Aquaculture Impacts to Fish Habitat along the Atlantic Coast

This issue of the Habitat Management Series provides a broad description of current and common marine aquaculture (mariculture) practices along the Atlantic seaboard and some potential effects on fish habitats. It should serve as an introduction to the topic and facilitate a discussion of the intersection of aquaculture planning and fishery habitat conservation.

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Why Aquaculture?

Marine aquaculture, or mariculture is a potentially vital and sustainable component of seafood production. Half of world seafood was sourced from aquaculture in 2016, and it is the fastest-growing sector in animal-based food production (NMFS 2017, FAO 2018). The current production in the United States is lagging on the world stage, contributing only 20% to U.S. seafood production, however significant opportunity for aquaculture industry growth exists (NOAA 2019a). The US aquaculture and mariculture industry was valued at $1.4 billion and produced 627 million pounds of meat and 1.2 million jobs in 2015 (NOAA 2019b). This industry creates jobs, supports communities, and promotes secondary industry as well as international trade (Slater 2017, NOAA 2019a). Human population growth means an ever-increasing need for food that may not be sustainable by shifting wild stocks; mariculture can help fulfill that need.

Effects on Habitats

Water Quality

The production of finfish and shrimp is often associated with impairment to water quality, however, macroalgae and bivalve culture may improve water quality through the removal of nutrients and suspended solids. On a global scale, marine and brackish water aquaculture cause a net reduction in nutrients (Verdegem 2013). Seaweed and bivalves reduce eutrophication, and bivalves improve water quality through filtration and grazing (Rose et al. 2015, Cerco and Noel 2007) and can control phytoplankton bloom intensity in shallow waters (Gallardi 2014). Fish and shrimp culture can cause nutrient loading in overcrowded, overfed, and poor flow conditions (Price et al. 2015), but placement in deeper waters and stronger currents reduces this risk (Gentry et al. 2016).

Equipment deployed in open and intertidal waters is subject to fouling, and exposed structures to accumulation of bird waste. Antifoulant treatments can contaminate water (Burridge et al. 2010) and physical removal may increase nutrients from bird waste, temporarily deplete oxygen levels as fouling organisms decay, and release toxins if antifoulants were used. There is a need for innovative antifouling strategies that are practical and environmentally responsible (Fitridge et al. 2012).

Sediment

An accumulation of nutrients, wastes, or excess feed can deplete oxygen and impair sediment conditions. Sediment deposition from biodeposits can alter benthic structure. However, accumulation is less likely with adequate flow and good husbandry. Recent investigations into the effects of elevated bivalve culture on the benthos have suggested that impacts are localized and minor by comparison with many other forms of aquaculture (Forrest et al. 2009).

Populations and Communities

In the marine environment, changes to the water column, benthos, flow, and the introduction of physical barriers/structure can impact populations and communities. However, they can also attract structure-oriented species and increase biomass and biodiversity on an otherwise featureless bottom. Gentry et al. (2019) reviewed ecosystem benefits of mariculture and provided a quantitative method to evaluate these benefits.

Marine life aggregates around structures, including aquaculture gear. Biofouling organisms are diverse and include microbes, algae, sponges, hydroids, worms, molluscs, arthropods, and tunicates. These communities provide a nursery habitat and food source to higher trophic levels, including fish. This so-called reef effect may result in a localized increase in biomass and local biodiversity during the production phase. Oyster and mussel mariculture can temporarily enhance populations of large macroinvertebrates and benthic fishes, including ecologically and commercially important species (Costa-Pierce and Bridger 2002, D'Amours et al. 2008, Forrest et al. 2009). Many of the structure-associated fish that are attracted to gear are highly valued for recreational and commercial fishing, and bivalve aquaculture gear can provide substantially better habitat than a shallow, nonvegetated seabed. Even the animals themselves can create habitat when colonists move into the interstitial spaces on and around cultured oysters and other bivalves.

There are other potentially negative biological effects from aquaculture. Disease transmission is a concern for fish, and escapees can outcompete and interbreed with wild fish stocks. Shellfish seed transfer between states may increase the risk of parasite and pathogen transmission if protocols are not established and enforced (see *Bivalve Culture* below for current initiatives). Structures like pens, cages, racks, and bags can exclude or deter resident fauna from their feeding grounds or migration routes. In the Delaware Bay, red knots, a threatened bird, rely on eggs deposited by horseshoe crabs, and research into the effect of shellfish aquaculture on horseshoe crabs and red knots is ongoing. Biocides, used to deter microorganisms in antifoulant treatments, can impact non-target organisms and the antibiotic varieties can lead to antibiotic resistance (Guardiola et al. 2012).

Common Practices

Mariculture along the Atlantic Seaboard includes algae (microalgae and macroalgae), bivalves (oysters, clams, scallops, and mussels), crustaceans (shrimp), and fish (salmon). As of 2016, Atlantic salmon and oysters were the largest components of this market (NMFS 2017). Common practices in this region, along with their known environmental effects, are described below. The most common aquaculture practices in each of the ASMFC states are shown in Table 1. Effects depend on the culture method and species, the size of the operation, and the site itself.

Tidal Water Mariculture

Coastal waters are used for growing shellfish, finfish, and algae. A variety of equipment, locations, and techniques are used to maximize growth and high-quality product.

Bivalve Culture

Bivalve aquaculture typically involves moving immature stock to areas that facilitate grow-out to market size. Juvenile oysters and clams sourced from hatcheries and nurseries are called seed. In areas with a healthy spawning population, newly settled oysters, called spat, can be obtained by laying cultch (typically broken oyster shell) or setting spat collectors just before spawning occurs. For clams and oysters, hatchery-produced seed is now more commonplace than transplanting native set.

This process, called shell planting, is an important part of natural oyster stock management programs in most oyster producing states, where it is done on a large scale. Seed and spat may be grown without any gear to house them (i.e. directly on shelled bottom), or in bags or cages to protect the growing organisms and facilitate maintenance and harvest. The timely harvest of cultured oysters has been shown to reduce rates of the pathogen *Perkinsus marinus* (Dermo) in native stocks (Ben-Horin et al. 2018). While only hard and soft shell clams and oysters are currently grown commercially, there is ongoing research into sourcing and growing sea scallops, razor clams, urchins, and surf clams.

Importing seed from other states or other countries may be necessary if local sources are insufficient. If seed importation is not properly managed, this may pose a risk of introducing disease, parasites, and potentially non-native species. Hatchery capacity is already strained in some areas, and those states are seeing significant increases in requests to import seed stock from out-of-state. Many states have developed specific regulations governing the interstate transport of shellfish products, including shellfish seed, to prevent the introduction or spread of diseases and parasites. To reduce this risk, shellfish growers should be familiar with regulations prior to importing seed from other states or regions. As aquaculture efforts expand, importation may become increasingly necessary, so the associated risks must be understood and minimized by managers. Importation protocols, such as the Hazard Analysis and Critical Control Points (HAACCP) standard operating procedure, should be rigorous enough to reduce the risk of introduction of pathogens or invasive species but also practical enough for the aquaculture industry to navigate in a timely manner. An Atlantic and Gulf Shellfish Seed Biosecurity Collaborative effort is underway to increase regulatory compliance and reduce risk of spreading shellfish diseases through transfers. The effort includes a hatchery certification protocol outlining Best Management Practices (BMPs) and disease surveillance which facilitates biosecure interstate commerce. Habitat managers along with agencies charged with aquaculture development should work cooperatively to encourage the development of regional scale tools (e.g., North Atlantic region, Mid-Atlantic region, and South Atlantic region).

Non-structured/Bottom Planting

Seed or spat can be spread across the bottom without containment (extensive shellfish culture), called non-structured or bottom-planting, in areas that are accessible by boat and conducive to growth, but not already occupied naturally by oysters or clams. Bottom planting reduces the amount of gear maintenance required, but moving stock (relay) and harvesting require the grower to dredge, pick, or tong the product. Predator screening is typically used to cover younger stocks of clams. Planted oysters have been shown to promote biodiversity by attracting settling invertebrates, bottom feeders, and fish (Forrest et al. 2009).

FLUPSYs

Floating upweller systems (FLUPSYs) are a popular way to grow clams and oysters from small seed until they are large enough to be deployed in gear for grow-out (Rivara et al. 2002). Stock is housed in suspended, mesh-bottomed compartments that tidal water circulates through from bottom to top, providing oxygen and algae and removing waste. FLUPSYs are often tied to or built into existing docks or boat slips, making them accessible from shore, and potentially alleviating some permitting concerns (such as total footprints of shading, etc.). FLUPSYs are typically used post-hatchery to raise seed to sub-adults prior to grow-out. There are concerns that waste can accumulate under the FLUPSY if flushing is not adequate. However, low flow areas are often avoided or overcome by the use of electric-powered pumps to provide desired current flow by growers.

Bags/rack-and-bag/predator nets

Options for intertidal aquaculture are considered intensive shellfish culture, which are grown in cages or bags set on the bottom; or in the water column suspended from a float (often called a Lentz System), attached to a stake, or laid on racks ("rack-and-bag"). Rack-and-bag is the most common of these systems for oysters. Bags or cages are set on racks in the intertidal or shallow sub-tidal zones, where naturally circulating tidal waters provide food and remove waste. Maintenance of bags requires removal of fouling to ensure good flow, typically by scrubbing, scraping, power washing, air drying, and salt dips. As the oysters grow, they are sorted and moved into gear with more space and larger mesh. Commercial clam producers sometimes use predator nets, which are usually attached by stakes under the substrate. Market-sized oysters and clams are easily harvested from bags by taking the entire bag and removing marketable oysters while sub-market oysters are returned to bags. Bags laid directly on the substrate are often secured with stakes and connected with lines to facilitate harvest and husbandry.

Cages/bottom screens

Oyster cages are also deployed directly on the bottom, typically in sub-tidal areas. This practice may enhance soft-bottom habitat by replacing it with structured bottom that may increase production and biodiversity. Cages become habitat for a variety of species, including juvenile and adult fish (Costa-Pierce and Bridger 2002). The Northeast Fisheries Science Center is studying how reef fish are using these cages (NOAA 2019c).

Suspension culture

Suspended bivalve culture systems include rope culture for mussels (vertical lines within the water column) and trays, bags, or lantern nets, which hang below the surface and shift with the tide. Mussel line culture can be started with hatchery-reared seed or through natural set, depending upon location.

Fish Farming

Open-net pens or cages are used to grow fish in coastal waters. Currents flow through the system removing waste and providing oxygenated water. Feed must be provided.

As described in Effects on Habitats above, fish farming can have significant effects on water quality and sediment, and net-pen aquaculture can alter local habits and ecosystems if they are not sited properly (Findlay et al. 1995).

Escaped fish can breed with wild fish and possibly alter genetic fitness or compete with native fish for resources. High population densities increase the chance for transmission of disease, which can then be transferred to wild populations or vice versa.

Informed siting, good husbandry, and regular maintenance are critical to mitigating effects. Siting in deep, well-mixed water reduces the accumulation of wastes that impair water quality and sediment (Price et al. 2015). Appropriate stock densities, feeding, and care reduce the risk of release of nutrients, antibiotics, pesticides, and growth enhancers (though not commonly used). Regular maintenance, including removal of fouling, is essential to avoid structural failure. In 2016, hundreds of thousands of non-native salmon were released in the San Juan Islands of Washington State when a heavily-fouled pen collapsed.

Atlantic salmon have been grown in Maine in open-net pens since the 1970s. Water quality impairments have been significantly reduced by the use of vaccines and integrated pest management, and the minimal to non-existent use of antibiotics and growth enhancers (Maine Seafood Guide – Salmon 2019). In 2016, Maine-raised salmon were upgraded from “avoid” to “good alternative” by the Monterey Bay Aquarium Seafood Watch Program, which rates seafood according to whether it supports a healthy ocean (Seafood Watch 2019). Improvements in feed efficiency, escape prevention (Rust et al. 2014), and effects on dissolved oxygen, turbidity, and nutrient enrichment have been seen in this industry (Price et al. 2015).

Other effects are more difficult to address. Feed is typically wild-caught coastal forage fish. Farms can attract and entangle predators such as cormorants, sharks, and marine mammals. The pens thereby alter predator behavior and subject them to adverse actions (i.e. lethal control measures) by net pen operators. Regular gear maintenance and stock tending result in increased boat traffic and dock use. The implementation of responsible production and husbandry practices as BMPs can mitigate many of these concerns. For example, the use of properly weighted (taut) predator nets have diminished entanglement risk to near-zero for sharks and marine mammals.

Seaweed Culture

Seaweeds are a highly nutritious food source, and the world’s largest mariculture crop. They are readily grown on longlines in open waters. These autotrophs remove carbon dioxide and nutrients and release oxygen. Seaweed culture has the potential to mitigate ocean acidification, hypoxia, and eutrophication. A review by Kim et al. (2017) found that seaweed aquaculture provides ecosystem services that improve conditions of coastal waters, and that these benefits need further study and better public awareness of the opportunities of this industry.

Integrated Multitrophic Aquaculture (IMTA)

IMTA is an exciting new field of mariculture and is being studied worldwide. Similar to polyculture in terrestrial agriculture, IMTA is the practice of growing multiple species together to reduce environmental effects, provide ecosystem services, and improve profit. The theory behind IMTA is that nutrient inputs are limited as the fish waste serves to promote plant growth. The removal of nutrients by algae and particulates by bivalves provides cleaner water for the other species in the system. Scientists at the University of Maine are looking into using benthic polychaetes, which can be sold as bait, to reduce impacts from salmon open-net pens (University of Maine 2019). For the marine environment, the greatest potential for IMTA systems is the use of less space to grow more species. This can limit user conflicts while still yielding environmental and economic benefits.

Land-Based Mariculture

While state waters are used to grow-out most marine species, there is a need for land-based systems that provide a more controlled environment. These typically include hatcheries and nurseries, though some species, like shrimp, most finfish, and bivalves, can be grown entirely on land. Land-based mariculture facilities are usually sited close to shore for access to seawater (though fresh water from wells can be used with the addition of salts), and produce effluent that may be discharged, accidentally or intentionally, to nearby surface waters. Fish hatchery effluent may be regulated by the National Pollutant Discharge Elimination System (NPDES), and some states require additional permitting. Some states do not require permits for bivalves with the understanding that water quality is not degraded and may even be improved (e.g., due to clearance and filtration by shellfish).

Environmental effects vary widely with the species being cultivated, the location, and the size and type of facility. Organisms lower on the food chain, like algae and bivalves, produce less waste. Pollutants found in aquaculture effluents are similar to those found in effluents from agriculture and municipal wastewater treatment plants, such as nutrients, organic matter, and suspended solids (Boyd and McNevin 2014). Less common effluents include dissolved salts, toxic substances, pesticides, and disease-control compounds.

Hatcheries and Nurseries

Hatcheries contain spawning brood stock and produce juveniles of various species; nurseries are used for further growth of bivalves prior to deployment in tidal waters. Microalgae is cultured in hatcheries and nurseries as feed for early life stages of fish and shellfish.

Upwellers and Raceways

These systems pass seawater through a series of tanks and out to surface waters. Upwellers, common for bivalves, circulate water from bottom to top. Raceways are horizontal rows of tanks. Stock may be moved between raceways for more growing space. Wastewater can contain nutrients and solids that affect receiving waters. If appropriate BMPs are not implemented for health requirements and the containment of nonnatives, there is a possibility of nonnative species and disease being released into the environment if regulations are not followed.

Recirculation Systems

These systems are similar to flow-through systems in types of effects, but because they recirculate and filter water, both water usage and effluent is reduced.

Ponds

Ponds are used to grow finfish, shrimp, and macroalgae, among other species. Broodstock are placed in a controlled, closed environment such as a natural or man-made pond to spawn. The larvae and juveniles can be separated by age or size and placed in different ponds for optimal growth. When they reach adult size, they may be kept for broodstock, released in aquatic ecosystems for fishing, or sold to consumers.

Sometimes untreated water is discharged with leftover nutrients and sediments to other water bodies and can increase the risk of eutrophication. BMPs can reduce or eliminate nutrients in effluent.

Siting Considerations

Thoughtful spatial planning before aquaculture facilities are sited can mitigate many of the potential environmental impacts, reducing unwanted results and amplifying the benefits of the industry. In fact, proper siting is usually the most important aspect of planning. Understanding the existing environment and how particular aquaculture methods and culture species might affect it is a critical step in reducing conflicts. The implementation of a siting strategy early in the process allows for public involvement and consideration of social benefits. This should include considering novel locations, such as offshore wind farms. As states develop areas for aquaculture, existing uses, sensitive species and habitats, and carrying capacity of the environment must be considered.

Minimizing Use Conflicts

Like any other form of agriculture, marine aquaculture requires space, so it must compete for real estate with other user groups, such as boaters, fishers, and landowners in the coastal zone. If uses are not compatible, conflict resolution with other users is required. While very few areas will be entirely conflict free, knowledge of how potential aquaculture areas are being used is critical to siting.

In some areas, misconceptions exist about impact of aquaculture on coastal habitats and the safety of farmed seafood, which can lead to conflict with stakeholders. While there are known potential negative effects, the general public is less aware of the potential benefits of aquaculture on habitats, particularly those provided by bivalve culture.

Protecting Habitats

An understanding of the existing resources and siting of potential aquaculture areas is critical to mitigating impacts to fish habitats. Sensitive microhabitats in prospective aquaculture areas should be identified and avoided. Corals, mangroves, and submerged aquatic vegetation (SAV), for example, are valuable microhabitats that are sensitive to nutrient fluxes and disturbance.

Leases should not be sited on to existing or historic SAV locations, since the equipment used can cause shading and increased sedimentation. NOAA identifies SAV as an “underwater neighborhood” that is essential habitat for federally managed species. With that being said, not all gear damages SAV (Vaudrey et al. 2009), and in certain circumstances, aquaculture can improve conditions for SAV by reducing turbidity (Dumbauld et al. 2009), adding nitrogen to the benthos, and sheltering new growth from currents (Normant pers. com. 2019). Scientists at the University of North Carolina are studying how aquaculture affects SAV growth (Blackburn 2015).

In the Delaware Bay there is concern about aquaculture activities interfering with foraging of red knots, a threatened species that relies on eggs deposited by horseshoe crabs. A number of research projects are under way looking at the effect of aquaculture on horseshoe crabs and red knots.

As the mariculture sector continues to grow in both volume and product diversity, it is likely to generate potential disturbances or threats to other important or critical habitats (for example long lines or net pens in designated Right Whale critical habitats along the eastern seaboard). Consultations with local, state, and federal permitting agencies during site selection are critical to understanding the nature and extent that new or expanding technologies will impact important habitats.

Carrying Capacity

Another important consideration for siting is carrying capacity, or how much aquaculture a given area can sustain without adverse environmental or social impacts. Too much aquaculture activity in a specific location will create other access and use limitations and erode public perception and support of aquaculture activities in certain areas. Determining optimal densities and spacing is an important aspect of BMPs and should be considered early in the lease siting process. This depends on the type of aquaculture, species in culture, and site-specific conditions. Fish aquaculture is associated with more significant environmental effects than bivalve aquaculture, including nutrient loading, sedimentation, lipids, turbidity, oxygen depletion (Pillay 2004, Rust et al. 2014), and rarely to sometimes, the use of antibiotics, pesticides, and growth enhancers. Overcrowding and poor husbandry increase the risk of disease transmission and escape.

Conclusions

This document outlined a number of the potential positive and negative impacts that may result from the culture of marine species along the Atlantic Seaboard. Inappropriately sited structures can obstruct migration as well as reduce available habitat for sensitive species. Improperly managed effluents can impair water quality and alter local community dynamics and trophic structure. These impacts, however, are species specific, with bivalve shellfish aquaculture demonstrating minimal detrimental effects (Crawford et al. 2003), balanced with a suite of ecosystem benefits.

Filter-feeding bivalves have been shown to abate eutrophication and algal blooms, enhance the growth of SAV, and benefit benthic macroinvertebrate communities and populations of ecologically and economically important fish. Oysters can also provide ecosystem services by removing excess carbon, reducing acidification, and improving water clarity and coastal resiliency (Gentry et al. 2019). Research has even demonstrated their potential to control disease in wild oyster populations.

The most critical way for habitat managers to avoid direct impacts to marine habitat is through the leasing and site selection process. Site-specific knowledge of sensitive species and habitats, coupled with the establishment of BMPs can mitigate problems like accumulation of food and wastes, disease transmission, water quality impairment, and escape. Research into the carrying capacity of various environments and mariculture practices is still in early stages but remains a critical area in need of support. Supporting research in aquaculture can have far-reaching benefits, particularly in near-shore communities that may be most at risk of economic effects of climate change.

Table 1. Current mariculture practices by state.

State	Method*	Species
Connecticut	Non-structured/bottom planting Bags/rack-and-bag/predator nets Cages/bottom screens Suspension culture Seaweed culture Flow-through systems	Hard clams and oysters Oysters Hard clams and oysters Oysters Kelp Shellfish hatchery
Delaware	Non-structured/bottom planting Bags/rack-and-bag/predator nets Cages/bottom screens	Oysters Oysters Oysters
Florida	Non-structured/bottom planting FLUPSYs Bags/rack-and-bag/predator nets Cages/bottom screens Suspension culture IMTA Hatcheries and nurseries Upwellers and raceways Recirculation systems Ponds	Clams Hard clams and oysters Hard clams and oysters Oysters Oysters Numerous species of fish and invertebrates Hard clams and oysters Hard clams and oysters Numerous species of fish and invertebrates Numerous species of fish and invertebrates
Georgia	Non-structured/bottom planting Bags/rack-and-bag/predator nets Hatcheries and nurseries	Hard clams Hard clams Oysters
Maine	Non-structured/bottom planting FLUPSYs Bags/rack-and-bag/predator nets Suspension culture Seaweed culture Open net pens and cages Hatcheries and nurseries Recirculation systems Ponds	Hard clams, soft shell clams, and razor clams Oysters Blue mussel Oysters, sea scallops, razor clams, hard clams, blue mussel Sea vegetables Atlantic salmon Atlantic salmon, eel, yellowtail Atlantic salmon, eel, yellowtail Atlantic salmon, eel, yellowtail
Maryland	Non-structured/bottom planting FLUPSYs Bags/rack-and-bag/predator nets Ponds	Soft shell clams and oysters Oysters and striped bass Oysters Striped bass
Massachusetts	Non-structured/bottom planting Bags/Rack-and-bag/predator nets	Softshell clam, oyster, quahog, bay scallop, blue mussel

	Cages/bottom screens	
	Suspension culture Seaweed culture	Offshore: blue mussel Inshore: seaweeds (*Gracilaria*, sugar kelp),
	Recirculation systems	Pacific white shrimp (*Vannamei* sp.)
New Hampshire	Non-structured/bottom planting	Oysters
	FLUPSYs	Oysters
	Bags/Rack-and-bag/predator nets	Oysters
	Cages/bottom screens	Oysters, quahog
	Suspension culture Seaweed culture	Offshore: blue mussel, seaweeds (*Gracilaria*, sugar kelp)
New Jersey	Non-structured/bottom planting	Hard clams and oysters
	FLUPSYs	Hard clams and oysters
	Bags/rack-and-bag/predator nets	Oysters
	Cages/bottom screens	Oysters
	Upwellers and raceways	Hard clams and oysters
New York	Non-structured/bottom planting	Hard clams and oysters
	FLUPSYs	Hard clams and oysters
	Cages/bottom screens	Oysters
	Upwellers and raceways	Hard clams and oysters
North Carolina	Non-structured/bottom planting	Clams and oysters
	Bags/rack-and-bag/predator nets	Clams and oysters
	Cages/bottom screens	Oysters
	Upwellers and raceways	Clams and oysters
	Recirculation systems	Numerous species of fish and invertebrates
	Ponds	Numerous species of fish and invertebrates
Rhode Island	Non-structured/bottom planting	Hard clams, soft shell clams, and oysters
	FLUPSYs	Oysters
	Bags/rack-and-bag/predator nets	Oysters
	Cages/bottom screens	Oysters and scallops
	Suspension culture	Kelp, mussels
	Upwellers and raceways	Oysters
South Carolina	Non-structured/bottom planting	Clams and oysters
	Bags/rack-and-bag/predator nets	Clams
	Cages/bottom screens	Oysters
	Upwellers and raceways	Clams and oysters
Virginia	Non-structured/bottom planting	Clams and oysters
	FLUPSYs	Oysters
	Bags/rack-and-bag/predator nets	Oysters

	Cages/bottom screens	Clams and oysters
	Hatcheries and nurseries	Clams and oysters
	Upwellers and raceways	Clams and oysters
	Recirculation systems	Clams and oysters

*The methods listed are the same as the categories found on pages 7-12 of the document. For multiple methods in a category (e.g. upwellers and raceways), the state may be carrying out one, some, or all of the method methods listed.

Resources for Best Management Practices

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Delaware http://www.dnrec.delaware.gov/fw/Fisheries/Pages/ShellfishAquaculture.aspx

Florida https://www.freshfromflorida.com/Divisions-Offices/Aquaculture

Georgia https://gacoast.uga.edu/outreach/programs/aquaculture/

Maine https://www.maine.gov/dmr/aquaculture/

Maryland http://dnr.maryland.gov/fisheries/Pages/aquaculture/index.aspx

Massachusetts https://www.mass.gov/service-details/aquaculture

New Hampshire https://seagrant.unh.edu/aquaculture

New Jersey https://www.nj.gov/dep/fgw/pdf/marine/shellfish_leasing_policy_atlantic.pdf

New York https://www.dec.ny.gov/outdoor/110882.html

North Carolina https://ncseagrant.ncsu.edu/aquaculture/

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ANTHROPOGENIC ACOUSTIC IMPACTS ON ATLANTIC FISHERIES PRODUCTION

REVISED BY R. GRANT GILMORE, JR., PH.D.

PHYSICS OF SOUND IN WATER

The ability to detect and/or produce sound is important for survival in many animals (Lanyon and Tavolga 1960; Stebbins 1983; Hauser 1997; Hauser and Konishi 1999; Rogers and Kaplan 2000). The importance of auditory stimuli is amplified in aquatic environments due to differences in the way sound, light, and chemicals behave underwater (Wenz 1962; Urick, 1983, 1984; Richardson et al, 1995; Au and Hastings 2008). Understanding the physical environment of water (higher density than air) and its physics reveals the importance of biological sound in water simply due to its lower attenuation rate (longer audible range) vs light and olfactory stimuli (Knudsen et al. 1948; Wenz 1962; Au and Hastings 2008; Ward 2015). Light attenuates rapidly in even the clearest water (longer wave lengths, reds and yellows, and the most energetic, ultraviolet, disappearing within a few meters). Blue disappears last, but at a maximum of 1,000 m. The majority of the ocean is in total darkness, as are some turbid coastal waters. Sound, not light, becomes the most important sensory energy field for many aquatic organisms including fish (Tavolga 1960, 1980; Richardson et al, 1995; Stocker 2002; Au and Hastings 2008; Staaterman et al. 2013).

LITERATURE CITED SECTION I.

MECHANISMS OF SOUND PRODUCTION: FISH/INVERTEBRATES

Bony fishes possess a sensitive auditory system that includes a cephalic auditory center in the brain and adjacent auditory sensors, an “inner ear” that contains three otoliths (“ear stones”) consisting of calcareous and organic matrices. Sounds moving through the fish vibrate the otoliths in contact with neurosensory organs. Many fishes contain a centrally located gas bladder that plays a major role in sound reception and production. Sound reception can be enhanced by a mechanical osteological connection (Weberian ossicles in ostariophysan fishes – catfishes, characins and carps/minnows) between the otoliths and the gas bladder, or membranous extensions from the gas bladder to the inner ear as in most sciaenids (drums, seatrout and croakers) (**Popper and Fay 2011**). Sonic muscles attached to the gas bladder are used to produce robust low frequency high energy calls in groupers (Epinephelidae), seabass (Serranidae), snappers (Lutjanidae) and drums/croakers (Sciaenidae**.** The sonic muscle vibrations associated with the gas bladder produce the species specific frequency patterns and various other diagnostic characteristics of the fish call. Other sound producing mechanisms include pharyngeal teeth (jacks: Carangidae), and boney fin spines (sea catfishes: Ariidae). Various crustaceans use their carapace or claws to produce sound, the most ubiquitous being the alpheid shrimp, “snapping shrimp” pops produced by cavitating gas bubbles produced by the distinctive morphology of their enlarged claw (Au and Banks 1998). The various sounds of crustaceans can make a major contribution to the “soundscape” of particular reef habitats (see soundscape section below).

Many fish have the same hearing frequency sensitivity that humans do (10 to 20,000 Hz: Tavolga 1960, 1980; Fine et al 1977; Popper 2003; Fay et al. 2008; Popper and Hastings 2009; Popper et al. 2005, 2014; Popper and Fay 2011) even though certain groups, the herrings, sardines and menhaden (clupeids) can detect ultrasound, frequencies above 100,000 Hz (Dunning et al. 1992; Fine et al. 1977b; Nestler et al 1992; Mann et al. 1997, 2001; Narins et al. 2013). Most fish produce sounds below 2.0 kHz (Tavolga 1960, 1980; Fine et al 1977; Popper 2003; Fay et al. 2008; Popper and Hastings 2009; Popper et al. 2005, 2014; Popper and Fay 2011). These lower frequency sounds are those that attenuate least and travel further underwater (Wenz 1962; Au and Hastings 2008; Ward 2015) and are the frequencies fish typically use for communication (Bass et al. 1997; Au and Hastings 2008; Popper and Fay 2011). Sound is the preferred means of communication and sensory detection in aquatic ecosystems, whether in turbid rivers (Borie et al. 2014) or oceanic continental shelves (Tavolga 1960, 1980; Fish 1964; Cato 1978, 1980; Rogers and Cox 1988: Au and Hastings 2008; Cotter, 2008; Gasc et al. 2013**).** LITERATURE CITED SECTION II.

WHICH FISH/INVERTEBRATES PRODUCE SOUND?

After World War II, a major effort was made to use war time technologies, undersea microphones, “hydrophones”, to classify the wide variety of “biological sounds” recorded by U.S. Navy personnel during their hunt for enemy submarines. The initial catalogue of fish sounds was produced by Fish and Mowbray (**1900)** recording from New England to Florida and Bermuda. In the 1970s literally thousands of bio-acoustic recordings were made in coastal Atlantic and estuarine waters from New England (Rountree et al.), Delaware (Connaughton…..) North Carolina (Luczkovich….), South Carolina (…..), Georgia/Florida (Barbieri…..), Mann, Baltz, Saucier, Holt,….Gulf of Mexico) and off Florida east coast between 30° 00’ & 26 ° 00’ N.. East Florida recordings continue to this day (ref.).
These observations include intensive estuarine investigations in addition to acoustic instrument deployments on deep reefs (*Lophelia*) to depths to 1,000 m using manned Johnson-Sea-Link submarines (**ref.** Gilmore et al. 2004; Gilmore, et al. 2003). Of the roughly800 fish species recorded from the Florida central east coast 269 species, 34% of the total species, are known to produce sound to communicate during social interactions and spawning.

The smallest species of fish, the gobies (*Gobiosoma bosc*: Gobiidae) and the largest teleost fish, the Goliath grouper, *Epinephelus itajara*, produce sounds in social heirarchies and in spawning (Mok 1981; Mann et al. 2008). Even larval fish can produce sound apparently for maintaining protective schools while foraging in the water column (Staaterman et al. 2014). Agonistic vocalizations can be used to delineate an individual’s territory and intimidate or deter conspecifics or predators (Ladich 1997; Vester et al. 2004; Maruska and Mensinger 2009… Mann, Koenig). The most significant sound producers belong to some of the most speciose regional fish families and also support regional fisheries (Groupers Epinephelidae, 23 species;

Sea basses, 50 species; Jacks, Carangidae, 29 species; Snappers Lutjanidae, 18 species; Grunts Haemulidae, 20 species; Porgies, Sparidae, 17 species; Drums/Croakers Sciaenidae, 26 species). Many of these sound producing species are benthic, or epi-benthic and structure (reef) associates. The most robust acoustic signals produced by these species are most often associated with spawning.
LITERATURE SECTION III.

WHY FISH PRODUCE SOUND: IMPORTANCE OF SOUND IN FISH LIFE HISTORY

How and why is sound used by fish? All living things spend most of their energy attempting to obtain more energy (feeding) and to reproduce. Fish do produce sounds when feeding, some more than others (Sartori and Bright, 1973; Mallekh et al. 2003; Hughes et al. 2014), but most undersea bio-acoustic observations indicate that feeding produces inadvertent sounds. The most ubiquitous sound production in fish is for communication: intraspecific communication (Myrberg 1900; Tricas and Boyle 2014; van Oosterom, et al. 2016), schooling (Moulton 1960; Kaatz 2002), social interactions (Ladich 1997), mate selection and reproduction (Mok and Gilmore 1983; Gilmore 1994, 2002, 2003a; Aalbers and Sepulveda 2012; almada et al. 1996; Bass et al. 1997; Brawn 1961b; Connaughton and Taylor 1995; Hawkins 1986, 2003;Hawkins et al. 1967, 2002; Lobel 2002, Lobel and Mann 1995; Luczkovich et al 1999, 2000, 2008; Mann et al. 2010; Mann and Lobel, 1995; Maruska et al. 2012; Montie et al. 2017; Nordeide and Folstad 2000; Nordeeide and Kjellsby 1999; Sprague et al. 1998). Successful reproduction insures fish and fisheries survival.

ACOUSTIC SOUNDSCAPES USED FOR FINDING CRITICAL SPAWNING AND NURSERY HABITATS

Sounds produced by other organisms, such as invertebrates (alpheid shrimp) in specific habitats, along with physical ambient sounds (ex. wind, waves, rain, water flow over objects), produce a diagnostic "soundscape"and act as cues for larval fish and invertebrates to find specific nursery habitats and avoid predation (refers… Radford et al. 2011; Vermeij et al. 2010; Remage-Healey et al. 2006; Hughes et al. 2014; Buscaino et al. 2012; Janik 2014; van Oosterom 2016).

Spawning aggregations are often accompanied with high energy choral displays, These robust acoustic displays likely aid in locating mates and spawning sites. Most spawning and acoustic displays occur during crepuscular and nocturnal periods (Gilmore 2003…Rountree, Mann, Luczkovich, Sprague, REFS…). The choral displays and spawning sites are used annually, some being documented for decades with fish returning to their favored spawning site to call mates (Groupers- Epinephelidae: refs….Gilmore and Jones 1993; Drums/Croakers -Sciaenidae: Gilmore 2003. Many fish species produce diagnostic sounds only when spawning. Some specific spawning sites have been acoustically monitored for over 40 years, the study period for east Florida bio-acoustic studies (Mok and Gilmore 1983; Gilmore 1994; Gilmore, 2003; Rountree et al. …..refs.).

Recent research indicate that other sciaenids and snook (Centropomidae) epinepheline groupers (Gag, *Mycteroperca microlepis*), sea basses (Serranidae), grunts (Haemulidae), and porgies (Sheepshead, *Archosargus probatocephalus*, Sparidae) also use the same spawning sites for decades and produce a variety of acoustic displays at these spawning sites (Gilmore 2003, Mann…..Walters, Spraguq, Luczcovich…….). Spawning habitat and its acoustic environment, or "soundscape", is critical for successful reproduction, particularly in fishes producing sound to attract mates. Estuarine sciaenids spawn in deep basins and channels where sound attenuates less. All these sound producing families and species support valuable regional fisheries.

Therefore, sound production and reception is most important in procreation at very specific spawning sites that are used annually for decades. These spawning sites are the most vulnerable locations to human impacts, particularly, to fish mating behavior and successful reproduction.

Adult fish sound production at spawning sites is critical for successful spawning and mate selection. Now research reveals that larval fish and invertebrates school and find critical nursery habitats based on distinctive habitat sounds, soundscapes, that allow them to find settlement sites and orient their swimming behavior. This means that the overall acoustic environment is extremely important to the most critical periods in the life history of a fish, spawning, larval migration and settlement when most fish mortality occurs.

LITERATURE CITED SECTION IV & V.

Anthropogenic Impacts to Fish Habitats and Fisheries

Anthropogenic sources of noise in the ocean include those that are episodic (acute) and ongoing or continuous (chronic). Both types may occur inshore or offshore. Episodic activities include pile driving, dredging, cable laying, and seismic surveys. The most ubiquitous continuous human sound sources along the east coast of the United States are associated with commercial and recreational boating and shipping. In certain coastal areas oil and gas drilling operations, and offshore wind energy operations are the most continuous and potentially disturbing anthropogenic sound sources.

Very loud undersea sounds are produced by water craft, shipping and boats. These sounds are the most ubiquitous underwater sounds produced by humans in coastal waters (Stocker 2002). Cargo and tanker traffic sounds are augmented inshore by thousands of recreational power boats. These sounds can be multiplied by complex reflected paths – scattering and reverberating because of littoral geography. The average shipping channel noise levels are 70-90 dB, which is as much as 45 dB over the natural ocean ambient noise in surface regions (Stocker 2002). Ships generate noise primarily by propeller action, propulsion machinery, generators, and hydraulic flow over the hull (Hildebrand 2005). Considering all of these noises together, noise generated from a large container vessel can exceed 190 dB at the source (Jasny 1999; see the case study below). In metropolitan areas and ports the diversity of cargo vessels are joined by a wide variety of watercraft in contributing to the dominant anthropogenic soundscape: commercial and private fishing boats, recreational watercraft, coastal industrial vessels, public transport ferries, military craft, jet skis, and many others. Even bridge auto traffic produces significant underwater sounds, particularly during periods of peak traffic.

Noise generated from anthropogenic sources covers the full frequency of bandwidth used by marine animals (0.001-200 kHz), and most audiograms of fishes indicate a higher sensitivity to sound within the 0.100-2 kHz range (Stocker 2002). Evidence indicates that fish as a group have very complex and diverse relationships with sound and how they perceive it. It should be noted that relatively little direct research has been conducted on the impacts of noise to marine fish. However, some studies and formal observations have been conducted that elucidate general categories of impacts to fish species. Noise impacts to fish can generally be divided into four categories: (1) physiological; (2) acoustic; (3) behavioral; and (4) cumulative. Add NOAA 2008 Tech memo “ocean noise” reference.

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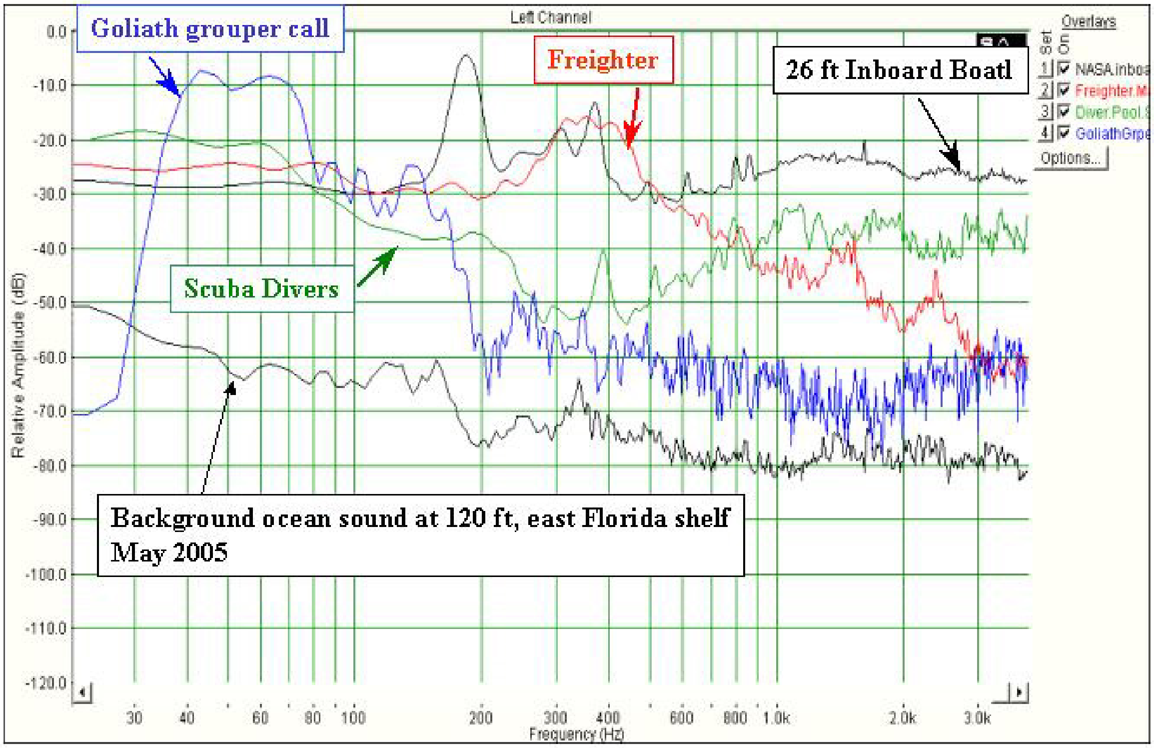
Figure 1. Illustrates the spectrum of various anthropogenic and fish (Goliath Grouper, *Epinephelus itajara*) sound sources. Note the low frequency sound region where most biologically important sounds are produced (<3 kHz.)



Behavioral impacts to fish

The most chronic and pervasive damaging acoustic human impacts on regional fisheries is associated with acoustic impacts causing behavioral changes that are critical life history activities required to maintain healthy populations, such as successful spawning. Most human generated chronic sounds are low frequency sounds below 1-5,000 Hz. (ref.). Most fish sound production and habitat soundscape acoustic signatures are at low frequencies, i.e. below 5 kHz. (**ref.**). This is the frequency region where underwater sound propagates best and therefore utilized by aquatic biota for biological purposes, communication, habitat location, predator avoidance, schooling, etc. (ref…..). It has been shown that anthropogenic sounds, such as boat motor sounds, can interfere with larval fish orientation to the diagnostic soundscape of nursery settlement sites (ref….) and spawning adult choral displays (Spotted Seatrout , *Cynoscion nebulosus*, Common Snook, *Centropomus undecimalis*, pers. Obs. R.G. Gilmore, Jr.). cod reference….add.refs.

Several studies indicate that catch rates of fish have decreased in areas exposed to seismic air gun blasts (Engås et al. 1996; Hastings and Popper 2005). These results imply that fish relocate to areas beyond the impact zone. One study indicated that catch rates increased 30-50 km away from the noise source (Hastings and Popper 2005). 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). Recent research indicates that both invertebrate and fish utilize a diagnostic soundscape to recognize and associate with specific habitats. An increase in ambient background noise created by vessel and boating activity can potentially reduce the ability of marine organisms, particularly larval forms, to receive auditory cues and settle in critical habitats that benefit survival (add larval fish references…..; Jasny 1999; Scholik and Yan 2002; Hastings and Popper 2005).

Physiological impacts to fish

As stated, most fish utilize low frequency sounds and are very sensitive to instense sounds below 1,000 Hz. Acoustic impacts include damage to auditory tissue that can lead to hearing loss or threshold shifts in hearing (Jasny 1999; Heathershaw et al. 2001; Hastings and Popper 2005). Temporary threshold shifts and permanent threshold shifts may result from exposure to low levels of sound for a relatively long period of time or exposure to high levels of sound for shorter periods. Threshold shifts can impact a fish's ability to carry out its life functions.

Any organ that reflects a pressure differential between internal and external conditions may be susceptible to pressure-related impacts. Some of the resulting effects on fish include a rupturing of organs and mortality (Hastings and Popper 2005). The lethality of underwater blasts on fish is dependent upon the detonation velocity 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, and the amount, type of explosive, detonation depth, 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 venosus are other organs that are typically injured after underwater blasts (Linton et al. 1985

).

The loudest anthropogenic noises are the sounds of marine extraction industries such as oil drilling and mineral mining (Stocker 2002). The most common sources of extraction sounds are from air guns used to create and read seismic disturbances (*add recent papers here…..NOAA review paper*). Air guns are used in seismic exploration to create a sound pressure wave that aids in reflection profiling of underlying substrates for oil and gas. These devices generate and direct huge impact noises into the ocean substrate. Offshore oil and gas exploration generally occurs along the continental margins; however, air gun activity in these areas propagates into the deep ocean and is a significant component of low frequency noise (Hildebrand 2005). Peak source levels of air guns typically are 250-255 dB. Following the exploration stage, drilling, coring, and dredging are performed during extraction which also generates loud noises. Energetic high frequency acoustic telemetry is also associated with positioning, locating, steering, and remotely operated vessel control to support extraction operations (Stocker 2002).

Other inshore industrial and construction activities contribute to the aquatic soundscape. Pile driving activities, which typically occur at frequencies below 1000 Hz, have led to mortality in fish (Hastings and Popper 2005). Intensity levels of pile driving have been measured up to 193 dB in certain studies (Hastings and Popper 2005). Refer to the chapter on Coastal Development for additional information on the effects of pile driving.

Underwater blasting with explosives is used for a number of purposes in coastal waters. Blasting is typically used for dredging new navigation channels in areas containing large boulders and ledges; 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 mortality to fish from underwater explosives has been well-documented (Hubbs and Rechnitzer 1952; Teleki and Chamberlain 1978; Linton et al. 1985; and Keevin et al. 1999). Generally, aquatic organisms that possess air cavities (e.g., lungs, swim bladders) are more susceptible to underwater blasts than are those without. In addition, 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 1982). However, early fish larvae tend to be less sensitive to blasts than are eggs or post-larval fish, probably because the larval stages do not yet possess air bladders (Wright 1982). Impacts to fishery habitat from underwater explosives may include sedimentation and turbidity in the water column and benthos and the release of contaminants (e.g., ammonia) in the water column with the use of certain types of explosives.

Sonar systems are used for a wide variety of civilian and military operations. Active sonar systems send acoustic energy into the water column and receive reflected and scattered energy. Sonar systems can be classified into low (<1 kHz), mid (1-20 kHz), and high frequency (>20 kHz). Most vessels have sonar systems for navigation, depth sounding, and "fish finding." Some commercial fishing boats also deploy various acoustic aversion devices (pingers) to keep dolphins, seals, and turtles from running afoul of the nets (Stocker 2002). There is little information on sonar and acoustic aversion devices on fish.

LITERATURE CITED SECTION VII.

Case Study: Human Sound Interference with Biological Sound Production, Spawning Habitat, Spawning Activity: The example below was taken from East Florida bio-acoustic research focused on in situ recordings of underwater sounds in native environments isolating specific fish spawning sites for long term monitoring and continuous acoustic assessment (**refs.**). This included long term deployment of hydrophones in freshwater tributaries, estuaries, continental shelf reef formations.

Single Freighter Engine/Propellar Noise Impact on Subtropical Reef Community: This case presentation reveals an example of vessel interference with biological sounds on a mid-continental shelf reef off East Florida where fishery species are known to spawn: groupers (Gag, *Mycteroperca microlepis*, Scamp, *M. phenax* and Red Grouper, *Epinephelus morio*; Black Sea Bass, *Centropristis striatus*, and various snappers, Red, *Lutjanus campechanus*, Mutton, *L. analis* and Lane, *L. synagris*. All these species use acoustic signals during mating events (**ref Rountree, Mann, Koenig…others**). The location is a rock reef formation known locally as Horseshoe Reef, **27º 35' 00" N., 80º 10' 00" W**. Three passive acoustic recording units (PAMS) constructed by NASA were deployed by the United Space Alliance 9 July 2004 for a period of 72 hrs continuously recording all sounds between 10 and 20,000 Hz.

Figure 2. Spectral curves for diurnal ambient reef sounds produced on Horseshoe Reef (black curve) are compared to nocturnal biological sounds produced by an unidentified organism, “knockers” whose pulses center around 1,000 Hz, and
fish calls (grouper/snapper) below 300 Hz (blue curve) with an approaching freighter 30 min away (purple curve), and same vessel nearby (red curve). Note that the greatest anthropogenic interference is below 600 Hz.

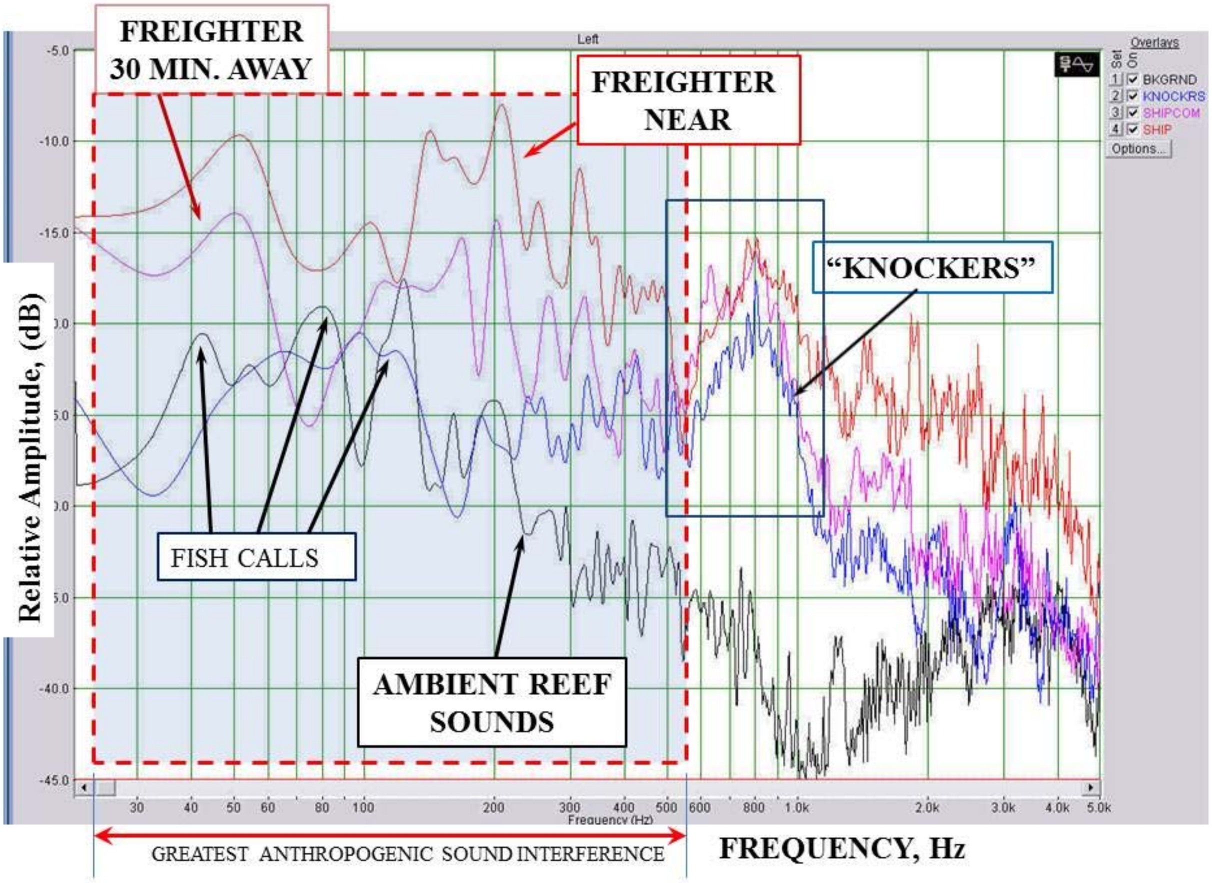
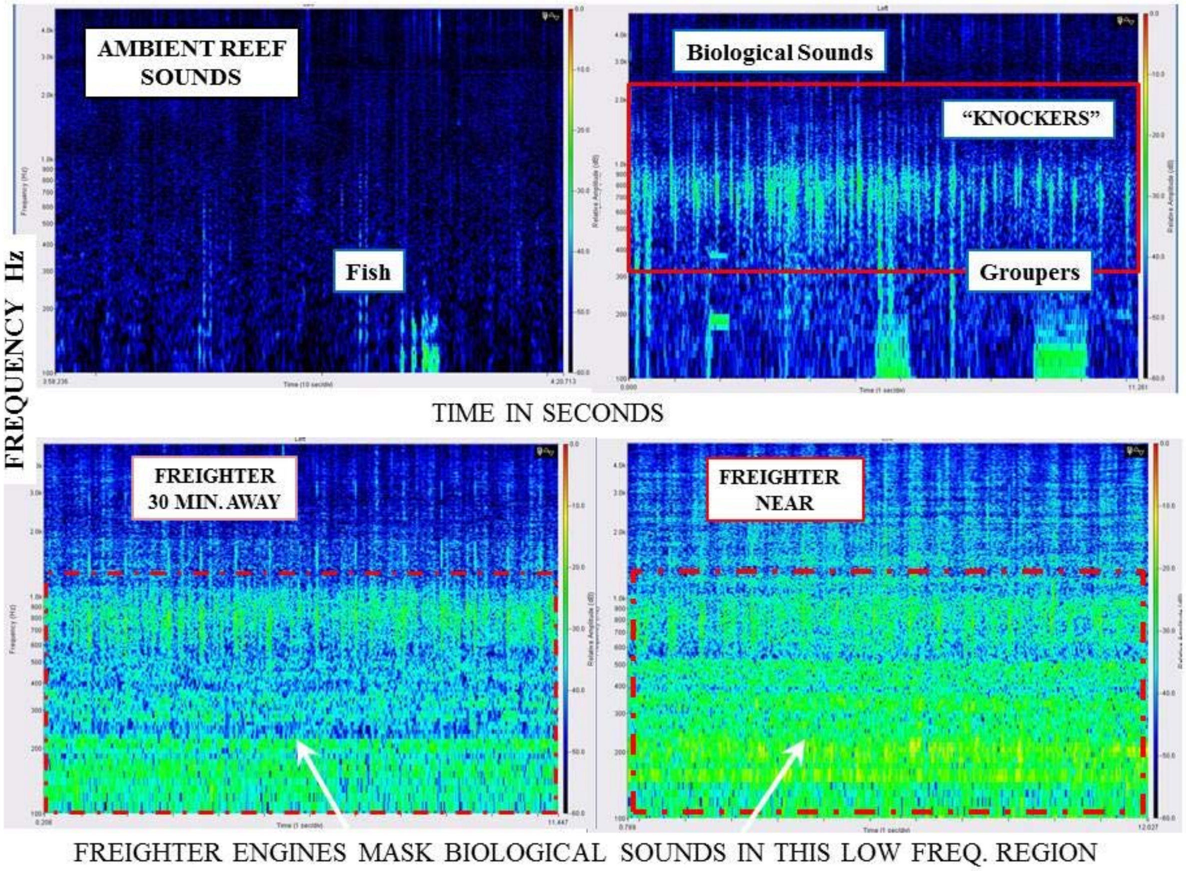


Figure 3. Horseshoe Reef sonogram depicting the same acoustic signals presented in Figure 2. revealing the greatest anthropogenic interference is from highly energetic sounds, engine and propellar noise below 600 Hz.



Data Gaps and Research Needs

There is little long term data on the effect of chronic anthropogenic sounds from vessel, boat and wind generators on the behavior of invertebrates and fish, particularly at spawning sites. This is of critical importance as it impacts periodic spawning events that are proving to be those periods when biological acoustic behaviors are most important. Most fishes studied to date produce sounds in association with intra-specific communication, and most during crepuscular and nocturnal courting and spawning events. This would likely be the most pervasive and influential impact of aquatic anthropogenic sounds.

New and unique acoustic recording systems that could be deployed by manned deep sea submarines and scuba divers were developed for this work (Gilmore et al. 2004; SFWMD.FOS work). Permanent estuarine acoustic recording stations were also maintained that could be monitored remotely via the Internet (Gilmore 2006, 2007, 2008). In addition, employed personnel and volunteers maintained nocturnal acoustic transects from 15 to 50 km in length along the entire length of the Indian River Lagoon at various times from 1978 to present producing thousands of hours of underwater recordings that include human produced sounds from water craft, ships, submarines, divers, dredges, auto traffic over bridges and explosions (bridge detonation) (Gilmore 1994, 1996, 2003,…ADD MIT symposium proceedings, Rountree et al. Fisheries reference). The following case study presents a clear example of intense anthropogenic sound production associated with regional shipping activities in a crowded shipping lane, the Florida Straits.

Long term observatories deployed at spawning sites where significant human activities occurs is necessary to determine mitigation measures.
LITERATURE SECTION VI.

Mitigation

There are several potential measures that could be implemented to mitigate these human impacts, particularly from vessel and boat traffic. The internal combustion engine and classical propeller have been used to propel ships and boats for over one hundred years. There are new technologies available to make vessel much quieter and less acoustically intrusive. This has been a goal of the navies of the world for half a century. It is time to adopt these same technologies for recreation and commercial shipping. Electric powered vessels are in use today. So are hydrophoils.

Critical fish spawning and aggregation sites can be mapped and made off limits (no motor zones) to vessels at night when spawning chorus events occur most often. These sites can be remotely monitored with technologies in use today. Violating vessels can be identified and tracked by their diagnostic acoustic signature.
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