subphylum Crustacea), bivalves (class Bivalvia). Group 2: bluefish (*Pomatomus saltatrix*), snapper (family Lutjanidae), tunas (*Thunnus* spp.), Atlantic salmon (*Salmo salar*), European seabass (*Dicentrarchus labrax*), lake sturgeon (*Acipenser fulvescens*), drum (family Sciaenidae), black sea bass (*Centropristis striata*). Group 3: Atlantic cod (*Gadus morhua*), European eel (*Anguilla anguilla*), squirrelfish (family Holocentridae), Atlantic croaker (*Micropogonias undulatus*), Atlantic herring (*Clupea harengus*), goldfish (*Carassius auratus*).

7.4 Potential Impacts of Underwater Sound to Fish and Invertebrates

As with marine mammals and sea turtles, fish and invertebrates may experience a range of impacts from underwater sound depending on physical qualities of the sound source and the environment, as well as the physiological characteristics and the behavioral context of the species of interest (Pieniazek et al. 2023). Examining the short and long-term effects of low-frequency sound on marine fishes and invertebrates is critical for understanding the broad range of impacts, especially impacts to important biological processes such as reproduction, larval development, and recruitment (Carroll et al. 2017).

It is important to note that—unlike mammals, whose hair cells do not regenerate—fishes are able to regrow hair cells that die or become damaged (Corwin 1981), making it unlikely that they would experience PTS; therefore, there are no thresholds focused explicitly on auditory injury.

However, fishes do experience TTS, and, when very close to impulsive sound sources or explosions, they could experience barotrauma, a term that refers to a class of injuries ranging from recoverable bruises to organ damage (which could ultimately lead to death; Stephenson et al. 2010; Popper et al. 2014). When the air-filled swim bladder inside the body of the fish quickly expands and contracts due to a rapid change in pressure, it could cause internal injuries to the nearby tissues (Halvorsen et al. 2011). The greater the difference between the static pressure at the site of the fish and the positive or negative pressures associated with the sound wave, the greater the risk of barotrauma. Therefore, impulsive sounds like those generated by impact pile driving or seismic airguns may present a risk of injury due to the rapid changes in acoustic pressure (Hamernik and Hsueh 1991).

For marine invertebrates, exposure to near-field, high-amplitude sound may cause anatomical damage and behavioral responses (Carroll et al. 2017). A review by Cones et al. (2024b) show that data from comparable studies of similar sound types and characterizations provide evidence that acoustic impacts to bivalves tend to be more severe with increasing received levels. Jézéquel et al. (2023) identified significant differences between the auditory thresholds of juvenile and subadult giant scallops, with juveniles being more sensitive, suggesting ontogenetic differences in hearing sensitivity. Giant scallop auditory thresholds below 500 Hz were quantified using particle acceleration and behavioral responses; the results showed maximum sensitivity at 100 Hz and that stronger valve closures occurred with exposure to lower frequencies and higher sound levels (Jézéquel et al. 2023).

Damage to invertebrate statocysts has been observed as a result of sound exposure, but it is unclear whether the hair cells can regenerate, like they do in fishes (Solé et al. 2013; 2017). Furthermore, most studies to date have focused on low-frequency sound, but a playback study using high-frequency stimuli (100–200 kHz sweeps) was reported to elicit a noise-induced physiological stress response in black sea urchins (*Arbacia lixula*) (Vazzana et al. 2020).

As with marine mammals, continuous, lower-level sources (e.g., vessel noise) are unlikely to result in auditory injury but could induce changes in behavior or acoustic masking. Generally speaking, since particle motion is most relevant within a few wavelengths of a sound source, impacts from underwater noise on marine invertebrates are likely to occur over very small spatial scales (Urick 1983; Kalmijn 1988; Popper and Hawkins 2018).

7.4.1 Thresholds for Physical and Auditory Injury

The sound exposure guidelines for fishes and sea turtles by Popper et al. (2014), which became an ANSI standard (#ASA S3/SC1.4 TR-2014), have become the widely accepted thresholds for physical and auditory injury for fishes, parts of which have been accepted by the NMFS.

Because hair cells in fish ears regenerate (Corwin 1981), fishes are unlikely to experience permanent hearing loss (PTS). They may, however, experience physical injury (including barotrauma) or TTS when close to impulsive sources. The thresholds for barotrauma and mortality were derived from a series of studies using a special testing apparatus that simulated signals from pile driving 10 m from a pile (Halvorsen et al. 2011; Casper et al. 2012; Halvorsen et al. 2012a; 2012b; Casper et al. 2013a; 2013b). An important component of this work was the ability to simulate both the pressure and particle-motion components of the sound field, which is rarely done in laboratory experiments. These studies showed that effects are greater in fishes with swim bladders than those without, and that species with closed swim bladders experienced greater damage than those with open swim bladders.

Popper et al. (2014) organize these effects into a graded set of categories, from most to least severe: (1) mortality and potential mortal injury (immediate or delayed death, e.g., from severe barotrauma often linked to explosions); (2) recoverable injury, defined as "injuries, including hair-cell damage, minor internal or external hematoma, etc.," which are not likely to result in mortality (**Table 11**); and (3) TTS, defined as any change in hearing of 6 dB or greater that persists. Barotrauma therefore spans two categories (fatal barotrauma falls under mortal injury, while non-fatal barotrauma is a recoverable injury), whereas TTS is a distinct, hearing-specific form of impairment. Consistent with the recoverable nature of these effects, the pile-driving studies described above found that many fish recovered from both physical injuries and TTS within 10 days of exposure (Casper et al. 2013b).

Unlike with marine mammals, Popper et al. (2014) do not distinguish between impulsive and non-impulsive sounds; instead they provide thresholds for each sound type (explosions, pile driving, seismic airguns, sonars, and continuous sounds). That said, studies focused on pile driving are used sometimes to draw conclusions about impacts from seismic airguns, and vice versa. This

method is used when there is a lack of comprehensive data for each source type. The thresholds are all given in terms sound pressure, not particle motion, though many have acknowledged that it would be more appropriate to develop thresholds in terms of particle motion (Popper and Hawkins 2018). Currently, there are no underwater noise thresholds for invertebrates, but the effect ranges are expected to be similar to those predicted for fishes in Group 1 (**Table 11**). While the Popper et al. (2014) work is more than a decade old, it still incorporates the most recent data on effects of exposure and focuses on hearing anatomy, which is very important to consider with fishes. Nonetheless, NMFS still recommends using older thresholds from the Fisheries Hydroacoustic Working Group (2008) which split fishes into two size classes (NMFS 2023). BOEM generally prefers use of the Popper et al. (2014) thresholds because the groupings are related to hearing anatomy. Currently, there are no thresholds for noise exposure in invertebrates.

Table 11. Acoustic thresholds for fishes for exposure to seismic airguns and pile-driving sounds

Fish Hearing Group	Mortality and Non-Recoverable Injury		Recoverable Injury		TTS
	L_{pk}	SEL	L_{pk}	SEL	SEL
Fish without swim bladder (Group 1)[a]	> 213	> 219	> 213	> 216	> 186
Fish with swim bladder not involved in hearing (Group 2)[a]	> 207	210	> 207	203	> 186
Fish with swim bladder involved in hearing (Group 3)[a]	> 207	207	> 207	203	186
Eggs and Larvae[a]	> 207	> 210	-	-	-
Fish ≥ 2 g[b]	-	-	206	187	-
Fish < 2 g[b]	-	-	206	183	-

[a] Popper et al. (2014). Note that Popper et al. (2014) use the notation "SEL_{cum}," but SEL without a subscript is the preferred nomenclature, used here to describe the energy that would be accumulated over an entire sound-producing event (i.e., installation of a pile). For seismic airguns, SEL_{cum} is more difficult to quantify, so the authors suggest using L_{pk} instead. See **Section 2.2** for further detail about the units of measurement.
[b] Fisheries Hydroacoustic Working Group (2008)

Injury from Explosives: Popper et al. (2014) present criteria for mortality and non-recoverable injury as a result of exposure to detonations. They note that it is difficult to disentangle the effects of the compressive forces of the shock wave (very close to the explosion) from the decompressive effect (area of negative pressure, further from the explosion), but both effects could lead to barotrauma or mortality in fishes. Several studies (e.g., Yelverton et al. 1975; Goertner 1978b) have worked with different species, charge sizes, and water depths—all important factors in predicting the effects of explosives. Popper et al. (2014) derive their thresholds using data from an older study, which represents the lowest amplitude that caused consistent mortality across species (Hubbs and Rechnitzer 1952). Therefore, for all fishes, regardless of hearing anatomy, the L_{pk} threshold for mortality and non-recoverable injury is given as a range of 229–234 dB re 1 µPa by Popper et al. (2014); however, in practice, 229 dB is generally used.

7.4.2 Thresholds for Behavioral Disturbance

NMFS currently uses an SPL criterion of 150 dB re 1 µPa for the onset of behavioral effects in fishes (NMFS 2023). The scientific rationale for this criterion is not well supported by the data (Hastings 2008), and there has been criticism about its use (Popper et al. 2019). Most notably, the differences in hearing anatomy among fishes suggest the use of a single criterion may be too simplistic (Popper 2023). Furthermore, a wide range of behavioral responses have been observed in the empirical studies thus far (ranging from startle responses to changes in schooling behavior), and it is difficult to ascertain which, if any, of those responses may lead to significant biological consequences.

Interestingly, several studies on free-ranging fishes (Hawkins et al. 2014; Roberts et al. 2016) have observed the onset of different behavioral responses at similar received levels ($L_{pk\text{-}pk}$ of 152–167 dB re 1 µPa). Popper et al. (2019) suggest that a received level of 163 dB re 1 µPa $L_{pk\text{-}pk}$ might be more appropriate than the current SPL criterion of 150 re 1 µPa. Studies on spawning Atlantic cod showed no substantially altered behavior when exposed to distant seismic airguns at received levels between 115 and 145 dB re 1 μPa^2 (McQueen et al. 2022). However, the same fish species were observed to decrease their activity levels and increase swimming depths when exposed to marine vibrator noise at the same exposure levels (McQueen et al. 2024). The authors suggest that the cod were probably more likely to be disturbed by continuous sounds than intermittent sounds.

Finally, given that most species are more sensitive to particle motion and not acoustic pressure, the criteria should, at least in part, be expressed in terms of particle motion. However, until there is further empirical evidence to support a different criterion, the 150 dB re 1 µPa SPL threshold remains in place as the interim metric that regulatory agencies have agreed upon.

8 Fish and Invertebrates—Impacts of Underwater Sound

8.1 Potential Impacts of Non-BOEM Acoustic Sources

Avoidance of vessels and vessel noise has been observed in several pelagic, schooling fishes, including Atlantic herring (*Clupea harengus*) (Vabø et al. 2002), Atlantic cod (*Gadus morhua*) (Handegard et al. 2003), and others (reviewed in De Robertis and Handegard 2013; Pieniazek et al. 2023). Fish may dive toward the seafloor, move horizontally out of a vessel's path, or disperse from their school (De Robertis and Handegard 2013). These types of changes in schooling behavior could render individual fish more vulnerable to predation but are unlikely to have population-level effects.

A body of recent work has documented other, more subtle behaviors in response to vessel noise but has focused mainly on tropical reef-dwelling fish. For example, Ambon damselfish (*Pomacentrus amboinensis*) antipredator responses (Simpson et al. 2016; Ferrari et al. 2018) and boldness (Holmes et al. 2017) seem to decrease in the presence of vessel noise, while nest-guarding behaviors seem to increase (Nedelec et al. 2017). Similar effects have been documented in the field where exposure to both vessel-noise playback and low-frequency pure tones reduced foraging and increased refuging in the dusky damselfish (*Stegastes fuscus*), though territory defense was unaffected (Lessa et al. 2025). However, there also is some evidence of habituation. Nedelec et al. (2016) found that domino damselfish (*Dascyllus trimaculatus*) increased hiding and ventilation rates after 2 days of vessel sound playbacks, but responses diminished after 1–2 weeks, indicating habituation over longer durations.

Evaluating the effects of noise on reproductive success and species survival requires considering not only dramatic impacts such as injury or mortality, but also more subtle changes in social behavior and communication. Data from a playback study on the African cichlid (*Astatotilapia burtoni*) showed that, when exposed to pure tones of 100 Hz–2 kHz (used to simulate the frequency range of vessel noise), the fish were less likely to interact with one another in territorial, courtship, or reproductive interactions, and females had a lower incidence of spawning and reduced hearing capabilities than non-exposed animals (Butler and Maruska 2020).

It is possible that vessel noise could induce physiological stress or lead to acoustic masking in fishes. Several studies have shown an increase in cortisol, a stress hormone, after playbacks of vessel noise (Wysocki et al. 2006; Nichols et al. 2015; Celi et al. 2016), but other work has shown that the handling stress of the experiment itself may induce a greater stress response than an acoustic stimulus (Harding et al. 2020; Staaterman et al. 2020). More recent work is beginning to link noise-induced behavioral change to physiological pathways. In the eastern striped trumpeter (*Pelates sexlineatus*), simulated intermittent boat noise increased resting and erratic movement, and produced subtle shifts in the gut microbiome, although overall microbial diversity was not significantly altered over the short term (Valenzisi et al. 2026).

The cavitation of vessel propellors produces low-frequency, nearly continuous sound that is audible by most fishes and invertebrates and could mask important auditory cues, including conspecific communication (Haver et al. 2021; Parsons et al. 2021). Stanley et al. (2017) demonstrated that the communication range of both haddock (*Melanogrammus aeglefinus*) and Atlantic cod (*Gadus morhua*; species with swim bladders but lacking connections to the ear) would be significantly reduced in the presence of vessel noise, which is frequent in their habitat in Cape Cod Bay. During the passage of a ferryboat, Vieira et al. (2021) found a reduction in acoustic energy of meagre (*Argyrosomus regius*) chorusing and a reduction in the ability to discriminate conspecific calls, suggesting a significant masking effect of vessel noise, which could impact spawning behavior (Vieira et al. 2021). Field studies of estuarine spawning aggregations reinforce this concern. In the northern GOA, vessel noise, interacting with environmental variables, influenced the spawning choruses of silver perch (*Bairdiella chrysoura*) and seatrout (*Cynoscion* spp.) (Boyle et al. 2025), and vessel passages were associated with reductions in red drum (*Sciaenops ocellatus*) spawning choruses in Saint Andrew Bay, FL (Price et al. 2026).

Generally speaking, species that are sensitive to acoustic pressure would experience masking at greater distances than those that are only sensitive to particle motion. Rogers et al. (2021) and Stanley et al. (2017) theorize that fish may be able to use the directional nature of particle motion to extract meaning from short range cues (e.g., other fish vocalizations) even in the presence of distant noise from vessels.

The great diversity of aquatic invertebrates, compounded by a relative lack of research on vessel noise specifically, makes it difficult to draw broad conclusions about effects on this taxonomic group. However, Davies et al. (2024) conducted a meta-analysis to investigate how different acoustic stimuli influence aquatic invertebrates' behavior and physiology. The study looked at 50 species under a range of experimental conditions with four sound types: anthropogenic, environmental, synthetic, and music. The authors concluded that anthropogenic and synthetic sounds had detrimental effects on the animals, particularly on defensive behaviors such as hiding, sheltering, and bivalve shell closure, while environmental sounds had slightly beneficial effects on their behavior (Davies et al. 2024).

In a laboratory playback study, Putland et al. (2023) exposed three life stages of hummingbird bobtail squid (*Euprymna berryi)* to 15 minutes of vessel sound at 150 dB re 1 µPa, resulting in TTS and a decrease in ventilation rate for all life stages; all life stages subsequently recovered in 2 hours. Some crustaceans seem to increase oxygen consumption (crabs: Wale et al. 2013) or show increases in some hemolymph (an invertebrate analog to blood) biomarkers like glucose and heat-shock proteins, which are indicators of stress (spiny lobsters: Filiciotto et al. 2014). Other species (American lobsters [*Homarus americanus*] and blue crabs [*Callinectes sapidus*]) show no difference in hemolymph parameters but spend less time handling food, defending food, and initiating fights with competitors (Hudson et al. 2022). One study examined the impacts of noise on locomotor activity of burrowing animals (the Manila clam [*Ruditapes philippinarum*], Norway lobster [*Nephrops norvegicus*], and brittlestar [*Amphiura filiformis*]) and showed that to some extent, noise changed the way they mediate sediment dynamics (Solan et al. 2016). More recent

studies continue to document species and tissue-specific effects across invertebrate taxa. In the estuarine crab (*Cyrtograpsus angulatus*), motorboat-noise-induced, oxidative-stress responses that varied by tissue, sex, and life stage, with adult males most affected by boat noise (Snitman et al. 2025). Behavioral effects have also been shown in reef mollusks. Boat-noise playback altered the behavior of the small giant clam (*Tridacna maxima*) and the spider conch (*Lambis lambis*), suggesting individuals expend energy responding to noise rather than feeding or, for *T. maxima*, remaining open for its symbiotic algae to photosynthesize (Havlik et al. 2026). Effects may extend to early life stages as exposure to realistic cargo-shipping noise produced intensity-dependent, proteome-level changes in developing blue mussel (*Mytilus edulis*) post-larvae, including altered abundance of proteins involved in metabolism, cytoskeletal organization, morphogenesis, and shell formation (Beauclercq et al. 2026).

While there does seem to be some evidence that hearing, certain behaviors, and stress biomarkers in invertebrates could be negatively affected by vessel noise, it is difficult to draw conclusions from much of this work since it is limited to the laboratory, and, in most cases, particle motion was not measured as the relevant cue.

8.2 Potential Impacts of BOEM-Related Sound Sources

8.2.1 Seismic Surveys (Airguns)

8.2.1.1 Fish

Very close to impulsive sound sources like seismic airguns, fish could experience barotrauma or TTS. McCauley et al. (2003) found damage to hearing structures in fish held in cages while an airgun passed overhead (5–800 m distance from the cages), but they did not measure hearing thresholds. In Popper et al. (2005), two species with hearing specializations experienced TTS when held 13–17 m from an airgun, and they recovered within 18 hours; additionally, the species with least-sensitive hearing showed no evidence of TTS. Several additional studies in subsequent years (e.g., Hastings 2008; McCauley and Fewtrell 2008; McCauley and Kent 2012) found mixed results depending on species, proximity to the airgun, and received levels.

Taken together, this body of work has shown that TTS and damage to hearing structures is possible from high-intensity sources. However, these types of effects are generally observed very close to the source (< 10 m), species without gas-filled cavities are less likely to sustain effects, and even those that do sustain effects can recover within several days of exposure. There is the potential for secondary effects; for example, after exposure, a fish with decreased fitness (due to decreased hearing sensitivity) may be more vulnerable to predation, less likely to find a mate, or unable to find food while their hearing is recovering. High-intensity sources may also cause stress responses, including increased cortisol and oxidative stress, which have been demonstrated in freshwater species exposed to airgun noise (Réalis-Doyelle et al. 2025).

Studies that have examined potential behavioral impacts to fishes have generally found that most species exhibit subtle, short-term changes when exposed to seismic airguns (Slabbekoorn et al.

2019). The research has covered a range of species, each with different hearing capabilities, and has employed a variety of methods. For example, some studies have used echosounders to observe potential changes in schooling behaviors of wild fish in the vicinity of impulsive sound sources (e.g., Dalen and Knutsen 1987; Jorgenson and Gyselman 2009; Peña et al. 2013; Hawkins et al. 2014). In some cases, fish swim lower in the water column and schooling behaviors are disrupted, but only temporarily (Slotte et al. 2004; Hawkins et al. 2014). Hynes et al. (2025) reported effects at larger distances (up to 60 km from the source) than had previously been studied, and the primary effect observed was that fish swam deeper in the water column, which is consistent with previous literature. Other work has held fish in cages or used video cameras to observe potential startle responses or changes in heart rate (Wardle et al. 2001; McCauley et al. 2003; Hassel et al. 2004; Boeger et al. 2006; Thomsen 2008), which appeared to be short-term responses.

Perhaps the most revealing studies have tagged or counted wild fish and observed their behavior in response to real airgun arrays. For example, van der Knaap et al. (2021) examined the response of free-ranging, tagged Atlantic cod (*Gadus morhua*) during multiple passes of a full-scale (2,950 in^3) seismic survey and found subtle changes in their behavior, with no evidence that cod left the area during the survey. In 2022, McQueen et al. (2022) found similar results with spawning Atlantic cod (*Gadus morhua*) when exposed to seismic airgun noise over two 1-week periods, with received SELs up to 145 dB re 1 μPa^2s, which was comparable to a full-scale industrial survey 5–40 km away. By comparing the residency and departure rates of tagged cod at both control and test sites over 3 years, the authors concluded that free-ranging cod were not displaced from spawning grounds, and they speculated that strong affinity to selected spawning sites overcame any behavioral effects of noise exposure. Similarly, Nguyen et al. (2025) monitored groundfish with baited cameras at control and impact sites before and after a 100-day commercial seismic survey along a continental slope off Newfoundland and Labrador, Canada. Abundance was not explained by seismic noise for any of the five commonly observed species; however, Atlantic cod (*Gadus morhua*) showed significantly longer arrival times to the baited cameras, indicating a subtle behavioral change consistent with the broader literature (Nguyen et al. 2025).

Finally, in the most comprehensive study to date, Meekan et al. (2021) used a before-after-control-impact design to examine the movements and behavior of fish assemblages (via both tagging and video surveys) during seismic surveys (2,600 in^3 arrays). All fishes sampled had swimbladders, but it was not known whether they were all hearing specialists. The team found no overall change in fish assemblages from the underwater videos, no significant changes in fish behavior (e.g., time to approach bait on the video), and no significant change in the movements of red emperor (*Lutjanus sebae*) between the high exposure and control areas; most fish stayed within 150 m^2 of the place where they were first detected. Because the team collected data several months prior to and after exposure to seismic airguns, used a full-scale seismic array, and had a high sample size, the results of this study do provide helpful insights into the overall effects of seismic airguns on fish behavior.

The studies described above cover a range of methods and have focused on different species, each with their own hearing capabilities. Yet a common trend that emerges is that fish often show an initial response (either a startle response or a change in schooling behavior), but this response decreases with repeated exposure or ramp-up of the sound source. There is not compelling evidence suggesting that fishes abandon their habitat, cease feeding, or show a prolonged disruption in normal diel patterns when a seismic survey passes nearby.

8.2.1.2 Invertebrates

Studies on the effects of seismic surveys on marine invertebrates have yielded mixed results, and several reviews point out that the varying experimental conditions make it difficult to draw meaningful conclusions across such a wide taxonomic group (Morley et al. 2014; Edmonds et al. 2016; Carroll et al. 2017).

Several studies have examined impacts of high-intensity sounds on benthic invertebrates. Day et al. (2017) found that airgun exposure changed blood chemistry and altered normal behaviors in burrowing scallops (*Pecten fumatus*) within several hundred meters of the source. Although mass mortality did not occur, rock lobsters (*Jasus edwardsii*) exposed to seismic airguns also exhibited reflex impairment and changes in blood chemistry. Follow-up work by Day et al. (2022) and Day et al. (2019) showed that these southern rock lobsters had impaired righting reflexes and significant damage to sensory hairs of the statocyst, and these effects persisted up to 365 days post-exposure and did not improve following molting. These results indicate that exposure to air gun signals at close ranges caused morphological damage to the statocyst of juvenile and adult rock lobsters, which can in turn impair complex reflexes (Day et al. 2019; 2022).

In contrast, Christian et al. (2003) observed no significant impacts on the behavior or health of adult snow crabs (*Chionoecetes opilio*) that were exposed to seismic airguns. Payne et al. (2007) also showed no obvious mortality or physiological changes in American lobster (*Homarus americanus*) exposed to airguns, but sub-lethal effects to blood biochemistry were observed. Alarm and startle responses have been observed in squid (S*epioteuthis australis*) (Fewtrell and McCauley 2012) and cuttlefish (*Sepia officinalis*) (Samson et al. 2014).

The apparent inconsistency across these invertebrate studies likely reflects differences in the species, water depths, and experimental conditions. For example, the southern rock lobster (*Jasus edwardsii*) and the scallop (*Pecten fumatus*), which were focal species of work by Day et al. (2017; 2019; 2022)), are deeper-water species from Australian waters, and the spiny lobster and bay lobster prevalent in the GOA differ markedly in habitat and depth distribution. Therefore, these studies may represent taxa that are not directly comparable, and when compounded by a general scarcity of high-quality studies, caution should be taken when interpreting results.

Finally, sessile benthic invertebrates such as corals and anemones remain very poorly studied with respect to seismic and other impulsive noise, and little to no recent research has been published on this topic. Given these limitations, it remains difficult to generalize about the scale and nature of acoustic impacts from seismic surveys across such a diverse group as marine invertebrates.

8.2.2 HRG Surveys

Only a handful of HRG sources (e.g., boomers, sparkers, bubble guns, and some SBPs) emit sounds at frequencies that are within the hearing range of most fishes and invertebrates. This means that side-scan sonars, MBESs, and some SBPs would not be audible, and thus would not affect these taxa.

For the sources that are audible, it is important to consider other factors such as source level, beamwidth, and duty cycle (Ruppel et al. 2022). Boomers, sparkers, hull-mounted SBPs, and bubble guns have source levels close to the threshold for injury for pressure-sensitive fishes, so unless a fish is within a few meters of the source, injury is highly unlikely (Popper et al. 2014; Crocker and Fratantonio 2016).

Behavioral impacts could occur over slightly larger spatial scales. For example, if one assumes an SPL threshold of 150 dB re 1 µPa for behavioral disturbance in fishes (Greater Atlantic Regional Fisheries Office 2022), sounds with source levels of 190 dB re µPa·m would fall below this threshold several hundred meters from the source (assuming 15*log(range) propagation loss). This means that the lowest-powered sparkers, boomers, and bubble guns would not result in behavioral disturbance to fishes beyond this distance, and this range would be even smaller for quieter sources like towed SBPs (Crocker and Fratantonio 2016). This expectation is supported by direct field evidence where McQueen et al. (2025) exposed wild, tagged Atlantic cod (*Gadus morhua*) to a real sparker source (up to the 800 J level) over a 40-hour period and found that all but one of the tagged cod remained at the test site, with no detectable changes in location, swimming depth, activity, or displacement attributable to the exposure. The authors concluded that the relatively low sound levels produced by an 800 J sparker do not greatly disturb cod, at least during the feeding season.

It should be noted that these numbers are reported in terms of acoustic pressure because there currently are no behavioral disturbance thresholds for particle motion. It is expected that behavioral impact ranges would be even smaller for particle-motion-sensitive species, including invertebrates. Because most HRG sources are typically “on” for short periods with silence in between, only a few “pings” emitted from an active acoustic source towed from a moving vessel would reach fish or invertebrates below, so any behavioral effects would be intermittent and temporary.

8.2.3 Geotechnical Surveys

Given the relatively low source levels from geotechnical surveys, they are unlikely to have impacts on fish or invertebrates. Animals would have to be in very close proximity to geotechnical equipment to even experience behavioral disturbance, based on the current SPL threshold of 150 dB re 1 µPa for behavioral disturbance (Greater Atlantic Regional Fisheries Office 2022). It is expected that behavioral impact ranges would be even smaller for particle-motion-sensitive species, including invertebrates.

8.2.4 Dredging

Mechanical or hydraulic dredging may be required to prepare areas for construction or to widen or deepen ports. Given the physical qualities of dredging and drilling noise, injury and auditory impairment are unlikely, but fishes and invertebrates could experience behavioral disturbance or masking close to these activities. No research has specifically looked at responses to these noise sources, but impacts are likely to be similar, though less intense, than those observed from vessel noise since these activities are not as widespread or frequent as vessel transits.

8.2.5 Drilling and Production

Very few studies have explicitly examined the effects of drilling noise on fishes. Spiga et al. (2017) conducted playback experiments of European seabass (*Dicentrarchus labrax*) in tanks and observed seabass responses to a mock predator after exposure to drilling noise. Control fish became immobile when the predator was present, and fish exposed to drilling noise spent more time sheltering in the safety zone. Opercular beat rate, which generally tracks with metabolic rate, was elevated during playbacks of drilling noise compared to control periods (Spiga et al. 2017). Kusku et al. (2020) examined on a regular basis over a 4-month period the opercular beat rate of Nile tilapia (*Oreochromis niloticus*) that were kept in tanks and exposed daily to either drilling or pile-driving noise. Similar to Spiga et al. (2017), they found that opercular beat rate was elevated in the presence of both sound types. They also found reduced growth in noise-exposed fish over the first 4 weeks; thereafter, the growth rate of exposed fish recovered to match that of control fish, although the earlier deficit means exposed individuals did not necessarily reach the same absolute size.

These studies suggest that chronic exposure to drilling noise could affect metabolic rates in fishes, which is generally consistent with the literature on fishes and other continuous noise sources like vessel noise (Klin et al. 2026).

Even fewer studies have addressed invertebrates. In one of the only experiments to isolate drilling noise, Gigot et al. (2023) exposed great scallop (*Pecten maximus*) larvae to playback of drilling and pile-driving sound and found that drilling noise reduced larval survival and metamorphosis and delayed settlement, whereas pile-driving noise had the opposite, stimulatory effect. These contrasting results underscore how little is known about invertebrate responses to drilling noise and caution against generalizing across sound types or life stages.

8.2.6 Vessels and DP Systems

Several types of vessels are used to support oil and gas activities (**Section 2.5.7**). For a description of the potential impacts of vessel noise on fish, see **Section 8.2.6**.

There is only one study that has explicitly examined the impacts of DP noise on fish (Peña 2019), and they found reactions similar to other vessel noise (e.g., some changes in schooling behavior and vertical displacement). Received levels were not measured in this study, so it is difficult to

predict the distance at which such reactions may occur. Effects are generally expected to occur over a relatively small area, especially for particle-motion-sensitive species. Some species also may become habituated to persistent vessel noise (Nedelec et al. 2016).

No studies have specifically examined the effects of DP noise on invertebrates. Because DP thrusters produce continuous, low-frequency broadband sound similar in character to vessel noise, any effects on particle-motion-sensitive invertebrates are expected to resemble those described for vessel noise (**Section 7.1**), primarily localized behavioral responses, though this remains untested.

8.2.7 Trenching and Pipeline Laying

Given the physical qualities of noise associated with trenching and pipeline laying, impacts to fishes and invertebrates are expected to be relatively minor and occur only over small spatial scales around the activity. These activities generate predominantly low-frequency, relatively continuous sound at source levels, below those of impulsive sources such as airguns or pile driving, and they proceed slowly along a fixed route rather than ensonifying a broad area. As a result, any behavioral disturbance would be limited to animals in the immediate vicinity and would be transient as the operation advances. No studies have directly measured fish or invertebrate responses to trenching or pipeline-laying noise, so these expectations are inferred from the broader literature on continuous, low-intensity sound sources.

8.2.8 Pile Driving

The installation of the relatively small pin piles typically used for oil and gas structures is unlikely to cause injury or mortality to fish and invertebrates, since noise levels are relatively low (**Section 2.5.9**). However, given the increase in offshore wind around the world, there is a now a suite of literature looking at effects of larger monopile installation on fish. Most of the literature cited below refers to potential impacts from driving these larger piles.

Literature on behavioral and physiological effects of pile-driving noise on fish has focused mostly on commercially important species like the European seabass (*Dicentrarchus labrax*), which lacks hearing specializations and has a closed swim bladder. Adult seabass generally dive deeper and increase swimming speed and group cohesion when exposed to intermittent and impulsive sounds like pile driving (Neo et al. 2014; 2018), but juveniles become less cohesive (Herbert-Read et al. 2017) and generally seem to be more sensitive to pile-driving noise than adults (Kastelein et al. 2017). There is also some evidence that respiration rates may be affected by pile-driving noise (Spiga et al. 2017).

Importantly, several studies have shown that European seabass are likely to habituate to pile-driving sounds over repeated exposure (Bruintjes et al. 2016; Neo et al. 2016; Radford et al. 2016). This trend is consistent with the findings from Stanley et al. (2023) and Jarriel et al. (2025), who found that black seabass (*Centropristis striata*) generally show short-term behavioral reactions, with no lasting impacts on spawning behavior.

Field studies on other species indicate that fish may be startled, temporarily displaced, or change their schooling behaviors during exposure to pile driving or other impulsive sources, but when the sound ceases, the fish resume normal behaviors relatively quickly (Hawkins et al. 2014; Iafrate et al. 2016; Krebs et al. 2016).

Overall, the research thus far indicates that fishes exhibit short-term behavioral or physiological responses to impulsive sounds like impact pile driving. Species with more sensitive hearing likely are more susceptible to TTS and behavioral disturbance—and at greater distances—than those with less sensitive hearing. These impacts are likely for only the larger pile-driving operations associated with offshore wind, rather than the smaller piles used for oil and gas infrastructure.

Sessile marine invertebrates like bivalves are sensitive to substrate-borne vibrations and may be affected by noise from driving large piles (Roberts et al. 2015; Spiga et al. 2016; Day et al. 2017). Jézéquel et al. (2022) observed behavior of giant scallops (*Placopecten magellanicus*) in response to a real pile-driving event at distances of 8 and 50 m from a pile (pile diameter of 0.3 m). None of the scallops exhibited swimming behavior, an energetically expensive escape response. At the close site only, scallops increased valve closures during pile-driving noise but returned to their pre-exposure behaviors within 15 minutes. A follow-up study revealed that reduced valve opening and rapid valve adduction resulted in a decrease in oxygen levels and an increase in metabolic rates, respectively, over baseline conditions (Cones et al. 2024a). In addition, they found that exposure to pile driving resulted in a weakened anti-predatory response, including fewer swimming events and a shorter time to exhaustion in comparison to unexposed scallops. Increased time spent with closed valves could reduce feeding opportunities and thus have energetic consequences, though the biological consequences of this effect have not been studied.

The potential impacts of impulsive noise on marine crustaceans are difficult to predict given the mixed results from studies on seismic airguns and the relative dearth of research on pile-driving noise. Though the sound sources are somewhat similar, the key difference is that acoustic energy from pile driving travels through the substrate, and it is not well understood how substrate-borne vibrations may affect animals that live in direct contact with the substrate. Pile-driving sounds have been shown to affect certain behaviors in crustaceans, such as reducing locomotor activity in Norway lobster (*Nephrops norvegicus*) (Solan et al. 2016), decreasing feeding activity in shore crabs (*Carcinus maenas*) (Corbett 2018), and inhibiting attraction to chemical cues in hermit crabs (*Pagurus acadianus*) (Roberts and Laidre 2019). The research thus far indicates that marine crustaceans may alter their natural behaviors in response to pile-driving sounds, but further work is required to understand the biological significance of these changes and how high levels of substrate-borne particle motion may affect their behavior (Hawkins et al. 2021; Wale et al. 2021; Popper et al. 2022; Solé et al. 2023). This insight is critical for understanding the spatial scale at which they may be affected by pile-driving noise.

Cephalopods can detect low-frequency sounds by sensing particle motion with their statocysts (Mooney et al. 2010), which, like fish ears, act like three-dimensional accelerometers and could be injured from high sound exposures. Damage to cephalopod statocysts has been observed in

several tank-based studies (André et al. 2011; Solé et al. 2022), and Jones et al. (2020) observed inking and jetting behaviors in longfin squid (*Doryteuthis pealeii*) when exposed to pile-driving noise in a tank. A follow-up field study found that alarm behaviors occurred with the first acoustic stimulus but diminished quickly. Responses were only observed in squid at the closest sample site (near site, within 8 m of the pile with no responses at the 50-m far site), suggesting that, at greater distances from pile driving, there is unlikely to be any alarm response (Cones et al. 2022). A similar field study was conducted by Jézéquel et al. (2025), which focused on behavioral responses of both longfin squid (*Doryteuthis pealeii*) individuals and shoals to repeated pile-driving sound exposure. In that study, pile driving induced short-term alarm responses and rapid habituation of squid. However, using the same field-based design, Jézéquel and Mooney (2024) found no statistical evidence of TTS in any longfin squid exposed to impulsive pile-driving sound. When exposed to particle acceleration equivalent to 500 m from installation of a 1.3-m diameter steel pile, longfin squid showed a reduction in feeding success, and squid abandoned predation attempts when noise was introduced (Jones et al. 2021).

Interestingly, additional work showed that interactions between males, as well as reproductive behaviors between males and females of the longfin squid (*Doryteuthis pealeii*), were unaffected by pile-driving noise, suggesting that the motivation to mate exceeds the potential stress that noise may introduce (Stanley et al. 2023). Lab studies of other cephalopods, such as cuttlefish (*Sepia officinalis*), also did not detect impacts of impulsive sounds on mating or egg laying (Solé et al. 2022). This work suggests that squid (and likely all cephalopods) are sensitive to low-frequency sound but may habituate to repeated exposures or recover quickly. When pile-driving noise co-occurs with feeding periods, it could negatively affect feeding but is unlikely to affect mating behaviors.

8.2.9 Decommissioning

The decommissioning process of oil and gas platforms may include partial or complete removal of the platform structure using an explosive-severance technique. When using explosives for platform severance, the underwater pressure signature of a detonation is composed of an initial shock wave followed by a succession of oscillating bubble pulses. When a fish is close to a detonation, there can be a rapid contraction and overextension of the swim bladder, resulting in damage to internal tissues (barotrauma). The distance at which barotrauma may occur is generally expected to be shorter than that at which auditory effects such as TTS or sensory hair-cell loss could occur.

Explosions related to decommissioning of oil and gas infrastructure would happen below the mudline, but most of the research has focused on open-water explosions (which are more relevant to Navy activities). For example, Jenkins et al. (2022) and Smith et al. (2022) exposed Pacific mackerel (*Scomber japonicus*) to a 6.2-kg, mid-water explosive in situ at distances ranging 21–807 m and found that there were increases in mortality observed at distances up to 157 m from the explosion; other non-auditory injuries (e.g., damage to swim bladder and kidneys) occurred up to 333 m from the source at received peak pressures (L_{pk}) of 226 dB re 1 µPa (Jenkins et al. 2022). At greater distances and lower received levels (400 m; 220 dB re 1 µPa), there is evidence of hair-cell

damage, suggesting that hearing would likely be impaired at this distance, although no hearing tests were conducted (Smith et al. 2022).

Interestingly, a similarly designed study with Pacific sardines (*Sardinops sagax*) (Dahl et al. 2020) showed that the greatest physical effects (burst capillaries, swim bladder rupture, and kidney rupture) occurred at the closest distances (< 50 m) and then at a secondary peak at 125–150 m; the secondary peak was likely explained by propagation pathways—reflections off the seafloor and sea surface may have converged at this distance and created a particularly rapid decrease in acoustic pressure. A follow-on study assessing Pacific mackerel to a 4.5 kg mid-water explosive using a similar set up found swim bladder bruising to the injury most indicative of exposure to an underwater explosion, and the greatest hair-cell loss occurred in fish at the closest distance, which was 150 m from the explosion (Bowman et al. 2024).

Fish and invertebrates that lack swim bladders are likely to be more resistant to underwater blasts than those with swimbladders (Goertner et al. 1994). Modeling work by Goertner (1978a) predicted that the range at which effects could occur in a non-swim bladder fish was 100 times smaller than that of a fish with a swim bladder. Keevin and Hempen (1997) report on several studies in which various invertebrate species were exposed to charges of different sizes. Overall, despite some studies lacking adequate controls and sample sizes, they conclude that invertebrates are resilient to pressure-related damage from underwater explosions.

Together, these studies show that acoustic injury to fish as a result of explosive detonation is possible, but the degree of effect would depend on whether the species has a swim bladder (and whether it is open or closed), as well as orientation of the fish at the time of detonation (Jenkins et al. 2023). Documented mortalities of several commercially and recreationally valuable fishes (e.g., red snapper [*Lutjanus campechanus*], vermilion snapper [*Rhomboplites aurorubens*], greater amberjack [*Seriola dumerili*], gray triggerfish [*Balistes capriscus*], and cobia [*Rachycentron canadum*]) resulting from the explosive removal of 24 platforms in 2017 and 23 platforms in 2018 constituted only a small portion of the total stocks in the GOA (Gallaway et al. 2020). Although the results from this study investigated only five recreationally and commercially important species, it can be reasonably assumed that other represented fish populations would respond similarly.

8.2.10 Aircraft

Offshore projects may require use of aircraft for crew transport during construction and maintenance. The penetration of noise from aircraft into the water is limited because much of the noise reflects off the water's surface. Due to the air-water interface, an animal needs to be close to the sea surface to be affected. Given that most fish and invertebrates do not spend significant time near the sea surface and the transient nature of aircraft, impacts on finfish and invertebrates from aircraft use are expected to be insignificant.

9 Birds

9.1 Importance of Sound to Birds

The research suggests that birds have a relatively restricted hearing range for airborne noise. Generally, aerial hearing sensitivity in non-nocturnal terrestrial birds occurs at frequencies between about 1 and 5 kHz, with absolute (best) sensitivity often approaching 0–10 dB re 20 µPa SPL at the most sensitive frequency, which is usually in the region of 2–4 kHz (Dooling 1980; 1982; 1992; Dooling et al. 2000).

The importance of in-air acoustic cues for aquatic birds is well documented (e.g., Searby et al. 2004; Lengagne et al. 2010). Recent psychoacoustic and electrophysiological in-air hearing tests have been completed on multiple species of diving seabirds, including great cormorants (*Phalacrocorax carbo*), long-tailed ducks (*Clangula hyemalis*), harlequin ducks (*Histrionicus histrionicus),* ruddy ducks (*Oxyura jamaicensis*), marbled murrelets (*Brachyramphus marmoratus*), common murres (*Uria aalge*), Atlantic puffins (*Fratercula arctica*), surf scoters (*Melanitta perspicillata*), white-winged scoters (*Melanitta deglandi*), black scoters (*Melanitta americana*), lesser scaups (*Aythya affinis*), common eiders (*Somateria mollissima*), red-throated loons (*Gavia stellata*) and northern gannets (*Morus bassanus*); these species share peak hearing sensitivities between 1.0 and 3.5 kHz (Therrien 2014; Crowell et al. 2015; 2016; Maxwell et al. 2016; 2017; Mooney et al. 2019; Larsen et al. 2020; Mooney et al. 2020; Smith et al. 2023a; 2023b).

The body of research on underwater hearing in diving birds is still emerging but growing steadily. The most substantial data come from studies on great cormorants and various sea duck species. Underwater hearing thresholds have been obtained in five species of marine birds: great cormorant (Johansen et al. 2016; Hansen et al. 2017; Larsen et al. 2020); long-tailed duck (Therrien 2014; McGrew et al. 2022); surf scoter (McGrew et al. 2022); common eider (McGrew et al. 2022); and common murre (at a single frquency [1 kHz], Hansen et al. 2023). Auditory sensitivity varied among the species tested, spanning over 30 dB in the frequency range of best hearing, with sensitivity in great cormorants comparable to seals and toothed whales at lower frequencies (1-4 kHz; Hansen et al. 2017).

Playback studies show that gentoo penguins (*Pygoscelis papua)*, African penguins (*Spheniscus demersus*), and common murres can react negatively to underwater sounds (Frost et al. 1975; Cooper 1982; Pichegru et al. 2017; Anderson Hansen et al. 2020; Sørensen et al. 2020), even though there is no data on underwater hearing thresholds from these species, with the exception of the common murre. One additional study has shown that gentoo penguins can exhibit Pavlovian conditioning to underwater sound playbacks paired with fish rewards (Rasmussen et al. 2022).

Current studies indicate diving bird species have the most sensitive underwater hearing in the 1–4 kHz range (e.g., Hansen et al. 2017; McGrew et al. 2022), which follows the frequency range of best hearing sensitivities of birds in air.

Currently, there are no regulatory thresholds related to seabird exposure to underwater noise, and no studies exist of bird hearing loss due to underwater sound exposures. One exception is the marbled murrelet, for which an auditory injury threshold of 202 dB re 1 μPa^2s was derived for underwater pile-driving noise through an expert convened workshop (Science Applications International Corporation 2011). Studies of in-air-based hearing threshold shifts in terrestrial birds are limited but show that the frequency of exposure is the hearing frequency most likely to be affected (Saunders and Dooling 1974; Niemiec et al. 1994; Ryals et al. 1999; Dooling and Popper 2007; U.S. Navy 2018). Existing studies indicate that birds are more resistant to hearing loss and auditory damage from acoustic exposures compared to mammals (e.g., Ryals et al. 1999; Saunders and Dooling 2018; Dooling et al. 2019). This trend is largely because birds regenerate the inner ear sensory hair cells responsible for hearing, even after intense noise or age-related damage. In chickens, this regeneration restores auditory thresholds within about four to five weeks (Sato et al. 2024; Miranda Portillo et al. 2025; Takeuchi et al. 2026), in part because birds can regenerate the inner ear auditory hair cells that are responsible for hearing, even after they have been damaged by intense noise exposure.

Vocalizations are essential to seabirds in air, and research is ongoing on seabirds utilizing underwater vocalizations for communication, foraging, or navigation. At least three species of penguins (i.e., king penguins, *Aptenodytes patagonicus*; macaroni penguins, *Eudyptes chrysolophus*; and gentoo penguins, *Pygoscelis papua*) produce short duration (mean = 0.06 seconds) underwater vocalizations during feeding dives (Thiebault et al. 2019).

9.2 Potential Impacts of BOEM-Related Sound Sources

Despite their generally low hearing sensitivity at low frequencies (< 1 kHz), it is possible that birds could detect some OCS-related noise and may be disturbed by it. While above water, birds may be exposed to airborne noise sources, including those from production platforms, vessels, and aircraft. Underwater noise from seismic surveys, drilling, production, trenching, or vessel traffic could affect seabirds and waterfowl that dive below the water surface to forage or avoid predators.

The degree of underwater noise exposure varies by species and foraging behavior. For most birds—such as surface feeders, plunge-divers, or those that briefly dip below the surface—exposure is likely minimal due to their short duration underwater. In contrast, pursuit-diving bird species may remain underwater for minutes, increasing the chance of sound exposure.

Researchers have documented a range of bird behavioral responses to noise, including no reaction, head turns, alert postures, startle responses, flying away, and increased call amplitude (e.g., Black et al. 1984; Ellis et al. 1991; Stalmaster and Kaiser 1997; Brown et al. 1999; Pytte et al. 2003; Rojek et al. 2007). These responses are influenced by several factors, including noise characteristics, distance from the source, and whether the noises resemble biologically relevant sounds, such as predator cues or alarm calls from other birds.

Seismic surveys produce intense underwater sound primarily through the firing of airguns, which may impact diving seabirds that forage underwater. Exposure depends on species-specific foraging behaviors, with pursuit-diving birds being most susceptible due to their extended underwater durations. Seismic noise can cause temporary disturbance or displacement from seabird foraging habitats, resulting in lost foraging opportunities and increased energetic effort spent foraging (Pichegru et al. 2017). It should be noted that studies performed by Stemp (1985) and Lacroix et al. (2003) did not observe any difference in distribution or abundance of seabirds due to seismic survey activity, nor did they observe increased mortality in the species studied. Behavioral effects are expected to be temporary. Masking of acoustic cues or disruption of foraging patterns may occur but are not expected to result in long-term harm.

Noise generated from offshore platforms during drilling and production includes both in-air and underwater components, though much of the related acoustic energy is below the hearing range for most seabirds (Crowell et al. 2015). Some seabirds are attracted to offshore structures, such as platforms, for resting or foraging (Tasker et al. 1986; Baird 1990; Montevecchi et al. 1999; Russell 2005; Ronconi et al. 2015). Therefore, species that are in the close proximity of platforms might experience disturbance or possible temporary displacement from airborne sounds around the platforms (Tasker et al. 1986; Russell 2005). Overall, although seabirds that are attracted to platforms may be more exposed to noise, the associated impacts are anticipated to be short term and localized.

During platform decommissioning, underwater explosives used to dismantle structures pose a higher risk to diving seabirds. Although the likelihood of birds being in proximity during detonation is low, there have been rare instances of seabird mortality due to underwater explosions (Cooper 1982; Brown and Adams 1983; Danil and St. Leger 2011). Birds are expected to vacate areas during the dismantling process, further reducing risk. Platform removal may cause short-term and localized disturbance and displacement of foraging and resting marine birds.

Seabirds may be exposed to both in-air and underwater noise generated by vessels associated with OCS activities. While many seabirds show minimal reactions to vessels and vessel noise, behavioral responses—such as alertness, flushing, avoidance, and temporary displacement—have been observed (e.g., Stalmaster and Kaiser 1997; Burger et al. 2010; Schwemmer et al. 2011). Birds foraging or resting in areas with heavy vessel traffic may be disturbed or displaced from the activity. Some species, such as albatrosses, are attracted to vessels (Hyrenbach 2001), while others, including diving birds, tend to avoid them (Burger et al. 2010; Schwemmer et al. 2011).

The physical presence of vessels may also contribute to disturbance independent of noise. Underwater vessel noise generally contains low-frequency energy, often below the hearing sensitivity of diving seabirds (e.g., McGrew et al. 2022), making significant impacts unlikely unless birds are in close proximity. However, continuous noise from vessels may mask biologically important sounds, particularly in areas like ports, where vessel activity is concentrated. Diving birds may show higher sensitivity to marine traffic noise and may avoid high-activity areas, potentially leading to reduced foraging efficiency and increased energetic costs (Natural Power 2018). Overall, vessel-related impacts on seabirds are typically short term and species specific.

Birds exposed to aircraft noise may exhibit short-term behavioral responses, such as head turning, increased vigilance, or flushing from nesting or foraging areas (e.g., Efroymson et al. 2000). These effects are generally transient and do not appear to significantly affect reproductive success, although it has been speculated that flushes from nests may be a good predictor of eventual reproductive loss (Awbrey and Bowles 1990). For example, several raptor species exposed to frequent, low-level military jet aircraft overflights and simulated mid- to high-altitude sonic booms have shown aircraft and detonation noise elicit some short-term behavioral responses but have little effect on reproductive success (Ellis et al. 1991). Studies of simulated aircraft noise at crested tern colonies indicated that increased exposure resulted in more head turning and alert responses, and the birds did not take flight unless sounds exceeded 85 dB (Brown 1990). Low-level (< 500 ft above ground level) military training flights have been shown to have no effects on the establishment, size, or reproductive success of wading bird colonies in Florida (Black et al. 1984). Additionally, birds have been shown to return to pre-disturbance behavior within 5 minutes of an aircraft disturbance (Komenda-Zehnder et al. 2003). Mitigation through careful flight routes and avoiding low-altitude flights near known colonies can reduce potential impacts. Overall, aircraft noise is expected to have only short-term, localized effects on seabird behavior and habitat use.

Lastly, onshore construction activities related to OCS projects can generate airborne noise that may affect nearby coastal and marine bird species. Noise can cause localized disturbance and temporary displacement, particularly when construction occurs near nesting colonies or roosting sites. Onshore construction noise also may mask bird vocalizations and interfere with essential communication, potentially disrupting important biological activities, including mating, parental care, or territory defense (Dooling and Popper 2007). However, seabirds generally are less vulnerable when construction activities are located away from nesting aggregations or scheduled outside the breeding season. Site-specific planning, such as locating pipeline corridors in low-sensitivity areas, can help minimize impacts. Overall, impacts from onshore construction noise are expected to be short term and minimal, especially with proper mitigation strategies in place.

10 Bats

10.1 Importance of Sound to Bats

Bats rely heavily on sound for critical life functions, including navigation, foraging, predator avoidance, and social communication. Most species use echolocation by emitting high-frequency signals and interpreting the returning echoes to detect and locate prey, avoid obstacles, and orient themselves in complex environments. Bats are the only terrestrial mammals capable of true echolocation (Lattenkamp et al. 2021). This sophisticated acoustic system enables bats to operate effectively in low-light or nocturnal conditions where visual cues are limited.

Bats primarily use ultrasonic frequencies for echolocation, and their hearing is most sensitive in the same frequency range as their echolocation calls. Echolocating bat hearing range is species specific and can range from 10–150 kHz, with highest sensitivity from 20–100 kHz, depending on the species (e.g., Fenton and Bell 1981; Moss and Schnitzler 1995; Koay et al. 1997; Schnitzler and Kalko 2001; Jones 2005; Heffner and Heffner 2008; Lattenkamp et al. 2021; Håkansson et al. 2022). Bats have reduced hearing sensitivity to low-frequency sounds (typically below ~5 kHz), and they are generally unable to hear frequencies below 500 Hz (e.g., Moss and Schnitzler 1995; Koay et al. 1997).

Traditional classification divided bats into two groups: Megachiroptera (megabats that rely primarily on sight and smell) and Microchiroptera (microbats that echolocate and primarily feed on insects; Jones and Holderied 2007; Teeling 2009). In this framework, only the fruit bat family (Pteropodidae) lacks laryngeal echolocation, while all 17 microbat families are capable of producing high-frequency calls through the larynx (Jones 2005; Jones and Holderied 2007; Teeling 2009; Nojiri et al. 2021; Håkansson et al. 2022).

However, recent phylogenetic research has led to a revised classification separating bats into two clades: Yinpterochiroptera ("Yin" bats) and Yangochiroptera ("Yang" bats). Yinpterochiroptera includes fruit bats and certain microbat families that rely more heavily on vision and smell and may have independently evolved constant frequency echolocation. In contrast, Yangochiroptera encompasses most microbat families and are distinguished by complex, frequency modulated echolocation signals and more specialized facial morphology for sound emission and reception. Sulser et al. (2022) found significant neuroanatomical differences between these two groups, particularly in the cochlear spiral ganglion, which processes auditory signals. Yang bats lack the bony structure known as Rosenthal's canal, providing additional space in the cochlea to accommodate more neurons, possibly enhancing auditory processing capabilities. In contrast, Yin bats retain the ancestral bony canal, potentially limiting neural space and associated acoustic processing.

In addition to echolocation, bats use a range of vocalizations for social communication, including mate attraction, territorial defense, maternal care, group cohesion, and conflict resolution. These social calls differ from echolocation in frequency, duration, and pattern—and are often species or

context specific. Social vocalizations are typically lower in frequency than echolocation calls, though some species produce ultrasonic communication sounds (Bohn et al. 2008; Smotherman et al. 2016).

Bats also possess unique adaptations to manage self-generated acoustic signals. Many species have large external ears—up to 2 inches in length—that serve as acoustic amplifiers and are crucial for spatial localization and echo detection (Jones and Holderied 2007). To prevent auditory damage from their own intense vocalizations, bats employ both mechanical and neural attenuation mechanisms. The stapedius muscle contracts in anticipation of call emission, reducing middle ear transmission by dampening vibrations through the ossicles (malleus, incus, and stapes). Concurrently, neural attenuation suppresses auditory processing during vocalization, preventing interference with echo perception (Jones and Holderied 2007). These adaptations ensure that bats maintain hearing acuity while emitting high-intensity echolocation signals.

While a small body of research (Simmons et al. 2015; Hom et al. 2016; Simmons et al. 2016) suggests that bats may be less susceptible to TTS compared to some other terrestrial mammals, the potential for auditory impacts from offshore noise sources cannot be ruled out. Research on bat sensitivity to anthropogenic noise, especially in offshore environments, is still limited, and further study is warranted.

10.2 Potential Impacts of BOEM-Related Sound Sources

The role of sound in the biology of bats is well established, but there is still limited understanding of how offshore anthropogenic noise may affect bats, if at all.

All bats are terrestrial; however, numerous studies have shown that many species will forage within or migrate over marine environments, sometimes at considerable distances from shore, including off North America (e.g., Stantec Consulting Services Inc. 2016; Dowling et al. 2017; Normandeau Associates Inc. and Ocean Tech Services LLC 2023; Willmott et al. 2023; Amichai et al. 2025). Bats that have the potential to be exposed to sound-producing activities in the OCS would be those that occur in coastal or offshore waters, or those that migrate over open-ocean areas. While migrating or foraging offshore, bats will use islands, vessels, and other offshore structures for resting or roosting (Constantine 2003; Cryan and Brown 2007; Pelletier et al. 2013; Thompson et al. 2015; Stantec Consulting Services Inc. 2016). A recent offshore bat monitoring study located 43 km offshore in the U.S. Atlantic OCS reported that 31–38% of all bat detections occurred during daylight hours, indicating diurnal offshore presence (Amichai et al. 2025). The same study found a strong seasonal pattern, with 89% of detections occurring in late summer and early fall, likely associated with bat migration (Amichai et al. 2025). There seems to be growing evidence that, at least in the Atlantic OCS, some bats are attracted to offshore structures and use them for roosting, resting, or foraging (Stantec Consulting Services Inc. 2016; Amichai et al. 2025).

Despite increasing evidence of offshore occurrence, limited data are available on bat behavior in these environments, and their exposure and responses to anthropogenic noise remain poorly

understood. They may be exposed to airborne noise sources, such as platform operations, vessel noise, aircraft noise, and platform removal. Bats do not dive into water; therefore, underwater acoustic impacts are not considered here. Although bats typically are nocturnal, individuals present offshore, such as during migration, are likely to remain over water rather than return to land daily, resulting in potential exposure to noise around the clock.

Bats have been reported to increase the amplitude of their vocalizations in the presence of broadband noise, which is known as the Lombard effect (Hage et al. 2013). Most acoustic energy from noise on platforms is below the most sensitive hearing range of bats (e.g., Moss and Schnitzler 1995; Koay et al. 1997), so it is unlikely to affect their ability to echolocate, but it could still cause them to increase their call amplitude. It is also possible that sounds may not be detected, and thus not be disturbing at all.

Very little is known about the impact of vessel noise on bats, and bats are occasionally have been observed offshore from transiting vessels, primarily at night during migration (Stantec Consulting Services Inc. 2016), and occasionally roosting on vessels (Thompson et al. 2015). If a bat responds to vessel noise, only short-term behavioral responses—such as startle responses, head turning, or avoidance responses—would be expected. Repeated exposures would be limited due to the transient nature of vessel use and regular movement of bats. Impacts to individual bats, if any, are expected to be minor and limited, and no long-term consequences for individuals or populations are expected.

Bats may be exposed to airborne noise from aircraft and helicopter activity while foraging or migrating offshore; however, such exposures are expected to be brief and infrequent due to the transitory and dispersed nature of flight operations. Behavioral responses to noise may include startle reactions, avoidance, or temporary changes in vocalization, or animals may exhibit no response. Helicopter overflights, which often occur at lower altitudes and slower speeds than fixed-wing aircraft, could increase the duration and likelihood of such responses, but any effects are anticipated to be short term and minor. While no studies have directly assessed aircraft noise impacts on bats, existing research suggests that bats may avoid noisy areas or adjust echolocation frequencies when exposed to sounds within their hearing range (e.g., Bates et al. 2008; Arnett et al. 2013). Given the limited duration and frequency of exposure, and bats' capacity for behavioral adaptation, long-term impacts on bat populations or critical behaviors are not expected.

11 Benthic Habitats and Communities

Many of the marine species that compose the benthic epifauna and infauna communities are likely to be sensitive to underwater sound. For a description of hearing capabilities and an overview of potential impacts, see **Sections 7 and 8**. Notably, sources that are coupled with the seabed (e.g., pile driving, drilling, dredging) or directed towards the seabed (e.g., seismic surveys) also can excite substrate and introduce substrate-borne vibrations.

The seafloor is not strictly a fluid medium, and it supports the propagation of shear waves in addition to compressional waves in the water column. A recent study confirmed that impact pile driving generates Scholte waves (Giordano et al. 2025), interface waves that travel along the boundary between the water column and the seafloor. Because Scholte waves spread cylindrically, they decay more slowly with distance than the compressional and shear waves and can carry energy farther along the seabed (Giordano et al. 2025). Their significance for benthic fauna is that Scholte waves produce particle motion at and near the seafloor, which generates substrate-borne vibrations that organisms living on or in the seabed are most likely to detect. This is particularly relevant for corals and other sessile, attached invertebrates that cannot move away from a vibration source and so may be exposed for the full duration of an activity. Like other marine invertebrates, these taxa detect the particle motion rather than the pressure component of sound (Roberts and Elliott 2017; Hawkins et al. 2021), and controlled studies show measurable responses: the mussel *Mytilus edulis*, for example, alters its valve behavior when exposed to substrate-borne vibration at levels within the range produced by pile driving and blasting (Roberts et al. 2015), and anthropogenic noise can disrupt the settlement of coral larvae onto suitable substrate (Lecchini et al. 2018). As with exposure to water-borne noise, exposure to substrate-borne vibration can cause various adverse effects on benthic organisms, including behavioral disturbance, physiological stress, and communication masking (Hawkins et al. 2021; Roberts and Howard 2022). However, more research is needed to understand the extent and degree of such impacts.

12 Pelagic Habitats and Communities

Pelagic communities are composed of many marine species that are sensitive to underwater sound. This section focuses specifically on the planktonic egg and larval stages of fishes and invertebrates, which represent one component of the broader planktonic community. For descriptions of hearing capabilities and potential impacts of underwater noise on other biota that occupy the pelagic environment, see **Sections 3 and 4** (marine mammals), **Sections 5 and 6** (sea turtles), and **Sections 7 and 8** (fish and invertebrates).

Planktonic eggs and larvae of both fishes and invertebrates may experience physiological effects when exposed to high-intensity, impulsive sounds from sources such as seismic airguns or pile driving.

Most of the research with seismic airguns has focused on relatively small spatial scales (i.e., 10s of meters) and has shown minimal effects even at these short distances (Kostyuchenko 1973; Holliday et al. 1987; Pearson et al. 1994; Booman et al. 1996; Saetre and Ona 1996; Govoni et al. 2008; Bolle et al. 2012). However, a study by McCauley et al. (2017) observed zooplankton after seismic airgun exposure and demonstrated elevated mortality rates at much larger distances than previous studies had shown (> 1,000 m). Vereide et al. (2025) aimed to test those findings at operationally realistic scales. They sampled zooplankton (*Calanus* spp.*)* around an active commercial seismic survey in the North Sea with a 3,060 in^3 airgun array. Immediate mortality in field-caught *Calanus* spp. never exceeded 35.%, showed no relationship with distance from the array, and fell within the natural background mortality levels reported for the region (11.6 to 59.8%). The vertical center of the mass also did not shift detectably with exposure, although the vertical spread of the layer increased with proximity to the source. Cultured *C. finmarchicus* exposed in bags near the array exhibited low immediate mortality but elevated cumulative mortality seven days post-exposure. The authors concluded that immediate effects of seismic surveys on zooplankton may be limited and is influenced by the number of airguns and directionality of the exposure. The discrepancy between these studies indicates that responses are likely species and context specific, and further research is needed to determine whether delayed mortality could have population-level consequences given that the rate of natural mortality is already very high for plankton.

A handful of studies have directly investigated the effects of pile-driving noise on eggs and larvae of marine fishes. Laboratory work by Bolle et al. (2012) and Bolle et al. (2014)—using a device similar to Halvorsen et al. (2012a)—showed sole (*Solea solea*), European sea bass (*Dicentrarchus labrax*), and herring (*Clupea harengus*) larvae were relatively resilient to mortality even at high received levels (exceeding SELs of 206 dB re 1 uPa^2s, which the authors surmise is equivalent to the received level at approximately 100 m from a 4-m diameter pile). Together, the tested larvae represent the entire range of swim bladder shape types described by Popper et al. (2014). This work suggests that fish larvae—regardless of differing hearing anatomy—may be relatively resilient to pile-driving noise, which is generally consistent with the early literature on seismic airguns (e.g., Kostyuchenko 1973; Holliday et al. 1987; Booman et al. 1996; Saetre and Ona 1996).

Research on invertebrate larvae is even more limited and has yielded mixed results. Two studies found little effect of exposure to seismic airguns on the embryonic or larval stages of spiny lobster

(received SEL: 185 dB re 1 µPa^{2}s; Day et al. 2016) or Dungeness crab (*Cancer magister*) (received SPL: 231 dB re 1 µPa; Pearson et al. 1994). While Aguilar de Soto et al. (2013) did show that scallop (*Pecten novaezelandiae*) larvae exposed to play back sounds of seismic airguns showed body abnormalities and developmental delays, the larvae were held 5–10 cm away from the speaker for 90 hours of playbacks, which does not represent real-world conditions of exposure to airgun noise. Results from Gigot et al. (2024) indicate that, when adult scallops (*Pecten maximus*) are exposed to pile-driving sounds in the lab for 10 weeks during gametogenesis, their larvae have an increased growth rate and faster metamorphosis compared to larvae from non-exposed parents. The exposed parents did have a lower gonadic volume than control adults, supporting the idea that increased growth rates at the larvae stage may be an adaptive strategy to stress exposure (i.e., animals transition through the mobile, water column phase faster and may avoid predation).

Solé et al. (2022) examined hatching and survival of cuttlefish (*Sepia officinalis*) eggs and larvae after exposure to 16 hours of pile-driving sound in the same chamber as in Bolle et al. (2012). The larvae and eggs were exposed to maximum of 170 and 167 dB re 1 µPa^2 for the pile-driving or drilling sounds, respectively, and assessed hatching success, larval survival, behavioral responses, and ultrastructural damage to sensory organs (i.e., electron-microscope-level injury to sensory hair cells). With increasing received sound level, hatching success decreased and larval mortality increased. A reduction in hatching success from 72% to 9% occurred in the most severe pile-driving treatment, and from 71% to 13% for the most severe drilling treatment relative to a silent control group. Similarly for larvae, survival rate decreased with increasing received sound level; from 100% to 10–19% survival in the loudest treatment for pile driving, and from 100% to 20–37% survival for the loudest drilling. Overall, the research suggests invertebrate larvae may be more sensitive to physiological effects from pile driving than fish larvae, but impacts would be limited to areas in very close proximity, and effects are likely to be species specific. Given naturally high rates of natural mortality in marine larvae, it is unlikely to have significant population-level effects.

Beyond physical effects, the planktonic larvae of fishes and invertebrates may experience behavioral impacts or acoustic masking from continuous sound sources like vessels, drilling, or dredging. Several studies have shown that larvae are sensitive to acoustic cues and may use these signals to navigate towards suitable settlement habitat (Simpson et al. 2005; Montgomery et al. 2006), stimulate metamorphosis into their juvenile forms (Stanley et al. 2012), or maintain group cohesion during their pelagic journey (Staaterman et al. 2014). For fish larvae that are sensitive to the pressure component of sound, the relevant detection range may extend somewhat farther, but the settlement and orientation cues documented to date still operate over relatively short distances (Simpson et al. 2005; Montgomery et al. 2006), so masking from continuous sources is likewise expected to be spatially limited.

13 Coastal Communities

Coastal communities are composed of many marine species that are sensitive to underwater sound. For descriptions of hearing capabilities and potential impacts of underwater noise, see **Sections 2 and 3** (marine mammals), **Sections 4 and 5** (sea turtles), and **Sections 6 and 7** (fish and invertebrates).

The only distinction here relates to the spatial scale of potential impacts. Most oil and gas-related activities occur far offshore and would not affect coastal communities. In coastal areas, noise from onshore construction, pipeline laying, or vessel traffic could occur.

It has been shown that coastal invertebrates such as crabs, oysters, mussels, and shrimp are capable of perceiving low-frequency sounds (e.g., Aguilar de Soto et al. 2013; Roberts et al. 2015; Charifi et al. 2017). In addition, the larval stages of some estuarine invertebrates may use acoustic cues to navigate towards appropriate settlement habitat or to initiate metamorphosis (Lillis et al. 2013; 2015; Stanley et al. 2015). Although these animals use natural acoustic cues for basic life functions, they are unlikely to be disturbed by most anthropogenic noise sources beyond a few wavelengths from the source, since particle motion does not propagate that far (Urick 1983; Kalmijn 1988; Popper and Hawkins 2018).

Acoustic pressure-sensitive species like manatees, coastal dolphins, fishes, and sea turtles could experience behavioral disturbance from vessel traffic as they pass through coastal areas; however, within very shallow areas (like mangrove habitats and estuaries), low-frequency sounds will not propagate due to the “low-frequency cutoff” (Urick 1983).

Therefore, the effects of underwater noise on coastal communities are expected to be minimal.

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