ABSTRACT

IMPACT OF VESSEL NOISE ON OYSTER TOADFISH (*OPSANUS TAU*) BEHAVIOR

AND

IMPLICATIONS FOR UNDERWATER NOISE MANAGEMENT

By

Cecilia S. Krahforst

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Major Department: Coastal Resources Management

ABSTRACT

Underwater noise and its impacts on marine life are growing management concerns. This dissertation considers both the ecological and social concerns of underwater noise, using the oyster toadfish (*Opsanus tau*) as a model species. Oyster toadfish call for mates using a boatwhistle sound, but increased ambient noise levels from vessels or other anthropogenic activities are likely to influence the ability of males to find mates. If increased ambient noise levels reduce fish fitness then underwater noise can impact socially valued ecosystem services (e.g. fisheries).

The following ecological objectives of the impacts of underwater noise on oyster toadfish were investigated: (1) to determine how noise influences male calling behavior; (2) to assess how areas of high vessel activity ("noisy") and low vessel activity ("quiet") influence habitat utilization (fish standard length and occupancy rate); and (3) to discover if fitness (number of clutches and number of embryos per clutch) is lower in "noisy" compared with "quiet" sites. Field experiments were executed in "noisy" and "quiet" areas. Recorded calls by males in response to playback

sounds (vessel, predator, and snapping shrimp sounds) and egg deposition by females (“noisy” vs. “quiet” sites) demonstrated that oyster toadfish are impacted by underwater noise. First, males decreased their call rates and called louder in response to increased ambient noise levels. Second, oyster toadfish selected nesting sites in areas with little or no inboard motorboat activity. Third, male oyster toadfish at “noisy” sites either had no egg clutches on their shelters or the number of embryos per clutch was significantly lower than in the “quiet” areas. Underwater noise and disturbance from vessels are influencing the fitness of the oyster toadfish.

The social significance of the growing concerns regarding underwater noise was investigated by identifying dominant themes found within two types of texts: four recent underwater noise management strategy papers and 14 texts from the federal enabling legislation. To uncover themes that might reveal underlying cultural patterns and values, word frequency of key terms in each set of documents was compared using a correspondence analysis and network analyses. The predominant theme within the noise management documents was "assessing the acoustic impacts and protecting marine life [esp. marine mammals]." The legislative documents spanned a range of concerns but focused primarily on themes associated with the trade-offs between human use and the environment, such as resource "conservation" and "development." In terms of marine life, the enabling federal legislation used “fish” and the noise management documents focused on “marine mammals” as their primary animal of concern. This disparity between document types explained the paucity of ecosystem services that were discussed in the noise management documents because fish and fisheries provide important ecosystem services to the human population. By focusing more on the concept of fish, the noise management documents would be more effective at incorporating ecosystem services, which is likely to be more socially accepted than the current management initiatives.

IMPACT OF VESSEL NOISE ON OYSTER TOADFISH (*OPSANUS TAU*) BEHAVIOR

AND

IMPLICATIONS FOR UNDERWATER NOISE MANAGEMENT

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By

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DEDICATION

This work is dedicated to those who never stopped believing in me.

Especially:

Dr. Roger A. Rulifson

&

My Family & Friends

Words cannot express my thanks.

The future belongs to those who believe in the beauty of their dreams.

-Eleanor Roosevelt

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There are many people that I need to thank for their assistance through this process. These individuals include my committee members, ECU faculty and staff, research support received from institutions outside of ECU, undergraduate assistants, volunteers, family, friends, and funding sources for this work. Your support and assistance made this work possible.

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am in your debt for your encouragement to read outside of my discipline and to look beyond ecology and into the area of physiology to help answer some of my questions. Thank you so much for your unwavering support and encouragement.

My social science committee members served such different roles but yet, they both worked to open my eyes to something new, social science, a concept that I have struggled with from the start of this dissertation. Dr. David K. Loomis worked hard at finding ways to identify with my biological mindset. All of the papers and books would never have changed my mind but your willingness to sit and chat with me helped to move me to better understand social values and their role(s) in management. I will never forget our discussions nor the coy way that you would drop a social term (procedural justice, distributive justice, norms, etc) into the conversation. These types of remarks, slowly helped me to understand the value of these concepts in everyday life, and thus their value to management. Without your persistence and patience, I do not think I would have made the connection. Dr. Jeffrey C. Johnson was an important member of my work from the start. When others told me that my work was not valuable you very pointedly disagreed with them, giving me hope that others would come to value my interests. As I was writing my proposal, you offered many dynamic points of view that led me to explore other areas of interest. At the end, it was so much fun to put our worlds together in a network analysis. Our conversations on the concept were enlightening and helped me to better understand the value of the data we had explored. Thank you for your encouragement, your advice, your guidance, and your willingness to stand-up for me when others argued against my work.

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protected and utilized in the environment. I realize now just how in-touch Dr. King was about the direction of management. When I started the CRM program, underwater noise problems were just beginning to be acknowledged. He told me back then to just wait, that the field of bioacoustics was soon to become important within the social framework. He couldn't have been more accurate because in 2016 there was a management initiative written to address the concerns of underwater noise. Thank you, Dr. King, for your encouragement and excitement about the work I had yet to start. Second, I really appreciate Dr. Hans Vogelsong for his support and assistance. When funding was difficult for me to conduct my initial dissertation research, Dr. Vogelsong came up with funding for me to execute the work. Because of his support, I was able to obtain preliminary data that we were able to use to get a grant. He also was extremely supportive of me and knew when to step in and offer his encouragement and support. Thank you, Dr. Vogelsong, for being there for me, as a director and a friend. Finally, Dr. Siddhartha Mitra has been a person I have been able to lean on for support and advice. I know that I can talk to Dr. Mitra about anything and during times of turmoil, and his snippets of advice gave me relief from anxiety and hope that things would improve. In the best of times, he was one of the first to offer his congratulations. In the worst of times, he was present and available to offer advice. Dr. Mitra, thank you for being present and attentive during each step of the way. Thank all of you for your guidance, support, and assistance throughout the process of completing the dissertation.

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"Volunteers don't get paid, not because they're worthless, but because they're priceless."

-Sherry Anderson

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LIST OF ABBREVIATIONS AND SYMBOLS

α...…………………………………………………………………...Attenuation factor for a sound

Δ…………………………………………………………………………………Difference

$p^2{}_{av}$………………………………………………………………………...Mean square pressure

$\bar{X}$…..……………………………………………………………………………Mean/average

acs……………………………………………………………………………………Acoustic

act…………………………………………………………………………...Active/activity

AFCA……………………………………………………...Anadromous Fish Conservation Act

After…………………………………………...The 10 min recording after a playback ended

ANOVA…………………………………………………………………Analysis of variance

AUP…………………………………………………………………..Animal Use Protocol

Before…………………………………………..The 10 min recording before a playback began

Both……………………Both low frequency bottlenose dolphin and inboard motorboat playback

cns…………………………………………………………………..Conserve/conservation

cst……………………………………………………………………………………..Coast

csv…………………………………………………………Comma separated values text file

CWA…………………………………………………………………………...Clean Water Act

CZMA…………………………………………………………..Coastal Zone Management Act

df…………………………………………………………………………Degrees of freedom

d…………………………………………………………………………...……Day(s)

Dim1……………………………………..Dimension 1 generated from a correspondence analysis

Dim2……………………………………..Dimension 2 generated from a correspondence analysis

During…………………..The 10 min recording during which a playback was played in the water dvl…………………………………………………………………...Develop/development

ECU………………………………………………………………East Carolina University

EBM…………………………………………………………..Ecosystem-based management

EPA………………………………………………………………Estuary Protection Act

ESA……………………………………………………………….Endangered Species Act

f…………………………………………………………………..Frequency/frequencies

F………………………………………………………F-statistic generated from an ANOVA

FABULS…………………………………………..Fish acoustic buoy underwater logging system

FFT…………………………………………………………………..Fast Fourier Transform

fsh…………………………………………………………………………………Fish

FWCA………………………………………………………...Fish and Wildlife Coordination Act

GPS……………………………………………………………….Global Positioning System

h……………………………………………………………………………………Hour(s)

HFDolphin…………………………………………..High frequency bottlenose dolphin playback

imp……………………………………………………………………………………..Impact

Inboard…………………………………………………………..Inboard motorboat playback

JBS………………………………………………………………………Jarrett Bay Site

kts………………………………………………………………...…Speed of a vessel in knots

LARS……………………………………………………Long-term Acoustic Recorder System

LFDolphin………………………………………...Low frequency bottlenose dolphin playback

L_s……………………………………...…..Sound source pressure level at a known distance

lnd……………………………………………………………………………………..Land

mmm……………………………………………………………………………Mammal

MMPA……………………………………………………………Marine Mammal Protection Act

mng………………………………………………………………………..Manage/management

MPAs……………………………………………………………………...Marine Protected Areas

mrn……………………………………………………………………………………..Marine

MSA…………………………….Magnuson-Stevens Fishery Conservation and Management Act

N…………………………………………………………………………..Number/amount

NEPA………………………………………………………National Environmental Policy Act

NERRS…………………………………………………..National Estuarine Research Reserves

NMM………………………………………………………………North Middle Marsh Site

NOAA………National Ocean and Atmospheric Administration published Gedamke et al. (2016)

nos………………………………………………………………………………………….Noise

NPR……………………………………………………………………….Newport River Site

NSF…………………………………………………………………..National Science Foundation

OA………………………………………………………………………………...Oceans Act

OCSLA……………………………………………………...Outer Continental Shelf Lands Act

Outboard…………………………………………………………Outboard motorboat playback

ρ…………………………………………………………………….Pearson correlation measure

p………………………………………….The p-value or the assessment of statistical significance

p_0……………………………………...………………Reference pressure (in this document 1 μPa)

p_{rms}…………………………………...………………Root mean square sound pressure level

$p_{rms}(r)$…….…………….…………………… Root mean square sound pressure level at a known distance

p_s…………...........…….Root mean square sound pressure level at r_0 (in this document, r_0 = 1 m)

pbl……...……………………………………………………………………………… Public pln……...………………………………………………………………………………Plan

prj……...……………………………………………………………………………….Project

PSD……...……………..…………………………………………………Power Spectral Density

QI……...……………………………………………………...………………………Quadrant I

QII……...……………………………………………………...……………………Quadrant II

QIII……...……………………………………………………...…………………...Quadrant III

QIV……...……………………………………………………...…………………..Quadrant IV

R……...……………………………………………………...……………R Statistical Software

r_0………………The reference pressure at the measurement distance (in this document $r_0 = 1$ m)

r…...………...…………………………………...……………..Distance from sound source (m)

RMS………..………………………………………………………. Root Mean Square Pressure

rsr……...……………………………………………………...………………………..Resource

S04……...……………………………………………………...………………..Southall (2004)

S09……...……………………………………………………...…………..Southall et al. (2009)

SA……...……………………………………………………...………………………….Sikes Act

SCUBA……...……………………………………Self-contained underwater breathing apparatus

SE……...……………………………………………………...…………………..Standard error

SEL……………………………………………………………………Sound Exposure Level

shp……...……………………………………………………...…………………………….Ship

Shrimp……...…………………………………………………..Snapping shrimp playback

SMM……...……………………………………………………...……South Middle Marsh Site

snd……...……………………………………………………...…………………………..Sound

SONAR……...…………………………………………….Sound Navigation and Ranging

SPLs……...………………………………………………………...……….Sound Pressure Levels

src……...……………………………………………………...…………………………..Source

TL….……………………………………….Transmission loss of the acoustic signal in dB re 1 μPa

t……...…………………………………………...The t-statistic generated from a Student *t*-test

vss……...……………………………………………………...…………………………..Vessel

WAAS……...…………………………………………………...Wide Area Augmentation System

WCPSA……...…………...………………………………Whale Conservation and Protection Act

WRDA……...……………………………………………………Water Resources Development Act

Wright……...……………………………………………………...……………...Wright (2014)

CHAPTER 1 INTRODUCTION TO THE IMPACT OF NOISE ON MARINE LIFE

Abstract

This chapter addresses the ecological and the social theories associated with underwater noise management. Boats cause noise that disrupts fish and other marine life. Because the noise of vessels often overlaps in frequency and is of higher amplitude than courtship calls of fish, vessels are likely to cause reduced fitness. In turn, this can influence ecosystem services like fisheries. When addressing the ecological theories, concepts such as communication theory, animal behavior, and alterations to the underwater noise environment are discussed. Further, I discuss the value of the oyster toadfish (*Opsanus tau*) as a model species, explaining why it was selected for the biological portion of this dissertation research. Social theories addressed in this chapter, include an assessment of the value of user knowledge and the benefit of incorporating broad scale perspectives in underwater noise management initiatives.

The Ecological Problem

The sensory systems of aquatic animals are highly adapted to their underwater environment. Under the right conditions, where other senses are less reliable, these animals can use sound signals to communicate and to sense their environment (for review see Stocker 2002). These acoustic signals may travel long distances (Urick 1983, Ellison et al. 1999, Frankel et al. 2002) but this depends on the charactersitics of the propagation environment, which is complicated and depends on the specific characteristics of a site.

Sound travels four and a half times faster in saltwater than in air (Urick 1983), but the speed of sound varies with temperature, pressure, and water depth. At mid-latitudes in deep water, the speed of sound decreases with depth until the sound reaches the velocity minimum (where speed of sound is slowest), which causes the water to act as a type of sound lens. Above and below this velocity minimum, sound is constantly bent back toward the channel, leading to decreased transmission loss of acoustic energy. In this channel, called the sofar (sound fixing and ranging) channel, sound can travel very long distances (Payne and Webb 1971, Urick 1983), which is useful for marine life. For example, a 20-Hz finback whale (*Balaenoptera physalus*) call can be audible over 1000 km or more in the right conditions, but this distance decreases to 280 km in light shipping traffic in the same sound propagation conditions (Payne and Webb 1971). In comparison, shallow waters (< 2 m) act like a high-pass filter where low frequency sounds (< 4 kHz) are filtered out of the sound field (Forrest et al. 1993). The cutoff frequency, or the frequency at which sounds cannot propagate through the water, is related to the sound wavelength and the water depth (m). In an environment with a rigid (i.e. sandy) bottom, the longest sound wavelength that can propagate is four times the water depth (Kinsler et al. 1982). In a more diffuse bottom type (i.e. mud), the longest wavelength that can propagate is two times the water depth (Gilbert and Zagar 1990). For a water depth of 1 m, effective sound propagation will range between 375 and 750 Hz, depending on the bottom type. So, the low-frequency sounds (< 1000 Hz) of marine life in very shallow water, are expected to propagate only a short distance from the sound source. For example, the courtship calls of a freshwater goby (*Padogobius martensii*) have a peak frequency of 100 Hz and thus a wavelength of 14.4 m. In a rocky freshwater environment that was less than 50 cm deep, the absorption coefficient of this call ranged between 60 and 90 dB/m (Lugli and Fine 2003). In comparison, a 250 Hz courtship boatwhistle sound (6 m wavelength) of an oyster toadfish (*Opsanus tau*) in 1 m water depth in a silty-sandy bottom, had an absorption coefficient of 3 to 9 dB/m. This courtship call was lost completely to the ambient environment by 5 m from the sound source (Fine and Lenhardt 1983). These studies, while in very different environments, demonstrate the importance of water depth and the wavelength of a sound source for effective sound transmission in very shallow waters.

To exploit underwater sounds, aquatic animals have evolved highly specialized mechanisms for both emitting and detecting sound (for review see Stocker 2002). They often produce, discern, and utilize sound for various life functions, including short- and long-range communication, orientation, predator-prey detection, aggressive displays, foraging, locating mates, and navigation (e.g. Au and Green 2000, Luczkovich et al. 2000, Luczkovich et al. 2002; for reviews see Clark 1990, Luczkovich et al. 2010). These mechanisms are important in sorting a variety of acoustic information to identify the pertinent sounds (e.g. predators and mates) within the soundscape.

Underwater there are three types of background sounds: biological/animal inputs ("biophony), non-biological natural sounds, like wind and rain ("geophony"), and man-made sounds ("anthropopophony," Götz et al. 2009). Anthropopophony is actually a source or noise that is defined as unwanted sounds that exceed a threshold, after which there are negative impacts on the behavior and physiology of organisms (for review see Götz et al. 2009). Additionally, noises (Figure 1.1) generally have a random waveform and contain energy across a broad range of frequencies (broadband, Urick 1983). Humans generate noise through underwater explosions, ship noise, seismic exploration, inshore and offshore construction, sound navigation and ranging (SONAR), acoustic deterrent/harassment devices, and other industrialized activities (for reviews see Urick 1983, Götz et al. 2009). These noises range from the low-frequency (< 1 kHz) sounds of shipping noise (e.g. Hatch et al. 2008) to the high-frequency sounds of SONAR (up to several hundred kHz, Götz et al. 2009) and have the potential to be loud (up to ~ 250 dB re 1 µPa, Nedwell et al. 2007, Abate 2010).

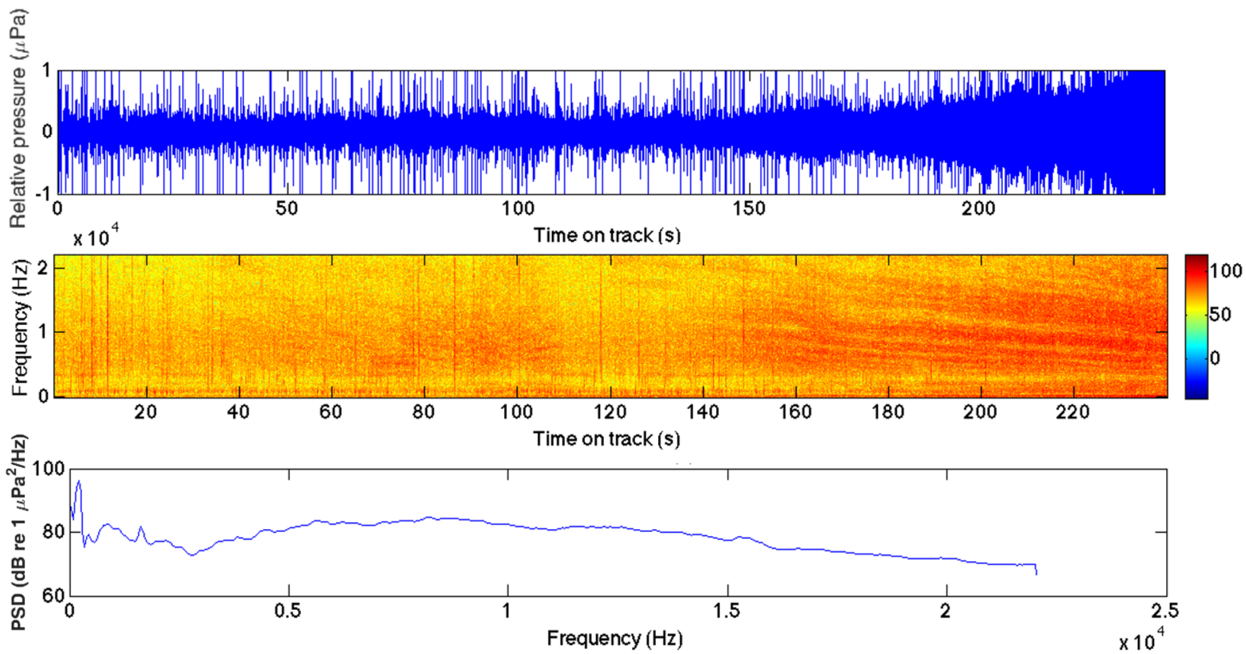

Figure 1.1. Recording of an inboard motorboat.

An example of the soundscape with an inboard (trawler) as it passed by the playback experiment that was set up in the field. This recording was made on August 20, 2013 at 01:45 AM the Newport River Site in NC. Top: Oscillogram of the sound of a trawler passing the site, demonstrating the variation in relative pressure as the vessel approaches the hydrophone. Middle: A spectrogram demonstrating the power and frequency of the soundscape as it varied in time. This spectrogram was created using an FFT of 1024 with a 512 point Hanning window (50% overlap). The hotter (red) the color, the higher the power (dB re 1 μPa) of the noise component in the soundscape. Bottom: A power spectral density curve, where the curve's peak demonstrates the fundamental frequency of the vessel noise.

A concern arises when anthropogenic sounds overlap (in space, frequency, and time) and exceed the sound pressure level (SPL) values (the difference between the pressures produced by a sound wave and the ambient pressure level at the same point in space measured over a specified time) of the ambient environment, thereby masking calls of marine life (for reviews, see Götz et al. 2009, Slabbekoorn et al. 2010). Masking is defined as a noise that is strong enough to reduce the detectability of biologically relevant sounds (Frisk et al. 2003), resulting in a dramatic reduction in the distance over which an animal can acoustically communicate and receive signals (for reviews see Frisk et al. 2003, Janik 2005, Götz et al. 2009). Masking of communication signals can cause behavioral disturbances (e.g. Engås et al. 1995, Nowacek et al. 2007, Parks et al. 2007; Sarà et al. 2007), hearing loss (Erbe and Farmer 1998, Scholik and Yan 2001; Ramcharitar and Popper 2004, Nowacek et al. 2007), and even death (for review see Götz et al. 2009). Richardson et al. (1995) devised theoretical zones of influence (Figure 1.2) to show the potential impacts of noise on animals. The largest zone of influence is detection, where animals can hear the noise, but the noise does not interfere with the animal's behavior and its ability to communicate. The smallest zone, which his nearest to the sound source, has SPL values that are expected to cause death. With an increased distance away from the sound source, the impacts from noise are expected to be less damaging, with masking as the final zone of influence expected to cause negative responses from organisms.

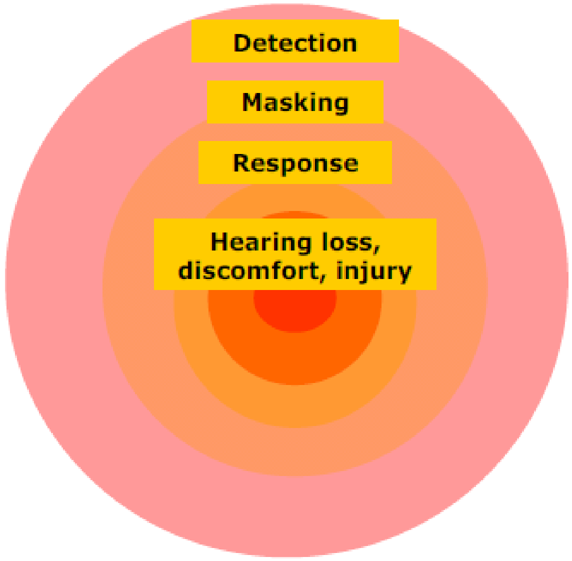

Figure 1.2. Theoretical zones of anthropogenic noise disturbance on marine life.

Theoretical zones of anthropogenic noise influence and the likely impact of the noise on marine animals (reprinted from: Richardson et al. 1995, see Appendix I for the copyright request). These zones can range from a few to several thousand kilometers from a sound source. Distances for each zone are highly dependent upon the sound type, frequency of the sound source, sound source pressure level, the distance between the receiver and the sound source, and the hearing ability/sensitivity of the receiver.

Many marine animals like fishes, invertebrates, and marine mammals can both produce and hear sounds, but within limited frequency ranges. Most fishes that produce sound emit signals at frequencies below 1 kHz (Figure 1.3) at SPL values that average around 123 dB re 1 µPa (Figure 1.4, e.g Luczkovich et al. 1999, Sprague and Luczkovich 2004, Vasconcelos et al. 2007, Locascio and Mann 2008, Parsons et al. 2009, Nelson et al. 2011, Parsons et al. 2013) but SPL values can reach higher levels (132 – 172 dB, Saucier and Baltz 1993, Luczkovich et al. 1999, Mok et al. 2009, Parsons et al. 2012), especially if fish are producing sound simultaneously in large aggregations. In addition, all fishes that have been tested can hear sounds. Some can only detect sounds at frequencies less than 1 kHz (Fish and Mowbray 1970, Popper et al. 2003, Ladich and Fine 2006, Ladich and Myrberg 2006), while others perceive additional sounds at frequencies above 3 kHz (Ross et al. 1995, Mann et al. 1997, Mann et al. 1998, Luczkovich et al. 2000). Even some crustaceans, cephalopods, and sea turtles are known to detect low-frequency sounds (O'Hara and Wilcox, 1990, Packard et al. 1990, Bartol et al.1999). Some marine invertebrates even produce high amplitude sounds. For example, snapping shrimp produce sounds greater than 180 dB re 1 μPa (Figure 1.4, Au and Banks 1998, Ferguson and Cleary 2001). Marine mammals also produce high amplitude signals that often exceed 170 dB re 1 μPa (Figure 1.4, e.g. Au 1993, Frankel 1994, Møhl et al. 2000, McDonald et al. 2001, Madsen et al. 2005, Parks and Tyack 2005, Zimmer et al. 2005), but also tend to utilize a wider range of frequencies (10 Hz – 100 kHz or greater, Figure 1.3) as compared to other marine animals. Therefore, it is likely that anthropogenic sounds will interfere most with the sounds of fishes over that of marine mammals and invertebrates because fishes are less likely to adapt to increased ambient noise levels in their environment.

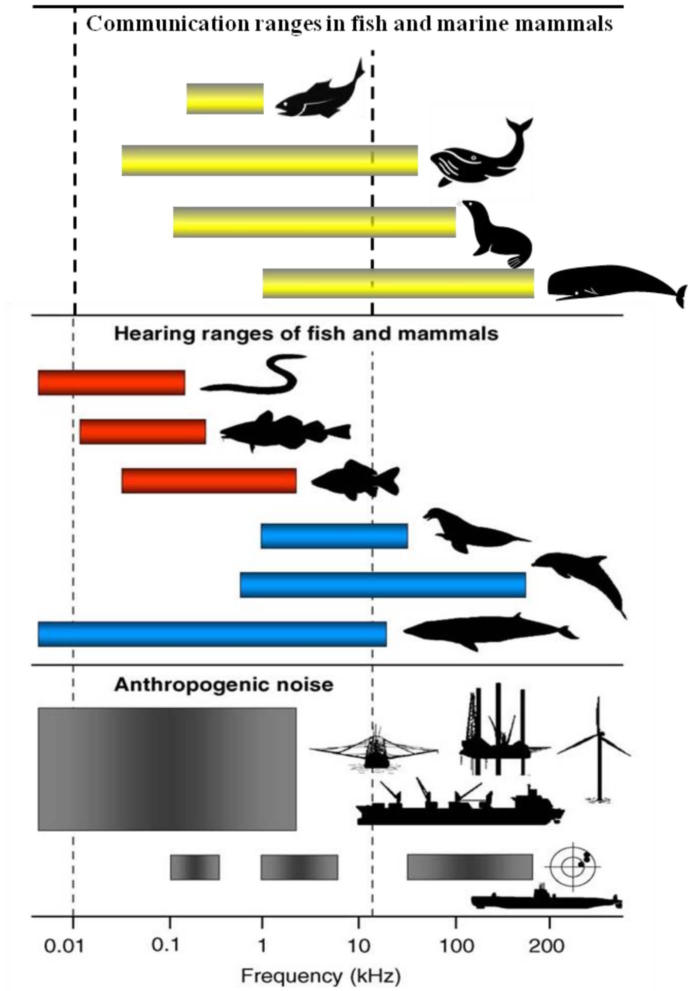

Figure 1.3. Frequency ranges among marine mammal acoustic communication and hearing as well as anthropogenic noise.

Typical frequency bands of sound production and hearing in marine mammals and fishes and the typical frequency bands of anthropogenic sounds. The dashed lines represent the typical hearing range of humans in air (modified from Götz et al. 2009, Slabbekoorn et al. 2010, see Appendix I for the copyright request).

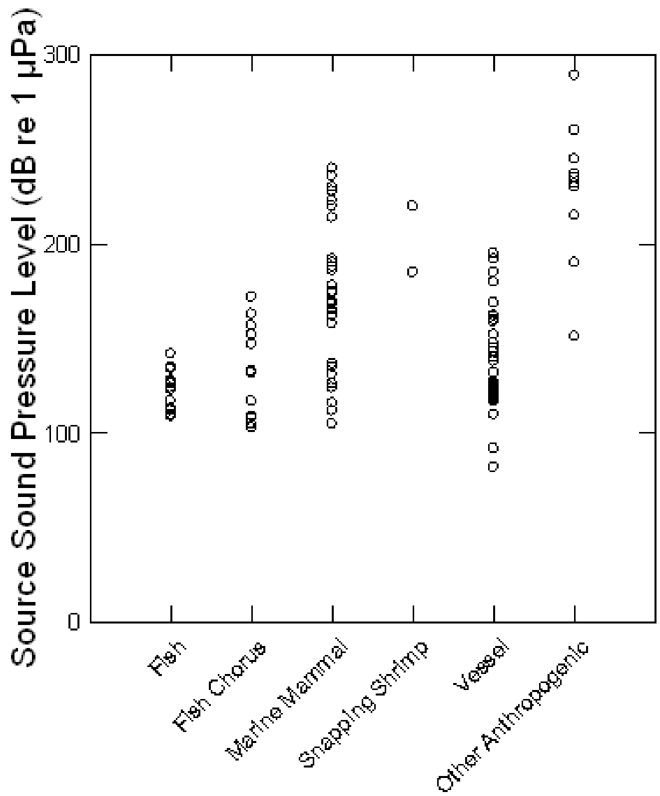

Figure 1.4. Underwater sound pressure level values (dB re 1 µPa) of various marine life and human-generated sounds.

Literature reported SPL values of marine animals and anthropogenic sounds (Data from: Cummings et al. 1968, Cummings and Thompson 1971, Thompson et al. 1986, Au 1993, Saucier and Baltz 1993, Frankel 1994, McDonald et al. 1995, Au and Banks 1998, Engås 1998, Au et al. 1999, Luczkovich et al. 1999, Arveson and Vendittis 2000, Au and Green 2000, Møhl et al. 2000, Ferguson and Clearly 2001, McDonald et al. 2001, Sprague and Luczkovich 2001, Erbe 2002, Madsen et al. 2002, Frisk et al. 2003, Møhl et al. 2003, Sprague and Luczkovich 2004, Madsen et al. 2005, Parks and Tyack 2005, Zimmer et al. 2005, Miller 2006, Maruska et al. 2007, Locascio and Mann 2008, Codarin et al. 2009, Hildebrand 2009, Maruska and Tricas 2009, Mok et al. 2009, Parsons et al. 2009, Picciulin et al. 2010, Nelson et al. 2011, McKenna et al. 2012, Parsons et al. 2012, Rowell et al. 2012, Parsons et al. 2013).

Since the 1970s, there has been concern that anthropogenic noise may be adversely affecting marine life (Payne and Webb, 1971, Richardson et al. 1995). Noise is energy that spreads long distances and can pass international boundary zones. As pollution is defined,

> *"…the introduction by man, directly or indirectly, of substances or energy into the maritime area, which results, or is likely to result, in hazards to human health, harm to living resources and marine ecosystems, damage to amenities or interference with other legitimate uses of the sea,"* (Götz et al. 2009),

anthropogenic noise is considered a pollution source (Götz et al. 2009). One significant contributor to underwater noise, especially in the lower frequency range (< 1000 Hz), is marine vessel traffic. Vessels produce noise from propeller cavitation, onboard machinery, and turbulence around the hull. The SPL values of the noise produced by a vessel are variable and the frequency of the noise is highly dependent upon the type, size, speed, and other operational characteristics of the individual vessel (Richardson et al. 1995, Hildebrand 2009). Generally, larger vessels produce lower frequency sounds. The lower the frequency of sound, the longer distance the sound travels (Arveson and Vendittis 2000) when the wavelength of the sound is not constrained by depth. Sound frequencies from vessel traffic are generally broadband signals that range between 10 Hz and 1 kHz (Figure 1.3) but small vessels (≤ 50 m) often produce peak frequencies slightly above 1 kHz (Arveson and Vendittis 2000). Measured SPL values for vessels have a broad range (Figure 1.4), from a trawler producing 82 dB re 1 μPa in water with a 300 m depth (Engås 1998) to 195 dB re 1 μPa for a cargo vessel traveling in water of an unspecified depth (Hildebrand 2009). Larger vessels contribute to higher SPL values than smaller vessels (e.g. Arveson and Vendittis 2000, Au and Green, 2000, Erbe, 2002, Frisk et al. 2003, Vasconcelos et al. 2007, Tyack 2008). The concern with vessel noise, especially with vessels ≤ 100 m length, is that they are often confined to coastal and continental shelf waters and their operations often overlap with marine animal distributions. Vessel noise can mask marine mammal and fish communication signals (for review see Götz et al. 2009). For fishes, vessel noise has the potential to mask all of the frequencies at which they produce sounds (Figure 1.3) and hear acoustic signals (for reviews see Götz et al. 2009, Slabbekoorn et al. 2010). Vessel noise that masks fish sound is of great concern, as expressed by (Götz et al. 2009):

> *"[vessel noise]…is potentially the greatest concern for species that produce low-frequency sounds…"*

Vessel noise may cause disturbance to many commercially important fishes, like catfishes (Ictaluridae), codfish (Gadidae), the drum fishes (Sciaenidae), grunts (Haemulidae), groupers (Serranidae), and snappers (Lutjanidae, Götz et al. 2009). While marine mammals also communicate within the same frequency range as shipping noise (Figure 1.3), they also use sounds outside of this range. However, vessel noise can still mask signals of marine mammals (e.g. Van Parijs and Corkeron 2001, Erbe 2002, Haviland-Howell et al. 2007) and fishes (e.g. Vasconcelos et al. 2007). Vessels disrupt the mating and reproductive activities as shown in freshwater turtles (*Graptemys* spp., Moore and Seigel 2006, Bulté et al. 2010) and fishes (Mueller 1980, Picciulin et al. 2010). Vessels also interfere with foraging behavior in marine mammals (Blane and Jaakson, 1994; Papale et al. 2012). Finally, vessel noise has been shown to mask environmental cues such as a predator sound in fishes (Luczkovich et al. 2000; Luczkovich and Sprague 2008).

There are five communication alteration categories used by animals to compensate for increased ambient noise levels. These are the Lombard effect (Lombard 1911, increased call amplitude), altered call rates, call frequency shifts, and increased call duration and/or repetition rate (Ulanovsky et al. 2004). Some marine animals have adapted to increased ambient noise levels by using increased call amplitude (Lombard effect). The Lombard effect has been demonstrated in a few marine mammals species (e.g. Scheifele et al. 2005, Holt et al. 2009, Miksis-Olds and Tyack 2009, Parks et al. 2011) and in two fish species (Holt and Johnston 2014, Luczkovich et al. 2016). Another acoustic adaptation by animals to increased ambient noise levels is increased call rates as demonstrated in some marine mammals (Asselin et al. 1993, Lesage et al. 1999) but not presently shown in fishes. Increased call duration and increased repetition rates (Miller et al. 2000) have been observed in the humpback whale (*Megaptera novaeangliae*) but not in fishes. Frequency shifts in response to increased ambient noise are evident in marine mammals (e.g. Au et al. 1985, Lesage et al. 1999, Morisaka et al. 2005, Parkset al. 2007) but not documented in fishes. One study on male oyster toadfish calls found no frequency alteration to its signal (Luczkovich et al. 2016). Finally, decreased call rates for the duration of the increased ambient noise levels and even after the noise subsides has been demonstrated in marine mammals (e.g. Finley et al. 1990, Lesage et al. 1999, Parks et al. 2007, Azzara et al. 2013) and the oyster toadfish (Krahforst et al. 2016). So far, research has demonstrated that marine mammals (often several species) have the ability to alter their calls in each of the five communication alteration categories. However, only a few marine fishes have been tested and demonstrate the ability to modify their acoustic calls, but in only two of the communication categories (decreased call rates and the Lombard effect).

Fishes have a less flexible mode of both sending and receiving acoustic signals as compared with marine mammals and other animal sound producers, making fishes less able to adapt. Research has shown that sound exposure to shipping noise raises cortisol levels in fishes (Wysocki et al. 2006), causes auditory masking (Scholik and Yan 2001, 2002, Vasconcelos et al. 2007), and increases heart rates (Graham and Cooke 2008) in fishes. Vasconcelos et al. (2007) explored the effects of ferry noise (~ 131 dB re 1 μPa at 20 m or ~ 143 re 1 μPa at 1 m) on the communication signals of the Lusitanian toadfish (*Halobatrachus didactylus*) under controlled laboratory conditions. Vessel noise (~ 131 dB re 1 μPa) did mask the ability of the Lusitanian toadfish to detect conspecific communication signals. They found a threshold shift of up to 36 dB at a hearing frequency of 50 Hz. This means that a 50-Hz signal needs to be up to 36 dB louder than the ambient noise level to be detected by Lusitanian toadfish at the same distance from the sound source when under the masking effects of a ferry boat. Observational studies (Engås et al. 1995, 1998, Sarà et al. 2007) also suggest that vessels alter fish behavior (e.g. swimming speeds and direction). Small boats can even influence nesting behavior in fishes, resulting in decreased embryo survival (Mueller 1980, Picciulin et al. 2010). These studies, however, were based on field observations and researchers were unable to determine whether these behavioral modifications were due to the presence of the vessel, operating conditions, and/or vessel noise.

Ultimately, our understanding of how noise impacts fishes and other marine animals is limited, making our ability to define mitigation measures difficult (Götz et al. 2009). Estimates have indicated that underwater anthropogenic noises are doubling each decade (Andrew et al. 2002, McDonald et al. 2006, McDonald et al. 2008) and some researchers and managers are concerned that these sounds are reducing fitness levels, changing behaviors, and, in extreme cases, causing injury and/or death to endangered species (Götz et al. 2009). This concern over increasing noise levels has resulted in the recommendation of the preparation of a "noise budget," which identifies known sound sources and their contribution to the total noise in a particular area of the ocean (Frisk et al. 2003). It is also imperative to define the zones of noise influence (Figure 1.2). Both a noise budget and the zones of influence require knowledge on sound propagation and transmission loss (degradation of noise level values across an environment) in the specific environment, as well as auditory thresholds, hearing mechanisms, and hearing frequency range for the animals of concern, and an understanding of how noise influences animal behavior (Thomsen et al. 2006, Götz et al. 2009). To date, there is limited research in all of the subject areas because each one is specific to the environment and the species/individual.

Model Species: Toadfish

Researchers have speculated that underwater noise can impact fish communication, habitat choice, and reproduction (Götz et al. 2009) but definitive proof is lacking and experimental procedures are difficult because 1) fishes often produce pelagic eggs, 2) they are highly mobile in space and time, and 3) sound propagation is complex in the field, making the results of lab experiments suspect. One species that is likely to reduce the difficulty of an experimental procedure to address the above questions is the oyster toadfish (*Opsanus tau*). The oyster toadfish range is along the mid-Atlantic coast from Massachusetts through Florida and its breeding season varies by location. On the Atlantic coast, breeding males have been observed from May through August (Gill 1907, Gudger 1910, Fish 1954, Gray and Winn 1961, Able and Fahay 2010). While the oyster toadfish is not a particularly valued by humans, it serves a very important role in the ecosystem.

Crabs (especially mud – Xanthidae, blue – *Callinectes sapidus,* and stone crabs – *Menippe mercenaria*) are important predators of juvenile oysters *Crassostrea virginica* on an oyster reef (Menzel and Hopkins 1956, Menzel and Nichy 1958, Bisker and Castagna 1987, Abbe and Breitburg 1992). Another important predator occurring on oyster reefs is the oyster toadfish (*Opsanus tau*), which preys upon mud crabs (*Panopeus herbstii* and *Eurypanopeus depressus*, Wilson et al. 1982, Gibbons and Castagna 1985). Thus, a trophic cascade involving predation at three trophic levels (oyster toadfish → mud crab → juvenile oysters) can occur. Grabowski (2004) conducted mesocosm experiments to explore the interaction among these species and found that in the presence of oyster toadfish, oyster consumption by mud crabs decreased by 86.5%. However, oyster toadfish did not significantly increase mud crab mortality when compared to a reef without oyster toadfish present. These results suggest an indirect behavioral effect occurred during this study, in which oyster toadfish reduced mud crab predation on oysters by simply being present within an oyster reef. Similar results were observed for the interaction among juvenile clams, mud crabs, and oyster toadfish (Bisker and Castagna 1987, Grabowski and Kimbro 2005). These studies suggest that mud crab foraging behavior is controlled by oyster toadfish through indirect behavioral avoidance interactions (Grabowski 2004, Grabowski and Kimbro 2005, Grabowski et al. 2008). If the mud crab population levels are not controlled by oyster toadfish, oysters are likely to decline from increased predation by mud crabs, which can reduce water clarity and lead to ecosystem-level impacts.

At a higher trophic level, bottlenose dolphin (*Tursiops truncatus*) are known predators of toadfishes (*Opsanus* spp.) and other soniferous (sound-producing) species. Gannon et al. (2005) demonstrated that bottlenose dolphin listen for soniferous fishes. McCabe et al. (2010) found that for bottlenose dolphins, sound-producing fishes composed 51.9% of their diets, whereas soniferous fishes made up only 6.3% of the available prey species in the environment. Furthermore, the Gulf toadfish (*Opsanus beta*) was the most abundant species in the stomachs of the surveyed bottlenose dolphins (McCabe et al. 2010). Other work further enhances the argument that bottlenose dolphins prey on toadfish (*Opsanus* spp.). Oyster toadfish have been found in the stomachs of stranded oceanic and estuarine bottlenose dolphins (Pate and Mcfee 2012). Additionally, fecal samples have been collected from live bottlenose dolphin and analyzed at the molecular level to determine prey species (Dunshea et al. 2013). These samples were compared to the diets (stomach contents) of stranded bottlenose dolphins. Toadfish (*Opsanus* spp.) were the second largest prey item in both the stomach and fecal sample analyses. These studies indicate that toadfish species (*Opsanus* spp.) are a preferred prey item for bottlenose dolphins.

Toadfish species even listen for the sounds of bottlenose dolphin. Remage-Healey et al. (2006) demonstrated that the Gulf toadfish reduced its calling rate by 50% when exposed to bottlenose dolphin sounds, as compared to snapping shrimp sounds. This suggests that toadfish (*Opsanus* spp.) are actually listening for and modifying their acoustic communication behavior in the presence of bottlenose dolphin sounds (pops and whistles, see Remage-Healey et al. 2006 for a detailed description of these acoustic signatures). If vessel noise masks these predator signals in the wild, it could lead to more efficient bottlenose dolphin hunting strategies and thus declines in desired prey species like toadfish (*Opsanus* spp.). Alternatively, vessel noise could mask the hearing of bottlenose dolphins and thus their predation on toadfishes (*Opsanus* spp.) could decline. However, Fine and Lenhardt (1983) found that the oyster toadfish's boatwhistle call is undetectable at distance less than 5 m from the fish when it is calling from a depth of 1 m. This finding indicates that any "passively listening" predator (e.g. Gannon et al. 2005) or conspecific in very shallow water (1 m) must be in the area close to the calling oyster toadfish to locate and respond to the fish making the call.

A behavior that some fishes might have evolved in response to the biosonar signals of marine mammals is the use of seagrass habitat as an acoustic refuge. The "acoustic refuge hypothesis" (for review see Wilson et al. 2013) suggests that seagrasses absorb and scatter an acoustic signal. Using high frequency (100 – 500 kHz) echosounders, McCarthy and Sabol (2000) demonstrated that seagrasses made it more difficult to detect underwater mines (self-contained explosive device) than sediment without seagrass. A second study, demonstrated up to an 88% reduction in sound propagation at low-frequencies (300-500 Hz) compared with sandy/bare type bottoms (Wilson et al. 2013). Additionally, research has shown that bottlenose dolphins echolocate less in seagrass when compared with sand habitats (Nowacek 2005). The author hypothesizes that this is due to seagrass cluttering the acoustic signal of the bottlenose dolphin. Essentially, the echoes from the seagrass and the associated epiphytes distort the bottlenose dolphin acoustic signal, making the signal more difficult to interpret (Nowacek 2005). Other research has demonstrated that bottlenose dolphin preferably hunt in navigation channels over seagrass beds (Allen et al. 2001). The authors suggest that seagrass is both a visual and an acoustic refuge for prey species. Seagrass blades baffle the signal of a fish sound, causing it to attenuate faster than would occur in sand (Wilson et al. 2013). Along this same line, seagrasses diffuse the echolocation signals of bottlenose dolphins, making it more difficult for them to acoustically hunt. Finally, seagrass offers prey species structure in which to hide, making it more difficult for bottlenose dolphins to forage visually in seagrass meadows compared with sand habitat (Allen et al. 2001). Taken together, these studies suggest that seagrass is likely to act as an acoustic and visual refuge for fishes from a predator. This evolved anti-predator response may evoke a similar reaction in fishes exposed to anthropogenic noises (like vessel noise). The result could be that soniferous fishes residing in seagrass habitat will be less impacted by noise than the fishes residing in sand habitats.

The concept of an acoustic refuge for soniferous fishes from anthropogenic underwater noise may be further expressed in terms of distance from busy navigational channels. Habitats near the navigation channel (in seagrass or not) are likely to be exposed to higher SPL values from the passage of a vessel than habitats far from the navigation channel. Sound pressures from the sound source are attenuated with distance due to spreading loss (Urick 1983). The experimental design used in the studies presented here (distance from a sound source, where the sound source is vessel noise in a navigation channel) is based on an acoustic propagation loss model developed for use in shallow water with boundary layers (water surface and substrate boundaries), which is called the cylindrical spreading model (Urick, 1983):

$$TL = 10 \log_{10} r, \tag{1.1}$$

where *TL* is transmission loss of the acoustic signal in dB re 1 μPa and *r* is the radius from the sound source (in m). In this model, the bottom and the water's surface create boundary layers through which the sound cannot transmit. As a result, sounds are reflected back toward the water column resulting in lower attenuation compared with the spherical spreading model (Figure 1.5). Cylindrical spreading is expected when the radius of propagation is greater than the water depth (Urick 1983). The spherical spreading model was not used in this study because it is best describes sound pressure spreading in deep water (i.e. where the radius of propagation is less than the water depth). In this type of environment, sound propagates without boundaries layers. The result is increased attenuation in comparison to the cylindrical spreading model (Figure 1.5). The spherical spreading model uses the following equation (Urick, 1983):

$$TL = 20 \log_{10} r, \tag{1.2}$$

where *r* and *TL* are the same as described in equation 1.1. The spherical spreading model assumes that sound radiates from a source equally in all directions (free field). As the sound spreads out spherically from the source, the sound attenuates more rapidly than it does in the cylindrical spreading model (Urick, 1983). The cylindrical spreading model was selected for this study because the shelters were in a water depth of ~ 1 m and the distance of propagation was 35 m. The distance of 35 m represents the space from the navigation channel's edge to the shelters furthest from the channel. Therefore in these studies, the range of acoustic propagation is greater than the water depth, which better fits the parameters of the cylindrical spreading model. Based on the cylindrical spreading model, a propagation loss of at least 15 dB is expected at 35 m from the navigation channel (Figure 1.5) from a vessel passing at the edge of the channel that is closest to the shelters.

In the cylindrical spreading model the root-mean-square (RMS) pressure (the square root of the average square values of the amplitude over an interval of time) is inversely proportional to the square-root of the source radius ($\sqrt{r}$). The result is that the SPL value received by the oyster toadfish declines with distance from the sound source. In these studies the sound source (vessel) occurs somewhere within the navigational channel. The cylindrical spreading model predicts a decrease of SPL by 10 dB for every 10-fold increase in the sound source radius. Following Sprague and Luczkovich (2004), who relied on the cylindrical spreading model of Urick (1983) to model sound attenuation of silver perch *Bairdiella chrysoura* calls, transmission losses at the oyster toadfish shelters near and far from the navigation channel were estimated using several equations. First, the equation for sound pressure level (dB re 1 μPa) is:

$$SPL = 20\ \log_{10} \frac{p_{rms}}{p_0}, \tag{1.3}$$

where p_{rms} is the root mean square (RMS) pressure measured at a known distance from the sound source and p_0 is the is the reference pressure (1 μPa for underwater measurements). Next, p_{rms} at radius r under the cylindrical spreading model is calculated using the following equation:

$$p_{rms}(\mathrm{r}) = \sqrt{r_0}\ \left(\frac{p_s}{\sqrt{r}}\right), \tag{1.4}$$

where r is the radius from the sound source, r_0 is the reference pressure at the measurement distance (here r_0 = 1 m), p_s is the RMS pressure measured at r_0 from the sound source, and p_{rms} (r) is the RMS pressure measured at known distance r.

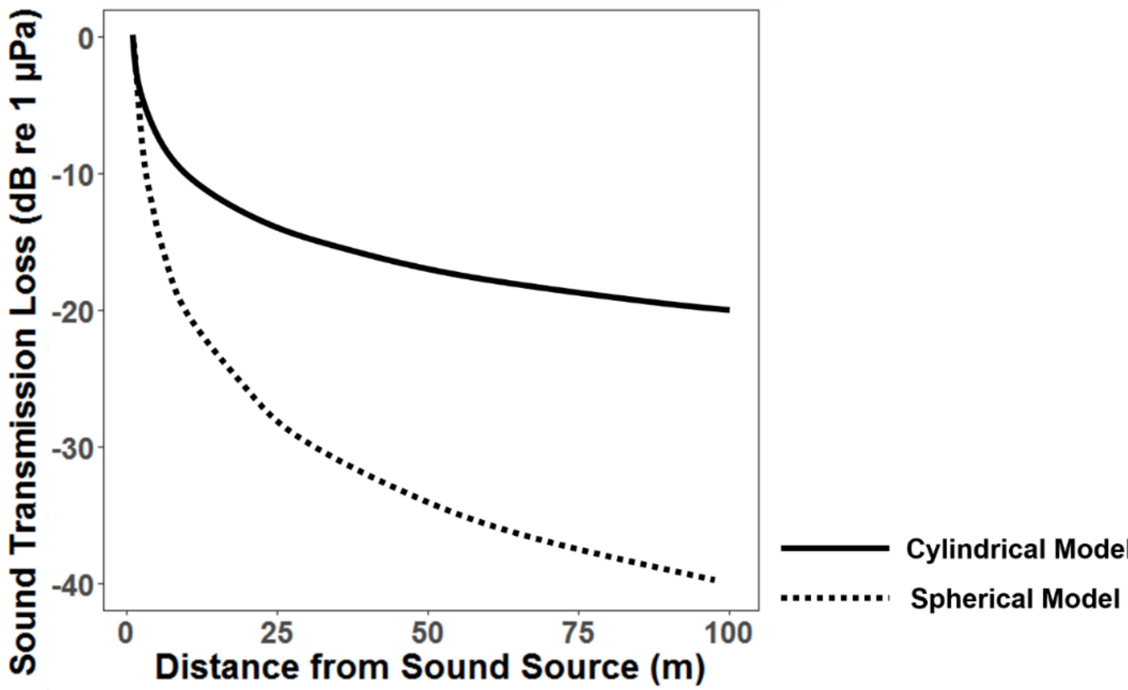

Figure 1.5. Cylindrical and spherical spreading models demonstrated the modeled sound transmission loss (dB re 1 µPa) with increased distance from the sound source (m).

Modeled transmission loss (dB re 1 µPa) values for the cylindrical and spherical spreading models.

Another related aspect of wave propagation in the conditions within this work, is that of a surface wave, where a wave is guided by two mediums (Wenz 1962). In these shallow water systems, a surface wave sets up between the surface of the water and the bottom sediment. However, some of the energy is transferred into the sediment, where grains move around but are not lifted off of the bottom. These grains tend to move parallel along with the acoustic wave (Bagnold 1946). Also important is the acoustic properties of the sediment itself. Sediments with trapped gas bubbles (e.g. mud) have different acoustical properties than those with less bubble trapping (e.g. sand). The bubbles within the sediment vibrate at their own resonant frequency (vibration frequency), becoming less effective at reflecting acoustic energy. This results in a higher attenuation of sound, especially at low frequencies, in mud versus sand sediment types (Anderson and Hampton 1980). For example, an 8 kHz signal has an attenuation value of 1750 dB/m in mud (Wood and Weston 1964). However, attenuation is proportional to the frequency of a sound source so for sounds less than 1000 Hz, we would expect that attenuation would be much lower. Regardless of the frequency of sound, sounds of vessels in sandy bottoms are likely to propagate further in sand than the sound from vessels moving over muddy bottoms. Because my two “noisy” sites (Newport River, NPR and North Middle Marsh, NMM) had sandy bottoms and my two “quiet” sites (South Middle Marsh, SMM and Jarrett Bay Site, JBS) had muddy bottoms, it is likely that sound waves moving through the sediment from passing vessels were attenuated to a greater degree in the “quiet” sites than in the “noisy” sites.

Recent research at the study sites demonstrated that near the edge of navigation channels, the attenuation of a signal produced by passing vessels can exceed that of the cylindrical spreading models (Figure 1.6, Sprague et al. 2016). These authors observed peak received SPL values measured at a shallow-water location (~ 1 m) of 124 - 132 dB re 1 µPa for various vessels (inboard, outboard, and a tugboat) passing within 100 - 400 m of the shallow-water recording hydrophone. They did not have source levels of the passing vessels but estimated spreading losses from changes in the received SPL values as the source vessels moved away from the hydrophone. Sound propagation in this strongly sloping environment, is not easy to model but the authors hypothesized that the excess attenuation of sound is likely associated with a steep upward slope from the dredged navigation channel to the shallow shelf (Figure 1.7), which contained bare sand or mud, seagrass beds, and marshes within each of the sites.

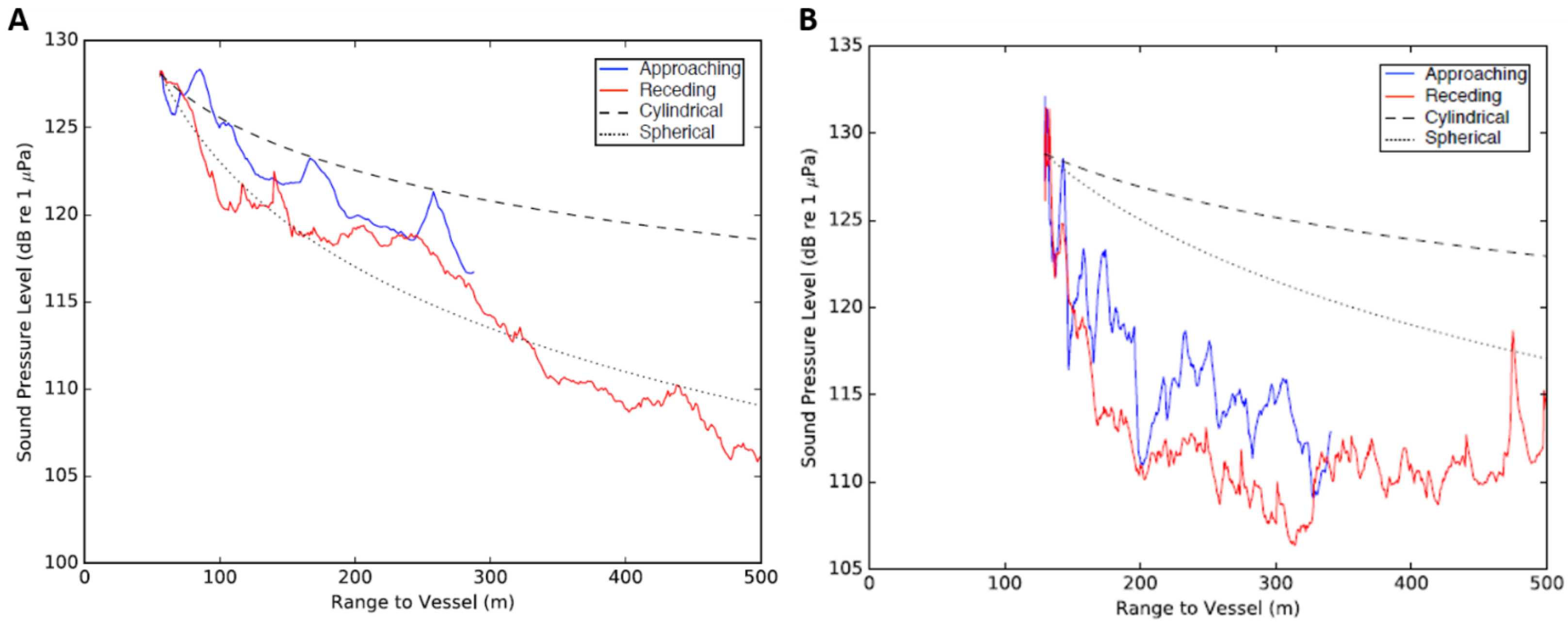

Figure 1.6. Sound pressure levels of vessels in the field at the NPR site.

The time-weighted average sound pressure level (SPL) of the recordings of A) an inboard motorboat and B) an outboard motorboat passing in the navigation channel in the area of the oyster toadfish shelters at NPR. Both predicted SPL values from the cylindrical and spherical spreading models are included for reference (reproduced from [Sprague et al. 2016], with the permission from the Acoustical Society of America, see Appendix I for the copyright permission letter).

In the studies presented in this document, oyster toadfish shelters nearer to the edge of a navigation channel are likely to be exposed to higher SPL values than oyster toadfish in shelters further from the navigation channel. In both cases (shelters near and far from the channel), the sound source SPL values from a passing vessel within the navigation channel will be higher than the received SPL values at the shelters in shallow water. As discussed earlier, transmission loss occurs with an increased distance from the sound source but there are other factors that additionally influence signal attenuation. Other sources of signal attenuation include: (1) the bottom type, (2) the slope and depth of the navigation channel, (3) the presence/absence of seagrass and other absorptive and reflective materials on the bottom, and (4) other natural sounds in the environment.

Apart from the ecological importance of toadfishes (*Opsanus* spp.), they are also model organisms for acoustics work (Tavolga 1958, Fish 1972, Winn 1972, Fine and Thorson 2008) and are one of the most well-studied soniferous fishes. They call from nests/shelters for long periods of time in shallow-water territories (Gray and Winn 1961, Barimo and Fine 1998, Thorson and Fine 2002a, 2002b) by contracting intrinsic sonic muscles on their swimbladder (Skoglund 1961, Fine et al. 2001). Oyster toadfish are also individually recognizable by distinctive characteristics around their mouth and eyes (Gray and Winn 1961) as well as by the sounds they produce (Thorson and Fine 2002a, 2002b).

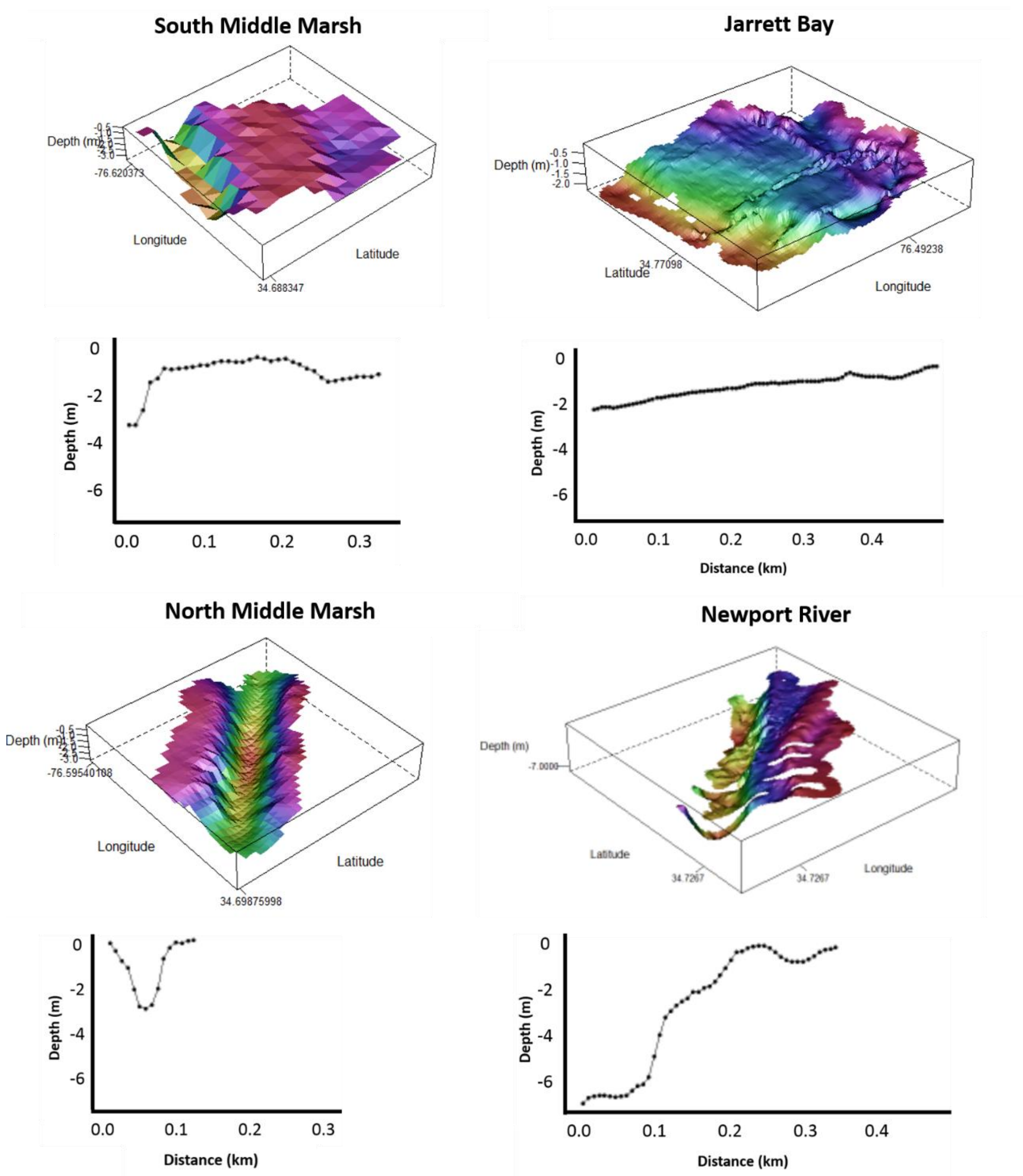

Figure 1.7. Bathymetric maps and a sample transect contour for each of the study sites. Bathymetric contours and sample transect contour for the quiet (top) and noisy (bottom) sites collected using a GPS/SONAR Lowrance HDs7 (200 Hz transducer) system (NMM, JBS, & NPR) or a Biosonics DT-X with a 420 kHz transducer (SMM). The shelters were placed in the shallow areas (pink, with a mean water depth of 1m) and the vessel passed by the shelters in the deep areas (blue, green, and/or yellow) of the navigation channels.

The oyster toadfish reproductive strategy is distinct and useful in acoustics work. When reproductively active males settle in a nest/shelter for up to a month (Gray and Winn 1961, Winn 1972) they create a tonal boatwhistle sound at a ~ 200 to 250 Hz fundamental frequency (Figure 1.8) to attract females (Gudger 1910, Gray and Winn 1961, Fish 1972, Winn 1972). Females then attach benthic eggs to the nest and the males fan and guard the eggs and larvae until they are free swimming (Gray and Winn 1961), which typically occurs around 3 to 4 weeks (Gudger 1910, Gray and Winn 1961). During this time, the male may continue to produce boatwhistles and attract additional females to his nest (Gray and Winn 1961, Mensinger et al. 2003, Mensinger and Tubbs, 2006).

Research has also been conducted on the auditory threshold of the oyster toadfish. It has an upper hearing range of 800 Hz (Fine 1978, Yan et al. 2000) and is most sensitive to sounds below 200 Hz (Fish and Offutt 1972). Recall that low-frequency vessel noise caused an increase in the auditory threshold by up to 36 dB in the Lusitanian toadfish (Vasconcelos et al. 2007), thus auditory threshold shifts are also likely in the oyster toadfish at vessel SPL values of 130 dB re 1 μPa or louder. In a study conducted in Newport River, NC USA, Sprague et al. (2016) demonstrated that the oyster toadfish hearing-weighted sound exposure level, which includes a time unit, from motorboats was 135 dB re $1\mu Pa^2 \cdot s$ for an inboard and 132 dB re $1\mu Pa^2 \cdot s$ for an outboard motorboat. This finding implies that oyster toadfish, like the Lusitanian toadfish, when exposed to vesel noise are likely to experience masking and may modify their behavior to overcome the masking effects of vessel noise, especially with noise occurring at low frequencies (< 1000 Hz).

The sound properties of oyster toadfishes grunts (used during agonistic encounters and alarm, Figure 1.9) and boatwhistles (used for advertisement calls during spawning season, Figure 1.8) have been described (e.g. Fish 1954, Fish 1972, Fine 1978, Fine and Lenhardt 1983, Thorson and

Fine 2002b, Maruska and Mensinger 2009) and are typically below 1 kHz (Fine 1978, Fine and Lenhardt 1983, Mitchell et al. 2008). Grunts of oyster toadfish have been observed in response to explosions and in reaction to other males and unripe females (Gray and Winn 1961) near the shelter. Boatwhistle call rates average 10 calls min^{-1} (Fine et al. 1977) but may increase to 25 calls min^{-1} when the male is in the presence of a ripe female (Fish 1972). Seasonally, the fundamental frequency of the boatwhistle call varies from 115 to 132 Hz (Fine 1978) but is within a 10 Hz range for an individual at a given point in time (Fine and Lenhardt 1983). From my observations in NC, a single oyster toadfish call can range in frequency between 150 and 350 Hz (Figure 1.8) but the average frequency of the dominant frequency of the call is typically between 200 and 250 Hz. Because oyster toadfish are calling in very shallow water and the fundamental frequency of their courtship call is low (Fine and Lenhardt 1983), the high-pass filter characteristics of very shallow water (Forrest et al. 1993) indicate that oyster toadfish courtship calls are not expected to propagate far (~5 m estimated in a water depth of 1 m, Fine and Lenhardt 1983). This suggests that conspecifics need to be close (within ~ 5 m) to the oyster toadfish's shelter to detect the call of a male. Duration of an oyster toadfish's boatwhistle call is the most variable, ranging between 64 and 164 ms (average = 119 ms, Fine and Lenhardt 1983) and is probably the least reliable acoustic characteristic in oyster toadfish calls. While diurnal differences in oyster toadfish calling rates are not defined, I can utilized the information from a similar species in the same genera. During daylight hours, male Gulf toadfish call less frequently when compared to the evening but they have longer calls during the day (Thorson and Fine 2002b). I expect the oyster toadfish to demonstrate the same diurnal variability in calling behavior as the Gulf toadfish.

Toadfish (*Opsansus* spp.) are excellent model organisms to test the impacts of anthropogenic noises on reproductive behavior because toadfish produce courtship sounds, have benthic eggs, and exhibit parental care within their nesting sites during the summer months. Thus, the oyster toadfish can be exposed to noise for extended periods of time without using cages or other confining materials to restrict their movements. If anthropogenic noises are loud enough, I hypothesize that they will mask the calls of male oyster toadfish (Figure 1.10), which will presumably lead to decreased female response and thus unsuccessful reproductive events.

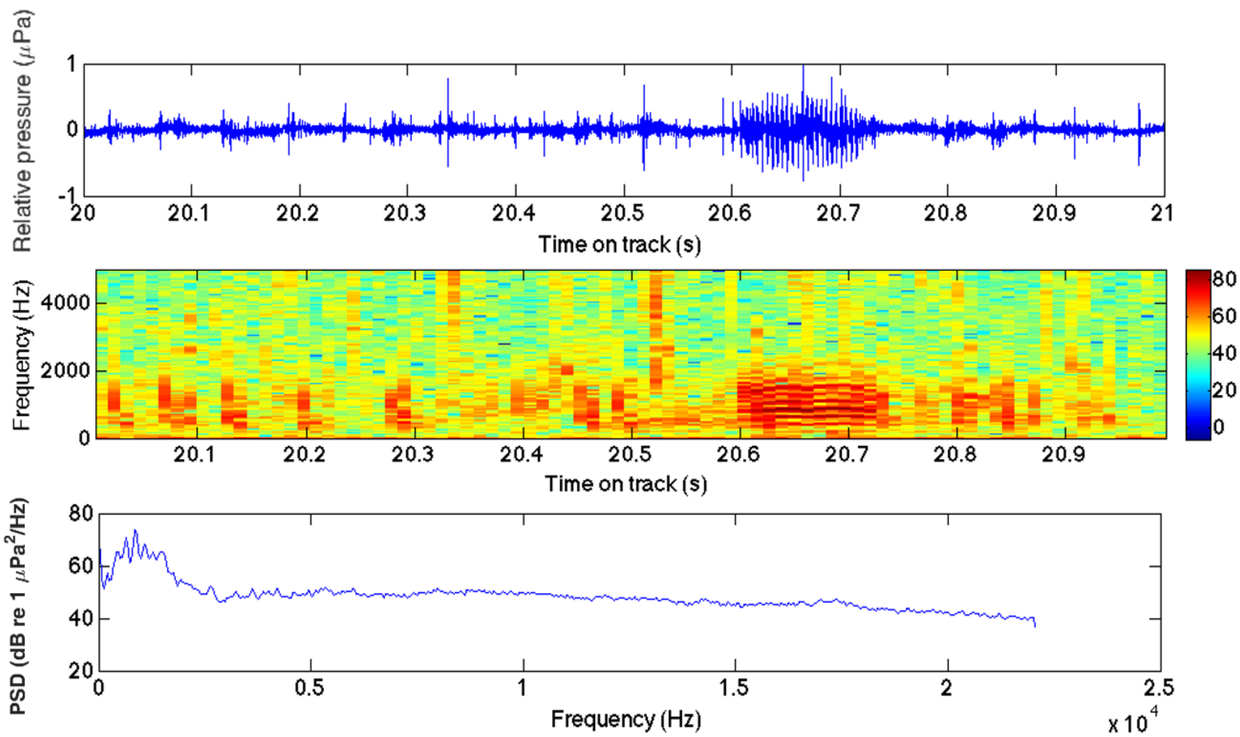

Figure 1.8. Recording of an oyster toadfish boatwhistle call.

An example of the boatwhistle sound from an oyster toadfish, with a fundamental frequency between ~ 200 and 250 Hz. This recording was made on July 25, 2013 at 03:50 AM at the Jarrett Bay Site in NC. Top: Oscillogram of the natural soundscape, demonstrating the variation in relative pressure of the ambient soundscape across time. The oyster toadfish boatwhistle is evident on this oscillogram between 20.6 and 20.75 s. Middle: A spectrogram demonstrating the power and frequency of the signal as it varies through time in the recording. This spectrogram was created using an FFT of 1024 with a 512 point Hanning window (50% overlap). The hotter (red) the color, the higher the power of the sound (in dB re 1 μPa). Bottom: A power spectral density curve, where the peak in this curve demonstrates the fundamental frequency of the boatwhistle sound.

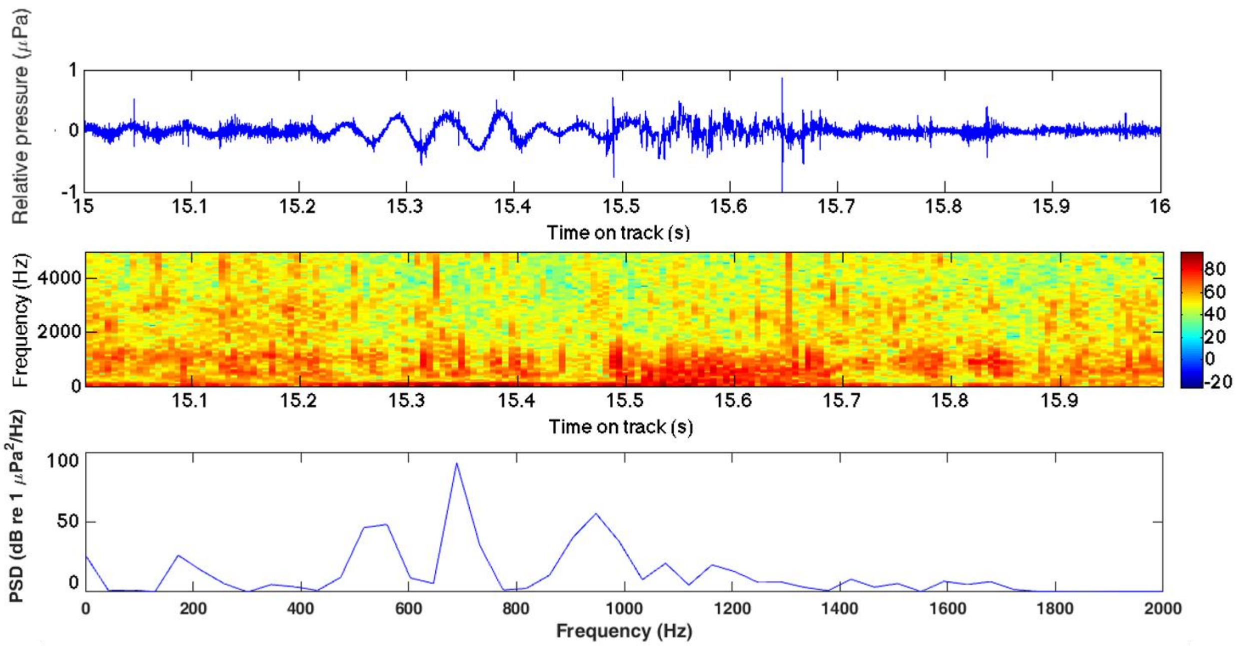

Figure 1.9. Recording of an oyster toadfish grunt call.

An example a grunt sound from an oyster toadfish, with a fundamental frequency of ~ 700 Hz. This recording was made on August 20, 2013 at 01:43 AM the Newport River Site in NC. Top: Oscillogram of the natural soundscape, demonstrating the variation in relative pressure over time. The oyster toadfish grunt call is evident in the oscillogram between 15.5 and 15.7 s. Middle: A spectrogram demonstrating the power and frequency of the signal as it varies in time through the recording. This spectrogram was created using an FFT of 4096 with a 512 point Hanning window (12.5% overlap). The hotter (red) the color, the higher the power of the sound (in dB re 1 μPa). Bottom: A power spectral density curve, where the peak in the curve demonstrates the fundamental frequency of the grunt sound.

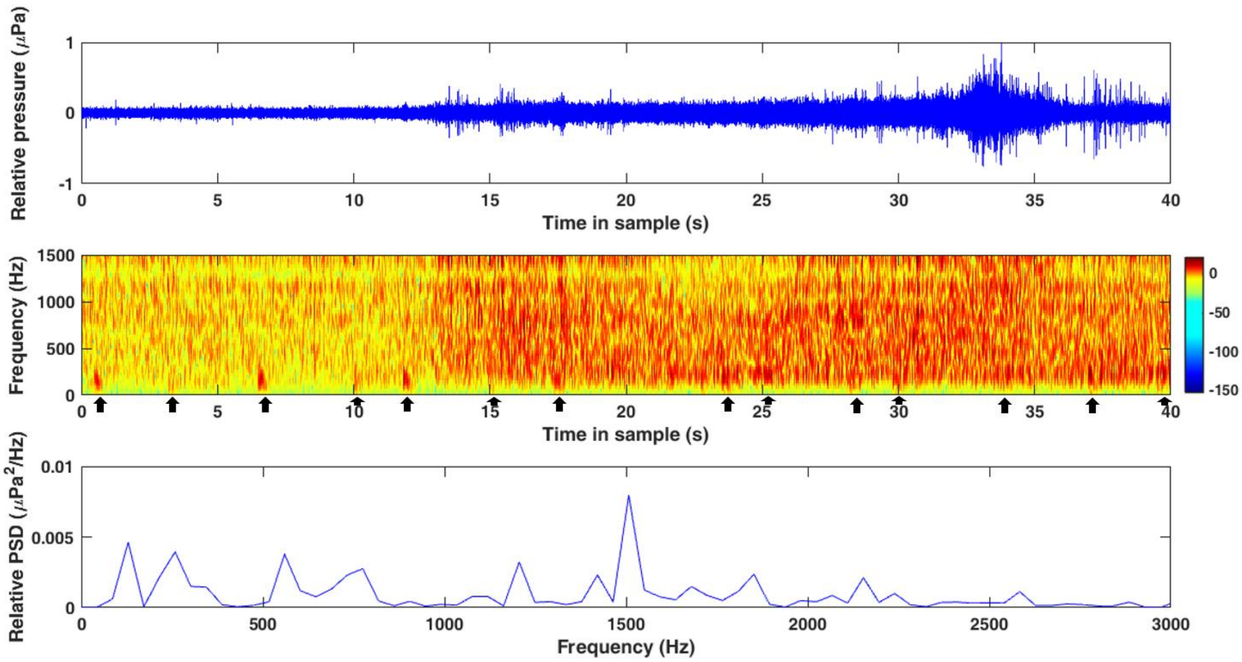

Figure 1.10. Recording of oyster toadfish boatwhistle calls during the passage of a motorboat.

An example of fourteen boatwhistle sounds from oyster toadfish recorded in the field as a vessel approached the hydrophone. This recording was made on April 12, 2014 at 06:57 PM at the Morehead City Port, NC. The boatwhistles occur throughout the recording and are marked with arrows. As the vessel approaches the hydrophone, the sounds of the oyster toadfish are less visually distinguishable from the background noise. Top: Oscillogram of the sounds in the recording, demonstrating the variation in relative pressure throughout the recording. Middle: A spectrogram demonstrating the power and frequency of the signal as it varies throughout the recording time period. This spectrogram was created with an FFT of 1536 with a 512 point Hanning window (33.3% overlap). The hotter (red) the color, the higher the power of the sound but this spectrogram is not calibrated and is thus in relative power (μPa) units. Bottom: The relative power spectral density curve, where the peak in this curve demonstrates the fundamental frequency of the passing vessel (1500 Hz).

Goals and Objectives

The aim of this portion of the dissertation is to better understand the impacts of underwater noise from vessels on oyster toadfish mating calls and reproductive output (number of embryos). The work was executed in the field first using playback experiments to assess how natural sounds (bottlenose dolphin and snapping shrimp) and vessel noise (inboard and outboard) impact communication rates and calling amplitude in the oyster toadfish. Second, a field experiment was executed to determine the impact of vessels and vessel noise on the fitness of the oyster toadfish.

Primary Goal: To test the masking effect of underwater noise on oyster toadfish communication, habitat use, and reproduction.

Experiment 1: Communication by Mating Oyster Toadfish

Objective 1: To determine the effect of vessel noise on oyster toadfish communication.

H_a1.1: Male oyster toadfish exposed to vessel noise will reduce the calling rate of (calls min^{-1}) courtship calls as compared with the pre-exposure calling rate.

Objective 2: To establish the effect of bottlenose dolphin sounds on oyster toadfish communication.

H_a2.1: Male oyster toadfish exposed to bottlenose dolphin sounds will reduce their courtship calling rate (calls min^{-1}) as compared with pre-exposure levels.

Objective 3: To ascertain the effect of snapping shrimp sounds on oyster toadfish communication.

H_o3.1: Male oyster toadfish exposed to snapping shrimps sounds will demonstrate no change in courtship calling rate (calls min^{-1}) as compared with pre-exposure call rates.

Objective 4: To determine if oyster toadfish communication signals, in response to bottlenose dolphin sounds, are altered in the presence of vessel noise.

H_a4.1: Male oyster toadfish exposed to both vessel noise and predator sounds will reduce their courtship calling rates (calls min^{-1}) as compared with the calling rates during the vessel noise stimulus alone.

H_a4.2: Male oyster toadfish exposed to both vessel noise and predator sounds will reduce their courtship calling rates (calls min^{-1}) as compared with the calling rates during the bottlenose dolphin stimulus alone.

Objective 5: To determine if oyster toadfish demonstrate other changes in their communication signals in response all of the playback sounds combined.

H_a5.1: Male oyster toadfish exposed to increased ambient noise levels will increase their courtship calling amplitude (dB, Lombard Effect) when exposed to noise as compared with pre-exposure levels.

H_o5.2: Male oyster toadfish exposed to increased ambient noise levels will not change their courtship calling duration (s) when exposed to noise as compared with pre-exposure levels.

H_o5.3: Male oyster toadfish exposed to increased ambient noise levels will not change their call fundamental frequency (Hz) when exposed to noise as compared with pre-exposure levels.

Experiment 2: Communication by Oyster Toadfish in Different Habitats

Objective 6: To assess the effect vessel noise and bottlenose dolphin sounds on oyster toadfish communication in different habitats (seagrass vs. sand).

H_a6.1: Oyster toadfish, regardless of the sound-exposure treatment, will communicate at higher rates (calls min^{-1}) in seagrass compared to sand habitat.

Experiment 3: Habitat use by Oyster Toadfish

Objective 7: To assess the effect of underwater noise on habitat use by oyster toadfish.

H_o7.1: Oyster toadfish occupancy rate (# fish/shelter) will not differ by the position of the shelter in relation to the navigation channel (near vs. far). Shelters "near" the channel represent "noisy" environments and shelters "far" from the channel represent "quiet" environments.

H_a7.2: Oyster toadfish occupancy rate (# fish/shelter) will be higher in shelters at sites with low vessel activity ("quiet" sites) as compared with sites with high vessel activity ("noisy" sites).

H_o7.3: Oyster toadfish standard lengths (mm) will not differ by the position of the shelter in relation to the navigation channel (near vs. far). Shelters "near" the channel represent "noisy" environments and shelters "far" from the channel represent "quiet" environments.

H_a7.4: Oyster toadfish will be larger (in standard length, mm) at sites with low vessel activity ("quiet" sites) as compared with sites with high vessel activity ("noisy" sites).

Experiment 4: Reproductive Output by the Oyster Toadfish

Objective 8: To examine the effect of underwater noise on oyster toadfish fitness.

H_o8.1: The number of oyster toadfish egg clutches on shelters will not differ by navigation channel position (near vs. far) at sites with low vessel activity.

H_a8.2: There will be more oyster toadfish egg clutches on shelters far from the navigation channel compared with near the channel at the sites with high vessel activity.

H_a8.3: At sites with high vessel activity, there will be fewer oyster toadfish embryos on shelters near compared with far from the navigation channel.

H_o8.4: At sites with low vessel activity, there will be no difference in the number of oyster toadfish embryos by channel position.

H_a8.5: Male oyster toadfish shelters at the sites with high vessel noise will have fewer embryos as compared with sites with low vessel noise.

The Social Problem

Environmental impacts and pollution, such as noise pollution, are a direct consequence of human behavior. Society sets norms, which are rules that guide behaviors, and these norms are applied to environmental issues. They help define the socially unacceptable environmental levels that influence management decisions (Fiske 1992, Cocklin et al. 1998; Smyth et al. 2007). One problem with the issue of underwater noise management is that it is unlikely for people to observe the direct consequences of underwater noise pollution. While humans do understand that noise pollution occurs in air, they often make conscious and unconscious adjustments to their behaviors to avoid the noise (e.g. they speak louder; this is known as the Lombard effect, move away from the sound, alter their talking frequency, and others, Lane and Tranel 1971).

The consequences of noise pollution, especially in fishes, are not as easily identified. In part, this is because noise is a short-lived pollution source that has been shown to impact behavioral movement patterns and habitat use of marine life (for reviews, see Götz et al. 2009, Slabbekoorn et al. 2010). Additionally, human hearing is not adapted for underwater sound detection and localization. While humans can detect and to some extent localize sounds underwater (Hollien 2005), most sounds are often undetected by humans. Even Jacques Cousteau, the inventor of modern day SCUBA diving, termed the ocean "the silent world," (Cousteau, 1956). It is difficult for people to care about noise pollution when it affects a sense that they do not often recognize as important underwater.

It is likely, however, that the users of a resource will be the first to observe the long-term consequences of a pollution source and be motivated to act (e.g. Neis 1992, Ames 1998, Johannes et al. 2000). Behavior can be modified by system relationships, emotions, social relationships, as well as formal and informal institutions (Hunt et al. 2013). Social relationships drive learning through knowledge but where knowledge is a result of the context in which individuals interact in a social setting (Jacobson 1996). In this type of social environment, cognition is dependent upon both the context and the interactive social environment of an individual, which is shaped by emotions (Jacobson 1996). In turn, these cognitions influence preferences, intentions, as well as action (Manfredo 2008), which can be applied to a natural resource setting. Subjective knowledge and cognition can be perceived as components of a mental model that shape an individual's behavior towards a management issue (Biggs et al. 2011, Hunt et al. 2013).

Research on manatees has shown that when people are more knowledgeable about a problem (e.g. motorboats injuring endangered manatees), they are more likely to desire a management action to rectify the issue (Aipanjiguly et al. 2003). This is because environmental attitudes are associated with an individual's self-interest (Sheppard et al. 1988), which is partially shaped through knowledge of the issue (Ferguson and Bargh, 2004). There is a positive relationship between attitude and knowledge (Olson et al. 1984; Armstrong and Impara 1991). For example, Aipanjiguly et al. (2003) demonstrated that people who are knowledgeable about manatee behavior and ecology are more likely to support conservation efforts when compared with people who are less knowledgeable. In this case, knowledge of manatee behavior was positively correlated in people with higher frequency of boat use, reported increased manatee sightings, and displayed higher fishing efforts. Less knowledge about manatee behavior was demonstrated by people engaged in other on-water activities, who reported lower boating use, identified fewer manatee sightings, and demonstrated a lower fishing effort. These data suggest that managerial desired behavioral changes, like boating activities around manatee habitat, are most effective when there is a set of beliefs that are associated with a behavioral norm and thus an understanding of the problem (Aipanjiguly et al. 2003).

The key to ecosystem-based management (EBM) is that human behavior may be transformed if the execution of a behavior is associated with its own benefits, rewards, and incentives within a person's own psycho-social regime (Miller and Dollard 1941). Ecosystem-based management is defined as an ecosystem (or place-based) management initiative that addresses both (1) the connection of ecosystem components and (2) the connections between people and the ecosystem (McLeod and Leslie 2009). Ecosystem-based management strategies require that managers acknowledge both the ecological impacts the required societal trade-offs needed to manage underwater noise. These trade-offs include the exploration of the benefits of environmental use to both individuals and society (Lubchenco and Sutley 2010). Ecosystem-based management includes the concept that the decisions made by managers need to reflect the goals and desires of users (Kelble et al. 2013). Thus, management initiatives must reflect both the natural environment as well as societal values and goals, which can be expressed through ecosystem services (Doren et al. 2009). This EBM strategy aids managers in understanding how society depends on and benefits from a specified ecosystem (Reyers et al. 2009).

Underwater noise management is a complex issue that involves a variety of users including recreationists (e.g. boating, SCUBA diving, whale watching, and fishing), people who use the environment for extracting goods and services (e.g. goods/food), and those who rely upon it for commerce (e.g. commercial fishing, shipping transport, and offshore oil/gas). Potential conflicts and trade-offs are vast when considering the issue of underwater noise management. Management initiatives need to reflect the concerns of as user groups (U.S. Commission on Ocean Policy 2004, Weinstein and Reed 2005). Some relevant environmental considerations include: 1) noise as a pollution source, 2) the interactions between vessels and marine life, 3) habitat protection, and 4) animal health, migration, and reproduction. Alternatively, social issues that need to be addressed that are related to underwater noise management include 1) the preservation of recreational activities, 2) cultural and historical values, 3) economics, and 4) national security. Underwater noise management issues such as wind farm development (e.g. Kempton et al. 2005) and Naval sound navigation and ranging (SONAR, e.g. Abate 2010) are just two examples of recent public involvement in environmental considerations that directly addresses concerns about underwater noise.

Goals and Objectives

As managers try to address this complex issue of underwater noise management, it is important for them to understand their own biases. Understanding these biases will help them devise a more comprehensive management strategy that incorporates the vast array of trade-offs involved in underwater noise management. The hope for these managers is then to create a management plan that addresses the many perspectives of the resource users who deal with and are affected by activities that produce underwater noise. Such a plan is likely to be better accepted by the users. The aim of this section is to conduct a content analysis using two types of documents: (1) underwater noise management documents and (2) relevant legislative documents. The legislation is the law of the land, which is devised by federal and state governments. Managers examine the law and determine how to enforce the law upon the resource users. Management initiatives (or regulations) are directives placed upon and adhered to by resource users. The purpose of the content analyses on these two types of documents is to assess thematic differences using word frequency information. These word frequency data obtained from the two types of documents can be analyzed by statistical procedures (e.g. correspondence analysis and network analysis) to understand thematic similarities and differences across the document types. This content analysis may reveal information about the value orientation of the authors of enabling legislation and the management initiatives. By revealing differences in themes among documents, managers can better assess the trade-offs required of them and their management initiates under EBM.

Objective 9: To identify themes in underwater noise management and relevant legislative documents.

H_a9.1: Word frequency counts from a text analysis reveals thematic differences among management and legislative documents.

H_a9.2: The underwater noise management documents focus on a theme of marine mammal protection and the concept of underwater noise.

H_a9.3: The legislative documents focus on a theme of human use of the environment but also consider the trade-offs between human use and the environment.

H_a9.4: The legislative documents fail to identify underwater noise as a primary theme.

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CHAPTER 2 AN OVERVIEW OF THE IMPACT OF VESSEL NOISE ON OYSTER TOADFISH (*OPSANUS TAU*) ACOUSTIC COMMUNICATION AND REPRODUCTION[1]

Abstract

Increased motorboat use has contributed to increased ambient underwater noise. The noise produced by these vessels may prevent the reception of male oyster toadfish courtship sounds by females. Field playback experiments were executed at two sites in which recordings of vessel noises, predator sounds (bottlenose dolphin *Tursiops truncatus*), and natural sounds (snapping shrimp Alpheidae) were played through an underwater speaker to determine how sound influences calling of male oyster toadfish (*Opsanus tau*). Calling rates declined during sound exposure for all playbacks except outboard motorboat noise and snapping shrimp sounds. Male oyster toadfish increased call sound pressure levels during vessel noise exposure, demonstrating evidence of the Lombard effect, but did not change the duration of their calls. In a second field experiment, I assessed how vessel noise impacts oyster toadfish reproductive output. Shelters were deployed near and far from a navigation channel at four sites: two sites with high vessel noise ("noisy") and two sites with low vessel noise ("quiet"). The shelters at one of the "noisy" sites had no oyster toadfish embryos throughout the spawning season; the other "noisy" site had some embryos, but there were fewer embryos at this site compared with the "quiet" sites. Vessel noise appears to have

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fitness consequences for the oyster toadfish, resulting in lowered reproductive success for males calling at the “noisy” sites with high vessel activity when compared with the reproductive success of males calling at “quiet” sites with low vessel activity.

Introduction

Underwater anthropogenic noise is a growing management concern. Low-frequency (≤ 500 Hz) noise has increased since pre-industrial conditions and is dominated by propeller noise from commercial shipping traffic (Hildebrand 2009). At frequencies less than 300 Hz, there has been at least a 20 dB increase in noise levels since pre-industrial times. This increase in noise is mostly attributed to noise from shipping traffic (Hildebrand 2009). Noise from small outboard motorboat propellers is an important component of the ambient noise levels in the mid-frequency bands (500 Hz – 25 kHz, Hildebrand 2009). Considering that these traffic noise frequencies overlap with the frequency ranges used for acoustic communication and the hearing range of marine organisms (Jensen et al. 2009, Slabbekoorn et al. 2010), increased noise sound pressure level (SPL) values from vessels might have deleterious impacts on marine animals that use sound for communication.

Environmental noise from vessels has been shown to mask communication calls of fishes and marine mammals, often causing a change in calling behavior. Acoustic pollution from vessel activities can affect habitat quality (Tyack 2008) by masking biologically relevant signals. Masking is defined as a noise that is strong enough to reduce the detectability of biologically-relevant sounds (Frisk et al. 2003). For example, Erbe (2002) modeled the call of a killer whale (*Orcinus orca*) and determined that its call would be masked by a tourist boat at distances of up to 14 km. Another study demonstrated that a small vessel traveling at 2.6 m/s (5 kts) reduces the communication range of bottlenose dolphins (*Tursiops sp.*) by 26% in shallow water and by 58% in deeper water (Jensen et al. 2009). Vessel noise can be a source of chronic harassment for many marine species (Haviland-Howell et al. 2007).

Marine mammals and humans often have a propensity to adapt their communication signals to improve call detectability. These changes may involve call frequencies alterations, call duration changes, call rate modifications, and call SPL value modulation (Ulanovsky et al. 2004). The first documented Lombard effect (increased call SPL values, Lombard 1911) was found in the human voice. Today, marine mammals have been observed utilizing the Lombard effect to overcome the masking effects of increased ambient noise (e.g. Scheifele et al. 2005, Holt et al. 2009, Miksis-Olds and Tyack 2009, Parks et al. 2011). Alterations in call rates by marine mammals has been demonstrated for multiple species (Finley et al. 1990, Asselin et al. 1993, Lesage et al. 1999, Parks et al. 2007, Azzara et al. 2013). Increased call duration and increased repetition rates (Miller et al. 2000) in response to increased ambient noise have been observed in the humpback whale (*Megaptera novaeangliae*). Finally, the demonstration of frequency shifts by marine mammals in response to increased ambient noise levels are prevalent in the literature (e.g. Au et al. 1985, Lesage et al. 1999, Morisaka et al. 2005, Parks et al. 2007). Marine mammals demonstrate the ability to alter their acoustic calls utilizing several methods to improve call detectability.

Noise from vessels can also mask the calls of fishes but fishes are less likely to adapt their acoustic calls than marine mammals. Research has demonstrated that one species of fish exhibits the Lombard effect in response to increased ambient noise levels to improve its call detectability (Holt and Johnston 2014). Alternatively, in response to a predator (bottlenose dolphin *Tursiops truncatus*) sound, soniferous fishes reduce their calling rates (Luczkovich et al. 2000, Remage-

Healey et al. 2006, Luczkovich and Keusenkothen 2008). Presently, fishes have been shown to have only two possible responses to increased ambient SPL values: to either increase the SPL values of their calls or decrease their call rates.

Due to the limited knowledge of vocal response of fishes to vessel noise, one must ask if the impacts of vessel noise are a concern for soniferous fishes. Vessel noise alters more than just the communication behavior of fishes. In the presence of vessels, fishes perform avoidance maneuvers (Engås et al. 1995, 1998, Sarà et al. 2007) in an attempt to evade vessels. Vessel noises also cause physiological responses in fishes like raised cortisol levels (Wysocki and Ladich, 2005) and an increased heart rate (Graham and Cooke 2008). Both increased heart rates and increased cortisol levels suggest increased stress responses that are due to the sound of vessels alone. Vessels can also cause masking in a species' hearing ability (Scholik and Yan 2001, 2002, Vasconcelos et al. 2007). For example, vessel noise (~ 131 dB re 1 μPa) masked the ability of the Lusitanian toadfish to detect conspecific communication signals. Vessel noise caused a threshold shift of up to 36 dB at a hearing frequency of 50 Hz. This means that a 50-Hz signal needs to be up to 36 dB louder than the ambient noise level to be detected by the Lusitanian toadfish (*Halobatrachus didactylus*) at the same range when a ferry boat is passing by the site. Impacts of vessel noise on fish physiology, hearing, and acoustic communication lead to questions about how vessel noise may affect fitness in fishes, which has not been examined.

Model Species

Toadfishes (*Opsanus* spp. Batrachoididae) are model organisms for acoustics work (Tavolga 1958, Fish 1972, Winn 1972, Fine and Thorson 2008). Oyster toadfish hear frequencies up to 800 Hz (Fine 1978, Yan et al. 2000), with maximum sensitivity below 200 Hz (Fish and Offutt 1972, Vasconcelos et al. 2007). Hair cell sensitivity both in the inner ear and lateral line of toadfishes is primarily driven by the "movement" of sound (or acoustic particle motion) across the body ("accelerometer mode," Fay and Edds-Walton 1997, Yan et al. 2000).

Male oyster toadfish produce a boatwhistle call (~ 150 - 350 Hz) to attract females (Gudger 1910, Gray and Winn 1961, Fish 1972, Winn 1972) to their nests over long periods of time in shallow-water territories (Gray and Winn 1961, Winn 1972, Barimo and Fine 1998, Thorson and Fine 2002a, 2002b) by contracting intrinsic sonic swimbladder muscles (Skoglund 1961, Fine et al. 2001). Females attach benthic eggs to the nest, and males guard the embryos and larvae until they are free swimming in 3 - 4 weeks (Gudger 1910, Gray and Winn 1961). The life history of oyster toadfish makes them an ideal species to test how vessel noise impacts their fitness. This study examines the effect of noise on reproduction in the oyster toadfish (*Opsanus tau*) by testing three hypotheses: (1) vessel noise and predator sounds will decrease the courtship calling rate of male oyster toadfish, (2) male fish will respond to increased ambient noise levels through the Lombard effect (increased call SPL values), and (3) the incidence of egg laying will decrease at otherwise suitable sites in the field.

Materials and Methods

Noise Levels at Sites

Vessel activity occurring within the navigation channel next to the oyster toadfish shelters was calculated at each site every ~ 9 d over 15 observation periods from April - August 2014. These observations occurred at or near (within 2 h) low tide. This time-frame was selected to facilitate the in-water work with oyster toadfish collections but resulted in a random sampling of vessel activity in relation to the time of day. An observer counted vessels and noted engine type (outboard vs inboard) for at least an hour during each observation period. Vessel count observations were averaged over the summer and extrapolated to a day (24-h period) for each site. By averaging the vessel count data collected over the entire summer (holiday vs. non-holiday) at different times of day (sunrise, sunset, and midday) and different days of the week (weekday vs. weekend), I assume that the variability demonstrated in this data set is also representative of daily variability in vessel activity during the same monthly time period. Based on the average vessel activity, sites were denoted as "quiet" or "noisy." At "quiet" sites, vessels were rarely observed in the navigation channel while at "noisy" sites, vessels were nearly always observed utilizing the navigation channel.

To obtain SPL values at the oyster toadfish shelters near and far from the channel, vessel and ambient sounds were recorded over a weekend with a digital hydrophone (44.1 kHz sampling frequency, icListen model HF, Ocean Sonics, Great Village, Nova Scotia, Canada) suspended 0.5 m above the bottom using a float collar. Water depths at each site ranged between 1 - 2 m, and the hydrophone position was identified with a Wide Area Augmentation System (WAAS)-enabled global positioning system (GPS). Sounds of vessels that passed by the hydrophone were recorded on the WAAS-GPS track positions every 1 - 8 s from a quiet platform (a nearby anchored boat). A linear interpolation was used to identify the position of the platform between track points. The distance and azimuth of passing vessels were determined using a laser range finder (TruPulse 360R, Laser Technology, inc., Centennial, CO, USA). The azimuth was corrected for magnetic declination using GeoMag Python package (Weiss 2014) and vessel position was calculated with the range finder data using the GeographicLib Python package (Karney 2016). Equations, provided in Beranek (1988) and Pierce (1989), were used to calculate the time-weighted average instantaneous sound pressure and time-weighted average SPL values as a vessel passed the recording hydrophone site. While data were collected at all four sites, only one site (NPR) provided reliable sound collection information from passing vessels. This site is primarily used to infer expected noise levels as vessels passed the shelters across the other three sites.

Vocal Communication

Playback sounds came from digital field recordings collected between 2006 and 2013 from Long-term Acoustic Recorder Systems (LARS-LF, Loggerhead Instruments, Sarasota, FL) or a Fish Acoustic Buoy Underwater Logging System (FABULS, East Carolina University, Greenville, NC). Except for the low-frequency bottlenose dolphin sounds ("LFDolphin"), sixty 10-s recordings were compiled in random order to create a single, 600-s composite playback recording. For "LFDolphin," recordings of bottlenose dolphin (*Tursiops truncatus*) were made on a Sony TCD-D8 analog cassette and an HTI 96 min hydrophone in Southern Lagoon, Turneffe Atoll, Belize (17.18760° N, 87.88763° W) in 2005. For this playback, seven recordings were used to compile the composite 600 s recording. In each of the playbacks, male oyster toadfish courtship calls were avoided or removed, but other sounds including snapping shrimp (Alpheidae), water noises, and some prominent fish were not removed.

Artificial shelters, naturally colonized by oyster toadfish, were made of half cinderblocks (with 20-cm sides) with a 7.62-cm PVC pipe zip-tied through the center. Forty-eight shelters were deployed at two locations (Figure 2.1) in Jarrett Bay (JBS) and Newport River (NPR) in NC (ECU Animal Use Protocol #D292, Appendix A) during May and June 2013. The shelters were situated evenly with four shelters per replicate and a total of 24 replicates (4 shelters x 6 replicates) per treatment. Each replicate was separated by a minimum distance of 3.7 m. The shelters in each replicate were arranged in a semicircle around a central 0.3 m (1.3 cm diameter) PVC pipe that was positioned 1 m behind the shelters (Figure 2.2). The pipe was used to position an underwater speaker (Clark Synthesis AQ 339), where sounds were played to the shelters through a laptop (Panasonic Toughbook, CF-30) and a 400 W amplifier (Pyle PLMRA400). A similar PVC pipe was positioned at the center of the shelters, 1 m in front of the speaker to support the InterOcean 902 hydrophone and calibrated listening system (with dB VU meter) used to obtain reference SPL values for playbacks. A third similar pipe was positioned 1 m in front of the shelters or a total of 2 m directly in front from the speaker. On this pipe, an HTI (96-min) hydrophone was connected to a TASCAM DR-40 digital recorder (mono wav recordings, 16-bit sampling rate at 44.1 kHz sampling rate) to obtain recordings of resident oyster toadfish. Both hydrophones were positioned 40 - 50 cm above the bottom.

Playback experiments, which occurred overnight (sunset to sunrise), started at least one month (July – August 2013) after the shelters were deployed to give oyster toadfish the opportunity to naturally recruit to the shelters. One of the six sound recordings was randomly presented to a single replicate, with each replicate receiving one playback treatment over a single experimental period. Sounds were recorded from each treatment with a TASCAM DR-40 for a total of 1800 s, with separate recordings of 600 s before, during, and after the sound exposure period. Playbacks consisted of the following: snapping shrimp (“Shrimp”, a natural background sound used as a control), low-frequency bottlenose dolphin sounds (“LFDolphin”), high-frequency bottlenose dolphin sounds (“HFDolphin”), inboard motorboat (“Inboard”), outboard motorboat (“Outboard”), and simultaneous playbacks of low-frequency bottlenose dolphin and inboard motorboat (“Both”). The sound source for the “Both” playback treatment was created by playing both “LFDolphin” and “Inboard” through two separate speakers.

The recorded files generated in the experiment were analyzed using Fast Fourier Transform (FFT) with a 4096 point Hanning window and 50% overlap in Raven Pro (version 1.5 Beta, The Cornell Lab of Ornithology, Bioacoustics Research Program, 2013). Playback power spectral density (PSD) curves versus frequency curves were compared visually among playback types. Additionally, mean square pressure (p^2_{av}, proportional to power) values were determined for the oyster toadfish hearing range (50 to 1000 Hz) and for frequencies < 10 kHz. These p^2_{av} values were calculated by (1) multiplying the average power spectral densities by the frequency bin size (10.8 Hz) to obtain the p^2_{av} within each frequency bin; (2) the square pressures within each frequency bin were summed to obtain the p^2_{av} values in the desired frequency bands (50 to 1000 Hz or < 10 kHz); (3) these values were converted into dB with a reference value of 1 μPa^2. Comparisons were made across the total 1800 s experimental recording period, by comparing spectrum level differences before, during, and after a playback experiment.

Oyster toadfish boatwhistle calls were counted by ear using Raven Pro 64 by a human listener (CSK). Changes in the number of boatwhistles (% change) were determined by comparing the call rate (#boatwhistles/60 s) before and during sound exposure. Call rate change within a playback treatment and among sites was compared with a two-way analysis of variance (ANOVA). To assess power spectral differences, a boatwhistle selection table and wav file were outputted from Raven and imported into Matlab as a “native” wav format. Calibration corrections were applied to these files to adjust for record level differences on the TASCAM and oyster toadfish call SPL values were computed in Matlab using the Welch method. Average power spectral densities from individual calls and call duration were compared for recording periods (before, during, and after) using a repeated measures ANOVA.

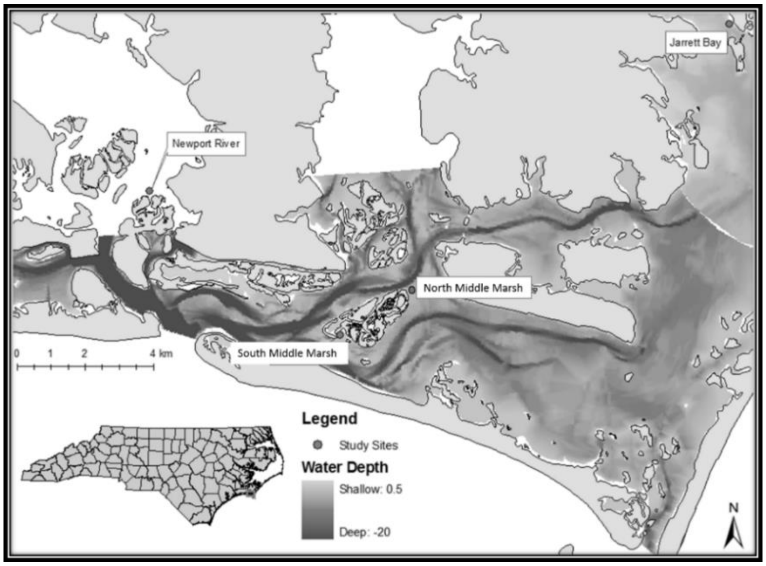

Figure 2.1. Study site map.

Sites where artificial oyster toadfish shelters were deployed. All deployments occurred in areas with a mean water depth of 1 m. The sites with the most vessel activity ("noisy") were North Middle Marsh (NMM) & Newport River (NPR) and the sites with the least vessel activity ("quiet") were South Middle Marsh (SMM) & Jarrett Bay (JBS). The playback experiments occurred at JBS and NPR and the fitness observations occurred across all sites.

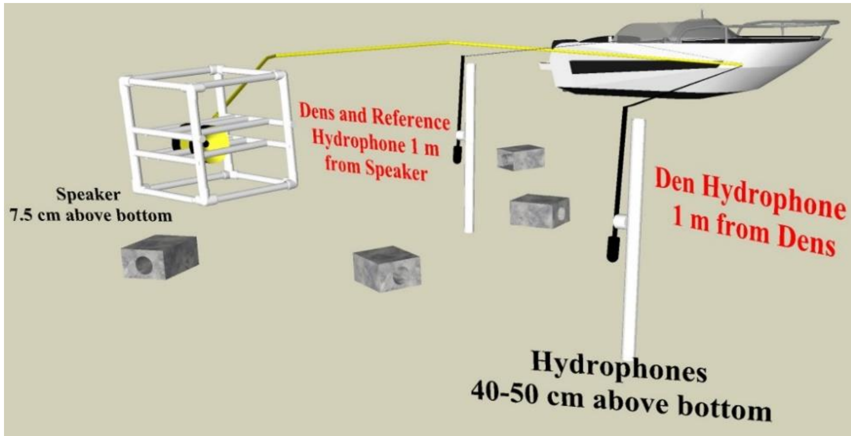

Figure 2.2. Diagram for the playback experiment set-up.

Diagram of how the oyster toadfish shelters were arranged and how the equipment was deployed to execute the playback experiment. All sites had a mean water depth of 1 m (reproduced from [Krahforst et al. 2016], with the permission from the Acoustical Society of America, see Appendix I for the copyright permission letter).

Reproduction

Artificial shelters were deployed at Newport River (NPR), North Middle Marsh (NMM), South Middle Marsh (SMM), and Jarrett Bay Site (JBS) in March 2014. Two of these sites (NMM & SMM) are within the Rachel Carson National Estuarine Research Reserve (NERRS permit #3-2014, Appendix A). The shelters were set near (~ 7 m) and far (~ 35 m) from the navigation channel at each site at a depth of ~ 1 m mid-tide. These distances were based on acoustic propagation measurements across all sites that indicated that at distances > 25 m (Figure 2.3), vessel noise decreases to ambient levels (< 124 dB re 1μPa, based on my field observations). As extrapolated from this field data, shelters near the navigation channel would receive high vessel noise that exceeded 124 dB re 1μPa, but shelters far from the navigation channel would receive vessel noise at or below ambient noise from these same vessels. Thirty-six shelters were deployed at each site (3 shelters x 6 replicates x 2 treatments). Each replicate contained three artificial shelters positioned with the opening facing the navigation channel. Three shelters per replicate were used in this experiment instead of the four shelters that were used in the communication experiment because and two sites were added.

After allowing for a month of natural recruitment to the shelters at each of the sites, the sites were sampled every ~ 9 d over 15 sampling periods (April - August 2014), for the number of oyster toadfish and the presence and number of embryos. Oyster toadfish were captured by surrounding each shelter with a hand net, flipping the shelter into the net, bringing it to the surface, and removing the fish. The number of oyster toadfish in each shelter was counted and the fish were transported to the boat and held in buckets with an air-stone (ECU Animal Use Protocol #D307, Appendix A). Oyster toadfish in shelters near and far from the navigation channel were kept in separate buckets, later measured, and released at the site of capture. Holding the fish ensured that they did not enter another shelter further down the line during the sampling period. The mean number of oyster toadfish by replicate ($N = 6 \times 2$ treatments) at each site and by navigation channel position were compared using repeated measures ANOVA for the fifteen sampled weeks. Within site differences by treatment (shelters in relation to channel position) were explored using a two-sample *t*-test with a pooled variance and a Bonferroni adjustment.

If a shelter contained embryos, the side of the shelter with the embryos was photographed with a Nikon AW1 digital camera, and the number of embryos was later counted from the photograph. The embryos were removed from the shelter and brought into the lab for another experiment. Differences in the number of egg clutches (presence/absence) by site and navigation channel position were determined using individual Pearson Chi-Square tests. Significant differences were determined at the $p < 0.05$ level.

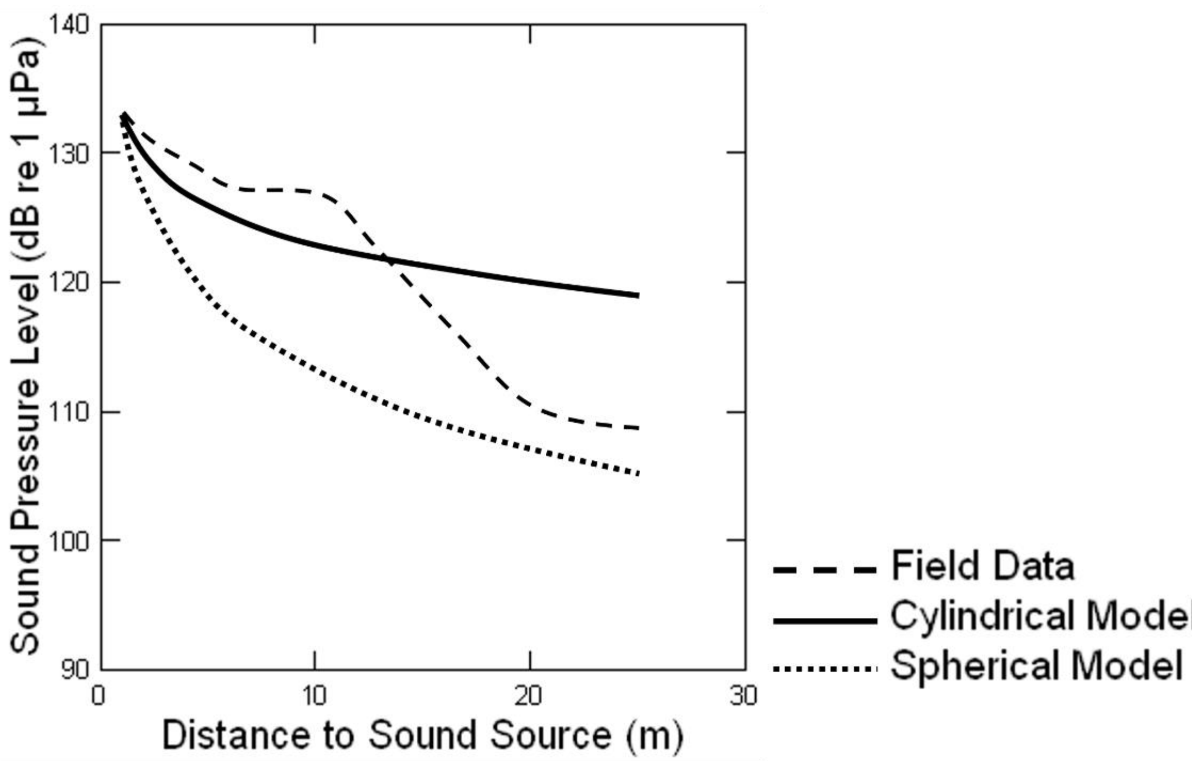

Figure 2.3. Acoustic propagation measurements of vessel noises in the field and the cylindrical and spherical spreading models of expected transmission loss within the sites.

Acoustic propagation measurement (SPL) values collected in the field (Field Data) made using two InterOcean 902 hydrophone and calibrated listening systems (with a dB VU meter) from playback experiments through an underwater speaker (Clark Synthesis AQ 339) of inboard and outboard motorboat sounds. One hydrophone was placed 1 m from the speaker and the second hydrophone was moved backward from the speaker. Measurements > 20 m were difficult to obtain due to the length of the hydrophone cable. For comparison, the expected transmission losses of the same amplitude sound are represented by both the cylindrical and spherical spreading models. For more acoustic measurements of vessel noise by site and bottom type, see Appendix B. For more acoustic measurements of a more broad scale frequency range see Appendix C.

To explore differences in the number of embryos, all shelters that lacked egg clutches were removed from further analysis. Shelters with egg clutches were used in an ANOVA analysis to determine differences in the number of embryos within a clutch by site and shelter position relative to the navigation channel. Next, hypothesis tests of the effects of the model including the individual effects and the combined effects were examined to determine which factors influenced the number of embryos on the oyster toadfish shelters. Significance levels were assessed at a $p < 0.05$.

Results

Playback Sound Characteristics

During the playbacks, the received power spectral densities of recorded sound in the field increased, compared with the recording before sound-exposure (Figure 2.4) but this increase was dependent upon frequency. When comparing the before and during playback mean square pressures (p^2_{av}) at frequencies < 10 kHz across all playback experiments and all sites, the "Both" playback caused the largest increase in p^2_{av} ($\Delta = +17$ dB re 1 μPa^2), followed by both "Inboard" ($\Delta = +6$ dB re 1 μPa^2) and "Outboard" ($\Delta = +6$ dB re 1 μPa^2) motorboats, then by "LFDolphin" ($\Delta = +5$ dB re 1 μPa^2), "HFDolphin" ($\Delta = +4$ dB re 1 μPa^2), and finally "Shrimp" ($\Delta = +3$ dB re 1 μPa^2) had the lowest amplitude increase at this frequency range. These results suggest that there were some differences in p^2_{av} by frequency within the playbacks, with "HFDolphin" and "Shrimp" causing the least differences < 10 kHz and "Both" and "Inboard" causing the most difference in the soundscape when played back to the oyster toadfish.

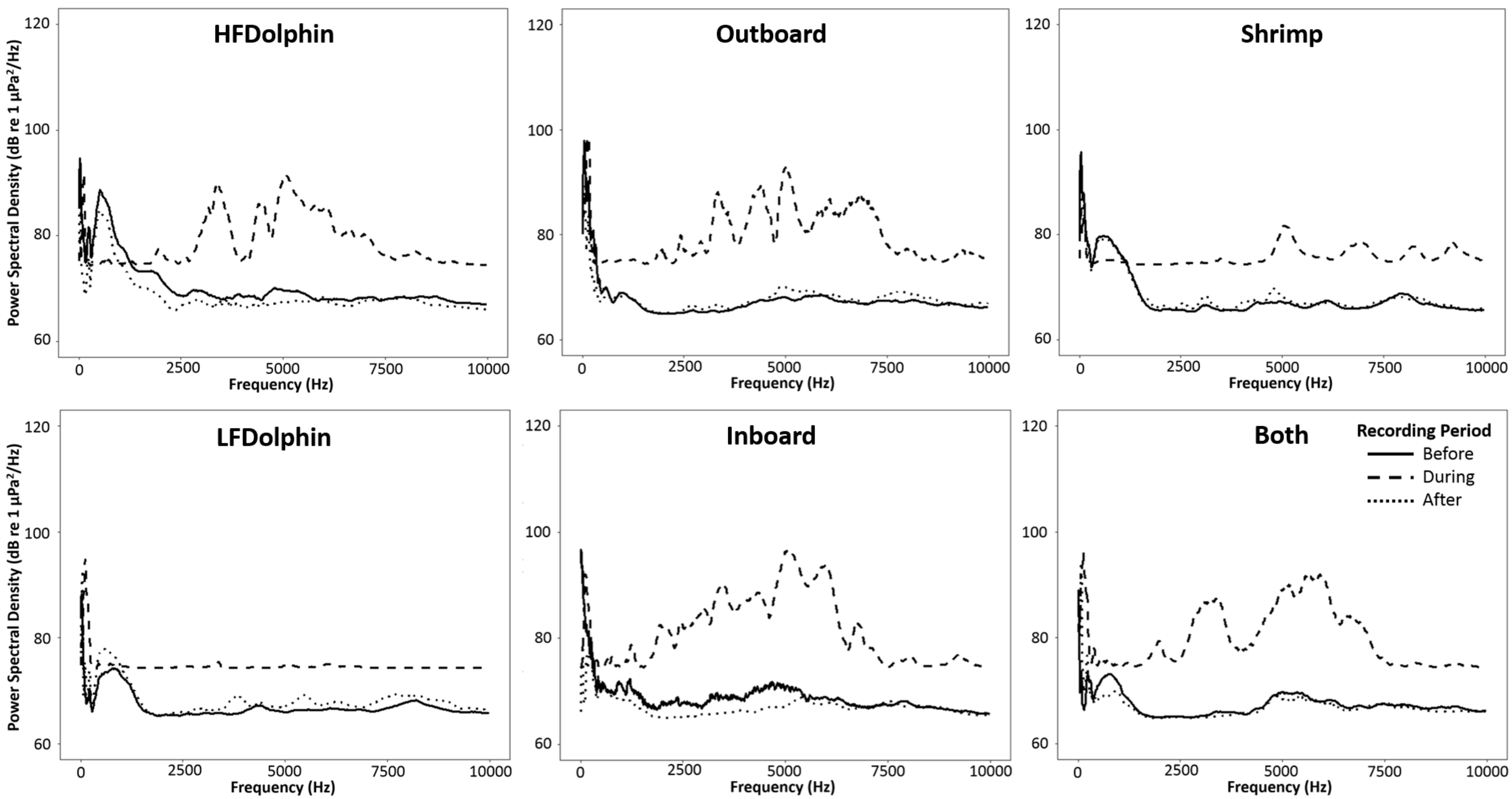

Figure 2.4. Power spectral density curves before, during, and after a playback experiment at JBS in sand.

An example of power spectral densities at 2 m from the speaker during one experiment at JBS in sand. Each of the power spectra are based on the estimates of power spectral densities (using Welch's method). The remainder of the PSD curves can be found in Appendix D.

Noise Levels at Sites

Acoustic propagation of vessel noises played back through an underwater speaker within the sites (at a mean depth of 1 m) exceeded the predictions of the cylindrical spreading model (Figure 2.3) after a distance of approximately 15 m from the sound source. In the experiments that follow, fishes near the navigation channel (< 15 m away from the sound source) will have SPL values that will exceed the predications of the cylindrical spreading model and fish greater than 15 m from the sound source, will have lower SPL values than expected from the cylindrical spreading model.

Inboard motorboat activity varied by site, with higher vessel counts at NPR (Table 2.1) than all of the other sites. For example, an inboard motorboat (10 - 15 m in length) that passed the Newport River site (NPR, Figure 2.1), produced a sound pressure level (SPL) value of 128 dB re 1 $\mu Pa^2 \cdot s$ at the oyster toadfish shelter area (Sprague et al. 2016) that was "near" the navigation channel (Figure 2.5A). This site averaged 32 inboard motorboats per day and these vessels ranged in length between a 4-m vessel and a 15-m tour boat. The Jarrett Bay Site (JBS) averaged 2 inboard motorboats per day but these inboards were smaller (4 - 8 m long) vessels used by local fishermen. At the other two sites (NMM and SMM), inboard motorboats were not observed. Across all of the sites, NPR had significantly more inboard activity (Table 2.2) than the other three sites.

Outboard motorboat activity was observed at all sites. An 8 - 10 m long sailboat with an outboard motorboat under power at NPR peaked at an SPL value of 132 dB re 1 $\mu Pa^2 \cdot s$ at the oyster toadfish shelter area "near" the navigation channel (Figure 2.5B). NPR and NMM had similar outboard motorboat counts (Table 2.1) but both SMM and JBS had significantly lower outboard motorboat vessel counts than the other two sites. Therefore during our observations, SPL values by a single vessel at the oyster toadfish shelters had peak levels around 132 dB re 1 $\mu Pa^2 \cdot s$, which is a 7.5-fold increase above average ambient noise levels (109.5 dB re 1 μPa) across all the sites. This increase in SPL value is likely to occur 338 times a day at NPR, 208 times NMM, and less than 15 times at JBS and SMM from vessel activity. Henceforth, NMM and NPR will be labeled as “noisy” sites and SMM and JBS will be considered “quiet” sites.

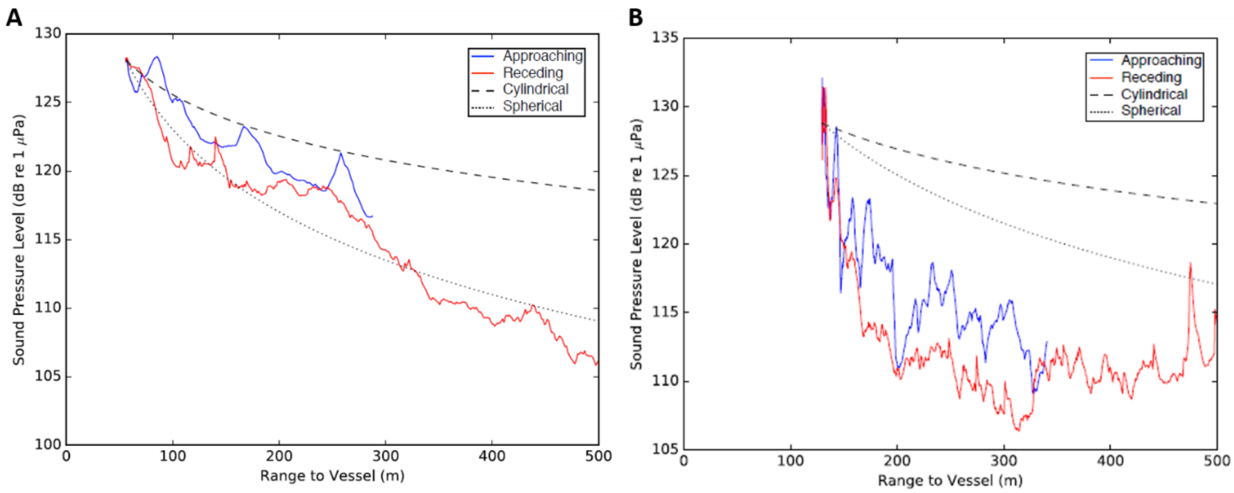

Figure 2.5. Sound pressure levels of vessels in the field at the NPR site.

The time-weighted average sound pressure level (SPL) of the recordings of A) an inboard motorboat and B) an outboard motorboat passing in the navigation channel in the area of the oyster toadfish shelters at NPR. Both predicted SPL values from the cylindrical and spherical spreading models are included for reference (reproduced from [Sprague et al. 2016], with the permission from the Acoustical Society of America, see Appendix I for the copyright permission letter).

Table 2.1. Site designation information on ambient noise level and vessel activity.

Noise level designation information for each of the sites. Measured ambient noise levels (dB re 1μPa) retrieved on the InterOcean 902 hydrophone and calibrated listening system. Peak SPL values (dB re 1μPa) measured at the "near" toadfish shelters only at NPR from an icListen model HF (Sprague et al. 2016). Mean number of vessels, separated by vessel type (inboard and outboard) and pooled vessel counts (total vessels), and extrapolated over a 24-h period from fifteen observations at each site.

Site	Noise Level Designation	Ambient Background SPL (dB re 1 μPa)	Peak SPL during Vessel Passage (dB re 1 μPa² · s)	Mean Vessel Counts (# vessels in 24-h)		Mean Total Vessel Count (# vessels in 24-h)
				Outboards	**Inboards**	
JBS	"Quiet"	109.4 (*SE* = 1)	124 – 134	13.2 (*SE* = 4.7)	2.3 (*SE* = 2.3)	15.5 (*SE* = 4.8)
SMM	"Quiet"	113.3 (*SE* = 2)	Not Measured	2.7 (*SE* = 0.6)	0.00 (*SE* = 0.0)	5.9 (*SE* = 2.7)
NMM	"Noisy"	Not Measured	Not Measured	207.7 (*SE* = 46.6)	0.00 (*SE* = 0.0)	207.7 (*SE* = 46.5)
NPR	"Noisy"	108.3 (*SE* = 1)	Not Measured	306.0 (*SE* = 85.9)	32.3 (*SE* = 7.3)	338.3 (*SE* = 85.9)

Table 2.2. Statistical test results for differences in inboard and outboard motorboat activity among sites.

Kruskal-Wallis test for differences in vessel activity among sites. Vessel activity is separated into outboard and inboard motorboats and significant differences between sites are marked with an asterisk.

Vessel Type	Site A	Site B	KW Statistic	p-value
Outboard	JBS	SMM	- 1.834	0.565
Outboard	NMM	NPR	0.062	1.000
Outboard	JBS	NMM	6.428	< 0.001*
Outboard	SMM	NMM	6.768	< 0.001*
Outboard	JBS	NPR	5.614	< 0.001*
Outboard	SMM	NPR	5.712	< 0.001*
Inboard	JBS	SMM	- 1.414	0.749
Inboard	NMM	NPR	5.187	0.001*
Inboard	JBS	NMM	- 1.414	0.749
Inboard	SMM	NMM	0.000	1.000
Inboard	JBS	NPR	4.471	0.009*
Inboard	SMM	NPR	5.187	0.001*

Vocal Communication

Toadfish boatwhistle rates decreased during playbacks of bottlenose dolphin sounds (low and high frequency), inboard motorboat sounds, and during the playback of both the inboard motorboat and low-frequency dolphin sounds. Snapping shrimp ("Shrimp") sounds and outboard motorboat noise ("Outboard") caused no change in the percent change of the male oyster toadfish courtship calling rates during the playback (Figure 2.6A). The percent change in male oyster toadfish calling rate varied significantly by site ("noisy" vs "quiet", ANOVA, $F_{1,9}$ = 13.34, p = 0.005) and by playback type (ANOVA, $F_{5,9}$ = 28.13, p < 0.001). There was also a significant interaction between site and playback type (ANOVA, $F_{5,9}$ = 49.92, p < 0.001). The ANOVA model explained 97.4% of the variability in oyster toadfish courtship calling rates (ANOVA, $F_{12.9}$ = 88.88, p < 0.001). "Shrimp" playbacks did not significantly alter oyster toadfish calling rates ($\bar{X}$ = - 15.6% relative to pre-period calling rate, *SE* = 42.6) and neither did the playbacks of the outboard motorboats ($\bar{X}$ = - 39.1%, *SE* = 60.9). For all other playbacks, there was a significant decline in the percent change of male oyster toadfish calling rate. Both bottlenose dolphin and inboard sounds ("Both") caused the greatest decrease in calling rates ($\bar{X}$ = - 100%, *SE* = 0), followed by high-frequency bottlenose dolphin sounds ("HFDolphin", $\bar{X}$ = - 95.1%, *SE* = 4.7), low-frequency bottlenose dolphin sounds ("LFDolphin", $\bar{X}$ = - 90.5%, *SE* = 6.2), and inboard motorboat noise ("Inboard", $\bar{X}$ = - 70.4%, *SE* = 11.05). The study sites also influenced calling rates, with the oyster toadfish from JBS ("quiet") having a 20.71% greater decline in courtship calling rate than for male oyster toadfish from the NPR ("noisy") site (Figure 2.6B).

The mean and median amplitude (in SPL) of oyster toadfish boatwhistles varied significantly among playback period ($F_{2,2088} = 6.24$, $p = 0.002$, Figure 2.7). Boatwhistles increased in amplitude during the playbacks, indicating the presence of the Lombard effect. Amplitude increased during the playback by an average of 8.3 dB re 1 μPa (*SE* = 0.5) across all sites but there was a site effect (Figure 2.8). At JBS, oyster toadfish boatwhistle calls increased by 11.6 dB re 1 μPa (*SE* = 0.7) on average during the playback, but at NPR the sound pressure level increase for oyster toadfish courtship calls during the playbacks was lower ($\bar{X}$ = 5.5 dB re 1 μPa, *SE* = 0.4). Boatwhistle amplitude increased from an average of 82.8 dB re 1 μPa (*SE* = 0.2) before the playbacks to 91.1 dB re 1 μPa (*SE* = 0.5) during the playback and decreased back to 81.6 dB re 1 μPa after the playback. To some extent, oyster toadfish males demonstrate the ability to alter the amplitude of their courtship calls in response to increased ambient noise levels.

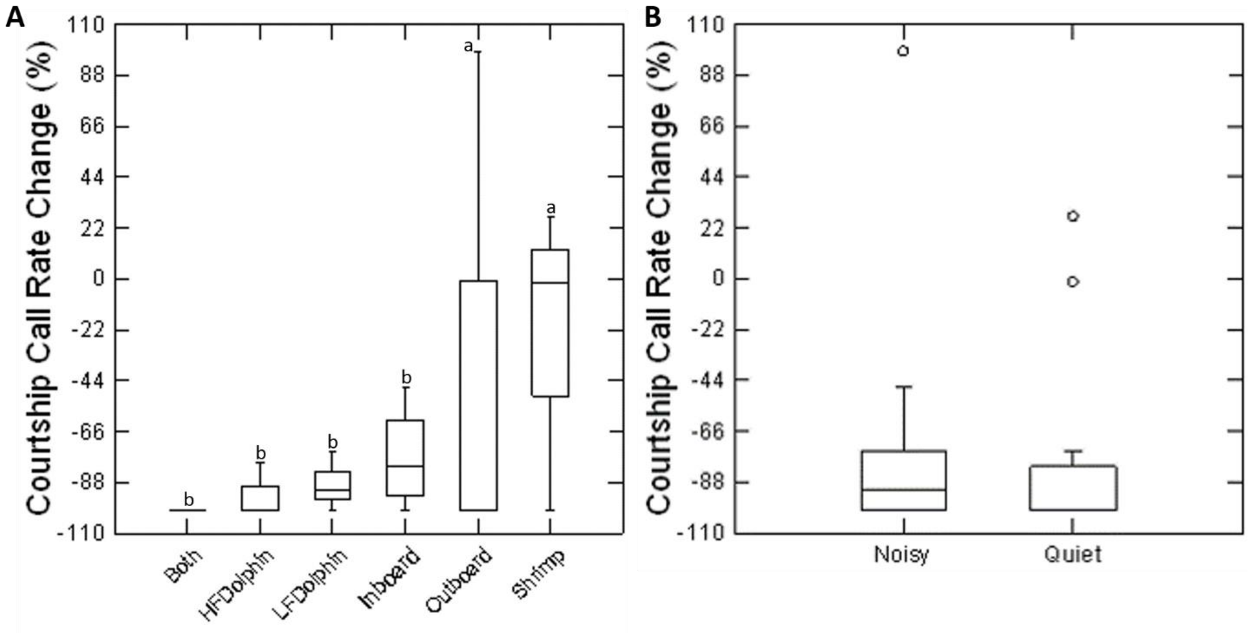

Figure 2.6. Changes in male oyster toadfish courtship calling rates in response to playback sounds at “noisy” and “quiet” sites.

Acoustic disturbance of oyster toadfish courtship calling rates. A) The median change in oyster toadfish courtship calling rate (% change) during the playback of various sound types is shown. Treatment groups with different lowercase letters represent significant ($p < 0.01$) differences. B) Oyster toadfish courtship calling rate change (%) by study site (“noisy” versus “quiet”). Boxplots show the median (50th percentile at the horizontal line) and the region which contains 50% of data around the median (25th to 75th percentiles). The vertical bars show the region in which observations fall within 1.5 x upper and lower interquartile ranges (lower: 25th to 50th percentile range; upper: 50th to 75th percentile range). Points outside of the 1.5 x the upper and lower interquartile ranges are shown as open circles (reproduced from [Krahforst et al. 2016], with the permission from the Acoustical Society of America, see Appendix I for the copyright permission letter).

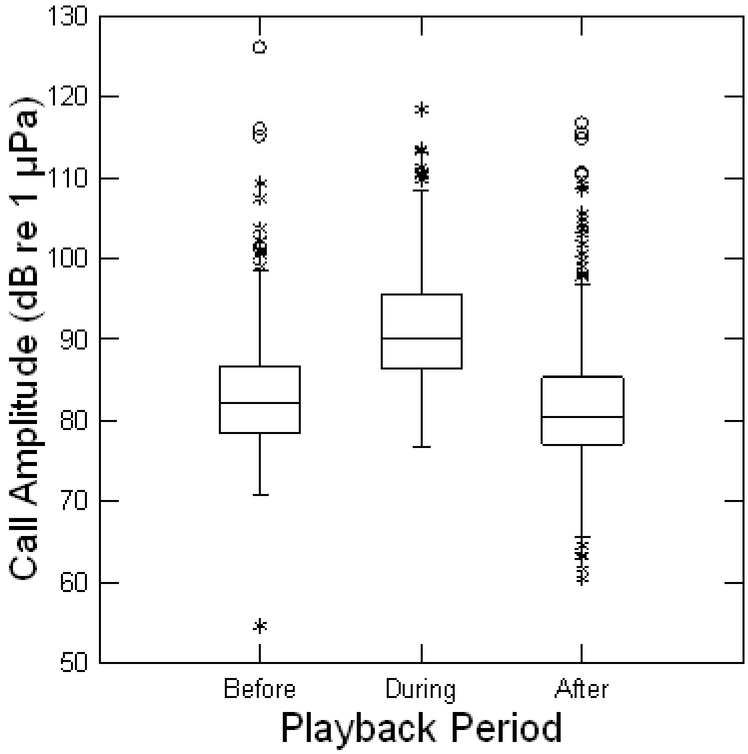

Figure 2.7. Changes in male oyster toadfish courtship call amplitude (dB re 1 µPa) by playback period.

Median call amplitude (dB re 1 µPa) for oyster toadfish courtship calls before, during, and after a playback, with all playback sound types and sites combined. Figure 2.6 contains a description of the box plot.

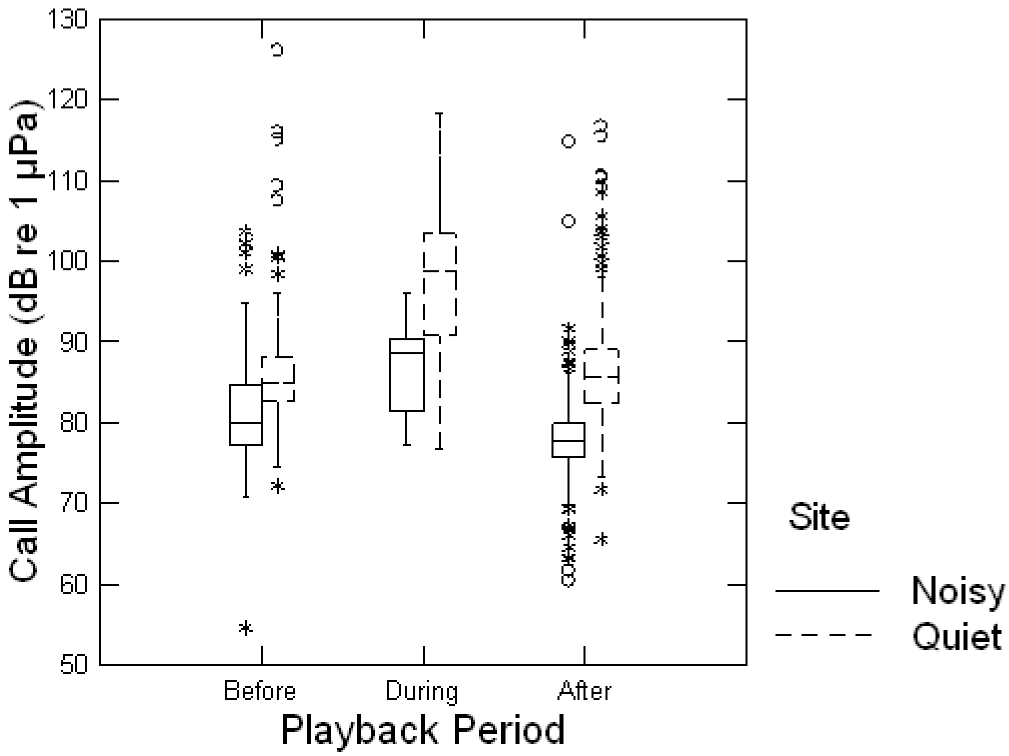

Figure 2.8. Changes in male oyster toadfish courtship call amplitude (dB re 1 µPa) by playback period at "noisy" and "quiet" sites.

Median call amplitude (dB re 1 µPa) for oyster toadfish courtship calls at a site with high vessel noise ("noisy") and low vessel noise ("quiet"). Call amplitude is presented by recording period: before, during, and after a playback, with all playbacks combined. Figure 2.6 contains a description of the box plot.

Oyster toadfish call duration did not vary significantly among the playback periods ($F_{1,2088}$ = 2.78, p = 0.096) and neither did call frequency. Oyster toadfish calling at JBS, overall had shorter call durations compared with those calling at the noisy site (Figure 2.9) but across playback periods their calling duration remained at similar levels. At JBS, the call duration averaged 0.16 s (SE = 0.005) before exposure, 0.12 s (SE = 0.005) during exposure, and 0.17 s (SE = 0.007) after sound exposure. At NPR the call duration averaged 0.35 s (SE = 0.003) before exposure, 0.31 s (SE =

0.006) during exposure, and 0.33 s (SE = 0.003) after sound exposure. Additionally, average call frequency remained the same (~200 to 250 Hz) throughout the experiment (Figure 2.10). These data suggest that oyster toadfish do not alter their call frequency nor the duration of their call in response to increase ambient noise levels.

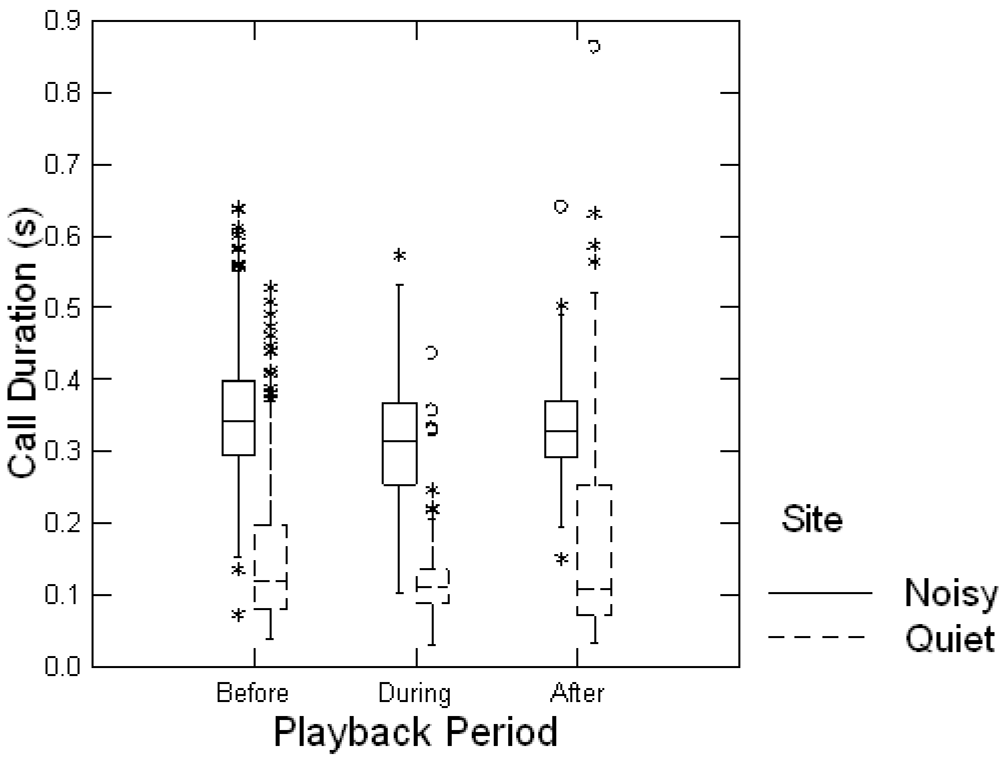

Figure 2.9. Changes in male oyster toadfish courtship call duration (s) by playback period at "noisy" and "quiet" sites.

Median call duration (s) for oyster toadfish courtship calls at a site with high vessel noise ("noisy") and low vessel noise ("quiet"). Call duration is presented by recording period: before, during, and after a playback, with all playbacks combined. Figure 2.6 contains a description of the box plot.

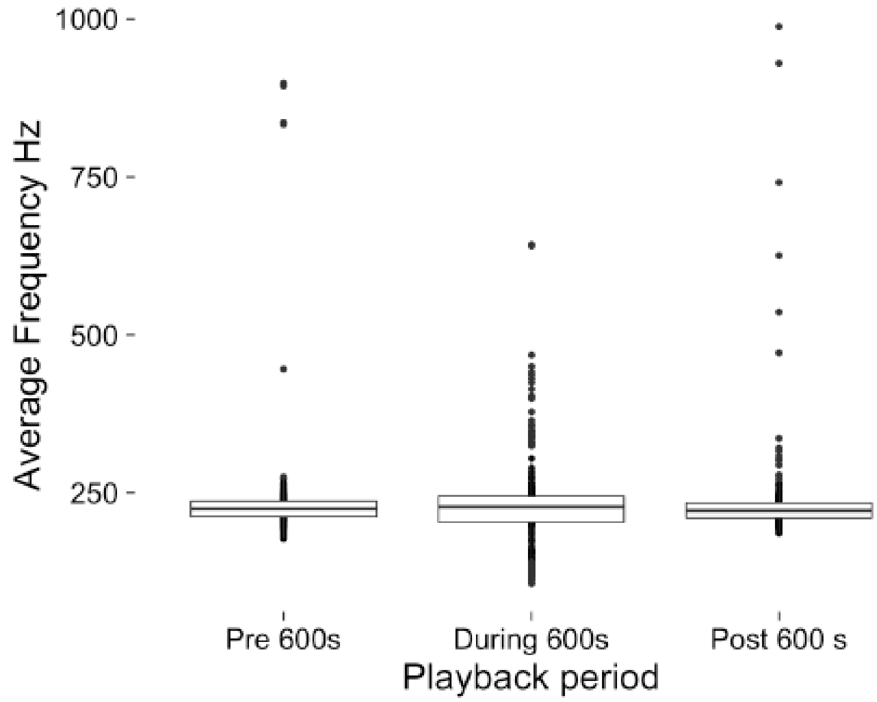

Figure 2.10. Changes in male oyster toadfish average courtship call frequency (Hz) by playback period, with all sites combined.

Median call frequency (Hz) for oyster toadfish courtship calls across both sites (reprinted from: Luczkovich et al. 2016). Call frequency is presented by recording period: before, during, and after a playback, with all playbacks combined. Figure 2.6 contains a description of the box plot (reproduced from [Luczkovich et al. 2016], with the permission from the Acoustical Society of America, see Appendix I for the copyright permission letter).

Reproduction

The number of egg clutches varied by site and this difference was not due to water quality (Appendix E). Of the 480 observations (15 weeks x 4 blocks x 2 treatments x 4 shelters) at each site, embryos were identified 19 times (1.0% of the observations). Jarrett Bay (JBS, a "quiet" site) had the most egg clutches with nine, NMM (a "noisy" site) and SMM (a "quiet" site) both had five egg clutches, and NPR (a "noisy" site) had no egg clutches. The number of clutches differed among sites (Pearson Chi-Square = 8.34, $df = 3$, $p = 0.039$). Additionally, there were more egg clutches on shelters near the navigation channel as compared with shelters that were far from the navigation channel ($\Delta = 9$, Pearson Chi-Square = 4.381, $df = 1$, $p = 0.036$).

The mean number of oyster toadfish embryos, only for the shelters with egg clutches (all shelters without clutches were removed, see Appendix F for this analysis with the zeros included), was marginally different among sites (ANOVA, $F_{2,13} = 3.18$, $p = 0.075$), and the "noisy" site (NMM) had fewer embryos per clutch ($\bar{X} = 193.6$, $SE = 82.4$) than the two "quiet" sites JBS ($\bar{X}=434.3$, $SE = 9.1$) and SMM ($\bar{X} = 423.3$, $SE = 67.3$). The mean number of embryos varied significantly by navigation channel position (ANOVA, $F_{1,13} = 20.67$, $p = 0.001$), with more embryos present (on average) on the shelters further from the navigation channel (Figure 2.11, $\Delta = 368.86$). Both "quiet" sites (JBS & SMM) had fewer embryos on average attached to shelters near the navigation channel as compared with shelters far from the navigation channel. Jarrett Bay had 384.5 (Bonferroni Test, $p = 0.094$) and SMM had 761.3 embryos (Bonferroni Test, $p = 0.001$) on shelters far from the navigation channel. In contrast, at the one "noisy" site that had embryos (NMM), there was no difference in the mean number of embryos (Bonferroni Test, $p = 1.00$) by channel position. There were on average 58 embryos per clutch on shelters far and 71 embryos per clutch on shelters near the navigation channel at NMM. There was also a significant interaction between site and navigation channel position (ANOVA, $F_{2,13} = 7.14$, $p < 0.008$).

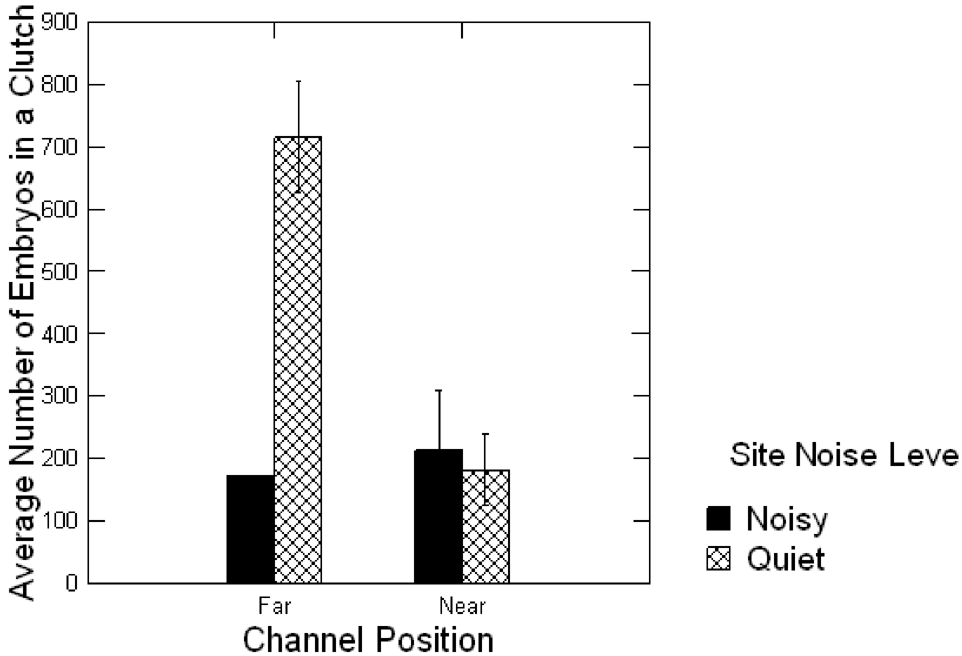

Figure 2.11. Embryo abundances at the sites with embryos present.

The number of embryos at the "quiet" sites (JBS & SMM) and one "noisy" site (NMM) on shelters near and far from the navigation channel. All shelters without embryos were removed from this analysis. The second "noisy" site (NPR), had no embryos present during the sampling period.

Discussion

Motorboats in the deep (6 m or less) navigation channels increased ambient SPL values at shallow (~ 1 m) oyster toadfish shelters. These noise levels are not expected to cause hearing loss (Popper and Hastings 2009) but affect fish behavior by decreasing the signal to noise ratio at the oyster toadfish shelters during playbacks. During playbacks, SPL values increased ambient sound enough to mask oyster toadfish courtship calls, potentially affecting the behavior of females. During the playback experiment, SPL values increased by an average of 8 dB re 1 μPa and oyster toadfish responded by increasing the boatwhistle SPL values by an average of 8.3 dB re 1 μPa (*SE* = 0.5) and there was no significant change in oyster toadfish call duration or frequency. However, oyster toadfish at the "noisy" site had longer call duration than those at the "quiet" site. In fact, the duration of the oyster toadfish living in the "noisy" site was nearly double that which was observed in the literature (0.064 s and 0.164 s, Fine and Lenhardt 1983). Therefore, oyster toadfish likely have adapted, over a prolonged time period, to use increased call duration to compensate for increased ambient SPL values at "noisy" sites. To compensate for short-term increases in sound pressure, oyster toadfish adjust their calling rate and amplitude. Yet, sound pressure levels at these sites will increase by up to 40 dB during the passage of a vessel. This level exceeds the levels I was able to obtain using sound playback experiments and a 40 dB increase in SPL value is likely to exceed the ability of male oyster toadfish to produce louder sounds.

Like their reactions to bottlenose dolphin sounds, inboard motorboats decrease calling rates of male oyster toadfish. In contrast, outboard motorboat sounds do not cause a significant change in oyster toadfish calls. Gray whales (*Eschrichtius robustus*) have shown a similar response, with decreased calling rates in the presence of a drillship but increased calling rates when exposed to an outboard motorboat (Dalhlheim et al. 1984). Reactions by oyster toadfish and gray whales are likely frequency-dependent. When SPL values increase within frequency bands that are above the hearing threshold of oyster toadfish ($f > 1000$ Hz), as is the case with outboard motorboats, then the fish is less likely to react to this increase in ambient noise. For example, snapping shrimp sounds have most of their acoustic energy at frequencies between 3 and 8 kHz (Knowlton and Moulton 1963). The results in this paper demonstrate no change in oyster toadfish calling from the snapping shrimp sound playback. The frequencies of outboard motorboat sounds are usually between 1 - 5 kHz (Au and Green 2000, Erbe 2002), which is above the hearing range of the oyster toadfish, thus oyster toadfish do not alter their call rates in response to outboard motorboat noise. Oyster toadfish response to vessel noise is dependent upon the frequency of overlap among the anthropogenic noise and their hearing as well as the fundamental frequency of their acoustic signals.

Male oyster toadfish maybe physiologically limited while attempting to overcome vessel noise. While calling in the oyster toadfish is not aerobically-limited (Amorim et al. 2002), calling may be susceptible to muscle fatigue. Mitchell et al. (2008) found that male oyster toadfish use 10.8% of their stored glycogen in 7.5 s while producing boatwhistle calls with a duration of 100 ms every 4 s (1.5 s of stimulation every minute). Therefore, the sonic muscles of the oyster toadfish are likely to be physiologically limited by the amount of stored glycogen. The fish are able to compensate for increased ambient noise up to a point but there is likely a limit to how loud and how much they can call and this limitation is related to muscle fatigue or glycogen storage. The cost for the male oyster toadfish's inability to adapt their calls in "noisy" areas is reduced fitness.

This study demonstrated that the areas with the most vessel noise and vessel activity had the fewest embryos, which suggests that females are depositing more eggs at shelters in "quiet" sites. The two closest sites (SMM and NMM) were 2.2 km apart (straight line distance) and had the same number of clutches, but the "quiet" site (SMM) had 700 more embryos overall than the "noisy" site although the number of shelters was not limited. Finally, more embryos were deposited on shelters far from the navigation channel as compared with near the navigation channel, suggesting that female oyster toadfish lay more eggs in areas that have the least amount of noise disturbance. This reduction in egg laying in "noisy" areas has previously been observed in birds. Great tit (*Parus major*) females lay smaller egg clutches in areas exposed to high vehicle traffic over areas of low vehicle traffic (Halfwerk et al. 2011). One explanation for female oyster toadfish laying more eggs in “quiet” areas is that of disturbance. First, male oyster toadfish in areas of high noise are less likely to be successful in protecting the embryos than males in areas of low vessel noise. Work on gobies (*Gobius cruentatus*) and damselfish (*Chromis chromis*) have demonstrated that exposure to boats causes the caregiver to leave the nest (Mueller 1980), spend more time inside the shelter, or spend less time caring for the embryos (Picciulin et al. 2010). While it is possible that temporary shelter avoidance by males due to vessel occurred in this study, it is unlikely that nest abandonment occurred because the shelters were checked weekly. If a clutch was present, the embryos were removed from the shelters. So, nest abandonment by male oyster toadfish would have had to occur within a week and this was not observed during the study. In terms of egg depositing behaviors by females, there are two possible explanations of why NMM had fewer embryos per clutch compared with the “quiet” sites. Presently, research has not shown if female oyster toadfish deposit their eggs all at once or over multiple spawning events. If she deposits her eggs all at once, then males at “noisy” sites are likely attracting smaller females, which would result in smaller egg clutches. However, if female oyster toadfish deposit eggs over multiple spawning events throughout the spawning season, a female may (1) abandon the nest in the process of depositing eggs, resulting in smaller egg clutches or (2) she may choose to lay smaller egg clutches on shelters as a result of vessel activity and noise in the area. All of these scenarios create a situation where vessel noise or presence leads to a loss in fitness in areas of high vessel noise compared to areas of low vessel noise.

Based on the acoustic propagation measurement in the field, oyster toadfish in shelters “near” the channel were exposed to higher SPL values than those “far” from the channel. In this study, the transmission loss of sounds from vessel activity exceeded that of the cylindrical model when distances from the sound source exceeded 15 m. Fine and Lendardt (1983) found similar results for low frequency pure tone sounds (< 1 kHz) in a water depth of 1 m. The authors suggest that the bottom characteristics of the sites play an important role in sound propagation, where a portion of the signal extends below the water line and into the sediment. In muddy environments sounds are attenuated faster than in sandy environments due to the resonance frequency of trapped bubbles (Anderson and Hampton 1980). The result is that sounds of vessels in sandy bottoms are likely to propagate further in sand than the sound from vessels moving over muddy bottoms. Because my two “noisy” sites (NPR and NMM) had sandy bottoms and my two “quiet” sites (SMM and JBS) had muddy bottoms, it is likely that sound waves moving through the sediment from passing vessels were attenuated to a greater degree in the “quiet” sites than in the “noisy” sites. This sediment wave component of the sound signal was not measured in this study but is nonetheless important in sound detection, especially for the oyster toadfish. Research has demonstrated the importance of sound detection through particle motion in this species (Fay and Edds-Walton 1997, Yan et al. 2000). Future works needs to be completed on measuring the entire sound field (both particle motion and particle pressure) that the fish detects as well as to improve out ability to effectively measure the full hearing ability of fish.

Vessel presence and noise appear to reduce habitat quality by masking courtship signals, reducing parental care, or even elevating stress in fishes and other marine animals. Deleterious effects observed in this study from vessels could be associated with vessel noise, vessel presence, and/or vessel wakes. More research in necessary to identify the direct cause of reduced fitness in the oyster toadfish at “noisy” sites as compared with “quiet” sites. Because one “noisy” site (NPR) had no embryos and the second, less “noisy” site (NMM) had embryos, I hypothesize that there is a threshold of disturbance for these animals. Three hundred vessels per day or more may exceed an animal’s ability to adapt to a site with high vessel activity.

It is interesting to note that the measured ambient noise level is higher at SMM (a “quiet” site) than at NPR (a “noisy” site, Table 2.1). I hypothesize that this is the result of sound-producing marine life at the sites. The “noisy” site ambient noise levels were lower because there were less sounds produced my marine life overall, compared with that of the “quiet” site. While not directly investigated in this study, the overall soundscape at sites with high and low noise needs to be further investigated.

This study suggests population-level effects of vessels on oyster toadfish, which is a common estuarine species. I hypothesize that presently in North Carolina there are sufficient suitable “quiet” areas for oyster toadfish to reproduce. However, no population counts have been completed on the oyster toadfish over an extended time period, so the current population status compared to historical levels is unknown. The effects of vessel noise and activity on oyster toadfish and other soniferous fish populations, needs to be further studied. One reason is that a decline in the oyster toadfish population, due to increased vessel use around coastal areas (Laist et al. 2001, Hildebrand 2009, Slabbekoorn et al. 2010), could indirectly impact the Eastern oyster (*Crassostrea virginica*) population. Mud crabs (Xanthidae) consume juvenile oysters and mud crabs are heavily preyed upon by adult oyster toadfish (Wilson et al. 1982, Gibbons and Castagna 1985). Thus, fewer oyster toadfish might further decrease oyster stocks.

Management of underwater noise created by vessel activity is important because of the alteration of habitat quality and potential food web shifts associated with predator avoidance of “noisy” habitats. Vessels impact oyster toadfish behavior and are likely to alter the behavior of other sound-producing fish species such as red drum (*Sciaenops ocellatus*), spotted seatrout (*Cynoscion nebulosus*), and weakfish (*Cynoscion regalis*). Vessels have been shown to cause nest abandonment in the yellow-blotched map turtle (*Graptemys flavimaculata*, (Bulté et al. 2010).

Vessels influence marine mammal behavior. For example, mother-calf pairs significantly increase their whistling rate after boat exposure in the Pacific humpback dolphins (*Sousa chinensis*, Van Parijs and Corkeron 2001). Generally, bottlenose dolphins were more frequently observed in areas of low vessel activity, compared with high vessel activity, and newborn bottlenose dolphins were not observed in high vessel activity areas (Rako et al. 2013). Therefore, multiple studies indicate that vessels reduce habitat quality, potentially having an impact on fitness for many marine species.

On-water vessel activity, especially from inboard motorboats, needs to be managed. It is masking male courtship calls of at least one species of fish (oyster toadfish) and is contributing to a reduction in fitness levels for this species. Vessel activity and noise likely impact other fish species as well, along with marine mammals and sea turtles but more research needs to be conducted to understand how vessels impact the population status and fitness of marine life. Noise reduction will improve habitat quality to the benefit of many marine species as well as the human users who desire to interact with marine life and who use them as a source of food.

Acknowledgments

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CHAPTER 3 THE IMPACT OF VESSEL NOISE ON OYSTER TOADFISH (*OPSANUS TAU*) COMMUNICATION[2]

Abstract

Male oyster toadfish (*Opsanus tau*) produce boatwhistle sounds to attract females to shelters in shallow water estuaries. Male oyster toadfish courtship calls are produced in a natural soundscape that includes sounds from other animals ("biophony") such as snapping shrimp (Alpheidae) and bottlenose dolphin (*Tursiops truncatus*, toadfish predators) sounds. The purpose of this study is to determine if soundscape alterations from vessels and predators cause an acoustic disturbance in male oyster toadfish courtship calling behavior. Six sound types were played to oyster toadfish in shelters positioned 1 m from an underwater speaker: snapping shrimp sounds ("Shrimp", control), low-frequency ("LFDolphin") and high-frequency ("HFDolphin") bottlenose dolphin biosonar, inboard ("Inboard") and outboard motorboat ("Outboard") noises, and a combination of both inboard and low-frequency predator sounds ("Both"). Male oyster toadfish courtship calling rates were quantified at 600 s intervals before, during, and after noise exposure and repeated measures ANOVAs were used to compare mean differences in the percent change of calling rates over the playback periods. Playback sound type and site ("noisy" vs "quiet") significantly influenced oyster toadfish courtship calling rates ($F_{12,9} = 88.88$, $p \leq 0.001$). The acoustic disturbance effect was as follows: "Shrimp" ≤ "Outboard" < "Inboard" ≤ "LFDolphin" ≤ "HFDolphin" ≤ "Both." These results suggest that vessel noises and bottlenose dolphin sounds (predator) were detected by male oyster toadfish and both sound types can impede the calling behavior of male fish. In busy navigation channels, repetitive vessel noise may reduce mating success (fewer calls resulting in fewer mating opportunities) for male oyster toadfish compared with males calling in a natural soundscape.

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Introduction

Since the 1970s, there has been concern that anthropogenic noise may be adversely affecting marine life (Richardson et al. 1995), with vessel noise as a significant contributor to the soundscape at frequencies below 1.5 kHz (Richardson et al. 1995, Hildebrand 2009). Vessel noise conflicts with the vocalizations of marine life in frequency and is often of higher amplitude than the calls of marine animals (for review see: Götz et al. 2009, Slabbekoorn et al. 2010), resulting in masking (Frisk et al. 2003, Luczkovich et al. 2016a, Luczkovich et al. 2016b). Masking is defined as a noise that is strong enough to reduce the detectability of biologically-relevant sounds (Frisk et al. 2003).

Fishes have been shown to respond to vessel activity through displacement and avoidance behaviors. Avoidance behaviors include altering their swimming patterns, as shown in bluefin tuna (*Thunnus thynnus*, Sarà et al. 2007), cod (*Gadus morhua*, Engås et al. 1998), and herring (*Clupea harengus*, Engås et al. 1995). Additionally, reproductive and parenting activities have been interrupted by vessel activity. A slow, outboard motorboat and a paddled canoe within 5 m of the nest can cause the longear sunfish (*Lepomis megalotis*) to abandon his nest for up to 60 s, opening the nest up to predation (Mueller 1980). Red-mouthed gobies (*Gobius cruentatus*) spent more time in their shelters and damselfish (*Chromis chromis*) spent less time caring for their nests when exposed to boat noise sounds (Picciulin et al. 2010). These results suggest that there may be a fitness cost for the fish that is associated with vessel noise exposure or simply vessel presence.

If an animal remains in its habitat, it may be able to compensate for the increase in ambient noise due to vessels. To improve the detectability of a vocal call, animals have been shown to increase call amplitude (called the Lombard effect described by Lombard 1911, e.g. Holt et al. 2009, Parks et al. 2011, Luczkovich et al. 2016b), call rate (e.g. Turnbull and Terhune 1993, Van Parijs and Corkeron 2001), call duration (e.g. Foote et al. 2004), or quiet down and wait until the noise decreases (Zelick and Narins 1985, Terhune 1994). Compensation abilities for fishes seem to be limited. Most fishes that produce sound emit signals at frequencies below 1 kHz at sound pressure levels (SPLs) that rarely exceed 135 dB re 1 μPa (e.g. Luczkovich et al. 1999, Sprague and Luczkovich 2004, Vasconcelos et al. 2007, Locascio and Mann 2008, Parsons et al. 2009), but SPLs can reach higher levels 147 dB (Luczkovich et al. 1999) and 172 dB re 1 μPa (Parsons et al. 2012) if fish are producing sound simultaneously in large aggregations.

Fish do respond to the sounds of predators. Bottlenose dolphin (*Tursiops truncatus*) are a known predator of soniferous fishes (e.g. Barros and Wells 1998). The playbacks of their calls have led to declines in calling SPL values for the silver perch (*Bairdiella chrysoura*, Luczkovich et al. 2000) and reduced calling rates in the longspine squirrelfish (*Holocentrus rufus*, Luczkovich and Keusenkothen 2008) and Gulf toadfish (*Opsanus beta*, Remage-Healey et al. 2006). Yet, there was no difference in calling behavior when the Gulf toadfish was exposed to snapping shrimp (*Alpheidae* sp.) sounds (Remage-Healey et al. 2006). Presently, we are unaware of how vessel noise will alter courtship communication sounds in fishes.

Toadfishes (Batrachoididae) are model organisms for acoustics work and are the most well-studied soniferous fishes. They are fishes with swimbladders that are far from the ear (Fish and Offutt 1972, McKibben and Bass 1999, Sisneros and Bass 2005). The inner ears of toadfishes (Batrachoididae) hear best at frequencies under 200 Hz (Fish and Offutt 1972, Vasconcelos et al. 2007) but can detect sound at frequencies up to 800 Hz. However, hair cell sensitivity both in the inner ear and lateral line of toadfishes is primarily driven by the "movement" of sound (or acoustic particle motion) across the body ("accelerometer mode," Fay and Edds-Walton 1997, Yan et al. 2000). Toadfish (*Opsanus* spp.) call from shelters for long periods of time in shallow-water territories (Gray and Winn 1961, Barimo and Fine 1998, Thorson and Fine 2002a, 2002b) by rapidly contracting intrinsic sonic muscles next to their swimbladder (Skoglund 1961, Fine et al. 2001). Reproductively active, males settle in a nest/shelter (Gray and Winn 1961, Winn 1972) and create a tonal boatwhistle sound to attract mates (Gudger 1910, Gray and Winn 1961, Fish 1972, Møhl et al. 2000). Females then attach benthic eggs to the nest and the males fan and guard the embryos and larvae for up to a month, until the larvae are free swimming (Gray and Winn 1961).

The goal of this research is to discover if oyster toadfish, exposed to vessel noise, will modify their vocal behavior to overcome the masking effects of vessel noise in order to attract a mate. To test this, I used playback experiments in the natural environment to determine how different sounds affect male oyster toadfish courtship calling rates.

Methods

Playback Recordings

The sounds used for the playback experiments were created from digital recordings made in the field. Five of the six playback sound types were compiled from 10 s field recordings made using automated passive acoustic dataloggers (Long-term Acoustic Recorder System, LARS, Loggerhead Instruments, Sarasota, FL or the Fish Acoustic Buoy Underwater Logging System, FABULS, East Carolina University, Greenville, NC) between 2006 and 2013 (Table 3.1). The low-frequency bottlenose dolphin sounds used for the playbacks were recorded on a Sony TCD-D8 analog cassette recorder and HTI 96 min hydrophone in Southern Lagoon, Turneffe Atoll, Belize (17.18760° N, 87.88763° W) in June 2005. These seven digital recordings were compiled in a random order to create a single composite recording, with each file utilized eight or nine times (two files were used eight times) to create a 600 s long recording. In all of the playbacks, sounds of oyster toadfish courtship calls were avoided or removed from these recordings, but other sounds like snapping shrimp, water noises, and some other prominent fish sounds that co-occurred with the desired playback sounds were not removed. These are natural background sounds that influenced the frequency components within the playback signals.

Table 3.1. Information on the compilation of playback sounds for the playback experiments. Specific information on the files that were used to compile each playback sound for the playback experiments. Recordings were made on a LARS and FABULS at Back Sound, a LARS for the Neuse and Pamlico Rivers, and a Sony TCD-D8 analog cassette recorder and HTI 96 min hydrophone in Belize (reproduced from [Krahforst et al. 2016], with the permission from the Acoustical Society of America, see Appendix I for the copyright permission letter).

Playback Type	Recording Dates	Digital Sampling Rate (Hz)	Recording Location
LFDolphin	03 Jun 2005	44,100	Turneff Atoll, Belize
HFDolphin	09 - 22 Jul 2012	44,100	Back Sound, NC, USA
Inboard	19 - 30 May 2006 28 - 30 Jun 2007 01 - 16 Jul 2007 29 - 31 Aug 2008 01 - 05 Sep 2008	22,050	Pamlico and Neuse Rivers, NC, USA
Outboard	20 - 31 May 2006 11 - 30 Jul 2006 13 - 16 Jul 2007 11 - 30 Jul 2012	22,050	Back Sound, Pamlico and Neuse Rivers, NC, USA
Shrimp	24 Jun 2008 09 - 31 Jul 2012 01 - 12 Aug 2012 16 - 30 Apr 2013	22,050	Back Sound and Neuse Rivers, NC, USA

Experimental Procedure

Oyster toadfish naturally colonized artificial shelters that were established for the playback experiments (Animal Use Protocol #D292, Appendix A). Artificial oyster toadfish shelters, composed of a cement cube block (with 20 cm sides) with a central opening and a 7.6 cm PVC pipe inserted into the opening, were deployed during May and June 2013 at two sites (Figure 3.1). One site was considered “noisy” because it was on the Intracoastal Waterway, which had a lot of vessel traffic. The second site was a “quiet” site because vessel traffic was rarely observed (for more details on site characterization see: Luczkovich et al. 2016b, Sprague et al. 2016). At each site, a total of 48 shelters were deployed. These shelters were situated evenly in 12 replicates of 4 shelters over two treatments (seagrass and sand). Each replicate was spaced horizontally at a minimum distance of 370 cm. In each replicate, the shelters were arranged in a semi-circle around a central 150 cm long PVC pipe with a 15.2 cm diameter that was positioned 100 cm behind the shelters (Figure 3.2). This pipe marked the position for a Clark Synthesis AQ 339 underwater speaker used for the playbacks. Another 150 cm long, 15.2 cm diameter PVC pipe supported a reference hydrophone (InterOcean 902 and calibrated listening system with a VU meter to measure SPL over all frequencies) that was positioned at 100 cm in front of the shelters at the center of the set-up. When deploying the hydrophones, a hydrophone cable was held onto the PVC pipe using 90° pipe insulation and an adjustable clamp. One hydrophone (HTI) was positioned 100 cm in front of the shelters (Figure 3.2), while a second hydrophone (InterOcean 902) was positioned 100 cm in front of the speaker to assess overall playback amplitude in the field. Both hydrophones were positioned at 40 to 50 cm above the bottom.

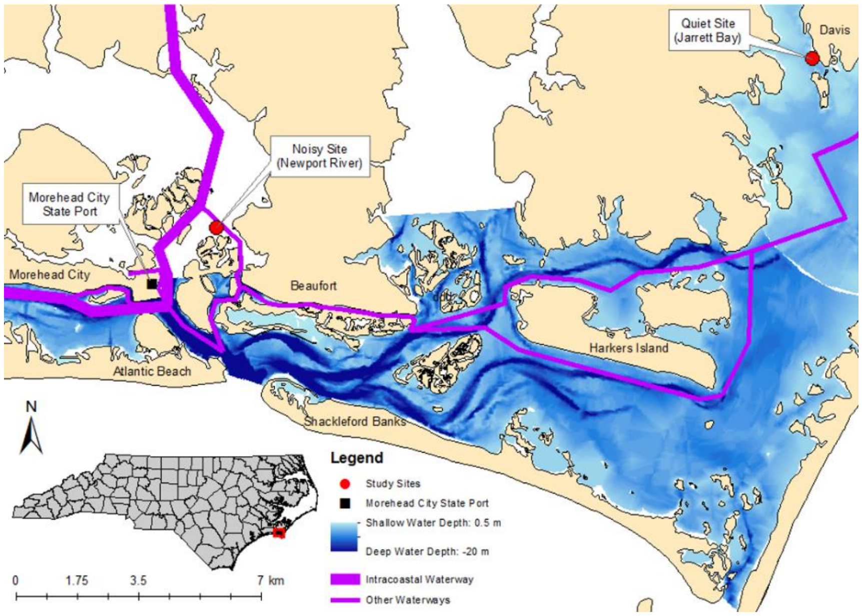

Figure 3.1. Study site map.

A map representing the study sites (red dots) for the playback experiments in Eastern North Carolina, USA. All shelters were placed in shallow water (mean depth of 1 m). Each site had a channel with sand flat that contained seagrass and was backed by a marsh. The "noisy" site is located along the Intracoastal Waterway and the "quiet" site is located away from the Morehead City State Port (black squares) and inlet traffic. The purple lines indicate some of the primary vessel navigation channels or waterways present within the area (reproduced from [Krahforst et al. 2016], with the permission from the Acoustical Society of America, see Appendix I for the copyright permission letter).

Playback experiments were conducted in July and August 2013, at least 1 month after the shelters were established to allow time for natural colonization by oyster toadfish. Six recordings of different types of sounds were used during the playback experiment. Each playback treatment consisted of 600 s of sound (sources described above) for the following sound exposure treatments: low-frequency bottlenose dolphin sounds ("LFDolphin"), high-frequency bottlenose dolphin sounds ("HFDolphin"), inboard motorboat ("Inboard"), outboard motorboat ("Outboard"), snapping shrimp ("Shrimp", a natural background sound used as a control), and the simultaneous playbacks of low-frequency bottlenose dolphin ("LFDolphin) and inboard motorboat ("Inboard") through two speakers ("Both"). Playbacks for a treatment at a single site occurred overnight between 1900 h and 0800 h, with one sound type played back at each replicate. The playback treatment was randomly selected during each nightly (sunset to sunrise) experiment. Recordings for 600 s before, during, and after sound exposure were made on a TASCAM DR-40E digital recorder (mono wav recordings, 44,100 Hz sampling rate, 16-bit sample size). The power spectra of the playback signals (amplitudes of the playback sound recordings at various frequencies) were assessed from a single experimental procedure.

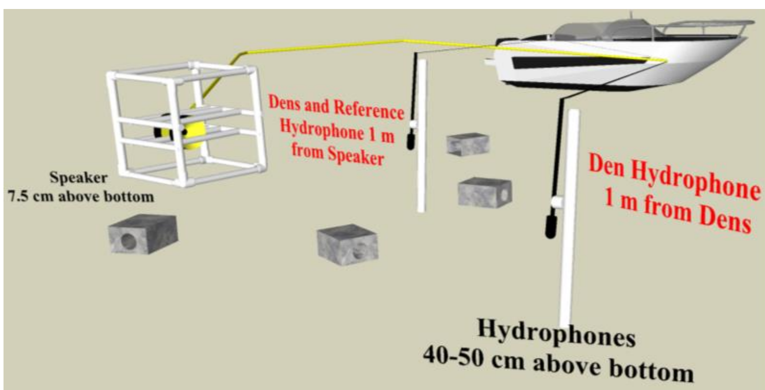

Figure 3.2. Diagram for the playback experiment set-up.

Diagram of how the oyster toadfish shelters were arranged and how the equipment was deployed to execute the playback experiment. All sites had a mean depth of 1 m (reproduced from [Krahforst et al. 2016], with the permission from the Acoustical Society of America, see Appendix I for the copyright permission letter).

Data Analysis

The recorded files generated in the experiment were analyzed using Fast Fourier Transform (FFT) with a 4096 point Hanning window and 50% overlap in Raven Pro (version 1.5 Beta, The Cornell Lab of Ornithology, Bioacoustics Research Program, 2013). Playback power spectral density (PSD) curves versus frequency curves were compared visually among playback types. Additionally, mean square pressure (p^2_{av}, proportional to power) values were determined for the oyster toadfish hearing range (50 to 1000 Hz) and for frequencies < 10 kHz. These p^2_{av} values were calculated by (1) multiplying the average power spectral densities by the frequency bin size (10.8 Hz) to obtain the p^2_{av} within each frequency bin; (2) the square pressures within each frequency bin were summed to obtain the p^2_{av} values in the desired frequency bands (f < 1000 Hz or f < 10 kHz); (3) these values were converted into dB with a reference value of 1 μPa^2. Comparisons were made across the total 1800 s experimental recording period, by comparing spectrum level differences before, during, and after a playback experiment.

The recordings were analyzed for oyster toadfish courtship calls in Raven Pro 64, with a human listener viewing interactively an oscillogram and spectrogram while playing back the recordings. Oyster toadfish call rates (number of boatwhistle calls/min) were assessed for the entire 600 s recording for all three recording periods. These call rates were used to identify changes in oyster toadfish calling behavior (% change) before and during playback exposure, and an analysis of variance (ANOVA) experimental design was employed to explore differences within a playback treatment. This ANOVA design was also applied to identify differences in courtship calling rates among experimental playback treatments and between sites, including differences in substrate type (seagrass or sand) within a single site. Bonferroni adjusted post-hoc analyses were used to assess differences in oyster toadfish calling rate (calls/60 s) by playback treatment and bottom type.

Results:

Characteristics of Playback Sounds

Playback sounds were different in terms of frequency and amplitude. The dominant frequencies within each playback varied, with all of the playbacks containing multiple peak frequencies (Table 3.2). In the playbacks, the received power increased compared with the recording period before sound-exposure (Figure 3.3) but this was dependent upon frequency. When comparing the before and during playback periods for mean square pressures (p^2_{av}) at frequencies < 10 kHz, "Both" low frequency dolphin and inboard motorboat caused the largest increase in p^2_{av} ($\Delta = +17$ dB re 1 μPa^2), followed by the "Inboard" ($\Delta = +6$ dB re 1 μPa^2) and "Outboard" ($\Delta = +6$ dB) motorboat playbacks, then "LFDolphin" ($\Delta = +5$ dB re 1 μPa^2), "HFDolphin" ($\Delta = +4$ dB re 1 μPa^2), and finally by the "Shrimp" ($\Delta = +3$ dB re 1 μPa^2) playback. When making comparisons limited to the auditory range of the oyster toadfish ($f < 1000$ Hz), the overall p^2_{av} value increased during the "Both" ($\Delta = +16$ dB re 1 μPa^2) and "LFDolphin" ($\Delta = +5$ dB re 1 μPa^2) playbacks but there was little to no overall increase in p^2_{av} in these low frequency components for "Inboard," "Outboard," and "Shrimp," playbacks ($\Delta = -1$ dB re 1 μPa^2). Finally, for the "HFDolphin" playback, there was actually a decrease in p^2_{av} at frequencies less than 1000 Hz ($\Delta = -7$ dB re 1 μPa^2). These results suggest that there were some differences in p^2_{av} by frequency within the playbacks. All six playbacks, after being played through the speaker, had a peak in p^2_{av} between 0 and 100 Hz (Figure 3.4). These low frequency components were associated with the sound of the hydrophone moving within the water column.

Table 3.2. Received mean square pressures (p^2_{av}, dB re 1 μPa^2) during the playback experiments.

The received mean square pressures (p^2_{av}, dB re 1 μPa^2) of the playback sounds collected on the HTI hydrophone (shelter hydrophone) that was 2 m in front of the speaker. The p^2_{av} are presented both in terms of the oyster toadfish hearing range (f < 1 kHz) and at f < 10 kHz, where f indicates frequency (Hz). Additionally, the dominant frequency components (Hz) within each of the playbacks source files are presented in order from lowest do highest dominant frequency.

Playback Sound Type	p^2_{av} Before (dB re 1 μPa^2)		p^2_{av} During (dB re 1 μPa^2)		p^2_{av} After (dB re 1 μPa^2)		Frequency Peaks (Hz)
	f < 1 kHz	f < 10 kHz	f < 1 kHz	f < 10 kHz	f < 1 kHz	f < 10 kHz	
"LFDolphin"	78.6	70.5	83.9	75.8	80.2	71.8	0 – 520 3300 – 3400 6000 – 6200
"HFDolphin"	90.5	80.6	83.0	84.4	90.4	80.5	10 – 30 80 – 140 3300 – 3400 4500 – 6200
"Inboard"	86.5	76.9	85.8	82.6	83.7	74.5	0 – 180 3300 - 3400 5000 – 5300 6000 – 6500
"Outboard"	84.2	71.9	83.1	81.2	84.7	80.8	0 – 50 100 – 180 4400 – 5200 6000 – 6300
"Both"	82.2	73.1	98.5	90.3	81.8	72.7	60 – 200 3200 - 4000 5600 – 6100
"Shrimp"	81.2	72.5	80.6	76.0	79.3	71.0	0 – 180 4600 – 5200 6000 - 6300

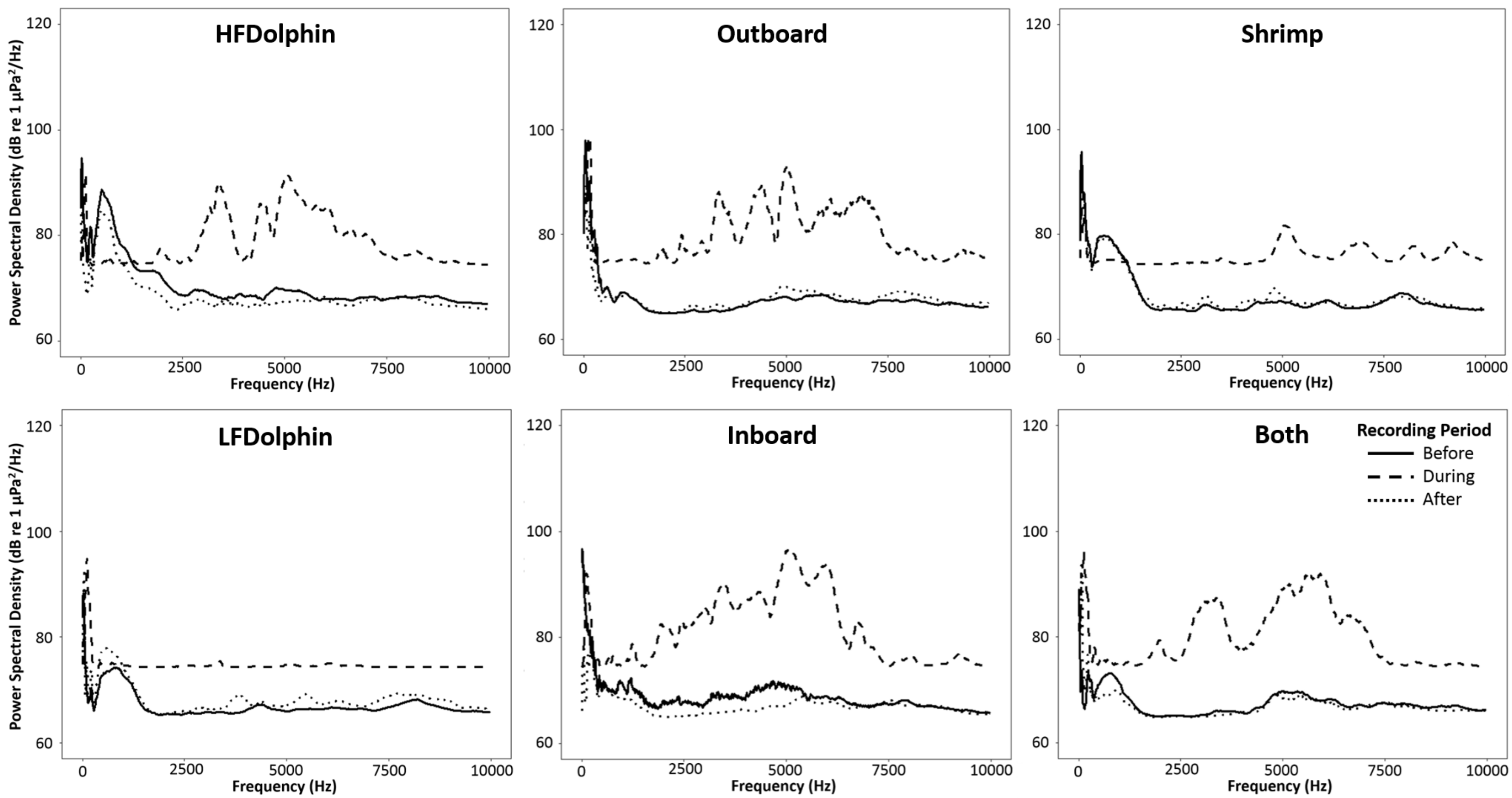

Figure 3.3. Power spectral density curves before, during, and after a playback experiment at JBS in sand.

An example of power spectral densities at 2 m from the speaker during one experiment at JBS in sand. Each of the power spectra are based on the estimates of power spectral densities (using Welch's method). The remainder of the PSD curves can be found in Appendix D.

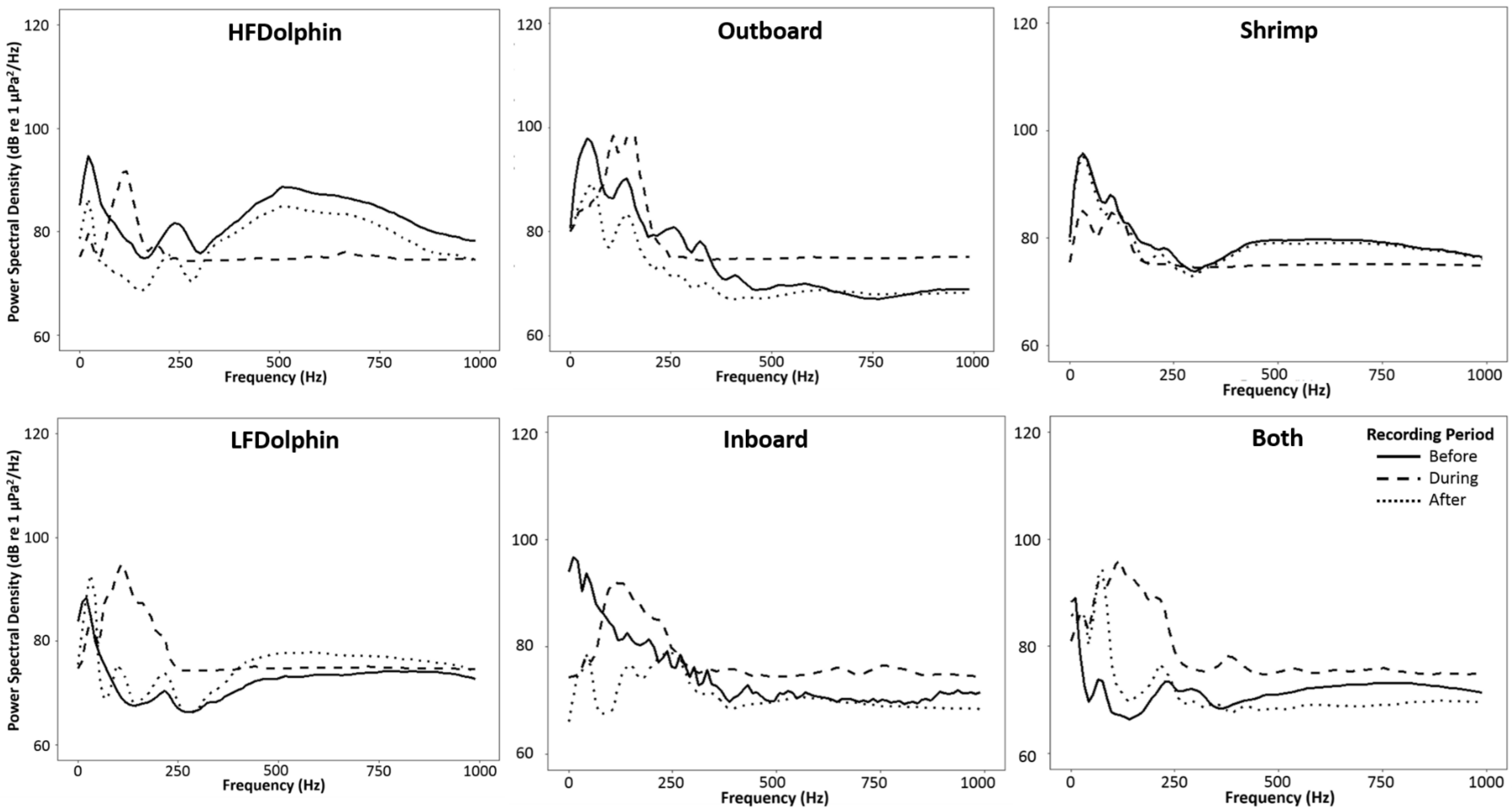

Figure 3.4. Power spectral density curves within the hearing range of the oyster toadfish before, during, and after a playback experiment at JBS in sand.

An example of power spectral densities within the hearing range of the oyster toadfish (50 to 1000 Hz) at 2 m from the speaker during one experiment at JBS in sand. Each of the power spectra are based on the estimates of power spectral densities (using Welch's method). The remainder of the PSD curves can be found in Appendix G.

Calling Rate Changes during Playback

The change in oyster toadfish courtship calling rate (%) varied significantly by site ("noisy" vs "quiet") and by playback type. The ANOVA model explained 97.4% of the variability in oyster toadfish courtship calling rates ($F_{12,9} = 88.88$, $p < 0.001$). Playback sound type alone explained 36.7% of this variability in the model ($F_{5,9} = 28.13$, $p < 0.001$) and site explained 3.5% of the model's variability ($F_{1,9} = 13.34$, $p = 0.005$). The interaction between site and playback type, however, explained 57.4% of the model's variability ($F_{5,9} = 43.92$, $p < 0.001$).

There were declines in oyster toadfish courtship calling rates during the sound playbacks, which varied among playback types. Differences were observed when comparing the before and during playback courtship calling rates as a function of playback sound type (Figure 3.5). Snapping shrimp playbacks ($\bar{X} = -15.6\%$ relative to before period calling rate, $SE = 42.56$) and outboard motorboat playbacks ($\bar{X} = -39.1\%$ relative to before period calling rate, $SE = 60.89$) had the least impact on change in male oyster toadfish calling rates. Oyster toadfish calling rate declined significantly during the inboard motorboat playbacks ($\bar{X} = -70.4\%$ relative to before period calling rate, $SE = 11.05$), low-frequency bottlenose dolphin playbacks ($\bar{X} = -90.5\%$ relative to before period calling rate, $SE = 6.16$), high-frequency bottlenose dolphin playbacks ($\bar{X} = -95.1\%$ relative to before period calling rate, $SE = 4.69$), and both bottlenose dolphin and vessel sounds playbacks ($\bar{X} = -100\%$ relative to before period calling rate, $SE = 0.00$). These latter inboard vessel and bottlenose dolphin playback types all caused significant declines in calling rates relative to snapping shrimp and outboard playback types, although these declines in calling rate responses did not differ from each other.

Oyster toadfish calling rates were different at the "noisy" and "quiet" sites. The oyster toadfish from the "quiet" site showed a 20.71% greater decline in calling rate than the fish from the "noisy" site (Figure 3.6). Thus, fish consistently inundated by anthropogenic noise seem to react differently to playback sounds than fish at sites with only a rare occurrence of anthropogenic noise.

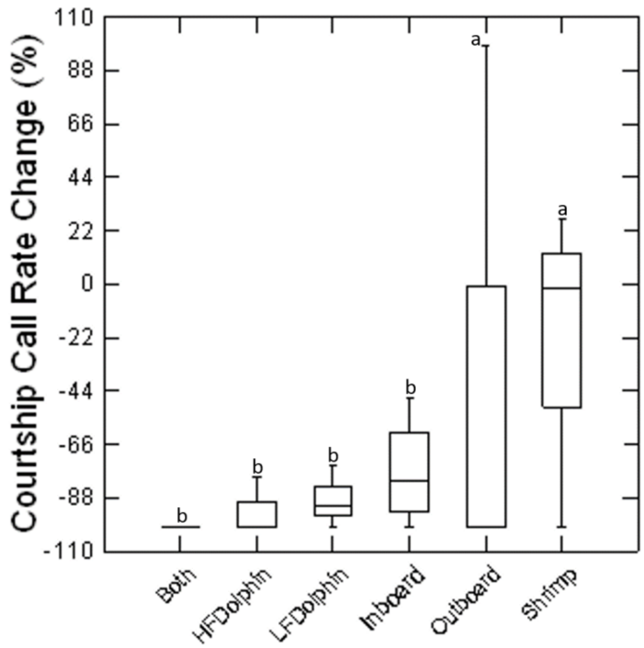

Figure 3.5. Changes in male oyster toadfish courtship call rates during playback experiments.

Acoustic disturbance of oyster toadfish courtship calling rates. The median change in oyster toadfish courtship calling rate (% change) during the playback of various sound types is shown. Playback treatment groups with different lowercase letters represent significant (p < 0.01) differences. Boxplots show the median (50th percentile at the horizontal line) and the region which contains 50% of data around the median (25th to 75th percentiles). The vertical bars show the region in which change in calling rates fall within 1.5 * the upper and lower interquartile ranges (lower interquartile: 25th to 50th percentile range; upper interquartile: 50th to 75th percentile range, reproduced from [Krahforst et al. 2016], with the permission from the Acoustical Society of America, see Appendix I for the copyright permission letter).

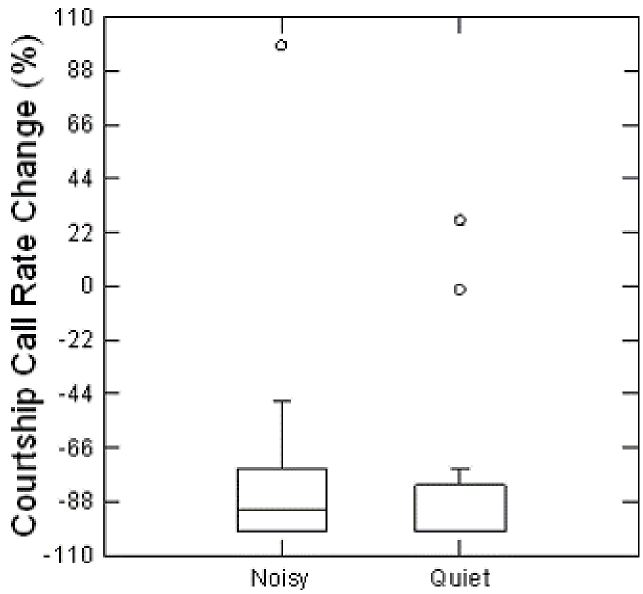

Figure 3.6. Changes in male oyster toadfish courtship call rates by site noise levels during the playback experiments.

Oyster toadfish courtship calling rate change (%) by study site ("noisy" versus "quiet" sites). Oyster toadfish reacted more at the "quiet" site compared with the "noisy" site (Δ = - 20.71, p = 0.005). Boxplots show the median (50th percentile at the horizontal line) and the region which contains 50% of data around the median (25th to 75th percentiles). The vertical bars show the region in which observations fall within 1.5 x upper and lower interquartile ranges (lower: 25th to 50th percentile range; upper: 50th to 75th percentile range). Points outside of the 1.5 x the upper and lower interquartile ranges are shown as open circles (reproduced from [Krahforst et al. 2016], with the permission from the Acoustical Society of America, see Appendix I for the copyright permission letter).

Calling Rate Changes After Playback

There was no difference in the rate (calls/60 s) of male oyster toadfish courtship calls before ($\bar{X}$ = 12.0 calls/60 s, *SE* = 3.07) and after ($\bar{X}$ = 11.1 calls/60 s, *SE* = 2.95) playback sound exposure of all sound treatments (Figure 3.7). Thus, oyster toadfish calling rates quickly (within 600 s) returned to pre-exposure rates after being subject to the different playback sounds. Differences in oyster toadfish courtship calling rates after the playbacks were evident between study sites. The ANOVA model, which included bottom type and site explained 70.0% of the variance in the data set. The "noisy" site had an average of 9.6 more calls on average than the "quiet" site (Figure 3.7, ANOVA, $F_{1,17} = 5.96$, $p = 0.026$). In addition, oyster toadfish residing in sandy bottoms called less ($\bar{X}$ = 5.7 calls/60 s, *SE* = 2.51) than oyster toadfish residing in seagrass bottom habitats ($\bar{X}$ = 16.0 calls/60 s, *SE* = 2.89, ANOVA, $F_{1,17} = 12.34$, $p = 0.003$) but this was dependent upon site (Figure 3.8). The interaction between site and bottom type was highly significant (ANOVA, $F_{1,17} = 17.33$, $p = 0.001$). At the "quiet" site, oyster toadfish calling rates were similar in sand ($\bar{X}$ = 8.3 calls/60 s, *SE* = 3.57) and seagrass ($\bar{X}$ = 3.9 calls/60 s, *SE* = 0.71). At the "noisy" site, oyster toadfish called more in seagrass ($\bar{X}$ = 28.0 calls/60 s, *SE* = 2.83) than in sand ($\bar{X}$ = 0.4 calls/60 s, *SE* = 0.16).

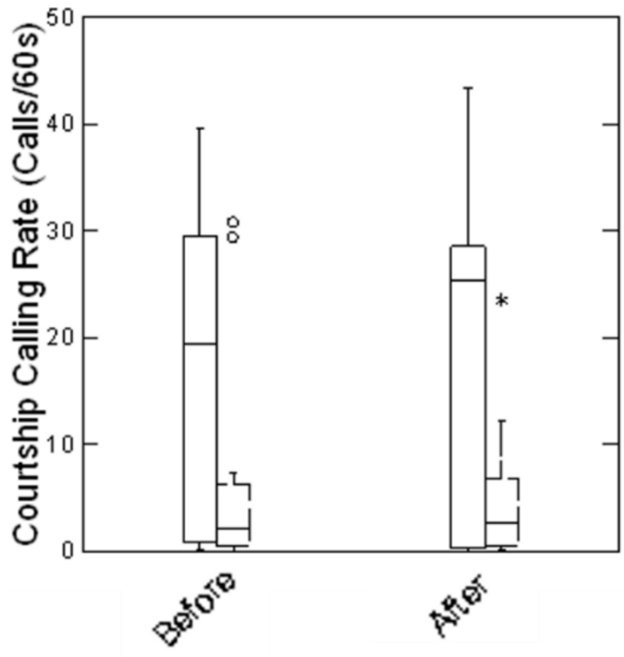

Figure 3.7. Changes in male oyster toadfish courtship call rates before and after the playback experiments.

Median oyster toadfish courtship calling rates (calls/60 s) before and after the playback experiment as a function of the study site (“noisy” vs “quiet”). The “quiet” site is represented by the dashed boxplot lines and the “noisy” site is represented by the solid boxplot lines. Boxplots and interpretation of the symbols are given in Figure 3.5 and Figure 3.6 (reproduced from [Krahforst et al. 2016], with the permission from the Acoustical Society of America, see Appendix I for the copyright permission letter).

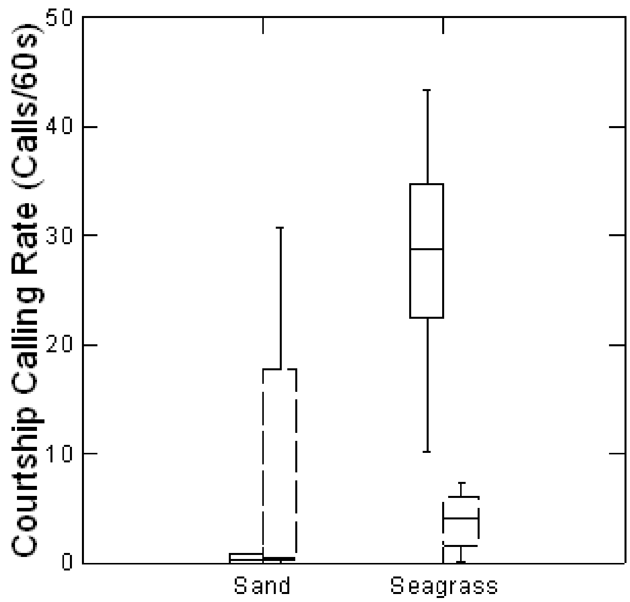

Figure 3.8. Changes in male oyster toadfish courtship call rates by bottom type during the playback experiments.

Oyster toadfish courtship calling rate (calls/60 s) before and after the playback experiment by site ("noisy" vs "quiet") and bottom type (seagrass vs sand). The "quiet" site is represented by the dashed line and "noisy" site is represented by the solid line. Boxplots and interpretation of the symbols are given in Figure 3.5 and Figure 3.6 (reproduced from [Krahforst et al. 2016], with the permission from the Acoustical Society of America, see Appendix I for the copyright permission letter).

Discussion:

Oyster toadfish reacted to inboard motorboat and bottlenose dolphin (predator) sound playbacks with a depressed calling rate during sound exposure. In a related study conducted using field recordings in heavily trafficked areas, Luczkovich et al. (2016a) also showed depressed calling rates in the oyster toadfish in an area with high vessel traffic relative to an area with low vessel traffic. Additionally, Luczkovich et al. (2016b) observed the Lombard effect in oyster toadfish at the same study sites described in this paper. The authors identified higher call amplitudes at the "noisy" compared with the "quiet" site. Here, I discuss the results of playback experiments from the standpoint of sound levels received by the oyster toadfish, their assumed hearing thresholds, and the ecological impacts of vessel noise.

The received levels of all of the playback sounds had the highest peaks between 50 Hz and 200 Hz, which is within the auditory range of the oyster toadfish (50 to 1000 Hz, Fish and Offutt 1972) but "Inboard," "LFDolphin," and "Both" contained the most energy at these frequency ranges. However, there were also multiple high-frequency peaks above 2000 Hz within all of the playbacks. These frequencies (f >2000 Hz) are believed to be outside of the oyster toadfish's auditory range. The power spectral densities increased within the hearing range (f < 1000 Hz) of the toadfish only for the "Both" and "LFDolphin" but it is important to remember that there is other sound-producing marine life at these sites. So, the minimal change in energy within these frequency bands, which was observed for the "Inboard" playback, could have been due to changes in the sounds produced by other marine fishes (e.g. Atlantic croaker, silver perch, oyster toadfish, etc). For three playbacks, "Shrimp," "Outboard," and "HFDolphin," I expected to see little or no energy change in these low-frequency bands because their peak frequencies are above that of the hearing range of the oyster toadfish. These playbacks were selected because of the higher frequency (f > 1000 Hz) components to their signals and were not expected to cause much of an increase in power spectra at these low frequencies. In the "Shrimp" and "Outboard" playbacks, there was nearly no change in the sound pressure for frequencies below 1000 Hz but for "HFDolphin," there was a decrease in sound pressure over the same frequency range. This decrease could have been attributed to other species responding to the sound within the area.

The received power spectra did not correspond to the observed changes in calling rates in the oyster toadfish. A small change in calling rates occurred in response to the “Outboard” and “Shrimp” playbacks. The greatest reduction in calling rates occurred for the “Both” playback, followed by “HFDolphin”, “LFDolphin”, and finally “Inboard” sounds. Therefore, predator sounds alone or in combination with inboards caused the greatest decline in oyster toadfish calling rates. However, inboards alone also caused a significant decline in calling rates, relative to “Shrimp” and “Outboard” motorboat playbacks. Multiple species of fish stopped feeding and scattered in the presence of an oncoming outboard motorboat in a common motorboat and fishing location (Mensigner et al. 2016). However, in an area that was not a fishing ground, the fish ignored the sound of the oncoming boat and continued feeding (Mensigner et al. 2016).

These changes in oyster toadfish calling rates do not seem to be associated with received levels of low-frequency (50 to 1000 Hz) sound during the playbacks. If low-frequency sound increases alone were causing the calling rate declines, these calling rate declines would not have been evident within the “HFDolphin,” and “Inboard” playbacks. Additionally, if high-frequency sounds alone were causing these calling rate differences I should have observed oyster toadfish calling rate declines for the “Outboard” playback but calling rate changes in the “Outboard” playback were not significantly different from “Shrimp.” Thus, the frequency content of the playback signal alone is not influencing oyster toadfish calling rate changes. I speculate that the fish are responding to the ecological context associated with that playback sound with predator sounds and inboard motorboat noise causing the greatest decline in calling rate. For example, the “HFDolphin” playback contained the sounds of other soniferous fishes (e.g. silver perch *Bairdiella chrysoura*).

Research has demonstrated that silver perch detect and respond to the higher frequency sound components of dolphins (Luczkovich et al. 2000). If silver perch are responding to the dolphin sounds and oyster toadfish detect these lower frequency shifts in the calls of silver perch (and other fish), then they may recognize that there is a nearby predator and thus react accordingly.

Regardless of the playback sound, there are some differences in calling rates by site. Oyster toadfish in the “noisy” site called more often than oyster toadfish in the “quiet” site. I speculate that a behavioral modification has occurred, in which oyster toadfish use quiet periods between vessel passages at the “noisy” site to call at higher rates. The same modification is not evident at the “quiet” site. Oyster toadfish sonic muscles are fatigue-limited (Mitchell et al. 2008), indicating that sustained elevated acoustic activity cannot be maintained for long time periods. Thus, the cost of burst calling behavior, observed at the “noisy” site, is a sonic muscle recovery period where the fish is less likely to call. This burst calling behavior would result in an oyster toadfish at a “noisy” site calling at an increased rate during quiet times until it utilizes its stored glycogen, then recovering during the “noisy” periods when a vessel is passing near the site. Such a behavioral strategy would maximize the call rate during quiet periods. However, if the male oyster toadfish loses its ability to be heard by a mate during the passage of a vessel, and if there are many vessel passages per day, then males residing in “noisy” sites could have decreased individual fitness, compared with males from a “quiet” site. Additionally, if vessel noise causes male oyster toadfish to leave the nest like it does for the longear sunfish (*Lepomis megalotis*, Mueller 1980) and damselfish (*Chromis chromis*, Picciulin et al. 2010), then nests could be more frequently preyed upon, further reducing an individual’s reproductive fitness.

In this study, there was also a bottom-type effect (seagrass vs sand). Overall, fish called more frequently in seagrass than in sand but there was an interaction with site noise level (“noisy” vs “quiet”). The “acoustic refuge hypothesis” (for review see Wilson et al. 2013) suggests that seagrasses absorb and scatter an acoustic signal. Using high frequency (100 – 500 kHz) echosounders, McCarthy and Sabol (2000) demonstrated that seagrasses made it more difficult to detect underwater mines (self-contained explosive device) than sediment without seagrass. A second study, demonstrated up to an 88% reduction in sound propagation at low-frequencies (300-500 Hz) compared with sandy/bare type bottoms (Wilson et al. 2013). Oyster toadfish may call more in seagrass because of the signal attenuation by seagrass but oyster toadfish may also be less impacted by ambient noise when residing in seagrass as opposed to sandy bottom types.

I did not directly analyze the received sound levels within the oyster toadfish shelters, but Sprague et al. (2016) conducted an analysis in the same area that: (1) created a sound exposure model and found that the sounds of passing vessels in the navigation channels near the sites were significantly higher at the “noisy” than the “quiet” site; (2) determined that the sound pressure level of the ambient soundscape at the “noisy” site was higher than the “quiet” site; (3) by using an oyster toadfish weighted hearing function and modeling the propagation of noise from passing vessels into the study site, the authors concluded that the noises of vessels should be audible by the oyster toadfish in their shelters.

Future studies are needed to further explore the behavioral effects of noise on fish. Observed differences between playbacks and sites could have been associated with the number and length distribution of the oyster toadfish population. Attempts were made to quantify the number of oyster toadfish and these will be reported in Chapter 4. Additionally, no visual observations of behavior during the playback experiments were assessed during this study and these studies need to be completed to understand how vessel activity can influence the reproductive success of this and other species of soniferous fishes.

Conclusion

The results of this work suggest that the content of a single sound within a soundscape alters the courtship calling behavior of male oyster toadfish, with inboard motorboats and bottlenose dolphin sounds causing declines in calling rates and snapping shrimp and outboard motorboats causing no significant change in calling rate behavior. However, oyster toadfish do compensate for their dominant soundscape by calling more frequently during quiet periods and by increasing the amplitude of their calls during noise exposure. Further research is underway to address how the soundscape influences fish fitness and development.

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CHAPTER 4 VESSELS REDUCE REPRODUCTIVE OUTPUT IN A VOCAL FISH SPECIES

Abstract

Vessel activity has caused a 7-fold increase in underwater low-frequency ambient noise levels since the 1950's. Because males of many fishes make courtship sounds to attract females in the same low-frequency range as vessels, increased vessel noise can interfere with mate recognition and spawning behaviors. Here, I test if oyster toadfish (*Opsanus tau*) females have a lower reproductive output in areas with high vessel activity. Oyster toadfish shelters, where males normally make mating calls to attract females, were deployed near and far from a vessel navigation channel at otherwise similar "noisy" (high vessel activity) and "quiet" (low vessel activity) sites. The number of oyster toadfish and the embryos attached to their shelters were quantified weekly at each site. Oyster toadfish were less abundant at "noisy" sites. The noisiest site (Newport River, NPR) had the fewest and the smallest oyster toadfish. The number of egg clutches also varied by site, with NPR containing no embryos; but egg clutches were present at the three other sites. At North Middle Marsh (a "noisy" site), the number of embryos was significantly smaller than at the two "quiet" sites. These data suggest that vessel noise is impacting the reproductive success of the oyster toadfish and may be lowering the fitness of other vocal fishes.

Introduction

Underwater anthropogenic noise is a growing management concern. Low-frequency ($\leq$ 300 Hz) noise has increased by up to 3 dB per decade between the 1960s and the early 2000s (McDonald et al. 2006, Hildebrand 2009), with an increase in at least 20 dB from pre-industrial conditions (Hildebrand 2009). Sound pressure squared is measured on a logarithmic scale (Urick 1983) so a 3 dB increase in sound pressure squared is equivalent to doubling the amplitude of ambient sound. This increase is, in part, attributed to increased vessel activity on the water (Rako et al. 2013a). At frequencies under 200 Hz, the propulsion system of vessels is the dominant source of noise energy. Cavitation, which is generated from the tips of the vessel's propeller blades, is a component of noise across a broadband frequency range (Hildebrand 2009) but is most dominate between 100 Hz and 1.0 kHz (Urick 1983). Hence, low-frequency (< 500 Hz) ambient noise is dominated by commercial shipping traffic and the noise generated from small vessels is an important component of the mid-frequency bands (500 Hz – 25 kHz, Hildebrand 2009). Considering vessel traffic overlaps the acoustic communication and the hearing ranges of marine life (Erbe, 2002, Haviland-Howell et al. 2007), then this increase in noise pollution from vessel activity may lead to impacts on animals within the marine environment.

Sound is an important mode of communication underwater. Marine life utilize acoustic communication for a variety of functions including mating, agonistic displays, disturbance, alarm calls, foraging, and navigation (Richardson et al. 1995, Luczkovich et al. 2010). Noise from vessel activities is a form of acoustic pollution that can affect habitat quality (Tyack 2008). Vessel noise has been shown can 'mask' biologically relevant signals (e.g. Vasconcelos et al. 2007, Krahforst et al. 2016). Masking is defined as a noise that is strong enough to reduce the detectability of biologically-relevant sounds (Frisk et al. 2003). Masking of communication signals can cause behavioral disturbances (e.g. Engås et al. 1995, Nowacek et al. 2007, Parks et al. 2007, Sarà et al. 2007), hearing loss (Erbe and Farmer 1998, Scholik and Yan, 2001, Ramcharitar and Popper 2004, Nowacek 2005, Vasconcelos et al. 2007), the Lomdard effect (Lombard 1911) or increased call SPL values (Scheifele et al. 2005, Holt et al. 2009, Miksis-Olds and Tyack, 2009, Parks et al. 2011, Holt and Johnston 2014, Luczkovich et al. 2016b), interference in communication rates (Finley et al. 1990, Asselin et al. 1993, Lesage et al. 1999, Parks et al. 2007, Azzara et al. 2013, Krahforst et al. 2016), and an increase in call duration and increased call repetition (Miller et al. 2000). Masking can even interfere with predator and prey detection (Luczkovich et al. 2000, Remage-Healey et al. 2006, Luczkovich and Sprague 2008, Krahforst et al. 2016).

The impact of vessel noise has been best studied in marine mammals. For example, Erbe (2002) modeled the call of a killer whale (*Orcinus orca*) and determined that it was masked by a tourist boat at distance of up to 14 km. Boat noise can be a source of chronic harassment for many species (Haviland-Howell et al. 2007) because vessel noise overlaps (in region, frequency, and time) and exceed the sound pressure level (SPL) of the ambient environment, especially the acoustic calls of fishes (Götz et al. 2009, Slabbekoorn et al. 2010). This reduces the active space in which an animal is able to detect a conspecific's call (Jensen et al. 2009). Based on a 3 dB per decade increase in amplitude at 20 Hz due to shipping noise (Andrew et al. 2002, McDonald et al. 2006), the active space of a finback whale's (*Balaenoptera physalus*) call was modeled to be reduced from 90 km in the 1960s to 32 km in 2001, under the same hypothetical environment but with increased vessel noise (Tyack 2008). Additionally, a small vessel traveling at 2.6 m/s (5 kts) reduces the communication range of bottlenose dolphins (*Tursiops sp.*) by 26% shallow water and 58% in deep water (Jensen et al. 2009). However, a key concept here is that marine mammals often show a propensity to adapt and alter their communication signals to improve the detectability of their calls. Some marine mammals alter the frequency of their calls (Au et al. 1985, Morisaka et al. 2005, Parks et al. 2007), the length of a call (Foote et al. 2004), the call structure (Morisaka et al. 2005), their calling rates (Van Parijs and Corkeron, 2001, Parks et al. 2007, Azzara et al. 2013), or the SPL values of their signal (Au et al. 1985, Scheifele et al. 2005) in response to increased ambient noise levels.

Vessel noise causes stress responses and altered hearing abilities in fishes. The heart rate of largemouth bass (*Micropterus salmoides*) increased by 67% when exposed to the noise of a combustion engine (Graham and Cooke 2008) but when exposed to a simulated predator attack, their heart rate increased by only 44% (Cooke et al. 2003). Additionally, various freshwater fishes exhibited elevated blood cortisol levels when exposed to ship noise. These increased cortisol levels were not evident in the fish exposed to no-noise and white-noise controls (Wysocki et al. 2006). Noise generated from vessel activity also leads to elevated auditory thresholds, or an inability to hear or respond to stimuli at SPL values lower than the threshold. An outboard motorboat elevated the auditory thresholds in the fathead minnow (*Pimephales promelas*) by a maximum of 13.5 dB, but these auditory threshold levels depended upon the tested frequency (Scholik and Yan 2002). Another study on the Lusitanian toadfish (*Halobatrachus didactylus*) demonstrated that vessel noise (~ 131 dB re 1 μPa) caused a 36 dB hearing threshold shift at 50 Hz (Vasconcelos et al. 2007). For a Lusitanian toadfish, a 50 Hz signal needs to be up to 36 dB above the background noise to be detected when there is a nearby vessel.

While fishes exhibit stress and auditory threshold responses to vessel noises, they also have a simple sound-producing mechanism, involving, in most cases, a pair of sonic muscles and swimbladder. Unlike marine mammals, the ability of fishes to alter their call characteristics in response to increased ambient noise levels is likely limited. Oyster toadfish (*Opsanus tau*) sonic muscles are prone to fatigue due to limited glycogen storage (Mitchell et al. 2008). This suggests that oyster toadfish have a physiological limitation to their ability to call at higher rates and at increased amplitudes. While previous research has demonstrated that oyster toadfish do respond to vessel noise by decreasing their calls (Krahforst et al. 2016) and by increasing their call SPL values (Luczkovich et al. 2016b, i.e. the Lombard effect Lombard 1911), they do not show the same ability to shift frequencies (Luczkovich et al. 2016b) as marine mammals do to avoid the same frequency bands at vessels (Parks et al. 2007). Therefore, it is unlikely that oyster toadfish will demonstrate the range of vocal modifications identified in marine mammals.

One way fishes may be able to adapt to noise is through avoidance behaviors, including habitat-use shifts. Some studies have found evidence of avoidance behaviors in fishes exposed to vessels such as reduced schooling behaviors (Sarà et al. 2007), swimming movements away from the vessel (Engås et al. 1995, 1998; Sarà et al. 2007), and reduced swimming speeds (Engås et al. 1998). These behavioral reactions, however, seem to be short-lived and disappear quickly after the noise exposure reaches its maximum level (Engås et al. 1995). Further research on settling larval fishes has demonstrated that the fish responded to sounds they had been previously exposed to but were repelled by other "foreign" sounds (Simpson et al. 2010). These studies suggest the importance of acoustic cues to fishes. At this time, no one has demonstrated that vessels have population-level consequences in fishes, such as lower survival or a decrease in reproductive output. In this study, I showed both a shift in habitat-use and a decline in reproductive output by the oyster toadfish in areas of high compared with areas of low vessel noise.

Model Species

Toadfishes (*Opsanus* spp.) are model organisms for acoustics work (Tavolga 1958, Fish 1972, Winn 1972, Fine and Thorson 2008). Oyster toadfish hear up to 800 Hz (Fine 1978, Yan et al. 2000), with the most sensitivity below 200 Hz (Fish and Offutt 1972, Vasconcelos et al. 2007). However, hair cell sensitivity both in the inner ear and lateral line of toadfishes is primarily driven by the "movement" of sound (or acoustic particle motion) across the body ("accelerometer mode," Fay and Edds-Walton 1997, Yan et al. 2000). Boatwhistles are produced by males residing in shelters for long periods of time in shallow-water territories (Gray and Winn 1961, Winn 1972, Barimo and Fine 1998, Thorson and Fine 2002a, 2002b). Mating calls are produced by rapid contractions of intrinsic sonic muscles, causing a vibration of the swimbladder (Skoglund 1961, Fine et al. 2001), which makes a tonal boatwhistle sound (Figure 4.1) that attracts females (Gudger 1910, Gray and Winn 1961, Fish 1972, Winn 1972). Females attach benthic eggs to the shelter and males fan and guard the embryos and larvae for up to a month until they are free swimming (Gudger 1910, Gray and Winn 1961). Because of the similarity of frequencies produced by some vessels (< 200 Hz, Hildebrand 2009) and the boatwhistle call (~200- 250 Hz average frequency of the dominant frequency, Figure 4.1) of the male oyster toadfish, the noise produced by vessels masks the courtship calls of male oyster toadfish (Figure 4.2, Krahforst et al. 2016). I hypothesize that masking of male oyster toadfish courtship calls will lead to decreased female attraction and reduced reproduction. The purpose of this work is to test the impact of vessels on the reproductive output of the oyster toadfish.

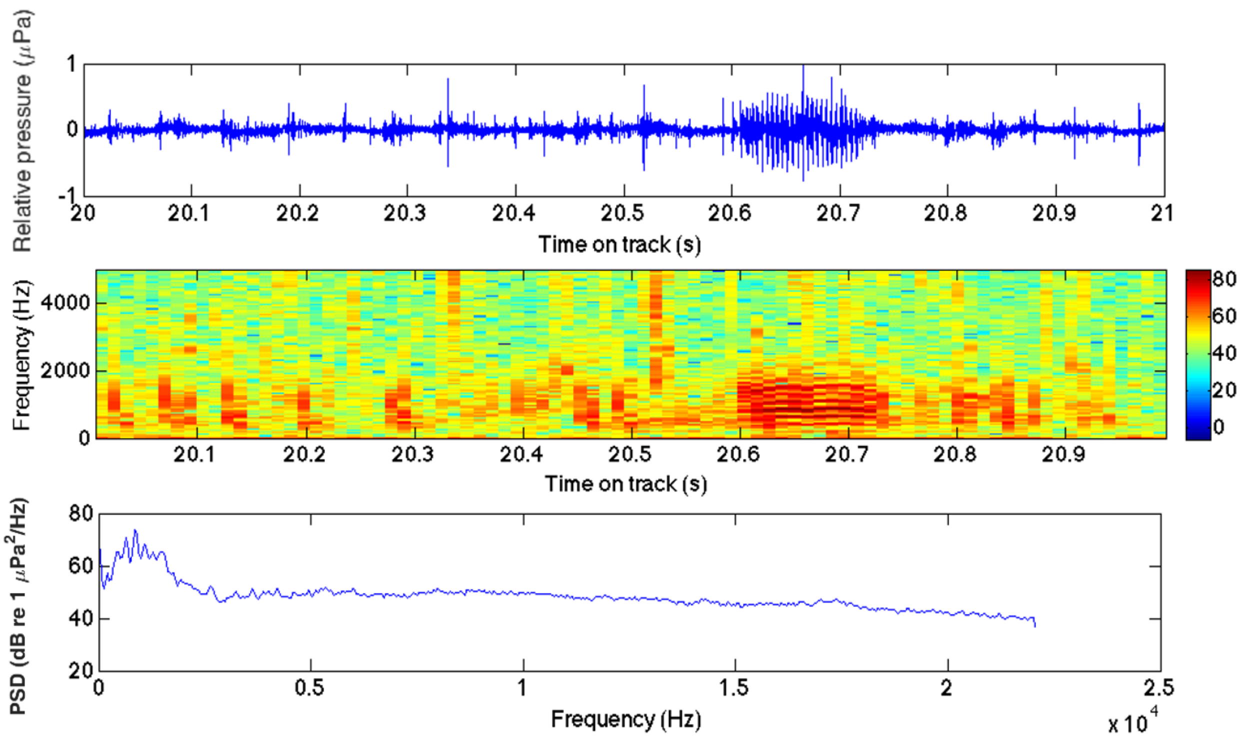

Figure 4.1. Recording of an oyster toadfish boatwhistle call.

An example of the boatwhistle sound from an oyster toadfish, with a fundamental frequency between ~ 200 and 250 Hz. This recording was made on July 25, 2013 at 03:50 AM at the Jarrett Bay Site in NC. Top: Oscillogram of the natural soundscape, demonstrating the variation in relative pressure of the ambient soundscape across time. The oyster toadfish boatwhistle is evident on this oscillogram between 20.6 and 20.75 s. Middle: A spectrogram demonstrating the power and frequency of the signal as it varies through time in the recording. This spectrogram was created using an FFT of 1024 with a 512 point Hanning window (50% overlap). The hotter (red) the color, the higher the power of the sound (in dB re 1 μPa). Bottom: A power spectral density curve, where the peak in this curve demonstrates the fundamental frequency of the boatwhistle sound.

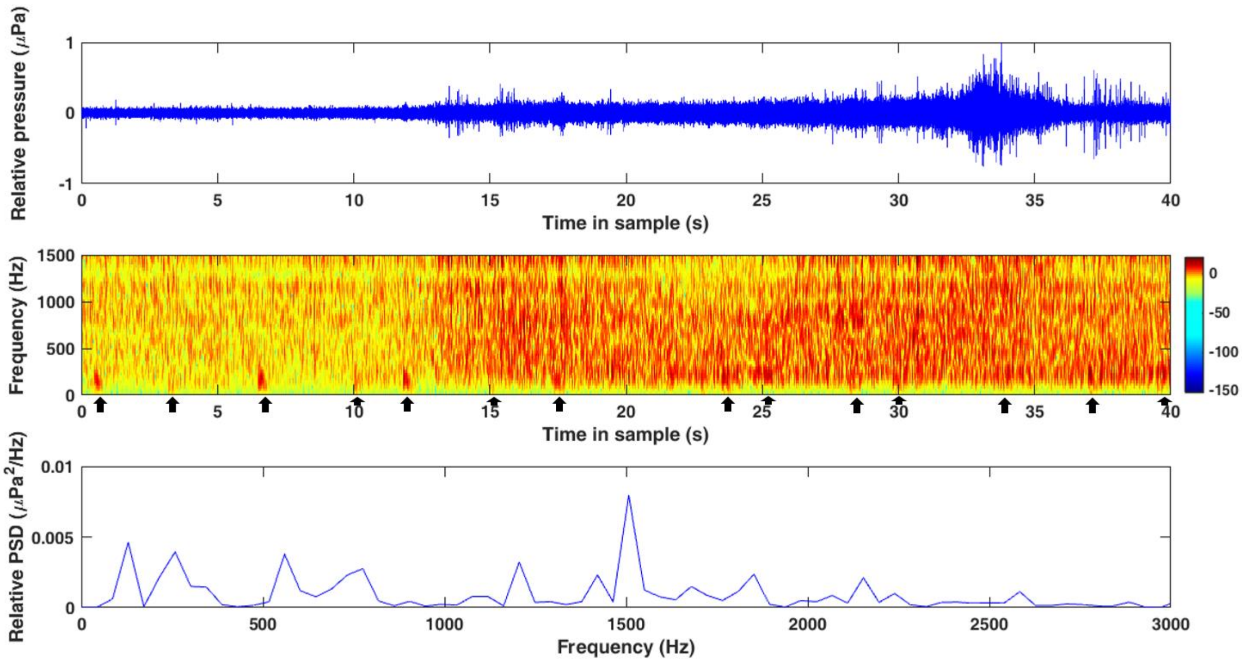

Figure 4.2. Recording of oyster toadfish boatwhistle calls during the passage of a motorboat. An example of fourteen boatwhistle sounds from oyster toadfish recorded in the field as a vessel approached the hydrophone. This recording was made on April 12, 2014 at 06:57 PM at the Morehead City Port, NC. The boatwhistles occur throughout the recording and are marked with arrows. As the vessel approaches the hydrophone, the sounds of the oyster toadfish are less visually distinguishable from the background noise. Top: Oscillogram of the sounds in the recording, demonstrating the variation in relative pressure throughout the recording. Middle: A spectrogram demonstrating the power and frequency of the signal as it varies throughout the recording time period. This spectrogram was created with an FFT of 1536 with a 512 point Hanning window (33.3% overlap). The hotter (red) the color, the higher the power of the sound but this spectrogram is not calibrated and is thus in relative power (μPa) units. Bottom: The relative power spectral density curve, where the peak in this curve demonstrates the fundamental frequency of the passing vessel (1500 Hz).

Materials and Methods

Basic Set-up

Artificial shelters made of a half cinderblock with a 3-inch PVC pipe zip-tied through the center were deployed at four locations in Core and Back Sounds in NC (Figure 4.3). At each site, a total of 36 shelters were positioned to face the navigation channel. Two treatments were placed at each site. One treatment was 7 m from the edge of the navigation channel ("near" treatment) while the second treatment was positioned 35 m from the edge of the navigation channel ("far" treatment). Each treatment (near vs. far) contained a total of six replicates, each with three oyster toadfish shelters (3 shelters x 6 replicates x 2 treatments, Figure 4.4). Every site was sampled at/near (~ 2 h) low tide by boat every ~ 9 d over a total of 15 weeks from Apr - Aug 2014. The purpose of sampling over low tide was to facilitate the extraction of oyster toadfish from their shelters. However, it also provided time variability for vessel counting. During each site visit, vessels using the navigation channel directly in front of the shelters were observed for at least one hour. The observer tallied the number and the type of vessels passing through the navigation channel next to the site. These vessel observations throughout the summer were averaged and extrapolated over a 24-h period for each site. A Kruskal-Wallis test was used to examine differences in vessel activity by site with significance set at a $p < 0.05$ level.

Sound Pressure Levels

In late March, artificial shelters for each treatment ("near" and "far") were placed at each site at a depth of ~ 1 m mid-tide. These treatment distances were based on acoustic propagation measurements across all sites (Figure 4.5) in shallow water (1 - 2 m) that indicated that at distances > 25 m, vessel noise (inboard and outboard motorboat sounds) played through an underwater speaker, were at or lower than maximum ambient noise levels (124 dB re 1μPa). At the sites, ambient noise levels were recorded on an InterOcean 902 hydrophone and calibrated listening system. Ambient noise ranged from 100 to 124 dB re 1μPa, with an average ambient SPL value of 109.5 dB re 1μPa across all sites. The intent of this experimental design was to ensure that when a vessel passed through the navigation channel, shelters "near" the channel would receive noise that exceeded 124 dB re 1μPa, while shelter "far" from the navigation would receive vessel noise at or near ambient levels.

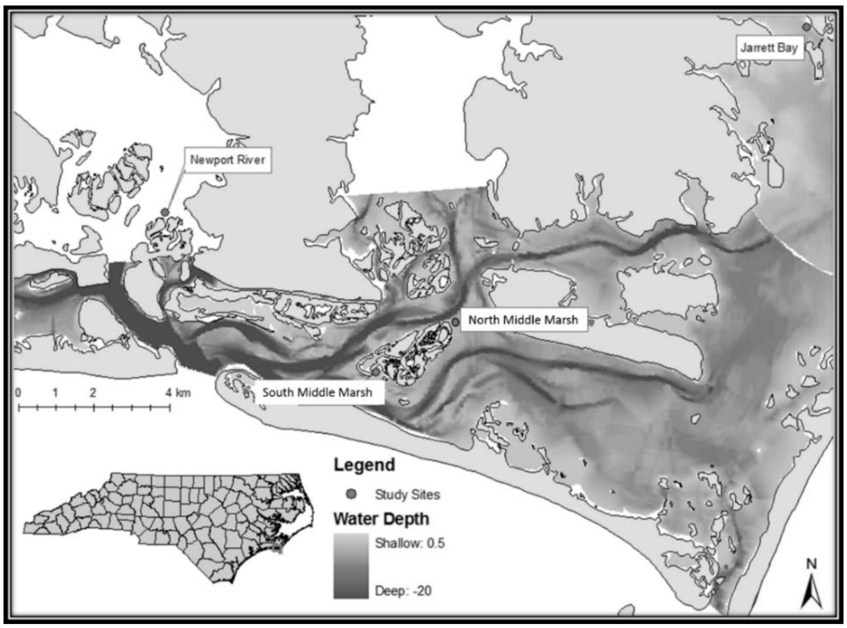

Figure 4.3. Study sites map.

Sites where artificial oyster toadfish shelters were deployed. The shelters were deployed in areas that had a mean water depth of 1 m. North Middle Marsh (NMM) & Newport River (NPR) were designated at "high vessel noise" sites and South Middle Marsh (SMM) & Jarrett Bay (JBS) were "low vessel noise" sites. Two sites (SMM & NMM) occurred within the Rachel Carson National Estuarine Research Reserve (NERRS permit 03-2014, Appendix A).

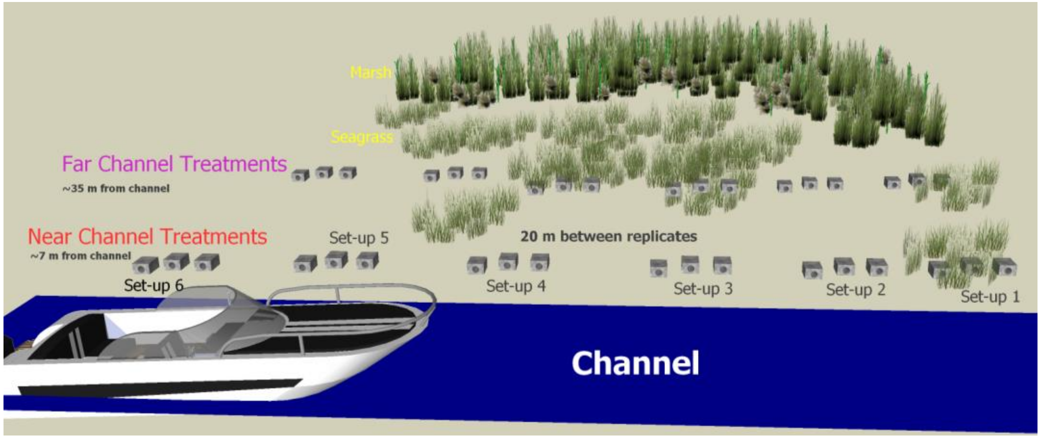

Figure 4.4. Site set-up to test the impact of vessel noise on oyster toadfish reproductive output.

At each site, oyster toadfish shelters were deployed at 7 m ("near") and 35 m ("far") from the edge of the navigation channel. Each treatment block had six replicates, each replicate contained three oyster toadfish shelters. At every site, some of the shelters were placed where there was seagrass and other shelters were just placed on the sand. Each site where the shelters were deployed, had a mean water depth of ~ 1 m, with seagrass interspersed within the deployed shelters. The presence or absence of seagrass at a specific replicate varied throughout the sampling period. The sites all contained a marsh behind the shelters to assist in the attenuation of wave action from the vessel activity at each of the sites.

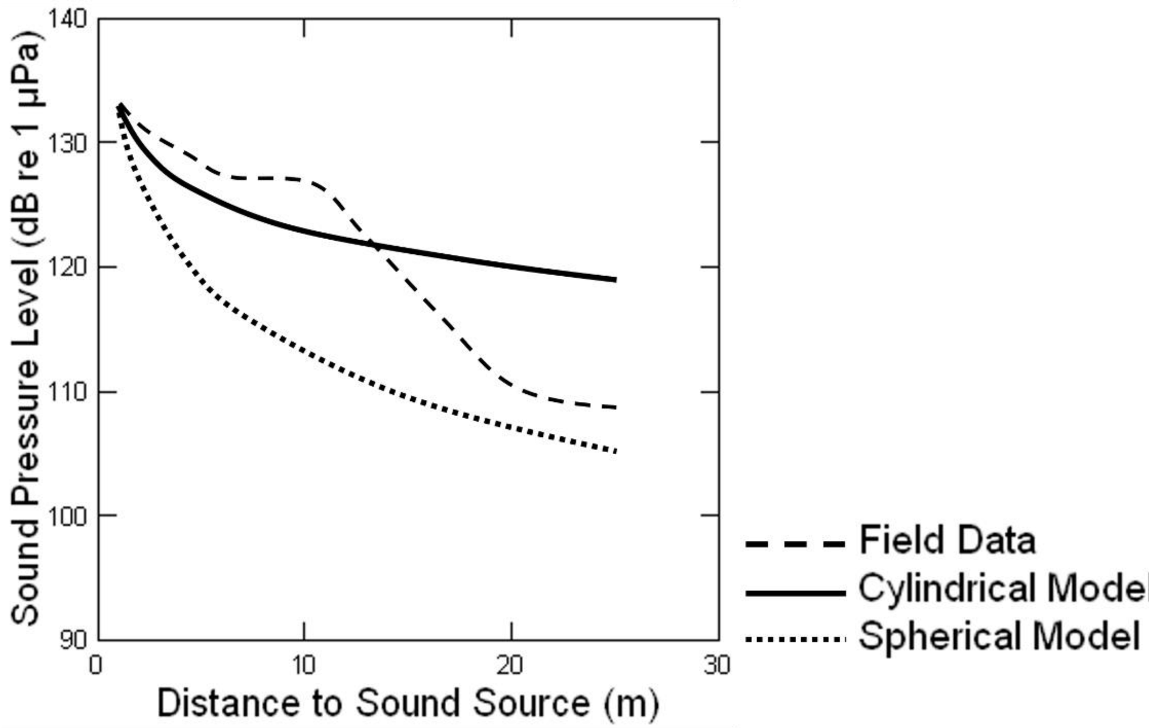

Figure 4.5. Acoustic propagation measurements of vessel noises in the field and the cylindrical and spherical spreading models of expected transmission loss within the sites.

Acoustic propagation measurement (SPL) values collected in the field (Field Data) made using two InterOcean 902 hydrophone and calibrated listening systems (with a dB VU meter) from playback experiments through an underwater speaker (Clark Synthesis AQ 339) of inboard and outboard motorboat sounds. One hydrophone was placed 1 m from the speaker and the second hydrophone was moved backward from the speaker. Measurements > 20 m were difficult to obtain due to the length of the hydrophone cable. For comparison, the expected transmission losses of the same amplitude sound are represented by both the cylindrical and spherical spreading models. For more acoustic measurements of vessel noise by site and bottom type, see Appendix B. For more acoustic measurements of a more broad scale frequency range see Appendix C.

Next, to assess potential SPL values at the shelters from a passing vessel, a cylindrical spreading model (based on Urick, 1983) was used to estimate transmission loss at a known distance (*r*). In the cylindrical spreading model, root-mean-square (RMS) pressure is inversely proportional to the square-root of the source radius ($\sqrt{r}$). Following Sprague and Luczkovich (2004), who relied upon the cylindrical spreading model of Urick (1983) to model sound attenuation of silver perch *Bairdiella chrysoura* calls, transmission losses at the oyster toadfish shelters near and far from the navigation channel were estimated using several equations. First, the equation for sound pressure level (dB re 1 μPa) is:

$$SPL = 20\ \log_{10} \frac{p_{rms}}{p_0}, \tag{4.1}$$

where p_{rms} is the root mean square (RMS) pressure measured at a known distance from the sound source and p_0 is the is the reference pressure (1 μPa for underwater measurements). Next, p_{rms} at distance *r* under the cylindrical spreading model is calculated using the following equation:

$$p_{rms}(r) = \sqrt{r_0}\ \frac{p_s}{\sqrt{r}}, \tag{4.2}$$

where *r* is the distance or range from the sound source (in m), r_0 is the reference pressure at the measurement distance (here r_0 = 1 m), p_s is the RMS pressure measured at r_0 from the sound source, and $p_{rms}(r)$ is the RMS pressure measured at known distance r.

$$p_s = 10^{L_s/20}, \tag{4.3}$$

where L_s is the measured sound source pressure level in dB re 1 μPa. This equation is derived from the cylindrical spreading transmission loss calculation:

$$L_s = \alpha * 20\log_{10}(p_s), \tag{4.4}$$

where L_s is the sound source level at a known distance (dB re 1 μPa), α is an attenuation factor calculated from the vessel sound acoustic propagation experiment completed in the shallow water.

In this case, α was 1.0, which was calculated from the slope of the acoustic propagation measurements taken in shallow water. Then these transmission loss curves were plotted alongside the data collected in the field (Figure 4.5 and Appendices B and C).

Sound source levels from vessel range from 120 to 180 dB re 1 μPa for inboard and outboard motorboats (Au and Green 2000, Erbe 2002, Frisk et al. 2003, Rako et al. 2013b). There are higher reported sound source levels for commercial ships (195 dB re 1 μPa, Frisk et al. 2003) but these were not observed directly in the navigation channel during the observation period at each site. The modeled sound presented here has a sound source level of 133 dB re 1 μPa so it is showing a sound source level that is in the lower range of the SPL value distribution for vessels. The generated transmission loss image, representing the transmission of sound between the navigation channel and the shelters, was generated in Systat (v. 13) from data derived from equations 4.1 through 4.4.

Collection of Oyster Toadfish

Oyster toadfish were captured by surrounding each shelter with a hand net, flipping the shelter into the net, bringing it to the surface, and removing the oyster toadfish. The total number of oyster toadfish in each shelter was counted, the oyster toadfish were transported to the boat and held in buckets with an airstone (ECU Animal Use Protocol #D307, Appendix A). Oyster toadfish in shelters near and far from the navigation channel were kept in separate buckets. Holding the fish in buckets served two purposes. First, it ensured that oyster toadfish that were removed from the shelters did not enter another shelter further down the line during the sampling period. Second, it provided the researcher ample opportunity to examine the toadfish and measure them for standard length (mm). After the fish were measured, the captured oyster toadfish were released at the site. Differences in the total number of oyster toadfish by replicate (N = 6 x 2 treatments) at each site and by navigation channel position were determined using repeated measures analysis of variance (ANOVA) for the fifteen sampled weeks. Within site differences by treatment were explored using a two-sample *t*-test with a pooled variance and a Bonferroni adjustment. Significance levels were assessed at a $p < 0.05$.

Differences in the standard lengths (mm) of the oyster toadfish were assessed by site, shelter position relative to the navigation channel, and month of collection in an ANOVA model. This method allowed me to assess the lengths of the toadfish across treatments but not within individual shelters. It was not feasible under the field conditions to measure each oyster toadfish as it was removed from a shelter. Secondly, it was not feasible to maintain 36 individual buckets with airstones on the boat to keep the fish within a single shelter separate. Thus, oyster toadfish lengths are reported by channel position and site. To determine which of the effects drove the differences in oyster toadfish standard lengths, individual hypothesis tests of the effects of that model were assessed. Significance levels were evaluated at a $p < 0.05$ level. Additional information regarding the recapture rates of the oyster toadfish among the sites can be found in Appendix H.

Oyster Toadfish Clutches

Once the oyster toadfish were removed from each shelter, the shelter was explored for oyster toadfish embryos. If a shelter contained embryos, it was photographed with a Nikon AW1 digital camera and the number of embryos was later counted using this photograph. Differences in the number of egg clutches (presence/absence) by site, navigation channel position, bottom type (seagrass or sand) and sampling month were determined using individual Pearson Chi-Square tests. Significant differences were determined at the $p < 0.05$ level.

To explore differences in the number of embryos, all shelters that lacked embryos were removed from further analysis (for an analysis with all of the zeros included, see Appendix F). This action removed an entire site (NPR) because it contained no embryos during the sampling season. Shelters with egg clutches were used in an ANOVA model to determine differences in the number of embryos within an egg clutch by site, shelter position relative to the navigation channel, and by month of collection. Next, hypothesis tests of the effects of the model including the individual effects and the combined effects were examined to determine which factors influenced the number of embryos on the oyster toadfish shelters. Significance levels were assessed at a $p < 0.05$.

Results

Vessel Activity

Experimental shelters were placed at sites that had varying levels of vessel activity. The two "quiet" sites (Jarrett Bay, JBS & South Middle Marsh, SMM) had on average ≤ 15 vessels per day while the two "noisy" sites (North Middle Marsh, NMM & Newport River, NPR) averaged more than 207 vessels per day (Table 4.1). The Newport River site, which is near the U.S. Intracoastal waterway, the North Carolina State Port at Morehead City, NC, a public boat ramp, and several marinas, had the most inboard and outboard motorboat activity and SMM had the least vessel activity across the sites. The SMM site is surrounded by seagrass and marsh habitats and is only accessible by vessels for a few hours a day, which reduces the vessel presence at this site. Outboard motorboat activity did not differ between the "noisy" sites but NPR had significantly more documented inboard motorboats than did NMM (Table 4.2). The "quiet" sites, however, did not differ in the amount of inboard or outboard motorboat activity.

Table 4.1. Estimated vessel counts of inboard and outboard motorboats at each of the sites. Vessels were visually counted and identified at each site for one hour during each sampling period. The averages collected throughout the summer were extrapolated to 24-h at each of the sites**.**

Noise Level	Site	Outboard Motorboat Activity (mean ± SE)	Inboard Motorboat Activity (mean ± SE)
"Quiet"	JBS	13.2 ± 4.7	2.3 ± 2.3
"Quiet"	SMM	2.7 ± 0.6	0.0 ± 0.0
"Noisy"	NMM	207.7 ± 46.6	0.0 ± 0.0
"Noisy"	NPR	306.0 ± 85.9	32.3 ± 7.3

Table 4.2. Differences in inboard and outboard motorboat activity across sites. Kruskal-Wallis test for differences in vessel activity among sites. Vessel activity is separated into outboard and inboard motorboats and significant differences between sites are marked with an asterisk.

Vessel Type	Site A	Site B	KW Statisitic	p-value
Outboard	JBS	SMM	-1.834	0.565
Outboard	NMM	NPR	0.062	1.000
Outboard	JBS	NMM	6.428	< 0.001*
Outboard	SMM	NMM	6.768	< 0.001*
Outboard	JBS	NPR	5.614	< 0.001*
Outboard	SMM	NPR	5.712	< 0.001*
Inboard	JBS	SMM	-1.414	0.749
Inboard	NMM	NPR	5.187	0.001*
Inboard	JBS	NMM	-1.414	0.749
Inboard	SMM	NMM	0.000	1.000
Inboard	JBS	NPR	4.471	0.009*
Inboard	SMM	NPR	5.187	0.001*

The transmission loss model of SPL values demonstrates that shelters near the navigation channel were exposed to higher vessel noise than oyster toadfish in the shelters far from the channel (Figure 4.5). In fact, the field measurements of transmission loss exceed that of the cylindrical spreading model at distances greater than 15 m. Based on these models a vessel passing through the channel with SPL value of 133 dB re 1 μPa would have an SPL value below 124 dB re 1μPa at 35 m from the edge of the navigation channel ("far" shelters).

Number of Oyster Toadfish and Length

A total of 1,177 oyster toadfish were found in the shelters throughout the sampling season. There was no difference in water quality across sites (see Appendix G for statistical analyses). The number of oyster toadfish was significantly influenced by site ($F_{3,40}$ = 78.97, p < 0.001) and navigation channel position (Δ=117, $F_{1,40}$ = 10.96 p = 0.002). Additionally, there was a marginal interaction between both site and navigation channel position ($F_{3,40}$ = 2.71, p = 0.058). The "noisiest" site, NPR, had the least number of oyster toadfish (N = 72), followed by SMM (N = 295), NMM (N = 400), and JBS had the most oyster toadfish (N = 410). There was no difference between JBS and NMM in the number of oyster toadfish present in the shelters (Δ = 10, t = 0.614, df = 254.5, p = 0.54). The NMM site did have significantly more oyster toadfish than SMM (Δ = 105, t = 2.415, df = 257.6, p = 0.016) and NPR (Δ = 328, t = 12.636, df = 184.29, p < 0.001). The "noisiest" site (NPR) also had less oyster toadfish than did SMM (Δ = 233, t = 10.813, df = 197.91, p < 0.001) and JBS (Δ = 338, t = 13.668, df = 202.52, p < 0.001). Finally, JBS had marginally more oyster toadfish than SMM (Δ = 115, t = 1.983, df = 262.00, p = 0.048). Therefore, the differences in the number of oyster toadfish by site observed in the ANOVA model are primarily due to the variables at a single site (NPR). Only one site (NMM) had differences in oyster toadfish observed by navigation channel position. At NMM, there were marginally more oyster toadfish in shelters far as compared with near the navigation channel ($\Delta = 36$, $t = 1.947$, $df = 127.79$, $p = 0.054$). At JBS ($\Delta = 15$, $t = 0.954$, $df = 129.62$, $p = 0.342$), SMM ($\Delta = 14$, $t = 0.854$, $df = 127.83$, $p = 0.395$), and NPR ($\Delta = 6$), $t = 0.758$, $df = 110.18$, $p = 0.450$) oyster toadfish abundance did not vary significantly by channel position.

An ANOVA model was used to explore standard length differences in oyster toadfish, with site, shelter position relative to the navigation channel, and month as independent variables. This model explained only 15.7% in the variance in the data set ($F_{37,1173} = 5.894$, $p < 0.001$). The individual effects hypothesis tests indicate that site ($F_{3,1173} = 5.036$, $p = 0.002$) and month ($F_{4,1173} = 2.739$, $p = 0.028$) were both influencing differences in oyster toadfish lengths. Oyster toadfish were largest at SMM ($\bar{X} = 103.90$ mm, $SE = 2.0$ mm), then NMM ($\bar{X} = 101.16$ mm, $SE = 1.4$ mm), JBS ($\bar{X} = 94.56$ mm, $SE = 1.3$ mm), and smallest at NPR ($\bar{X} = 56.27$ mm, $SE = 5.5$ mm). Secondly, collected oyster toadfish were smallest in the month of April ($\bar{X} = 66.74$ mm, $SE = 5.2$ mm), followed by May ($\bar{X} = 91.56$ mm, $SE = 2.0$ mm), July ($\bar{X} = 94.54$ mm, $SE = 1.7$ mm), August ($\bar{X} = 96.89$ mm, $SE = 1.6$ mm), and the month of June had the largest oyster toadfish ($\bar{X} = 105.53$ mm, $SE = 1.8$ mm). Additionally, the interaction between site and month is marginally different ($F_{11,1173} = 1.738$, $p = 0.061$) and the interaction between site, month, and navigation channel position is also significantly different ($F_{11,1173} = 1.995$, $p = 0.026$). However, navigation channel position alone does not influence the difference in oyster toadfish lengths across sites ($F_{1,1173} = 0.043$, $p = 0.836$). The results of the ANOVA model were primarily because of the NPR site, which had smaller oyster toadfish than all of the other sites (Figure 4.6).

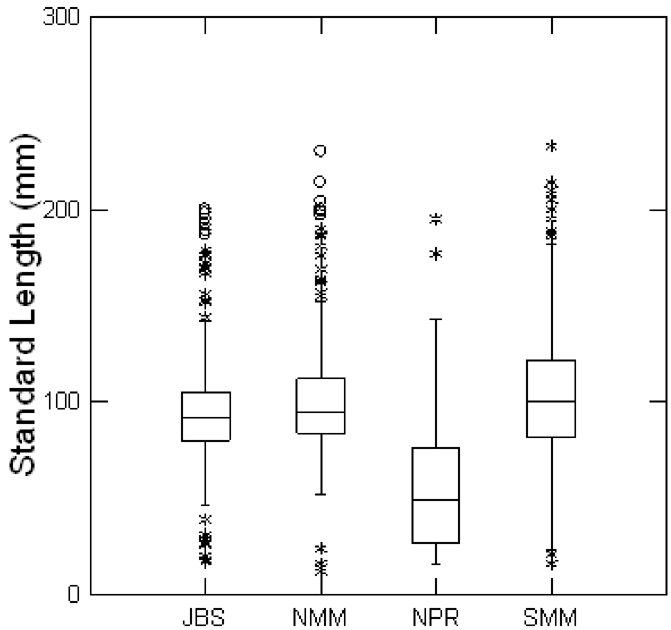

Figure 4.6. Oyster toadfish standard lengths at the sites.

The standard lengths of oyster toadfish in the shelters were obtained during each sampling period. There were no differences in oyster toadfish lengths at the “noisy” and the “quiet” sites. Boxplots show the median (50th percentile at the horizontal line) and the region which contains 50% of data around the median (25th to 75th percentiles). The vertical bars show the region in which observations fall within 1.5 * upper and lower interquartile ranges (lower: 25th to 50th percentile range; upper: 50th to 75th percentile range). Points outside of the 1.5 * the upper and lower interquartile ranges are shown as open circles.

Reproductive Output

The number of egg clutches varied by site. Of the 480 total observations (15 weeks * 4 blocks * 2 treatments * 4 shelters) at each site, embryos were identified 19 times (1.0% of the observations). Jarrett Bay (JBS, a “quiet” site) had the most egg clutches (N = 9), NMM and SMM had the same number of egg clutches (N = 5 clutches each), and NPR had no egg clutches during the sampling season. The number of egg clutches found on the oyster toadfish shelters throughout the summer was different by site (Pearson Chi-Square = 8.34, $df = 3$, $p = 0.039$). Additionally, there were more egg clutches on shelters near the navigation channel as compared with shelters that were far from the navigation channel ($\Delta = 9$, Pearson Chi-Square = 4.381, $df = 1$, $p = 0.036$). Oyster toadfish predominately had clutches during three sampling months May ($N = 7$), June ($N = 10$), and July ($N = 2$), with no embryos present at any of the sites in April and August. Finally, bottom type (seagrass or sand) at the shelters did not significantly influence the presence of embryos on the shelters ($\Delta = 1$, Pearson Chi-Square = 0.284, $df = 1$, $p = 0.594$)

To explore differences in the number of embryos, all shelters that lacked embryos were removed from further analysis. This means that one site (NPR) was completed removed from the analysis because no embryos were present throughout the sampling season. By removing all observations without embryos, only 19 samples remained for further analysis. Site, month, and shelter position were included the ANOVA analysis as independent variables. The ANOVA model explained 82.6% of the variability within the dataset ($F_{8,10} = 5.953$, $p = 0.006$). The ANOVA effect hypothesis tests demonstrate that none of these factors are individually significant but the interaction term among all three factors was significant ($F_{3,10} = 5.279$, $p = 0.019$). Oyster toadfish are depositing the most eggs on shelters located at SMM ($\bar{X} = 347.20$, $SE = 186.7$), then JBS ($\bar{X} = 327.44$, $SE = 77.8$), and finally NMM ($\bar{X} = 205.40$, $SE = 61.8$). Oyster toadfish are also depositing more eggs on shelters far from the navigation channel ($\bar{X} = 607.00$, $SE = 122.6$) as compared with near the navigation channel ($\bar{X} = 191.07$, $SE = 42.8$). Finally, the highest average embryo count occurred in June ($\bar{X} = 330.80$, $SE = 90.6$), followed by May ($\bar{X} = 317.00$, $SE = 101.2$), and then July ($\bar{X} = 91.50$, $SE = 47.5$). These data indicate that multiple factors are likely influencing where female oyster toadfish deposit their eggs but it seems that the "quietest" locations (far from the navigation channel and at sites with low vessel activity, Figure 4.7) have the most embryos per clutch.

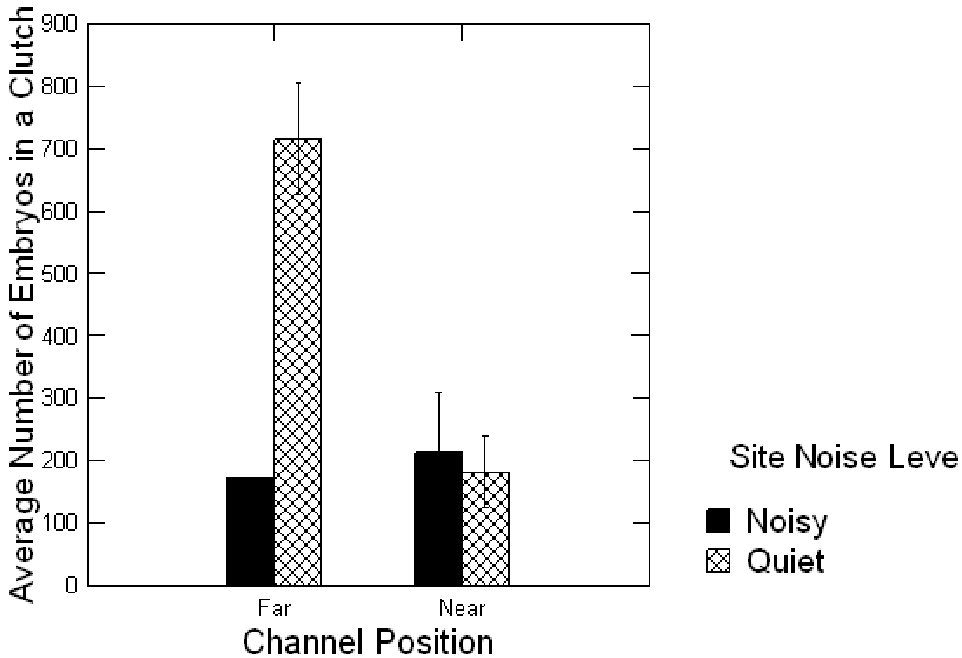

Figure 4.7. Embryo abundances at the sites with egg clutches present.

The number of embryos at the "quiet" sites (JBS & SMM) and one "noisy" site (NMM) on shelters near and far from the navigation channel. All shelters without embryos were removed from this analysis. The second "noisy" site (NPR), had no embryos present during the sampling period.

Discussion

Vessels are influencing the ambient noise levels at the sites. Vessel activity was highest in the "noisy" sites with SPL values higher at the shelters near as compared with shelters far from the navigation channel. The magnitude of difference in the SPL values was 15.4 dB re 1μPa, which may not seem like much but a difference in 3 dB re 1μPa is equivalent to the doubling of the ambient noise level (Rako et al. 2013a). It is also important to note the cylindrical spreading model underestimates the transmission loss at the sites. Fine and Lendardt (1983) found similar results for low frequency pure tone sounds (< 1 kHz) in a water depth of 1 m. The authors suggest that the bottom characteristics of the sites play an important role in sound propagation, where a portion of the signal extends below the water line and into the sediment. In muddy environments sounds attenuate faster than in sandy environments due to the resonance frequency of trapped bubbles (Anderson and Hampton 1980). The result is that sounds of vessels in sandy bottoms are likely to propagate further in sand than the sound from vessels moving over muddy bottoms. Because my two "noisy" sites (NPR and NMM) had sandy bottoms and my two "quiet" sites (SMM and JBS) had muddy bottoms, it is likely that sound waves moving through the sediment from passing vessels were attenuated to a greater degree in the "quiet" sites compared with the "noisy" sites. This sediment wave component (particle motion) of the sound signal was not measured in this study but is nonetheless expected to be important in sound detection, especially for the oyster toadfish. This species primarily detects sound through particle motion (Fay and Edds-Walton 1997, Yan et al. 2000). Future works needs to be completed on measuring the entire sound field (both particle motion and particle pressure) to better understand the detection thresholds of the oyster toadfish.

Sprague et al. (2016) modeled the sounds of a passing inboard, an outboard, and a tugboat at the NPR site and found that the cylindrical spreading model often underestimated the attenuation of the signal between the navigation channel and the shelters positioned near the channel. It was hypothesized that the steep slope of the navigation channel, leading to the channel's edge resulted in increased signal attenuation, above that expected from the cylindrical spreading model. Therefore, near the navigation channel, the oyster toadfish in the shelters would have been exposed to peak SPL values that ranged between 124 and 132 dB re $1\mu Pa^2 \cdot s$ or between 117 and 123 dB re $1\mu Pa^2 \cdot s$, when F-weighted (weighted for the oyster toadfish hearing range). The oyster toadfish in shelters far from the navigation channel would have been exposed to the same sounds from the passing vessels but at levels 15.4 dB re $1\mu Pa$ lower than those near the channel. Next, sound exposure levels (SELs), which include a time (of vessel passage) component, were explored at NPR with the same three vessels (Sprague et al. 2016). The SEL values ranged between 143 and 144 dB re $1\mu Pa^2 \cdot s$ or between 132 and 137 dB re $1\mu Pa^2 \cdot s$ when F-weighted. Therefore, the SEL of a vessel passing oyster toadfish in shelters near the navigation channel is well above ambient noise, even when F-weighted. At shelters far from the navigation channel, these SEL values are expected to be lower due to signal attenuation.

Oyster toadfish show only a slight preference for “quiet” areas. The site with the lowest total number of oyster toadfish was NPR, a “noisy” site. At NPR there were 80% (on average) less total oyster toadfish than the other three sites. The other “noisy” site (NMM) had one of the largest oyster toadfish counts, with only 2.5% fewer oyster toadfish than the site with the most oyster toadfish (JBS). The two “quiet” sites had different oyster toadfish distributions with SMM having 28% fewer oyster toadfish than the JBS site. However, only NMM (a “noisy” site) had oyster toadfish unevenly distributed across shelters near and far from the navigation channel, with more fish in shelters far from compared with near the navigation channel. Secondly, the length of the oyster toadfish also was not evenly distributed throughout the sites. The smallest fish, which were 18.7% smaller (on average) than the oyster toadfish residing at the other three sites, were found at NPR. At NMM some of the largest oyster toadfish were collected and on average they were only 2.9% smaller than the fish found at SMM. At the “quiet” sites, there were slight differences in oyster toadfish lengths, with JBS having 8.7% smaller oyster toadfish (on average) than SMM. There was no difference in oyster toadfish length by navigation channel position. These data suggest that large oyster toadfish are avoiding the “noisiest” site (NPR), which had the most inboard and outboard motorboat activity. At NMM, which has a lot of outboard motorboat activity but no inboard motorboats, large oyster toadfish were present and abundant but were selecting shelters far over near the navigation channel. However, there was little difference in the total number of oyster toadfish and their length distribution within these “quiet” sites. Thus, high rates of outboard motorboat noise are less likely to impact oyster toadfish than sites that have high inboard and outboard motorboat noise. Inboard motorboat noise produces sound frequencies between 0.01 and 5 kHz at source SPL values between 110 and 195 dB re 1 μPa (Au and Green 2000, Erbe 2002, Frisk et al. 2003, Picciulin et al. 2010). Outboards, in comparison, produce noise between 0.2 and 40 kHz (Jensen et al. 2009) with a similar range in source sound pressure levels. Therefore, oyster toadfish at NPR are more likely to have their calls masked by inboards than oyster toadfish at the other three sites because NPR had significantly more inboard motorboats than the other three sites.

Next, oyster toadfish embryos were more dominant and in greater quantities at the “quiet” sites and far from the navigation channel. First, at NPR there were no egg clutches but at the other three sites, there were between 5 and 9 clutches on the shelters throughout the sampling season. The JBS site had the most clutches and NMM and SMM had the same number of clutches. Yet, more clutches ($\Delta = 9$) were observed on shelters far from the navigation channel as compared with near the channel. As for the number of embryos per clutch on an oyster toadfish shelter, SMM had the most embryos per clutch and NMM had the least, with 40.8% fewer embryos per clutch than SMM. Whereas, JBS had only 5.8% fewer embryos per clutch than SMM. At all of the sites, oyster toadfish deposited more embryos (68.5%) per clutch far from the navigation channel as compared with near the channel but this difference was not significant at the NMM site. The results of these analyses suggest that female oyster toadfish are depositing more embryos far from the navigation channel as compared with near the channel.

The length of the oyster toadfish across all sites does not explain the information about embryo counts. While the largest oyster toadfish were found at SMM and SMM had the most embryos per clutch, the concept of larger females depositing more eggs is not maintained when exploring the other two sites. The second "quiet" site (JBS) had smaller oyster toadfish than NMM and SMM yet JBS had the second most embryos per clutch. NMM had the second largest oyster toadfish but had fewer embryos per clutch than the two "quiet" sites. Lengths of oyster toadfish in the shelters with embryos may have influenced egg counts but direct observations of oyster toadfish lengths in a shelter with embryos were not collected in this study. In the future, this is an important parameter that needs to be explored. Regardless of the oyster toadfish lengths, the present data indicate that the high rate of outboard motorboat activity at NMM may be leading to smaller egg clutches. The males in the "noisy" sites may be attracting smaller females with less eggs than the males at the "quiet" sites.

Outboard motorboats passing by the sites can influence oyster toadfish behavior in several ways. There is a potential issue to male oyster toadfish nest caring behavior. Other work has shown altered nesting behavior in species exposed to noise. Mueller (1980) found that longear sunfish (*Lepomis megalotus*) spawners left their nests more often when exposed to boat activity, leaving their nests more vulnerable to predator attacks. In a second study, Picciulin et al. (2010) determined that damselfish (*Chromis chromis*) spent less time caring for their nests when exposed to boat noise, compared with times with no boat noise. Additionally, red-mouthed gobies (*Gobius cruentatus*) spent more time in their shelters when exposed to boat noise (Picciulin et al. 2010).

Highly mobile fishes in areas commonly exposed to motorboats responded to an outboard motorboat by scattering away from their provided food source (Mensinger et al. 2016). Thus, male oyster toadfish in areas of “high” vessel noise are likely to be less successful caregivers, which may result in increased embryo mortality. In this study, it is unlikely that embryo mortality is an confounding issue because (1) the shelters were checked each week and the embryos were removed for another study and (2) dead embryos leave behind evidence of the egg casing and there was little evidence of embryo mortality at all of the sites.

Behavioral modifications to nesting activities in the presence of vessels have been observed among species other than fishes. The nesting yellow-blotched map turtle (*Graptemys flavimaculata*) often abandoned their nesting attempts when a boat approached (Moore and Seigel 2006). In a bird species, the great tit (*Parus major*), females laid smaller clutches in areas exposed to high vehicle traffic noise over areas with low vehicle traffic noise (Halfwerk et al. 2011). These studies suggest that oyster toadfish nesting activities may be influenced by the presence of vessels or vessel noise.

There are two possible reasons, related to reproductive activities, why there were fewer embryos per clutch at NMM (“noisy” site) compared with the “quiet” sites. At this point, there is no clear understanding on how female oyster toadfish deposit their eggs (all at once or over multiple spawning events). If females deposit their eggs all at once, then males at “noisy” sites are likely attracting smaller females resulting in smaller egg clutches. If, however, females deposit eggs over multiple spawning events in the presence of vessel noise, a female may (1) abandon the nest in the process of depositing eggs, resulting in smaller egg clutches or (2) she may choose to lay smaller egg clutches on shelters. While the behaviors of male and female oyster toadfish were not quantified in this study, behavioral modifications due to vessel noise exposure would explain why there are more embryos at the "quiet" locations as compared with the "noisy" locations. In the future, direct observations are needed of oyster toadfish exposed to vessel noise.

Ultimately, vessel presence and noise seems to be reducing habitat quality for fishes, whether it is from masking courtship communication signals (Vasconcelos et al. 2007, Krahforst et al. 2016), reducing parental care (Mueller 1980, Picciulin et al. 2010), or even the elevation of stress in fishes (Wysocki et al. 2006, Graham and Cooke 2008). Other marine life, including some endangered species, are likely to be similarly impacted by vessel noise. There may be a threshold for disturbance that these animals can tolerate under normal conditions. For example, even with higher vessel (outboards) activity at the "noisy" NMM site, the oyster toadfish at this site were as abundant as the two "quiet" sites and of similar length distributions, yet still had some, albeit lower, reproductive output. At the Newport River (NPR), the "noisiest" site (inboard and outboard motorboats), there were few oyster toadfish and the fish present were smaller than at the other sites, and no reproductive output was observed. On average, there were 130 more vessels per day at NPR than NMM and more inboard motorboat activity. All of the other measured variables in this study did not explain these finding at NPR.

The NPR site may have reached its maximum "no-effect sound exposure level" (NESEL). By NESEL I am suggesting that there is a limit to the number of vessels that can pass by an area in a day and still have a functioning ecosystem or oyster toadfish population. At NPR, there is a shift in the oyster toadfish distribution and is likely to be the case for other economically valuable sound-producing fish species in the families like Gadidae (Atlantic cod, *Gadus morhua*), Serranidae (groupers *Epinephelus* or *Mycteroperca* sp.), Sciaenidae (red drum *Sciaenops ocellatus*, spotted seatrout *Cynoscion nebulous*, and weakfish *C. regalis*). It is also probable that these threshold shifts are present for other endangered marine life like sea turtles and marine mammals. Therefore, it is important to consider establishing vessel noise management guidelines to enhance habitat quality and reduce the risk of species habitat shifts due to increased ambient noise conditions associated with vessel activity.

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Contributions

C.S. Krahforst and J.J. Luczkovich conceived the initial studies, while M.W. Sprague and M.L. Fine assisted in improving the design. C.S Krahforst and M.W. Sprague conceived the acoustic propagation study. C.S. Krahforst and M.E. Rose executed the studies and ran the analyses. J.J. Luczkovich and M.L Fine provided statistical and theoretical guidance. All of the co-authors contributed to writing the manuscript.

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CHAPTER 5 HOW SHIFTING PARADIGMS OF THE VALUE OF NATURE HAS INFLUENCED ECOSYSTEM-BASED MANAGEMENT: THE CASE OF MANAGING UNDERWATER NOISE

Abstract

Underwater noise is a recent management concern and the ecosystem impacts of underwater noise are not fully understood. Recent noise management documents have been written to address the impacts of underwater noise on marine life. Here a text analysis of word frequency data was used in a correlation analysis to determine themes within four underwater noise management documents. This analysis was compared with the same type of analysis for fourteen relevant legislative documents that could address the issue of underwater noise. The word frequency data obtained from the text analyses of the management and legislative documents were compared using a correspondence analysis and two (words and documents) network analyses. The results suggest that managers are primarily concerned with issues associated with underwater noise and the protection of marine mammal populations. Dominant words within the management texts include "acoustic," "impact," "marine," "mammal," "noise," "sound," and "source." The legislative documents span a range of concerns but focus primarily on words associated with the trade-offs between human use and the environment. These words included "conservation," "fish," "plan," "project," and "public." Some of the legislative documents related to a conservation (defined as the greatest good for the greatest number of people for the longest time) perspective, while others concentrated on development or the industrialization of natural resources. These legislative concerns (conservation and development) were notably absent in the noise management documents. For an effective ecosystem-based management initiative addressing underwater noise, managers need to better incorporate social values and human-use into their management plans.

Introduction

Society disproportionately relies on the coastal zone and its functions for many ecosystem services, including recreation (e.g. boating, SCUBA diving, whale watching, and fishing), extraction of goods and services (e.g. goods/food), and commerce (commercial fishing, shipping transport, offshore oil/gas). Although these activities generate viable ecosystem services to the public, they also threaten ecosystem health (Mallin et al. 2000, Weinstein et al. 2007) through environmental degradation including those impacts associated with underwater noise. To achieve a balance between societal needs and environmental health there must be the development of management strategies that achieve an acceptable combination of trade-offs (U.S. Commission on Ocean Policy 2004, Weinstein and Reed 2005) between ecosystem services and environmental health. One such trade-off is between anthropogenic noise from coastal industrialization (e.g. wind farms, oil and gas exploration, SONAR, etc.) as well as other ecosystem services and their impacts on the marine environment.

Environmental Considerations

While underwater noise is not directly addressed as a pollution source in the current enabling legislation, it can be considered a source of pollution. According to Götz et al. (2009),

> *"[p]ollution means the introduction by man, directly or indirectly, of substances or energy into the maritime area, which results, or is likely to result, in hazards to human health, harm to living resources and marine ecosystems, damage to amenities or interference with other legitimate uses of the sea."*

Thus, underwater noise is a type of energy pollution that can spread long distances, may impact the health of marine life, and can, therefore, be identified as a pollution source (Götz et al. 2009) that threatens ecosystem health and its services.

Human use can disturb habitats in many ways. For example, motorboats disturb habitats by anchoring, vessel groundings, seagrass propeller scars, alien species introduction, and pollution by noise, fuels, oils, defouling treatments, and human waste (Burgin and Hardiman 2011). Additionally, larval fish are known to use sounds to orient themselves to nursery habitats (Simpson et al. 2010) and these habitats have specific soundscape signatures (Radford et al. 2010). Thus, noise generated in these habitats due to human activities is likely to impact the ambient sound signatures and hence the ability of larval fishes to find nursery grounds. The result could be decreased fish stocks, suggesting a decline of both a socially-valuable and economically valuable ecosystem services.

The presence of vessels influences the behavior of marine life. Marine mammals, for example, are a valuable economic ecosystem service in terms of coastal tourism (e.g. Hoyt 2000). However, ships are known to strike marine mammals, causing severe or lethal injuries (Laist et al. 2001). Humpback whales (*Megaptera novaeangliae*) avoid vessels by altering their swimming behavior (Bauer and Herman 1986). Vessels have interrupted the feeding and traveling behaviors of beluga whales (*Delphinapterus leucas,* Blane and Jaakson 1994). However, noise alone from these vessels influences marine mammal behavior. Dolphin species (*Tursiops sp.*, *Cephalorhynchus sp.*, and *Stenella sp.*) alter their surface behavior, diving intervals, and group formation and orientation in response to vessel noise (Au and Perryman 1982, Janik and Thompson 1996, Nowacek et al. 2001, Ribeiro et al. 2005, Lemon et al. 2006, Papale et al. 2012). Dolphins (*Stenella sp.*) also react to the sounds of ships at distances of 6 miles or more away by splashing less, increasing their swimming speed rate, and by staying underwater for longer time periods (Au and Perryman 1982). Marine mammals can therefore be behaviorally impacted by human activities, which can impact the ecosystem services they provide to society. Noise response is also evident in fishes, which provide several ecosystem services including goods and services, recreation, commerce, and tourism (e.g. Holmlund and Hammer 1999). Atlantic cod (*Gadus morhua*), for example, alter their swimming behavior when exposed to vessel noise (Engås et al. 1995, 1998) as do other fishes (Sarà et al. 2007). Other reactions of marine life to vessel noise/activity include the alteration of communication signals. Both marine mammals (e.g. Van Parijs and Corkeron 2001, Morisaka et al. 2005, Jensen et al. 2009) and fishes (Krahforst et al. 2016, Luczkovich et al. 2016a) have altered their calling behavior when exposed to vessel noise. While there is no direct evidence that altered calling behaviors can directly impact the health of an animal, there is indirect evidence that these noises could impact migration and reproductive behavior of marine life (Krahforst this volume, Chapters 2-4). These types of underwater noise impacts to fish and fisheries can impact socially valuable ecosystem services.

Underwater noise can also impact animal health, migration, and reproduction. In terms of health, underwater noise is known to cause increases in stress responses in fishes (Wysocki et al. 2006, Graham and Cooke 2008) and whales (Rolland et al. 2012). Noise can even cause injury or death in fishes (e.g. Popper and Hastings 2009). For migration interruptions, more research needs to be conducted on this topic, but Heide-Jørgensen et al. (2013) found that seismic survey noise leads to increased risk of narwhal (*Monodon monoceros*) ice entrapment. They speculate that the narwhals were altering their migration patterns to avoid the noise. Additionally, anthropogenic noise in some cetaceans has led to the avoidance of calving and foraging grounds (Kvadsheim et al. 2007). While there is limited information on the impact of vessel noise on specifically reproduction, there is some evidence that the presence of vessels influences fitness and nesting behaviors in aquatic life. Bulté et al. (2010) showed that nesting yellow-blotched map turtles (*Graptemys flavimaculata*) tended to abandon their nesting attempts when boats approached them.

The longear sunfish (*Lepomis megalotis*) leave their nests more often when exposed to boat activity, which leaves their nests more vulnerable to predation (Mueller 1980). Other fish species have also been shown to spend less time caring for their nests when exposed to vessel noise (Picciulin et al. 2010). Finally, the work in this dissertation (Chapter 3) suggests that vessel noise reduces the calling behavior of the oyster toadfish (*Opsanus tau*, Krahforst et al. 2016). Areas with high vessel noise also have less reproductive output than areas with low vessel noise (Chapter 4). Taken together, the results from Chapters 2 - 4 of this dissertation work suggest that environmental noise, especially from vessels, can impact the reproductive output and fitness in at least one marine fish. The result can be a decline in fish stocks, which are an important ecosystem service.

The following introductory sections will address two concepts. First, I consider a historical perspective of how people perceive nature and how these perceptions influence the values of users as well as how a resource is managed. This history for addressing underwater noise is important for managers because it is necessary for managers to address all existing perspectives to develop a socially-acceptable management strategy. Second, I will explore the social components that need to be addressed when dealing with underwater noise. The social considerations include the following ecosystem services: (1) preservation of recreation, (2) cultural and historical values, (3) economics, and (4) national security. For each of these concepts, I will offer examples that may impact underwater noise management. The goal of these sections is to assist the reader in understanding the interconnectedness between the social and ecological issues surrounding underwater noise management. The final step, which is the goal of this paper, is to explore the current themes of underwater noise management plans and the relevant legislation. These analyses will reveal additional themes that need to be included in noise management strategies to create an effective management initiative.

Shifting Paradigms in People's Perception of Nature

Underwater noise associated with short- and long-term anthropogenic activities is a new management concern that is in the early stages of being addressed in policy and is starting to become a component of agencies management strategies (Gedamke et al. 2016) and is mandated by the National Ocean Policy (Lubchenco and Sutley 2010). As these management strategies are being established, it is important that managers focus on an ecosystem-based (or holistic) management strategy. Ecosystem-based management (EBM) is defined as an ecosystem (or place-based) management initiative that addresses both (1) the interconnectedness of ecosystem components and (2) the interconnections between people and the ecosystem in the form of ecosystem services (McLeod and Leslie 2009). Ecosystem-based management strategies require that managers acknowledge both the ecological impacts and the required societal trade-offs associated with ecosystem services needed to manage underwater noise. Ecosystem-based management includes the concept that the decisions made by managers need to reflect the goals and desires of users (Kelble et al. 2013), which can be expressed through ecosystem services (Doren et al. 2009).

Throughout history, there have been shifts in the focus of management (Table 5.1). The industrialization era (before the 1960s), was a time period that was ruled by maximum productivity. Management of resources was non-existent for most of this time-period. Prior to the late 1800s, industrial productivity was a primary concern, resulting in an anthropocentric value orientation. Anthropocentric values focus on tangible assets (production materials, goods, and services, Hendee and Stankey 1973, Mcfarlane and Boxall 2003) over intangible (nature for nature's sake) assets (Mcfarlane and Boxall 2003).

By the late 1800s it was decided, through both the romantic notions of John Muir (preservation) and Gifford Pinchot (conservation) along with the impacts (logging, etc.) of resource exploitation, that something had to done about overexploitation of natural resources. These concepts ushered in the Expert era, where federal agencies were created and staffed by experts who were to manage the resources on the behalf of the Nation's people (Meine 1995) but management primarily focused on a single ecosystem service, often managing only a single, desired species of value (Yaffee 1999). Pinchot brought to the U.S. (from Germany) the concept of conservation ("the greatest good for the greatest number for the greatest time," Pinchot 1947), while Muir argued for preservation (land unspoiled by humans, Meine 1995). The two views (preservation versus conservation) of the ecosystem came to a head during the Hetch Hetchy dam debate (Meine 1995). Pinchot believed that resources should not be wasted. He felt that using the Hetch Hetchy valley in Yosemite as a dam to store water was a valuable use of the resource. Muir argued that destroying the Hetch Hetchy valley for the purpose of water storage was not worth the loss of the natural wilderness of the valley (Meine 1995). Here was a first great debate in U.S. history with regards to conservation vs preservation of a natural resource.

In the early 1900s, the concept of wildlife protection also became apparent, with the allocation of funds for the first national public lands. By the 1920s, protection was evolving into management, where habitat and restoration were based on the ability of a native species to naturally sustain itself (Meine 1995). This shift in thinking led to population assessments of entire communities and, in fisheries, to the idea of the "maximum sustainable yield," (Meine 1995). These concepts, however, became lost in the light of World War II. World War II ushered in a time of need and with that the increasing desire for resources and thus the concept of maximum productivity for a resource (Meine 1995).

Table 5.1. Major management eras (bold) derived from thought paradigms that established the characteristics that drove ecosystem management during the specified time period.

Generalized management eras (bold) and the primary characteristics associated with these eras (Loomis and Hawkins not published contact: D. Loomis at loomisd@ecu.edu). Each era has a series of paradigms derived from societal needs and desires about the ecosystem (Yaffee 1992, Loomis and Hawkins unpublished). The primary characteristics of each thought paradigm are described to assist in understanding the change in the management focus throughout each era.

Years	Paradigm	Characteristics
Industrialization		Environmental use for maximum productivity Management (if present) focused on single use
1620s-1820s	No Systematic Framework	Anything goes
1825-1880s	Exploitation/Disposal	Acknowledgement of limited natural resources
1885-1920s	Expert (Progressive) Approach	Agencies were established so that specialists managed resources
1920s-1960	Commodity Era	Resources utilized for development after WWII
Environmental Movement		Emergence of protection and preservationist values Litigation, conflict, and competition brought about by contradictory ecosystem services
1960s-1970s	Multiple Use	Resources used for productivity but managed for several human-uses
1970s-1980s	Environmentally-Sensitive-Multiple-Use	Resources managed for productivity with environmental protection to ensure continued and future human-use
Ecosystem Approach		Environment needs to be managed for socially desired ecosystem services
Early 1990s	Ecosystem Management	Management for ecosystem biota protection
Late 1990s	Ecoregional Management	Management for whole ecosystem protection
2000s- Today	Ecosystem-Based Management	Management of the whole ecosystem based on socially-acceptable environmental levels, derived from ecosystem services

During the industrialization era, underwater noise was not yet a concern. However, the technological advances on SONAR during World War I and II ushered in extensive progress on underwater acoustics research. Some of this work included using SONAR to navigate and find combatants underwater (Klein 1968, Lasky 1977), long-range propagation, the discovery of the sound fixing and ranging (SOFAR) channel, and the measurements of background noise levels. Ambient noise levels were measured because they influenced the effectiveness of SONAR (Lasky 1977). At this time, scientists and managers were unaware of the potentially damaging effects of SONAR and other sources of anthropogenic noise on marine life.

As the industrialization era weakened and the postwar U.S. stabilized, the era of the environmental movement was ushered in, starting in the 1960s. This was an era of required public involvement in management, where conflicts and competition arose based on multiple uses of a natural resource. Users or interested parties of a resource advocated for their desired resource state and thus the type of management of that resource (Loomis and Hawkins unpublished, contact: D. Loomis at loomisd@ecu.edu). The environmental movement led to concepts of protection and preservation of the ecosystem (Loomis and Hawkins unpublished). The concept of multiple use dominated people's nature perceptions (Yaffee 1999). This concept focused on production yields of multiple uses rather than a single use. For example, the Multiple-Use Sustained-Yield Act of 1960 sought to balance wood production and other uses of the natural resource (Meine 1995). Additionally, the concept of sustainability, taken to mean the continual production of the desired products, began to pervade management perspectives (Anderson 1995).

As society began exposing the problems civilizations were causing for the environment (Botkin, 1990), the multiple-use concept evolved into the environmentally-sensitive-multiple-use paradigm and this perspective persisted into the 1980s (Yaffee 1999). This paradigm was similar to the multiple-use perspective but brought in the concept of the minimization of negative environmental impacts (Yaffee 1999). Environmentally-sensitive-multiple-use perspectives caused a shift between an anthropocentric to a biocentric value orientation (Yaffee 1999). Biocentric views focus on the preservation of the natural purity of an ecosystem, if necessary, at the expense of human use (Hendee and Stankey 1973). In this perception, the primary focus of natural resource management is not tangible assets but rather the understanding that nature provides value independent of humans' ability to use it (intangible assets, Mcfarlane and Boxall 2003).

During this paradigm shift, underwater noise was just beginning to be recognized as a concern (Williams et al. 2015) and the first published literature expressed interest in the impacts of "shipping noise" on baleen whale acoustic communication behavior (Payne and Webb 1971). While concern began to be expressed over the impact of underwater noise, the concept was not really developed until the 1990s. Between the 1960s and 1980s, research primarily addressed basic principles like acoustic propagation (e.g. Steinberg et al. 1972, Urick 1983, Ames and Lee 1987) and the identification of sounds by various marine life and their mechanisms of sound generation (e.g. Van Heel 1962, Fish and Mowbray 1970, Tavolga 1971, Watkins 1981).

The conflict of the earlier decades between contradictory ecosystem services led to an era that started in the 1990s that was focused on ecosystem services. In this era, environmental needs were expected to be managed for socially desired ecosystem services. Within the ecosystem management era, either ecological integrity or ecological health of a system were maximized (Francis 1993). Ecological integrity is the ability of an ecosystem to maintain and support its ecological processes and the communities that rely upon it (Karr 1993). Ecological health, however, is a concept about the managed state of a resource, where an intensively used resource is able to sustain the ecological processes necessary to sustain human use (Karr 1993). Under this ecosystem paradigm, the first priority is the protection of the ecosystem followed by the needs of users (Francis 1993). Beginning in the late 1990s, this paradigm shifted slightly to an ecoregional management view, which takes the focus off of the biota and instead prioritizes the ecosystem as a whole, as defined by a geographical space (Yaffee 1999). Additionally, ecocentric value orientation became defined, which focused on the interconnectedness of all the components of an ecosystem rather than focusing on specific elements of the biota (Yaffee 1999). For the purposes of this paper, biocentric and ecocentric value orientations will be grouped under the biocentric term.

The establishment of the biocentric viewpoint within society has led to the concept compromise and balance between different uses of the environment (Kessler et al. 1992). Today, we are still in the era of ecosystem services but are evolving to an ecosystem-based management strategy, where management of an ecosystem is based on socially acceptable environmental levels, derived from ecosystem services (Loomis and Hawkins unpublished). Within resource users, there is a continuum of value orientation, with anthropocentric on one side and biocentric on the other. Generally, biocentric views are favored more by females and by the younger (< 43 years old) generations while males and the older generation favor a more anthropocentric perspective (Tarrant and Cordell 2002, Mcfarlane and Boxall 2003). These views are then associated with management strategies. People with biocentric views are generally more supportive of protection-oriented management compared with people with anthropocentric views (Mcfarlane and Boxall 2003). These people with a biocentric viewpoint value nature itself (the intangible) as an ecosystem service. However, those supportive of resource extraction (i.e. productivity as an ecosystem service) generally have an anthropocentric viewpoint rather than a biocentric view of nature

(Mcfarlane and Boxall 2003). The difficulty with this continuum is that there is both a need for both ecosystem services (the tangible and the intangible) in a population that is constantly growing and demanding more resources (Kessler et al. 1992). To achieve a balance between societal needs and environmental health there must be the development of management strategies that achieve an acceptable combination of trade-offs to the desired ecosystem services (U.S. Commission on Ocean Policy 2004, Weinstein and Reed 2005), which requires interagency cooperation and stakeholder involvement in collaborative problem-solving of the management problem under discussion (Yaffee and Wondolleck 1997), in this case underwater noise.

The U.S. Navy, for example, produces noise that harms marine animals. In the early 2000s, Naval SONAR activities became correlated with mass stranding events of marine mammals (e.g. Balcomb and Claridge 2001, Frantzis 2004, Parsons et al. 2008). Legal actions were taken by environmental groups against the U.S. Navy to prevent the use of SONAR in order to protect marine life (Associated Press 2016). However, the Navy is tasked with national security (protection) of the U.S., which includes being prepared for an attack (Kiamos 2001). SONAR testing helps make sailors ready for any military action against the U.S. (Abate 2010). Conflict has thus arisen between those with a biocentric value orientation (e.g. marine mammal protection at any cost) and anthropocentric value orientation (e.g. naval preparedness at any cost). The key to management is the consideration of both value systems and thus a much needed compromise between combative groups.

As members of the era of ecosystem approach, it is important that managers move away from the expert approach that was dominant at the turn of the 20th century and acknowledge socially-accepted ecosystem states. The human population within the U.S. has grown over 4 times between 1900 and 2017 (U.S. Census Bureau 2017). Resources are and will continue to become limited.

The result is increased demand for an ever dwindling resource. Management decisions addressing underwater noise need to reflect the goals, values, desires, and benefits of the ecosystem services provided to the users. It is important to understand societal value gained from an ecosystem service because it helps inform decisions and assists with identifying trade-offs required for the implementation of a specified management strategy (Kelble et al. 2013).

> *"Where multiple desirable but competing objectives exist, it is not possible to maximize each.....[and] in any system with multiple competing objectives, it will not be possible to meet every one," (U.S. Commission on Ocean Policy, 2004).*

Thus, it is necessary to capture the values (both natural and societal) of an ecosystem, utilizing some type of measurable variable (Loomis and Paterson 2014a, 2014b). Keys to this process are that these variables are grounded in ecological and social theory and also effectively relate to societal values in terms of ecosystem services (Doren et al. 2009). This process includes stakeholder involvement and the utilization of user value orientation into the underwater noise management initiative process.

Social Considerations

The management of underwater noise should utilize an EBM strategy, which includes an understanding of what society desires in terms of ecosystem service (Reyers et al. 2009). Ecosystem services function as social, economic, and cultural values (Wallace 2007) and involve concepts like the preservation of recreational activities, the retention of cultural and historical values, the consideration of economics and maintenance national security. All of these ecosystem services need to be addressed by noise management initiatives.

Underwater noise management strategies often focus on noise-free (or "silent") marine protected areas (MPAs, Gedamke et al. 2016). Yet, it is also important that recreational experiences are maintained. Silent MPAs will reduce user access thus inhibiting recreational experiences by users such as boaters and fishermen. Generally, marine protected areas have been perceived as threatening to recreational fishers (Salz and Loomis 2005). This proposal to establish silent MPAs is an example of the expert approach versus an ecosystem-based management approach. As experts, managers expect MPAs to be widely accepted by users because, according to the experience of the experts, MPAs rationally are a way of effectively managing underwater noise. Yet, some users do not view MPAs as an acceptable management strategy. While managers may like the concept of "silent" MPAs, some users are likely skeptical of their benefits. For an EBM strategy, it is important to recognize and address these issues by understanding the social perspective and why some users feel MPAs threaten their desired ecosystem service.

Part of what is important here is that underwater noise is a complicated issue, often not an obvious source of an ecosystem problem from the viewpoint of resource users. Therefore, it can be difficult for resource users to consider and understand how underwater noise may influence their livelihoods. An expert approach to management would simply force protection of an area regardless of its social impacts. However, an EBM approach would attempt to understand the various ecosystem services provided by a specified area, which would influence the management strategy. This EBM approach would balance the desired ecosystem services of an area with the need to protect the environment (see Chapter 6).

Research has not been conducted on the historical/cultural aspects of underwater noise. So, to demonstrate this concept of cultural and historical values as an ecosystem service, I will use an example that explores the impact of climate change on a fishery. Climate change, like underwater noise, is a complicated issue whose direct effects are difficult for the public to accept. Rock lobster (*Jasus edwardsii*) fishermen in Tasmania, for example, observed drastic changes in their fishery that were consistent with changes expected from climate change (Nursey-Bray et al. 2012). These fishermen reported observing differences in species distributions (region/time of year) and changes to kelp beds (Nursey-Bray et al. 2012), both of which are associated with climate change impacts. Yet, 80% percent of these fishers (1) did not acknowledge the existence of climate change, (2) did not believe climate change with a problem, or (3) did not have an attitude of climate change acceptance. Further, 20% of the respondents believed that even if climate change was an issue, that the impact(s) due to climate change were of little/no concern to them (Nursey-Bray et al. 2012). A key point here is that there are psychosocial values that are tied to the resource that influences the knowledge that is possessed by an individual user. A failure to recognize and understand these values within a management framework will likely result in a failure of the management goal. Users have a preconceived understanding of their environment based on history and their social relationships (Pollnac and Johnson 2005). Most of the impacts of underwater noise, like with climate change, are difficult for people to see and accept. Thus, it is imperative the underwater noise managers address the perceptions of the resource users to create a more effective management initiative that will conserve ecosystem services as well as protect the environment.

Economic analyses suggest that there is a trade-off between environmental and social costs and economic benefits for the nation. Managers need to understand all forms of ecosystem services and manage according to multiple uses as well as environmental protection. Here offshore wind energy is used as an example of how economic incentives can influence decisions that incur environmental costs. Cape Wind was the first of its kind in the United States, an offshore wind energy project off of Cape Cod. Offshore wind energy competes with coal, natural gas, and petroleum, all of which contribute to air pollution and climate change (Kempton et al. 2005). Wind energy, however, is an untapped resource that is considered to be cost-competitive and produces very little pollution compared with conventional energy sources (Kempton et al. 2005). Wind farms working at a 40% capacity, would likely displace ~ 1800 tons of carbon dioxide per year (Snyder and Kaiser 2009) and this would also offset the use of freshwater by conventional energy sources by 0.7 to 2.1 million gallons per year (Snyder and Kaiser 2009). Support for wind farms among the public, however, is variable primarily because of social values, the perception of procedural justice, and socially desired ecosystem services (Kempton et al. 2005).

Within the state of Massachusetts, Cape Cod, and Cape Cod's Islands area, where Cape Wind was proposed, wind farms were generally supported by the public (64% for and 22% against in Massachusetts & 55% for and 35 against in Cape Cod and the Islands area in surveys by Kempton et al. 2005). Supporters argued that wind farms generate clean and renewable energy and reduce the nation's reliance on foreign energy. In the wind farm supporters' minds, the lack of oil and oil security in the Middle East can be offset by an increase in energy generation from wind farms. People who opposed the wind farm primarily said that it is a bad location because of the aesthetics of the area and that a private company should not benefit from public resources. When assessing their aesthetics argument closer, the researchers found that the opponent's focused on biocentric ecosystem services such as the value of the ocean and the uniqueness of Nantucket Sound (Kempton et al. 2005). Those interviewed who opposed the wind farm argued that the ocean belongs to the marine life and stated that a single commercial entity should not profit from a public resource (Kempton et al. 2005) or rather that a single ecosystem service was not worth the loss of all of the other socially valued ecosystem services in the area. Other public concerns of those arguing against the wind farms were anthropocentric and included the potential impact on property values in the towns surrounding the wind farm, tourist reduction, and altering the character of these areas (Kempton et al. 2005). In surveys conducted in relation to Cape Wind, the authors did not mention any questions and results related to ocean noise. The key point here is that there is a continuum in regards to people's values of the ecosystem services provided to the Cape Wind area. These perceptions and others need to be addressed by managers in their management strategies.

The arguments against the wind farms for the Cape Wind project boil down to the concepts of value and trade-offs. The opposition generally values biocentric beliefs such as protecting the ocean, keeping it free of human industrialism. Others focus on an anthropocentric argument by valuing traditions like sailing and fishing that are common in the area designated for the wind farm project. Local opponents desired to maintain their seascape view, which they assumed would be present forever. The supporters of wind farms value cleaner air, less human sickness and mortality that occurs with conventional energy sources, and the desire for energy security (Kempton et al. 2005). The real question for the public becomes does the global, invisible benefits of wind power outweigh the local (biological and social) costs that will be incurred within the selected area (Hoppe-Klipper and Steinhäuser 2002)? A related question is, are offshore wind farms feasible and competitive without federal subsidies (Snyder and Kaiser 2009)? These social questions and others need to be explored prior to the creation of a wind farm and the establishment of management initiatives. Are people willing to accept the consequences (including those associated with underwater noise) for the benefit of society as a whole or are the consequences too great and unknown for people to support the establishment of wind farms?

When addressing the issue of national security, the expert approach is less valued in favor of the nation's safety. The argument is that the need for national security (i.e. the protection of this country from military threats) outweighs the environmental and social costs of the activity. With the issue of national security, however, we need to consider the impacts of many other ecosystem services rather than focusing on a single ecosystem service. Let us consider the next case of Naval SONAR (sound, navigation, and ranging) and its impact on the marine environment. The oceans and coasts around the United States are a buffer zone that the U.S. Navy utilizes to reach its national security objectives (Abate 2010).

> "*The Navy is charged with maintaining, training, and equipping combat-ready naval forces capable of winning wars, deterring aggression, and ensuring freedom of the seas*," (Kiamos, 2001).

Navy SONAR is used in training exercises to track submarines, defend against attacks (Vassar 2009), to navigate, to communicate with other vessels, to determine water depths, to identify nearby vessels, and to locate mines. To maintain military readiness, the Navy conducts regular SONAR testing (Abate 2010). These SONAR systems, however, can have sound pressure level (SPL) values between 180 and 235 dB re 1 $\mu Pa^2/Hz$ at 1 m, depending on the type of SONAR utilized and the range of frequencies produced (10 Hz to > 10 kHz, Palmer 2010).

Due to the intensity of Navy SONAR noise, it has been linked to damage to marine life. Navy SONAR exercises across the world are often followed by mass strandings events of marine mammals (e.g. Balcomb and Claridge 2001, Frantzis 2004, Parsons et al. 2008). Shortly after Naval exercises, these stranded animals were found hemorrhaging in the inner ears and from other air spaces in the head (Balcomb and Claridge 2001, Ketten 2005). Some had bleeding around the brain, emboli in the lungs, and lesions in the liver and kidneys, which resemble the symptoms of decompression sickness (Jepson et al. 2003, Fernàndez et al. 2004, 2005, Jepson et al. 2005). In 1994, the first ocean noise pollution case was filed under National Environmental Policy Act (NEPA) and the Marine Mammal Protection Act (MMPA) and since then, public awareness and concern over the issue of underwater noise have grown (Abate 2010). This increased awareness is because people view marine mammals as providing an ecosystem service both by observing their presence and valuing the economic and tourism services provided by these animals.

Zirbel et al. (2011) assessed public attitude in the Washington, D.C. area to determine how the public viewed Navy SONAR impacts on marine life. Most of those surveyed (75%) believed that the Navy should not be exempt from marine mammal protection regulations during times of peace. This indicated the value society holds on protecting marine mammals. Slightly more than half of the respondents (51.3%) believed that Navy SONAR impacts marine mammals and 75.8% of the respondents believed that if Navy SONAR does impact marine mammals, then it should be regulated. On the other hand, 19.5% of respondents believed nothing should be done and only one respondent believed that SONAR should be stopped completely if marine mammals were impacted by the activity (Zirbel et al. 2011). If the attitudes of the public in Washington, D.C. can be extrapolated to the U.S., then the public does not feel that marine mammal protection should result in a complete moratorium on SONAR testing by the Navy. Rather, the public believes that regulations on SONAR use should occur to reduce the impacts of SONAR on marine mammals. Thus, managers should find a middle ground; regulating Naval SONAR to some extent while protecting marine mammals.

On one hand, regulating Navy SONAR poses a risk for national defense by prohibiting the Navy from preparing for national defense, which is within their legal right and responsibility (Palmer 2010). On the other hand, it appears that the public asks: "are the costs worth the benefit?" and "can we minimize the costs to marine mammals and still maximize the benefits of SONAR use?" Around the world, other governments are adopting a different strategy. The European Parliament called for the European Union member states to adopt a moratorium on high-intensity naval SONAR activities until assessments can be conducted on SONAR impacts on marine life (Florenz 2004). The World Conservation Union, of which several U.S. governmental agencies are members, adopted a resolution in 2004 that calls its members to use caution with military activities due to their potential impacts on marine life and to encourage the development of underwater noise control mechanisms (The World Conservation Union 2005). Underwater noise, especially from Naval SONAR is a concern around the world, but there is not consensus about what to do to address the issue. Therefore, it is important to determine the socially valued ecosystem services within a managed area and manage according to societal need. In this case, adaptive management is key because there will likely be times when national security becomes a primary concern to the public and the nation.

The issues presented here are not simple problems but rather very complex and a single issue can span multiple categories of ecosystem services. Additionally, people's attitudes and values associated with an issue varies and can change over time based on a set of circumstances. Sometimes, people are skeptical of a management action, while the beliefs and values of others are set within norms that have been driven by history. Yet, others are unsure about what to believe because the issue is complex and the benefits may not be clear to the general public. The key for EBM managers is to understand user perception on the issue of underwater noise management and do their best to actively include the public in the decision-making process.

Content Analysis

Ecosystem-based management requires an understanding of (1) the connection of ecosystem components and (2) the connections between people and the ecosystem (McLeod and Leslie 2009). An effective EBM plan needs to incorporate all of these perspectives to address the issue of underwater noise. One way to gain these perspectives is to analyze texts written by people. The text a person writes or the words he says helps explain his perspective on an issue or the concept(s) that are of primary concern to his perspective (Woodrum 1984). Here, I will be using content analysis to determine themes of underwater noise management strategies and applicable enabling legislation.

One method to understand a person's perception of underwater noise is to run a content or text analysis on documents written by that individual. This method helps to assess values, intentions, attitudes and thought processes of the authors who write them (Duriau et al. 2007). An assumption in this type of analysis is that the text written by a person is indicative of his/her cognitive thoughts (Woodrum 1984). Here, we can explore the value paradigm (e.g. expert vs EBM approach) of the authors. The concept of content analysis is based on the function of communication. Language is a type of behavioral manifestation, where individual differences can be discerned as well as the social processes that shaped the thinking of the document's author. Commonly used words show information on what people are paying attention to and what people are thinking about, which reveals a person's priorities, intentions, and thoughts. Nouns, verbs, and some adjectives and adverbs convey information about the content of communication (Tausczik and Pennebaker 2010). Word frequency indicates cognitive centrality or the focus of a person's conversation (Ryan and Bernard 2003, Duriau et al. 2007), from which can be inferred an individual's perception of the importance of a subject (Semin and Fiedler 1988, Abrahamson and Hambrick 1997).

Words, written or spoken, in underwater noise management are valuable because they can reveal an individual's focus and thus what information a person is interested in concerning the environment. Language provides clues as to how people process information and how they apply the information to the environment (Tausczik and Pennebaker 2010). Text analysis on content words can be applied to management and federal legislative texts to explore the themes of a document, or rather, the perception of how the authors view the environmental problem in question and how they choose to address the issue.

A word correlation network, like that of a social network, is a method to explore the connections among nodes (in this case the nodes represent words). These connections can then be used to infer themes of similarities or differences among a variety of documents (Schnegg and Bernard 1996, Borgatti et al. 2013). Prominent themes are revealed by words with strong ties in the network from words that occur at high frequencies across each of the documents (Schnegg and Bernard 1996). Similarly, words with weak ties are often found in low word counts for some documents but these same words have a high frequency within only a few documents. This dissimilarity suggests dissimilar themes across documents (Schnegg and Bernard 1996). Other important patterns of word use to look for are words that connect with other words in the network that would otherwise be disconnected from each other (Freeman 1979). These "high betweenness" words could be important concepts that help reveal an overarching theme and thus can help unify the documents (Borgatti et al. 2013). These revealed themes offer a window into the worldview of the authors and thus the primary motivation for their written work.

This paper will focus on text analyses of underwater noise management documents and applicable legislative documents, with a goal of inferring themes (i.e. author cognition) for each document type. First, assessments will be addressed in two groups of documents (management and legislation), then both will be simultaneously explored in terms of word frequency, word use similarities within a network, and cognitive centrality of key words to demonstrate themes inherent in the viewpoints of the authors. This work will end with a discussion on the authors' value orientation paradigm and how it may influence the perspectives present in the management initiatives.

Methods

Noise Management Documents

Four noise management documents were selected for analysis to identify the key strategies to address U.S. underwater noise management (Table 5.2). In this paper, management documents are defined as documents that suggest strategies to regulate the consequences of underwater noise. These management documents could have been written by federal agencies or by other interested organizations. Generally, the underwater noise management documents addressed the concerns of underwater noise as well as provided a perspective on how to manage the issue. Three of the identified documents focused on the impacts of noise on cetacean behavior (Southall 2004, Southall et al. 2009, Wright 2014). Two of these documents were written by the same author (Southall 2004, Southall et al. 2009) but one document focused primarily on vessel noise (Southall 2004) while the other focused on the other aspects anthropogenic noise (Southall et al. 2009). Wright (2014) was published by the World Wildlife Federation, which is a non-governmental organization (NGO). This document focused on cetaceans and attempted to address the impacts underwater noise and discussed how to manage it. The final document is a draft document produced by the National Oceanic and Atmospheric Administration (NOAA, Gedamke et al. 2016) and not only attempts to address all aspects of underwater noise but also be inclusive of other aquatic life.

Table 5.2. Abbreviations for the legislative and noise management documents included in the correspondence and document network analyses.

Enabling legislation and management documents with their assigned abbreviations for the correspondence and document network analyses.

Document Type	Document Name	Abbreviation	Document Network Analysis Abbreviation
Legislation	Anadromous Fish Conservation Act	AFCA	AFC
Legislation	Clean Water Act	CWA	CWA
Legislation	Coastal Zone Management Act	CZMA	CZM
Legislation	Endangered Species Act	ESA	ESA
Legislation	Estuary Protection Act	EPA	EPA
Legislation	Fish and Wildlife Coordination Act	FWCA	FWC
Legislation	Marine Mammal Protection Act	MMPA	MMP
Legislation	Magnuson-Stevens Fishery Conservation and Management Act	MSA	MSA
Legislation	National Environmental Policy Act	NEPA	NEP
Legislation	Oceans Act	OA	OA
Legislation	Outer Continental Shelf Lands Act	OCSLA	OCS
Legislation	Sikes Act	SA	SA
Legislation	Water Resources Development Act	WRDA	WRD
Legislation	Whale Conservation and Protection Study Act	WCPSA	WCP
Management	Gedamke et al. 2016	NOAA	NOA
Management	Southall 2004	SO4	S04
Management	Southall et al. 2009	S09	S09
Management	Wright 2014	Wright	Wrg

The noise management documents were downloaded online in a digital format (Adobe pdf) and converted to ASCII text. Before these documents were utilized in the text analysis, word strings that could be made into existing abbreviations were replaced with their abbreviations. This created a code for a specific word string that keeps the word string together in the word frequency count. For example, the phrase national marine sanctuary(ies) was altered to NMS and the Marine Mammal Protection Act was replaced with MMPA. A total of 28 word strings were replaced with their abbreviations. Additionally within these documents, some words were used with a management perspective, while the same word was used later in the document to address biological concepts. For these words, a synonym word or partial word was used to replace the original word for one of the two categories (management and biological). This synonym (or partial word replacement) word was not previously used in the document. For example, the word "marine" might have applied to an animal ("marine mammal") or habitat ("marine habitat") in a biological sense, but it could have also been used in terms of management as in "marine minerals," "marine resources," and "marine spatial planning." So, when the word "marine" was used in a management sense, it was replaced with "saltwater" within the text. This occurred with a total of 26 words within the text (Table 5.3). The purpose of this was so that the words would plot separately based on their context (management or biological) and additional information could be further assessed from their use. These words and word string replacements were completed using the find and replace function in a text editor program (Notepad). After the results were obtained, each replaced word was the restored with its original word to create word clouds, which is useful to visualize word frequency use. Word clouds were created for each group of documents (management and enabling legislation) and for each word category (biological and social).

Table 5.3. Word replacements for the text analysis to separate managerial related terms and biologically relevant terms within the management documents.

Word replacements for the words that could be utilized as either biological or management terms. The original word (or words) is (are) shown along with the grouping category (biological or management) that was altered, the synonym word or partial word that was used as a replacement in the text, and an example of how that word was used in the specified sense before the synonym or partial word replaced it.

Original Word	Category Altered	Synonym Word	Example
Acoustic	Biological	Audible	"acoustic habitats"
Active/Activity	Biological	Endeavor	"vocally active species"
Area	Management	Vicinity	"protected area"
Biologically	Management	Biol	"biologically important areas"
Change	Management	Chan	"change in noise condition"
Condition	Biological	Demeanor	"environmental condition"
Different	Biological	Diff	"soundscapes are different across the frequency spectrum"
Effect	Management	Pursuance	"effects of chronic noise"
Environment/Environmental	Biological	Envir	"marine environment"
Impact	Management	Impinge	"anthropogenic activity impacts"
Internal	Biological	Visceral	"internal organs"
Level	Biological	Lev	"level of hearing"
Marine	Management	Saltwater	"marine noise pollution"
Natural	Management	Crude	"crude gas"
Number	Management	Numb	"number of noise producers"
Ocean	Biological	Ocea	"pristine ocean habitats"
Population	Management	Pop	"adverse population impacts"
Produce	Biological	Compose	"sounds produced by animals"
Reduce	Biological	Diminished	"diminished reproductive success"
Response/Responsibility	Management	Compelled	"responsibility to analyze the impacts"
Risk	Biological	Imperil	"health and disease risk [of certain species]"
Sound	Biological	Voice	"use of sound for communication by marine mammals"
State	Biological	Stature"	"state of an animal"
Underwater	Biological	Undersea	"animal movement and behavior underwater"
Use	Management	Exert	"human use patterns"
Water	Biological	Wat	"[detect] changes in water flow"

Enabling Legislative Documents

Federal legislation documents that were associated with the aquatic environment, the species of concern, or the regulation of military activities were identified. From these, fourteen of the enabling legislation documents were selected for further analysis (Table 5.2) based on their ability to incorporate noise pollution in their legislative statutes. While most of them did not directly address noise pollution, those that were selected had provisions that addressed potential impacts related to underwater noise (e.g. population-level impacts, habitat, and ecosystem functioning). These legislative documents extensively discussed environmental concerns as well as needed social considerations for management.

For the text analysis, words were not replaced in the federal legislative documents. This is because the words utilized in these documents were used consistently and generally non-overlapping with other words in a social or environmental context. In other words, social and environmental considerations used different terms for management and biological issues rather than the same term as was the case with the noise management documents. This is partly because the federal legislative documents addressed social concerns to a greater degree than the noise management documents.

Text Analysis

After the documents were prepared, they were brought into R statistical software (hereafter referred to as R, R Core Team 2013) and a text analysis was executed utilizing the text mining guidelines in the package "TextMiningO" (Williams 2016). Following these guidelines, a corpus (collection of texts) was created, where all documents within a grouping (management or enabling legislation) were analyzed in a single corpus. Next within each corpus the numbers, punctuations, and undesirable words were removed. For example, 174 English language stop words were removed that included pronouns, prepositions, conjunctions, determiners, and some adverbs. Additional words were removed that held no meaning in terms of management decisions or biological impacts. Some examples of these words were: “number,” “one,” “like,” “example,” and “discuss.” The objective was to have nouns, verbs, adjectives, and some adverbs left in the texts that represented the subject matter of interest. Next, the documents were stemmed, which removes the English ending (“es,” “ed,” “ing,” and “s”) from the words. Finally, a document term matrix was created, which creates a comma separated values text file (csv file) of the terms remaining and their frequency of use within each of the documents. For the management corpus, 5,247 content words remained and 3,343 content terms remained in the federal legislation corpus.

The corpus for each document type was utilized to identify the most frequently used words. For the four noise management documents, words that were used at a frequency rate of 100 times or more in all four documents were selected for further analysis. These comprised of a total of 76 words that made up 33% of the total words in the documents. For the fourteen federal legislation documents, terms that were used at a frequency of 200 times or more across all of the documents were kept for further analysis. These comprised of a total of 102 words and these words were 49.5% of the total remaining words in the documents. While there were other valuable words that occurred at lower word frequencies, often only a few documents strongly utilized the word, while the other documents rarely (or never) used the same word. Because these words were so limited across the documents within a single corpus, these words were not selected for further analysis. The resulting limited lists of words were more manageable to generate and interpret word clouds and the other types of analyses than the original lists of over 3,300 terms.

Once the word frequencies were computed, words were assigned to a category (biological or management) based on how they were used in most sentences within the documents. Words were identified using the "find" function in the text editor program (Notepad) and the identified word was explored as to how it was used in the sentence and (if need be) the sentences before and after its use to determine its category (biological or management). This occurred in all of the documents within a corpus. These word categories were separated into two csv documents, imported into R, and word clouds were generated from each using the "Word Cloud" package in R. These world clouds were visually used to assess dominant themes within a single corpus (management or legislation).

Analysis of Words in Combined Legislative and Management Texts

The final step in the process was to determine how the noise management documents related to the applicable federal legislation in terms of word commonality and frequency. For the enabling legislative documents, a few words were removed from the top 200 words. These words included terms that focused on the description of who was responsible to act on natural resources, such as "administration", "secretary," and "state." For the management documents, no words were removed from the top 100 terms before the next analysis step. To make the documents directly comparable, the original word frequency data for both management and legislative documents were converted into proportions for each document. Any terms that had a combined proportion of 20% or more within each set of documents were analyzed further. Some words were dominant in only the legislative documents while others were primarily dominant in the noise management documents. More words than this 20% would have been too difficult to view in visual displays.

This process reduced the total word count to a total of 20 words within both texts. Next, these words were converted back into actual counts (word frequencies) for all further analyses, because the input data required by the correspondence analysis in based on counts, but it converts this information back into proportions (Greenacre 2007).

Correspondence analysis is a multivariate statistical technique that can be used with categorical data like word frequency counts in the documents examined here and is similar conceptually to a principal component analysis used on continuous data (Greenacre 2007). Correspondence analysis can be used to identify writing patterns underlying word frequency counts in the documents into two dimensions, called factors. Correspondence analysis summarizes the word frequency counts, arranged as an m x n contingency table with N = 18 documents (combined for both manage and legislation) as rows and N = 20 words as columns (the 20 dominant words within all of the documents), by computing factor scores on the two dimensions for each row and column item. Then the factor scores for each item in the rows (each document's factor score on dimension 1 and dimension 2) and columns (each word's factor score on these same two dimensions) can be plotted in a bi-plot of dimensions 1 and 2. The details of the underlying factor score computations can be found in Greenacre (2007).

A correspondence analysis was executed using the 18 documents and the 20 words from the "CA" function in the "FactoMineR" package (Lê et al. 2008) in R. The analysis was used to generate two new dimensions to further assess the relationship between the words and the selected documents. Next, the "fviz_ca_biplot" function in the "Factoextra" package (Kassambara and Mundt 2016) was utilized to create a biplot of the words and the documents plotted amongst the two new dimensions created in the correspondences analysis. These data were used to assess differences and similarities in themes across documents by plotting the words and the documents in new dimensions. When the documents or words plot with each other within the two-dimensional plot, the words that plot in groups have something in common. However, when the documents of words plot opposite each other along a dimension, then they are on opposite ends of the spectrum or dissimilar from each other by the factor(s) during that specific dimension (Greenacre 2007).

Next, the "cor" and "qgraph" functions in the "qgraph" package (Epskamp et al. 2012) in R were used to create two correlation matrices that were utilized in the network analyses. The first network analysis explores content word similarities and differences (Table 5.4) and the second analysis assessed document (Table 5.5) similarities and differences. For the network analysis based on the content words, a 16 x 16 word matrix was created using the 18 documents as variables. The content word network analysis was limited from 20 to 16 total words to ensure an analysis could be run because the number of words to be correlated needed to be less than the total number of documents (18) in the analysis. The two least dominant words of the final 20 selected in each of the document sets (management or legislative) were removed for the correlation analysis. The words that were eliminated from this analysis were "active/activity", "coast", "land", and "ship". For the document network analysis, an 18 x 18 document matrix was created using the 20 words as variables. The two outputted square matrices were based on Pearson correlation measures (ρ) as measures of word or document similarity. To visualize these networks, I used "qgraph" with a "spring" embedder network layout. For the word content network analysis, words were used as nodes and similarity measures among the documents were used as ties among the nodes. For the document network analysis, the documents were used as nodes and the similarity measures among the words within the documents were used as ties among the nodes. The "spring" embedder layout uses the Fruchterman-Reingold algorithm, which is force-directed, to arrange the nodes (Epskamp 2013). Essentially, the algorithm uses a sum of the force vectors (defined by similarity) acting on a node to determine the position of the node and minimizes the total energy of force acting upon a single node. The outputted networks were presented in two ways. First, with all positive and negative correlation value connections ($-1.0 < \rho < 1.0$), regardless of the significance level. The second networks are presented with only significant correlation values used as ties. For the word content network, this significance level was set at $p < 0.01$ but for the document network, the significance level was set at $p < 0.10$. This difference in significance levels between the networks was adjusted because only one network connection within the document network was significant at a $p < 0.01$ level. This network produced too few ties to assess relationships among the documents. Therefore, the probability of significance level was raised for only the document network to $p < 0.10$.

Node eigenvector centrality statistics were obtained using the “eigen” function in the “base” package of R. These centrality values were plotted using the “ggplot2” package (Wickham and Chang 2016) to create scatter-plots of eigenvector centrality measurements. These data were used to explore node (word or document) centrality within each network and thus further assess the similarities and differences between the selected documents.

Table 5.4. Correlation matrix for the words selected for the network analysis.

Correlation matrix of the 16 words selected for network analysis. This matrix shows the similarities and differences among the 18 documents. Word abbreviations are presented in Table 5.8.

	acoust	**conserve**	**develo**	**fish**	**impact**	**mammal**	**marin**	**manag**	**nois**	**plan**	**project**	**public**	**resourc**	**sound**	**sourc**	**vessel**
acoust	1	-0.08	0.16	0.13	0.80	0.15	0.34	0.26	0.87	-0.23	-0.11	-0.18	0.02	0.90	0.71	0.02
conserve	-0.08	1	0.28	0.90	0.05	0.40	0.47	0.68	-0.13	0.61	-0.02	0.27	0.42	-0.13	-0.19	0.82
develo	0.16	0.28	1	0.32	0.27	0.02	0.15	0.55	0.09	0.67	0.82	0.74	0.88	0.17	0.08	0.37
fish	0.13	0.89	0.32	1	0.20	0.11	0.28	0.83	0.07	0.57	-0.05	0.13	0.47	0.07	-0.01	0.82
impact	0.80	0.05	0.27	0.20	1	0.39	0.59	0.41	0.93	-0.07	-0.05	-0.03	0.07	0.91	0.90	0.13
mammal	0.15	0.40	0.02	0.11	0.39	1	0.94	0.06	0.23	-0.01	-0.15	0.08	-0.11	0.21	0.23	0.32
marin	0.34	0.47	0.15	0.28	0.59	0.94	1	0.28	0.40	0.09	-0.16	0.11	-0.03	0.44	0.45	0.46
manag	0.26	0.68	0.55	0.83	0.41	0.06	0.28	1	0.27	0.74	0.10	0.47	0.53	0.25	0.18	0.75
nois	0.87	-0.13	0.09	0.07	0.93	0.23	0.40	0.27	1	-0.24	-0.13	-0.21	-0.06	0.90	0.87	0.01
plan	-0.23	0.61	0.67	0.57	-0.07	-0.01	0.09	0.74	-0.27	1	0.38	0.83	0.59	-0.25	-0.31	0.71
project	-0.10	-0.02	0.82	-0.05	-0.05	-0.15	-0.16	0.10	-0.13	0.39	1	0.60	0.81	-0.12	-0.16	< 0.01
public	-0.18	0.27	0.74	0.13	-0.03	0.08	0.11	0.47	-0.21	0.83	0.60	1	0.54	-0.16	-0.21	0.39
resourc	0.02	0.42	0.88	0.47	0.07	-0.11	-0.03	0.53	-0.06	0.59	0.81	0.54	1	-0.02	-0.12	0.36
sound	0.90	-0.13	0.17	0.07	0.91	0.21	0.44	0.25	0.90	-0.25	-0.12	-0.16	-0.02	1	0.93	-0.02
sourc	0.71	-0.19	0.08	-0.01	0.90	0.23	0.45	0.18	0.87	-0.31	-0.16	-0.21	-0.12	0.93	1	-0.07
vessel	0.02	0.82	0.37	0.82	0.13	0.32	0.46	0.75	0.01	0.71	< 0.01	0.39	0.36	-0.02	-0.07	1

Table 5.5. Correlation matrix for the documents in the network analysis.

Correlation matrix of the 18 documents in the network analysis. This matrix shows the similarities and differences among the twenty words within the documents. Document abbreviations are presented in Table 5.2.

	AFCA	CWA	CZMA	ESA	EPA	FWCA	MMPA	MSA	NEPA	OA	OCSLA	SA	WRDA	WCPSA	NOAA	S04	S09	Wright
AFCA	1.00	0.10	0.02	0.82	0.02	0.61	0.01	0.53	0.31	0.02	0.02	0.77	0.11	0.43	-0.34	-0.53	-0.35	-0.46
CWA	0.10	1.00	0.33	0.15	0.54	0.33	-0.04	0.27	0.41	0.14	0.40	0.43	0.52	-0.15	-0.48	-0.37	-0.37	-0.42
CZMA	0.02	0.33	1.00	-0.08	0.08	0.09	-0.21	0.04	0.18	0.72	0.79	0.20	0.05	-0.23	-0.29	-0.42	-0.31	-0.27
ESA	0.82	0.15	-0.08	1.00	-0.02	0.28	0.17	0.70	0.12	-0.07	-0.02	0.61	-0.05	0.49	-0.25	-0.45	-0.34	-0.37
EPA	0.20	0.54	0.08	-0.02	1.00	0.63	-0.20	-0.04	0.35	0.02	0.08	< 0.01	0.95	-0.21	-0.28	-0.35	-0.25	-0.26
FWCA	0.61	0.33	0.09	0.28	0.63	1.00	-0.23	0.14	0.33	-0.06	0.04	0.61	0.74	-0.06	-0.46	-0.56	-0.47	-0.51
MMPA	0.01	-0.41	-0.21	0.17	-0.20	-0.23	1.00	0.18	-0.19	-0.02	-0.15	-0.11	-0.22	0.37	-0.10	0.21	0.24	0.17
MSA	0.53	0.27	0.04	0.70	-0.04	0.14	0.18	1.00	-0.08	-0.09	0.01	0.46	-0.09	0.28	-0.13	-0.15	-0.32	-0.31
NEPA	0.31	0.41	0.18	0.12	0.35	0.33	-0.19	-0.08	1.00	0.41	0.21	0.30	0.38	-0.05	-0.27	-0.48	-0.13	-0.19
OA	0.02	0.14	0.72	-0.07	0.02	-0.06	-0.02	-0.09	0.41	1.00	0.67	< -0.01	< -0.01	-0.12	-0.25	-0.28	-0.10	-0.16
OCSLA	0.02	0.40	0.79	-0.02	0.08	0.04	-0.15	0.01	0.21	0.67	1.00	0.19	0.059	-0.20	-0.40	-0.41	-0.30	-0.34
SA	0.77	0.43	0.20	0.61	< 0.01	0.61	-0.11	0.46	0.30	< -0.01	0.19	1.00	0.09	0.06	-0.43	-0.59	-0.49	-0.50
WRDA	0.11	0.52	0.05	-0.05	0.95	0.74	-0.22	-0.09	0.38	< -0.01	0.06	0.09	1.00	-0.23	-0.36	-0.37	-0.28	-0.35
WCPSA	0.43	-0.15	-0.23	0.49	-0.21	-0.06	0.37	0.28	-0.05	-0.12	-0.20	0.06	-0.23	1.00	-0.02	0.16	-0.07	0.04
NOAA	-0.34	-0.48	-0.29	-0.25	-0.28	-0.46	-0.10	-0.13	-0.27	-0.25	-0.40	-0.43	-0.36	-0.02	1.00	0.59	0.55	0.82
S04	-0.53	-0.37	-0.42	-0.45	-0.35	-0.56	0.21	-0.15	-0.48	-0.28	-0.41	-0.59	-0.37	0.16	0.59	1.00	0.33	0.62
S09	-0.35	-0.37	-0.31	-0.34	-0.25	-0.47	0.24	-0.32	-0.13	-0.10	-0.30	-0.49	-0.28	-0.07	0.55	0.33	1.00	0.59
Wright	-0.46	-0.42	-0.27	-0.37	-0.26	-0.51	0.17	-0.31	-0.19	-0.16	-0.34	-0.50	-0.35	0.04	0.82	0.62	0.59	1.00

Results

Noise Management Documents

A total of 76 words occurred 100 times or more within the selected noise management documents. Twenty (26.3%) of these words fell into the biological term category and the remainder (56 words) were identified as words related to management. The most dominant biological term was “marine” (Figure 5.1, Left), which often related to “marine species,” “marine environment,” and “marine mammal.” The word “marine” made up 13.7% of the total biological terms, followed by “species” (9.4%), “mammal” (8.2%), “habitat” (6.4%), “whale” (5.5%), and “fish” (5.4%). The most dominant management term was “noise” (Figure 5.1, Right), which made up 9.7% of the total management terms. The word “noise” was often associated with “noise levels,” “underwater noise,” “noise-producing,” and “noise impacts.” Other terms that were important in the management category were “sound” (4.9%), “source” (3.5%), “acoustic” (3.3%), and “activity” (3.0%). The key themes within the noise management documents are (1) defining animal or habitats that are potentially impacted by underwater noise (“mammal,” “habitat,” “whale,” and “fish”) and (2) addressing management concerns associated with underwater noise (“sound,” “source,” “noise,” “acoustic”).

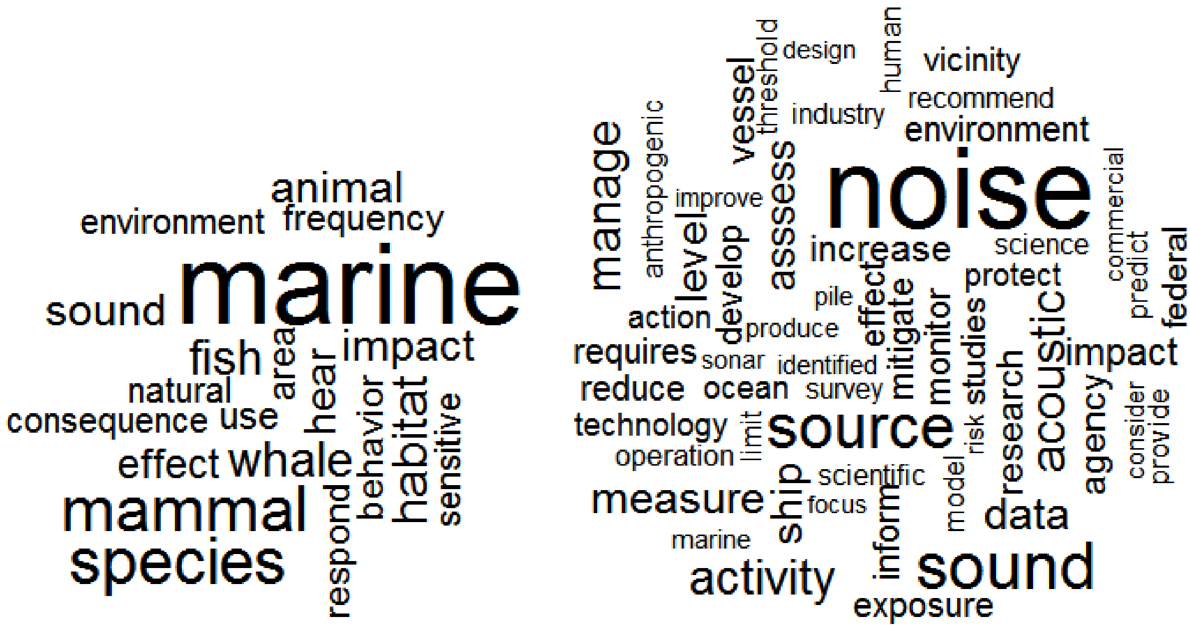

Figure 5.1. Word clouds for the words in the noise management documents.

Word clouds of the biological terms (left) and management terms (right) that occurred 100 times or more within the noise management documents. The size of the word indicates the frequency of the word use. The larger the word, the more it was utilized in the texts.

Legislative Documents

i. Environmental and Social Concerns

A total of fourteen enabling legislation documents were identified that could address the issue of underwater noise (Table 5.2). Only one (7.1%) of the examined legislation (National Whale Conservation and Protection Study Act) addressed the issue of underwater noise (Table 5.6) and the rest did not directly mention the issue of noise impacts on marine life. However, there are other provisions in these legislative documents where underwater noise could be regulated. Four (28.6%) of the legislative documents addressed concerns over waterway pollution. Concerns over habitat protection were present within all of the identified enabling legislation (100%). Two (14.3%) of the documents addressed concerns over the interaction between vessels and animals, primarily cetaceans. Finally, seven (50.0%) of the fourteen documents addressed concern over the impact of human activities on animal health, migration, and reproduction.

Based on the fourteen selected federal legislative documents, social trade-offs in response to managing the environmental concern directly addressed the social concepts of preservation of recreation, the maintenance of cultural and historical values, economics, and national security. Ten of the fourteen documents (71.4%) addressed the need to preserve recreation in the managed region (Table 5.7). Six (42.9%) of the enabling legislation documents suggested the need to retain cultural and historical values when adopting management strategies. Economics, or the concept of a trade-off between environmental and social costs and economic benefits, was mentioned as a concern in twelve of the identified legislation (92.9%) documents. Finally, two (14.2%) of the selected federal legislation mentioned concerns about national security. Here the argument is the need for national security (i.e. the protection of this country from military threats) outweighs the environmental and social costs of the activity.

Table 5.6. Environmentally related concerns addressed in the federal legislative documents.

Federal legislation documents that were identified as potentially being able to address the issue of noise pollution. The X's columns indicate the main environmental concern(s) within each legislative document under which the issue of noise pollution can be addressed.

Federal Legislation	Noise Guidelines	Pollution	Interactions between Vessels and Animals	Habitat Protection	Animal Health, Migration, and Reproduction
Anadromous Fish Conservation Act (AFCA)				X	X
Clean Water Management Act (CWA)		X		X	
Coastal Zone Management Act (CZMA)		X		X	
Endangered Species Act (ESA)				X	X
Estuary Protection Act (EPA)				X	
Fish and Wildlife Coordination Act (FWCA)		X		X	X
Magnuson-Stevens Fishery Conservation and Management Act (MSA)				X	X
Marine Mammal Protection Study Act (MMPA)			X	X	X
National Environmental Policy Act (NEPA)				X	
Ocean Act (OA)		X		X	
Outer Continental Shelf Lands Act (OCSLA)				X	
Sikes Act (SA)				X	X
Water Resources Development Act (WRDA)				X	
Whale Conservation and Protection Study Act (WCPSA)	X		X	X	X

Table 5.7. Socially related concerns addressed in the federal legislative documents.

Federal legislation that was identified as potentially being able to address the issue of noise pollution. The X's indicate the main social concern(s) within each legislative document.

Federal Legislation	Preservation of Recreation	Cultural & Historical Values	Economics	National Security
Anadromous Fish Conservation Act (AFCA)			X	
Clean Water Act (CWA)	X			
Coastal Zone Management Act (CZMA)	X	X	X	
Endangered Species Act (ESA)			X	X
Estuary Protection Act (EPA)	X			
Fish and Wildlife Coordination Act (FWCA)	X		X	
Magnuson-Stevens Fishery Conservation and Management Act (MSA)	X	X	X	
Marine Mammal Protection Study Act (MMPA)		X	X	
National Environmental Policy Act (NEPA)	X	X	X	
Ocean Act (OA)	X	X	X	
Outer Continental Shelf Lands Act (OCSLA)	X	X	X	
Sikes Act (SA)	X		X	X
Water Resources Development Act (WRDA)	X		X	
Whale Conservation and Protection Study Act (WCPSA)			X	

ii. Text Analysis

A total of 102 words occurred 200 times or more within the selected federal legislative documents. Thirteen (12.3%) of these terms were used in a biologically related way and the remainder of 89 terms were used in a management-related way within a sentence. Two biologically related terms were dominant in the word cloud (Figure 5.2, Left). The word "water" occurred 17.7% of the time while "fish" occurred 17.1% of the time. Other important biological terms in these documents were "marine" (10.8%), "species" (10.0%), "coast" (8.2%), "mammal" (7.3%), "river" (6.0%), and "environment" (5.9%). The biological terms in these documents generally relate to a specific group of animals ("fish"/"mammal") or habitat ("coast"/"river"/ "environment"). For the management terms in these enabling legislation documents there were two dominant terms "secretary" (7.2%) and "state" (6.7%) in the word cloud (Figure 5.2, Right). The word "secretary" is often used to describe an individual with authority to make an action. For example, "secretary authorizes," "secretary of commerce carries out," and "secretary of state," are common ways in which secretary was used in these legislative documents. The term "state" is often used to describe the responsibilities of the states within the U.S. For example, "each state allocates," "in cooperation with the states," "states negotiate and enter into agreements," are some ways in which "state" is used within the federal legislation. Other management terms that are important in these documents include "fisheries" (2.8%), "administration" (2.8%), "program" (2.8%), "project" (2.7%), "federal" (2.6%), "plan" (2.5%), "manage" (2.2%), and "public" (2.0%). The key concepts within the enabling legislation are (1) defining the authorities responsible for enforcement ("secretary," "state," "federal"), (2) identifying resource concerns ("fisheries," "public"), and 3) defining ways to deal with the issue ("programs," "projects," "plans").

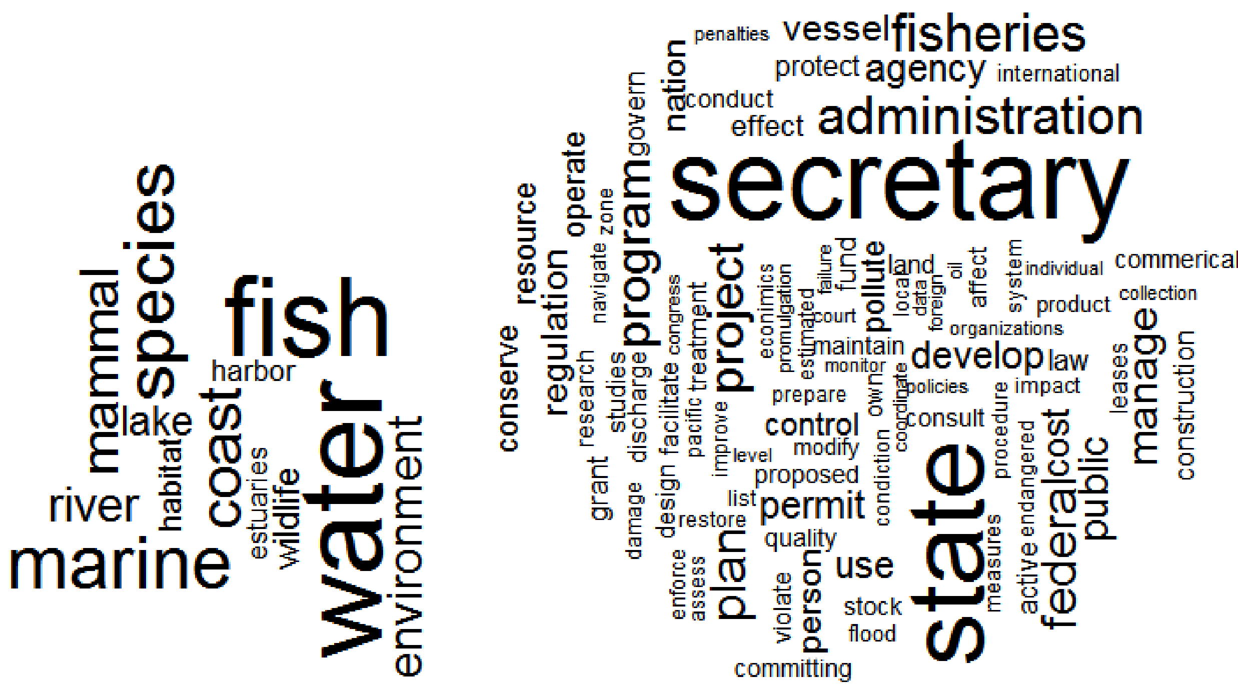

Figure 5.2. Word clouds for the legislative documents.

Word clouds of the biological terms (left) and management terms (right) that occurred 200 times or more within the federal legislative documents. The size of the word indicates the frequency of the word use. The larger the word, the more it was utilized in the texts.

Combining Legal and Management Texts

A total of twenty words were identified for further analysis based on the combined legal and management texts. Two words ("land" and "plan") never occurred in the noise management documents but were present at least one time in most of the federal legislative documents (Table 5.8). Because the word "land" was present in the enabling legislation documents, it demonstrates that these documents address the terrestrial realm while the noise management documents do not. It is understandable that the noise management documents do not include the word "land" because these documents focus on the marine environment. Also, the legislation documents call for a "plan" of action or a "planning" process for human use. The reason why the word "plan" is not a part of the noise management documents is because these noise management plans are expected to be the plan of action to address the concerns of the enabling legislation. One word ("source") never occurred in the federal legislative documents but was present in all of the noise management documents. This is because bioacousticians and physicists working on the issue of underwater noise often focus on a sound source level (dB re 1 μPa) to understand how noise may impact marine life. Other rare words in the legislative documents included "acoustic," and "noise," both of these words were dominant within the noise management documents. These three terms are most associated with managing the impacts of underwater noise and measuring sound source levels. Because only one of the federal legislative documents actually addressed underwater noise as an environmental issue (Table 5.6), it is not surprising these terms are not dominant in the enabling legislation.

Six words were present in all of the selected documents. These words were "active/activity," "conserve/conservation," "develop/development," "manage/management," "public," and "resource," (Table 5.8). These words suggest commonalities in the topics discussed, which included the themes of conservation and management of public resources. It is interesting to note that the word "fish" was utilized more in the legislative documents than "mammal," (Figure 5.2). While "fish" was used in all of the noise management documents, "mammal" was more frequently found in these documents (Figure 5.1). The noise management documents focus their efforts on marine mammals, while the legislative documents are generally more focused on "fish" more than "mammals." For both sets of documents, the most common themes were "development," "vessels," and "ships." The noise management documents focused on these issues in terms of "acoustic noise" or "sound source levels," whereas the federal legislation focused on the need to create "projects" or how the "activity" directly impacted the resource.

Table 5.8. Word abbreviations and frequency of occurrence in both the legislative and noise management documents.

Words occurrence in the legislative and noise management documents. The values (%) indicate the percentage of the documents within each category that contained (presence/absence) the specified word within the document categories. The word abbreviations are utilized in the network analysis.

Word	Abbreviations	Enabling Legislation	Management Documents
Acoustic	acs	14.3%	100%
Active/Activity	act	100%	100%
Coast	cst	71.4%	100%
Conserve/Conservation	cns	100%	100%
Develop/Development	dvl	100%	100%
Fish	fsh	85.7%	100%
Impact	imp	64.3%	100%
Land	lnd	92.9%	0%
Mammal	mmm	42.9%	100%
Manage/Management	mng	100%	100%
Marine	mrn	78.6%	100%
Noise	nos	21.4%	100%
Plan	pln	100%	0%
Project	prj	92.9%	100%
Public	pbl	100%	100%
Resource	rsr	100%	100%
Ship	shp	57.1%	100%
Sound	snd	50%	100%
Source	src	0%	100%
Vessel	vss	64.3%	100%

i. Correspondence Analysis

Correspondence analysis was used to generate factor scores in two dimensions for each of the legislative and management documents and for the words used within these documents. Words with similar factor scores (column scores) in the two dimensions will plot close to one another in a biplot (Figure 5.3), indicating that they were used with similar frequency in the documents.

Likewise, documents with similar factors scores (row scores) will plot together in the same two-dimensional space. In this way, one can understand how the documents and words are similar one another in terms of word-use frequency. This analysis can reveal patterns in language use in the documents and thus underlying themes of the documents.

The correspondence analysis was conducted on the selected sixteen words (blue abbreviations in lower case, Figure 5.3) within the two document sets (red abbreviations in upper case, Figure 5.3). The two dimensions explain 58.5% of the variance within the data set and ranges between resource protection and conservation. Dimension one (Dim1) explains 37.7% of the variance (Figure 5.3). Words associated with the left side of dimension 1 (quadrants II and III) include words like, "marine (mrn)," "mammal (mmm)," "noise (nos)," "sound (snd)," "impact (imp)," and "source (src)." These words are often used in the documents when addressing the concept of protection. Some phrase examples within the legislative documents include: "to protect marine mammals," "reducing potential adverse effects on whales" and "affect the balance of marine ecosystems." Within the noise management documents, some examples of the use of these words within phases include: "risk of chronic noise on… habitat," "noise impacts to spawning areas," "explore alternatives to sound sources with adverse effects," and "sound sources can affect marine ambient noise [levels]." Words associated with the right side of dimension 1 (quadrants I and IV), focus on the concept of "conservation," are words like "fish (fsh)," "conserve (cns)," and "resource (rsr)." Some example of the use of these words in phrases include "fishery conservation," "protection of essential fish habitats," and "conserve endangered species." Dimension 2 (Dim2) in the correspondence analysis explains 20.8% of the variation in the data set (Figure 5.3). The words in this dimension range from environmental preservation to human use. Within quadrants I and II, words are associated with human use. Words like "develop (dvl)," "project (prj)," sound (snd)," and “ship (shp),” load within these quadrants. Some example of the use of these words in phrases include, “resource development projects “commercial shipping,” “human-generated sounds,” and “sound-producing activities.” The words within quadrants III and IV, address concepts of environmental preservation and include words like “marine (mrn),” “fish (fsh),” and “conserve (cns).” Example phrases used within these documents include “population impacts to marine mammals,” “conserve and enhance essential fish habitat,” “conservation and recovery plan,” and “conservation and management of species of concern.”

Within the correspondence analysis, the documents factor scores plot in the same region of the bi-plot as the scores for the words that are used frequently within the documents, suggesting the general theme for each of the documents. Eight of the fourteen (57.1%) enabling legislation documents have factor scores in quadrant I (Table 5.9), which contains words that focus on human use and resource conservation. All four of the noise management documents (100%) have factor scores in quadrant II, which indicates a theme of resource protection and human use. Only two (14.3%) legislative documents fall into quadrant III, which has a theme of protection but viewpoint of environmental preservation. Finally, four (28.6%) of the legislative documents fall within quadrant IV. This quadrant deals with the concept of environmental preservation and has more of a resource conservation viewpoint. The analysis shows that groupings exist among the documents indicating some similarities and differences with themes based on the dominant words that were selected for this analysis.

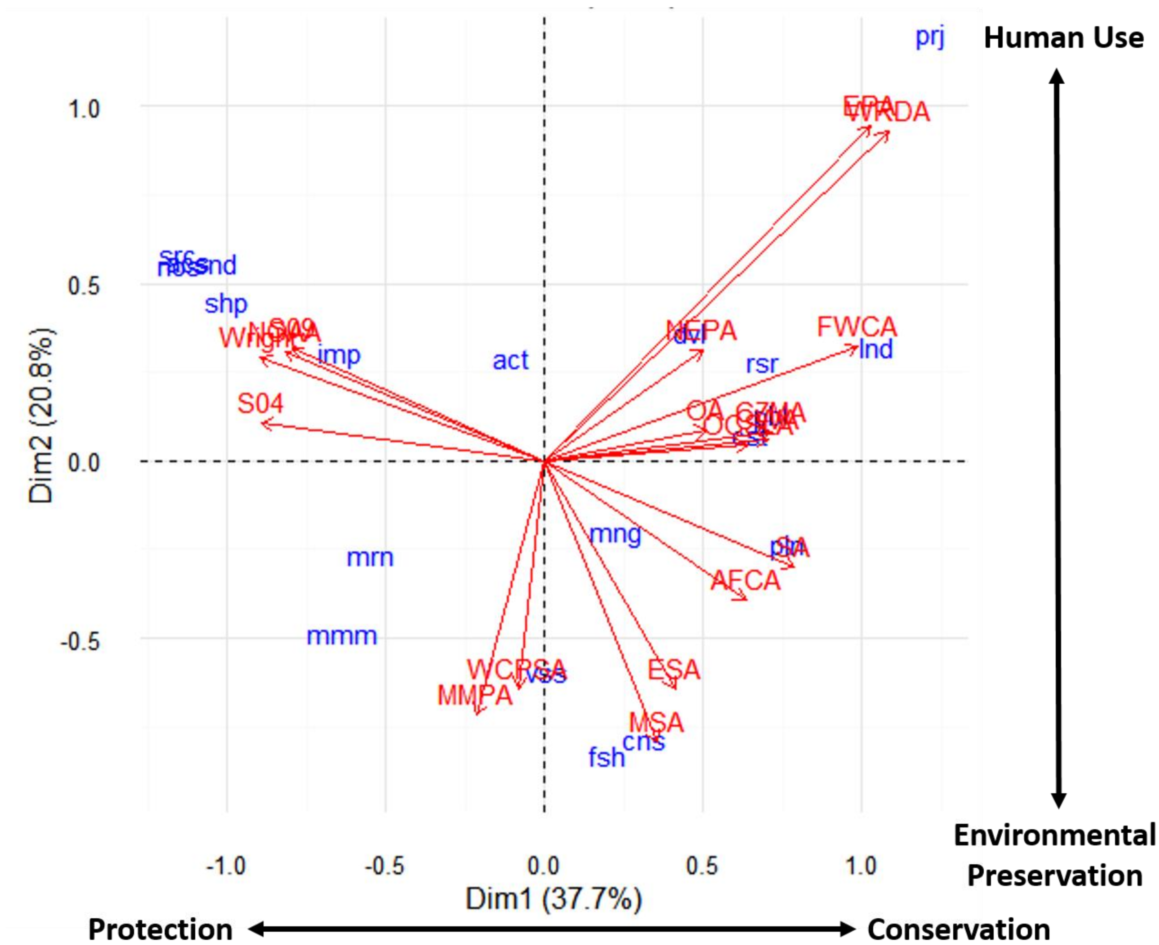

Figure 5.3. Correspondence analysis for the dominant words in the management and legislative documents.

Correspondence analysis of the most dominant words within the management and federal legislative documents. Federal legislative documents are denoted in red and the dominant words are in blue. Dimension 1 (Dim1) contains 37.7% and dimension 2 (Dim2) explains 20.8% of the data's variability. Word abbreviations are provided in (Table 5.8) and document abbreviations are found in (Table 5.2).

Table 5.9. Quadrant plot information of the legislative and management results from the correspondence analysis.

Quadrant results for the correspondence analysis (Figure 5.3). Quadrant I (QI) is associated with human use and resource conservation. Quadrant II (QII) addresses resource protection and human use. Quadrant III (QIII) focuses on protection and environmental preservation. Quadrant IV deals with environmental preservation and resource conservation.

Document Type	Documents	QI	QII	QIII	QIV
Legislative	Anadromous Fish Conservation Act (AFCA)				X
Legislative	Clean Water Act (CWA)	X			
Legislative	Coastal Zone Management Act (CZMA)	X			
Legislative	Endangered Species Act (ESA)				X
Legislative	Estuary Protection Act (EPA)	X			
Legislative	Fish and Wildlife Coordination Act (FWCA)	X			
Legislative	Magnuson-Stevens Fishery Conservation and Management Act (MSA)				X
Legislative	Marine Mammal Protection Study Act (MMPA)			X	
Legislative	National Environmental Policy Act (NEPA)	X			
Legislative	Ocean Act (OA)	X			
Legislative	Outer Continental Shelf Lands Act (OCSLA)	X			
Legislative	Sikes Act (SA)				X
Legislative	Water Resources Development Act (WRDA)	X			
Legislative	Whale Conservation and Protection Study Act (WCPSA)			X	
Management	Gedamke et al. 2016 (NOAA)		X		
Management	Southall 2004 (S04)		X		
Management	Southall et al. 2009 (S09)		X		
Management	Wright 2014 (Wright)		X		

ii. Network Analysis of the Words

For this section, it is important to reiterate the results of the correspondence analysis. First, both the correspondence analysis and this word network analysis are based on the same Pearson correlation matrix that was generated from the words selected among all of the documents (Table 5.4). The correspondence analysis demonstrates that certain words are associated with (i.e. plotted with) the enabling legislative documents. These words include "project (prj)," "plan (pln)," "resource (rsr)," "fish (fsh)," "conserve (cns)" and "develop (dvl)," "manage (mng)", and "vessel (vss)," (Figure 5.3). Secondly, the correspondence analysis also revealed words that plot with the noise management documents. These words include "marine (mrn)," "mammal (mmm)," "sound (snd)," "source (src)", "impact (imp)," "noise (nos)," and "acoustic (acs)," (Figure 5.3). These associations between words and the document types are important to remember for the interpretation of the word network analysis.

In the word correlation network analysis, similarities and differences (correlations) among words were examined from the 18 documents (14 legislative and 4 management). These correlations are displayed as a network, with words most similar to each other in terms of the frequency of usage, plotting close together (Figure 5.4) with the plot's orientation driven by the "spring" embedder. This layout assumes that links between nodes are like springs, with an ideal length (i.e. node distance) and an ideal spring strength (inversely proportional to the length). The nodes are then moved around in space to minimize the total stress of all of the springs connecting the nodes (Borgatti et al. 2013).

The network produced from the most common (N = 16) words in the enabling legislation and management documents had two dominant groupings (Figure 5.4). The first grouping are words that are primarily associated with underwater noise levels and are primarily found in the noise management documents (Figure 5.4, blue) and all have significant correlations ($p < 0.01$) values of $\rho \geq 0.7$. These words are "acoustic (acs)," "impact (imp)," "noise (nos)," "sound (snd)," and "source (src)." Two other words that are less correlated ($\rho < 0.7$) to these underwater noise level terms but still associated with the underwater noise words are "marine (mrn)" and "mammal (mmm)." These two words are strongly correlated to each other ($\rho \geq 0.9$) but most connected to the network by the word “impact (imp).” This word grouping, that primarily represents the terms present in the underwater noise management documents (Figure 5.3), will be called “underwater noise concerns.” The second grouping within the word network analysis (Figure 5.4, red and purple) includes words like “manage (mng),” “vessel (vss),” “conserve (cns),” “fish (fsh),” “develop (dvl),” “plan (pln),” “public (pbl),” “project (prj),” and “resource (rsr).” All of these words are positively correlated ($\rho > 0.2$) but some groups are more strongly correlated than others. The word “develop (dvl)” is strongly correlated ($\rho > 0.6$) with “project (prj),” “resource (rsr),” “plan (pln),” and “public (pbl).” Additionally, the word “vessel (vss),” is strongly ($\rho > 0.6$) correlated with “fish (fsh),” “conserve (cns),” and “manage (mng).” Finally, there are important connector words like “resource (rsr)” and “plan (pln)” that help connect together the words of this section. This word grouping will be called “human use of the resource” and most of these words are associated with the enabling legislative documents (Figure 5.3). It is important to note that there are words that are negatively correlated between the two groupings (“underwater noise concerns” and “human use of the resource”). These words are “plan (pln),” “public (pbl),” “project (prj),” “conserve (cns),” and “resource (rsr),” and are negatively correlated with all of the words in the “underwater noise concerns” group, except the word “impact (imp)” (Figure 5.4, purple lines). These negative correlations, however, are not significant ($p > 0.05$) correlations within the network (Figure 5.5). Two words, “manage (mng)” and “vessel (vss),” plot with both the noise management documents and the enabling legislation documents (Figure 5.3), show a positive correlation between the “noise management concern” grouping and the “human use of the resource” grouping through the words “impact (imp)” and “marine (mrn),” (Figure 5.4 purple).

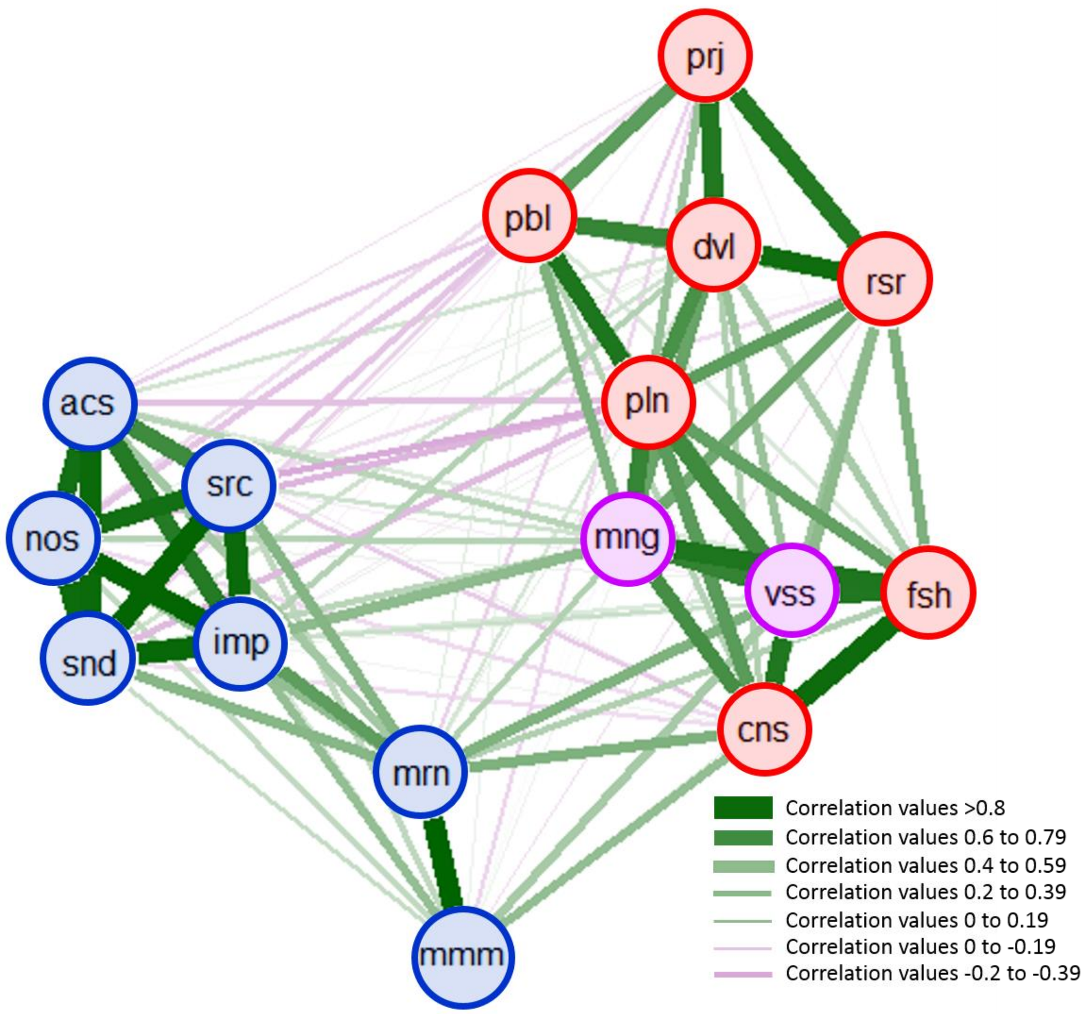

Figure 5.4. Network analysis of the dominant words identified in the legislative and noise management documents.

A network of word correlation relationships (Table 5.5) within the management and enabling legislative documents. Line thickness and darkness indicates stronger word correlations. Positive correlations are represented by green lines and negative correlations are shown using purple lines. Based on the results of the correlation analysis (Figure 5.3), words with red circles are mostly associated with enabling legislation and words with blue circles are mostly associated with the noise management documents. Words with purple circles plot with both sets of documents.

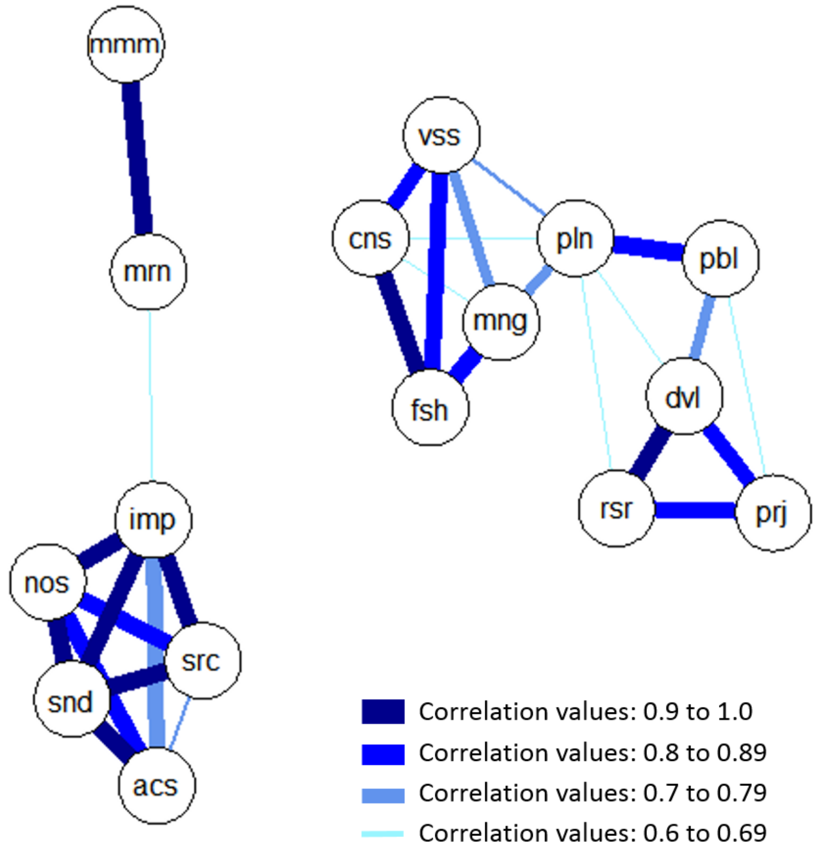

Figure 5.5. The significant correlations generated from the network analysis of the dominant words identified in the management and legislative documents.

Correlations between words with significantly positive relationships ($p < 0.01$) identified by blue line connections. Thicker and darker lines indicate higher correlations between words. All negative relationships were not significant.

When I explore significant correlations among words, the arrangement of the network becomes slightly modified. However, within the "human use of the resource" grouping, there are now two subgroupings focused on human resource use. The first subgrouping includes words like "develop (dvl)," "resource (rsr)," and "project (prj)." These words are highly connected ($0.7 \leq \rho \leq 0.79$, Figure 5.5) together and make-up a subgrouping that I will call "resource development." This subgrouping is connected to the second subgrouping by the word "public (pbl)", which is significantly correlated ($0.70 \leq \rho \leq 0.79$) with the word "develop (dvl)." The word "public (pbl)" is also significantly correlated ($0.80 \leq \rho \leq 0.89$) with the word "plan (pln)." The second subgrouping within the "human use of the resource" grouping, consists of words like "vessel (vss)," "conserve (cns)," "manage (mng)," "fish (fsh)," and "plan (pln)." All of the connections with this second subgrouping are significant, but the correlation values range between weak ($0.60 \leq \rho \leq 0.69$) to strong ($0.90 \leq \rho \leq 1.00$). This subgrouping addresses a range of concepts but primarily addresses conservation and management. Therefore, I will call this subgrouping "conservation." Thus, the "human use of the resource" group within the word correlation network, contains primarily two themes (1) "resource development" and (2) resource "conservation."

Based on significant relationships, for the grouping that address "underwater noise concerns," there are two subgroupings. The first grouping uses the following terms "sound (snd)," "source (src)," "acoustic (acs)," "noise (nos)," and "impact (imp)." Most of these correlations are strong ($\rho \geq 0.80$) but one of the connections has a slightly lower correlation value of $0.70 \leq \rho \leq 0.79$ (Figure 5.5). These words represent a subgrouping that I will call "acoustic impacts." This "acoustic impacts" subgrouping is weakly correlated ($0.60 \leq \rho \leq 0.69$) to the second subgrouping by a single word "marine (mrn)" through the word "impact (imp)." The second subgrouping within the "underwater noise concern" grouping of the network, includes two words: "marine (mrn)" and "mammal (mmm)." These two words are strongly correlated ($0.90 \leq \rho \leq 1.00$, Figure 5.5) together. This subgrouping primarily addresses conservation and protection of marine mammals. Thus, I will call this subgrouping "preservation." By preservation, I mean the attempt to maintain the current condition of the resource and not allow further degradation from human activities. Therefore, the underwater noise concern group within the word network addresses two themes (1) "acoustic impacts" and (2) "preservation."

The “human use of the resource” and the “underwater noise concern” groups are not significantly correlated with each other (Figure 5.5) in the word network analysis. The “human use of the resource” group clusters together words that convey human values of a resource (anthropocentric value orientation), such as “resource development” and “conservation.” These themes are commonly associated with the examined enabling legislation (Figure 5.3). The “underwater noise concern” group, clusters words together that have a more biocentric value orientation, such as “acoustic impacts,” and “preservation.” These themes are commonly associated with the noise management documents (Figure 5.3). This network correlation of word use analysis reveals a de-emphasis of human development and conservation and emphasizes marine mammal protection and the impacts of noise when underwater noise concerns are being addressed within a document.

iii. Network Analysis of the Documents

The correlation network analysis of the documents demonstrates similarities and differences (correlations) among the 18 documents (14 legislative and 4 management) based on the 20 most dominant words. Among the enabling legislation, there are two dominant groups and multiple subgroupings. The two primary themes for the enabling legislation documents are “development” and “conservation.” Under the primary theme of “development,” there are three subgroupings. The Oceans Act (“OA”), Coastal Zone Management Act (“CZM”) and the Outer Continental Shelf Lands Act (“OCS”) exist within its own subgrouping (Figure 5.6). Similar themes across this subgrouping address words like “coast (cst),” “develop (dvl),” “plan (pln),” and “resource (rsr”). This subgrouping then addresses concepts related to “coastal development of a resource.” A second subgrouping includes the Fish and Wildlife Coordination Act (“FWC”), Water Resources Development Act (“WRD”), and Estuary Protection Act (“EPA”). Words like “develop (dvl),” “land (lnd),” and “project (prj)” are dominant within these documents, suggesting a second theme of “land development.” Finally, a third weakly grouped pair of enabling legislation that addresses the concept of “development” is that of National Environmental Policy Act (“NEP”) and the Clean Water Act (“CWA”). Words such as “activity (act),” “develop (dvl),” and “public (pbl)” indicate a theme of “public resource development.” Under the second primary theme of “conservation,” there are two subgroupings present within the enabling legislation corpus. The fourth subgrouping for the enabling legislation documents includes the Marine Mammal Protection Act (“MMP”) and the Whale Conservation and Protection Study Act (“WCP”). Dominant words within this subgrouping include “conserve (cns),” “marine (mrn),” “mammal (mmm),” and “vessel (vss).” This subgrouping is primarily focused on “conserving marine mammal welfare,” particularly in relation to vessel activity (i.e. ship strikes). The fifth subgrouping exists between the Endangered Species Act (“ESA”), Magnuson-Stevens Fishery Conservation and Management Act (“MSA”), Anadromous Fish Conservation Act (“AFC”), and the Sikes Act (“SA”). Words strongly associated with these documents include “conserve (cns),” “fish (fsh),” “manage (mng),” and “plan (pln).” Other important but less dominant words across these documents include “activity (act),” “develop (dvl),” and “resource (rsr).” These enabling legislative documents suggest a theme of “resource conservation through management plans” due to the activities associated with resource development. So, within the enabling legislation, themes range from resource conservation to development, with some of the legislation focusing more strongly on conservation and others focusing more so on resource development.

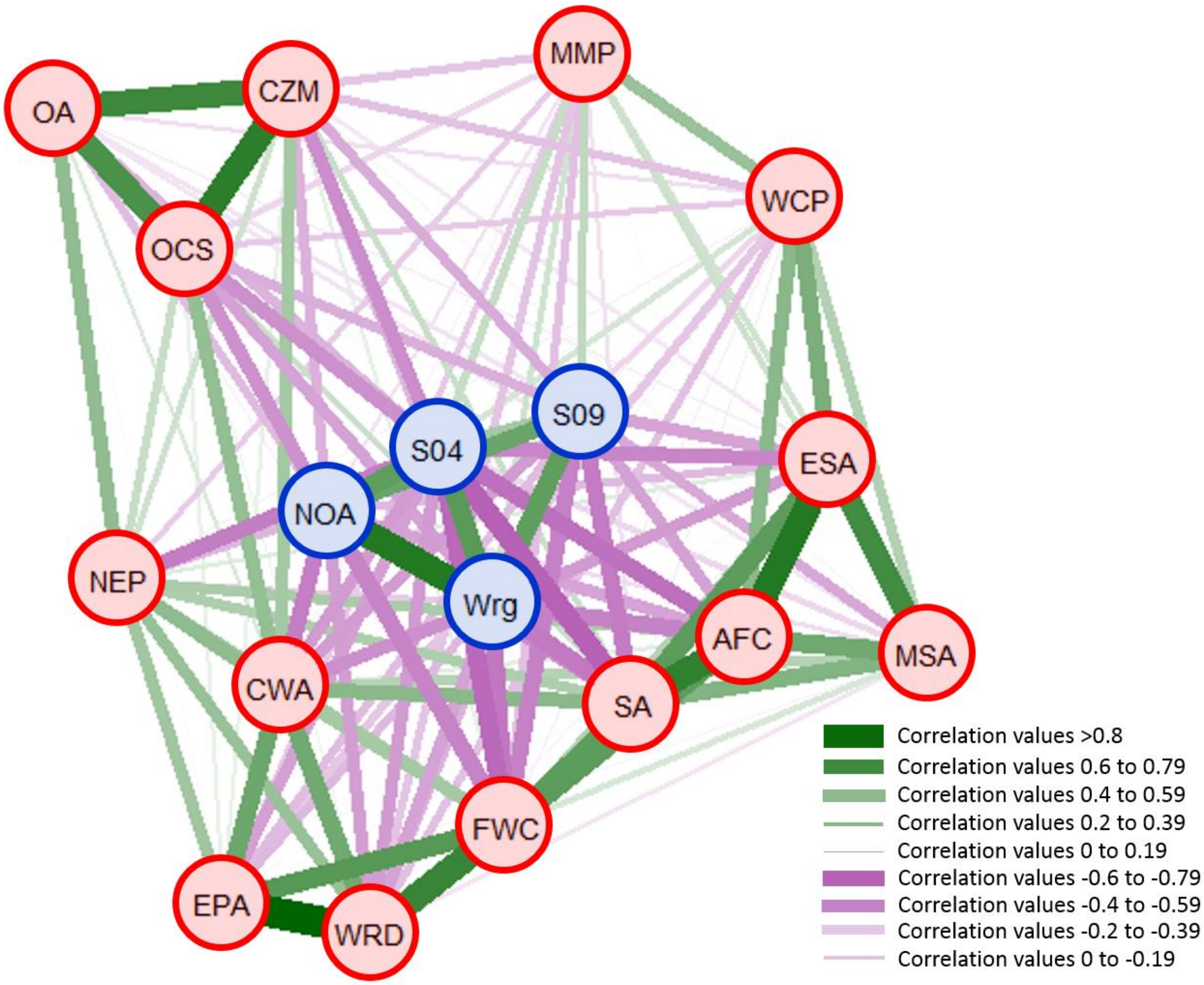

Figure 5.6. Network analysis of the noise management and enabling legislation documents.

A network of document correlation relationships (Table 5.5) based on the words present within the documents. Line thickness and darkness indicates stronger word correlations. Positive correlations are represented by green lines and negative correlations are shown using purple lines. Documents with red circles represent enabling legislative documents and documents with blue circles are noise management documents. Abbreviations for the documents are found in Table 5.2.

This network analysis also reveals relatively strong ($\rho \geq 0.70$) correlations between the noise management documents (the sixth subgrouping within the network). The words most associated with these documents include "acoustics (acs)," "activity (act)," "impact (imp)," "mammal (mmm)," marine (mrn)," "noise (nos)," "ship (shp)," "sound (snd)," and "source (src)." These words suggest an overarching theme of "acoustic impacts on marine mammals." These noise management documents are primarily negatively associated with the enabling legislation (Figure 5.6), with the only two exceptions. The MMPA ("MMP") is positively correlated ($0.17 \leq \rho \leq 0.24$) with the two Southall documents ("S04" and "S09") and the Wright document ("Wrg"). Additionally, the WCPSA ("WCP") is positively correlated with the one of the Southall ("S04") and the Wright ("Wrg") documents. These relationships demonstrate the theme of "conserving marine mammal welfare" within these three management documents but this theme is not as strong within the NOAA ("NOA") document, which places emphasis on both fish and marine mammals. All other enabling legislation included in this analysis, are negatively correlated with the management documents. This suggests a lack of thematic similarities, including the theme of "development."

The significant ($p < 0.1$) relationships within the document network (Figure 5.7) suggest that of the six subgroupings within the network model, only four of these relationships are significant and remain connected. These remaining connected documents include the themes of "coastal development of the resource," "resource conservation through management plans," "land development," and "acoustic impacts on marine mammals." However, the theme focusing on the "coastal development of the resource" that includes the Oceans Act ("OA"), Coastal Zone Management Act ("CZM") and the Outer Continental Shelf Lands Act ("OCS") is no longer connected to the overall document network. Four enabling legislative documents the Clean Water

Act ("CWA"), Marine Mammal Protection Act ("MMP"), National Environmental Policy Act ("NEP") and the Whale Conservation and Protection Study Act ("WCP") are no longer connected to any node within the network. This suggests their themes of "conserving marine mammal welfare" and "public resource development" are not well represented in any of the other enabling legislation nor in the noise management documents. Finally, it is important to note that the only significant ($p < 0.1$) negative correlations occur between one of the Southall documents ("S04") and the Fish and Wildlife Coordination Act ("FWC") and the Sikes Act ("SA"). These two enabling legislative documents are a part of the subgroupings that address the themes of "resource conservation through management plans" and "land development." This information further reiterates a lack of the themes of "conservation" and "needed development for ecosystem services" throughout the noise management documents.

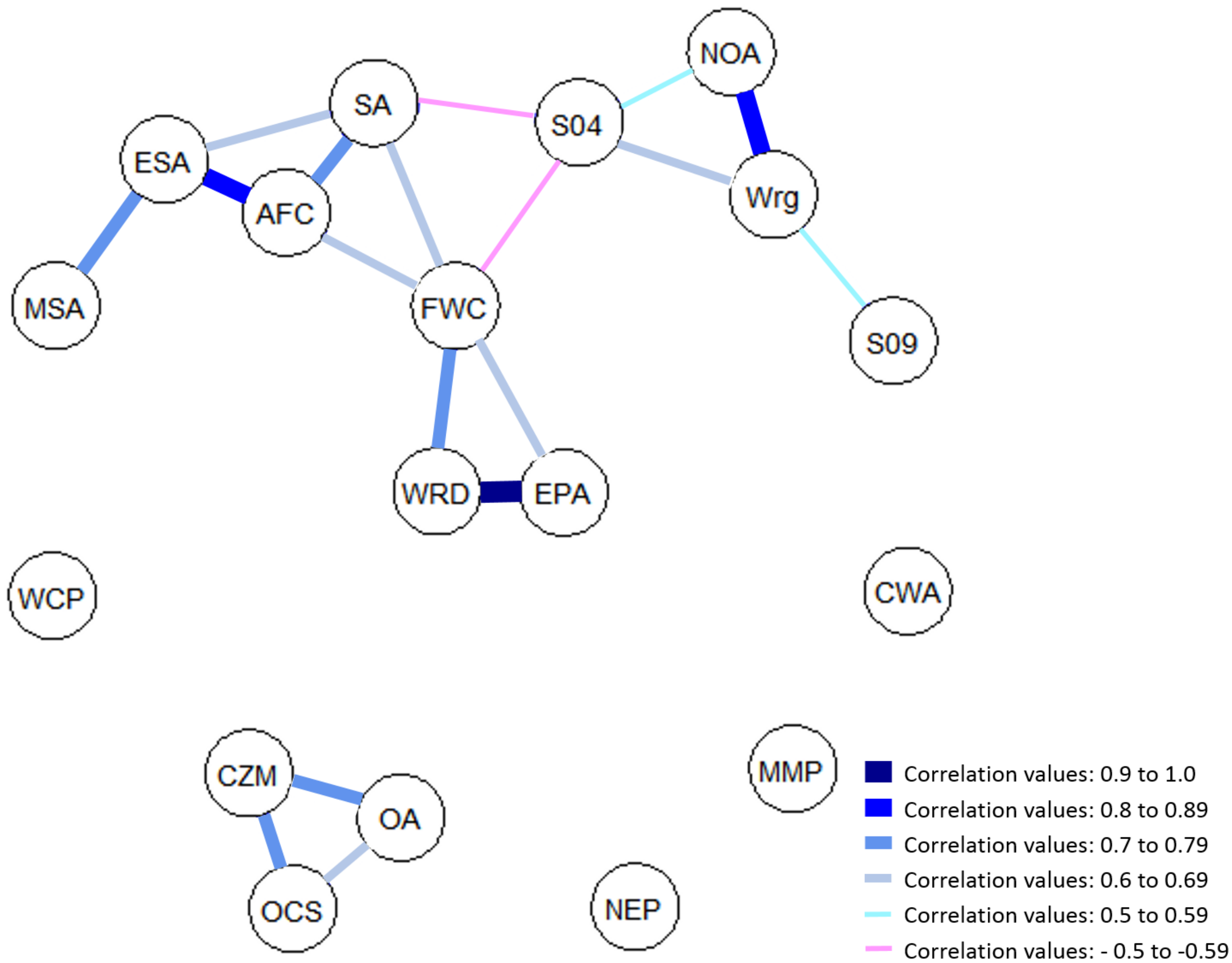

Figure 5.7. The significant correlations generated from the network analysis of the documents.

Correlations between documents with significant relationships ($p < 0.1$). Positive relationships are identified by blue line connections and negative relationships with pink line connections. Thicker and darker lines indicate higher correlations between documents.

iv. Network Analysis Centrality Measures

Within the word correlation network (Figure 5.4), keywords become apparent as connectors. When two words are highly correlated with a third word, but not each other, the third word is said to be highly central. Network centrality indices can be computed that summarize each word's overall network centrality, that is, how often the word is connected to other words within the network. Terms with high eigenvector centrality (≥ 0.25), which is the measure of total network centrality and is equal to the sum of the centralities of the nodes adjacent to the word (Borgatti et al. 2013), include "conserve (cns)," "develop (dvl)," "fish (fsh)," "impact (imp)," "manage (mng)," "marine (mrn)," "plan (pln)," "resource (rsr)," and "vessel (vss)," (Figure 5.88). These terms are words that are central to other words, indicating that they are common along a path connecting any two words within the network. These are words that are central to the themes used in all of the documents (legislative and management) comprising the network. Of these nine important connector words, two are commonly correlated with the noise management documents ("marine (mrn)" and "impact (imp)," Figure 5.3), suggesting a theme of "assessing impacts on marine life/environment." Five other terms are important in the legislative documents ("conserve (cns)" "develop (dvl)," "fish (fsh)," "plan (pln)," and "resource (rsr)"), indicating two primary themes. The first enabling legislation theme addresses "resource conservation, specifically of fish, through management plans." The second theme addresses "the development of a resource." Finally, two of these central words are correlated with both sets of documents ("vessel (vss)" and "manage (mng)"), demonstrating the "need to manage vessel activity," within both management and enabling legislation documents.

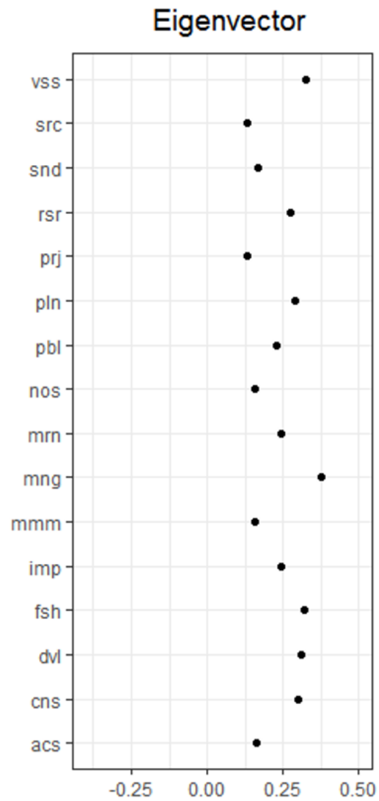

Figure 5.8. Term network eigenvector centrality measurements.

Network eigenvector centrality measurement values that were calculated from the word correlation network (Figure 5.4). Words are represented by three letters described in Table 5.8.

Differences within a network are also important to explore. In this correlation word network (Figure 5.4), words like "acoustic (acs)," "mammal (mmm)," "noise (nos)," "project (prj)," "public (pbl)," "sound (snd)," and "source (src)," are words with low eigenvector centrality values (Figure 5.8). These words suggest concepts that are disconnected in the word correlation network and thus disconnected across the analyzed documents. Of the seven weakly connected words, five of them were primarily associated with the noise management documents ("acoustic (acs)," "mammal (mmm)," "noise (nos)," "sound (snd)," and "source (src)," Figure 5.3) while the remaining two words (“public (pbl),” and “project (prj)”) are associated with the enabling legislative documents in the correspondence analysis. These are words that suggest disparate themes across the document sets. The enabling legislation documents do not discuss underwater noise impacts and the majority of the documents do not focus on mammals. The noise management documents lack sufficient discussion about fishes and ecosystem services in terms of public rights/needs and projects that are associated with the development of ecosystem services.

The centrality measures derived from the document network analysis (Figure 5.6) reveals a few highly central (connector) documents. Documents with high eigenvector centrality (Figure 5.9) include Anadromous Fish Conservation Act (“AFCA”), Clean Water Act (“CWA”), the Fish and Wildlife Coordination Act (“FWCA”), and the Sikes Act (“SA”). These are enabling legislation documents are highly central to other documents within the network, indicating that they are common along a path connecting any two documents within the network. Generally, six documents have low centrality values. These low centrality documents include all four management documents (“Gedamke et al. 2016 (NOAA),” “Southall 2004 (S04),” “Southall et al. 2009 (S09),” and “Wright 2014 (Wright)”) and two enabling legislation documents (“Marine Mammal Protection Act (MMPA)” and “Whale Conservation and Protection Study Act (WCP)”). These documents are highly disconnected from the network demonstrating that the dominant theme of “marine mammal protection” is not of central importance within the document network. The result is that these noise management documents have disparate themes that often do not overlap with the majority of the enabling legislative documents.

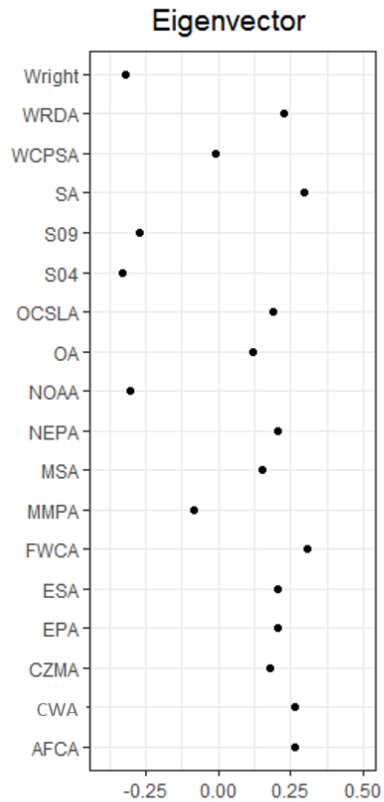

Figure 5.9. Document network eigenvalue centrality measurements.

Network eigenvector centrality measurement values that were calculated from the document correlation network (Figure 5.6). The documents are represented by abbreviations described in Table 5.2.

Discussion

Through the comparisons of all three analyses (correspondence, word network, and document network) themes emerge across the document types. The overarching theme within the noise management documents is "assessing the acoustic impacts on marine life or the marine environment." This theme is consistently demonstrated in each of the text analyses, with a focus on "acoustic impacts," "protection or preservation," and "marine mammals" (Table 5.10). For the enabling legislation, there are two principal themes. The first addresses "resource conservation." This theme is demonstrated within a total of six of the legislative documents (Table 5.10). The second theme addresses "resource development," which is demonstrated through the remaining eight legislative documents (Table 5.10). Themes are disconnected between the enabling legislation and the underwater noise management documents. This disconnect was primarily demonstrated in the document network analysis, where most enabling legislation were negatively correlated to the noise management documents. Both the management and the enabling legislative documents express interest in how human-use is impacting the marine environment or marine life but focus on different concerns and strategies.

The noise management documents focus strongly on environmental preservation and protection, in particular, the impact of noise on marine mammals. While other marine species were included in the analysis of the noise management corpus, the correspondence analysis consistently plotted the word "mammal" among other noise management terms, suggesting the importance of this word in the language used in these documents. In terms of environmental concerns, the federal legislative documents focus on the impact of human activities on fish. While other species and marine mammals are included in the legislative documents as dominant words, they are less frequent in these documents than that of other animals. For example, the Sikes Act, the Anadromous Fish Conservation Act, the Endangered Species Act, and the Magnusson-Steven's Act all correlate more strongly with the work "fish" over the word "mammal" (Figure 5.10). Because the noise management documents are supposed to support the concepts presented in the legislative documents, the noise management documents should address noise impacts on fish and fisheries more often than they do now because of the importance of these themes within the legislative framework.

Table 5.10. Predominant themes within the three text analyses (correspondence, word network, and document network).

Dominant themes derived from the text analyses among selected document groupings of the enabling legislation and noise management documents. The abbreviations for all of the documents are described in Table 5.2.

Document Grouping	Correspondence Analysis Themes	Word Network Analysis Themes	Document Network Analysis Themes
AFCA, ESA, MSA, & SA	Environmental preservation & conservation	Conservation & resource development	Resource conservation through management
CWA & NEPA	Human use & conservation	Resource development	Public resource development
CZMA, OA, & OCSLA	Human use & conservation	Resource development	Coastal development of resources
EPA, FWCA, & WRDA	Human use & conservation	Resource development	Land development
MMPA & WCPSA	Environmental preservation, conservation, and protection	Preservation	Conserving marine mammal welfare
NOAA, S04, S09, Wright	Human use & protection	Preservation & acoustic impacts	Acoustic impacts on marine mammals

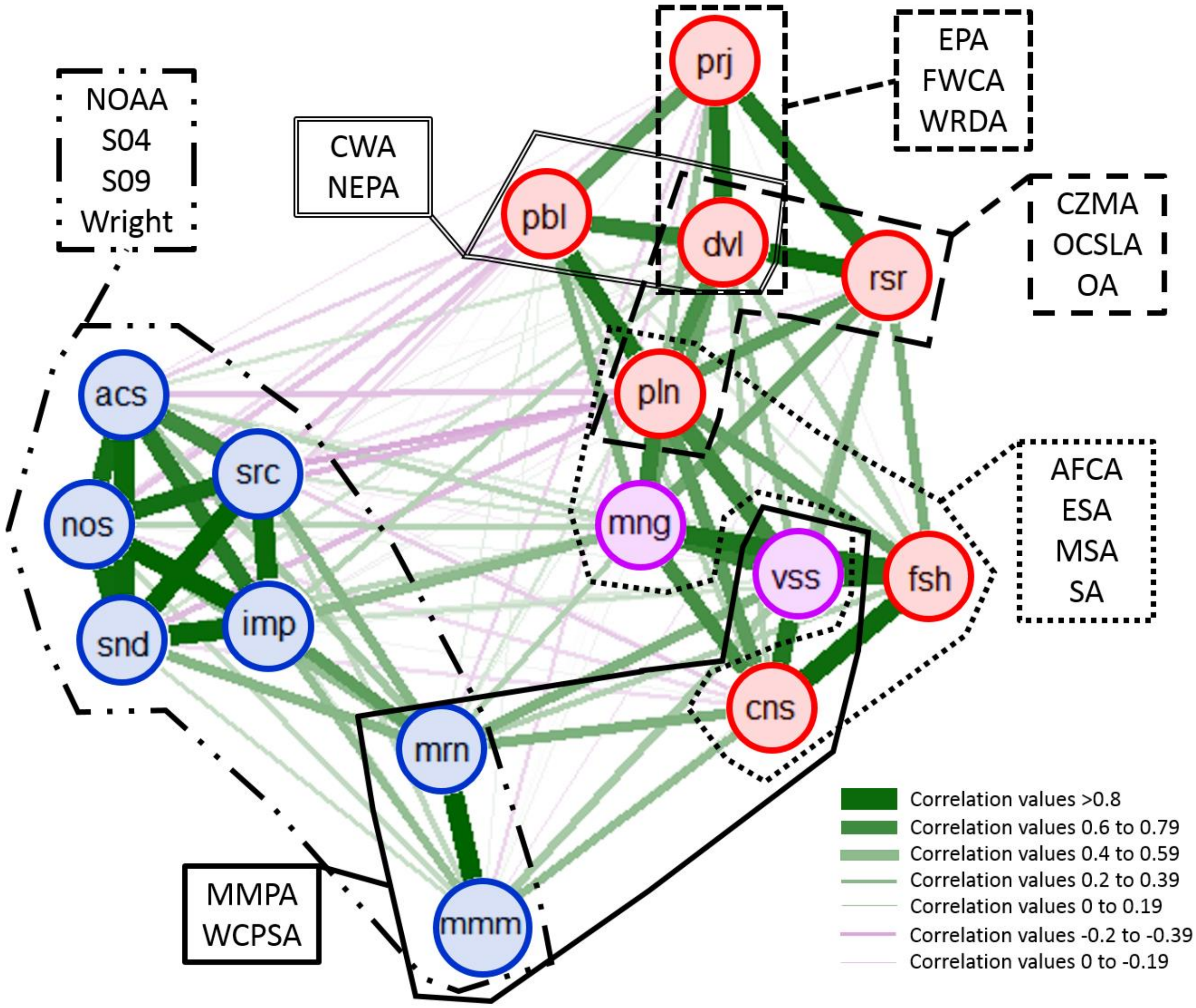

Figure 5.10. Word network analysis with dominant loading words in the legislative and noise management documents.

The word network analysis (Figure 5.4) with documents groups identified based on the words that most strongly correlated with each of them. The black lines around the words indicate the primary words identified within each of the document groups. A description of the network labels is present in Figure 5.4.

Second, and of no less importance, is that of the management of human use on the environment. The noise management documents indicate the most important management words are “noise (nos),” “sound (snd),” and “source (src),” (Figure 5.10). They do express the need to “manage (mng),” in particular, the need to manage the generation of noise from anthropogenic activities. These activities include the oil and gas industry, SONAR, ships, and pile driving, but the noise management document themes also focus on management tools such as predicting impacts, modeling risk, monitoring impacts, mitigating damage, and reducing noise through technology. The concept here is a biocentric value orientation with an ecosystem approach to resource management (Yaffee 1999). Hence, these underwater noise managers are focusing on the intangible more than the tangible assets. In our current paradigm of ecosystem-based management, both the intangible and the tangible assets are important to consider (Botkin 1990) and underwater noise managers need to address more of the tangible assets (i.e. ecosystem services) in their management initiatives.

For the legislative documents, there is more diversity of word use than in the noise management documents for their intentions to manage human use. These human use words include activities like fisheries, vessel activity, navigation, commercial use, construction and development activities (including oil and gas and wind farm development), discharge and pollution activities as well as regulatory actions to control these human use activities. Some of these words include planning, permitting, penalties, enforcement, and leases. Other terms that are important are words that address the value that humans place on the environment and its resources, like words such as costs and economics. These legislative documents focus primarily on the anthropocentric value orientation and need to evolve into the concepts of ecosystem-based management; better addressing the intangible viewpoints.

In terms of social values and environmental use, the two sets documents rarely overlap. The legislative documents focus primarily on how the use of natural resources is going to impact the economic situation or a particular human use. The noise management documents address noise-related concerns and how those impact the natural environment. Human use is only brought into the discussion when attempting to reduce impacts due to certain activities and the economic issues and incentives are not a primary focus of these documents. To rectify the differences in human use in each of the document sets, it is important for two things to happen. First, managerial documents addressing underwater noise need to address a larger dimension of human use concerns such as addressing economic issues that drive projects like offshore wind development and fisheries. They also need to address the underwater noise problem in a more broad-scale sense, like addressing its impact to projects that are already underway and its potential impacts on the fishery as well as other ecosystem services. Second, it is important that the federal government recognizes underwater noise as a source of pollution. This is already happening in the European Union (Palmer 2010) but has yet to be fully recognized here in the U.S. For management strategies to be successful in the U.S., the legislative documents need to be modified (or at least recognize) to include underwater noise as a pollution concern. While noise is a stated concern in the National Whale Conservation and Protection Study Act, it is not directly represented in any of the other legislation identified in this document. The inclusion of noise into the legislative documents will help managers to identify the areas that are most important to address, thereby releasing funds to better understand the problems associated with underwater noise. The goal is to allow more research to be conducted on the issue, which can offer more information to managers on the impacts of noise on species other than marine mammals and on the how to better regulate noise associated with recreational, commercial, and industrial activities. Additional research can also provide managers with information regarding human values, better helping them devise management strategies that will be effective.

One aspect of human dimensions that needs to be better understood and addressed by managers is the concept of human concern over the problem of underwater noise management. This includes understanding people's perceptions of the problem and the trade-offs they are willing to make to address the problem. When devising a management plan, trade-offs are necessary but the trade-offs need to be perceived as fair to those that are most impacted, this is because human use and natural environments are inter-connected. It is necessary to understand how users react to regulations because user response can compromise the intent of a regulation if the regulation is not socially acceptable (Radomski and Goeman 1996).

Managers need to understand that "social capital" (i.e. cultural and social qualities of human communities) changes the nature of the game because it alters the relationship between the players and modifies what an individual can achieve (Jentoft et al. 1998). The users of a resource and the society at large possess knowledge of that resource (Dyer and McGoodwin 1994) that is based on their experiences. Thus, there is an understanding within a community about the limitations of a resource and its threshold that can assist managers in understanding concepts like carrying capacity, ecosystem stress and potential collapse points (Gladwin et al. 1995). If utilized properly, this information gained from users could offer more effective and equitable solutions to underwater noise management challenges (Dyer and McGoodwin 1994).

Goals in resource management of underwater noise need to address both basic scientific knowledge as well as social knowledge (Korten 1981, Reich 1985). Yet, as demonstrated in the content analysis, underwater noise managers have a limited understanding of social management preferences and are largely focused on a biocentric value orientation. The content analysis demonstrates that the underwater noise management documents focus on the themes of protection, especially of marine mammals, of the impacts of underwater noise and lacks the incorporation of the value of ecosystem services. This perspective results in a lack of understanding about ecosystem values provided to the community and the trade-offs and costs people are willing to accept for ecosystem-based management decisions (Loomis and Paterson 2014b). If societal value operationalizes the resource state, including defining accepted behaviors, policies, and plans (Lockwood et al. 2010) and management offers the designed plans and legislative support to maximize the desired social values (Loomis and Paterson 2014b), then the acceptance and enforcement of management strategies by society is more likely to occur.

One key example that illustrates this problem with the underwater noise management documents can be assessed by looking at the two animal words within the correlation bi-plot and the word correlation network analysis. These two animal words are “mammal” and “fish.” As has been demonstrated throughout this dissertation that fish behavior and reproductive output are impacted by vessel noise and vessel presence (Chapters 2-4). Underwater noises cause stress (Wysocki et al. 2006, Graham and Cooke 2008), mask the hearing ability (Scholik and Yan 2001, 2002, Vasconcelos et al. 2007), alters swimming behavior (Engås et al. 1995, 1998, Sarà et al. 2007), and impact parental care (Mueller 1980, Picciulin et al. 2010) in fishes. Additionally, fishes are important prey for marine mammals (e.g. Gannon et al. 2005, Berens McCabe et al. 2010, Pate and Mcfee, 2012, Dunshea et al. 2013) as well as for humans. Yet, the word “fish (fsh)” does not plot with the noise management documents in the correspondence analysis (Figure 5.3) nor does it plot with the words that are associated with underwater noise (“acoustics (acs),” “source (src),” “noise (nos),” and “sound (snd)”) in the word correlation network (Figure 5.4). In fact, the word "fish (fsh)" correlates at values between -0.01 < ρ < 0.13 (Table 5.5) with these underwater noise terms. However, the word "mammal (mmm)" correlates with these same terms at higher correlation values (0.15 < ρ < 0.23). If I use the word "marine (mrn)" which correlates with "mammal (mmm)" at a ρ = 0.94, then "marine (mrn)" correlates with the underwater noise terms at much higher correlation values (0.34 < ρ < 0.45). These words ("marine (mrn)" and "mammal (mmm)") plot with the underwater noise management documents in the correspondence analysis (Figure 5.3) and are connected with the noise associated words ("acoustic (acs)," "source (src)," "noise (nos)," "sound (snd)") within the word correlation network analysis (Figure 5.4). These data suggest that the noise management documents are strongly focused on marine mammals but fail to effectively address fishes. Yet, fishes are an important focus of the legislative documents. In the word correlation network analysis, the word "fish (fsh)," is strongly correlated with the words "conserve (cns)" (ρ = 0.89), "manage (mng)," (ρ = 0.83), and "vessel (vss)," (ρ = 0.82). These correlations demonstrate the importance of "fish" to human-use and the need to conserve fish to ensure the future of this ecosystem service. Fish and fisheries is a resource valued by resource users and this theme is present in the legislative documents. Yet, fish and fisheries are not strongly correlated with the themes addressed in the noise management documents. Hence, one modification underwater noise managers can make to their management plans that will help managers better incorporate social values is to better address fish and fisheries within the noise management plans. This type of focus shift within the noise management documents will start the process to create an underwater noise management plan that addresses not only a biocentric but also an anthropocentric value orientation.

Future Research Needs

There is limited information about how people perceive underwater noise and whether it is believed to be an ecosystem concern. In terms of the legislative structure, underwater noise management is a recent concern that has yet to be adequately addressed. While recently written noise management documents suggest methods to monitor and mitigate damage to marine life from noise, they also fail to sufficiently address social values. Social values are key to management because they drive acceptance of a management initiative and reduce the likelihood of resource exploitation for the benefit of an individual over that of society (Weeks and Packard 1997, Jentoft et al. 1998). For noise management, the inclusion of social values is particularly of concern because little is known about underwater noise issues within the general public and the issue is vast both by impacted geographical area as well as across multiple disciplines.

During the 1990s the public began to express their concerns over underwater noise, beginning with the issues associated with Naval SONAR testing ranges (Abate 2010). There is still time to create a modified underwater noise management strategy that addresses the trade-offs between environmental protection and human use. However, much work needs to be completed for this strategy to be effective. First, an understanding of the social values associated with underwater noise is imperative. The text analysis completed in this document suggests that managers are primarily focused on the effects of noise on marine mammals, while the legislative documents focus on impacts of other kinds of pollution on fishes and habitat degradation. Managers need to understand the perspectives held by people to best manage the issues associated with underwater noise. What types of organisms/habitats/etc. does the public want to conserve? What types of activities are the public most concerned about losing when addressing underwater noise management? What ecosystem services are most valued by the resource users? What type of underwater noise management strategies will the public support? Public inclusion in the management process is the only way to find out the answers to these questions and what types of trade-offs users are willing to accept for the intended impacts associated with underwater noise management. The hope, at the end of the process, is that management initiatives will reflect social values and are thus publicly supported and socially maintained.

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CHAPTER 6 SUMMARY OF FINDINGS AND IMPLICATIONS FOR FUTURE UNDERWATER NOISE MANAGEMENT DECISIONS

Abstract

Underwater noise management under an ecosystem-based management plan needs to address theoretical concepts in ecology and the social sciences. In this section, I present the main findings of this dissertation research. Within the ecological concept, underwater vessel noise caused reduced calling rates and the Lombard effect in the courtship calling behavior of male oyster toadfish (*Opsanus tau*). Sites with high vessel activity also had lower oyster toadfish abundance and less embryos per clutch but this was dependent upon the type of vessels utilizing the navigation channels near the sites. The social problem focused on the thematic difference among noise management and enabling legislative documents. I found that the noise management documents focused on the theme of "assessing the acoustic impacts and protecting marine life [esp. marine mammals]." Enabling legislation, however, focused on the themes of resource "conservation" and "development." Both sets of documents need to be more inclusive of a variety of uses to properly address ecosystem-based management. Finally, all of the social and ecological concepts addressed within this dissertation are combined to present a suggestion on how underwater noise managers can better incorporate ecosystem services within their management initiatives.

The Ecological Problem

Experiment 1: Communication by Mating Oyster Toadfish

The impact of vessel noise by oyster toadfish communication was addressed in Chapters 2 & 3. The objectives of these chapters included experiments on how vessel noise, predator (bottlenose dolphin *Tursiops truncatus*) sounds, and snapping shrimp sounds (control) influence oyster toadfish (*Opanus tau*) courtship calling behavior. I explored four acoustic calling behaviors in response to playback sounds: calling rate (# calls min^{-1}), calling amplitude (Lombard effect, Lombard 1911), calling duration (s), and call fundamental frequency (Hz). These playback experiments were conducted in the field on oyster toadfish that had naturally colonized artificial oyster toadfish shelters deployed in two sites.

First, I explored the impact of playback sounds on the calling rate (calls min^{-1}) of oyster toadfish. Each playback period contained three recording periods: before, during, and after sound exposure and the number of oyster toadfish courtship sounds were quantified. The following hypotheses were tested:

H_a1.1: Male oyster toadfish exposed to vessel noise will reduce the calling rate of (calls min^{-1}) their courtship calls as compared with the pre-exposure calling rate.

Results: Reject H_o for inboard but accept H_o for outboard motorboat noise.

H_a2.1: Male oyster toadfish exposed to bottlenose dolphin sounds will reduce their courtship calling rate (calls min^{-1}) as compared with pre-exposure levels.

Results: Reject H_o for both high-frequency and low-frequency dolphin sounds.

H_o3.1: Male oyster toadfish exposed to snapping shrimp sounds will demonstrate no change in courtship calling rate (calls min^{-1}) as compared with pre-exposure call rates.

Result: Accept H_o for snapping shrimp sounds.

H_a4.1: Male oyster toadfish exposed to both vessel noise and predator sounds will reduce their courtship calling rates (calls min^{-1}) as compared with the calling rates during the vessel noise stimulus alone.

Result: Reject H_o for the playback that contained both inboard and low-frequency dolphin sounds.

H_a4.2: Male oyster toadfish exposed to both vessel noise and predator sounds will reduce their courtship calling rates (calls min^{-1}) as compared with the calling rates during the bottlenose dolphin stimulus alone.

Result: Reject H_o for the playback that contained both inboard and low-frequency dolphin sounds.

I identified alterations in oyster toadfish calling rates in response to the playback sounds (Chapters 2 & 3). Both predator and inboard motorboat sounds caused the greatest decline in calling rates, followed by predator sounds alone, and then inboard motorboat sounds alone. The playback sounds of snapping shrimp and outboard motorboats did not significantly alter oyster toadfish calling rates.

Second, I explored how the combined playback sounds influenced call amplitude (dB), call duration (s), and the fundamental frequency (Hz) of the courtship call for the oyster toadfish. I used the same playback experiments as the call rate research but this time explored how call amplitude (dB), call duration (s), and call fundamental frequency (Hz) changed during and after sound exposure, compared with before sound exposure. The following hypotheses were explored:

H_a5.1: Male oyster toadfish exposed to increased ambient noise levels will increase their courtship calling amplitude (dB, Lombard Effect) when exposed to noise as compared with pre-exposure levels.

Result: Reject H_o with all sound playbacks combined.

H_o5.2: Male oyster toadfish exposed to increased ambient noise levels will not change their courtship calling duration (s) when exposed to noise as compared with pre-exposure levels.

Result: Accept H_o with all sound playbacks combined.

H_o5.3: Male oyster toadfish exposed to increased ambient noise levels will not change their call fundamental frequency (Hz) when exposed to noise as compared with pre-exposure levels.

Result: Accept H_o with all sound playbacks combined.

The playback experiments increased the sound pressure level (SPL) of the ambient background soundscape and the oyster toadfish demonstrated a similar increase in their average call SPL value during playback exposure. The level of increase was site dependent, with oyster toadfish at the "noisy" site increasing their call amplitude to half that of oyster toadfish at the "quiet" site.

For courtship call duration (s) and fundamental frequency (Hz) of the oyster toadfish boatwhistle call, there was little to no change in the male's calling behavior. At the "quiet" site, the call duration was on average lower throughout the experiment than oyster toadfish calling at the "noisy" site. Additionally, the fundamental frequency of the courtship call remained the same throughout the experiment at both sites.

Ultimately, the oyster toadfish demonstrated alterations in their calling behavior in response to increased ambient noise levels. Based on these results, oyster toadfish have the ability to decrease their calling rate and increase their calling amplitude but do not alter their call duration nor the fundamental frequency of their calls in response to increased ambient noise levels. The playback sounds in this experiment were low amplitude in comparison to what was measured by a passing vessel at one of the sites (Sprague et al. 2016). However, the level of response was dependent upon the typical noise level conditions of the sites and the context of the noise being played into the environment. Fish living at the "noisy" site called more during the quiet periods and demonstrated a lower amplitude increase for their calls compared with fish from the "quiet" site. Male fish living in the "quiet" site called consistently across the playback periods with higher amplitude calls as comapred with fish at the "noisy" site. It is also interesting to note that, while oyster toadfish did not display changes in call duration throughout the recording period, but at the "noisy" site the males had longer calls than the males at "quiet" sites (Chapter 2). Thus, it seems that oyster toadfish have different methods of altering their calling behavior based on their typcial soundscape charcteristics.

In terms of playbacks, oyster toadfish reacted more to the sounds of predators and the inboard motorboat noise than to the outboard motorboat noise and the snapping shrimp sounds. Similar results were observed with gray whales (*Eschrichtius robustus*) in response to inboard and outboard motorboats (Dalhlheim et al. 1984). These whales increased their calling rates when exposed to outboard motorboats but decreased their calling rates when a drillship (inboard) was present. Hence, marine life do respond to the sounds and presence of vessels but their response is likely dependent upon the frequency, amplitude, and the context of the noise.

The frequency or frequencies to which an animal responds is partly dependent upon on the hearing and communication calls of the individual species. Oyster toadfish, for example, have an auditory range up to 800 Hz (Fine 1978, Yan et al. 2000) and the dominant frequency of their courtship call is between 150 - 350 Hz (Gudger 1910, Gray and Winn 1961, Fish 1972, Winn 1972). I measured boatwhistle call amplitudes as low at 81 dB re 1 μPa, while other work has demonstrated call amplitudes up to 130 dB re 1 μPa (Fine and Thorson 2008). In comparison, outboard motorboats produce fundamental frequencies between 1 and 5 kHz (Au and Green 2000, Erbe 2002) with SPL values between 110 and 180 dB re 1 μPa (Au and Green 2000, Erbe 2002, Hildebrand 2009). While the outboard motorboat is generally louder than the calls of male oyster toadfish, the outboard noise does not overlap with the frequency of the oyster toadfish call. The result is that oyster toadfish do not show a response in calling rate when exposed to an outboard motorboat playback. Inboard motorboats, however, generate noise with a fundamental frequency between 10 and 1000 Hz (Urick 1983), with source SPL values between 117 and 195 dB re 1 μPa (Møhl et al. 2000, Madsen et al. 2002, Møhl et al.2003). Thus, there is limited ability for the male fish to compete with these inboard noises because they overlap in frequency as well as are generally louder than the calls male oyster toadfish. My results confirm this concept of frequncy- and amplitude-dependent reactions, in that the playback of inboards caused a 70.4% reduction in the calling rate of the male oyster toadfish but outboards only reduced oyster toadfish calling rate by 39.1%.

Contextually, there is also something happening outside of the measured hearing range of the oyster toadfish. The oyster toadfish seems to be responding to the ecological context associated with a playback sound. Not only did the low-frequency sounds of inboard motorboats, low-frequency dolphin, and the combined sounds of inboard and low-frequency dolphin cause a reduction in oyster toadfish calling rate but so did the high-frequency dolphin sound playback. If oyster toadfish were only responding to the frequency and amplitude components of a sound signal, then they should not have responded to the high-frequency dolphin sound. Yet, the high-frequency dolphin sound is a sound of a predator to oyster toadfish (Pate and Mcfee 2012, Dunshea et al. 2013). So, the oyster toadfish are responding to something within their hearing range in the high-frequency dolphin playback that likely informs them of a nearby predator. This high-frequency dolphin playback sound was recorded at a nearby site and contained sounds of other calling fish, along with the sound of dolphins. So, it is possible that the oyster toadfish are responding to other environmental cues, like the sounds of other fish species (e.g. silver perch *Bairdiella chrysoura*). Research has demonstrated that silver perch detect and respond to the higher frequency sound components of dolphins (Luczkovich et al. 2000). If silver perch are responding to the dolphin and oyster toadfish detect these lower frequency shifts in the calls of silver perch (and other fish), then they may recognize that there is a nearby predator and thus react accordingly. For the outboard motorboat, this contextual component has been demonstrated by Mensinger et al. (2016). Multiple species of fish stopped feeding and scattered in the presence of an oncoming outboard motorboat in a common motorboat and fishing location. However, in an area that was not a fishing ground, the fish ignored the sound of the oncoming boat and continued feeding. This contextual component of a sound needs to be further explored to fully understand how marine life react to anthropogenic noise.

Work on other species further support the hypothesis of a noise response from marine life to vessels. North and South Atlantic right whales (*Eubalaena* sp., Parks et al. 2007) and sperm whales (*Physeter macrocephalus*, Azzara et al. 2013) both decrease their calling rates in response to large ships. Both of these whales demonstrate a wide range of frequencies within their calls with much higher amplitudes than that of oyster toadfish. Atlantic right whales call at fundamental frequencies between 20 Hz and 20 kHz at SPL values around 137 and 192 dB re 1 μPa (Parks and Tyack 2005). Sperm whale calls range between 50 Hz and 4 kHz with SPL values around 165 - 236 dB re 1 μPa (Møhl et al. 2000, Madsen et al. 2002, Møhl et al. 2003). Hence, the behavioral response in terms of calling behavior of these whale species is likely associated both frequency and amplitude overlap from large ships in the area. Finally, humpback whales (*Megaptera novaeangliae*) did not demonstrate changes in call rate or call amplitude in response to outboard motorboats (Au and Green 2000). This species produces a high SPL value call (170 - 175 dB re 1 μPa, Frankel 1994) at a wide frequency range (50 Hz to 2200 Hz, Green et al. 2007). While the frequency range of this species overlaps that of outboard motorboats, the calls of humpback whales are mostly higher amplitude and can be low frequency than that of outboards and are thus less likely to acoustically impact this species.

Marine mammals demonstrate a wider range of acoustic compensation techniques compared with fishes. These acoustic responses include frequency shifts (Au et al. 1985, Lesage et al. 1999, Parks et al. 2007), increased call durations and/or repetition rates (Au et al. 1985, Finley et al. 1990, Miller et al. 2000, Foote et al. 2004), the Lombard effect (Au et al. 1985, Scheifele et al. 2005, Holt et al. 2009, and Parks et al. 2011), increased call rates (Lesage et al. 1999, Dehlheim 1987), and decreased call rates (Finley et al. 1990, Lesage et al. 1999, Parks et al. 2007, Azzara et al. 2013). In comparison, research has thus far shown that fishes respond to increased ambient noise by only decreased call rates (Holt and Johnson 2014, Krahforst et al. 2016, Chapter 3) and the Lombard effect (Holt and Johnson 2014, Luczkovich et al. 2016, Chapter 2). However, the sonic muscles of the oyster toadfish are likely aerobically limited by the amount of stored glycogen (Mitchell et al. 2008). This limits their ability to call louder and longer to adapt to increases in ambient noise levels. Hence, it is necessary to understand the physiological limitations of fish sound production mechanisms and the other forms of behavioral adaptations fishes exhibit to overcome increased ambient noise levels in the environment.

Experiment 2: Communication by Oyster Toadfish in Different Habitats

A second, related concept explored in Chapter 3 is how sounds of vessels and predators influenced oyster toadfish communication in different benthic habitats (seagrass vs. sand). I used the same playback sounds and sites at described for Experiment 1 but I ran the experiment in sand and in seagrass, looking solely at differences in the calling rate of the oyster toadfish.

> **H_a6.1:** Oyster toadfish, regardless of the sound-exposure treatment, will communicate at higher rates (calls min^{-1}) in seagrass compared to sand habitat.
>
> **Result:** Support to reject H_o but is dependent on site noise level.

The theoretic concept in this experiment is that seagrass is an acoustic refuge for oyster toadfish (for an overview see: Wilson et al. 2013).

The results of this work demonstrated that overall oyster toadfish had higher calling rates in seagrass compared with sand but this was dependent upon the site. At the "noisy" site, there was an increase in the number of calls in seagrass compared with sand. At the "quiet" site, this difference by bottom type was not evident (Chapter 3).

One key assumption here, as demonstrated by Wilson et al. (2013), is that low-frequency sounds attenuate more quickly in seagrass than sand. According to my field sound propagation measurements, seagrass at my sites did not seem to be attenuating the playback sounds of vessels more than did the sand habitat (Appendix B), but SPL values were across a broad frequency range. More research needs to be conducted on this concept. While attenuation of these low-frequency signals within the sites might not have been apparent, attenuation of high-frequency signals like bottlenose dolphin biosonar signals are likely to occur due to the frequency of bubble resonance and the wavelength of the sound. Hence, the oyster toadfish could be using the seagrass as both an acoustic (Nowacek 2005) and visual refuge from predators in the area (Allen et al. 2001). In "quiet" sites seagrass may be less valuable as an acoustic refuge for oyster toadfish from predators because there is less anthropogenic noise and thus an acoustic signal from a predator (like a dolphin) may be more detectable from a further distance than in a "noisy" site, allowing the fish more time to detect and respond to a nearby predator.

Another assumption made in this work is that sound propagation as measured by sound pressure at the hydrophone matches the sound pressure detected by the fish with no additional information. This assumption is likely to be incorrect because oyster toadfish can detect both sound pressure and particle motion (Fay and Edds-Walton 1997, Yan et al. 2000). I did not measure particle motion in my experiments. The results of the acoustic propagation work conducted in Fine and Lendardt (1983) and in Chapters 2 &3 of this dissertation suggest that transmission loss of low-frequency (< 1 kHz) signals exceeds that of the cylindrical spreading model by a distance of 15 m or more from a sound source. Yet, a portion of the sound propagates into the sediment. In muddy environments, these signals attenuate faster than in sandy environments due to the resonance frequency of trapped bubbles (Anderson and Hampton 1980). The result is that sounds from vessels in sandy bottoms are likely to propagate further in sand than the sound from vessels moving over muddy bottoms. This makes sounds at the "noisy" site, which had a sandy bottom, more detectable to oyster toadfish through the ground than sound at the "quiet" site (muddy bottom). Hence, a vessel moving past the "noisy" site may be more disturbing to an oyster toadfish in a shelter than that of an oyster toadfish in a "quiet" site. Future research needs to better explore how to effectively measure sounds as the animal senses them, which includes understanding how sound travels through the sediment.

Experiment 3: Habitat use by Oyster Toadfish

The concept of oyster toadfish habitat use is explored in Chapter 4. This section addressed the objective of how underwater noise from vessel activity influenced habitat use by oyster toadfish. To conduct this work, I executed a field experiment where artificial oyster toadfish shelters were deployed near (5 m) and far (35 m) from a navigation channel at "noisy" and "quiet" sites. For this field experiment, I explored the concepts of oyster toadfish occupancy rates and oyster toadfish lengths (standard length) within the deployed shelters. The following hypotheses were tested:

> **H_o7.1:** Oyster toadfish occupancy rate (# fish/shelter) will not differ by the position of the shelter in relation to the navigation channel (near vs. far). Shelters “near” the channel represent “noisy” environments and shelters “far” from the channel represent “quiet” environments.
>
> > **Result:** Support to reject H_o at one "noisy" site (NMM). At the remaining sites three sites, I accept H_o.
>
> **H_a7.2:** Oyster toadfish occupancy rate (# fish/shelter) will be higher in shelters at sites with low vessel activity (“quiet” sites) as compared with sites with high vessel activity (“noisy” sites).
>
> > **Result:** Support to reject H_o in one "noisy" site (NPR). At the remaining sites three sites, I accept H_o.

H_o7.3: Oyster toadfish standard lengths (mm) will not differ by the position of the shelter in relation to the navigation channel (near vs. far). Shelters "near" the channel represent "noisy" environments and shelters "far" from the channel represent "quiet" environments.

Result: Accept H_o at all four sites.

H_a7.4: Oyster toadfish will be larger (in standard length, mm) at sites with low vessel activity ("quiet" sites) as compared with sites with high vessel activity ("noisy" sites).

Result: Support to reject H_o at one "noisy" site (NPR) but at the other "noisy" site (NMM) I accept H_o. The "noisy" sites are not equivalent by noise level from vessel activity. There may be a noise threshold that was exceeded at NPR but not at NMM, influencing the size of the oyster toadfish using each of the sites.

Oyster toadfish length and occupancy within the artificial shelters differed by site and channel position. The Newport River (NPR) site ("noisy") had significantly fewer oyster toadfish than the three other sites in this study (Chapter 4). Hence, the site with the most inboard motorboat activity and the most combined vessel activity overall, had the least oyster toadfish. This site also had the least number of recaptures (Appendix H). Only one "noisy" site (North Middle Marsh, NMM) had significantly more oyster toadfish far as compared with near the channel. This indicates that the site with high outboard motorboat activity but little or no inboard motorboat activity had a lot of oyster toadfish, but they preferentially selected shelters far from the navigation channel. Finally, oyster toadfish standard length distribution differed only at the NPR site.

Generally, the results of the work presented here on oyster toadfish length distribution and shelter occupancy across the sites indicate that vessel presence and noise is reducing habitat quality. I have already demonstrated that vessels alter the calling behavior of male oyster toadfish (Experiment 1), likely masking the ability for conspecific females to detect courtship calls. Others have demonstrated that vessel presence and noise masks the hearing ability in fishes (Scholik and Yan 2001, 2002, Vasconcelos et al. 2007). Vessel noise or presence also alters fish swimming behavior in the form of swimming speed and direction (Engås et al. 1995, 1998, Sarà et al. 2007). Vessel noise or presence raises stress levels in fishes, as measured by cortisol (Wysocki et al. 2006) and heart rate (Graham and Cooke 2008). While I did not directly measure cortisol or other physiological indicators of stress in this study, I assume that the oyster toadfish in the "noisy" areas have heightened stress-related indicators. Oyster toadfish are likely avoiding the NPR site because it is a more difficult site to call for mates and rear embryos due to competition with vessel noise. Future research on this subject needs to include measurements of a stress indicator, like cortisol, in response to vessel presence/noise.

It is relatively common for animals to avoid noise-inundated areas. For marine mammals, this behavior has been demonstrated in dugongs (*Dugong dugon*, Anderson 1981, Preen 2000). Historical (the 1970s) locations of dugong sightings that now have a lot of vessel traffic have displaced this species to less desirable habitat (Preen 2000). Secondly, bottlenose dolphins also demonstrate this avoidance behavior, with more dolphin sightings in areas of low vessel traffic over areas of high vessel traffic (Bejder et al. 2006, Rako et al. 2013). Interestingly, Rako et al. (2013) determined that newborn dolphins were not encountered in the high vessel traffic locations but they were observed in the low vessel traffic locations. Finally, vessels can even interrupt feeding behaviors. Blane and Jaackson (1994) found that beluga whales (*Delphinapterus leucas*) stopped feeding in response to vessels.

The presence of vessel activity, as well as dredged, deep navigation channels, could be resulting is habitat patchiness. Within the terrestrial realm, roads interrupt ecological flow among a habitat or area (Forman and Alexander 1988), which impacts animal behavior. For example, traffic noise reduces bird counts by 33% in comparison to areas of low traffic noise (Reijnen et al. 1995). The data presented on occupancy in Chapter 4, support this concept in the aquatic realm. Oyster toadfish are 80% less abundant in the site with the most inboard motorboat activity. At this site, in particular, vessel noise may be disturbing these fish and causing them to leave. It certainly is the site with the least recaptures (Appendix H) and this is not due to water quality (Appendix E) or general habitat availability (pers. observation). Future research needs to focus on questions about habitat patchiness and how underwater noise influences fishes because they are valuable to management decisions. If fishes are leaving an area because of vessels, then it is likely marine mammals will follow their prey. Displacement of one species can lead displacement of several others, which can result in an impact on human-valued ecosystem services.

Experiment 4: Reproductive Output by the Oyster Toadfish

The next step I addressed was the impact of vessel noise on oyster toadfish reproduction (Chapter 4). For this objective, I used the same experimental set-up as Experiment 3. However, I examined the oyster toadfish shelters for the presence of embryos. The following hypotheses were assessed:

H_o8.1: The number of oyster toadfish egg clutches on shelters will not differ by navigation channel position (near vs. far) at sites with low vessel activity.

Result: Accept H_o at both "quiet" sites.

H_a8.2: There will be more oyster toadfish egg clutches on shelters far from the navigation channel compared with near the channel at the sites with high vessel activity.

Result: Support to reject H_o at one "noisy" site (NMM) but at the other "noisy" sites no egg clutches were present so, I accept H_o.

H_a8.3: At sites with high vessel activity, there will be fewer oyster toadfish embryos on shelters near compared with far from the navigation channel.

Result: I only analyzed one of the "noisy" sites (NMM) here because the second "noisy" site did not have any embryos present during the sampling season. I accept H_o at the "noisy" NMM site.

H_o8.4: At sites with low vessel activity, there will be no difference in the number of oyster toadfish embryos by channel position.

Result: I reject H_o at both "quiet" sites.

H_a8.5: Male oyster toadfish shelters at the sites with high vessel noise will have fewer embryos as compared with sites with low vessel noise.

Result: I reject H_o for both "noisy" sites.

Egg clutches were found at three of the four sites; NPR (a "noisy" site) contained no embryos throughout the sampling period. The lack of egg clutches at this "noisy" site is likely associated with the concept that the site is not an ideal habitat for oyster toadfish. At the three sites with embryos, there was no significant difference in the number of clutches. Overall, egg clutches were more common near compared with far from the navigation channel. The other three sites (NMM, SMM, and JBS) were acceptable habitats for oyster toadfish because 1) there was a lot of large oyster toadfish at these sites and 2) egg clutches were observed at each of these sites.

While the same number of clutches was similar at NMM and South Middle Marsh (SMM), there were 40.8% fewer embryos per clutch at NMM (a "noisy" site) compared with SMM (a "quiet" site). Yet, there was no difference in the number of embryos per clutch across both of the "quiet" sites. At both of these "quiet" sites, 68.5% more embryos were deposited far compared with near the navigation channel. However, at the "noisy" site (NMM), there was no difference in the number of embryos by navigational channel position. I expect vessel noise is causing a problem for the oyster toadfish at NMM because NMM ("noisy") and SMM ("quiet") had no difference in the total number egg clutches observed throughout the season, yet NMM had significantly fewer embryos than both "quiet" sites. There was no length difference (overall) for the oyster toadfish between these three sites (Experiment 3). While SMM had fewer oyster toadfish than both NMM and JBS, NMM still had fewer embryos per clutch than did the other two "quiet" sites. I observed only outboard motorboats at the NMM site (Experiment 3). These results suggest that there is something occurring behaviorally among the oyster toadfish in response to vessels; primarily outboard motorboats at NMM.

Based on current literature, anthropogenic noise influences animal fitness and parental care behavior. Vessel activity in an area has caused longear sunfish (*Lepomis megalotus*) to leave their nests (Mueller 1980). Damselfish (*Chromis chromis*) and red-mouthed gobies (*Gobius cruentatus*) spent less time caring for their nests in response to vessel activity (Picciulin et al. 2010). Nesting yellow-blotched map turtles (*Graptemys flavimaculata*) abandoned their nesting attempts in response to an approaching vessel (Moore and Seigel 2006). Therefore, concepts like nest abandonment and/or reduced parental care of the embryos is likely in the oyster toadfish in response to vessel noise. There is also potential that male oyster toadfish in "noisy" areas are attracting smaller females, which will have a smaller amount of eggs to lay in the nest. It would be advantageous to future research to explore sex-length distribution within "quiet" and "noisy" sites, and the potential of nest-abandonment and reduced parental care due to vessel noise and presence.

A second, important concept that has been demonstrated in a bird species, the female great tit (*Parus major*), is the concept of a female choice in laying smaller egg clutches in areas of high over low vehicle traffic noise (Halfwerk et al. 2011). There is no evidence that a female oyster toadfish lays one clutch or multiple clutches in a season. If the latter is true then, a female may (1) abandon the nest in the process of depositing eggs in response to vessel activity/noise, resulting in smaller egg clutches or (2) may choose to lay smaller egg clutches on shelters located in areas with high vessel noise. In this study, these behaviors were not quantified and future research needs to focus on female behavior in response to vessel noise in particular, reproductive output.

General Assessments and Future Directions

These studies demonstrate the following key points. (1) Vessel noise reduced calling rates and altered calling behavior in the male oyster toadfish. (2) A site with high inboard motorboat activity had smaller and less oyster toadfish compared with sites with low inboard motorboat activity. (3) Oyster toadfish in shelters at "noisy" sites contained less embryos than those in shelters at "quiet" sites. The argued concept is that the sounds of inboard motorboats are masking the courtship calls of male oyster toadfish, making these sites less desirable habitat compared with other sites. Sites with high outboard motorboat activity are of less concern because these sounds do not mask the calls of male oyster toadfish. However, these high outboard motorboat noise sites likely influence the nesting behavior of the oyster toadfish. The result is fitness consequences for male oyster toadfish that select sites that have high amounts of vessel noise/activity compared with sites with low amounts of vessel noise/activity.

The results of this dissertation research are generally supported by other marine and terrestrial research that argues that vessel noise is influencing animal behavior and fitness. Work on fishes have demonstrated masking of conspecific calls in the presence of vessel noise (Scholik and Yan 2001, 2002, Vasconcelos et al. 2007). Calling behavior alterations in calling rate (e.g. Dalhlheim et al. 1984, Finley et al. 1990, Parks et al. 2007, Azzara et al. 2013) and the Lombard effect have been demonstrated in marine mammals (Au et al. 1985, Scheifele et al. 2005, Holt et al. 2009, and Parks et al. 2011) and fishes (Holt and Johnson 2014, Krahforst et al. 2016, Luczkovich et al. 2016). Avoidance behaviors of areas with high vessel noise has been demonstrated in some marine mammals (Anderson 1981, Preen 2000, Bejder et al. 2006, Rako et al. 2013) and, in birds, as a response to traffic noise (Reijnen et al. 1995). Finally, a study on a bird species also confirms the concept of smaller clutch sizes in areas of high traffic noise over areas of low noise (Halfwerk et al. 2011). The research presented in this study, along with the current body of literature on the subject, further argues the need to manage or reduce vessel noise within the natural environment.

Future research directions need to address numerous areas of work. The needed research supported by the ecological component of this dissertation includes several concepts. (1) The need to measure acoustic propagation of noise through the sediment, including understanding transmission loss between a deep navigation channel and the very shallow water that serves as nesting habitat for male oyster toadfish (e.g. Sprague et al. 2016). (2) The need to further assess the role of seagrass as an acoustic refuge in terms of both low-frequency and high-frequency sounds (e.g. McCarthy and Sabol, 2000, Nowacek 2005, Wilson et al. 2013). (3) It is important for us to understand how fishes respond to a sound's context, which in part depends on its learned behaviors (e.g. Mensinger et al. 2016). (4) We need to make assessments of behavioral observations of both male and female oyster toadfish during vessel exposure. Some of the inclusive behavioral observations that need to be assessed are (A) stress-level measurements (e.g. Wysocki et al. 2006, Graham and Cooke 2008), (B) alterations to parenting behaviors (e.g. Mueller 1980, Picciulin et al. 2010), and (C) nest abandonment (e.g. Moore and Seigel 2006) with and without the presence of vessel noise. Answers to these and other questions will provide a better understanding of the behavioral implications of vessel noise to fishes; resulting in a more effective underwater noise management strategy for fish populations and ultimately fisheries.

The Social Problem

In this section of the dissertation, I used text analyses to explore the similarities and differences of themes among noise management and enabling legislation documents (Chapter 5). After making word selections within the documents that represented some primary themes, I conducted two types of analyses. First, a correspondence analysis was used to explore how the selected words within the documents plotted among the noise management and enabling legislation documents along two newly generated axes. Second, I generated both a network analysis of the words and the documents. These networks demonstrated positive and negative correlation relationships among the nodes to further assist in exploring the thematic focus of the documents. Finally, I discussed thematic concerns between the document types and suggested ways to improve the themes among the documents to better address ecosystem services (i.e. societal value). Within this social science problem, the following hypotheses were tested:

H_a9.1: Word frequency counts from a text analysis reveals thematic differences among management and legislative documents.

Result: I reject H_o for both documents types (noise management and enabling legislation).

H_a9.2: The underwater noise management documents focus on a theme of marine mammal protection and the concept of underwater noise.

Result: I reject H_o for the noise management documents.

H_a9.3: The legislative documents focus on a theme of human use of the environment but also consider the trade-offs between human use and the environment.

Result: I reject H_o for the enabling legislation documents.

H_a9.4: The legislative documents fail to identify underwater noise as a primary theme.

Result: I reject H_o for the enabling legislation documents.

The words selected for the analyses demonstrated themes across the documents. Thematic similarities between the two sets of documents showed an interest in how human use is impacting the environment. The noise management documents had an overarching theme of, "assessing the acoustic impacts on marine life or the marine environment." Primary concepts that were focused on within these documents included "acoustic impact," "protection or preservation," and "marine mammals." The enabling legislation, however, had two themes. The first theme "resource conservation" was demonstrated through words such as, "conserve," "manage," "plan," and "fish." The second theme was "resource development," with words such as "activity," "develop," and "resource" dominating these documents. Hence the overarching themes between the document types (enabling legislation vs. noise management) displayed some differences among the perception of resource management.

The dissimilarities in thematic focus among the documents became more apparent in the document network analysis. This analysis demonstrated that most of the noise management documents were negatively correlated with the enabling legislation. Dissimilar words between these two document sets included sound-related words like "acoustic," "source," noise," and "sound," which, in the correspondence analysis, loaded among the noise management documents. Additional dissimilar words addressed marine life like "marine," "mammal," and "fish," where "fish" plotted with enabling legislation and "marine" and "mammal" plotted with the noise management documents. Other words like "public," "develop," resource," and "conserve" primarily loaded upon the enabling legislative documents.

In terms of human use of the environment, there is some disparity across the themes among the documents. Noise management documents focused on noise-related concerns and how these activities impacted the natural environment. In these documents, human use was only addressed in discussions associated with the reduction of impacts due to certain activities. The noise management documents expressed the need to "manage," specifically to manage "noise," "sound," and "[sound] source[s]." Management initiatives included predicting impacts, modeling risk, monitoring impacts, mitigating damage, and reducing noise through technology. The enabling legislation documents, however, focused on how environmental use was going to impact economics and human use of the resource. Human-activity concepts such as fisheries, vessel activity, navigation, commercial use, construction, development, and pollution were key concepts related to human-use within the enabling legislation. Other considered concepts within the enabling legislated included costs and economics. The enabling legislation, suggested management initiatives such as planning, permitting, penalties, enforcement, and leases. Thus, the noise management documents had a more biocentric value orientation whereas the enabling legislation focused more on an anthropocentric value orientation.

Today, ecosystem-based management is mandated by National Ocean Policy (Lubchenco and Sutley 2010) and required management initiatives needed to addresses both (1) the interconnectedness of ecosystem components and (2) the interconnections between people and the ecosystem in the form of ecosystem services (McLeod and Leslie 2009). This concept requires that underwater noise management plans need to address both intangible (nature for nature's sake) and tangible (production materials, goods, and services) assets of the environment (Botkin 1990). However, noise management documents focused on the intangible, while the enabling legislation focused more on the tangible assets of the environment. Hence, this disparity (intangible vs. tangible) is where efforts need to be made to improve future management decisions as they relate to underwater noise management.

Both sets of documents (noise management and enabling legislation) are missing an important piece of ecosystem-based management. The enabling legislation needs to recognize underwater noise as a source of pollution. This is already happening in the European Union (Palmer 2010). Only one of the U.S. legislative documents (National Whale Conservation and Protection Study Act) actually mentioned underwater noise as a concern. The noise management documents, however, need to address a larger group of human use concerns such as economics and the required trade-offs between resource management and human-use. An example of this issue with noise management documents occurs with the word "fish."

The word "fish" did not strongly correlate with the noise management documents nor did it correlate with the words associated with underwater noise management concerns like "acoustic," "source," "noise," and "sound." The words "marine" and "mammal" however plotted with these noise management concerns. The word "fish" was correlated with the enabling legislation documents. "Fish" is an important word in relation to ecosystem services. Fish and fisheries are valued by resource users, as demonstrated in the enabling legislation. Because of the value of "fish" to society, noise management documents need to place more emphasis in addressing fish-related ecosystem services.

Under ecosystem-based management resource managers need to address both basic scientific knowledge as well as social knowledge (Korten 1981, Reich 1985) within their management initiatives. Current underwater noise management strategies focus on a protection theme, especially the protection of marine mammals, and lacks the incorporation of human values like ecosystem services. This perspective results in a lack of understanding in how human's value an ecosystem resource as well as the trade-offs and costs people are willing to accept for the management (Loomis and Paterson 2014b) of underwater noise. Understanding these concepts are important to management because user response to a regulation can compromise the intent of that regulation if users do not accept the desired action(s) (Radomski and Goeman 1996). On the other hand, if users understand and accept a regulation, it can actually lead to a more effective management strategy (Dyer and McGoodwin 1994) for the challenges addressed by underwater noise management. Thus, understanding the social values of a resource can actually enhance the management plan and lead to more effective management of a resource, as it relates to underwater noise.

Combining the Problems

For ecosystem-based management (EBM) the issue of underwater noise poses several problems, both in terms of ecosystem interconnectedness and how people rely upon the ecosystem for its services. These noise-induced problems include: 1) impacts to an ecosystem through pollution; 2) impacts of animal health, migration, and reproduction; 3) impacts to habitat, including nursery grounds; 4) population-level impacts to marine species such as fishes, invertebrates, and marine mammals (including some threatened and endangered species); 5) impacts to ecosystem functioning; 6) economic impacts to society, like fisheries; 7) the inhibition of national security measures; 8) impacts to recreational activities, like fishing and whale watching; 9) impacts to the maintenance of cultural and historical ecosystem services. As a pollution source (Götz et al. 2009), underwater noise has the potential to impact overall ecosystem function, as well as ecosystem services provided by the many economically valuable species of the ecosystem, not just marine mammals or endangered species.

The text analysis (Chapter 5) of the noise management documents reveals that words like “marine” and “mammal” are centrally focused, indicating the importance of these animals in the management documents. For the enabling legislation, the word “fish” was centrally focused, suggesting that fishes play an important role in these legislative documents. This disparity is important in an EBM strategy because noise impacts will affect fishes (Chapters 2-4). This concept is important to marine mammals, as well as, ecosystem services. There is an interconnectedness among fishes and marine mammals, in that fishes (especially soniferous fish) are an important food source for some marine mammals (e.g. Gannon et al. 2005, McCabe et al. 2010, Pate and Mcfee 2012, Dunshea et al. 2013). Historically, marine mammals were primarily valued as a supplementary food source (Colten and Arnold 1998, Hovelsrud et al. 2008, Lotze and Worm 2009) and for the use of their blubber as oil (Dolin 2008), but today are valued by society primarily through economics (i.e. tourism, e.g. Hoyt 2000) and ecosystem functioning (i.e. food web dynamics and biodiversity, e.g. Lotze et al. 2006). Even historically, finfish and shellfish were utilized more often to sustain the human population than marine mammals by coastal people (Colten and Arnold 1998, Lotze and Worm 2009). Fishes provide many human-valued ecosystem services related to ecosystem functioning (e.g. food web dynamics, nutrient cycling, biodiversity, etc), cultural services (e.g. food, medicine, control of algae, recreation), informational services (e.g. stress, resilience, etc), and economics (e.g. fisheries, Holmlund and Hammer 1999). The extent of ecosystem services provided by fishes, their importance in the enabling legislation, the interconnectedness between marine mammals and fishes, and their historical value suggests that an EBM approach should have a primary focus on fish and fisheries rather than marine mammals.

By addressing noise impacts to fish and fisheries as part of an EBM strategy, managers can also satisfy the desires of those who wish to protect marine mammals, as well as those who tie needed management to ecosystem functioning and ecosystem services.

The issues resulting from underwater noise management are much more broad scale than has been discussed in this document. Examples of other activities that underwater noise management can influence include boating, SCUBA diving, whale watching, fishing, as well as activities where people use the environment for extracting goods and services (e.g. goods/food), and those who rely upon it for commerce (e.g. commercial fishing, shipping transport, and offshore oil/gas). It is important that management initiatives on underwater noise reflect the concerns of all these user groups (U.S. Commission on Ocean Policy 2004, Weinstein and Reed 2005) because management is most effective when there is a set of beliefs that are associated with behavioral norms (e.g. Aipanjiguly et al. 2003). A comprehensive EBM underwater noise management plan should include all such user groups.

The difficulty in marine resources management today is that any management decision needs to reflect the goals, values, desires, and benefits of that resource to society (Kelble et al. 2013). The shift in the management scheme from biocentric to an EBM approach is meant to assure long-term yield of ecosystem services and thus human well-being (Rosenberg and McLeod 2005). It is important to understand societal value gained from an ecosystem service because it helps informs decisions and assists at identifying trade-offs required for the implementation of a specified management strategy (Kelble et al. 2013).

> "*Where multiple desirable but competing objectives exist, it is not possible to maximize each…..[and] in any system with multiple competing objectives, it will not be possible to meet every one*," (U.S. Commission on Ocean Policy 2004).

Thus, it is necessary to capture the values (both natural and societal) of an ecosystem utilizing some type of measurable variables in an EBM framework (Loomis and Paterson 2014a, 2014b). Keys to this process are that these variables are grounded in ecological theory and also effectively relate to societal values in terms of ecosystem services (Doren et al. 2009).

As a result of this shift toward the use of the EBM concept, I have generated a diagram with the purpose of demonstrating some of the key considerations (social and ecological) needed for an inclusive management approach (Figure 6.1). The social side of the EBM model (on the bottom right of Figure 6.1) suggests some approaches to including social theory into management initiatives. For example, interviewing resource users can provide valuable information about the limitations of a resource (e.g. collapse points, carrying capacity, and stress, Gladwin et al. 1995). Surveys can also be valuable in understanding socially accepted behaviors within the resource as well as acceptable management plans and policies (Lockwood et al. 2010). These concepts essentially operationalize the trade-offs people are willing to accept between resource management and resource use (Loomis and Paterson 2014b). On the ecological side of the EBM model (to the bottom left of Figure 6.1), I have diagrammed the concept of a holistic ecosystem approach to management. There are three main components (ecosystem-level, habitat, and population-level impacts) addressed along this ecological perspective within the EBM model. These ecological components include multiple species (marine mammals, fishes, and invertebrates) rather than focused on a single species or group (e.g. marine mammals). The idea here is that the population of one species will depend on several other species as well as other biotic and abiotic factors within the ecosystem. A pollution source like noise can have impacts on any of these species or at any ecosystem level, and these effects can influence other species (interconnectedness of the ecosystem). To maintain a healthy ecosystem it is necessary to look at all of the factors influencing that system.

For example, the work presented in this dissertation focused on a single fish species: the oyster toadfish, which is a species that is not highly valued by society for providing an important direct ecosystem service (e.g. food). This species, however, plays an important role in the ecosystem. The oyster toadfish is actually a keystone predator, whose removal or loss would lead to community-level consequences on oyster reef habitats. Oyster toadfish (*Opsanus tau*) preys upon mud crabs (*Panopeus herbstii* and *Eurypanopeus depressus*, Wilson et al. 1982, Gibbons and Castagna 1985) as well as other crabs (e.g. blue crabs *Callinectes sapidus* and stone crabs *Menippe mercenaria*, personal observations). These crabs are important predators of juvenile hard clams (*Mercenaria mercenaria*) and eastern oysters *Crassostrea virginica* (Menzel and Hopkins 1956, Menzel and Nichy 1958, Bisker and Castagna 1987, Abbe and Breitburg 1992). If the mud crab (and other crab) populations are not controlled by the oyster toadfish, then oysters will likely decline from increased crab predation. In turn, this can result in decreased water clarity as well as reduced oyster availability for human consumption, which are both important ecosystem functions to the human population. Thus, oyster toadfish do provide an important ecosystem service through this trophic cascade

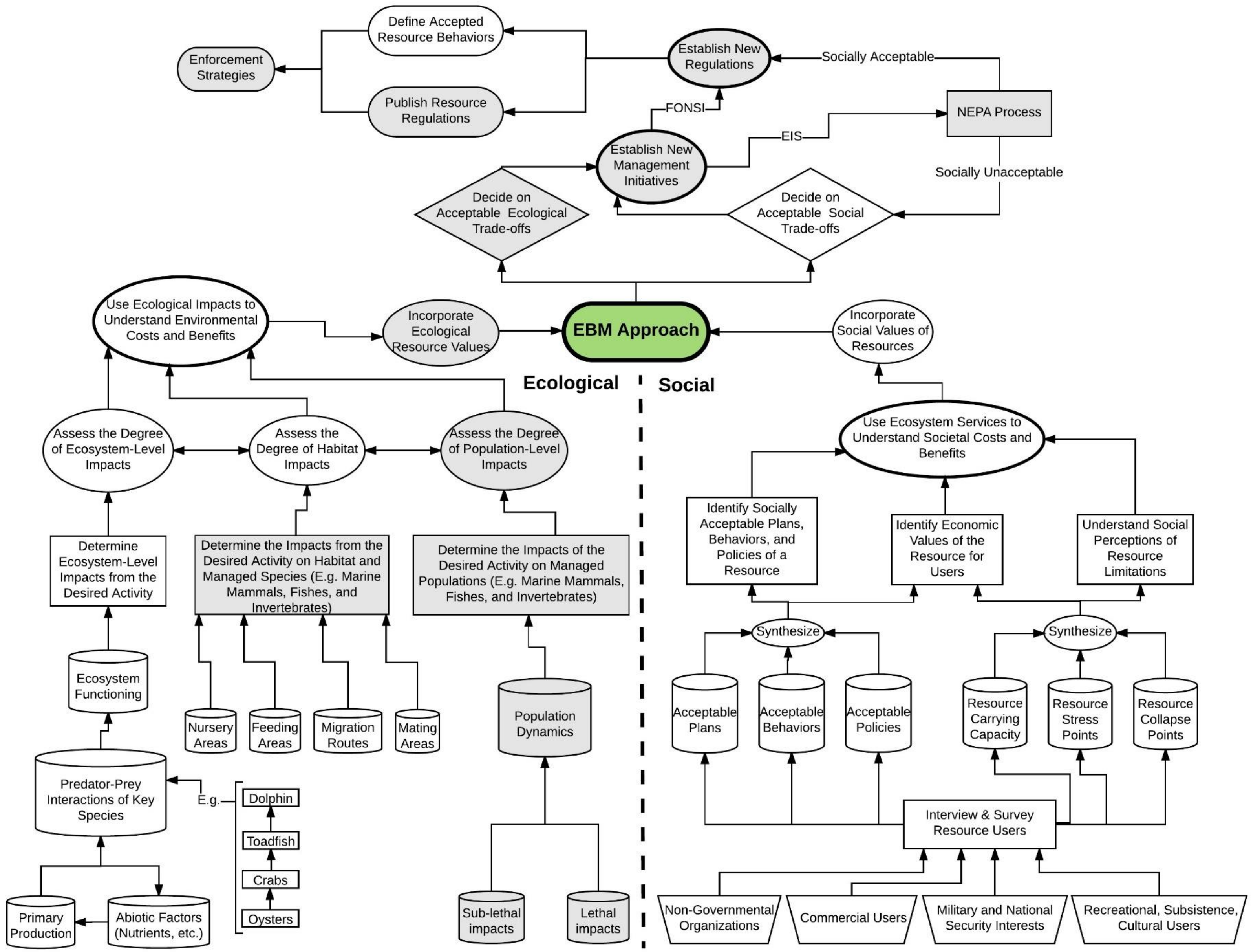

Define Accepted Resource Behaviors
Enforcement Strategies
Publish Resource Regulations
Establish New Regulations
Socially Acceptable
FONSI
NEPA Process
EIS
Establish New Management Initiatives
Socially Unacceptable
Decide on Acceptable Ecological Trade-offs
Decide on Acceptable Social Trade-offs
Use Ecological Impacts to Understand Environmental Costs and Benefits
Incorporate Ecological Resource Values
EBM Approach
Incorporate Social Values of Resources
Ecological
Social
Assess the Degree of Ecosystem-Level Impacts
Assess the Degree of Habitat Impacts
Assess the Degree of Population-Level Impacts
Use Ecosystem Services to Understand Societal Costs and Benefits
Determine Ecosystem-Level Impacts from the Desired Activity
Determine the Impacts from the Desired Activity on Habitat and Managed Species (E.g. Marine Mammals, Fishes, and Invertebrates)
Determine the Impacts of the Desired Activity on Managed Populations (E.g. Marine Mammals, Fishes, and Invertebrates)
Identify Socially Acceptable Plans, Behaviors, and Policies of a Resource
Identify Economic Values of the Resource for Users
Understand Social Perceptions of Resource Limitations
Synthesize
Synthesize
Ecosystem Functioning
Nursery Areas
Feeding Areas
Migration Routes
Mating Areas
Population Dynamics
Acceptable Plans
Acceptable Behaviors
Acceptable Policies
Resource Carrying Capacity
Resource Stress Points
Resource Collapse Points
Predator-Prey Interactions of Key Species
E.g.
Dolphin
Toadfish
Crabs
Oysters
Primary Production
Abiotic Factors (Nutrients, etc.)
Interview & Survey Resource Users
Sub-lethal impacts
Lethal impacts
Non-Governmental Organizations
Commercial Users
Military and National Security Interests
Recreational, Subsistence, Cultural Users

Figure 6.1. A diagram that suggests an approach to ecosystem-based management that incorporates both social and ecological resource values (on the previous page).

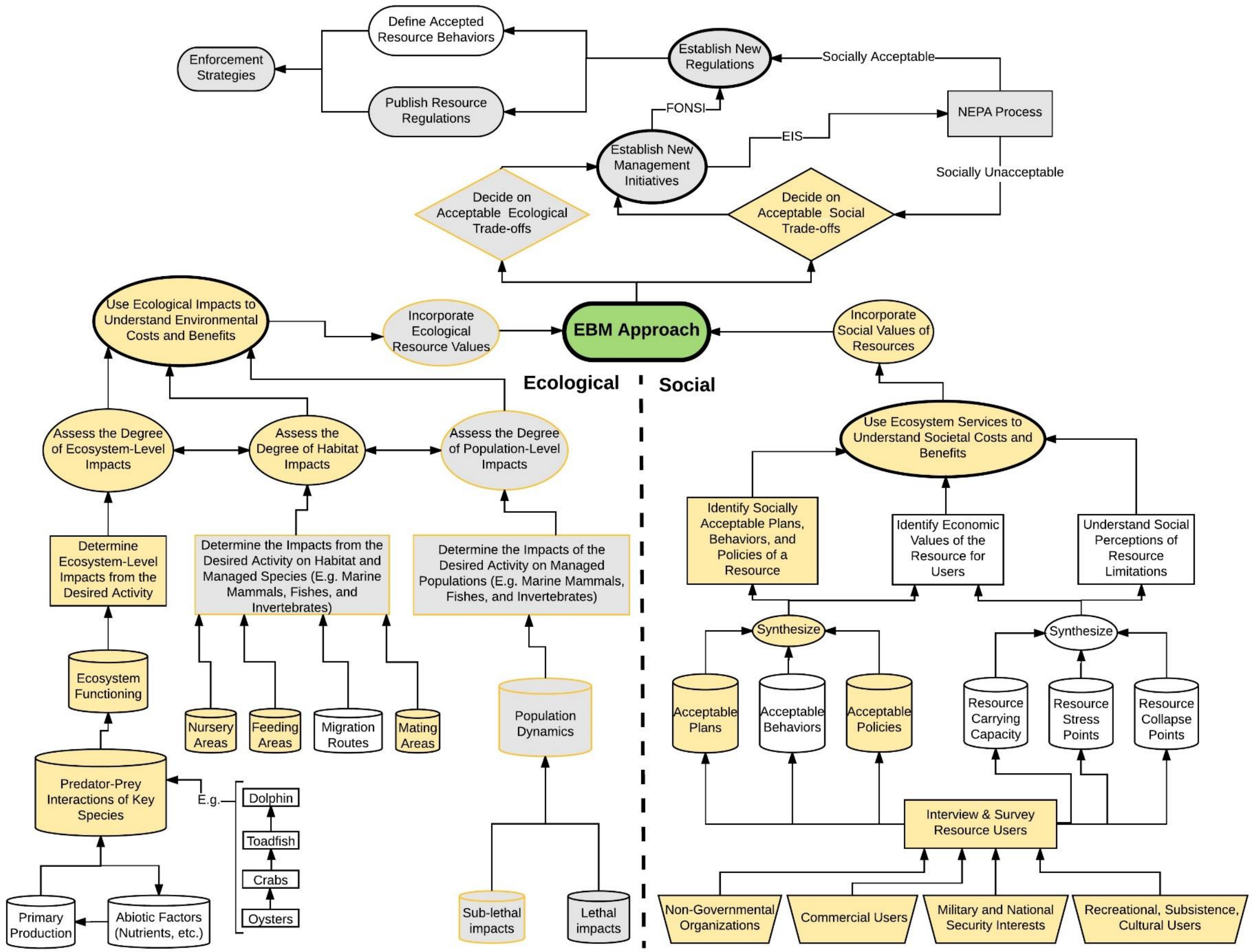
This diagram demonstrates a more inclusive approach to ecosystem-based management (EBM) by suggesting ways in which managers can incorporate both social and ecological resource values within their management plans. The trapezoids are a data gathering stage, cylinders represent the establishment and maintenance of a research database, ellipses are analysis and synthesis stages, ovals are endpoints or termination stages, and diamonds are decision point stages within the management diagram. The shapes with a thick line demonstrate important information incorporation steps. The dashed line demonstrates an initial separation of information gathering within the ecological and social systems. These systems are combined in the new management initiative stage. Environmental impact statement (EIS) and findings of no significant impact (FONSI) are current components of the National Environmental Policy Act (NEPA), which is the enabling legislation already in place that requires an EIS review and comment period. The greyed symbols indicate stages that are currently the focus of management agency initiatives.

By taking the example of the oyster toadfish and using the information addressed within this dissertation, I can demonstrate how the management diagram can apply to this simple example (Figure 6.2). The oyster toadfish is important in predator-prey dynamics as demonstrated earlier with the trophic cascade. If, oysters (as a food source) are important to people, then keeping a healthy toadfish population is important because toadfish help control the crabs that consume the oysters and other bivalves (Wilson et al. 1982, Gibbons and Castagna 1985). However, based on this dissertation research vessels are also influencing the presence of oyster toadfish and shifting their habitat to sites with low vessel activity or noise. Areas of high vessel noise are also presumably having population-level effects on oyster toadfish through reduced fitness. Thus maintaining a healthy oyster toadfish population, which is important to the population levels of oysters and clams (ecosystem service) relies on many factors, one of which is the presence of the oyster toadfish.

Along similar lines, bottlenose dolphin are known predators of oyster toadfish and other soniferous fishes (e.g. Gannon et al. 2005, McCabe et al. 2010, Pate and Mcfee 2012, Dunshea et al. 2013). So the loss of soniferous fish species from a habitat due to noise could lead to avoidance behavior from dolphins and other marine mammals as they follow their prey to areas with less noise. Alone, dolphins do provide a direct ecosystem service through their importance in recreational enjoyment and tourism (e.g. Orams 2002, Lusseau 2005, Bejder et al. 2006) but dolphins are also tied for their food source (fish). Fish provide multiple ecosystem services that people value. Fishing is economically important, especially in coastal states (U.S. Department of the Interior et al. 2011) and the interconnectedness of fish and fisheries relates to economic social values, which are particularly important to political and business resource stakeholders within the U.S. This is one of the reasons why the word "fish" was so important in the enabling legislation and central in the documents considered in the text analysis in Chapter 5. The result of preserving an ecosystem service like food (i.e. fish or oysters) is that the predators (dolphin) also can benefit from these actions. By approaching management using this EBM strategy (focusing on ecosystem services), conflict among user groups is likely to be reduced because managers will take into account their social values at an early stage and manage a resource according to the needs of society as well as continued ecosystem functioning (Meinzen-Dick et al. 2004).

In Southern Australia, the government desired to establish marine protected areas (MPAs) but they wanted to target their management strategy on ecosystem services as well as the biophysical needs of the system (Bryan et al. 2010). So, community representatives were identified and interviewed in an attempt to understand what resources were valued and how they were valued in the ecosystem. The areas with the highest social value in terms of abundance (amount of ecosystem services available), diversity (types and evenness of ecosystem services), rarity (concentration of ecosystem services), and risk (combination of social value and threat to ecosystem services) were prioritized for MPAs. The areas identified by users as high social value actually coincided with ecologically-based priority areas, which suggests a possible convergence of social and biological values (Bryan et al. 2010). Hence, using social values in the decision-making process is likely to enhance social learning (Blackstock et al. 2007), increase the likelihood of perceived fairness (Reed et al. 2008), and increase the overall acceptability and quality of a management decision (Plummer and Armitage 2007).

As a society, we have moved away from the expert approach to management that began in the industrialization era and have moved towards a more holistic ecosystem approach to management. This EBM approach needs to have more than a single-species or single-function focus. Managers need to look not only at the whole ecosystem (biotic and abiotic) but also should include humans and human needs within that ecosystem, making humans a necessary component of the ecosystem. The noise management initiatives need to include other species that are valuable to humans (like fishes) rather than having a primary focus on marine mammals. I am advocating here that we all work at incorporating a broad-scale approach to management, where there is a connection drawn between biological factors and societal values through ecosystem services and where the public becomes involved in the process that will end in a management initiative that weighs costs and benefits to both the ecosystem and to society as a whole.



Define Accepted Resource Behaviors
Enforcement Strategies
Publish Resource Regulations
Establish New Regulations
Socially Acceptable
NEPA Process
FONSI
EIS
Establish New Management Initiatives
Socially Unacceptable
Decide on Acceptable Ecological Trade-offs
Decide on Acceptable Social Trade-offs
Use Ecological Impacts to Understand Environmental Costs and Benefits
Incorporate Ecological Resource Values
EBM Approach
Incorporate Social Values of Resources
Ecological
Social
Assess the Degree of Ecosystem-Level Impacts
Assess the Degree of Habitat Impacts
Assess the Degree of Population-Level Impacts
Use Ecosystem Services to Understand Societal Costs and Benefits
Determine Ecosystem-Level Impacts from the Desired Activity
Determine the Impacts from the Desired Activity on Habitat and Managed Species (E.g. Marine Mammals, Fishes, and Invertebrates)
Determine the Impacts of the Desired Activity on Managed Populations (E.g. Marine Mammals, Fishes, and Invertebrates)
Identify Socially Acceptable Plans, Behaviors, and Policies of a Resource
Identify Economic Values of the Resource for Users
Understand Social Perceptions of Resource Limitations
Synthesize
Synthesize
Ecosystem Functioning
Nursery Areas
Feeding Areas
Migration Routes
Mating Areas
Population Dynamics
Acceptable Plans
Acceptable Behaviors
Acceptable Policies
Resource Carrying Capacity
Resource Stress Points
Resource Collapse Points
Predator-Prey Interactions of Key Species
E.g.
Dolphin
Toadfish
Crabs
Oysters
Interview & Survey Resource Users
Primary Production
Abiotic Factors (Nutrients, etc.)
Sub-lethal impacts
Lethal impacts
Non-Governmental Organizations
Commercial Users
Military and National Security Interests
Recreational, Subsistence, Cultural Users

Figure 6.2. An ecosystem-based management strategy demonstrating the concepts addressed in this dissertation, including both social and ecological resource values (on the previous page).

The ecosystem-based management (EBM) approach demonstrates the steps that were addressed within this dissertation (yellow). The literature and results presented in this dissertation are just a few examples of the need to be more inclusive within the ecosystem-based management approach. A full description of the symbols and abbreviations within this suggested management strategy is found in Figure 6.1.

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APPENDIX A: ANIMAL USE PROTOCOLS AND NATIONAL ESTUARINE RESEARCH RESERVE PERMIT

Table A.1. Animal use protocol (AUP) and permits issues for the work presented in this dissertation.

East Carolina University's AUP number designations and the Rachel Carson National Estuarine Research Reserve's permit number, with the designed chapters in which the permits were utilized.

Permit Number	Issued Organization	Applicable Chapters	Page #
AUP #D292	East Carolina University	Chapters 2 & 3	307
AUP #D307	East Carolina University	Chapters 2 & 4	308
Permit # 3-2014	Rachel Carson National Estuarine Research Reserve	Chapters 2 & 4	309-310

East Carolina University

Animal Care and Use Commitee
212 Ed Warren Life Sciences Building
East Carolina University
Greenville, NC 27834

252-744-2436 office
252-744-2355 fax

June 17, 2013

Joseph Luczkovich, Ph.D.
Department of ICSP/Biology
Flanagan Building
East Carolina University

Dear Dr. Luczkovich:

Your Animal Use Protocol entitled, "The Masking Effects of Fish Communication by Boat Noise on Male Oyster Toadfish Communication Signals" (AUP #D292) was reviewed by this institution's Animal Care and Use Committee on 6/17/13. The following action was taken by the Committee:

"Approved as submitted"

A copy is enclosed for your laboratory files. Please be reminded that all animal procedures must be conducted as described in the approved Animal Use Protocol. Modifications of these procedures cannot be performed without prior approval of the ACUC. The Animal Welfare Act and Public Health Service Guidelines require the ACUC to suspend activities not in accordance with approved procedures and report such activities to the responsible University Official (Vice Chancellor for Health Sciences or Vice Chancellor for Academic Affairs) and appropriate federal Agencies.

Sincerely yours,

SBMcRae

Susan McRae, Ph.D.
Chair, Animal Care and Use Committee

SM/jd

enclosure

East Carolina University.

Animal Care and Use Commitee
212 Ed Warren Life Sciences Building
East Carolina University
Greenville, NC 27834
252-744-2436 office
252-744-2355 fax

March 18, 2014

Joseph Luczkovich, Ph.D.
Department of Biology
Howell Science Complex
East Carolina University

Dear Dr. Luczkovich:

Your Animal Use Protocol entitled, "The Impact of Vessel Noise on the Benthic Invertebrate Community and Oyster Toadfish Diet, Condition, and Reproduction" (AUP #D307) was reviewed by this institution's Animal Care and Use Committee on 3/18/14. The following action was taken by the Committee:

"Approved as submitted"

A copy is enclosed for your laboratory files. Please be reminded that all animal procedures must be conducted as described in the approved Animal Use Protocol. Modifications of these procedures cannot be performed without prior approval of the ACUC. The Animal Welfare Act and Public Health Service Guidelines require the ACUC to suspend activities not in accordance with approved procedures and report such activities to the responsible University Official (Vice Chancellor for Health Sciences or Vice Chancellor for Academic Affairs) and appropriate federal Agencies. **Please ensure that all personnel associated with this protocol have access to this approved copy of the AUP and are familiar with its contents.**

Sincerely yours,

S McRae

Susan McRae, Ph.D.
Chair, Animal Care and Use Committee

SM/jd

Enclosure

Print Form

Research Permit

N.C. National Estuarine Research Reserve
Dr. John Fear
101 Pivers Island Road
Beaufort, N.C., 28516
Phone: 252-838-0884
Fax: 252-838-0890
www.nccoastalreserve.net
John.Fear@ncmail.net

Date:	2/18/2014
Principal Investigator Name and Title:	Cecilia S. Krahforst, Ph.D. Student
Address:	250 Flanagan Suite, East Carolina Uni.
City and State:	Greenville, NC
Zip Code:	27858
Phone:	(252)917-7210
Fax:	
Email:	krahforstc06@students.ecu.edu

Permit #: 3-2014
(To be filled in by NCNERR)

Designated contact person and address (if different from above):

If student, give major advisor, school, and degree sought:
Dr. Joseph J. Luczkovich, East Carolina University, Degree Sought: Ph.D. in Coastal Resources Management

Usual number of participants in field work in Reserve:	2-3
Project Title:	**Boat noise impacts on oyster toadfish**
Funding Source(s):	**ICSP/CRM and NSF DIGs (pending)**
Funded Amount/Year:	**$13,500**
Project Duration:	**3 years**

Work Description (Please fill out A-D or attach a concise 1-2 page project summary):

A: Abstract

B: Sampling Locations (list both Reserve and non-Reserve sampling locations)

C: Project Objectives

D: Methods (include sampling devices/methods, frequency, assays, etc...)

Applicant Signature*		Date:	2/18/2014
NC NERR Research Coordinator Approval	Heath Wel	Date:	2/18/2014

Permit Expiration Date**	12/31/2016

** maximum duration = 3 years, permits may be renewed

* Submittal of this application indicates that the applicant will abide by the permit conditions and will keep Reserve staff appraised of major permit deviations. Please mail or email this application to Dr. John Fear at the address above.

NC COASTAL RESERVE & NATIONAL ESTUARINE RESEARCH RESERVE

APPENDIX B: SOUND PRESSURE LEVEL CURVES FROM VESSEL NOISE PLAYBACKS ONLY OBTAINED FROM FIELD MEASUREMENTS

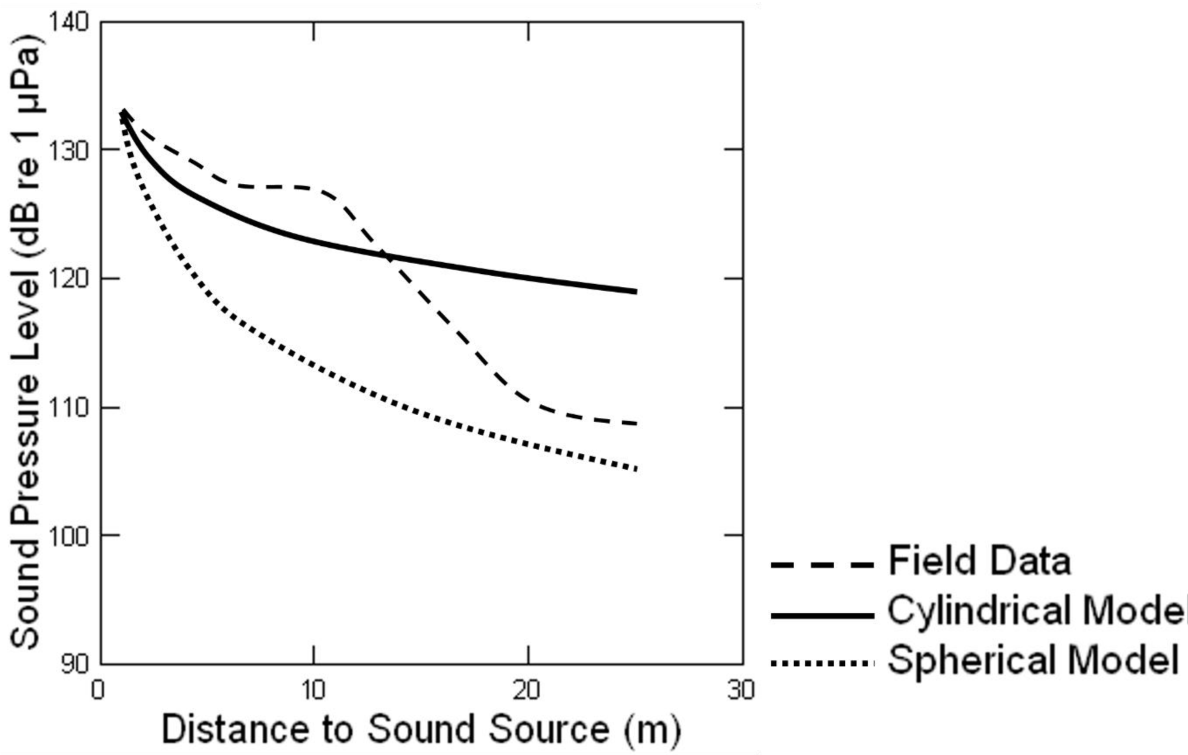

Figure B.1. Acoustic propagation measurements in the field and the cylindrical and spherical spreading models of expected transmission loss within all of the sites and bottom types for vessel noises.

Acoustic propagation measurement (SPL) values for both SAV and sand combined collected in the field (Field Data) made using two InterOcean 902 hydrophone and calibrated listening systems (with a dB VU meter) from playback experiments through an underwater speaker (Clark Synthesis AQ 339) of inboard and outboard motorboat sounds. One hydrophone was placed 1 m from the speaker and the second hydrophone was moved backward from the speaker. For comparison, the expected transmission losses of the same amplitude sound are represented by both the cylindrical and spherical spreading models.

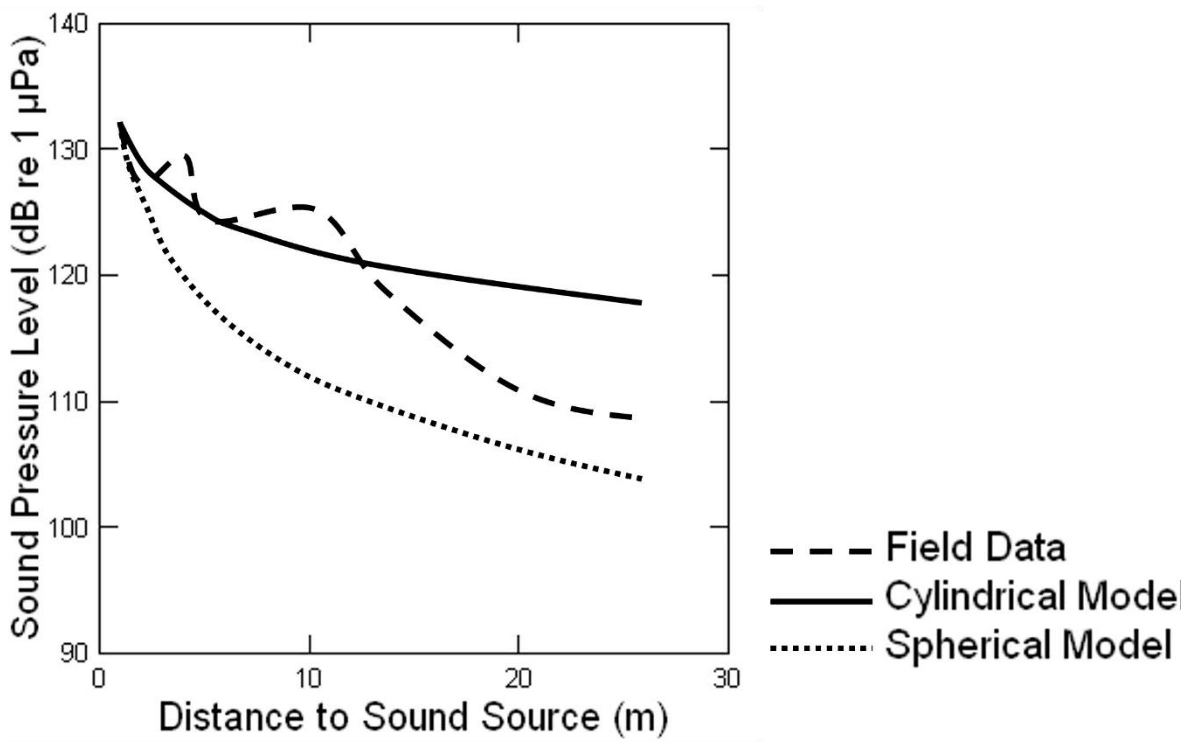

Figure B.2. Acoustic propagation measurements in the field and the cylindrical and spherical spreading models of expected transmission loss within all of the sites but only in sand for vessel noises.

Acoustic propagation measurement (SPL) values for sand collected in the field (Field Data) made using two InterOcean 902 hydrophone and calibrated listening systems (with a dB VU meter) from playback experiments through an underwater speaker (Clark Synthesis AQ 339) of inboard and outboard motorboat sounds. One hydrophone was placed 1 m from the speaker and the second hydrophone was moved backward from the speaker. For comparison, the expected transmission losses of the same amplitude sound are represented by both the cylindrical and spherical spreading models.

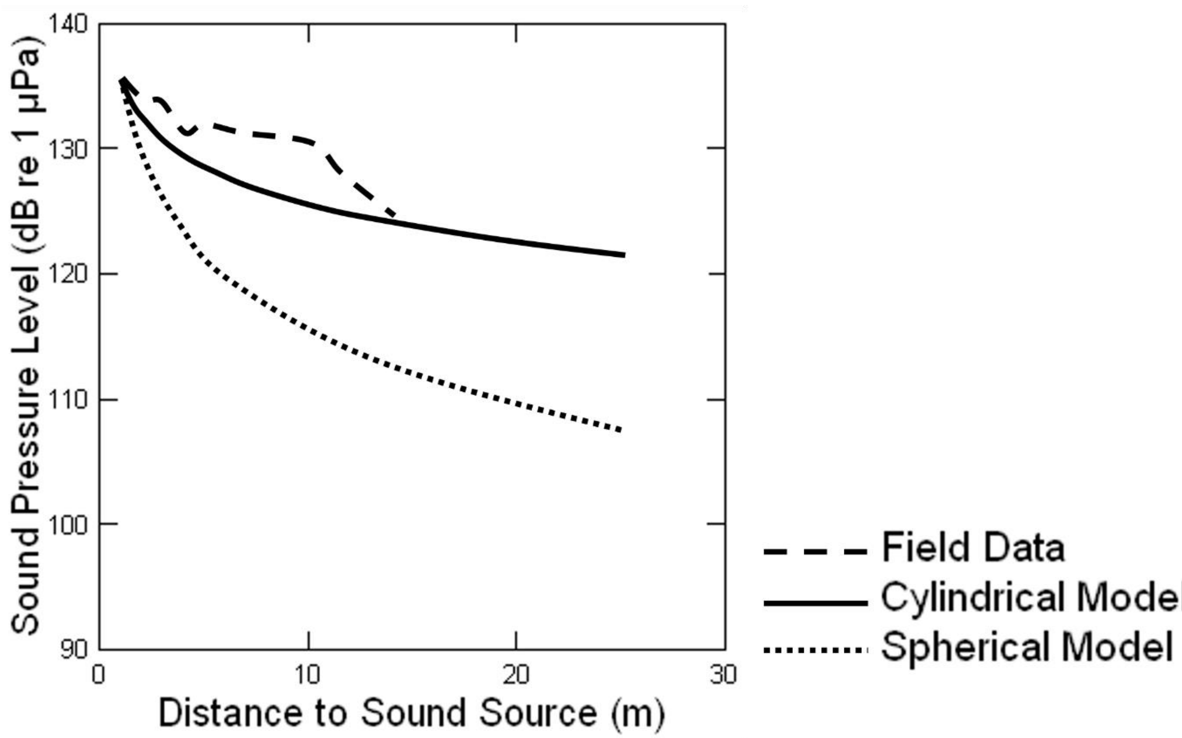

Figure B.3. Acoustic propagation measurements in the field and the cylindrical and spherical spreading models of expected transmission loss within all of the sites but only in SAV for vessel noises.

Acoustic propagation measurement (SPL) values for SAV collected in the field (Field Data) made using two InterOcean 902 hydrophone and calibrated listening systems (with a dB VU meter) from playback experiments through an underwater speaker (Clark Synthesis AQ 339) of inboard and outboard motorboat sounds. One hydrophone was placed 1 m from the speaker and the second hydrophone was moved backward from the speaker. For comparison, the expected transmission losses of the same amplitude sound are represented by both the cylindrical and spherical spreading models.

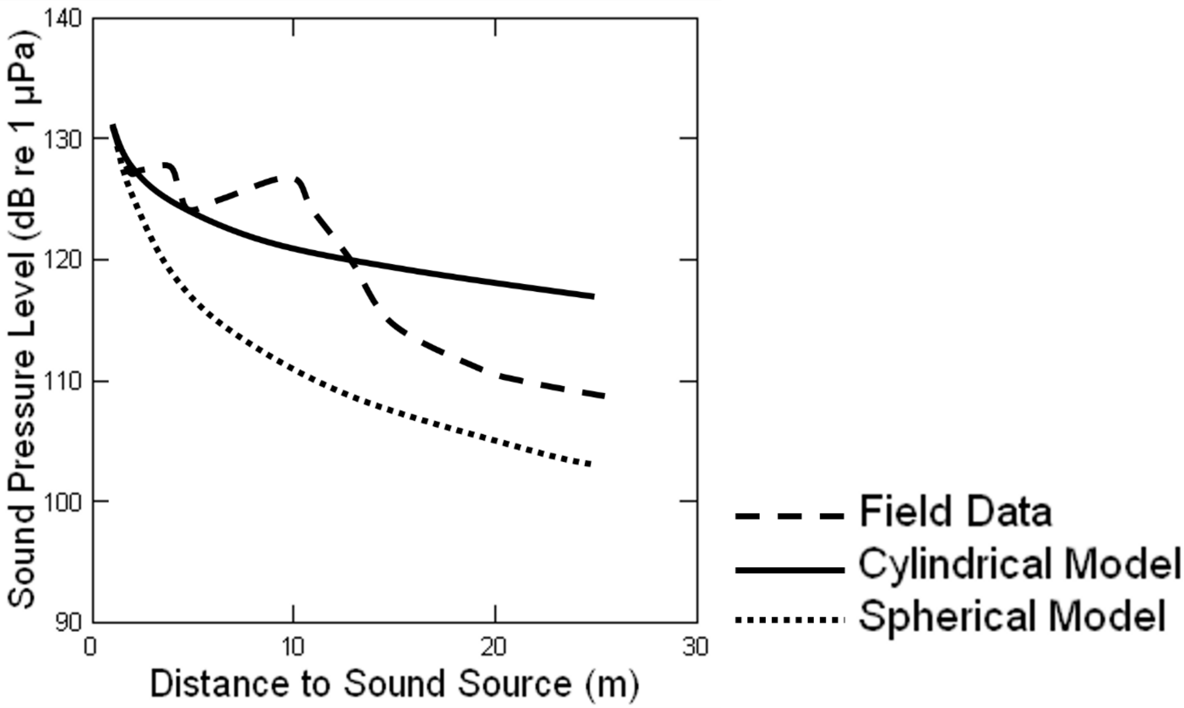

Figure B.4. Acoustic propagation measurements in the field and the cylindrical and spherical spreading models of expected transmission loss within JBS and all bottom types for vessel noises.

Acoustic propagation measurement (SPL) values at JBS for both SAV and sand combined collected in the field (Field Data) made using two InterOcean 902 hydrophone and calibrated listening systems (with a dB VU meter) from playback experiments through an underwater speaker (Clark Synthesis AQ 339) of inboard and outboard motorboat sounds. One hydrophone was placed 1 m from the speaker and the second hydrophone was moved backward from the speaker. For comparison, the expected transmission losses of the same amplitude sound are represented by both the cylindrical and spherical spreading models.

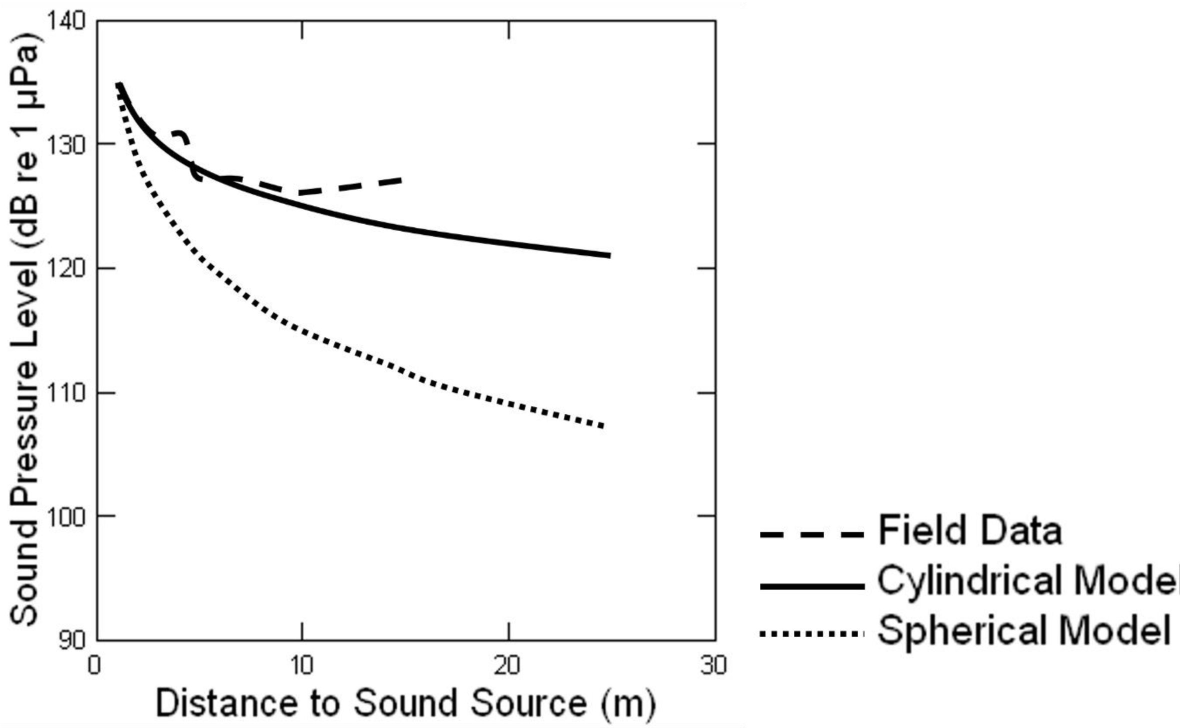

Figure B.5. Acoustic propagation measurements in the field and the cylindrical and spherical spreading models of expected transmission loss within NPR and all bottom types for vessel noises.

Acoustic propagation measurement (SPL) values at NPR for both SAV and sand combined collected in the field (Field Data) made using two InterOcean 902 hydrophone and calibrated listening systems (with a dB VU meter) from playback experiments through an underwater speaker (Clark Synthesis AQ 339) of inboard and outboard motorboat sounds. One hydrophone was placed 1 m from the speaker and the second hydrophone was moved backward from the speaker. For comparison, the expected transmission losses of the same amplitude sound are represented by both the cylindrical and spherical spreading models.

APPENDIX C: SOUND PRESSURE LEVEL CURVES FROM ALL EXPERIMENTAL PLAYBACK SOUNDS OBTAINED FROM FIELD MEASUREMENTS

Lists of playback sounds for the sound propagation loss data collected within the sites. For this section, all of the sounds are combined in the propagation curves.

Pure Tones
100 Hz
150 Hz
200 Hz
250 Hz
300 Hz
400 Hz
500 Hz
600 Hz
700 Hz
800 Hz
900 Hz
1000 Hz

Other Sound
Low Frequency Dolphin
Inboard
High Frequency Dolphin
Snapping Shrimp
Oyster toadfish Boatwhistle
Oyster toadfish Grunt
White Noise

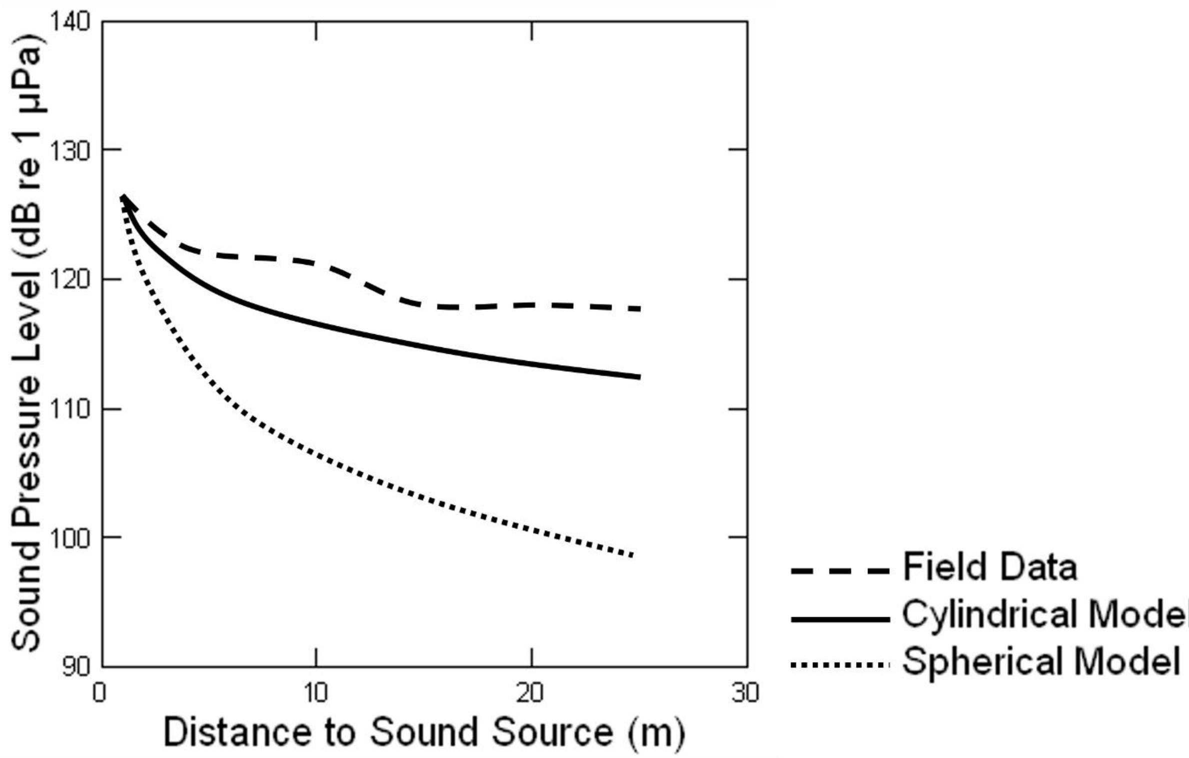

Figure C.1. Acoustic propagation measurements in the field and the cylindrical and spherical spreading models of expected transmission loss within all of the sites and across all bottom types for all of the playback sounds.

Acoustic propagation measurement (SPL) values at all of the sites for both SAV and sand combined collected in the field (Field Data) made using two InterOcean 902 hydrophone and calibrated listening systems (with a dB VU meter) from playback experiments through an underwater speaker (Clark Synthesis AQ 339). A total of twenty sounds were played back for this experiment. One hydrophone was placed 1 m from the speaker and the second hydrophone was moved backward from the speaker. For comparison, the expected transmission losses of the same amplitude sound are represented by both the cylindrical and spherical spreading models.

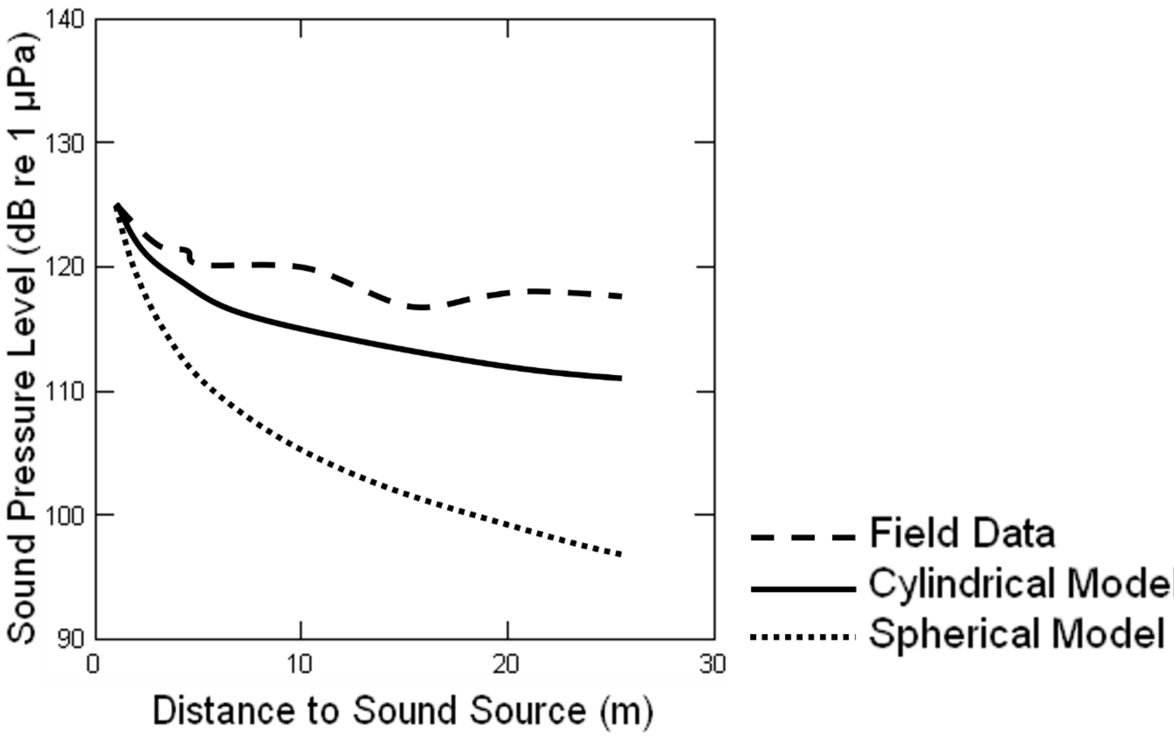

Figure C.2. Acoustic propagation measurements in the field and the cylindrical and spherical spreading models of expected transmission loss within all of the sites and over sandy bottoms only for all of the playback sounds.

Acoustic propagation measurement (SPL) values at all of the sites in sand only collected in the field (Field Data) made using two InterOcean 902 hydrophone and calibrated listening systems (with a dB VU meter) from playback experiments through an underwater speaker (Clark Synthesis AQ 339). A total of twenty sounds were played back for this experiment. One hydrophone was placed 1 m from the speaker and the second hydrophone was moved backward from the speaker. For comparison, the expected transmission losses of the same amplitude sound are represented by both the cylindrical and spherical spreading models.

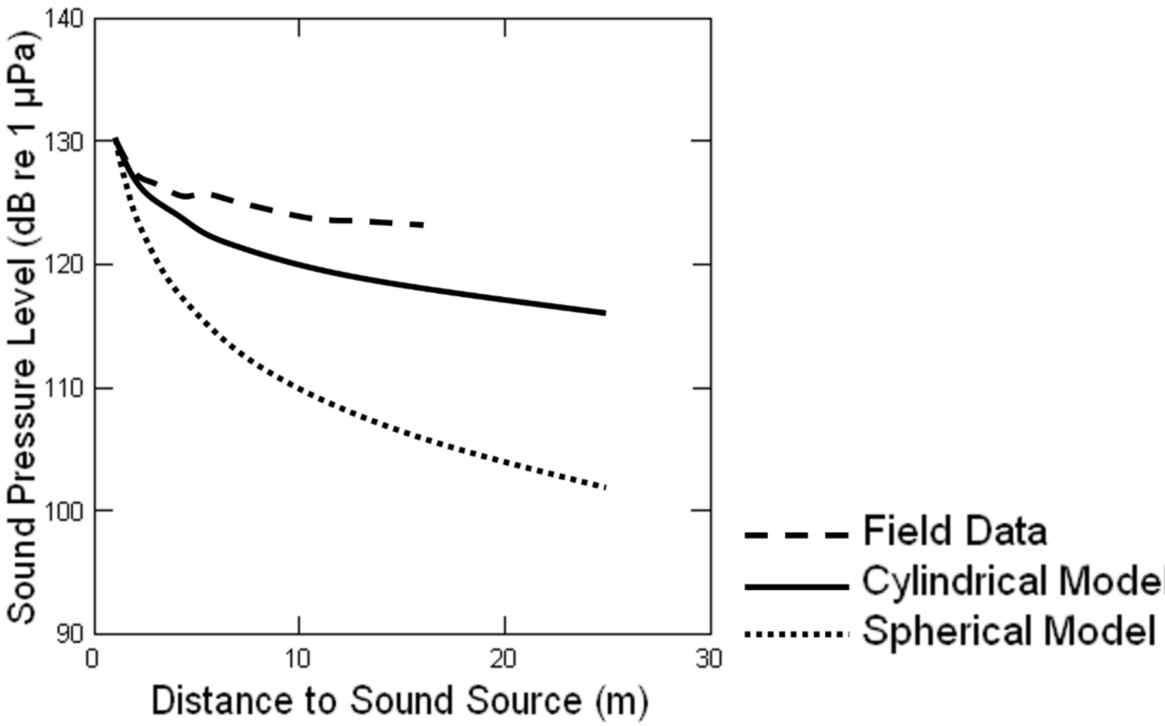

Figure C.3. Acoustic propagation measurements in the field and the cylindrical and spherical spreading models of expected transmission loss within all of the sites and over SAV bottoms only for all of the playback sounds.

Acoustic propagation measurement (SPL) values at all of the sites in SAV only collected in the field (Field Data) made using two InterOcean 902 hydrophone and calibrated listening systems (with a dB VU meter) from playback experiments through an underwater speaker (Clark Synthesis AQ 339). A total of twenty sounds were played back for this experiment. One hydrophone was placed 1 m from the speaker and the second hydrophone was moved backward from the speaker. For comparison, the expected transmission losses of the same amplitude sound are represented by both the cylindrical and spherical spreading models.

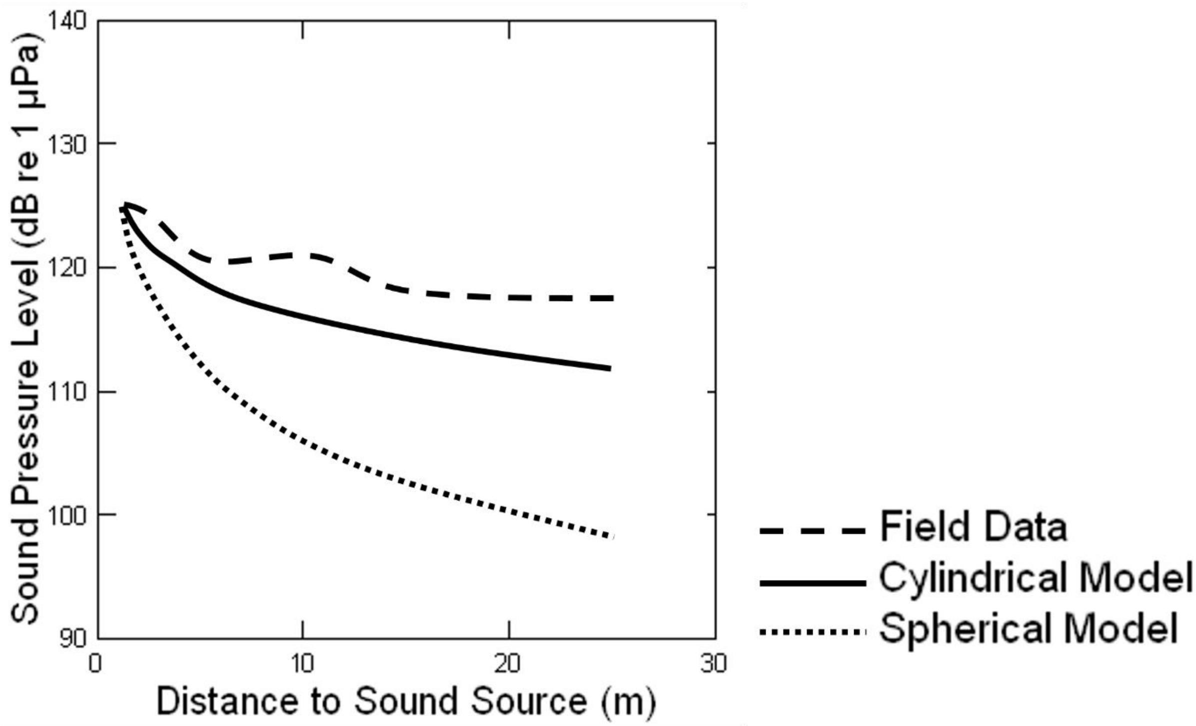

Figure C.4. Acoustic propagation measurements in the field and the cylindrical and spherical spreading models of expected transmission loss within JBS only and across all bottom types for all of the playback sounds.

Acoustic propagation measurement (SPL) values at JBS for both SAV and sand combined collected in the field (Field Data) made using two InterOcean 902 hydrophone and calibrated listening systems (with a dB VU meter) from playback experiments through an underwater speaker (Clark Synthesis AQ 339). A total of twenty sounds were played back for this experiment. One hydrophone was placed 1 m from the speaker and the second hydrophone was moved backward from the speaker. For comparison, the expected transmission losses of the same amplitude sound are represented by both the cylindrical and spherical spreading models.

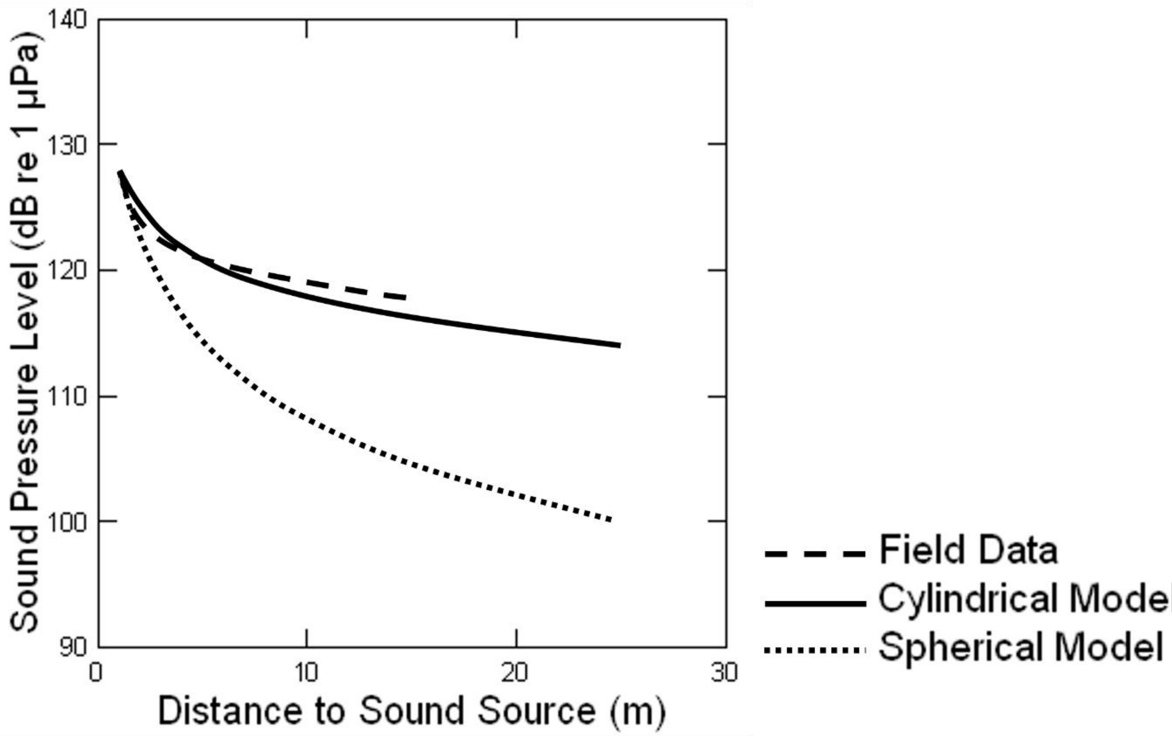

Figure C.5. Acoustic propagation measurements in the field and the cylindrical and spherical spreading models of expected transmission loss within NPR only and across all bottom types for all of the playback sounds.

Acoustic propagation measurement (SPL) values at NPR for both SAV and sand combined collected in the field (Field Data) made using two InterOcean 902 hydrophone and calibrated listening systems (with a dB VU meter) from playback experiments through an underwater speaker (Clark Synthesis AQ 339). A total of twenty sounds were played back for this experiment. One hydrophone was placed 1 m from the speaker and the second hydrophone was moved backward from the speaker. For comparison, the expected transmission losses of the same amplitude sound are represented by both the cylindrical and spherical spreading models.

APPENDIX D: POWER SPECTRAL DENSITY CURVES FROM THE PLAYBACK EXPERIMENTS

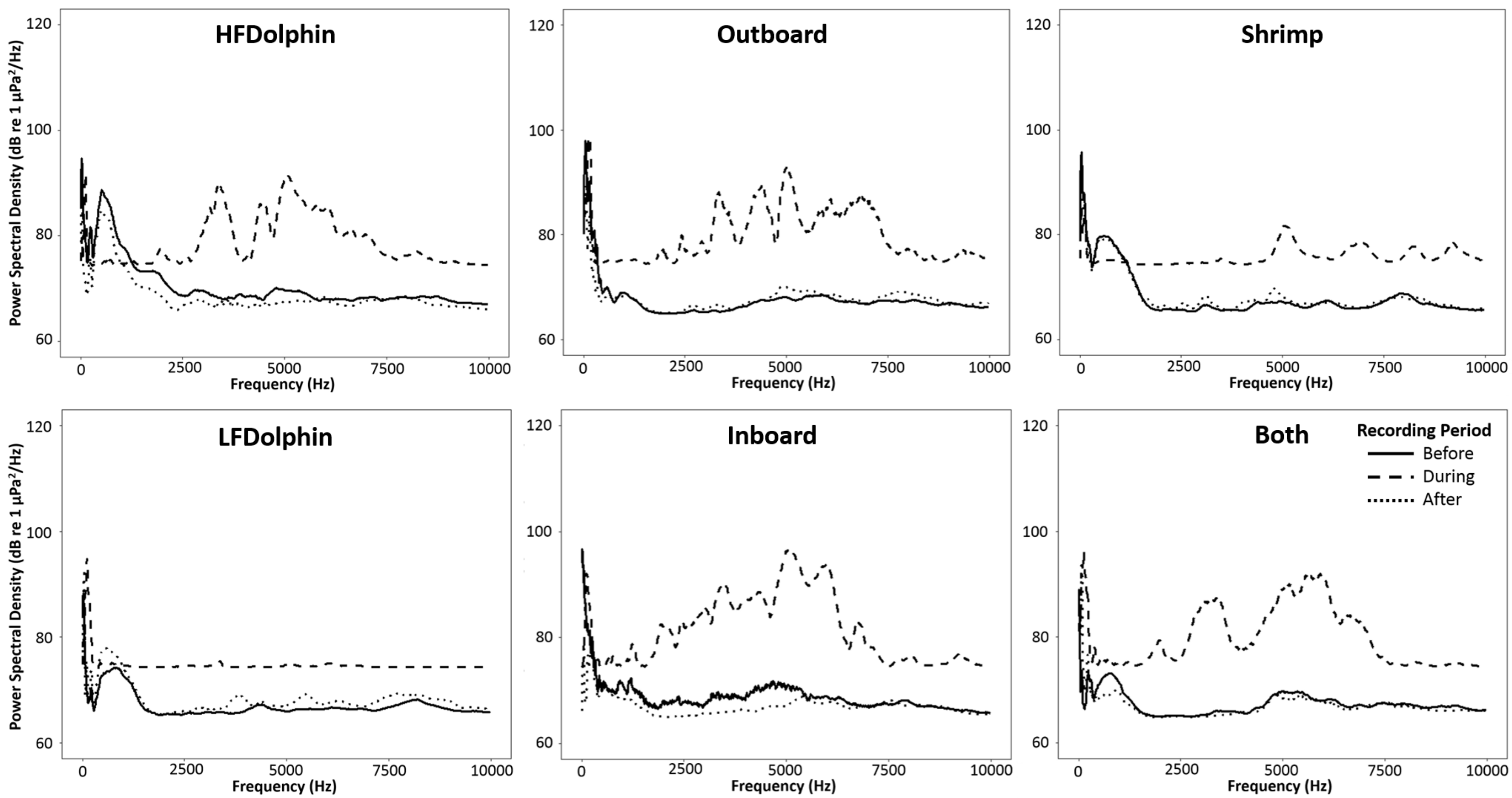

Figure D.1. Power spectral density curves before, during, and after a playback experiment for JBS in sand.

Power spectral densities at 2 m from the speaker during the JBS experiment over sand. Each of the power spectra are based on the estimates of power spectral densities (using Welch's method).

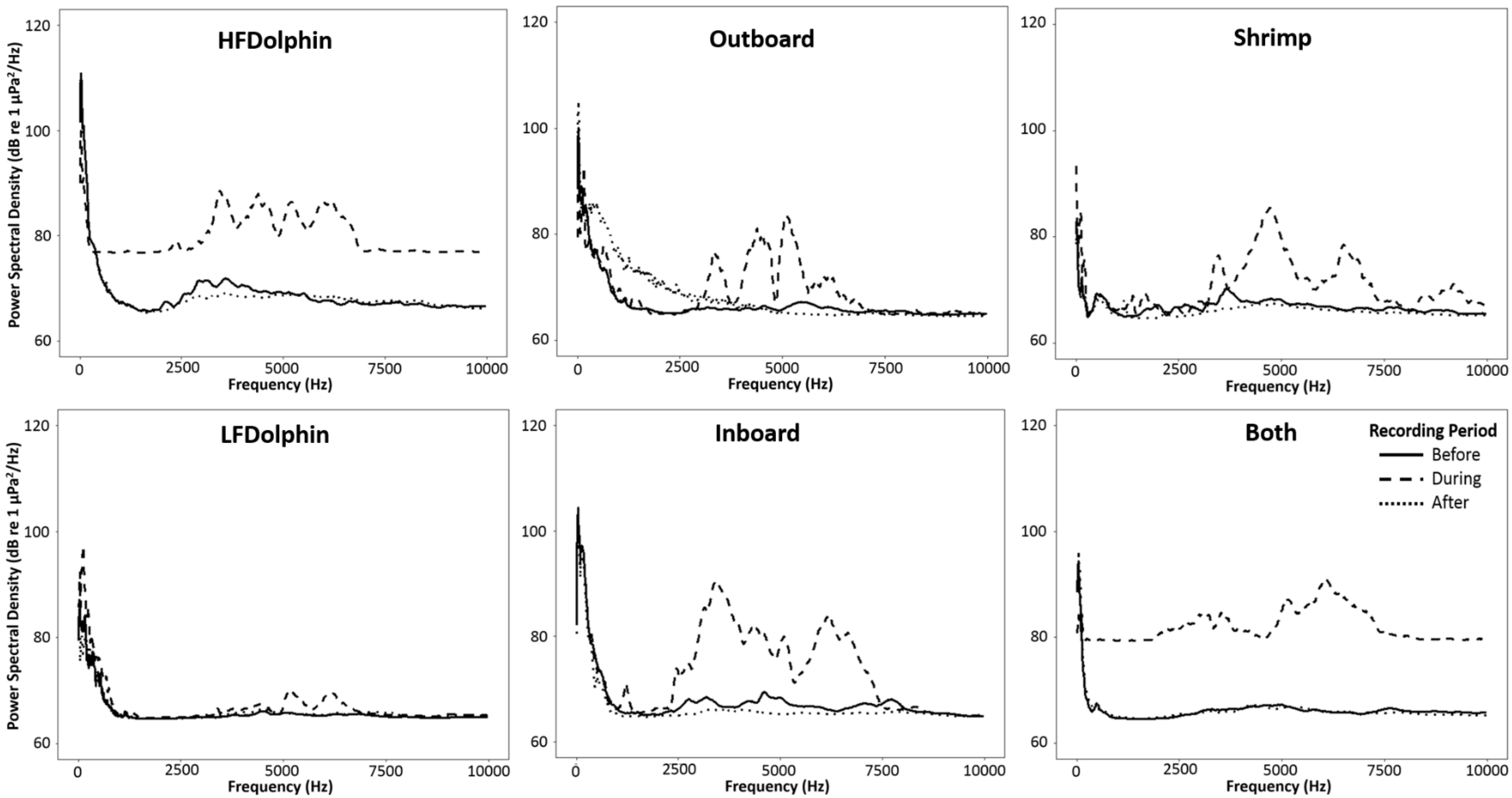

Figure D.2. Power spectral density curves before, during, and after a playback experiment for JBS in SAV.

Power spectral densities at 2 m from the speaker during the JBS experiment over SAV. Each of the power spectra are based on the estimates of power spectral densities (using Welch's method).

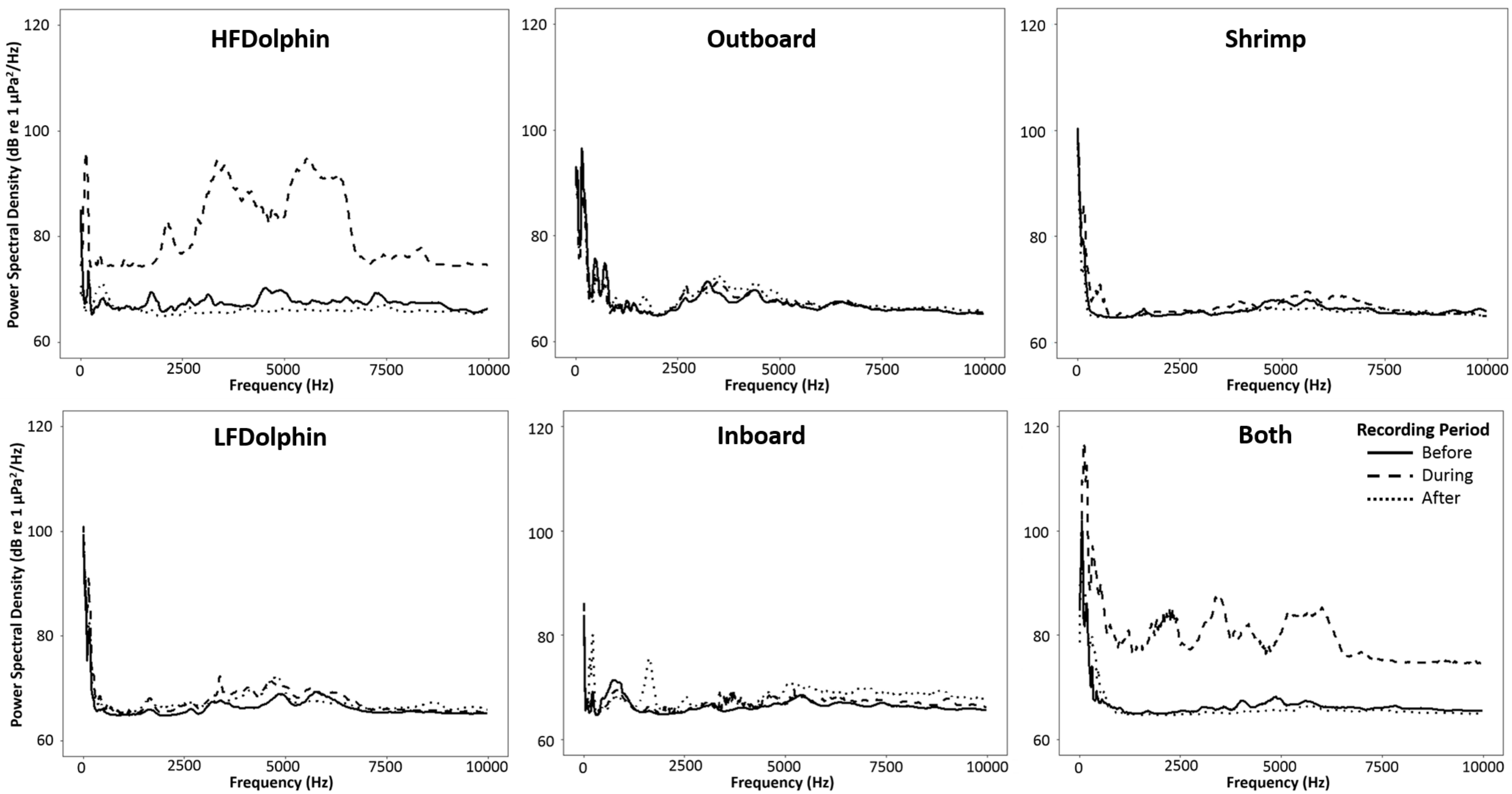

Figure D.3. Power spectral density curves before, during, and after a playback experiment for NPR in sand.

Power spectral densities at 2 m from the speaker during the NPR experiment over sand. Each of the power spectra are based on the estimates of power spectral densities (using Welch's method).

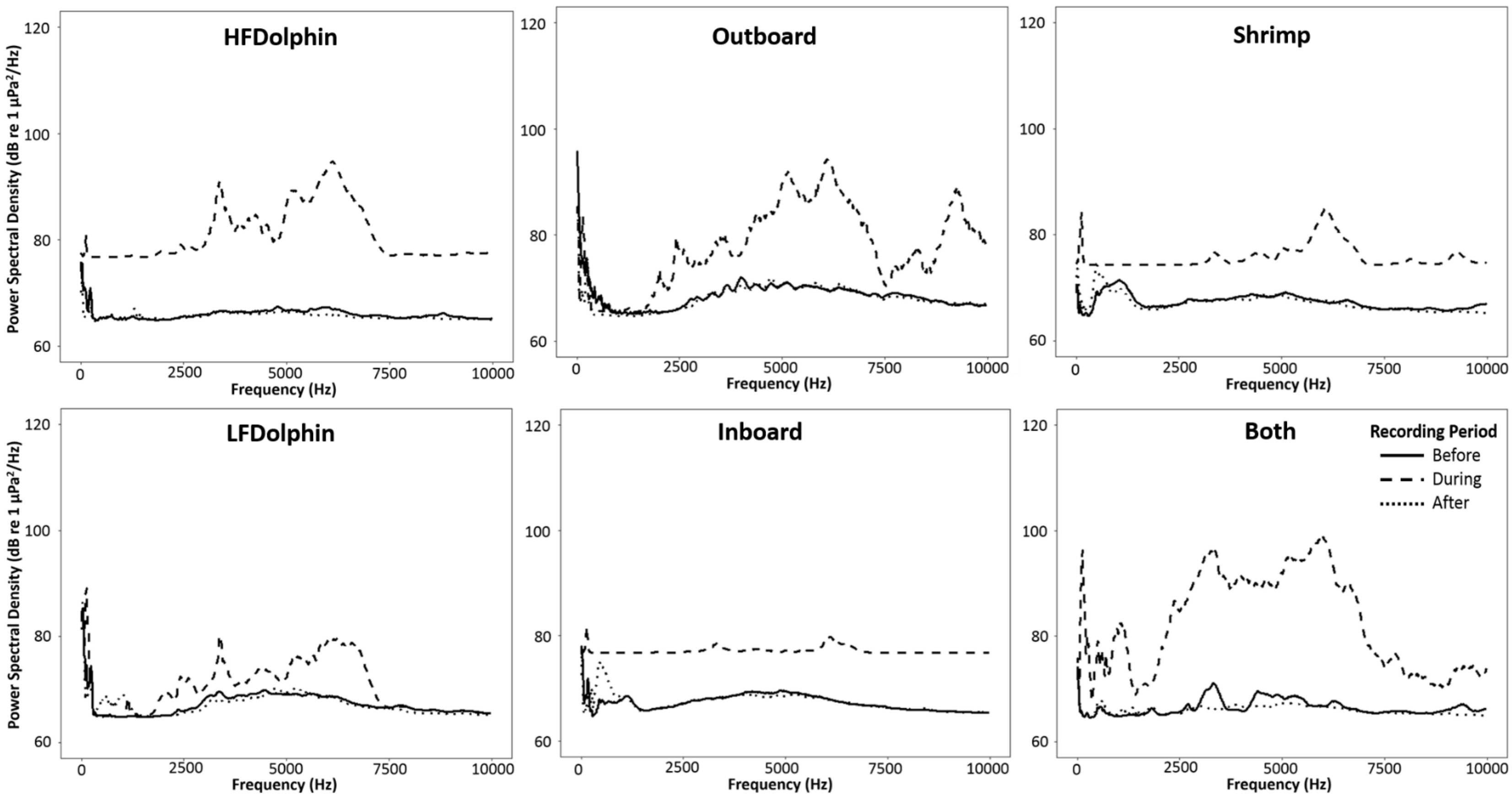

Figure D.4. Power spectral density curves before, during, and after a playback experiment for NPR in SAV.

Power spectral densities at 2 m from the speaker during the NPR experiment over SAV. Each of the power spectra are based on the estimates of power spectral densities (using Welch's method).

APPENDIX E: WATER QUALITY DATA AMONG SITES

Water quality measurements were made at each site during the weekly visits throughout the sampling seasons. The following parameters were collected using a YSI Pro10 handheld unit: dissolved oxygen (DO, mg/l), salinity, and temperature (^{o}C). Additionally, turbidity was measured using a secchi disk (cm) within each of the channels at the sites. Paired two-sample *t*-tests with a pooled variance and a Bonferroni adjustment were used to determine differences in the water quality parameters with the designated site noise level. There was no difference in temperature (Bonferroni Test, p = 0.73), salinity Bonferroni Test, p = 0.36), DO (Bonferroni Test, p = 0.09), and turbidity (Bonferroni Test, p = 0.53). These results indicate that the measured water quality parameters are not causing the behavioral shifts observed within the toadfish (Chapters 2-4).

Table E.1. Means ± standard error for the measured water quality variables. Sites are grouped by noise level.

Site Noise Level	Temperature (^{0}C)	Salinity	DO (mg/l)	Turbidity (cm)
Quiet	25.92 ± 4.12	31.51 ± 3.93	6.80 ± 1.64	1.07 ± 0.61
Noisy	25.77 ± 4.29	30.41 ± 4.42	7.46 ± 1.24	1.01 ± 0.27

APPENDIX F: ANOVA ANALYSIS OF NUMBER OF EMBRYOS IN OYSTER TOADFISH CLUTCHES THAT INCLUDES ALL OF THE SHELTERS WITHOUT ANY CLUTCHES PRESENT

To explore differences in the number of embryos all shelters were considered in this analysis. This includes all of the observations that lacked embryos. All oyster toadfish shelters were used in an analysis of variance (ANOVA) model to determine differences in the number of embryos within an egg clutch by site, shelter position relative to the navigation channel, by month of collection, and seagrass presence or absence. An ANOVA model was run with the number of embryos as the dependent variable. Within the model channel position (near vs. far), site noise level ("noisy" vs. "quiet"), seagrass (presence vs. absence), and month of collection where the independent variables. Finally, total vessel counts (combined number of inboard and outboard motorboats) and total toadfish counts were included in the ANOVA model as covariates. Next, hypothesis tests of the effects of the model including the individual effects and the combined effects were examined to determine which factors influenced the number of embryos on the oyster toadfish shelters. Significance levels were assessed at a $p < 0.05$.

These embryo data are zero-inflated. Of the 480 total observations (15 weeks * 4 blocks * 2 treatments * 4 shelters) at each site, embryos were only identified 19 times (1.0% of the observations) throughout the sampling season. The overall ANOVA model was marginally significant ($F_{42,2044} = 1.40$, $p = 0.046$) and explained a total of 2.4% of the variability within the data set. Unfortunately, no individual variable was driving this observed difference. All of the individual and grouped hypothesis tests had $p > 0.05$ values.

There is little interpretation that can be assessed with these results. Ultimately, I can only conclude that the sample size is not large enough to demonstrate the factor(s) that are driving these observed differences. Part of the reason for this is that a shelter is kept in the analysis regardless of if a toadfish is present or not. The toadfish did demonstrate preferences for sites based on certain characteristics and these are addressed in Chapter 4. So, the ultimate issue with this data set is that we are trying to both understand embryo distribution as well as toadfish distribution and this is all too variable for the analysis to show interpretable results. In Chapter 4, I present several analysis that deal with all of the concepts. First, I explore the variability to toadfish among sites and shelters. Then, I explore the variability among clutches (presence or absence). Finally, I focus only on the clutches that have embryos. By doing this stepwise analysis, I can explain some of the variability within each step and this information helps inform the next step of the analysis process. The analysis presented above, that includes all of the zeros, cannot possibly take into account all of the variability within the data set. To demonstrate, the model presented with all of the zeros here in the appendix explains only 2.4% of the variability within the data set. However, my analysis in Chapter 4 on just the clutches with embryos (excluding the zeros) explains 82.6% of the variance in the data set. Therefore, I am more inclined to trust the Chapter 4 analysis over the analysis presented in this appendix.

APPENDIX G: POWER SPECTRAL DENSITY CURVES FROM THE PLAYBACKS OVER THE HEARING RANGE OF THE OYSTER TOADFISH

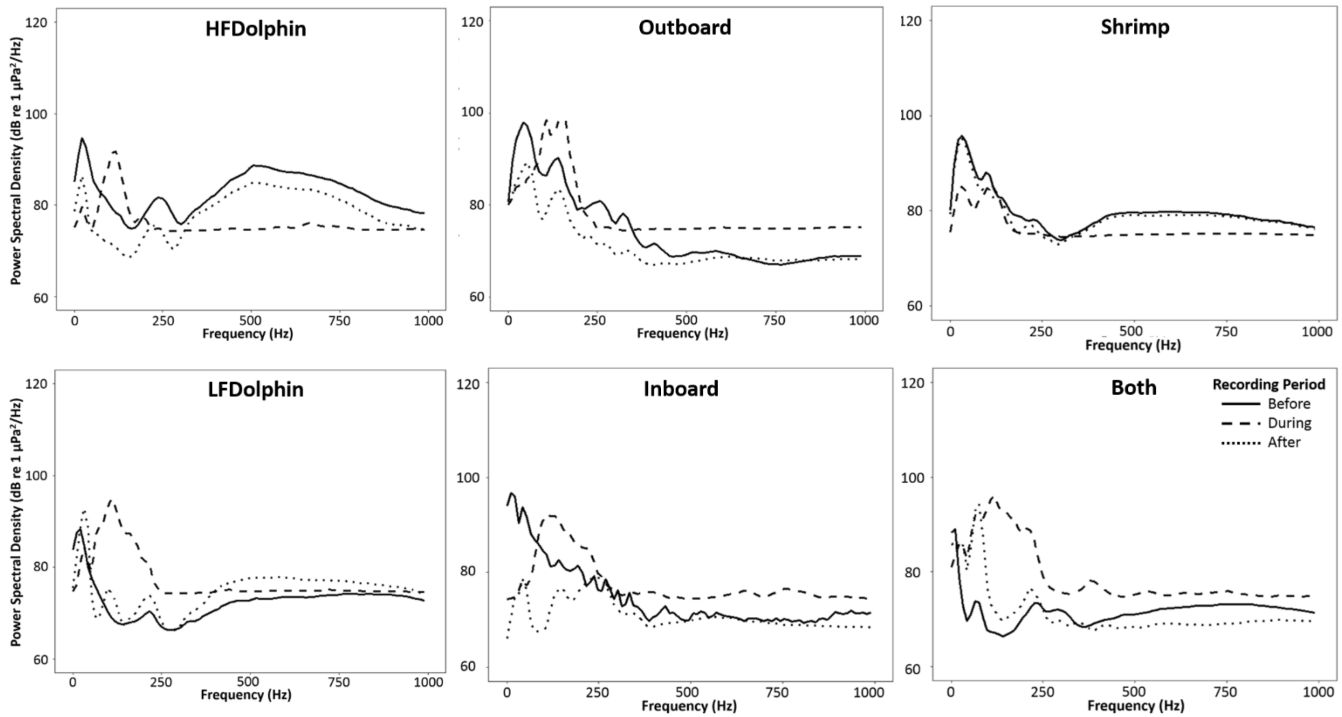

Figure G.1. Power spectral density curves within the hearing range of the oyster toadfish during a playback experiment for JBS in sand.

Power spectral densities in the hearing range of the oyster toadfish (50 to 1000 Hz) at 2 m from the speaker during one playback experiment at JBS in sand. Each of the power spectra are based on the estimates of power spectral densities (using Welch's method).

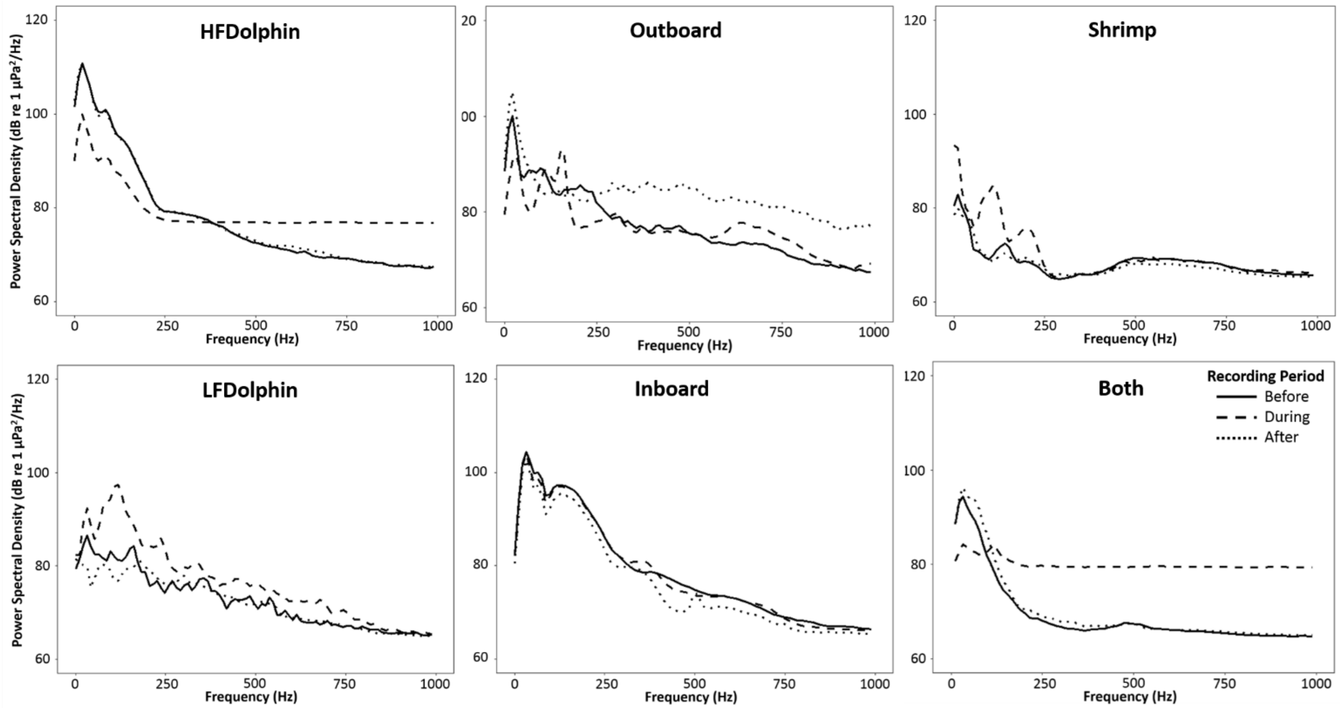

Figure G.2. Power spectral density curves within the hearing range of the oyster toadfish during a playback experiment for JBS in SAV.

Power spectral densities in the hearing range of the oyster toadfish (50 to 1000 Hz) at 2 m from the speaker during one playback experiment at JBS in SAV. Each of the power spectra are based on the estimates of power spectral densities (using Welch's method).

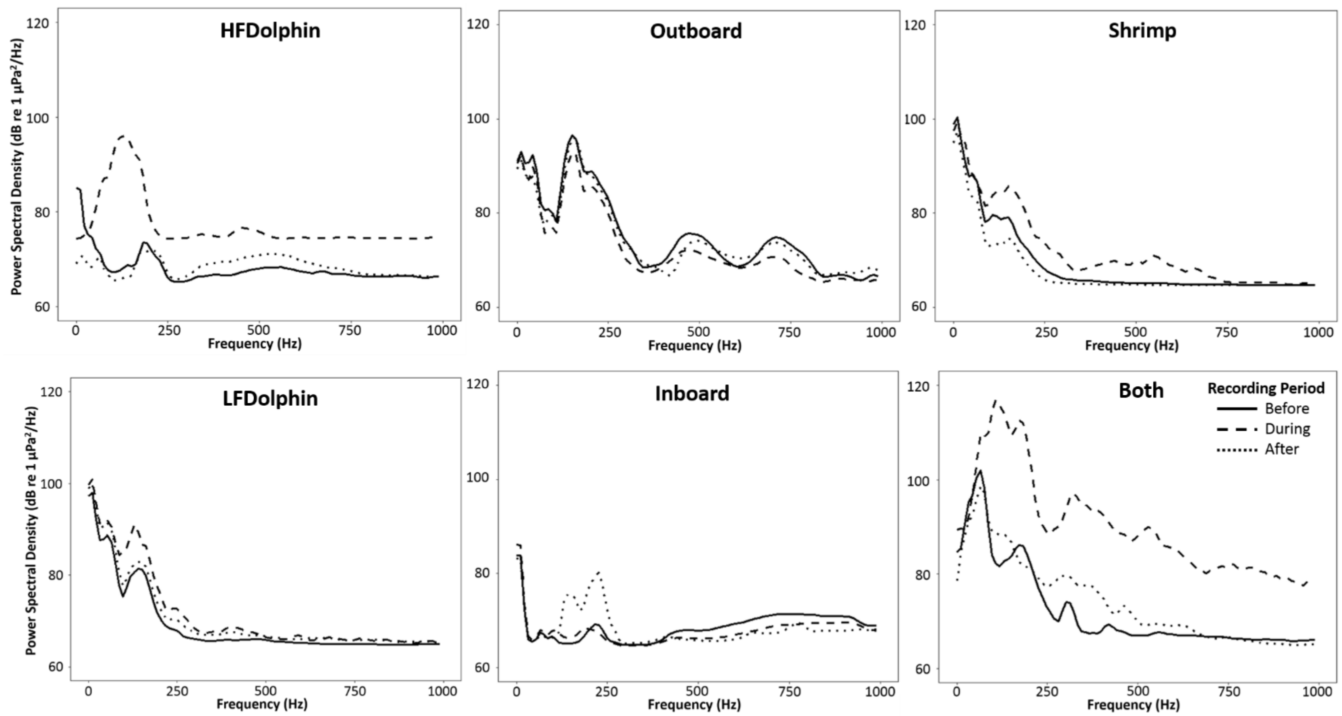

Figure G.3. Power spectral density curves within the hearing range of the oyster toadfish during a playback experiment for NPR in sand.

Power spectral densities in the hearing range of the oyster toadfish (50 to 1000 Hz) at 2 m from the speaker during one playback experiment at NPR in sand. Each of the power spectra are based on the estimates of power spectral densities (using Welch's method).

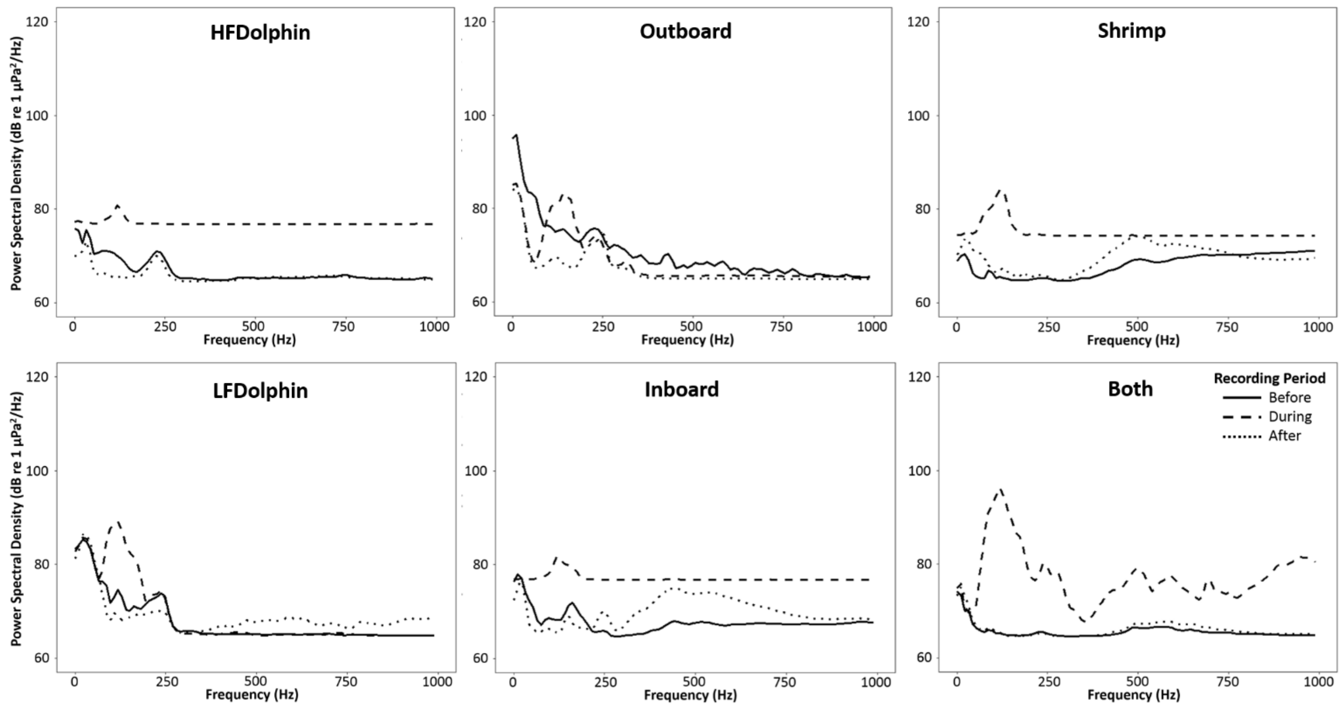

Figure G.4. Power spectral density curves within the hearing range of the oyster toadfish during a playback experiment for NPR in SAV.

Power spectral densities in the hearing range of the oyster toadfish (50 to 1000 Hz) at 2 m from the speaker during one playback experiment at NPR in SAV. Each of the power spectra are based on the estimates of power spectral densities (using Welch's method).

APPENDIX H: OYSTER TOADIFSH RECAPTURE RATES AMONG THE SITES

After each of the oyster toadfish were measured, each fish was marked with a small cut in the caudal fin. This mark provided me with the ability to calculate recapture rates of the oyster toadfish within a site throughout the summer. Each time fish were collected and measured, they were examined for this caudal fin cut. If present, the fish was marked as a recapture. If the cut was not present, the fish was marked as a new fish to the area. These new fish were also marked before being returned to the field. Recapture rates were calculated using the following equation:

$$R_{RT} = \frac{T_F - M_F}{M_T}, \tag{G.1}$$

where R_{RT} denotes recapture rate, T_F is the total number of oyster toadfish captured during the sample day, M_F is the number of marked fish collected during the sample day, and M_T is the total number of marked oyster toadfish released at the site throughout the sampling season. This recapture rate was then converted into a percent by multiplying by 100. An analysis of variance (ANOVA) was used to analyze the recapture rate of oyster toadfish. In this analysis, recapture rate was the dependent variable, independent variables were month of collection, channel position (near vs. far), and site. Finally, the total number of toadfish collected during that sampling period was used as a covariate in the ANOVA analysis. The site variable was composed of four sites: South Middle Marsh (SMM), North Middle Marsh (NMM), Newport River (NPR), and Jarrett Bay Site (JBS), where JBS and SMM are considered “quiet” sites and NMM and NPR are considered “noisy” sites.

Throughout this study, a total of 1,177 oyster toadfish were collected, with an average recapture rate of 3% (*SE* = 0.3) during the study. The ANOVA model was significant ($F_{4,77}$ = 12.83, p < 0.001) and explained 74.5% of the total variance within the data set. Month of collection was a significant factor within the model ($F_{4,77}$ = 28.25, p < 0.001). Across all sites, oyster toadfish recapture rates were highest in July, followed by June, August, and May had the lowest recapture rates (Figure H.1). April is not included in the assessment because initial captures were made at the end of April. Site was also a significant factor within the ANOVA model ($F_{3,77}$ = 10.58, p = 0.035). Recapture rates were similar at NMM ($\bar{X}$ = 5, SE = 0.7), JBS ($\bar{X}$ = 3, SE = 0.5), and SMM ($\bar{X}$ = 3, SE = 0.4) but the highest overall recapture rate occurred at NMM (Figure H.2). The NPR site had an average recapture rate of only 0.2 (SE = 0.1). So NPR is likely strongly influencing the site results in the ANOVA analysis. Finally, the number of collected fish was the last significant factor in the model ($F_{1,77}$ = 10.64, p = 0.002). There is a positive correlation (ρ = 0.72) between the number of oyster toadfish collected and the number of fish recaptured. Recapture rates steadily increased with an increase in the number of fish (Figure H.3), with the highest recapture rates occurring when 20 or more fish were captured.

This average recapture rate (3%) is in agreement with the average recapture rates (2.5%) found by Schwartz (1974) from oyster toadfish in Maryland. However, his recapture rates vary between 0 and 5%, whereas my average recapture rates vary between 3 and 13%. These results suggest that oyster toadfish show higher site fidelity than those in Maryland. The site fidelity is likely associated with the reproductive strategy employed by male oyster toadfish, where males establish nests month (Gray and Winn, 1961; Winn, 1972), call from shelters to attract females (Gudger 1910; Gray and Winn 1961; Fish 1972; Winn 1972), and guard embryos for up to a month after a female lays eggs in his nest (Gray and Winn, 1961). In NC, the most clutches were observed in May through July (Chapter 4), when there was the highest oyster toadfish recapture rates.

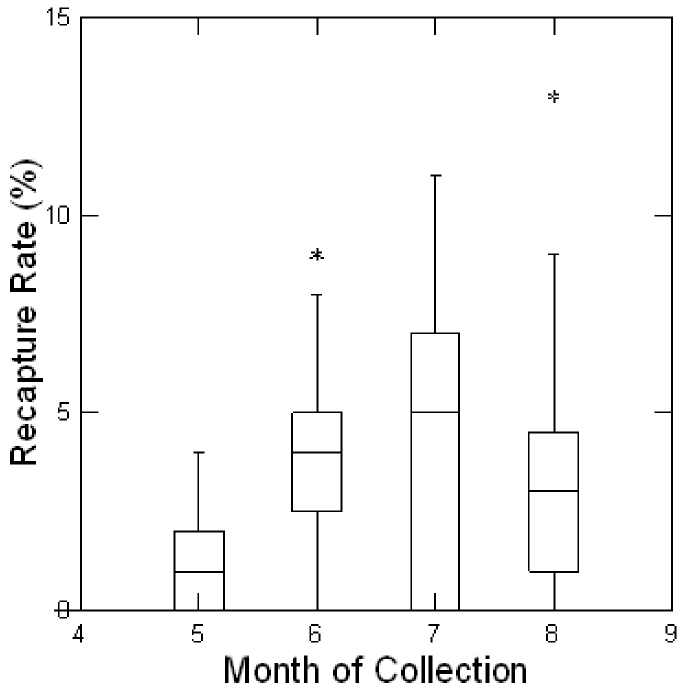

Figure H.1. Oyster toadfish recapture rates (%) by month of collection.

Median oyster toadfish recapture rates in 2014 grouped throughout the month of capture, where each month from May (5) through August (8) contains four sampling periods that occurred approximately one month apart. Boxplots show the median (50th percentile at the horizontal line) and the region which contains 50% of data around the median (25th to 75th percentiles). The vertical bars show the region in which observations fall within 1.5 x upper and lower interquartile ranges (lower: 25th to 50th percentile range; upper: 50th to 75th percentile range). Points outside of the 1.5 x the upper and lower interquartile ranges are shown as open circles.

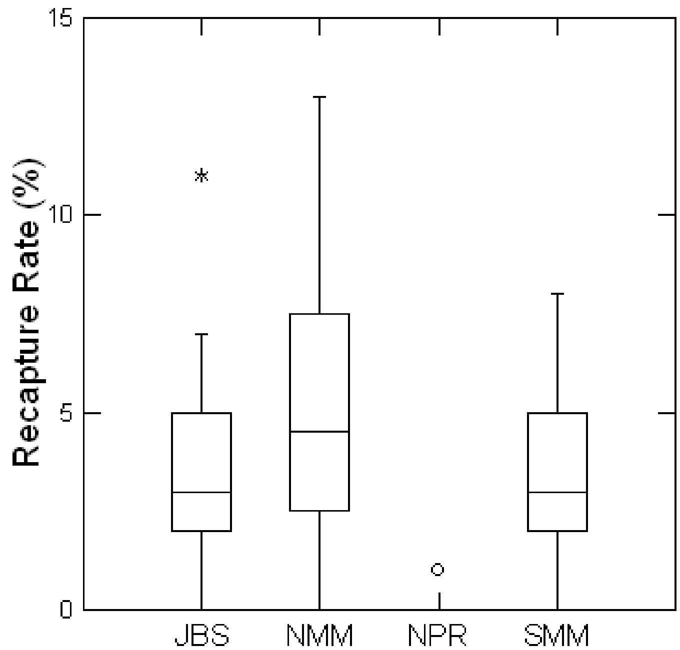

Figure H.2. Oyster toadfish recapture rates (%) by site.

Median oyster toadfish recapture rates in 2014 grouped throughout sampling season by site. The "noisy" sites are Newport River (NPR) and North Middle Marsh (NMM) and the "quiet" sites are South Middle Marsh (SMM) and Jarrett Bay Site (JBS). The boxplot explanation is in Figure H.1.

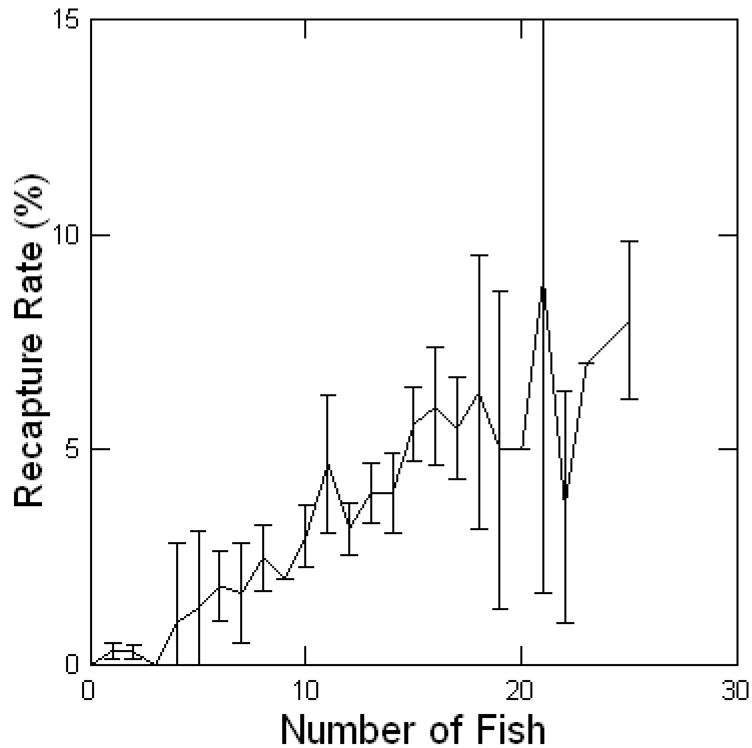

Figure H.3. Linear relationship between oyster toadfish recapture rates (%) and the total of oyster toadfish collected.

Oyster toadfish recapture rates in 2014 grouped throughout sampling season across all sites. The variation in the recapture rate is represented by the standard error bars.

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American Institute of Physics	Krahforst et al. 2016	Portions of Chapter 2	340
American Institute of Physics	Sprague et al. 2016	Data utilized in Chapters 1 & 2	340
American Institute of Physics	Krahforst et al. 2016	Figures 2.2, 2.6, 3.1, 3.2, 3.5, 3.6, & 3.7	340
American Institute of Physics	Krahforst et al. 2016	Table 3.1	340
American Institute of Physics	Luczkovich et al. 2016	Figure 2.10	340
American Institute of Physics	Sprague et al. 2016	Figures 1.5 & 2.5	340
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Type of Publication: Book

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Book ISBN: 978-0125884419
Book Author: Richarson, W. J., Greene, C. R., Malme, C. I., Thomson, D. H.
Book Year: 1995
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Table J.1. The original published proceedings of meetings on acoustics (POMA) articles that are used in this dissertation.

The original articles as they are published in POMA. Some of the information within the dissertation has been slightly modified due to the addition of data. However, the original articles are presented here without modification. These articles are reprinted with the permission of the Acoustical Society of America.

Publication Location	Source	Applicable Chapters	Page #
POMA	Krahforst et al. 2016	Chapters 2 & 3	346-361
POMA	Luczkovich et al. 2016	Chapter 2	362-376
POMA	Sprague et al. 2016	Chapters 1 & 2	377-391

The impact of vessel noise on oyster toadfish (Opsanus tau) communication

Cecilia S. Krahforst, Mark W. Sprague, and Joseph J. Luczkovich

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View online: http://dx.doi.org/10.1121/2.0000313
View Table of Contents: http://asa.scitation.org/toc/pma/27/1
Published by the Acoustical Society of America

Proceedings of Meetings on Acoustics

Volume 27 http://acousticalsociety.org/

Fourth International Conference on the Effects of Noise on Aquatic Life

Dublin, Ireland

10-16 July 2016

The impact of vessel noise on oyster toadfish (*Opsanus tau*) communication

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Male oyster toadfish (*Opsanus tau*) produce boatwhistle sounds to attract females to shelters in shallow water estuaries. Calls are produced in a natural soundscape that include snapping shrimp (*Alpheidae* sp.) and bottlenose dolphin (*Tursiops truncatus*, toadfish predators) sounds. The purpose of this study is to determine if soundscape alterations from vessels and predators cause acoustic disturbance in toadfish courtship calling behavior. Six sound types were played to toadfish in shelters positioned at 1 m from an underwater speaker: snapping shrimp sounds (Shrimp, control), low-frequency (LFDolphin) and high-frequency (HFDolphin) bottlenose dolphin biosonar, inboard (Inboard) and outboard motorboat (Outboard) noises, and a combination of vessel and predator sounds (Both). Toadfish calling rates were quantified in 600 s intervals before, during, and after noise exposure and an ANOVA was used to compare mean rates. Playback type and site (noisy vs quiet) significantly influenced toadfish calling rates ($F = 88.88$, $p \leq 0.001$). The acoustic disturbance effect was as follows: Shrimp $<$ Outboard $<$ Inboard $<$ LFDolphin $<$ HFDolphin $<$ Both. These results suggest that vessel noises and dolphin sounds are detected by male toadfish. In busy navigation channels, repetitive boat noise may reduce mating success (fewer mating opportunities) for toadfish in a natural soundscape.

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Proceedings of Meetings on Acoustics, Vol. 27, 010031 (2017)

1. INTRODUCTION

Since the 1970s, there has been concern that anthropogenic noise may be adversely affecting marine life (Richardson et al. 1995), with vessel noise as a significant contributor at frequencies below 1.5 kHz (Hildebrand 2009; Richardson et al. 1995). Vessel noise conflicts with the vocalizations of marine life in frequency and is often of higher amplitude (for review see: Götz et al. 2009; Slabbekoorn et al. 2010), resulting in noise that masks the calls of marine animals (Frisk et al. 2003; Luczkovich et al. 2016a; Luczkovich et al. 2016b)

Fishes have been shown to respond to vessel activity through displacement and avoidance behaviors. Avoidance behaviors include altering their swimming patterns, as shown in bluefin tuna (*Thunnus thynnus*, Sarà et al. 2007), cod (*Gadus morhua*, Engås et al. 1998), and herring (*Clupea harengus*, Engås et al. 1995). Additionally, reproductive and parenting activities have been interrupted by vessel activity. A slow, outboard motorboat and a paddled canoe within 5 m of the nest can cause the longear sunfish (*Lepomis megalotis*) to abandon his nest for up to 60 s, opening the nest up to predation (Mueller 1980). Red-mouthed gobies (*Gobius cruentatus*) spent more time in their shelters and damselfish (*Chromis chromis*) spent less time caring for their nests when exposed to boat noise sounds (Picciulin et al. 2010).

If an animal remains in its habitat, it may be able to compensate for the increase in ambient noise. To improve the detectability of a vocal call, animals have been shown to increase call amplitude (e.g. Luczkovich et al. 2016b; Parks et al. 2011; Holt et al. 2009), call rate (e.g. Van Parijs and Corkeron 2001; Turnbull and Terhune 1993), call duration (e.g. Foote et al. 2004), or quiet down and wait until the noise decreases (Terhune 1994; Zelick and Narins 1985). Compensation abilities for fishes seem to be limited. Most fishes that produce sound emit signals at frequencies below 1 kHz at sound pressure levels (SPLs) that rarely exceed 135 dB re 1 µPa (e.g. Locascio and Mann 2008; Luczkovich et al. 1999; Parsons et al. 2009; Sprague and Luczkovich 2004; Vasconcelos et al. 2007), but cumulative SPLs can reach higher levels (147 dB re 1 µPa) if fish are producing sound simultaneously in large aggregations (e.g. Luczkovich et al. 1999). Bottlenose dolphin (*Tursiops truncatus*) are a known predator of soniferous fishes (Barros and Wells 1998). The playbacks of their calls have led to declines in calling intensity for the silver perch (*Bairdiella chrysoura*, Luczkovich et al. 2000) and reduced calling rates in the longspine squirrelfish (*Holocentrus rufus*, Luczkovich and Keusenkothen 2008) and Gulf toadfish (*Opsanus beta*, Remage-Healey et al. 2006). Yet, there was no difference in calling behavior when the Gulf toadfish was exposed to snapping shrimp (*Alpheidae* sp.) sounds (Remage-Healey et al. 2006).

Toadfishes (Batrachoididae) are model organisms for acoustics work and are the most well-studied soniferous fishes. They are fishes with swimbladders that are far from the ear and detect sounds by both particle motion and sound pressure (Fish and Offutt 1972; McKibben and Bass 1999; Sisneros and Bass 2005). In terms of sound pressure, toadfishes hear best at frequencies under 200 Hz (Fine 1981; Fish and Offutt 1972; Vasconcelos et al. 2007) but can detect sound at frequencies up to 800 Hz. Toadfish call from shelters for long periods of time in shallow-water territories (Barimo and Fine 1998; Gray and Winn 1961; Thorson and Fine 2002a, 2002b) by rapidly contracting intrinsic sonic muscles next to their swimbladder (Skoglund 1961). When reproductively active, males settle in a nest/shelter (Gray and Winn 1961; Winn 1972) and create a tonal boatwhistle sound to attract females (Fish 1972; Gray and Winn 1961; Gudger 1910; Møhl et al. 2000). Females then attach benthic eggs to the nest and the males fan and guard the eggs and larvae for up to a month, until the larvae are free swimming (Gray and Winn 1961).

The goal of this research is to discover if oyster toadfish, exposed to boat noise, will modify their vocal behavior to overcome the masking effects of vessel noise in order to attract a mate. To test this, we used playback experiments in the natural environment to determine how different sounds affect male oyster toadfish courtship calling rates.

2. METHODS

A. PLAYBACK RECORDINGS

The sounds used for the playback experiments were created from digital recordings made in the field. Five of the six playback sound types were compiled from 10 s field recordings made using automated passive acoustic dataloggers [Long-term Acoustic Recorder System (LARS), Loggerhead Instruments, Sarasota, FL or the Fish Acoustic Buoy Underwater Logging System (FABULS), East Carolina University, Greenville, NC] between 2006 and 2013 (Table 1). The low-frequency bottlenose dolphin sounds used for the playbacks were recorded on a Sony TCD-D8 analog cassette recorder and HTI 96 min hydrophone in Southern Lagoon, Turneffe Atoll, Belize (17.18760° N, 87.88763° W) in June 2005. These seven digital recordings were compiled in a random order to create a single composite recording, with each file utilized eight or nine times (two files were used eight times) to create a 600 s long recording. In all of the playbacks, sounds of oyster toadfish courtship calls were avoided or removed from these recordings, but other sounds like snapping shrimp, water noises, and some other prominent fish sounds that co-occurred with the desired playback sounds were not removed. These are natural background sounds that influenced the frequency components within the playback signals.

Table 1: Specifics on what was used to compile each playback for the experiments. Recordings were made on a LARS and FABULS at Back Sound, a LARS for the Neuse and Pamlico Rivers, and a Sony TCD-D8 analog cassette recorder and HTI 96 min hydrophone in Belize.

Playback Type	Recording Dates	Digital Sampling Rate (Hz)	Recording Location
LFDolphin	03 Jun 2005	44,100	Turneff Atoll, Belize
HFDolphin	09 - 22 Jul 2012	44,100	Back Sound, NC, USA
Inboard	19 - 30 May 2006 28 - 30 Jun 2007 01 - 16 Jul 2007 29 - 31 Aug 2008 01 - 05 Sep 2008	22,050	Pamlico and Neuse Rivers, NC, USA
Outboard	20 - 31 May 2006 11 - 30 Jul 2006 13 - 16 Jul 2007 11 - 30 Jul 2012	22,050	Back Sound, Pamlico and Neuse Rivers, NC, USA
Shrimp	24 Jun 2008 09 - 31 Jul 2012 01 - 12 Aug 2012 16 - 30 Apr 2013	22,050	Back Sound and Neuse Rivers, NC, USA

B. EXPERIMENTAL PROCEDURE

Oyster toadfish naturally colonized artificial shelters that were established for the playback experiments (Animal Use Protocol #D292). Artificial toadfish shelters, composed of a cement cube block (with 20 cm sides) with a central opening and a 7.6 cm PVC pipe inserted into the opening, were deployed during May and June 2013 at two sites (Figure 1). One site was considered "noisy" because it was on the Intracoastal Waterway, which had a lot of boat traffic. The second site was a "quiet" site because boat traffic was rarely observed (for more details on site characterization see: Luczkovich et al. 2016b and Sprague et al. 2016). At each site, a total of 48 shelters were deployed. These shelters were situated evenly in 12 replicates of 4 shelters over two treatments (seagrass and sand). Each replicate was spaced horizontally at a minimum distance of 370 cm. In each replicate, the shelters were arranged in a semi-circle around a central 150 cm long PVC pipe with a 15.2 cm diameter that was positioned 100 cm behind the shelters (Figure 2). This pipe marked the position for a Clark Synthesis AQ 339 underwater speaker used for playbacks. Another 150 cm long, 15.2 cm diameter PVC pipe supported a reference hydrophone (InterOcean 902 with a VU meter to measure SPL over all frequencies) positioned at 100 cm in front of the shelters at the center of the set-up. When deploying the hydrophones, a hydrophone cord was held onto the PVC pipe using 90° pipe insulation and an adjustable clamp. One hydrophone (HTI) was positioned 100 cm in front of the shelters (Figure 2), while a second hydrophone (InterOcean 902) was positioned 100 cm in front of the speaker to assess overall playback amplitude in the field. Both hydrophones were positioned at 40 to 50 cm above the bottom.

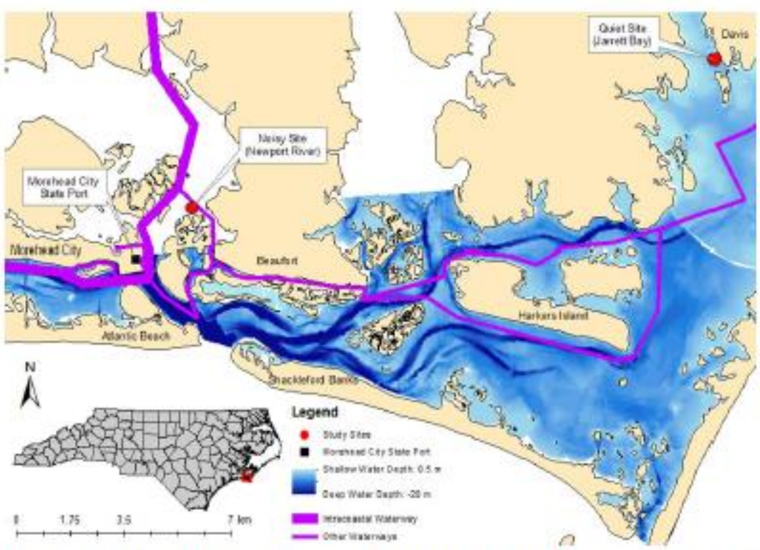

Figure 1. A map representing the study sites (red dots) for the playback experiments in Eastern North Carolina, USA. The noisy site is located along the Intracoastal Waterway and the quiet site is located away from the Morehead City State Port (black squares) and inlet traffic. The purple lines indicate some of the primary boat channels or waterways present within the area.

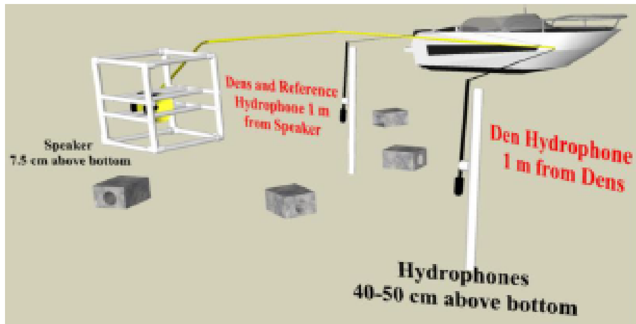

Figure 2. Diagram of how the oyster toadfish shelters were arranged and how the equipment was deployed to execute the playback experiment

Playback experiments were conducted in July and August 2013, at least 1 month after the shelters were established to allow time for natural colonization by oyster toadfish. Six recordings of different types of sounds were used during the playback experiment. Each sound type consisted of 600 s recordings (sources described above) for the following sound exposure treatments: low-frequency bottlenose dolphin sounds ("LFDolphin"), high-frequency bottlenose dolphin sounds ("HFDolphin"), inboard motorboat ("Inboard"), outboard motorboat ("Outboard"), snapping shrimp ("Shrimp", a natural background sound used as a control), and the simultaneous playbacks of low-frequency dolphin and inboard motorboat ("Both"). This final sound type ("Both") was created by simultaneously playing both "LFDolphin" and "Inboard" playbacks through two speakers. Playbacks for a treatment at a single site occurred overnight between 1900 h and 0800 h, with one sound type played back at each replicate. The playback treatment was randomly selected during each nightly (sunset to sunrise) experiment. Recordings for 600 s before, during, and after sound exposure were made on a TASCAM DR-40E digital recorder (mono wav recordings, 44,100 Hz sampling rate, 16-bit sample size). The power spectra of the playback signals (amplitudes of the playback sound recordings at various frequencies) were assessed from a single experimental procedure.

C. DATA ANALYSIS

The recorded files generated in the experiment were analyzed using Fast Fourier Transform (FFT) with a 4096 point Hanning window and 50% overlap in Raven Pro (version 1.5 Beta, The Cornell Lab of Ornithology, Bioacoustics Research Program, 2013). Playback power spectral density (PSD) curves versus frequency curves were compared visually among playback types. Additionally, mean square pressure (p^2_{av}, proportional to power) values were determined for the oyster toadfish hearing range (50 to 1000 Hz) and for frequencies < 10 kHz. These p^2_{av} values were calculated by: (1) multiplying the average power spectral densities by the frequency bin size (10.8 Hz) to obtain the p^2_{av} within each frequency bin; (2) the square pressures within each frequency bin were summed to obtain the p^2_{av} values in the desired frequency bands (50 to 1000 Hz or < 10 kHz); (3) these values were converted into dB with a reference value of 1 μPa^2. Comparisons were made across the total 1800 s experimental recording period, by comparing spectrum level differences before, during, and after a playback experiment.

The recordings were analyzed for oyster toadfish courtship calls in Raven Pro 64, with a human listener viewing interactively an oscillogram and spectrogram while playing back the recordings. Oyster toadfish call rates (number of boatwhistle calls/min) were assessed for the entire

600 s recording for all three recording periods. These call rates were used to assess changes in oyster toadfish calling behavior (% change) before and during playback exposure, and an Analysis of Variance (ANOVA) experimental design was employed to explore differences within a playback treatment. This ANOVA design was also applied to identify differences in courtship calling rates among experimental playback treatments and among sites that differed in substrate type (seagrass or sand). Bonferroni adjusted post-hoc analyses were used to assess differences in oyster toadfish calling rate (calls/60 s) by playback treatment and bottom type.

3. RESULTS

A. CHARACTERISTICS OF PLAYBACK SOUNDS

Playback sounds were different in terms of frequency and amplitude. The dominant frequencies within each playback varied, with some playbacks containing multiple peaks (Table 2). In the playbacks, the received power spectral densities increased, compared with the recording before sound-exposure (Figure 3) but this was dependent upon frequency. When comparing the before and during playback mean square pressures (p^2_{av}) at frequencies < 10 kHz, "Both" caused the largest increase in p^2_{av} (Δ = +16.7 dB re 1 μPa^2), followed by "Inboard" (Δ = +12.2 dB re 1 μPa^2), "Outboard" (Δ = +7.8 dB), "HFDolphin" (Δ = +5.5 dB re 1 μPa^2), and "LFDolphin" (Δ = +4.9 dB re 1 μPa^2). At this frequency range, the overall difference in p^2_{av} for the "Shrimp" playback was - 1.9 dB. When making comparisons limited to the auditory range of the oyster toadfish (50 to 1000 Hz), the overall p^2_{av} value during the playbacks was highest for the "Outboard", followed by "Both", then "LFDolphin", "Inboard", "HFDolphin", and "Shrimp" had the lowest p^2_{av} value (Table 2). However, the p^2_{av} values before the playback period, within the auditory range of the oyster toadfish were variable. After correcting the during playback p^2_{av} values by subtracting the p^2_{av} values from the recording before sound exposure, "Both" caused the most increase in p^2_{av} (Δ = +13.6 dB re 1 μPa^2), followed by "LFDolphin" (Δ = +10 dB re 1 μPa^2), "Outboard" (Δ = +4.4 dB re 1 μPa^2), and then the "Inboard" playback (Δ = +3.9 dB re 1 μPa^2) at 2 m from the speaker. Finally, two playbacks actually caused a decrease in the p^2_{av} value within the auditory range of the oyster toadfish. The "HFDolphin" playback resulted in a decrease of 4.5 dB re 1 μPa^2 and "Shrimp" produced a decrease in p^2_{av} by 3.9 dB re 1 μPa^2. All six playbacks, after being played through the speaker, had a 100 Hz peak (Figure 4), with quick roll-off after 200 to 300 Hz. These results suggest that there were some differences in p^2_{av} by frequency within the playbacks, with "HFDolphin" and "Shrimp" causing the least differences < 1000 Hz and "Both" and "Inboard" causing the most difference in the soundscape when played back to the oyster toadfish.

Table 2. The received mean square pressures (p^2_{av}, dB re 1 μPa^2) of the playback sounds collected on the HTI hydrophone (shelter hydrophone) that was 2 m in front of the speaker. Here the dominant frequency components (Hz) within each of the playbacks source files and the p^2_{av} are presented both in terms of the toadfish hearing range (50 < f < 1,000 Hz) and at f < 10,000 Hz, where f indicates frequency.

Playback Sound Type	p^2_{av} Before (dB re 1 μPa^2)		p^2_{av} During (dB re 1 μPa^2)		p^2_{av} After (dB re 1 μPa^2)		Frequency Peaks (Hz)
	50 Hz < f < 1000 Hz	f < 10,000 Hz	50 Hz < f < 1000 Hz	f < 10,000 Hz	50 Hz < f < 1000 Hz	f < 10,000 Hz	
Low-Frequency Dolphin	92.0	86.5	102.0	91.4	94.9	89.3	258 - 269, 732 - 742, 1130 -1141, 3370 - 3380
High-Frequency Dolphin	103.4	95.1	98.9	100.6	99.8	84.4	958 - 968
Inboard Motorboat	97.8	93.5	101.7	105.7	91.6	90.8	247 - 258
Outboard Motorboat	102.1	94.6	106.5	102.4	95.1	88.2	301 - 312, 894 - 904
Both Inboard Motorboat and Low Frequency Dolphin	91.1	86.3	104.7	103.3	98.1	89.4	237 - 247, 711 - 721, 1130 - 1141
Snapping Shrimp	100.3	93.4	96.4	91.5	99.2	92.5	0 - 11, 22 - 32, 118 - 129, 5599 - 5609

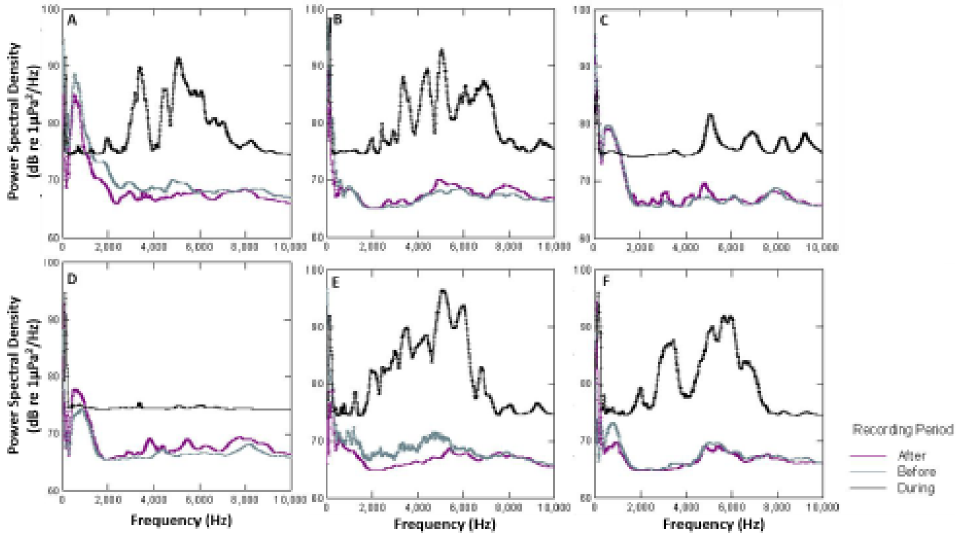

Figure 3. Power spectral densities at 2 m from the speaker during one experiment in sand. Each of the power spectra show standard error bars that are based on the estimates of power spectral densities (using Welch's method). A: "HFDolphin", B: "Outboard", C: "Shrimp", D: "LFDolphin", E: "Inboard", and F: "Both".

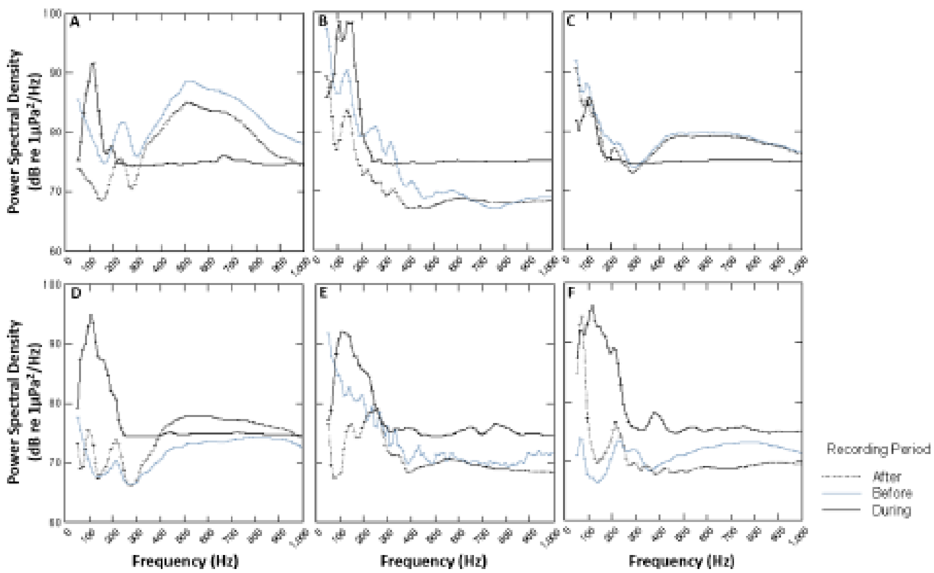

Figure 4. Power spectral densities in the hearing range of the oyster toadfish (50 to 1000 Hz) at 2 m from the speaker during one experiment in sand. Each of the power spectra show standard error bars that are based on the estimates of power spectral densities (using Welch's method). A: "HFDolphin", B: "Outboard", C: "Shrimp", D: "LFDolphin", E: "Inboard", and F: "Both".

B. CALLING RATE CHANGES DURING PLAYBACK

The change in oyster toadfish courtship calling rate (%) varied significantly by site (noisy vs quiet) and by playback type. The ANOVA model explained 97.4% of the variability in oyster toadfish courtship calling rates (F = 88.88, $p < 0.001$, df = 12). Playback sound type alone explained 36.7% of this variability in the model (F = 28.13, $p < 0.001$, df = 5) and site explained 3.5% of the model's variability (F = 13.34, p = 0.005, df = 1). The interaction between site and playback type, however, explained 57.4% of the model's variability (F = 43.92, $p < 0.001$, df = 5).

There were declines in oyster toadfish courtship calling rates during the sound playbacks, which varied among playback types. Differences were observed when comparing the before and during playback courtship calling rates as a function of playback sound type (Figure 5). Snapping shrimp playbacks ($\bar{X}$ = - 15.6% relative to before period calling rate, SE = 42.56) and outboard motorboat playbacks ($\bar{X}$ = - 39.1% relative to before period calling rate, SE = 60.89) had the least impact on change in oyster toadfish calling rates. Oyster toadfish calling rate declined significantly during the inboard motorboat playbacks ($\bar{X}$ = - 70.4% relative to before period calling rate, SE = 11.05), low-frequency dolphin playbacks ($\bar{X}$ = - 90.5% relative to before period calling rate, SE = 6.16), high-frequency dolphin playbacks ($\bar{X}$ = - 95.1% relative to before period calling rate, SE = 4.69), and both dolphin and boat sounds playbacks ($\bar{X}$ = - 100% relative to before period calling rate, SE = 0.00). These latter inboard vessel and dolphin playback types all caused significant declines in calling rates relative to snapping shrimp and outboard playback types, although these declines in calling rate responses did not differ from each other.

Calling rates were different at the noisy and quiet sites. The oyster toadfish from the quiet site showed a 20.71% greater decline in calling rate than fish from the noisy site (Figure 6). Thus, fish consistently inundated by anthropogenic noise seem to react differently to playback sounds than fish at sites with only a rare occurrence of anthropogenic noise.

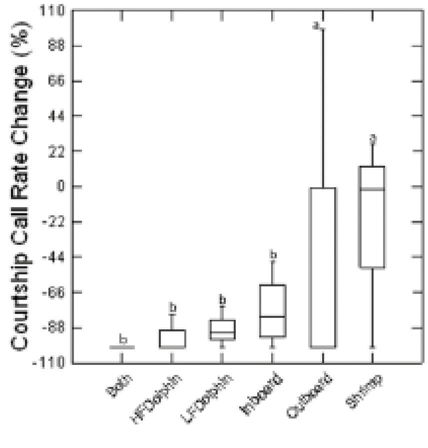

*Figure 5. Acoustic disturbance of oyster toadfish courtship calling rates. The median change in oyster toadfish courtship calling rate (% change) during the playback of various sound types is shown. Treatment groups with different lowercase letters represent significant (p < 0.01) differences. Both predator and bottlenose dolphin sounds ("Both") caused the largest decline in courtship calling behavior. High-frequency and low-frequency bottlenose dolphin playbacks and inboard motorboat playbacks caused similar declines in calling rates. Outboard motorboat and snapping shrimp sounds caused the least change in calling rates. Boxplots show the median (50th percentile at the horizontal line) and the region which contains 50% of data around the median (25th to 75th percentiles). The vertical bars show the region in which change in calling rates fall within 1.5 * the upper and lower interquartile ranges (lower interquartile: 25th to 50th percentile range; upper interquartile: 50th to 75th percentile range).*

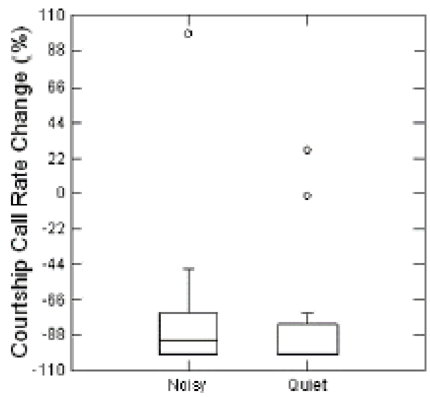

*Figure 6. Oyster toadfish courtship calling rate change (%) by study site (noisy versus quiet sites). Oyster toadfish reacted more at the quiet site compared with the noisy site (Δ = - 20.71, p = 0.005). Boxplots show the median (50th percentile at the horizontal line) and the region which contains 50% of data around the median (25th to 75th percentiles). The vertical bars show the region in which observations fall within 1.5 * upper and lower interquartile ranges (lower: 25th to 50th percentile range; upper: 50th to 75th percentile range). Points outside of the 1.5 * the upper and lower interquartile ranges are shown as open circles.*

C. CALLING RATE CHANGES AFTER PLAYBACK

There was no difference in the rate (calls/60 s) of oyster toadfish courtship calls before ($\bar{X}$ = 12.0 calls/60 s, *SE* = 3.07) and after ($\bar{X}$ = 11.1 calls/60 s, *SE* = 2.95) playback sound exposure of all types (Figure 7). Thus, oyster toadfish calling rates quickly (within 600 s) returned to pre-exposure levels after being exposed to the different playbacks. Differences in oyster toadfish courtship calling rates before the playbacks were evident between study sites, with the noisy site having an average of 9.6 more calls than the quiet site (Figure 7, ANOVA, $F = 9.43$ $p = 0.003$). In addition, oyster toadfish residing in sandy bottoms called less ($\bar{X} = 5.7$ calls/60 s, $SE = 2.51$) than oyster toadfish residing in seagrass bottom habitats ($\bar{X} = 16.0$ calls/60 s, $SE = 2.89$, ANOVA, $F = 6.69$ $p = 0.013$) but this was dependent upon site (Figure 8). At the quiet site, oyster toadfish calling rates were similar in sand ($\bar{X} = 8.3$ calls/60 s, $SE = 3.57$) and seagrass ($\bar{X} = 3.9$ calls/60 s, $SE = 0.71$). At the noisy site, oyster toadfish called more in seagrass ($\bar{X} = 28.0$ calls/60 s, $SE = 2.83$) than in sand ($\bar{X} = 0.4$ calls/60 s, $SE = 0.16$).

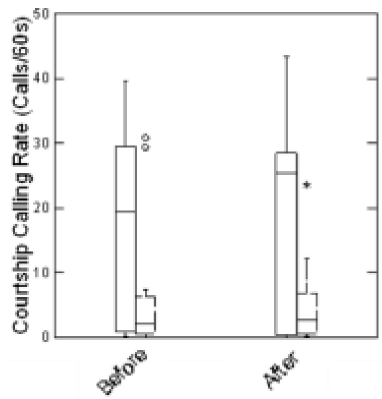

Figure 7. Median oyster toadfish courtship calling rates (calls/60 s) before and after the playback experiment as a function of the study site (noisy vs quiet). The quiet site is represented by the dashed boxplot lines and the noisy site is represented by the solid boxplot lines. Boxplots and interpretation of the symbols are given in Figures 5 and 6.

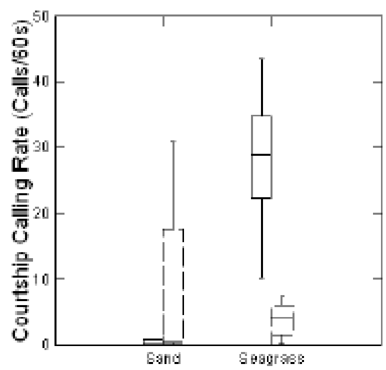

Figure 8. Oyster toadfish courtship calling rate (calls/60 s) before and after the playback experiment by site (noisy vs quiet) and bottom type (seagrass vs sand). The quiet site is represented by the dashed line and noisy site is represented by the solid line. The oyster toadfish in a sandy bottom type had 10.3 fewer calls on average than the oyster toadfish in a seagrass bottom type habitat. Boxplots and interpretation of the symbols are given in Figures 5 and 6.

4. DISCUSSION

Oyster toadfish reacted to inboard motorboat and dolphin (predator) sounds with a depressed calling rate during sound exposure. In a related study, Luczkovich et al. (2016a) also showed depressed calling rates in the oyster toadfish in an area with high boat traffic relative to an area with low boat traffic. In this volume, Luczkovich et al. (2016b) observed the Lombard effect in oyster toadfish at the same study sites described in this paper. The authors identified higher call amplitudes at the noisy compared with the quiet site. Here, we discuss the results of playback experiments from the standpoint of sound levels received by the oyster toadfish, their assumed hearing thresholds, and the ecological impacts of vessel noise.

The received levels of the playback sounds had the highest peaks between 50 Hz and 300 Hz, which is within the auditory range of the oyster toadfish (50 to 1000 Hz, Fine 1981; Fish and Offutt 1972). However, there were multiple high-frequency peaks above 2000 Hz, which are believed to be outside of the oyster toadfish's auditory range. The power spectral densities within this range ($f < 1000$ Hz) during the playbacks for "Both", "LFDolphin", "Inboard", and "Outboard" increased the power spectra relative to the before exposure levels. In contrast, this was not the case for "HFDolphin" and "Shrimp" playbacks, which actually demonstrated decreases in the power spectra within the same frequency range. These playbacks were selected because of the higher frequency ($f > 1000$ Hz) components to their signals and were not expected to cause much of an increase in power spectra at these low frequencies. The actual decrease in power spectra at these low frequencies ($f < 1000$ Hz) was unexpected and is likely due to other vocal marine life (e.g. other nearby soniferous fishes) altering their calling behavior due to the playback sounds.

The received power spectra did not correspond to the observed changes in calling rates in the oyster toadfish. A small change in calling rates occurred in response to the "Outboard" and "Shrimp" playbacks. The greatest reduction in calling rates occurred for the "Both" playback, followed by "HFDolphin", "LFDolphin", and finally "Inboard" sounds. Therefore, predator sounds alone or in combination with inboards caused the greatest decline in oyster toadfish calling rates. However, inboards alone also caused a significant decline in calling rates, relative to "Shrimp" and "Outboard" motorboat playbacks.

These changes in oyster toadfish calling rates do not seem to be associated with received levels of low-frequency (50 to 1000 Hz) sound during the playbacks. If low-frequency sound increases alone were causing the calling rate declines, these declines would not have been evident within the "HFDolphin" playback. Additionally, if high-frequency sounds alone were causing these calling rate differences we should have observed oyster toadfish calling rate declines for the "Outboard" playback but calling rate changes in the "Outboard" playback were not significantly different from "Shrimp". Thus, the frequency content of the playback signal alone is not influencing oyster toadfish calling rate changes. We speculate that the fish are responding to the ecological context associated with that playback sound with predator sounds and inboard motorboat noise causing the greatest decline in calling rate.

Regardless of the playback sound, there are some differences in calling rates by site. Oyster toadfish in the noisy site called more often than oyster toadfish in the quiet site. A behavioral modification has likely occurred, in which oyster toadfish use quiet periods between vessel passings at the noisy site to call at a higher rate. The same modification is not evident at the quiet site. Oyster toadfish sonic muscles are fatigue-limited (Mitchel et al. 2008), indicating that sustained elevated acoustic activity cannot be maintained for long time periods. Thus, the cost of burst calling behavior, observed at the noisy site, is a sonic muscle recovery period where the fish is unable to call. This burst calling behavior would result in an oyster toadfish at a noisy site calling at an increased rate during quiet times until it utilizes its stored glycogen, then recovering during the noisy periods when a vessel is passing near the site. Such a behavioral strategy would maximize the call rate during quiet periods. However, if the male oyster toadfish loses its ability to be heard by a mate during the passage of a vessel, and if there are many vessel passages per day, then the males residing in noisy sites could have decreased individual fitness, compared with males from a quiet site. Additionally, if vessel noise causes male oyster toadfish to leave the nest, like it does for the longear sunfish (*Lepomis megalotis*, Mueller 1980) and damselfish (*Chromis chromis*, Picciulin et al. 2010), then nests could be more frequently preyed upon, further reducing an individual's reproductive fitness.

In this study, there was also a bottom-type effect (seagrass vs sand). Overall, fish called more frequently in seagrass than in sand but there was an interaction with site noise level (noisy vs quiet). The acoustic refuge hypothesis (for an overview see: Wilson et al. 2013) suggests that seagrasses absorb and scatter an acoustic signal (McCarthy and Sabol 2000), causing up to an 88% reduction in low-frequency sound propagation compared with sandy/bare type bottoms (Wilson et al. 2013). Oyster toadfish may call more in seagrass because of the signal attenuation by seagrass but oyster toadfish may also be less impacted by ambient noise when residing in seagrass as opposed to sandy bottom types.

We did not directly analyze the received sound levels within the oyster toadfish shelters, but Sprague et al. (2016) conducted an analysis in the same area that: (1) created a sound exposure model and found that the sounds of passing vessels in the channels near the sites were significantly higher at the noisy site than the quiet site; (2) determined that the sound pressure level of the ambient soundscape at the noisy site was higher than the quiet site; (3) by using a toadfish weighted hearing function and modeling the propagation of noise from passing vessels into the study site, the authors concluded that the noises of vessels should be audible by the oyster toadfish in their shelters.

Future studies are needed to further explore the behavioral effects of noise on fish. Observed differences between playbacks and sites could have been associated with the number and size distribution of the oyster toadfish population. Attempts were made to quantify the number of oyster toadfish and these will be reported in a future study. Additionally, no visual observation of behavior during the playback experiments was assessed during this study and these studies need to be completed to understand how vessel activity can influence the reproductive success of this and other species of soniferous fishes.

5. CONCLUSION

The results of this work suggest that the content of a single sound within a soundscape alters the courtship calling behavior of male oyster toadfish, with inboard motorboats and dolphin sounds causing declines in calling rates and snapping shrimp and outboard motorboats causing no significant change in calling rate behavior. However, oyster toadfish do compensate for their dominant soundscape by calling more frequently during quiet periods and by increasing the amplitude of their calls during noise exposure (Luczkovich et al. 2016b). Further research is underway to address how the soundscape influences fish fitness and development.

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The Lombard effect in fishes: How boat noise impacts oyster toadfish vocalization amplitudes in natural experiments

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The Lombard effect in fishes: How boat noise impacts oyster toadfish vocalization amplitudes in natural experiments

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The Lombard effect (an involuntary increase in vocal levels in noisy environments) has been shown for humans, birds, and mammals. Here, we use experimental playbacks of vessel noise and other natural sounds in the normal soundscape of the oyster toadfish *Opsanus tau* to test if the Lombard effect occurred. Experiments were conducted at a noisy site adjacent to a port with high vessel traffic and in a quiet embayment. We played back vessel noise (inboard and outboard motor noise), predator sounds (bottlenose dolphins) and snapping shrimp sounds for 600 s and recorded the vocalizations made by toadfish in experimental dens during 600 s periods before, during, and after the playback period. Average call power of vocalizations increased by 6.8 dB during and 8.7 dB re 1 μPa^2 after playbacks of noise relative to pre-period levels, demonstrating the Lombard effect in toadfish. Fish at the noisy site had higher average call power relative to the quiet site. There was no change in the fundamental frequency of calls in after noise playback (average frequency was 224-233 Hz). Communication signals by oyster toadfish males may be masked by very loud vessels, and the Lombard effect is an attempt to overcome masking.

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1. INTRODUCTION

The Lombard effect was discovered by Etienne Lombard over 100 years ago (Lombard, 1911). Human speakers will increase their voices in noise, raising both the sound intensity and changing the frequency of their speech to overcome background noises (Zollinger and Brumm, 2011). The Lombard effect has also been documented in animals, including monkeys, whales, birds, and frogs (Brumm and Zollinger, 2011; Hotchkin and Parks, 2013; Kaiser and Hammers, 2009). Although the Lombard effect has been demonstrated in a species of freshwater fish in a laboratory study (Holt and Johnston, 2014), it has not been documented in free-ranging fishes subjected to increased levels of ambient or anthropogenic noise. In these previous studies on animals, the Lombard effect concept has been expanded include more than amplitude changes alone, because background noises can cause shifts in call frequency spectra, call duration, and rate of calling. For example, North Atlantic right whales *Eubalaena glacialis* and South Atlantic right whales *E. australis* produce higher fundamental frequencies and call at a lower rate in the presence of vessel activity than without vessels (Parks et al., 2007).

Ecologically, an increase in vocalization amplitude due to the Lombard effect can maintain an animal's "active space" – the region around the animal where its communication signal is detectable by other conspecifics (like potential mates and competitors). The active space of an animal's vocalizations is dependent upon the acoustic properties of the environment, the frequency and amplitude of the emitted call, the hearing sensitivity of the intended receiver, and the ambient noise level (Miksis-Olds and Tyack, 2009). Increasing masking noise leads to a decrease in the active space in which animals are able to detect a conspecific signal (Jensen et al., 2009; Van Parijs and Corkeron, 2001). For example, a finback whale's (*Balaenoptera physalus*) 20 Hz call may be audible at over 1000 km in ideal conditions but moderate shipping noise can reduce this range to 90 km (Payne and Webb, 1971). As shipping noise has continued to increase, the active space of this same call has been reduced to 32 km (Tyack, 2008), which amounts to a 97% total reduction in active space, with a 65% reduction in just the past 30 years.

Evolutionarily, the Lombard effect has been hypothesized to be the result of positive selection for animals with louder mating calls in noise-filled soundscapes, which have resulted in increased reproductive fitness (Brumm and Slabbekoorn, 2005). Animals that exhibit the Lombard effect have a higher chance of attracting mates and communicating to others in the presence of increased noise levels in the environment than those animals that do not exhibit this effect (Brumm and Slabbekoorn, 2005). Without the Lombard effect, the conspecific signal becomes masked (Jensen et al., 2009; Vasconcelos et al., 2007), which could result in decreased fitness. For example, female American treefrogs (*Hyla cinerea*) needed a higher amplitude of a synthetic call stimulus to exhibit behavioral responses to male courtship calls in the presence of noise compared with females exposed to the same stimulus without noise (Ehret and Gerhardt, 1980). In another study, brown tree frogs (*Litoria ewingii*), increased the average pitch of their calls by 4.1 Hz/dB of traffic noise, increasing the active space of the signal by 24% (Parris et al., 2009). The Lombard effect ultimately increases the chances of a male attracting a mate. Animals that have the ability to increase the amplitude of their vocalizations can compensate for increased background noise levels, thus communicating effectively with mates and conspecifics (Brumm and Slabbekoorn, 2005).

Given the relative benefits and costs of the Lombard effect in other species and the increasing noise levels in the sea, several questions arise: Do marine fishes exhibit the Lombard effect in a natural environment with vessel noise? Do fishes have the ability to increase their vocal amplitude or shift vocalization frequencies in order to increase their active space and communicate with others in noisy shipping areas? How does vessel noise affect a fish's ability to communicate? In this paper and two others presented at this meeting (Krahforst et al., 2016; Sprague et al., 2016), we attempt to answer these questions.

Here we demonstrate the Lombard effect using field playback experiments in oyster toadfish *Opsanus tau* living at a site near an active navigation channel in a coastal port (noisy site) and a site far from the port in a secluded estuarine embayment with few passing vessels (quiet site) in North Carolina (USA). Oyster toadfish make advertisement boatwhistle calls from oyster reefs or other shelter sites during summer (May – September) along the Western Atlantic Ocean (Gray and Winn, 1961). These boatwhistle calls are made by males to attract females to the calling sites (nests in a hard substrate) for mating. The females deposit clutches of eggs that adhere to the hard substrate, which are fertilized and then guarded by the males. Mating success and attraction of females depend on the males being heard by females that are passing near the calling sites. Vessel noise has been shown to interfere with the reception of the mating calls by females (masking) in a related species of toadfish (Vasconcelos et al., 2007).

Finally, it has been shown that other types of sounds, besides vessel noise, are able to influence males calling rates, specifically sounds from a predator on oyster toadfish, the bottlenose dolphin *Tursiops truncatus* (Dunshea et al., 2013; Gannon et al., 2005; McCabe et al., 2010). Bottlenose dolphins are sound producers that can produce stress responses and suppress calling rates in Gulf toadfish (Remage-Healey et al., 2006). In a related study in this volume (Krahforst et al., 2016), we report the suppression of oyster toadfish mating calls due to bottlenose dolphin sound playbacks. Below, we present the results of experimental vessel noise and bottlenose dolphin playbacks on the oyster toadfish vocalization amplitude and call frequency to examine the Lombard effect in a natural environment with and without vessel noise.

2. METHODS

A. STUDY SITES

Playback studies were conducted in natural environments in North Carolina, USA. We established experimental shelters at two sites, one a noisy site (Newport River, NPR) and at a quiet site (Jarret Bay, JBS; Fig. 1). Our characterization of these sites as "noisy" and "quiet" are based on three lines of evidence. First, the noisy site had high levels of observed boat activity (>100 vessels per day) and the quiet site had low levels of boat activity (<25 vessels per day). Second, noise levels at the NPR site were measured to establish background noise baselines (Sprague et al., 2016). Finally, the noisy site (NPR) was near a busy State of North Carolina cargo port and the Intracoastal Waterway, which is the main route for commercial and pleasure vessels heading north and south along the USA's eastern seaboard. The North Carolina State Port area and Intracoastal Waterway have very high vessel densities, as measured by the AIS (Automatic Information System) signals broadcast from passing vessels in 2013 (Fig. 1). Our noise measurements, vessel counts conducted by us at each site, plus the annual AIS estimates of vessel density led us to characterize NPR as a noisy site. The quiet (JBS) had very few AIS targets passed by in 2013, and our visual counts and noise measurements confirmed this site was quiet.

B. PLAYBACK EXPERIMENTS

Cement block shelters (cube with 20 cm sides, and with an internal opening containing 7.6 cm PVC tube), or oyster toadfish "dens", were deployed in 1-m water depth in May and June 2013 (Fig. 2). Forty-eight dens were placed at each site, in replicated experimental units (four dens per experimental unit, 12 experimental units per site) with 96 total dens at both sites. Experimental oyster toadfish dens were colonized rapidly after deployment (within one month), prior to playback experiments. Visual inspection of toadfish in the dens was completed by a snorkeler during daylight prior to the playbacks. Experimental playbacks were done at night in July and August 2013 beginning after sunset (2000-2015 local time) and continuing until all replicates had been exposed to sound playbacks (~0600 local time on the next morning). Occupancy was roughly 25-50% of dens based on the visual inspection (at least one fish per four dens). Animal protocols were approved by East Carolina University's Institutional Animal Care and Use Committee under Animal Use Protocol (#D292).

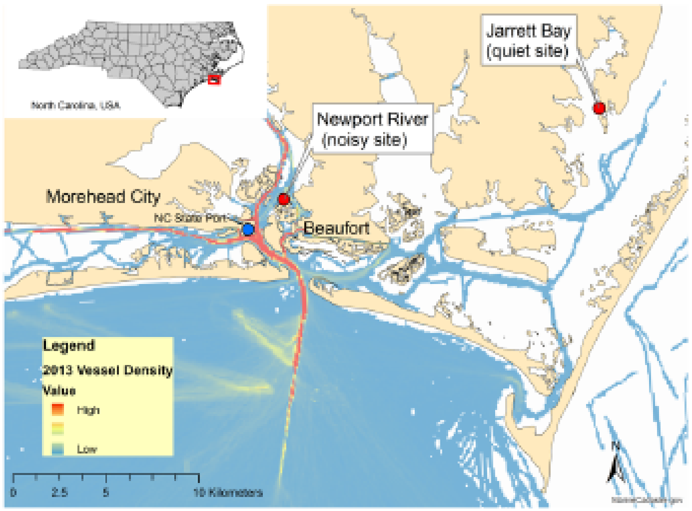

Figure 1. Study sites (red dot symbols) for playback experiments near Morehead City, North Carolina, USA. The noisy site was at Newport River (NPR), which is near the North Carolina State Port (blue dot) and the US Intracoastal Waterway (high vessel density shown in red shading, source: BOEM and NOAA, marinecadastre.gov). The quiet site was located at Jarrett Bay (JBS) an area with no AIS-equipped vessels.

Playback experiments were conducted in July and August 2013. The following playback experimental design was replicated twenty times at noisy site (NPR) and twenty-four times at the quiet site (JBS). There were forty-four total playback trials, each trial with a randomly assigned sound type played through a single speaker to a set of four oyster toadfish dens. Playbacks treatments were done using six recordings of sound types (snapping shrimp, six playbacks; inboard vessel motor, ten playbacks; outboard vessel motor, six playbacks; low-frequency bottlenose dolphin sounds, six playbacks; high-frequency dolphin sounds, eight playbacks; and simultaneous playback of both inboard vessel motor and low-frequency dolphin sound, eight playbacks). Details of these sounds' spectra and source levels are given elsewhere in this volume (Krahforst et al., 2016).

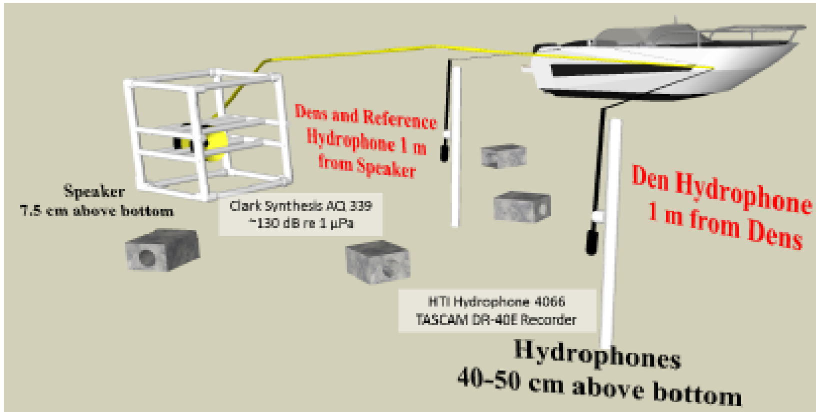

Figure 2. Experimental playback setup, with an underwater speaker, oyster toadfish dens, the amplifier on an anchored boat with the motor off, and two hydrophones (Reference hydrophone at 1 m and recording hydrophone at 2 m).

We played back these sound types from an anchored vessel (motor shut off) via a computer (Panasonic Toughbook CF-30), through a 400 W amplifier (Pyle PLMRA400), and an underwater speaker (Clark AQ 339). Two hydrophones were deployed to measure received levels and fish responses: (1) a reference hydrophone (InterOcean Model 902 calibrated listening system) positioned 1 m from the speaker in the center of the dens was used to get received sound pressure levels (SPL_{rms} in dB re 1 µPa), measured within the frequency range of the system (20 to 20,000 Hz); (2) a den hydrophone (HiTech, model HTI 96-min), which was positioned 2 m from the speaker, behind the shelters to make recordings of fish responses. Recordings (600 s prior to playback, 600 s during playback, and 600 s after playback) of male oyster toadfish boatwhistle calls were made from the latter hydrophone on a TASCAM DR-40 digital recorder at 44.1 kHz sampling rate to 16-bit sample size wav files. These files were later processed for received levels and call power measurements after correcting for differences in record level. See our companion paper (Krahforst et al., 2016) for a summary of received sound levels and representative spectra at the latter hydrophone.

C. Data Analysis

Recorded wav files were imported into Raven Pro (http://www.birds.cornell.edu/raven), oyster toadfish boatwhistle calls were identified by a listener, and a selection box was drawn around each audible call on the spectrogram interface of the software. The selection box defined the spectral and temporal extent of each call. Oyster toadfish call start times, ends times, minimum and maximum frequencies as defined by that box were exported as a selections table from Raven. The selection table and the "native" wav file was next imported to Matlab (http://www.mathworks.com). A calibration correction was applied to adjust for the HTI 96-min hydrophone sensitivity and sound recordings were corrected for record-level differences after computing call power in Matlab.

We determined the oyster toadfish call power using the Welch power spectral density algorithm (Welch, 1967), which computed the time-averaged power spectral density for the measured sound pressures for each call. All fish call power measurements were computed as mean squared sound pressure levels in dB re 1 µPa^2, which are proportional to average sound power. We obtained these mean squared sound pressure levels by summing the time-averaged power spectral density samples from the Welch algorithm from the minimum call frequency to the maximum call frequency and multiplying the sum by the frequency sample interval between each of the samples (i.e., the frequency sample interval from the FFT used in the Welch algorithm).

We compared average call power of the calls in the pre-, during-, and post-playback periods using a repeated measures Analysis of Variance (ANOVA). The Lombard effect was computed by subtraction of the average call power in the pre-playback period from the post-playback average call power, for replicates in which calls occurred in both periods. A one-sample t-test was used to compare the differences D computed for each replicate with detectable calls within sound-playback treatments using formula:

$$D = CP_{post} - CP_{pre}$$

where CP_{post} is the average call power post-playback and CP_{pre} is the pre-playback average call power. Measurements of sound pressure levels and oyster toadfish call power are displayed graphically as box plots. Box plots show the 50% range around the median (horizontal line) with upper and lower bounds of the box defined by the interquartile range (between the 25th and 75th percentiles). Vertical lines (upper and lower "whiskers") are defined by 1.5 x interquartile range, and points falling within this region are shown. Points shown outside of the range indicated by the vertical lines are extreme measurements.

3. RESULTS

Ambient sound pressure levels SPL_{rms}, measured at the reference hydrophone, were increased during playback by 15 dB to 40 dB re 1 µPa relative to pre-playback and post-playback levels (Fig. 3). The smallest increase in SPL_{rms} occurred during the snapping shrimp playback, and the greatest increase occurred during the simultaneous playback of high-frequency dolphin and large vessel sounds, and of the outboard motor sound playbacks.

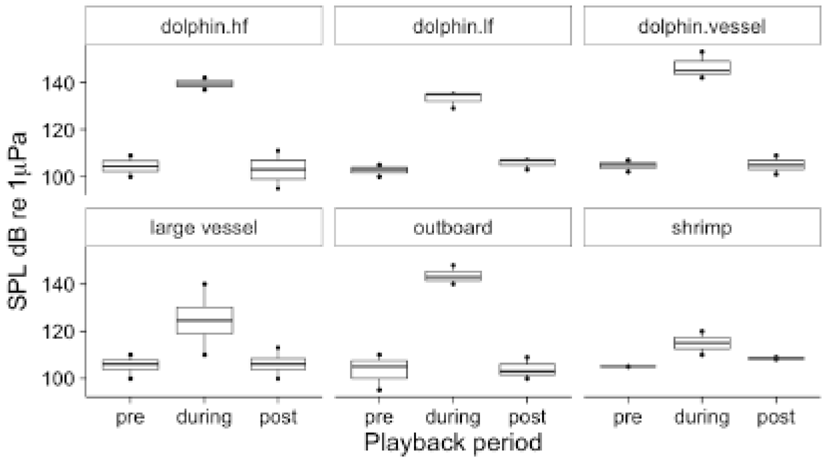

Figure 3. Ambient sound pressure levels (SPL_{rms} dB re 1 µPa) before, during, and after playbacks measured 1 m from source speaker at reference hydrophone, for playbacks of various types. SPLs were read directly off an InterOcean 902 calibrated listening system VU meter and represent the energy over entire spectrum (20-20,000 Hz).

Oyster toadfish were regularly detected on recordings from the recording hydrophone while making boatwhistle reproductive advertisement calls. Agonistic oyster toadfish grunt calls were also detected, and although these were uncommon, they are included in this analysis. The rate of advertisement calling by males fell during playbacks; in the case of simultaneous dolphin and vessel sound playbacks, no calls were detected during playback. Please see further results on call rate changes from these experiments elsewhere in this volume (Krahforst, et al., 2016).

The average call power increased during and after playbacks, from 95.2 dB re 1 μPa^2 in the pre-playback period, to 102.0 dB re 1 μPa^2 during playbacks, and to 103.9 dB re 1 μPa^2 after the playbacks (Fig. 4). A repeated-measures ANOVA was used to compare the average power of the calls among playback periods, allowing us to reject the of the hypothesis of equality of mean call power among playback periods (P = 0.036). The subtraction of the pre-period average call power for these data yielded a Lombard effect of between 6.8 dB (during playback) and 8.7 dB re 1 μPa^2 (after playback).

The call power generally followed the same pattern of increased power during and after playback when compared to the pre-playback period (Fig. 5). This pattern was true for natural sounds of snapping shrimp (shrimp), high-frequency dolphin (dolphin.hf), and low-frequency dolphin (dolphin.lf) sound playbacks. The average call power of the oyster toadfish varied by playback type.

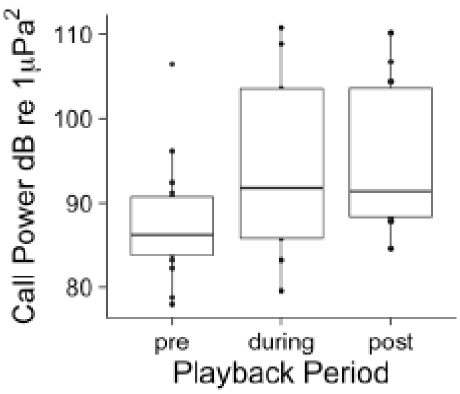

Figure 4. Oyster toadfish average call power (dB re 1 μPa^2) of boatwhistle and grunt calls during 600 s periods pre-playback, during playback, and post-playback, for all playback types combined. For interpretation, see box plot description in the Data Analysis section.

Oyster toadfish exposed to snapping shrimp, predator, and vessel sound playbacks increased their call power in all treatments, significantly increasing the post-playback average call power after the pre-playback average call power was subtracted (Table 1; one-sample t-test of the post-pre difference D, with expected $\mu = 0$, $t = 4.301$, $df = 14$, $P = 0.001$). The Lombard effect occurred for all sound type playbacks. The inboard motor (large vessel) sounds caused the greatest increase in average call power in the post-playback period when compared with the pre-playback period ($\bar{D}$ = 15.7 dB), and the outboard motor sound the least ($\bar{D}$ = 4.7 dB), although there were no significant differences among means of the playback sound types (pairwise t.tests among treatments, P = 1.0 for all treatment comparisons; Fig. 6).

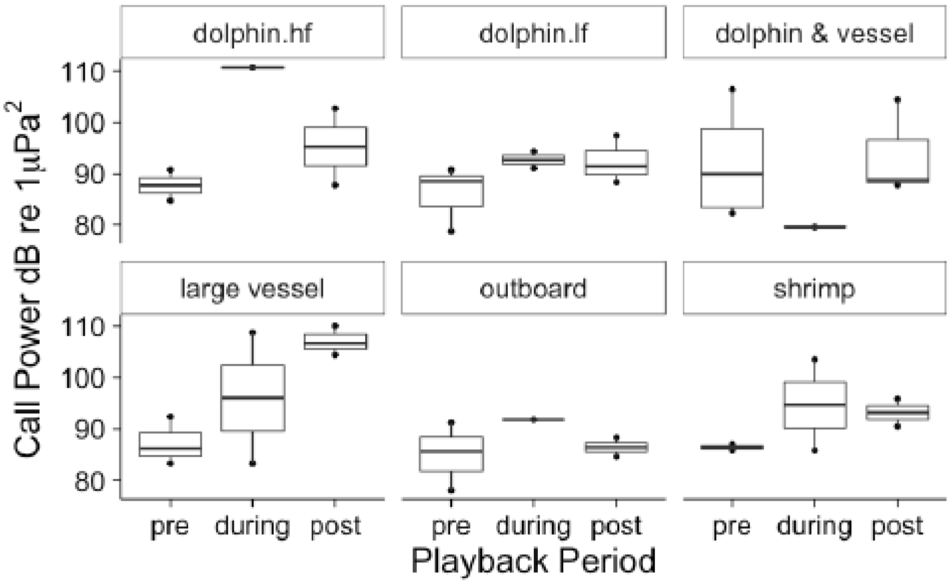

Figure 5. The call power (dB re 1 µPa²) of oyster toadfish boatwhistle and grunt calls during 600 s periods pre-playback, during playback, and post-playback, for each of the playback types. The sound spectra for each of the playback types are given in Krahforst et al. (2016). Playback sound type names are given above each plot: dolphin.hf is high-frequency dolphin sound, dolphin.lf is low-frequency dolphin sound, dolphin & vessel sound is simultaneous playback of low-dolphin and large vessel sound, large vessel sound, outboard motor sound, and shrimp is snapping shrimp, **Alpheus** *sp., sound.*

Table 1. The average call power in the pre-playback (CP_{pre}) and post-playback (CP_{post}) periods. $\overline{D}$ is the mean difference between the $CP_{post} - CP_{pre}$ for all replicates within each playback type, s.e.m. is the standard error of the mean for D, and N is the number of replicates.

Playback treatment	CP*pre* *dB re 1µPa²*	CP*post* *dB re 1µPa²*	$\overline{D}$ *dB*	s.e.m.	N
Shrimp	86.5	93.2	6.7	2.65	2
Outboard	81.8	86.5	4.7	1.85	2
Large Vessel	91.9	107.1	15.1	1.66	3
Dolphin, high-frequency	87.8	95.3	7.5	7.45	2
Dolphin low-frequency	86.0	92.4	6.4	2.70	3
Vessel & Dolphin	87.4	93.7	6.3	5.37	3
Overall means	87.2	95.3	8.1	1.88	15

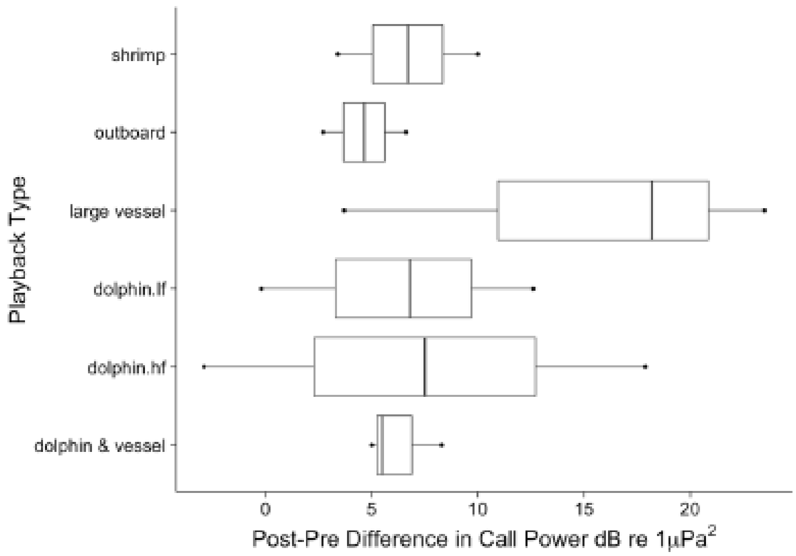

Figure 6. The difference in average call power (post-playback minus pre-playback average call power) as a function of playback sound type, with trials at both sites combined.

The average call power differed between the noisy and quiet sites in the pre-playback period. Average call power increased following the same pattern of higher power than the pre-playback period in the during- and after-playback periods when all sound playback types are combined (Fig. 7). Thus, there was evidence of the Lombard effect at both the noisy and quiet sites, but the noisy site also had oyster toadfish that were louder in the pre-playback period than in the quiet site.

The frequency of the calls did not change relative to the pre-playback frequency which was 228 Hz (Fig. 8). Thus, there was no evidence of a Lombard effect in terms of a change in pitch of the call. The were no significant differences in average call frequency between pre-playback period, during-playback period or post-playback period or in terms of minimum or maximum call frequency (Table 2).

Table 2. The average, minimum and maximum frequency (Hz) of oyster toadfish boatwhistle and grunt calls in before, during and after periods of the playback experiments.

Playback Period	Average Frequency (Hz)	Minimum Frequency (Hz)	Maximum Frequency (Hz)
Pre-playback	228.2	177.3	898.6
During Playback	224.2	106.2	643.0
Post-Playback	233.9	185.6	988.0
All periods	228.1	106.2	988.0

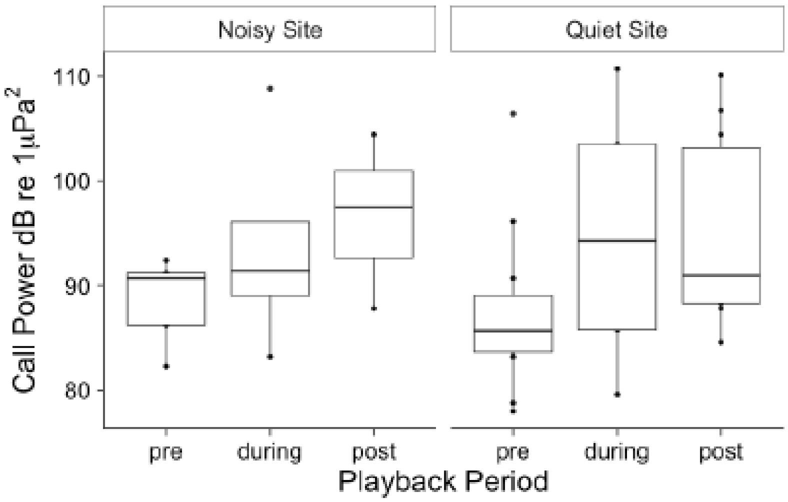

Figure 7. The median call power of oyster toadfish boatwhistle and grunt calls during 600 s periods pre-playback, during playback, and post-playback, for each of the playback type at noisy (NPR) and quiet (JBS) sites.

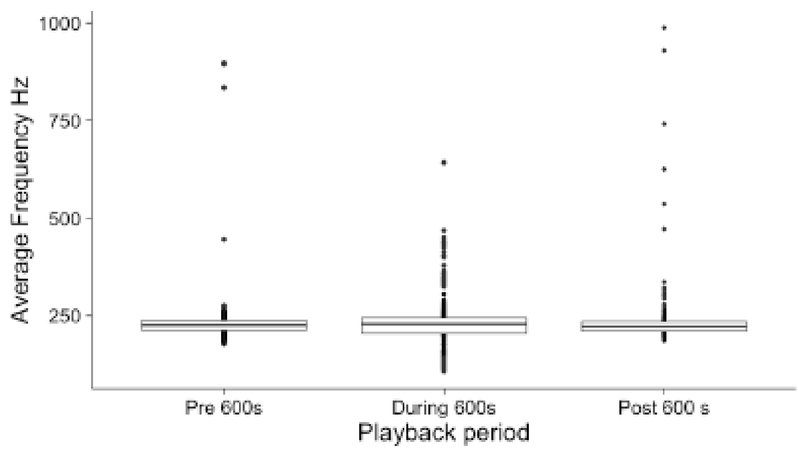

Figure 8. The average frequency of oyster toadfish boatwhistle and grunt calls during 600-s periods pre-playback, during playback, and post-playback, for all playback types combined.

4. DENS. DISCUSSION

There was an increase in oyster toadfish average call power during and after playbacks of the six sound types. However, no change in call frequency was observed due to the playback of anthropogenic noise or predator sounds.

The Lombard effect was estimated to be between 6.8 dB during the playback period and 8.7 dB re 1 μPa^2 immediately after the playback period for oyster toadfish. Thus, non-predatory noises, whether natural background sounds, like snapping shrimp, or anthropogenic sounds, like inboard and outboard motor sounds, caused the Lombard effect in oyster toadfish. The large vessel Lombard effect was estimated to be 15.7 dB re 1 μPa^2 in the post-playback period, while the outboard motor effect was estimated to be 4.7 dB re 1 μPa^2. Although sound playbacks increased the difference in average call power after playback significantly (rejection of the null hypothesis of no change in average call power), the six sounds types tested did not differ significantly in the terms of the effect of noise on the average call power. There were fifteen replicated dens that met the criterion of having multiple calls detected in both the pre-playback and post-playback periods, consequently there was low statistical power to detect a difference among treatment means.

While all oyster toadfish showed an increase in average call power after playback, some playbacks that included predator sounds also caused a reduction in the calling rate (Krahforst et al., 2016). In the case of the simultaneous playback of vessel noise and the dolphin predator sounds, there were no boatwhistle calls observed during playback (Krahforst et al., 2016), although there was one grunt detected. This shows the context-dependent nature of the Lombard effect that we observed: in the case of a natural predator sound, oyster toadfish decreased their calling rates, and stopped calling altogether when a predator sound was played with vessel noises. Many calls that were observed during playbacks of the dolphin predator sounds were louder than pre-playback calls, but there were very few of them, and some were actually lower in amplitude after playbacks (the post- playback minus pre-playback difference was negative). We cannot say with certainty that the Lombard effect occurred during these predator sound playbacks but appeared to have an effect after playbacks.

There was an overall higher call power in the pre-period at the noisy site (NPR). In a related study published in this volume, we measured the SPL_{rms} sound pressure levels were measured at the oyster toadfish dens at the noisy site (NPR) and reached an SPL_{rms} of 110 dB to 130 dB re 1 μPa during the passage of an inboard motor vessel (Sprague et al., 2016). At the Rachel Carson Estuarine Research Reserve South Middle Marsh site, another nearby quiet site, the SPL_{rms} was 80 dB to 100 dB re 1 μPa, yielding up to a 30 dB difference in maximum levels of ambient noise between the noisy and the quiet site (Sprague et al., 2016). At the noisy NPR site, the sound-exposure level (SEL) during various vessel types passing was estimated to be 132 dB to 135 dB re 1 $\mu Pa^2 \cdot s$ after being weighted for oyster toadfish hearing (Sprague et al., 2016). Thus, ambient noise at the noisy NPR site is largely due to vessels passing by frequently, thus yielding high sound exposure levels for oyster toadfish in those dens. It appears that at the noisy NPR site, the approximately 30 dB increase in SPL above background ambient noise and 132 dB to 135 dB re 1 $\mu Pa^2 \cdot s$ toadfish-weighted sound exposure level due to vessel noise has produced a larger Lombard effect in the fish that were present at the site.

We have demonstrated that both anthropogenic vessel noises and natural background sounds such as snapping shrimp can cause the Lombard effect in oyster toadfish. The Lombard effect has been previously demonstrated in a freshwater fish, the blacktail shiner, *Cyprinella venusta* (Holt and Johnston, 2014). This study extends the Lombard effect in fishes to include oyster toadfish, a marine fish that is subjected to noise occurring in busy ship channels.

Large vessels in the area near our noisy site produced sound pressure levels comparable to those SPLs we produced experimentally with our loudspeakers (Sprague et al., 2016), and the vessel noise was common at that site due to the Intracoastal Waterway nearby. Although sound pressure levels were comparable to those produced by a vessel passing by, particle motion fields will be produced by passing vessels as well. We did not measure particle motion produced by either passing vessels or our loudspeakers during sound playback. Fishes like the oyster toadfish are sensitive to particle motion (Popper and Fay, 2011) and Zeddies et al., 2012 showed that plainfin midshipman fish *Porictlhhys notatus* uses the particle motion field for phonotaxis. Thus, one could ask if the particle motion field produced by our speaker system [(Zeddies et al., 2012)] accurately simulated the particle motion field of a vessel passing by our site. We cannot answer this question at the current time, but particle motion measurements during playback of sounds from our speakers and from passing vessels are planned in the near future.

Vessel noise at levels similar to those used in our playbacks may have ecological consequences such as masking, in which female toadfish cannot hear males' calls (Vasconcelos et al., 2007). Continuous vessel noise can have increased metabolic costs for the males (Amorim et al., 2002), and may cause sonic muscle fatigue (Mitchell et al., 2008) in an attempt to overcome the noise. In addition, in variable vessel noise areas, such as near a navigation channel, there could be an increase the rate of detection by predators if the signal-to-noise ratio increases due to the Lombard effect and remains high after noise stops. We observed increased oyster toadfish amplitudes after the sound playbacks ended, which could expose fish to bottlenose dolphin predators. Thus, there could be an inherent trade-off between the Lombard effect and the risk of predation, as had been suggested for birds (Patricelli and Blickley, 2011).

Finally, bottlenose dolphin predator sounds did produce a small Lombard effect in our study, but this was coupled with a decline in calling rates, producing very few calls on which to measure the effect during bottlenose dolphin sound playback treatments. The few calls that did occur (grunts rather than boatwhistles) were elevated in amplitude. In contrast to the vessel sounds, the predator sound playback resulted in reduced oyster toadfish calling rates (Krahforst et al., 2016), thereby making the Lombard effect absent during playbacks and smaller amplitude increase in the after-playback period. The predator sounds inhibited calling by males, reducing the mating opportunities and likely fitness. The same response has been observed previously in Gulf toadfish *Opsanus beta* (Remage-Healey et al., 2006) and in silver perch *Bairdiella chrysoura* (Luczkovich et al., 2000). When both vessel noise and bottlenose dolphin sounds co-occurred in our playback experiments, the calling rates of oyster toadfish were dramatically lower (Krahforst et al., 2016), suggesting that the involuntary increase amplitude of vocalizations (the Lombard effect) can be suppressed in times of danger, perhaps due to the increase in stress hormone cortisol inhibiting the vocal motor pathway (Remage-Healey et al., 2006). Additional research needs to be completed to assess the ecological, physiological, energetic, and reproductive consequences of the Lombard effect in fishes.

5. CONCLUSION

There was an increase in oyster toadfish average call power during and after playbacks of the six sound types. The Lombard effect due to all background noises was estimated to be between 6.8 and 8.7 dB re 1 μPa^2 for oyster toadfish. There was no change in the dominant frequency of the oyster toadfish boatwhistle calls due to background noise.

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Noise propagation from vessel channels into nearby fish nesting sites in very shallow water

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Noise propagation from vessel channels into nearby fish nesting sites in very shallow water

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Noise exposure has been shown to have negative impacts on fish. This study introduces the F-weighting function for assessing the effects of audible sounds on fish. Sound levels with the F-weighting function emphasize the frequencies that the fish can detect and suppresses frequencies the fish cannot detect. A hydrophone was placed at locations of shelters or "dens" colonized by oyster toadfish Opsanus tau in very shallow water (1 – 2 m depth). Sounds produced by three representative passing vessels – an inboard boat, an outboard boat, and a tugboat pushing a barge – in nearby channels were recorded. Each vessel produced sounds at the den location at levels audible to the fish. The vessel sounds were not loud enough to produce temporary threshold shifts or permanent hearing losses in the fish, but they were loud enough to produce behavioral effects, masking of conspecific and predator sounds, the Lombard effect, and possibly an increase of stress hormones. Also, for comparison with the noisy site, sounds were measured at a quiet site where no vessels were present. The loudest sounds at the quiet site had similar sound pressure levels to the quietest sounds at the noisy site at a time when no vessels were detected.

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1. INTRODUCTION

Without question ambient noise in the ocean is increasing due to human activity (McDonald *et al.*, 2008; Hildebrand, 2009), primarily shipping and seismic surveys. In coastal and estuarine waters, sources of anthropogenic noise include ships, boats, SONAR, and construction activities. Development of coastal and estuarine areas leads to an increase of these activities, increasing ambient noise (Haviland-Howell *et al.*, 2007; Rako *et al.*, 2013) and its potential impacts on animals that inhabit these waters.

Fish exposure to noise could result in behavioral responses, masking of important sounds, temporary threshold shifts, permanent hearing loss, other physical injury, or even mortality (see Popper and Hastings, 2009, for an extensive list of studies). One behavioral response to noise is avoidance of noisy areas (Engås *et al.*, 1996; Engås and Løkkeborg, 2002; Slotte *et al.*, 2004). Wardle *et al.* (2001) observed C-start responses in reef fish exposed to seismic air gun blasts but did not observe any long-term behavior changes in fish repeatedly exposed to the sounds. Masking caused by increased ambient noise due to boats and other noise sources can result in decreased ranges of detectability (Sprague and Luczkovich, 2004; Codarin *et al.*, 2009) of conspecific sounds such as advertisement calls or noise produced by predators. Ship noise elevates cortisol levels in several freshwater fishes, in comparison to no-noise and white-noise controls (Wysocki *et al.*, 2006). Largemouth bass *Micropterus salmoides* had a 67 % increase in heart rate when exposed to vessel noise from a combustion engine (Graham and Cooke, 2008). This heart rate increase was higher than that measured for a simulated predator attack (44 %, Cooke *et al.*, 2003). Finally, it took the largemouth bass nearly double the amount of time to recover from the engine sound than from the sound of a canoe (Graham and Cooke, 2008).

Male oyster toadfish *Opsanus tau* produce the well-documented boatwhistle sound (Gray and Winn, 1961; Fish and Mowbray, 1970; Fine, 1978) as an advertisement call. They colonize shallow water (1–2 m depth) shelters or "dens" in which benthic eggs are deposited. Often these dens are near boat and ship channels where anthropogenic noise can be loud. Noise exposure is associated with decreased oyster toadfish calling rates and decreased embryo abundance (Krahforst *et al.*, 2016). Exposure of oyster toadfish to noise at sound pressure levels as low as 115 dB re 1 μPa has been shown to cause the Lombard effect (Luczkovich *et al.*, 2016) where the fish produce louder sounds after the noise ends than the sounds they produced before noise exposure.

Toadfishes, including the oyster toadfish, are hearing generalists (Yan *et al.*, 2000; Vasconcelos and Ladich, 2008; Bhandiwad and Sisneros, 2016) with hearing sensitivities that fall off drastically at frequencies greater than 1000 Hz (see the solid dots in Fig. 1). Fine (1981) determined the threshold of hearing of the oyster toadfish is 77 dB re 1 μPa at 90 Hz.

Since animals, including fish, respond behaviorally only to sounds that they can detect, weighting functions that emphasize the frequencies that the animal can detect, and suppress frequencies the animal cannot detect, are useful. Southall *et al.* (2007) developed the M-weighting function for marine mammals with the frequency response function

$$M(f) = \frac{f^2(f_{\mathrm{low}} + f_{\mathrm{high}})^2}{(f^2 + f_{\mathrm{low}}^2)(f^2 + f_{\mathrm{high}}^2)}, \tag{1}$$

where f is frequency, and f_{low} and f_{high} are minimum and maximum frequencies based on the audiogram of the species of interest. Note that the form of the M-weighting function given in Eq. (1) is normalized so the maximum value of $M(f)$ is 1 (or 0 dB). We introduce an F-weighting function for use in examining behavioral responses to noise exposure in fish. The F-weighting has the same form as the M-weighting function with f_{low} and f_{high} values chosen to mimic the fish species hearing sensitivity,

$$F(f) = \frac{f^2(f_{\mathrm{low}} + f_{\mathrm{high}})^2}{(f^2 + f_{\mathrm{low}}^2)(f^2 + f_{\mathrm{high}}^2)}. \tag{2}$$

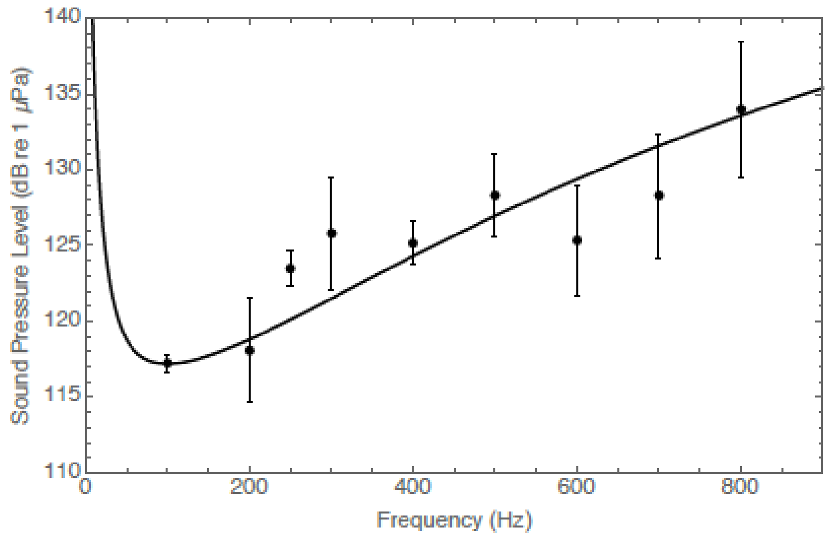

***Figure 1. Audiogram of an oyster toadfish* Opsanus tau *with the inverse of the F-weighting frequency response superimposed, described herein. The solid dots are reproduced from audiogram data in Yan* et al. *(2000), and the solid curve is the inverse of the F-weighting frequency response function $F(f)$ adjusted so its 100 Hz value matches the audiogram value at the same frequency,* $117.2\,\mathrm{dB} - 20\log_{10} F(f)$.**

For oyster toadfish, we use $f_{\mathrm{low}} = 33.33\,\mathrm{Hz}$ and $f_{\mathrm{high}} = 300\,\mathrm{Hz}$, resulting in a frequency response curve similar to the oyster toadfish audiogram (Fig. 1). The complex filter function for the F-weighting (and also the M-weighting) function is

$$H_F(s) = \frac{4\pi^2 (f_{\mathrm{low}}^2 + f_{\mathrm{high}}^2) s^2}{(s + 2\pi f_{\mathrm{low}})^2 (s + 2\pi f_{\mathrm{high}})^2}, \tag{3}$$

where s is the Laplace transform frequency (related to Fourier transform frequency f by $s = 2\pi i f$). This filter function $H_F(s)$ can be used in a software-based filter to impose the weighting function on sound recordings.

The time-weighted average sound pressure is a measure of the average sound pressure measured with an exponential time constant,

$$p_T(t) = \sqrt{\frac{1}{T} \int_{-\infty}^{t} [p(t')]^2 e^{-(t-t')/T}\, dt'}, \tag{4}$$

where t is time, T the time constant, and $p(t')$ the instantaneous sound pressure at time t'. Standard time constant values are slow response, 1.000 s; fast response, 0.125 s; and impulse response 0.035 s. The time-weighted average sound pressure can be combined with a frequency weighting function to give a time and frequency weighted average sound pressure. These values are usually reported in decibel form as time-weighted average sound pressure levels,

$$SPL(t) = 20 \log_{10} \left(\frac{p_T(t)}{p_{\mathrm{ref}}} \right), \tag{5}$$

where p_{ref} is the reference pressure (1 μPa in water).

Sound exposure and sound exposure level are quantifications of the received sound energy due to sounds above the background for some acoustic event (Southall *et al.*, 2007). Sound exposure is

$$E = \int_{t_1}^{t_2} \left(p^2(t) - \overline{p^2_{\mathrm{amb}}}\right) dt, \tag{6}$$

where $p(t)$ is the received acoustic pressure at time t, $\overline{p^2_{\mathrm{amb}}}$ the mean square ambient pressure, t_1 the time of the beginning of the event, and t_2 the time of the end of the event. Sound exposures due to multiple events can be summed to give a total sound exposure. The sound exposure level is

$$SEL = 10\log_{10}\left(\frac{E}{p^2_{\mathrm{ref}}}\right). \tag{7}$$

Sound exposures and sound exposure levels are often computed using frequency weightings such as *A*-weighting for human sound exposure and *M*-weighting for marine mammal sound exposure.

In this study, we measured *SPL* values at oyster toadfish den sites in loud areas near boat channels and in quiet areas far from boat channels to determine whether the toadfish adults and larvae were were exposed to boat sounds loud enough to result in behavioral or physiological effects. We also recorded ambient sounds at each site. Our sites were located near Beaufort Inlet, NC on the east coast of the USA (see Fig. 2). The

Figure 2. Study sites near Beaufort Inlet, NC, USA. Left: location of Beaufort Inlet on the east coast of the USA. (Image from Landsat ©2016 Google with map data from SIO, NOAA, US Navy, NGA, and GBCO.) Right: locations of the four study sites on a nautical chart. NPR–Newport River site, SMM–South Middle Marsh site, NMM–North Middle Marsh site, and JBS–Jarret Bay site. The NPR and SMM sites are discussed in this study. (Image ©2016 Google with NOAA Raster Navigational Chart displayed.)

Newport River site (NPR) is located near the Port of Morehead City and adjacent to Atlantic Intracoastal Waterway. The South Middle Marsh site (SMM) is located in the Rachel Carson Estuarine Research Reserve far from vessel traffic. We recoded sounds at the toadfish nesting sites when boats passed in the nearby channel and calculated sound exposure levels due to these boat passages.

2. METHODS

We recorded vessel sounds and ambient sounds using a hydrophone placed at oyster toadfish den locations. We also recorded the positions of the vessels as they passed the site. We placed a hydrophone (icListen model

HF, Ocean Sonics, Great Village, Nova Scotia, Canada) in a float collar suspended ~ 0.5 m above a weight on the seafloor at the toadfish den location in each site. The hydrophone recorded sounds continuously with a 44 100 Hz sampling frequency. The water depth at each location was 1–2 m, and the position of the hydrophone was determined with Wide Area Augmentation System-enabled Global Positioning System (WAAS-GPS). We anchored our vessel nearby with the engine off and recorded a WAAS-GPS track of positions every 1–8 s to account for movement the movement of our vessel. We used linear interpolation to obtain our vessel position between track points. We measured the distance and azimuth to passing vessels using a laser rangefinder (TruPulse 360R, Laser Technology, inc., Centennial, CO, USA). We corrected azimuth readings for magnetic declination using the GeoMag Python package (Weiss, 2014), which uses data from the World Magnetic Model (NOAA National Centers for Environmental Information, 2016). We calculated the vessel position from each rangefinder reading using the GeographicLib Python package (Karney, 2016), which computes latitude and longitude positions and distances between them using the WGS84 ellipsoid (National Imagery and Mapping Agency, 2000). We used linear interpolation to obtain passing vessel positions between laser rangefinder readings.

We computed time-weighted average SPL values using Eqs. (4) and (5) with a fast time constant (0.125 s) both during vessel passages and at times when there were no vessels present using unweighted recordings and also F-weighted recordings. We computed sound exposure levels for vessel passages for unweighted and F-weighted recordings using Eqs. (6) and (7).

3. RESULTS

In this study we present three recordings from the NPR site representing three types of vessels that are common in the channels and one recording from the quiet SMM study site. Recording 1 has noise produced by a large inboard boat. Recording 2 has noise produced by a sailboat powered by an outboard engine. Recording 3 has noise produced a tugboat pushing a large barge in the Atlantic Intracoastal Waterway, which passes within 600 m of the NPR site. Recording 4 was made in the SMM site.

A. RECORDING 1: INBOARD VESSEL

A 10–15 m inboard boat passed the NPR toadfish den location in the adjacent boat channel as shown in Fig. 3. Figure 4A is a graph of the average power spectrum from the 10 s interval during which the received inboard vessel sound was loudest. Figure 4B is a graph of the time-weighted average SPL vs. time for the inboard boat passage for both unweighted and F-weighted SPL values. The peak time-weighted average SPL and the SEL from the inboard boat passage are in Table 1. Figure 5 is a graph of the time-weighted average SPL vs. range to the inboard boat for both unweighted and F-weighted sounds. While the attenuation of the unweighted SPL is similar to spherical spreading, the attenuation of the F-weighted SPL is similar to cylindrical spreading.

B. RECORDING 2: OUTBOARD VESSEL

An 8–10 m sailboat powered by an outboard engine passed the NPR toadfish den location in the adjacent boat channel as shown in Fig. 6. Figure 7A is a graph of the average power spectrum from the 10 s interval during which the outboard vessel sound was loudest. Figure 7B is a graph of the time-weighted average SPL values vs. time for the outboard boat passage for both unweighted and F-weighted SPL values. The peak time-weighted average SPL and the SEL from the outboard boat passage are in Table 1. Figure 8 is a graph of the time-weighted average SPL vs. range to the outboard boat for both unweighted and F-weighted

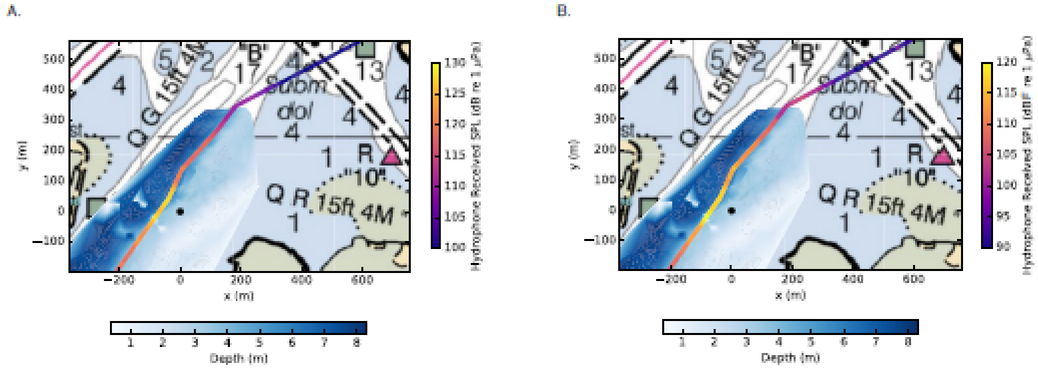

Figure 3. Inboard vessel path and received sound pressure level from Recording 1. The vessel path and a contour depth plot (blue tones, color bar below figure) are superimposed on a NOAA nautical chart of the study site. The hydrophone location is indicated by the black dot at $(x, y) = (0\,\mathrm{m}, 0\,\mathrm{m})$. *The yellow-orange-magenta tones of the vessel path curve (color bar to the right of the figure) represent the received hydrophone time-weighted average sound pressure level (time constant* $0.125\,\mathrm{s}$) *when the vessel is at the location on the curve indicated by the color. A. Unweighted sound pressure levels. B.* F*-weighted sound pressure levels.*

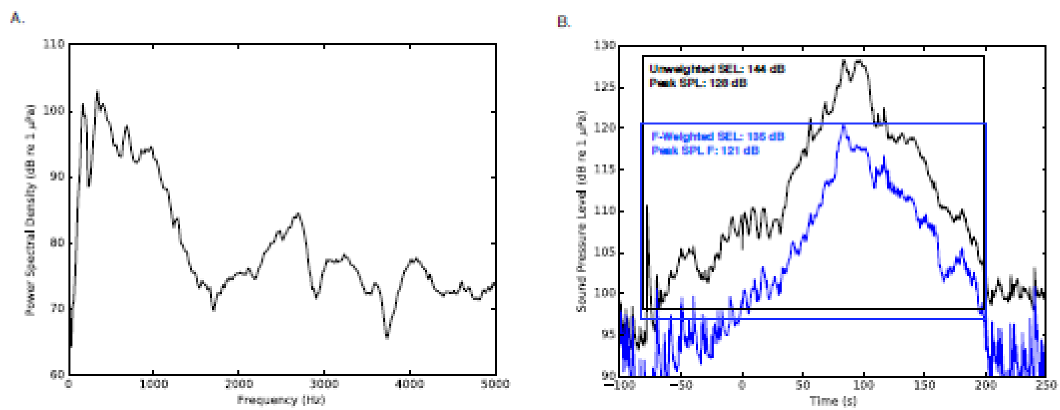

Figure 4. A. Recording 1 average power spectrum taken during the loudest $10\,\mathrm{s}$ *interval of the inboard boat passage. The sampling frequency is* $44\,100\,\mathrm{Hz}$*, and the power spectra were taken with 2048-sample Hanning windowed FFTs with 1024-sample overlaps. B. Recording 1 time-weighted average sound pressure level (time constant* $0.125\,\mathrm{s}$) *vs. time for the inboard boat passage. The black curve shows unweighted sound pressure levels with a peak of* $128\,\mathrm{dB}$ re $1\,\mu\mathrm{Pa}$ *and the blue curve shows* F*-weighted sound pressure levels with a peak of* $121\,\mathrm{dB}$ re $1\,\mu\mathrm{Pa}$. *The unweighted sound pressure levels above the background are inside the black rectangle resulting in an unweighted sound exposure level of* $144\,\mathrm{dB}$ re $1\,\mu\mathrm{Pa}$. *The* F*-weighted sound pressure levels that are above the background are inside the blue rectangle resulting in an* F*-weighted sound exposure level of* $135\,\mathrm{dB}$ re $1\,\mu\mathrm{Pa}$.

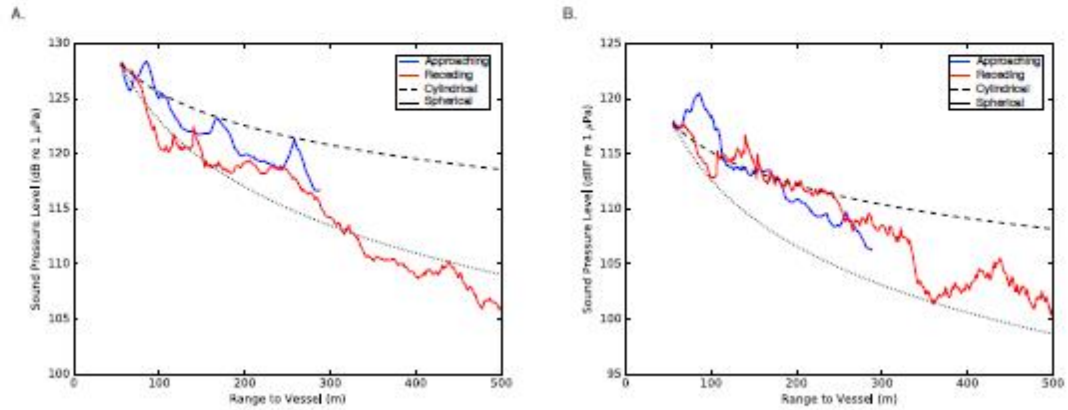

Figure 5. Recording 1 time-weighted average sound pressure level vs. vessel range for the inboard boat passage with spherical and cylindrical spreading curves. A. Unweighted sound pressure levels. B. F-weighted sound pressure levels.

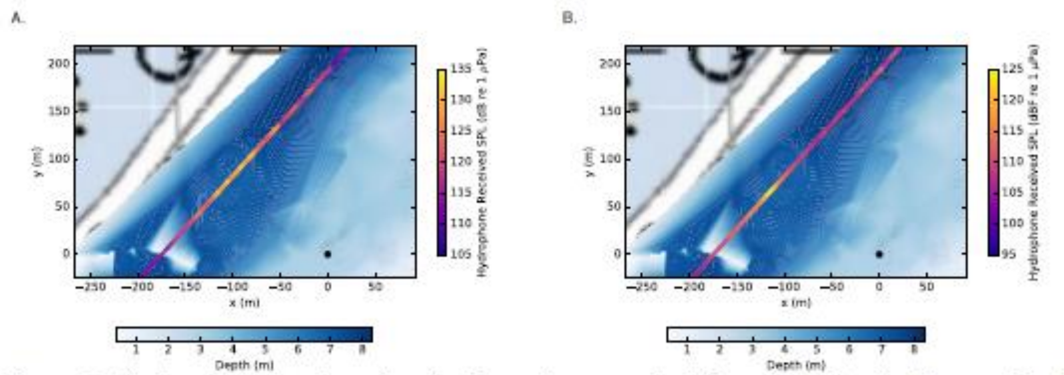

Figure 6. Outboard vessel path and received sound pressure level from Recording 2. The vessel path and a contour depth plot (blue tones, color bar below figure) are superimposed on a NOAA nautical chart of the study site. The hydrophone location is indicated by the black dot at $(x, y) = (0\,\mathrm{m}, 0\,\mathrm{m})$. The yellow-orange-magenta tones of the vessel path curve (color bar to the right of the figure) represent the received hydrophone time-weighted average sound pressure level (time constant $0.125\,\mathrm{s}$) when the vessel is at the location on the curve indicated by the color. A. Unweighted sound pressure levels. B. F-weighted sound pressure levels.

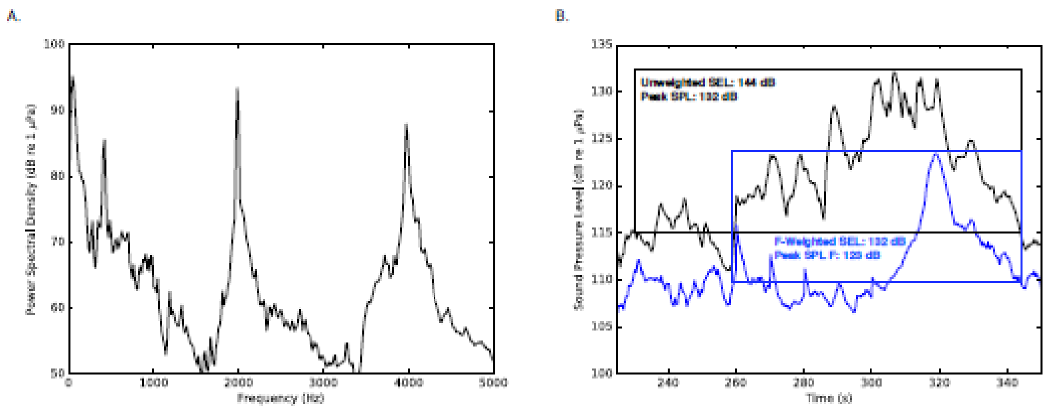

Figure 7. A. Recording 2 average power spectrum taken during the loudest 10 s ***interval of the outboard boat passage. The sampling frequency is*** 44 100 Hz***, and the power spectra were taken with 2048-sample Hanning windowed FFTs with 1024-sample overlaps. B. Recording 2 time-weighted average sound pressure level (time constant*** 0.125 s***) vs. time for the outboard boat passage. The black curve shows unweighted sound pressure levels with a peak of*** 132 dB re 1 μPa ***and the blue curve shows*** **F*****-weighted sound pressure levels with a peak of*** 123 dB re 1 μPa. ***The unweighted sound pressure levels above the background are inside the black rectangle resulting in an unweighted sound exposure level of*** 144 dB re 1 μPa. ***The*** **F*****-weighted sound pressure levels that are above the background are inside the blue rectangle resulting in an*** **F*****-weighted sound exposure level of*** 132 dB re 1 μPa.

sounds. The attenuation of both the unweighted and F-weighted SPL is greater than that due to spherical spreading.

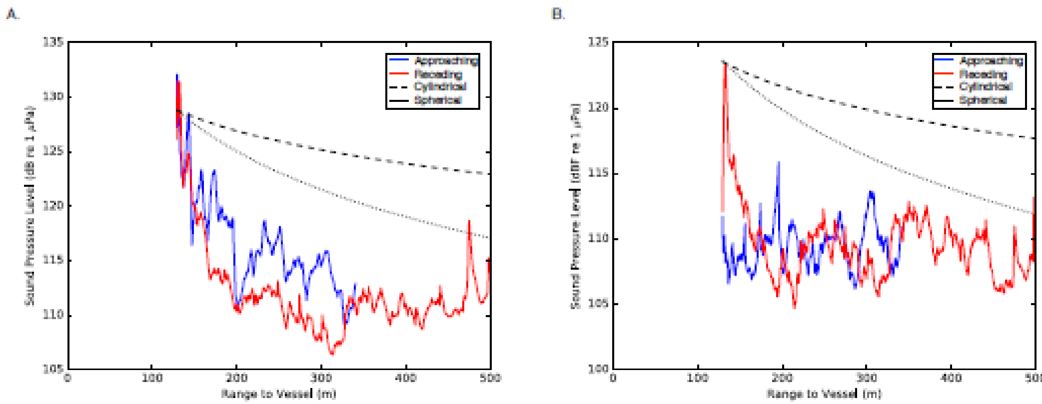

Figure 8. Recording 2 time-weighted average sound pressure level vs. vessel range for the outboard boat passage with spherical and cylindrical spreading curves. A. Unweighted sound pressure levels. B. F-weighted sound pressure levels.

C. RECORDING 3: TUGBOAT

A large tugboat pushing a barge southward on the Atlantic Intracoastal Waterway passed the NPR toadfish den location as shown in Fig. 9. The Atlantic Intracoastal Waterway is about 600 m from the toadfish den location, farther away than the channel used by the other two vessels recorded for this study. Figure 10A is a graph of the average power spectrum from the 10 s interval during which the tugboat sound was loudest. Figure 10B is a graph of the time-weighted average SPL values vs. time for the tugboat passage for both unweighted and F-weighted SPL values. The peak time-weighted average SPL and the SEL from the tugboat passage are in Table 1. We do not present a graph of the time-weighted average SPL vs. vessel range for the tugboat because the vessel passed very far from the hydrophone and the sound path was not direct when it passed behind the island.

Table 1. Peak time-weighted sound pressure levels and sound exposure levels from vessel recordings at Newport River (NPR) site.

		Peak SPL (dB re 1 μPa)		SEL (dB re 1 μPa)	
Recording	Vessel	Unweighted	F-Weighted	Unweighted	F-Weighted
1	Inboard	128	121	144	135
2	Outboard	132	123	144	132
3	Tugboat	124	117	143	137

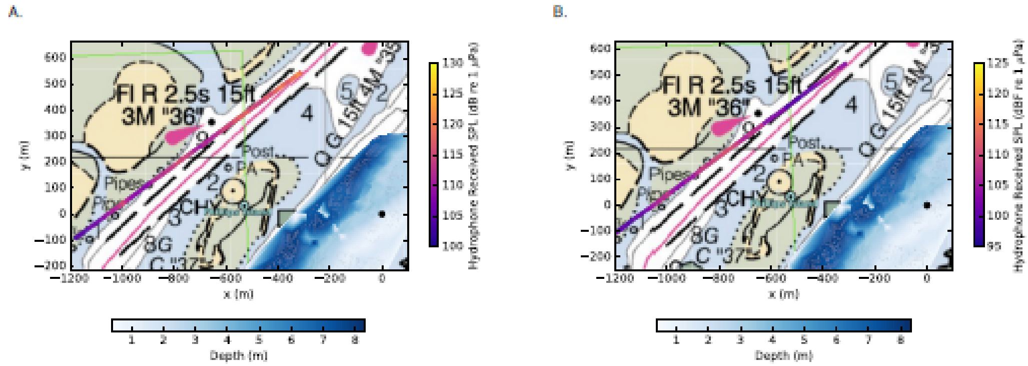

Figure 9. Tugboat path and received sound pressure level from Recording 3. The vessel path and a contour depth plot (blue tones, color bar below figure) are superimposed on a NOAA nautical chart of the study site. The hydrophone location is indicated by the black dot at $(x, y) = (0\,\mathrm{m}, 0\,\mathrm{m})$*. Barge positions when it was behind the small island from the hydrophone position were estimated by extrapolation because we were unable to record the vessel position at those times. The yellow-orange-magenta tones of the vessel path curve (color bar to the right of the figure) represent the received hydrophone time-weighted average sound pressure level (time constant* $0.125\,\mathrm{s}$*) when the vessel is at the location on the curve indicated by the color. A. Unweighted sound pressure levels. B.* F*-weighted sound pressure levels.*

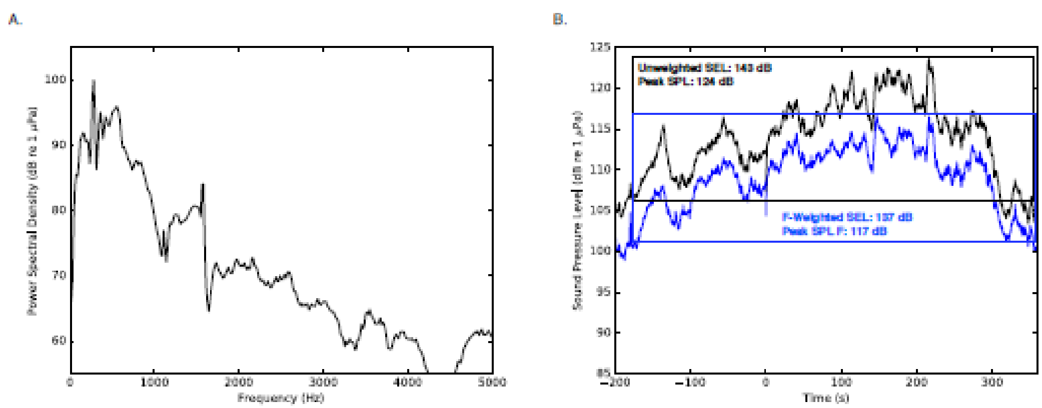

Figure 10. A. Recording 3 average power spectrum taken during the loudest $10\,\mathrm{s}$ *interval of the tugboat passage. The sampling frequency is* $44\,100\,\mathrm{Hz}$*, and the power spectra were taken with 2048-sample Hanning windowed FFTs with 1024-sample overlaps. B. Recording 3 time-weighted average sound pressure level (time constant* $0.125\,\mathrm{s}$*) vs. time for the tugboat passage. The black curve shows unweighted sound pressure levels with a peak of* $132\,\mathrm{dB}$ re $1\,\mu\mathrm{Pa}$ *and the blue curve shows* F*-weighted sound pressure levels with a peak of* $123\,\mathrm{dB}$ re $1\,\mu\mathrm{Pa}$*. The unweighted sound pressure levels above the background are inside the black rectangle resulting in an unweighted sound exposure level of* $144\,\mathrm{dB}$ re $1\,\mu\mathrm{Pa}$*. The* F*-weighted sound pressure levels that are above the background are inside the blue rectangle resulting in an* F*-weighted sound exposure level of* $132\,\mathrm{dB}$ re $1\,\mu\mathrm{Pa}$.

D. RECORDING 4: SOUTH MIDDLE MARSH

We also recorded sounds at the SMM toadfish den location. This site was protected from a vessel channel 1000 m away by sandbars. Vessels passing in the channel did not produce increased SPL values on our recordings. Figure 11 is a graph of time-weighted average SPL values vs. time, both unweighted and F-weighted for a recording from SMM. For reference, the time-weighted average SPL values from the NPR inboard vessel passage are shown on the same graph.

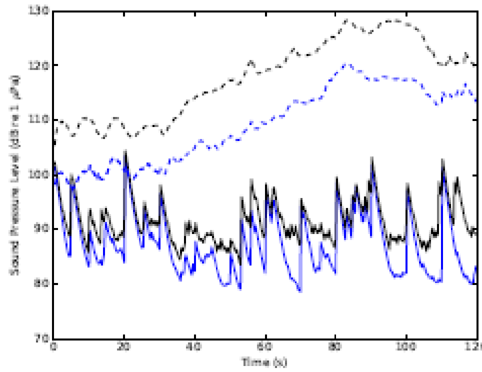

Figure 11. Time-weighted average sound pressure level (time constant* 0.125 s*) vs. time for the South Middle Marsh (SMM) toadfish den location. The solid curves are levels from a recording in SMM, and the dashed curves are from the recording in the Newport River (NPR) during Recording 1 shown in Fig. 4 for comparison. The black curves show unweighted sound pressure levels, and the blue curves show F-weighted sound pressure levels.

4. DISCUSSION

Vessels passing shallow toadfish den locations in nearby channels produce sounds that are audible to toadfish. The outboard boat produced the loudest sounds at the den location with a peak time-weighted average SPL of 132 dB re 1 μPa unweighted and 123 dB re 1 μPa F-weighted, while the inboard boat produced peak a peak time-weighted average SPL of 128 dB re 1 μPa unweighted and 121 dB re 1 μPa F-weighted. The more distant tugboat produced a peak time-weighted average SPL of 124 dB re 1 μPa unweighted and 117 dB re 1 μPa F-weighted. These SPL values are lower than levels we would expect to cause temporary threshold shifts or permanent hearing loss (Popper and Hastings, 2009), but it is possible that these sound levels could produce a behavioral response or could result in increased stress hormones in the fish. This noise could also cause masking of courtship calls in females looking to mate. The received SPL values produced by passing vessels in this study were as loud as the test sounds that produced the Lombard effect in oyster toadfish (Luczkovich *et al.*, 2016).

The NPR site was one of the noisy sites, and the SMM site was one of the quiet sites at which Krahforst *et al.* (2016) counted the numbers oyster toadfish embryos in dens during spawning season. That study found fewer embryos in dens at noisy sites than at quiet sites and also found an increase in the number of embryos in dens in noisy sites with increased distance from the vessel channel where the vessel noise is attenuated. The results presented here support the hypothesis that reduced embryo counts between in oyster toadfish dens at noisy sites is affected by vessel noise exposure. A possible cause of reduced embryo counts is masking–the males may not be heard by females in noisy areas leading to lowered reproductive output.

We suggest that the F-weighting of SPL values and SEL values is useful for assessing the possible impact of a sound on fish behavior, increase of stress hormones, and masking because the fish respond to sounds they can detect, not to those they cannot detect. In a recent study on the effectiveness of different frequency weighting functions on predicting human annoyance due to traffic noise (Torija *et al.*, 2016) found that different weighting functions were effective in different contexts. We suggest that a frequency weighting function that emphasizes audible frequencies is most appropriate for the behavior-response/stress context. Future studies are needed to confirm this. We recommend against reporting only F-weighted SPL values and SEL values. Instead, we suggest researchers report both the weighted and unweighted levels for completeness and for use in the proper context.

It is interesting that the SEL values from the different vessel passages were very similar. The inboard boat (Recording 1) produced an SEL of 144 dB re 1 µPa unweighted and 135 dB re 1 µPa F-weighted. The outboard boat (Recording 2) produced an SEL of 144 dB re 1 µPa unweighted and 132 dB re 1 µPa F-weighted, and the tugboat (Recording 3) produced an SEL of 143 dB re 1 µPa unweighted and 137 dB re 1 µPa F-weighted. The F-weighted SEL values of the inboard boat and tugboat are greater than that of the outboard boat because the outboard boat produced more sound in higher frequencies, which are suppressed in the F-weighting scheme and which are inaudible to oyster toadfish, than the other two vessels did. The tugboat SEL is comparable to the SEL values of the other two vessels even though it was not as loud (and much farther away) because it produced sound at levels above the background level for a much longer time than the other vessels did.

The received SPL vs. vessel range plots (Figs. 5 and 8) indicate that the attenuation of the sound produced by vessels in than channel can be greater than the cylindrical spreading losses expected in such extremely shallow water. This attenuation could occur as the sound propagates over the steep upward slope of the seafloor at the edge of the vessel channel. We cannot make strong conclusions about these measurements, though, because we did not have a reference hydrophone monitoring the source level of the vessels. Increases or decreases in received SPL could be the result of source level changes. A more comprehensive study of sound propagation from the channel into the shallows is needed better quantify the sound attenuation due to the channel edge.

Comparison of the sound recordings from the noisy NPR site with those from the quiet SMM site show that the loudest SPL values in the SMM recording (with no vessels present) are comparable to the quietest SPL values in the NPR recordings, which occurred at times when no vessels were observed in the vicinity. This supports the hypothesis that vessel noise is the main factor in the loudness of the NPR site.

We did not measure particle motion in this study. As a hearing generalist, oyster toadfish detect the particle motion portion of the sound (Popper and Hastings, 2009). There was most certainly particle motion associated with the sounds we recorded because there is particle motion component of a propagating acoustic wave, but we did not attempt to measure it. In a future study we will measure particle motion produced by vessel noise at toadfish den locations.

5. CONCLUSION

In this study we analyzed sounds recorded in very shallow oyster toadfish den locations at a noisy site near busy a vessel channel and at quiet site shielded from vessel noise. We found that sounds produced by passing vessels propagate into the den locations at the noisy site and recorded vessel noise loud enough to be audible to the fish. The SPL values and SEL values we recorded during vessel passages were not loud enough to produce temporary threshold shifts or permanent hearing losses in the fish, but they were loud enough to produce behavioral effects, masking, the Lombard effect, and possibly an increase of stress hormones. We introduced the F-weighting for assessing the effects of audible sound on fish. Further study is needed to determine if this frequency weighting is optimum.

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