Atlantic States Marine Fisheries Commission
Habitat Management Series #17
Fall 2024

Anthropogenic Noise Impacts on Atlantic Fish and Fisheries:

Implications for Managers and Long-Term Productivity

Enhancing, preserving, and protecting Atlantic diadromous, estuarine, and coastal fish habitats

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prepared by the
ASMFC Habitat Committee

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Cover Photo: Energy produced by offshore wind farms depends on the rotation of the turbine located at the tops of these structures. Credit: BOEM

Anthropogenic Noise Impacts on Atlantic Fish and Fisheries

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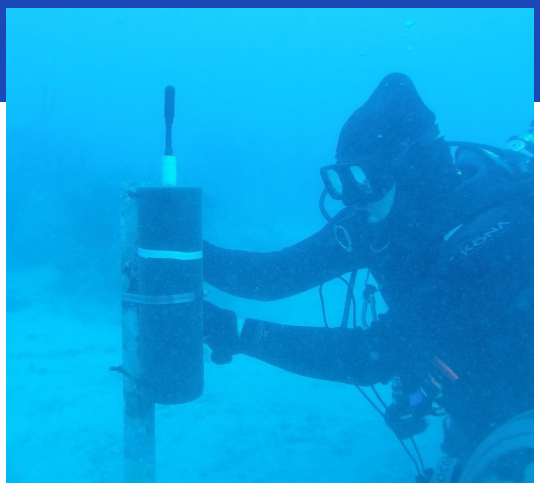

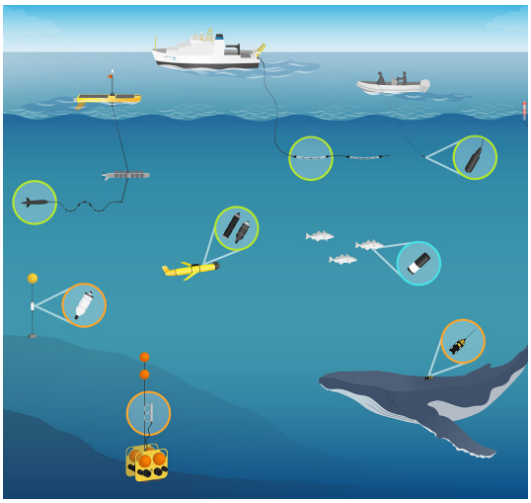

Top: Deployment Acoustic Recorder in Florida Keys National Marine Sanctuary

Center: NOAA Fisheries studies marine animals by using a variety of technologies to record underwater sounds, including archival passive acoustic recordings (orange), real-time acoustic data collection (green), and active acoustics (blue).

Bottom: Schooling fish.

ACKNOWLEDGEMENTS

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Edited by Brendan J. Runde

Objective and Introduction

Objective

Many types of human-generated noise impact coastal and marine fishes through disruption of physiological processes and interruption of auditory communication. In turn, fish health and behavior can be affected. These impacts might be short-term or long-term and can lead to changes in spawning aggregations, habitat use, reproductive success, and mortality. The purpose of this report is to summarize the importance of the impacts of anthropogenic noise to fishes managed by the Atlantic States Marine Fisheries Commission.

While there is vast literature on the production and use of sound by marine mammals, including the effects of human-generated sound on these taxa, this is beyond the scope of this report, given ASMFC's fisheries management focus.

Introduction

The oceans are full of both natural and anthropogenic sounds. The auditory system is the most important sensory system for many aquatic organisms, including most fishes (Au and Hastings, 2008; Richardson et al., 2013; Staaterman et al., 2014, 2013; Stocker, 2002; Tavolga, 1980, 1960). Because water is denser and more viscous than air, the propagation of light and the diffusion of chemicals in water are both severely inhibited. In contrast, sound can move over four times faster and travel farther with less transmission loss underwater than it can through the air (Rogers and Cox, 1988; Ward, 2015).

Many human activities occurring in coastal and marine habitats add noise to the natural soundscape, and these noises affect aquatic organisms and their interactions with one another (Duarte et al., 2021). For example, as rates of sound production correlate to rates of spawning and reproductive success, any disruptions to the effective communication range for fish and invertebrate species has the potential to reduce reproductive output and recruitment.

This report aims to provide general information about the importance of sound to marine species, the impacts that anthropogenic noise can have on marine species, and the characteristics of natural sounds and anthropogenic noise. This document also describes mitigation measures for certain human-induced noise. Finally, the report provides references to a list of data gaps and research needs to improve our understanding of the impact of noise on marine organisms, including fish.

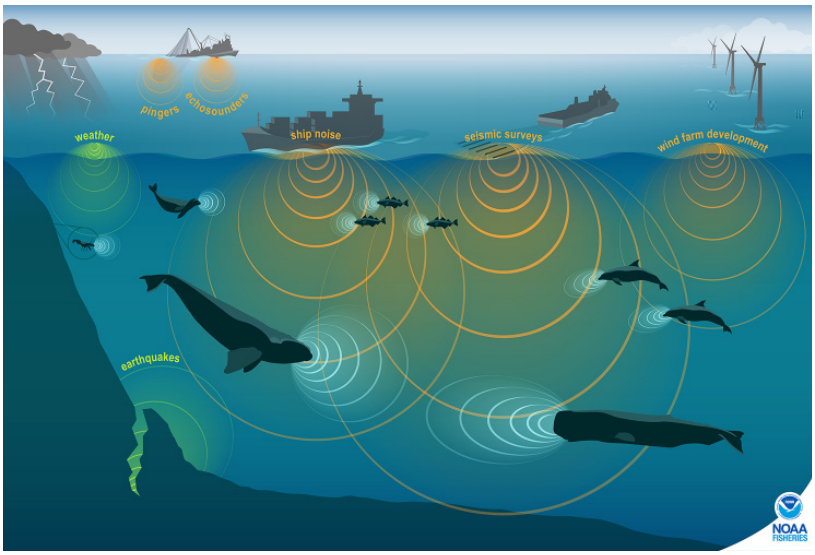
Offshore wind farm. Credit: BOEM

The Natural Soundscape and Its Importance to Fishes

The natural soundscape of the ocean environment includes abiotic activity such as tectonic activity, sea surface agitation, and sea ice activity. These sounds range from <10 Hz to >150,000 Hz with varying intensities and intermittency. Ocean waves and tectonic activity produce constant low frequency noises of a moderate intensity, while dramatic seismic events, such as earthquakes or volcanic eruptions, and glacier calving produce relatively short bursts of very loud sounds. Weather, such as precipitation or high wind speeds, contributes to surface agitation causing increased abundance of 100-10,000 Hz noise (Martin et al., 2014; Nowacek et al., 2007; Peng et al., 2015). Sea surface agitation results in secondary sources of noise such as bubbles or spray.

Some fishes and other marine animals produce sound intentionally as part of their communication, reproduction, predator avoidance, foraging, or navigation and orientation (Peng et al., 2015), as well as unintentionally while they move, forage, and release gas (Fine and Parmentier, 2015). Field and laboratory studies of fish physiology and behavior indicate that sound is a preferred sensory mechanism to detect predators or prey, find suitable habitat, orient, migrate, communicate, attract mates, and coordinate spawning (Putland et al., 2018). Not only do many species use sound to locate reproductive partners or indicate reproductive intent (Bass et al., 1997; Lamml and Kramer, 2005; Maruska and Mensinger, 2009; Montie et al., 2017), but some species, like the Pacific marine toadfish, *Porichthys notatus*, become more sensitive to certain frequencies of their counterpart's sounds during periods of reproductive availability (Maruska et al., 2012; Sisneros, 2009). Rates of sound production correlate to rates of spawning and reproductive success. Territorial species use aggressive, threatening calls to delineate an individual's territory and intimidate or deter competitors or predators (Ladich, 1997; Maruska and Mensinger, 2009; Vester et al., 2004). Other uses of sound include navigation and orientation, especially for planktonic larval stages of fishes and invertebrates (Radford et al., 2011; Vermeij et al., 2010), avoidance of predators (Hughes et al., 2014; Remage-Healey et al., 2006), communication (Buscaino et al., 2012; Janik, 2014; Van Oosterom et al., 2016), and the determination of suitable habitats for settlement (Simpson et al., 2004).

Soniferous fishes managed by the ASMFC include most prominently members of the family Sciaenidae (e.g., Atlantic croaker, *Micropogonias undulatus*; red drum, *Sciaenops ocellatus;* and spotted seatrout, *Cynoscion nebulosus*). However, evidence also exists of sound production from members of Clupeidae (e.g., Atlantic menhaden, *Brevoortia tyrannus* and other shads and herrings), Acipenseridae (e.g., Atlantic sturgeon, *Acipenser oxyrhincus*), Moronidae (e.g., striped bass, *Morone saxatilis*), Serranidae (e.g., black sea bass, *Centropristis striata*), Pomatomidae (e.g., bluefish, *Pomatomus saltatrix*), and more (Fish et al., 1952; Fish and Mowbray, 1970; Johnston and Phillips, 2003; Rice et al., 2022; Wilson et al., 2004).



NOAA Fisheries studies marine animals by using a variety of technologies to record underwater ocean sounds. Marine animals live in a noisy habitat with combined noises from humans, nature, and other species. This conceptual illustration shows images of human, marine animal, and environmental sources of sound and approximately proportional sound waves. Credit: NOAA Fisheries.

Sources of Anthropogenic Noise in the Oceans

Noise generated from human activities covers the full frequency of sound energies used by marine fishes (Duarte et al., 2021). The contribution of human noise to the ocean soundscape has increased over time as activities such as shipping, mineral and oil mining, and coastal construction have grown in scale (Pijanowski et al., 2011). Novel and emerging human activities, such as offshore aquaculture and renewable energy development, also produce noise during construction, operation, maintenance, and eventual decommissioning.

Anthropogenic sources of ocean noise are acute (episodic) and chronic (ongoing or continuous). Both types may occur within estuaries, on the continental shelf, or in open-ocean regions. Acute sources include construction activities such as pile driving, dredging, cable laying, bridge removal, and seismic surveys. Chronic sources include vessel traffic (i.e., commercial and recreational boating and shipping activities) and energy production (e.g., operation of wind turbine generators, or oil and gas extraction).

The figure pictured at right (from Duarte et al., 2021) shows the duration and spatial scale of both natural sounds and anthropogenic noise in the ocean. It also compares the frequencies of marine animal sound production and hearing ranges with anthropogenic noise sources. These visual displays demonstrate that the scale, frequency, and extent of anthropogenic noise overlaps with the activity of marine animals' behavior in different ways.

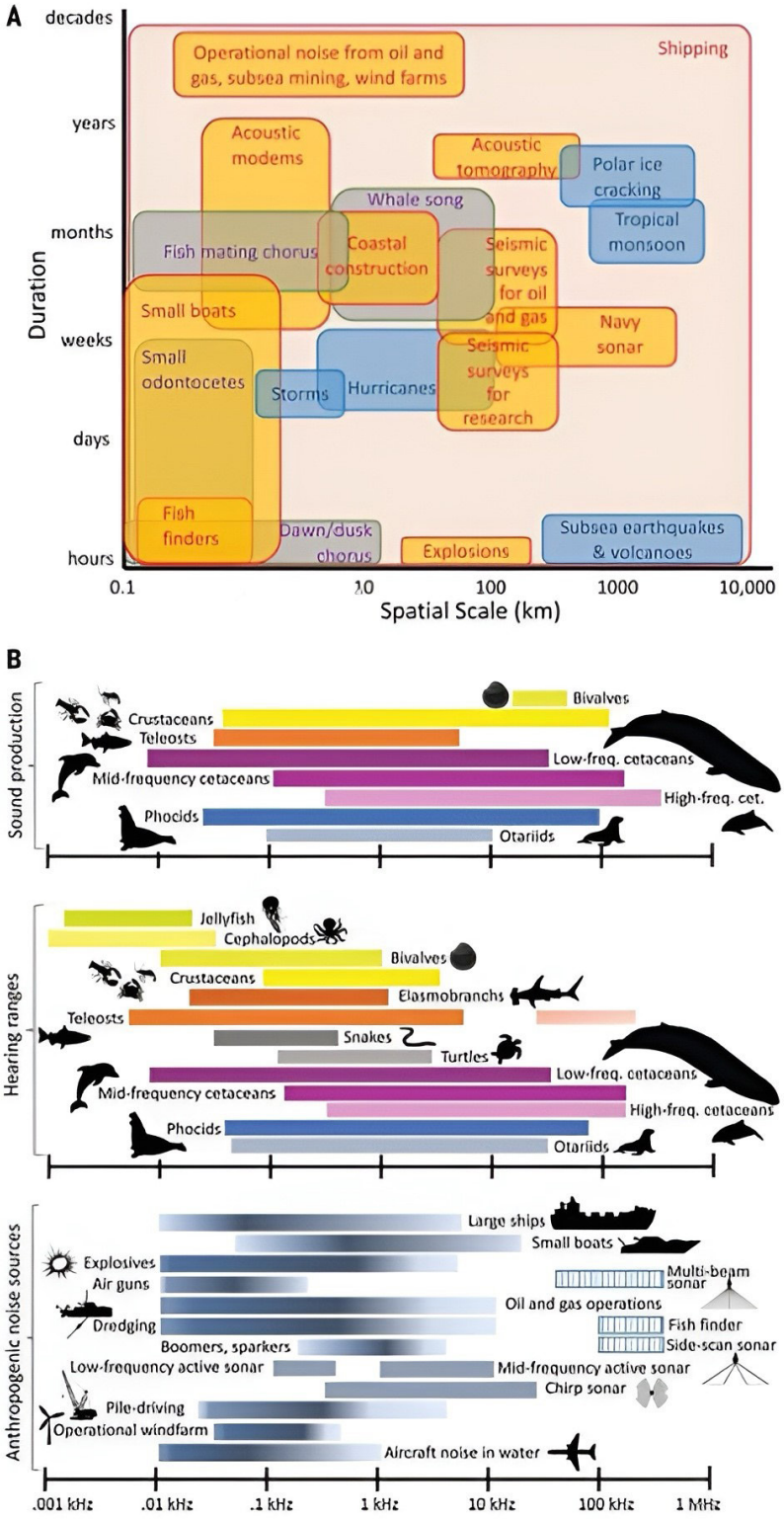


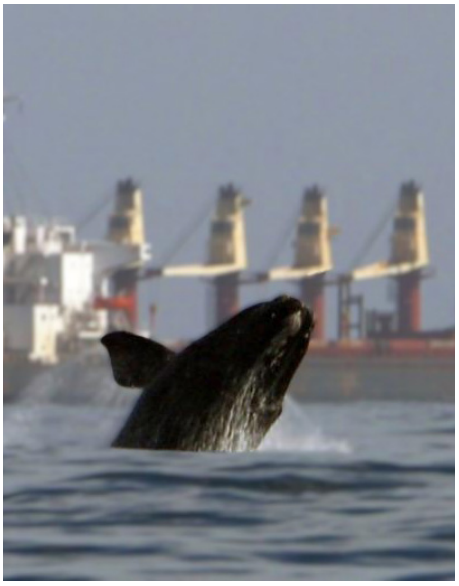
Figure 1 (from Duarte et al 2021). ***(A)*** *Stommel diagram showing the spatial extent and duration of selected biophony (rounded gray squares), geophony (rounded blue squares), and anthrophony (rounded yellow squares) events. Events (rounded squares) reflect the spatial and temporal period over which signals or bouts of signals typically occur. Although some sound sources, such as those used in*

hydrographic surveys, do not propagate particularly far, survey efforts can cover a large spatial extent (an entire Exclusive Economic Zone). "Dawn/dusk chorus" refers to the daily sounds produced by a collection of species (e.g., fish, snapping shrimp). Shipping noise encompasses the full range of spatial and temporal scales. ***(B)*** *Approximate sound production and hearing ranges of marine taxa and frequency ranges of selected anthropogenic sound sources. These ranges represent the acoustic energy over the dominant frequency range of the sound source, and color shading roughly corresponds to the dominant energy band of each source. Dashed lines represent sonars to depict the multifrequency nature of these sounds.*

VESSEL ACTIVITY

Watercraft of all kinds produce undersea noise and are the most common sources of anthropogenic noise in coastal waters (Stocker, 2002). These sources of noise can be amplified due to surface and seafloor reflections as well as scattering and reverberating because of the geography and geology of the submerged shoreline and bottom. Many watercraft generate low-frequency sound from propeller action, propulsion machinery, generators, and water flow over the hull (Hildebrand, 2005). The sounds generated from a large container vessel can exceed 190 decibels (dB) at the source (Jasny, 1999). Metropolitan areas and ports contain a diverse array of watercraft which constitute the dominant human-derived soundscape: commercial and private fishing boats, recreational watercraft, industrial vessels, public transport ferries, military craft, personal watercraft, and others. Significant underwater sound production can also be generated from bridge automobile traffic, particularly during peak traffic periods.

Additionally, most vessels have sonar systems for navigation, depth sounding, and "fish finding" that may cause acute or episodic noise disturbance. Some commercial fishing boats also deploy various acoustic deterrent devices to prevent negative interactions with dolphins, seals, and turtles (Stocker, 2002). There is little information on the effects of acoustic deterrent devices on fish, however.

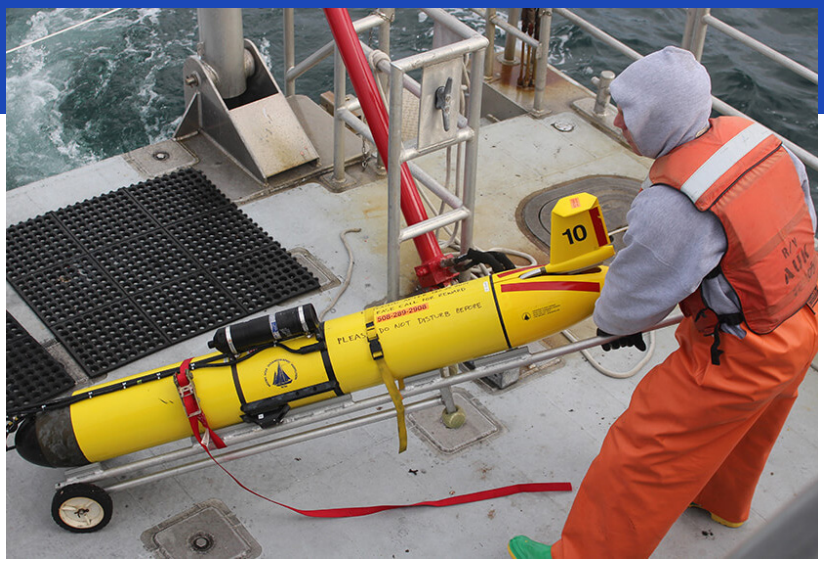


Tanker ship within hearing range of a breaching North Atlantic right whale. Credit: Florida Fish and Wildlife Conservation Commission

GEOLOGICAL AND GEOPHYSICAL SURVEYS

Geological and geophysical (G&G) surveys are performed to gather information about the seafloor including bathymetry, surficial sediment, sub-surface sediment, and the topology of an area. These surveys are performed for a multitude of uses including resource extraction and wind power siting. Not all G&G surveys produce noise that is known to be within the hearing range of marine animals.

Sonar systems are used for a wide variety of civilian and military operations. Active sonar systems send sound energy into the water column. Sonar systems can be classified into low (<1,000 Hz), mid (1,000 – 20,000 Hz), and high frequency (>20,000 Hz). Low and mid frequency systems emit sound that overlaps with the acoustic detection of many marine animals. Sub-bottom profilers are a type of high-resolution seismic system that produce imaging of the seafloor's sub-surface. These can be shallow penetration (2–20 m) or deep penetration systems and operate at a wide range of frequencies (400 – 24,000 Hz) and produce varying levels of peak sound (212- 250 dB; (Mooney et al., 2020)). Seismic air guns are used for a deeper penetration of acoustic sound into the seafloor and are used primarily for oil and gas exploration and siting



A researcher gets ready to launch a type of autonomous underwater vehicle, called a "glider." The glider records all sounds as it follows a programmed path. Photo: Anne Smrcina/NOAA

of offshore cables. Air guns generally produce sound at 200-210dB at a range below 100 Hz. While morbidity of fish and other animals has not been associated with air gun exposure, changes in behavior have been observed. Following exposure in a laboratory setting, American lobster, *Homarus americanus*, changed their feeding levels, and physiological changes were also measured (Payne et al., 2007).

Studies investigating the effect of full-scale G&G surveys on wild fish populations have shown effects in some cases. Atlantic herring, *Clupea harengus,* schools in the wild were not observed to change their swimming speed, swimming direction, or school size during exposure to a full-scale seismic survey (Peña et al., 2013). However, other studies have found that trawl and long-line fish catches during full-scale G&G surveys decreased within the area of the seismic survey and at ranges of up to 33 km (Engås et al., 1996). When catch rates and behavior were observed to change during seismic surveys, fish were observed to return to the site of the survey within hours or days after the survey completion (Løkkeborg et al., 2012).

High frequency sonar telemetry is associated with vessel positioning, locating, steering, and remotely operated vessel control. Ultrasonic frequencies (generally 200,000 - 400,000 Hz), also known as multibeam echosounders, are used for sonar mapping. Multibeam echosounder surveys collect bathymetry and seafloor hardness information used for nautical chart updates, benthic habitat characterizations, fisheries habitat modeling, and surficial sediment analysis. These ultrasonic frequencies are generally outside of the known range of acoustic detection by marine animals.

RENEWABLE ENERGY CONSTRUCTION & OPERATION

Renewable energy is a growing segment of the United States' electrical generation portfolio as we attempt to combat climate change and become more energy secure (Chow et al., 2003; Dincer, 1999; Pimentel et al., 2002; Valentine, 2011). While the nation's renewable energy portfolio has to date been mainly composed of land-based technologies, coastal and marine energy sources in the form of tides, currents, waves, and especially offshore wind have the potential to provide a large amount of energy to the future power grid (Pelc and Fujita, 2002). These energy sources are not without impacts to marine fish welfare, movements, and behavior. The impacts of offshore wind development on the marine environment have been widely discussed in recent years, and monitoring of wind farms in Europe has generated some knowledge about long-term effects (e.g., Gimpel et al., 2023; Stenberg et al., 2015), from which we along the U.S. Atlantic coast can learn. Along the U.S. Atlantic only a handful of projects are built or currently under construction, although many more have been or will soon be permitted. The effects of offshore wind farms on this ecosystem are just beginning to be examined, thus it is likely we will learn more as construction continues and additional projects enter the operational phase. The impact of noise produced by wind farms can occur during construction, operation, maintenance, and decommissioning.

Of the studies performed to assess these impacts, construction noise, specifically pile driving, has produced high levels of sound pressure and acoustic particle motion in the water column and seabed (Nedwell and Howell, 2004; Thomsen et al., 2006; Tougaard et al., 2012). During pile driving for offshore wind construction, the broadband peak sound pressure level has been measured at 189 dB at 400 m and a modeled level of 228 dB at 1m with a dominant frequency of 315 Hz, however these levels depend on the size of the piles (Thomsen et al., 2006; Tougaard et al., 2012). These noise levels are within the perception ranges of Atlantic cod, *Gadus morhua*; dab *Limanda limanda*, Atlantic salmon, *Salmo salar;* and Atlantic herring, *Clupea harengus* (Thomsen et al., 2006). Documented behavioral reactions in Atlantic cod and sole *Solea solea* were observed up to tens of kilometers from the source (Andersson, 2011).

Planned wind turbine generator capacities are increasing, which will require ever larger pile sizes. Alternative foundation types such as gravity based or suction buckets reduce installation noise substantially, but these are less commonly proposed for U.S. east coast projects. To date, most offshore wind installations worldwide have used fixed turbines. Floating offshore wind technology, which will have substantially reduced installation noise and is required for deeper waters, is in its nascent stages (although sites that would require floating technology have been leased along the U.S. west coast) and thus little is known about differences in operational noise between floating and fixed turbines. There is some evidence that jacketing monopile turbines reduces the chronic noise from operation (Thomsen et al., 2015), however to date, actual noise levels emitted by floating platforms has not been documented. As this technology advances, there is a need to determine the noise levels and frequencies which different floating platform types emit and at what distances.

NOAA and TNC researchers investigate the impacts of construction noise on structure-oriented fish using fine-scale telemetry. Credit: Brendan Runde, TNC.

Operational noise at offshore wind farms includes sound produced by both the turbines (Tougaard et al., 2020) and increased vessel traffic (Nedwell and Howell, 2004). Underwater sound produced by turbine operation is generated by the moving mechanical parts within the nacelle (i.e., turbine housing) as well as possible wind-induced vibration of the tower (Tougaard et al. 2020). Operational noise of a 1.5MW turbine (at 110m distance) has been measured between 120 – 142 dB with dominant frequencies at 50, 160, and 200 Hz at wind speeds of 12 m/s (Thomsen et al., 2006). Distance from the noise source, wind speed, and turbine size all impact noise levels measured during turbine operation (Tougaard et al. 2020). Also, vessel noise in the Tougaard et al. (2020) analysis was louder than that of turbines, but distance from the noise source varied as did turbine size (max turbine size was 6MW). Noise produced during wind turbine operation was found to be detectable at a distance of several kilometers by fishes sensitive to sound pressure, however species sensitive to motion (as opposed to pressure) were found to be affected within only tens of meters (Andersson, 2011). It is estimated that operational noise of wind turbines is within the perception range of Atlantic cod and herring up to a distance of approximately 4 km, while for dab and Atlantic salmon up to 1 km (Thomsen et al., 2006).

OIL, GAS, AND MINERAL EXTRACTION

Some of the loudest anthropogenic noises are generated by marine extraction industries such as oil drilling and mineral mining (Stocker, 2002). The most common source of sounds is from air guns used to create and read seismic disturbances (Hawkins and Popper, 2016; Popper et al., 2014, 2005; Popper and Hastings, 2009). Air guns are used to generate and direct huge impact noises into the ocean substrate. The sound pressure wave created aids in reflection profiling of underlying substrates for oil and gas exploration. Peak source sound levels typically are 250-255 dB. Following the exploration stage; drilling, coring, and dredging are performed during extraction.

Resource extraction in marine waters produces chronic noise disturbance including from vessel noise (the impacts of vessel noise are described above); noise is also produced by the operation of extraction machinery, depending on platform type. Spence (2007) reviewed research on noise generated by oil and gas extraction found that fixed platforms had lower underwater radiated noise levels than floating platforms, and gravel islands appear to have the lowest source levels of any oil and gas industry activity. Semisubmersible platforms were found to generate the most underwater noise, which was highest when thrusters were operating and drilling was occurring. Levels were measured at 20-50+ dB in the frequency range of 20 – 1000 Hz during drilling operations, with the dominant frequencies at 130, 200, 350, and 600 Hz (Spence, 2007). On all platform types, noise from large power generation equipment is likely to be a dominant cause of underwater noise, for example from the operation of turbines, compressors, and large pumps (e.g., mud pumps). This noise is thought to be more significant when equipment is hard mounted directly to the platform (Spence, 2007).

Offshore oil platform and support vessels. Credit: BOEM

COASTAL AND MARINE CONSTRUCTION

Inshore industrial and construction activities drastically alter the aquatic soundscape and have caused documented mortality and severe behavioral change in fishes and other marine animals. Underwater blasting with explosives is sometimes used for dredging new navigation channels in rocky substrates, decommissioning and removing bridge structures and dams, and construction of new in-water structures such as gas and oil pipelines, bridges, and dams. The potential for injury and death to fish from underwater explosives has been well-documented (Hubbs and Rechnitzer, 1952; Keevin et al., 1999; Linton et al., 1985; Teleki and Chamberlain, 1978). Moreover, some construction (including that related to offshore wind) requires pile driving. This typically occurs at frequencies below 1000 Hz, and has been documented to cause negative or disruptive physiological and behavioral effects on fish (Mueller-Blenkle et al., 2010), including Atlantic cod (Thomsen et al., 2012) and sturgeons (Popper and Calfee, 2023).

Impacts of Anthropogenic Noise on Fishes

Sound energy is transmitted through both sound pressure and water particle motion. Thus, to understand whether and how noises are likely to impact fishes, it is necessary to understand their sensitivity to both sound pressure and particle motion. Fishes have very complex and diverse interactions with sound and how they perceive it. Hearing systems and capabilities vary based on anatomy, including presence of a swim bladder or other gas-filled organs and position relative to the inner ear, as well as other factors (Popper and Hawkins, 2018). Sensitivity varies by species and among larval, juvenile, and adult stages (Wright et al., 2010). Many species have the same hearing frequency sensitivity that humans do (10 to 20,000 Hz; (Fay, 2009; Fine, 1977a; Popper and Fay, 2011; Popper and Hastings, 2009; Tavolga, 1960, 1980), and most fish produce sounds below 200,000 Hz (Fay, 2009; Fine, 1977a; Tavolga, 1960, 1980). Sound frequencies below 100,000 Hz scatter and dissipate least, travel farthest underwater (Au and Hastings, 2008; Popper and Fay, 2011; Wenz, 1962), and are used for communication among fishes (Au and Hastings, 2008; Bass et al., 1997; Popper and Fay, 2011). Certain groups of fish, such as *Clupeidae* (herrings, shad, sardines, and menhaden), can detect ultrasound frequencies above 100,000 Hz (Fine, 1977b; Mann et al., 2001, 1997; Narins et al., 2013; Nestler et al., 1992), however the strongest response has been documented at 40,000 Hz (Wilson et al., 2009).

The frequency at which different species perceive sound is highly variable (Monczak et al., 2017), however for most fishes, sound production and habitat soundscape acoustic signatures are at frequencies below 5,000 Hz (Fish and Mowbray, 1970; Myrberg and Fuiman, 2002). For example, black drum (*Pogonias cromis*) were found to have the highest neurological response to sounds at 82, 166, and 249 Hz (Monczak et al., 2017). This is also the range of frequencies where underwater sound propagates best. Most human-generated chronic noise is below 5,000 Hz (Au and Hastings, 2008; Richardson et al., 2013), which is of concern as fish are very sensitive to intense sounds below 1,000 Hz.

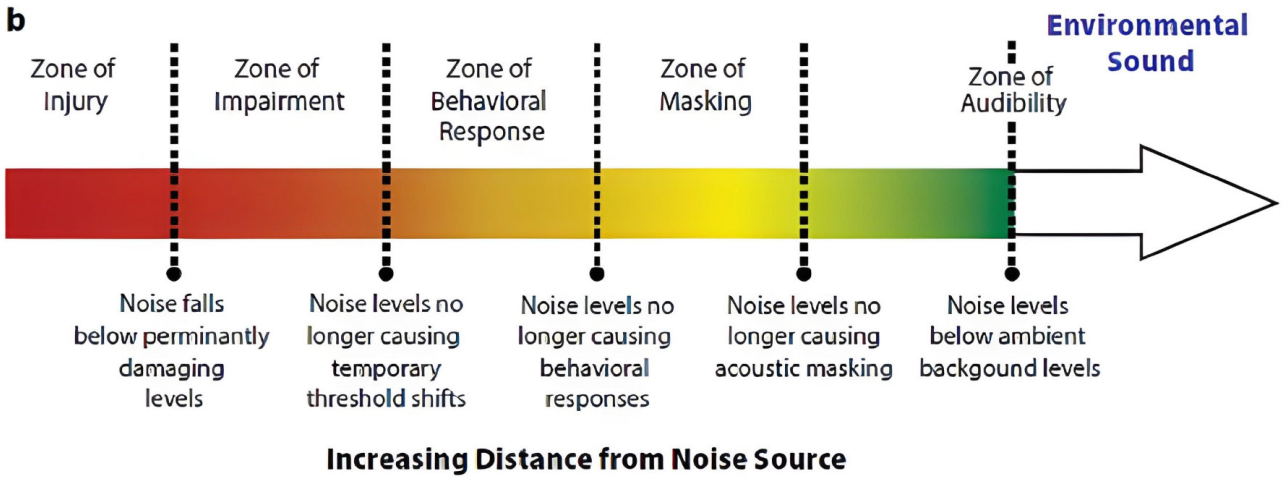


Figure 2. The potential effects of noise with distance from source. Generally, noise and impact on individual animals may be greater closer to the source. Effects change with increasing distance from the source because acoustic signals change, for example decreased dB. Figure from Mooney et al. 2012, modified from Dooling and Blumenrath (2013).

PARTICLE MOTION VERSUS SOUND PRESSURE

Although there is growing evidence that fish and invertebrates are sensitive to the particle motion caused by underwater noise (Casper and Popper, 2010; Hawkins and Popper, 2017; Mooney et al., 2020, p. 201; Mueller-Blenkle et al., 2010; Nedelec et al., 2016; Popper and Hawkins, 2018; Solé et al., 2017), particle motion itself is technically challenging to measure. This difficulty has led to poor assessments of the impacts of particle motion on fish and invertebrates (Popper and Hawkins, 2018). There is more information and research on effects of sound pressure in bony fishes and to a lesser extent invertebrates. As such, much of the information below describes the impact of sound pressure.

PHYSIOLOGICAL EFFECTS

Physiological impacts of sound to fish include damage to ear, nerve, and lateral line tissue that can lead to sound sensing loss or threshold shifts in hearing (Hastings and Popper, 2005; Heathershaw et al., 2001; Jasny, 1999). Threshold shifts result from exposure to low levels of sound for a relatively long period of time or high levels of sound for shorter periods, which may be temporary or permanent. Recovery from threshold shifts appears to require more time for fish species that vocalize (Amoser and Ladich, 2003). Threshold shifts can impact a fish's ability to carry out its life functions. Any organ with a markedly different density than seawater (e.g., swim bladder) may be susceptible to pressure-related impacts. Some of the resulting effects on fish include rupturing of organs and death (Hastings and Popper, 2005).

Near field (close proximity) percussion events produced by pile driving and explosions can have a lethal impact on fish through particle motion and sound wave compression. However, the distance from the disturbance and environmental setting (water density, turbulence, etc.) undoubtedly has major influences on potential physiological effects from particle motion and need further study before they can be treated in detail (Keevin et al., 1999; Thomsen et al., 2015). The lethality of underwater blasts on fish is dependent upon the intensity of the explosion; however, a number of other variables may play an important role including the size, shape, species, and orientation of the organism to the shock wave; the amount, type, and detonation depth of explosive; water depth; and bottom type (Linton et al., 1985).

Fish with swim bladders are the most susceptible to underwater blasts due to the effects of rapid changes in hydrostatic pressures on this gas-filled organ. The kidney, liver, spleen, and sinus structures are other organs typically injured after underwater blasts (Linton et al., 1985). Smaller fish are more likely to be impacted by the shock wave of underwater blasts than are larger fish, and eggs and embryos tend to be particularly sensitive (Wright and Hopky, 1998). However, early fish larvae tend to be less sensitive to blasts than eggs or post-larval fish, probably because the larval stages do not yet possess swim bladders (Wright and Hopky, 1998). Cephalopods can experience significant trauma to their statocysts, structures necessary for balance and position, at cellular and subcellular levels (André et al., 2011). Additionally, playback of seismic air gun recordings induced delayed development and malformation of New Zealand scallop larvae (De Soto et al., 2013).

Effect of anthropogenic noise on zooplankton is a relatively recent topic of interest, tangential to the main subject of the paper but relevant as physiological impacts to zooplankton indirectly affect fishes since many species feed on zooplankton. Abundance of dead larval and adult zooplankton increases two to threefold within one hour after

passage of an active seismic air gun; elevated mortality extended at least 1.2 km from the air gun signal (McCauley et al., 2017). Simulations based on these findings estimate a 22% reduction of zooplankton population within the survey area and declining to 14% within 15 km and 2% within 150 km (Richardson et al., 2017, p. 201). In contrast, the copepod, *Calanus finmarchicus*, was only negatively affected when in close proximity (≤ 10 m) to an active seismic air gun (Fields et al., 2019).

Anthropogenic noise that falsely trigger fish responses may cause animals to expend energy without benefit (Stocker, 2002). Masking biologically significant sounds may compromise feeding, spawning, community bonding, and schooling synchronization. For species in which males broadcast calls to attract females to a spawning location (e.g., oyster toadfish, *Opsanus tau*; silver perch, *Bairdiella chrysoura*; black drum, *Pogonias cromis;* spotted seatrout, *Cynoscion nebulosus*; red drum, *Sciaenops ocellatus*), masking of these acoustic signals by noise may interfere with reproduction (Smott et al., 2018). Further, the effect of noise on each of these behaviors is compounded when considering that the behaviors are inter-related; for example, a change in the ability or desire to feed compounded with reduced communication may lead to a more severe reduction in spawning success.

Behavioral response of fishes to noise is varied and dependent on the species sound perception and the characteristics of the source of noise. While not a comprehensive list, the following provide some examples of behavioral responses.

- When exposed to noise from piling installation, Atlantic cod initially responded by freezing in place. Following the initial onset of noise, Atlantic cod and sole increased swimming speed for the duration of the piling installation activity. In contrast, other fish species appeared to habituate to the repetitive noise (Andersson, 2011).
- Elasmobranch species that are more active swimmers appear to be more sensitive to sound than more sedentary species. Elasmobranchs have been shown to be sound curious, often seeking out the source. Sudden noises that are ~20-30 dB above ambient sound can induce a startle response, but habituation over time has been known to occur (Casper and Popper, 2010).
- Turbine and tidal turbine noise can obscure sounds associated with mudflats resulting in delayed metamorphosis of estuarine crabs (Carroll et al., 2017).
- Increased ambient noise created by watercraft activity potentially reduces the ability of marine organisms, particularly larval forms, to receive the appropriate sound cues to settle in critical habitats (Hastings and Popper, 2005; Holles et al., 2013; Jasny, 1999; Lillis et al., 2016; Scholik and Yan, 2002; Simpson et al., 2016; Staaterman et al., 2014; Stanley et al., 2012).

CUMULATIVE EFFECTS

The most chronic and pervasive impacts on regional fish stocks occur when human generated sounds cause behavioral changes that affect critical life history activities required to maintain healthy populations. Several studies have indicated that increased background noise and sudden increases in sound pressure can lead to elevated levels of stress in many fish species (Hastings and Popper, 2005). Chronic noise levels ≥123 dB can elicit physiological (weight

loss, decreased condition, and elevated and variable heterophil:lymphocyte ratio), behavioral (increased piping and tail adjustments and reduced stationarity), and vocal (increased clicking) stress responses in the lined seahorse, *Hippocampus erectus* (Andersson, 2011). Similarly, Southern Australia scallops, *Pecten fumatus,* exposed to seismic air gun signals resulted in altered physiology (hemolymph biochemistry) and behavior (development of a flinch response and increased recessing reflex) which intensified with repeated exposure (Day et al., 2017).

These examples, as well as others described in this report, demonstrate that noise impacts key life events (e.g., foraging, navigation, and spawning) in many species. This can produce cumulative impacts at many scales. For instance, individual animals that experience repeat exposure to acute noise impacts or experience chronic noise are most likely to have cumulative physiological impacts that reduce their individual fitness. Yet, population level impacts may occur if the acute or chronic noise impacts spawning aggregations or behavior over multiple occasions or locations. Either of these scenarios could lead to population level effects over time if, for example, spawning success or aggregations are interrupted. Examining these cumulative impacts at a range of scales is a priority for future research, especially as sound-producing ocean uses – including offshore wind construction – continue to intensify.

EFFECTS ON BIOGENIC HABITATS

Alteration of the soundscape has the potential to impact biogenic fish habitats. Eastern oyster, *Crassostrea virginica,* larval settlement increased in the presence of oyster reef habitat sounds (Lillis et al., 2013). In response to sediment vibrations, blue mussel, *Mytilus edulis* respiration rates decreased resulting in altered valve gape, oxygen demand, and waste removal (Roberts et al., 2015). Unlike shellfish, Scleractinian corals appear resistant to soft tissue and skeletal damage after repeated exposure to a 3D seismic survey (Heyward et al., 2018). Seagrass meadows, which provide not only a structural habitat for species to forage and avoid predators, but also act as an acoustic refuge for prey species including fishes by attenuating high frequency sounds (100,000 Hz) such as those used by bottlenose dolphin, *Tursiops truncatus* (Wilson et al., 2013), may be impacted by noise. Submerged aquatic vegetation exposed to low frequency sounds (50-400 Hz at 157 ± 5 dB re 1 μPa^2) can develop physical damage to root and rhizome cellular structures, specifically amyloplasts responsible for starch production and storage, gravity sensing, and vibration reception (Solé et al., 2021).

EFFECTS ON FISHERIES CATCH RATES

Anthropogenic noise has been demonstrated to affect catch rates. Several studies indicate that catch rates of fishes decreased in areas exposed to seismic air gun blasts (Engås et al., 1996; Hastings and Popper, 2005); abundance and catch rates for Atlantic cod, *Gadus morhua;* and haddock, *Melanogrammus aeglefinus*, did not return to pre-disturbance levels during the five-day monitoring period (Engås et al., 1996). These results imply that fish relocate to areas beyond the impact zone (area of highest sound intensity), which have been corroborated with visual studies on fish abundance before and after seismic surveys (Paxton et al., 2017). One study indicated that catch rates increased 30-50 km away from the noise source, implying that redistribution of fish populations may occur over broad areas (Hastings and Popper, 2005). Seismic surveys may have positive, no change, or negative effect on fishery catch rates due to variable responses among fish species such as no response, dispersal, avoidance, and decreased responsiveness to bait (Carroll et al., 2017). While fish abundance can decrease due to increased anthropogenic noise, such as from wind farm operation, it is unclear the extent to which the increased noise from wind farm operation affects individual behaviors (Mooney et al., 2020).

Mitigation

When noise cannot be avoided, measures could be implemented to mitigate certain anthropogenic acoustic impacts. New technologies continue to emerge that reduce vessel noise, rendering them less acoustically intrusive. For instance, the use of alternative propeller designs and propulsion systems such as diesel-electric hybrid, electric motors, liquid natural gas pumps, and rotor sails that are quieter than internal combustion engines can be employed. Ship generators are also a substantial source of vessel noise. Insulated or sound proofed ship hulls may be used aboard ships with generators to further reduce acoustic impacts. Furthermore, when in port, vessels could power down their generators and connect to onshore power systems when possible.

Bubble curtains are used during monopile foundation installation to, minimizing acoustic impacts to fish and protected species. Double bubble curtains are especially effective and can lower sound energy levels by up to 90%.
Credit: DEME Group

In addition to modifying hardware and ship practices, informed marine spatial planning can be used to manage location and timing of when harmful sounds are generated. Acoustic transects can be used to isolate and map specific sites based on sound production of fishery aggregations (Gilmore et al., 2003; Gilmore Jr, 1994; Luczkovich et al., 1999; Rountree et al., 2002) as well as the broader ambient soundscape (Chou et al., 2021). For example, critical spawning and aggregation sites can be designated as off limits to vessels, dredging, seismic, construction, and other sound generating activities at night which is when spawning chorus events typically occur. These sites can be remotely monitored with vessel tracking technologies such as automatic identification systems (AIS) to identify violating vessels. To mitigate episodic noise impacts, such as from offshore construction, seasonal restrictions on activities could be combined with spatial planning.

Novel seismic survey methods, including higher sensitivity hydrophones, benthic stationary fiber-optic receivers, parabolic reflectors, and non-impulsive, very low frequency marine vibroseis, may reduce the potential detriment caused by these activities (Chou et al., 2021). Continued study of these technologies and their relative impact on marine life should be prioritized.

The construction of some infrastructure types, including offshore wind turbine foundations, generally involves pile driving at present. However, other foundation types including "quiet" technologies such as pulse prolongation, vibropiling, foundation drilling, gravity base foundation, suction bucket jacket, mono bucket foundation, and floating foundations, are all potentially viable alternatives (Koschinski and Lüdemann, 2020). When possible, one or more

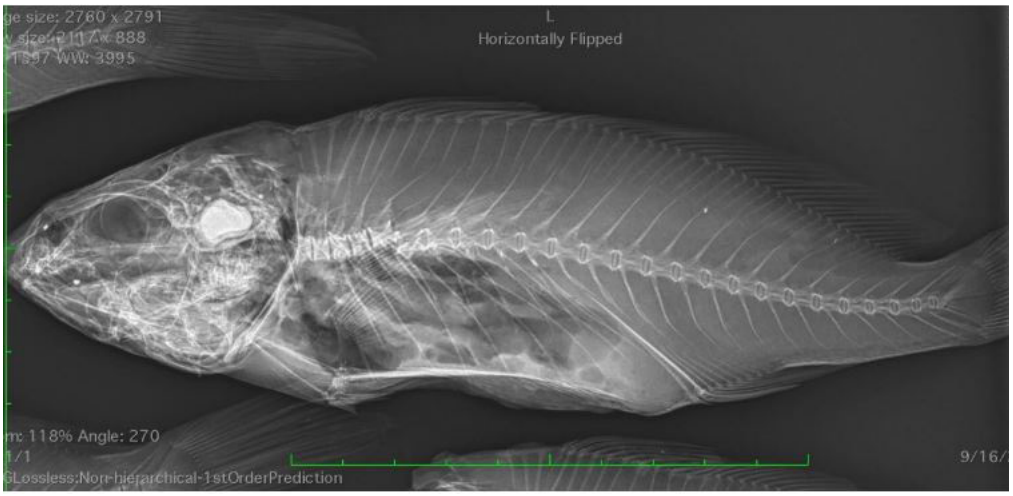
Data Gaps and Research Needs

sound dampening measures such as bubble curtains, isolation casings, hydro sound dampers, dewatered cofferdams, and double/mandrel piles should be used in conjunction with pile driving.

Multiple sound exposure level metrics such as cumulative, peak, single-strike, and number of strikes should be considered when evaluating the potential effect of pile driving and other impulsive sounds and establishing allowable exposure criteria (Halvorsen, 2011). Furthermore, deterrence strategies such as soft-start and ramp-up are intended to scare away mobile species as noise levels are gradually increased (Andersson, 2011; Chou et al., 2021). Each of these are areas for continued research to better inform best practices, exposure criteria, and noise thresholds.

DATA GAPS AND RESEARCH NEEDS

There are still many unknowns about the impact of anthropogenic noise on the physiology and behavior of fishes. Some of these include species-specific effects, the impact on fishing catch rates, synergistic impacts of multiple sources of anthropogenic noise, and many other questions. In 2020, the New York State Energy Research and Development Authority (NYSERDA) convened a working group of over 40 stakeholders and experts who identified and prioritized data gaps and research needs specific to the effects of sound and vibration on fishes and invertebrates (Popper et al., 2021). We direct the reader to this document for more information on research needs.



Signs of acute skeletal trauma and barotrauma in an Atlantic croaker; however, "a definitive cause for the skeletal trauma is not grossly or histologically evident". Credit: VIMS, NC State, NOAA Fisheries

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