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Quantifying changes in fish habitat use in coastal waters of Louisiana, USA: a hydroacoustic approach

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QUANTIFYING CHANGES IN FISH HABITAT USE IN COASTAL WATERS OF LOUISIANA, USA: A HYDROACOUSTIC APPROACH

A Dissertation

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DEDICATION

To all the fish who so often go unappreciated, those that made it, those that did not, and my best to the virtual ones, I wouldn't have made it this far without you.

And to Kallie Lynn, I dedicate to you, this fine piece of prose…

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ABSTRACT

The development of reliable tools for identifying essential fish habitat (EFH) has proven problematic. Knowledge of the distribution and biomass of fishes over discrete habitat types is a prerequisite for effective use of EFH in the management of important commercial and recreational fish species. Resolution of the influence of habitat type and environmental factors on the distribution of fishes is confounded by limitations of traditional sampling gears. To date, hydroacoustic technology has been widely accepted as a tool for surveying fishery resources; however few studies have implemented acoustics in ultra shallow (<2 m) coastal waters. Efforts should be made to utilize hydroacoustics for quantifying changes in fish distributions within estuarine environments given the benefits provided through acoustic technology (e.g. ease of deployment, reduced sampling effort, and non-invasive sampling attributes).

A technique was developed for acoustically sensing fishes in the shallow, turbid waters of Barataria Bay, Louisiana. A robust and lightweight remotely-controlled transducer platform was designed for deploying acoustic gear. Sources of scattering within the bay were identified through a series of exclosure net experiments designed to quantify potential effects of plankton and suspended solids on acoustic scattering. Analysis filters were developed to reduce the effects of bubble-induced noise, often observed during periods when wind speeds were greater than 4.5 m s^{-1}. Side-aspect acoustic target strength-length and target strength-weight relationships were derived for tethered individuals of bay anchovy (*Anchoa mitchilli*) and Gulf menhaden (*Brevoortia patronus*), with best fit models incorporating data from both species at the lateral perspective. Greater mean fish biomass and fish size were associated with higher salinity

and oyster shell habitat in Barataria Bay when compared to nearby soft-bottom habitats. Results of acoustic mobile surveys of the Freeport Sulphur Mine Artificial Reef are presented and illustrate the flexibility and adaptability of the acoustic system for monitoring spatial and temporal changes in fish distributions. I conclude that acoustics can be successfully implemented as a complementary survey technique and can serve as a valuable tool to fishery managers for quantifying fish distributions associated with estuarine habitats.

GENERAL INTRODUCTION

Links between coastal wetlands and fishery production have been well documented (Boesch and Turner 1984; Conner and Day 1987; Herke et al. 1992; Houde and Rutherford 1993; and Mitsch and Gosselink 1993). Estuarine systems, in particular, have been shown to serve as nursery habitat to many transient and resident fishes, including many important commercial and recreational species (Shenker and Dean 1979). The United States Congress recognized the importance of protecting habitats that are critical to fish life history with the Sustainable Fisheries Act (SFA) of 1996, and identified essential fish habitat (EFH) as those waters and substrates necessary for spawning, breeding, feeding, or growth to maturity (Benaka 1999). The SFA emphasized the need for an ecosystem management approach, creating the impetus for understanding the recruitment processes, growth, predator-prey relationships, migration patterns, and habitat use, not only of managed species, but also of their forage base (Wascom 1997).

Knowledge of the distribution and biomass of fishes within an estuarine system, in addition to growth and productivity, are needed to make effective management use of the concept of EFH. Four levels of information are necessary for identifying and classifying EFH: estimates of production rates of a species in relation to its habitat type (level 4), estimated growth, reproduction, and survival rates based on habitat utilization by life-history stage (level 3), relative density abundance by habitat (level 2), and species distribution (level 1) (NMFS 2003). It can be inferred that habitat utilization supporting optimal growth, reproduction, and survival, should result in the highest relative productivity for that organism. Therefore, areas supporting higher productivity and survival are indicative of increased habitat value (NMFS 2003). Given that estuarine

habitats are highly variable and complex, and the dependence of fish upon these available habitat types is not well understood (Able 1999; Minello 1999), it is difficult to effectively manage and protect habitats deemed valuable without sound scientific knowledge of the functional dependence of all life-history stages of fishes on available habitat.

The well-publicized loss of Louisiana's wetlands has led to a heightened awareness of the potential impact of both habitat loss and alteration on fishes. Louisiana is experiencing a wetland loss rate of approximately 77 km^2 yr^{-1}, despite restoration efforts (Barras et al. 2003), which accounts for an estimated 80-90% of the total wetland loss in the US (Dahl 2000; Raynie and Beasley 2000). It is anticipated that by the year 2050, Louisiana could lose an additional 1,200-2,500 km^2 of wetlands, resulting in a 53 km retreat of the current coastline in some areas (Raynie and Beasley 2000). These astounding figures can be attributed to a wide variety of environmental and geophysical processes such as global warming, eustatic sea level rise, storms, oil and natural gas extraction (levee and canal formation), subsidence, and leveeing of the Mississippi River (Mitsch and Gosselink 1993).

Despite the widespread land loss, Louisiana's coastal wetlands continue to be among the most productive in North America and support a $274 million commercial fishery (USDOC 2005) and a $1.2 billion recreational fishery (Gentner et al. 2001) with a combined retail value of $2.85 billon in 2003 (LCWCRTF 2006). Greater than 50% of US fisheries harvests are estuarine dependent, with a much greater fraction found within the Gulf of Mexico (GOM) (Houde and Rutherford 1993). Within the GOM, approximately 70-80% of fishery landings are from waters surrounding the Mississippi

delta (Nelson et al. 2002). Although important, fishery production is not the only benefit of healthy coastal wetland systems; these wetland areas also provide storm abatement, habitat for migratory waterfowl, nutrient cycling, and opportunities for eco-tourism (Mitsch and Gosselink 1993). The lack of a sound scientific understanding of the effects of habitat alterations on the distribution of fishes further supports the need for evaluation and possible classification of EFH.

Essential fish habitat is a simple concept to embrace, but very difficult to quantify. This may be attributed to the lack of a universal standard by which to quantify the components of EFH as stated in the SFA (Benaka 1999). The lack of a well-defined understanding of the functional links between habitat value and fish utilization may be partly attributable to gear collection biases; collectively a function of selectivity, gear avoidance, or ineffective gear performance. Therefore the development of sampling techniques that afford researchers the ability to collect data on the fish community at small spatial scales (habitat-specific) would greatly improve our understanding of the role of habitat type within a fish life history context.

The use of hydroacoustics as a tool for monitoring changes in fish distributions has been widely accepted in the scientific community due to advances in technology and its many advantages over traditional net surveys including: high resolution spatio-temporal data, reduction in gear bias, reduction in survey effort, and minimal ecological impact (Simmonds and MacLennan 2005). However, despite the advantages offered through the use of acoustics, methods for allocating acoustic data at a species-specific level have not yet been fully developed (Guillard et al. 2004). Additionally, biological data are often necessary for validation (MacLennan and Simmonds 1992), acoustic range

and data quality are adversely affected by environmental conditions (Kubecka 1996), and successful data collection and interpretation require trained personnel. In spite of these caveats, hydroacoustic technology may prove to be a useful complimentary tool in the identification of the function and relative value of available habitats to fish, ultimately leading to the use of acoustics in the identification of EFH.

To date, hydroacoustics have been widely used in rivers (Burwen and Fleischman 1998; Di Iorio and Grossman 2002), lakes and reservoirs (Brandt et al. 1991; MacLennan and Simmonds 1992; Rudstam et al. 1993; Rudstam et al. 1999), and deep-water systems (Lima and Castello 1995; Stanley and Wilson 1998) to estimate fish abundance. However, very few studies have attempted to utilize hydroacoustics for estimating biomass and density of fish communities in ultra-shallow waters (<2 m) (Kubecka 1996; Kubecka and Wittingerova 1998). In shallow waters, acoustic range and subsequently, data quality, are primarily functions of water depth, particularly in horizontal-aspect surveys, and care must be taken to limit unwanted scattering from boundaries (water surface and water-substrate interface), to maximize survey efforts.

This project was a portion of a larger effort utilizing a multi-gear approach (gill nets, seines, push trawls, and hydroacoustics) for evaluating fish distributions at reference points within Barataria Bay, Louisiana. Through a cooperative effort between Louisiana State University and the Louisiana Department of Wildlife and Fisheries (LDWF), I was able to conduct routine sampling at established LDWF stations for an integrated approach to evaluating gear performance and the potential for incorporating acoustics into LDWF sampling strategy. The focus of my dissertation was to develop a method for using horizontal-aspect hydroacoustics to monitor changes in fish distributions at established

survey stations in Barataria Bay, and to ascertain the potential for predicting the gillnet catches through various metrics (e.g. density, biomass, abundance, effort). A brief synopsis of the dissertation follows.

The successful collection of acoustic data required a robust platform for reliably and consistently deploying the acoustic gear while providing the ability to manipulate the transducers to accommodate fluctuations is water level, substrate type, and environmental conditions. In Chapter 1, I describe the development of this platform which was designed to standardize gear deployment and optimizing data quality and range. The first step to interpreting acoustic data is the recognition and identification of potential scattering sources within survey regions. In Chapter 2, I describe field experiments used to identify these scattering sources and present analysis techniques for quantifying changes in acoustic fish density, biomass, and size distributions for the survey in March 2004. In Chapter 3, I develop empirical models for bay anchovy (*Anchoa mitchilli*) and Gulf menhaden (*Brevoortia patronus*), relating both fish length and weight to target strength to enhance efforts to describe the distributions of these two dominant and important forage species (Thompson and Forman 1987; Rozas and Reed 1994; Thayer et al. 1999; Jones et al. 2002). In Chapter 4, I use similar analysis techniques presented in Chapter 2 to analyze the seasonal changes in fish biomass, density, and size distributions in Barataria Bay. Additionally, I incorporate the models developed in Chapter 3 for describing bay anchovy and Gulf menhaden TS distributions. Lastly, in Chapter 5, I present the use of acoustics for estimating seasonal changes in fish biomass, density, and area of influence associated with the Freeport Sulphur Mine Artificial Reef, the largest intentional artificial reef in the world, located approximately 11 km southeast of Barataria Bay.

The overall objective of this project was to assess the feasibility of the use of acoustics in ultra-shallow estuarine waters (<2 m) and to develop a method for quantifying changes in fish distribution associated with estuarine habitats in Barataria Bay, Louisiana. Information and methods derived during this study will be used in future efforts of evaluating and identifying EFH of estuarine fishes in coastal Louisiana.

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CHAPTER 1: A LIGHTWEIGHT TRANSDUCER PLATFORM FOR USE IN STATIONARY SHALLOW WATER HORIZONTAL-ASPECT ACOUSTIC SURVEYS

1.1 INTRODUCTION

There has been recent interest in the use of hydroacoustics for surveying fish distributions in shallow waters (<5 m water depth) (Kubecka and Wittingerova 1998; Mous et al. 1999; Krumme and Saint-Paul 2003). The physical limitations of the environment require that transducers be deployed and aimed horizontally to maximize survey range. Although most shallow water studies have used mobile survey techniques for monitoring both abundance and distribution of fish, data quality can be adversely affected both by vessel motion and sea state (Mous et al. 1999; Knudsen and Sægrov 2002). In addition, fish avoidance may contribute to biases in estimates (Guillard et al. 2004; Drašík and Kubecka 2005).

In estuarine systems, stationary acoustic surveys are useful for describing the distribution of ensonified fishes, while avoiding some challenges presented by mobile surveys (Trevorrow 1998; Mous et al. 1999). To date few designs have allowed both for stationary acoustic sampling in shallow waters and for remote control of transducer position and orientation (Kubecka et al. 1994; Krumme and Saint-Paul 2003; Krumme and Hanning 2005). Furthermore, previous designs have not been capable of quick retrieval and deployment.

I developed two transducer platforms for quickly deploying a side-looking transducer array over shallow estuarine habitats to quantify fish density and abundance associated with discrete habitat types. This design required that the platform be light enough for single-user deployment, while remaining stationary in the presence of tidal

and wind-driven flow characteristic of coastal Louisiana. Additionally, I required full mobility of the transducer array to account for water level fluctuations and to maximize beam range.

1.2 METHODS AND MATERIALS

1.2.1 Platforms

The platform base (Figure 1.1) was constructed of hollow aluminum tubes, welded for rigidity, with a 1 m^2 footprint. Two vertical aluminum tubes were welded to the center support of the platform base to serve as a guide for the sled assembly (SA, Figure 1.1). The SA was constructed from a 30 cm^2 aluminum plate to which a motor assembly was attached (Figure 1.2). An ACME threaded stainless steel rod (SR, Figure 1.1) was passed through a threaded collar (TC) in the center of the sled to raise and lower the SA, allowing for full vertical range of motion within the water column. A hand wheel (HW, Figure 1.1) was attached to the top of the SR to quickly adjust transducer elevation within the water column. Each full turn of the wheel resulted in a net movement of 2.5 cm of the SA.

A waterproof electric gear motor, interfaced with a magnetic limiter switch (12-48 VDC; Deep Ocean Engineering, Inc.), was mounted to the sled assembly to adjust transducer pitch relative to the water surface. The motor assembly was remotely actuated by a momentary switch wired into a top-side box (Figure 1.3), and was configured to adjust the pitch of the transducer array at 1° s^{-1}. Transducer heading, pitch, and roll were monitored in real-time by updates from a TCM2 card (4800 Baud; ±5 VDC; PNI Corp.) mounted to the transducer array (Figure 1.2). The TCM2 card was configured to transmit

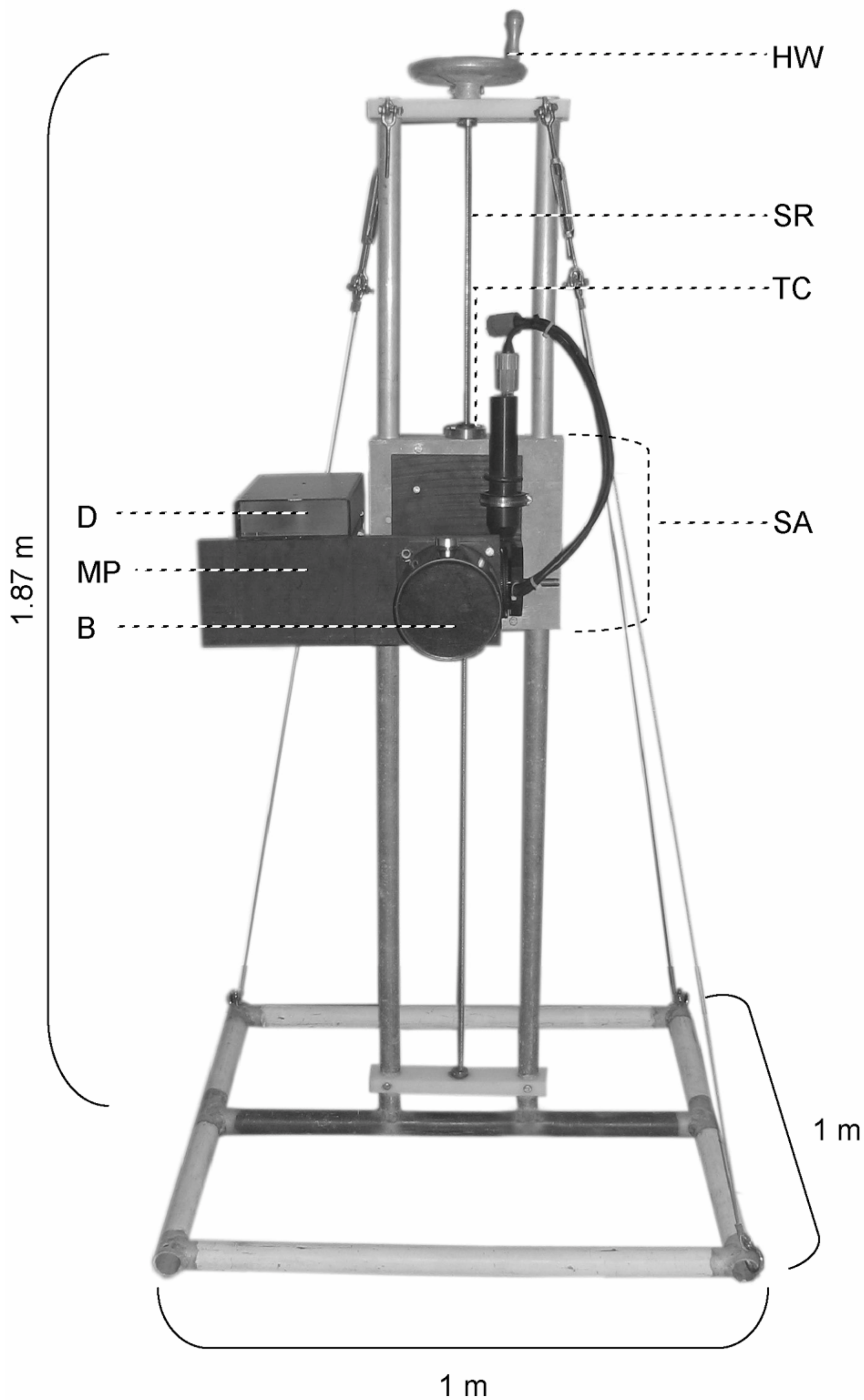


Figure 1.1. Transducer array platform, equipped with a BioSonics 420 kHz split-beam transducer (B) and DIDSON (D). Acoustic gear are mounted onto the sled assembly (SA) with the mounting plate (MP). Legend: HW: hand wheel, SR: threaded stainless steel rod, TC: threaded collar. Each full rotation results in a net movement of 2.5 cm.

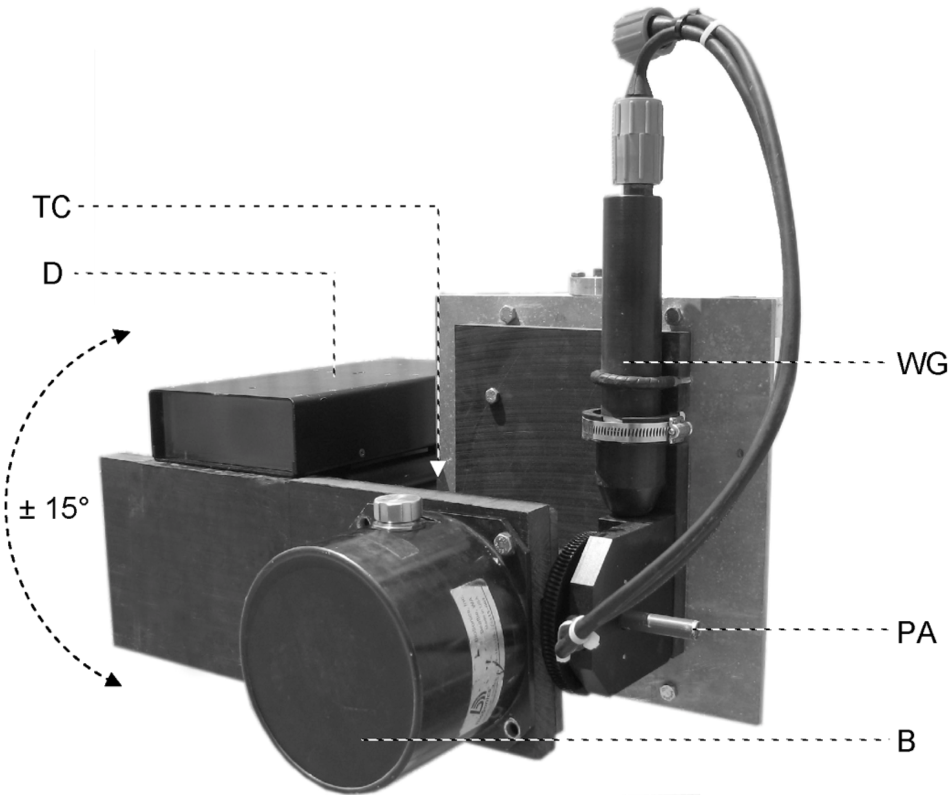


Figure 1.2. Image of sled assembly, containing electric worm gear (WG) enclosed in a watertight housing. The gear interfaces with a magnetic limiter switch (ML) providing the capacity for ±15° of pitch manipulation. The transducer array (BioSonics 420 kHz split-beam (B) and DIDSON (D)) is mounted onto the sled assembly with the mounting plate (MP) and pivots along the pivot axis (PA). The TCM2 card (TC) is attached behind the mounting plate.

data through the RS-232 serial COM port of a laptop housed within the top-side box. Data were time referenced and saved as a text file for use in data analysis. The motor assembly was capable of adjusting transducer pitch from ±15°, although the assembly could be manipulated to provide a greater range of pitch if necessary. The range in mobility allowed for optimization of the placement of the acoustic beam within the water column to reduce boundary effects common in shallow waters and to maximize survey range (Trevorrow 1998).

1.2.2 Top-side Box

Unpredictable meteorological conditions require a weather resistant container to protect sensitive electronic equipment and to house the computers used for data collection. A top-side box, 189 L capacity storage box (Contico; Figure 1.2), was weatherproofed and outfitted with a ventilation fan, battery charger, volt meter, light source, and four deep-cycle marine batteries (12 VDC). The components of the top-side box, including the transducer motors, were powered by two batteries wired in parallel. The BioSonics equipment and laptop computers were hardwired into the box and received power from two batteries wired in parallel (12 VDC). The remaining two batteries were wired in series to provide power for a dual-frequency identification sonar (DIDSON, 24 VDC) unit, used to collect acoustic images of fish. The sonar equipment, computers, and transducer motors could be powered with the batteries for greater than 12 hr at a time and were charged at the end of each day.

1.2.3 Survey Methods

A BioSonics 420 kHz split-beam (2ºx 6º) transducer and a DIDSON (1.1/ 1.8 MHz) were bolted to a high density Delrin mounting plate (MP, Figures 1.1 and 1.2) and

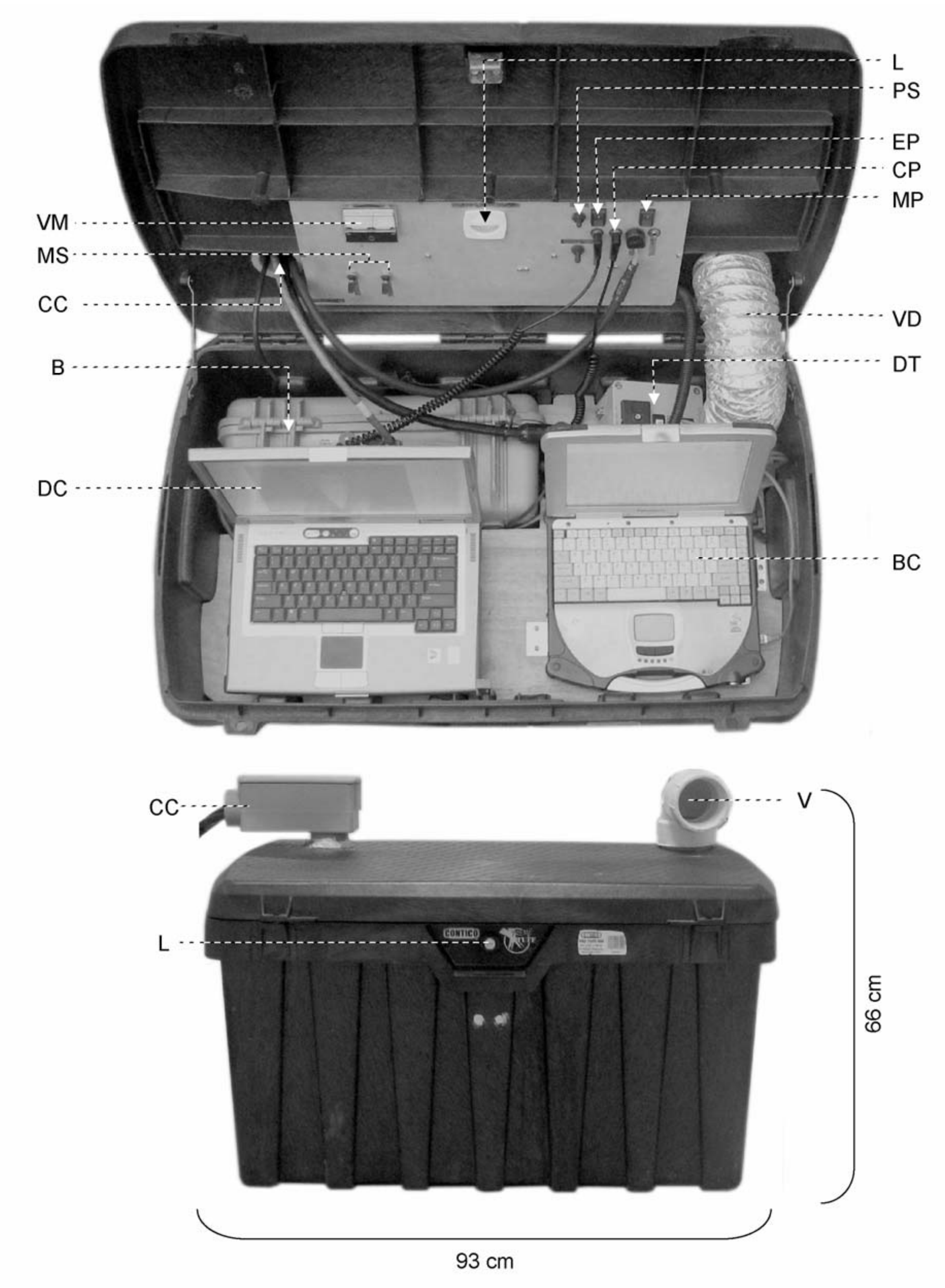
attached to the SA. Platforms were routinely deployed from a 7 m pontoon boat in water depths less than 2 m. Water depths were measured, the transducer array was centered in the water column, and the transducer pitch was adjusted remotely to maximize the sampling range of the BioSonics equipment.

1.3 RESULTS AND DISCUSSION

Transducer platforms provided flexibility for stationary and stable acoustic monitoring, particularly in ultra-shallow waters (<2 m) characteristic of coastal Louisiana. Platforms have been in use for more than 2 years and have performed well in challenging conditions, particularly in areas of tidal flow (tidal channels), where current speeds average 0.5- 0.8 m s^{-1} (Marmer 1948; Byrne 1976). Deployment, data collection, and retrieval were conducted by a single user, although a second person was on board for safety. Integration of the top-side box allowed for use on small open survey vessels (3- 7 m) where a consistent power supply can often be unreliable. The platforms allowed for easy and fast adjustments to the vertical position and pitch of the acoustic beam relative to the water surface. Transducers were easily repositioned to maximize range and data quality as water levels, current direction, and velocity fluctuated. I found that data quality and range was best when transducers were centered in the water column and aimed 1-2° upwards from horizontal. The ability to fine tune the angle and vertical position of the transducers in the water column often enabled high quality data to be collected out to 30 m in water depths of 2 m.

Habitat type did not hinder either the performance or placement of the transducer platforms. The open base design provided stability when deployed over oyster shell.

Figure 1.3. Image of weatherized top-side box in two orientations: (a) bird's eye view and (b) frontal view. Legend: VM: volt meter, MS: momentary motor switches for each platform, CC: cable chase, B: BioSonics 420 kHz DE-X echosounder, DC: DIDSON computer, LS: lamp, PS: main power switch, EP: BioSonics echosounder power switch and input jack, CP: input jack for computer power, MP: motor power switch and input jacks for each platform, VD: vent duct, DT: DIDSON top-side unit, BC: BioSonics computer, V: vent, L: locking latch. Dimensions for the height, width, and depth of the top-side box are shown. Batteries, battery charger, and ventilation fan are secured below computers.


L
PS
EP
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MP
VM
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DT
B
DC
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V
L
CONTICO
66 cm
93 cm

Retrieval of the platforms was more difficult over the soft unconsolidated mud habitat as the weight of the platforms often caused them to sink into the substrate. Regardless of habitat type, platforms were well balanced even in the presence of tidal flow and turbulent, choppy-wave conditions.

The ability to precisely aim the acoustic beam has greatly improved our ability to consistently collect high quality acoustic data in shallow waters, regardless of substrate type. The integration of a remotely actuated motor has enhanced data quality when compared to data collected prior to the use of the platforms. Wind speeds greater than 6 $m\ s^{-1}$ often result in a high degree of entrained air bubbles that can impede practical use of acoustic equipment in shallow waters and may exceed post-processing filter techniques. Although data collected during intemperate weather is not suitable for analysis, the platforms were well adapted to the adverse environmental conditions and are expected to perform well in deeper water settings.

Future improvements include the use of solar panels integrated into the surface of the top-side box, permanent integration of minicomputers with small flat panel displays dedicated to data collection, eliminating the need for laptop computers and reducing system power requirements, and installation of environmental sensors to collect physico-chemical data. Modifications to the current configuration could significantly reduce the power budget and allow for extended deployments (multiple days). Furthermore, wireless technology could serve for remote data transfer to facilitate continuous long-term monitoring in remote coastal locations.

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CHAPTER 2: HYDROACOUSTICS AS A TOOL FOR ASSESSING FISH BIOMASS AND SIZE DISTRIBUTION ASSOCIATED WITH DISCRETE HABITATS IN A LOUISIANA ESTUARY

2.1 INTRODUCTION

Knowledge of the distribution and biomass of fishes in an estuary is a prerequisite for effective ecosystem management and serves as a metric in quantifying essential fish habitat (EFH). Resolution of the influences of physical and biological factors on fish distributions is confounded by limitations (e.g. gear bias) of traditional fish sampling methodologies. Essential fish habitat is a simple concept to embrace, but very difficult to quantify. To make effective use of the concept of EFH, efforts should be made to protect habitats that differentially favor production of fishes through management actions. Furthermore a universal standard is needed to quantify and delineate the components of EFH as defined in the Sustainable Fisheries Act of 1996.

Most sampling techniques (e.g. nets and traps) have inherent biases that may render fishery assessments misleading (Hubert 1996) and therefore the need exists to develop a standardized technique, such as the integration of hydroacoustics and net collections, to quantify changes in fish distributions for management strategies to be effective. Although the level of information afforded through acoustic and biological sampling does not fulfill all of the classification criteria of EFH, it will help to establish a baseline for comparisons within and between estuarine systems. My goal was to evaluate the use of hydroacoustics and biological sampling to develop a method for assessing fish distribution and biomass in the ultra-shallow waters (<2 m) of coastal Louisiana.

Hydroacoustics has been widely used in rivers (Burwen and Fleischman 1998), lakes and reservoirs (Rudstam et al. 1999; Simmonds and MacLennan 2005), and deep-

water systems (Lima and Castello 1995; Stanley and Wilson 1998) as a tool for surveying fishery resources. However, few studies have been conducted in water depths less than 5 m. Shallow-water (>5 m water depth) horizontal surveys have recently been made possible due to advances in transducer and post-processing technology, particularly the development of narrow acoustic beams (Kubecka 1996; Kubecka and Wittingerova 1998; Simmonds and MacLennan 2005). In shallow waters, horizontal beaming is often chosen over vertical beaming because vertical sampling is ineffective (Knudsen and Sægrov 2002) due to fishes being distributed near both the water surface and sediment water interface (Kubecka and Wittingerova 1998). Knudsen and Sægrov (2002) demonstrated that fish presence was underestimated by 20-100% with vertical beaming in three Norwegian lakes when compared to horizontal beaming in shallow waters (Kubecka and Wittingerova 1998).

Commonly cited advantages of acoustics include: a non-invasive survey technique capable of acquiring high-resolution spatio-temporal data with reduced sampling effort and a potential capacity for surveying large areas (Simmonds and MacLennan 2005). Limitations of hydroacoustic surveys include: taxonomic ambiguity which requires biological data to verify species composition; acoustic range and data quality are adversely affected by environmental conditions; and successful data collection and interpretation requires highly trained personnel. Additionally, shallow water surveys are particularly susceptible to physical and environmental conditions as horizontal acoustic range is largely a function of water depth, and the interfaces of the sediment and the surface can elicit strong scattering responses that may be confused with scattering from nearby fish targets. However, some limitations may be reduced when care is taken

to aim the acoustic beam to maximize sampling range in shallow waters (Pedersen and Trevorrow 1999).

Two standard outputs are derived during the processing of hydroacoustic data. Acoustic volume backscattering strength (S_v), an integration of the acoustic energy scattered from discrete targets per unit volume of water (MacLennan et al. 2002), is often considered as a proxy for fish biomass (MacLennan and Simmonds 1992). Volume backscattering strength (S_v) is usually compared and indexed with biological data (Swartzman and Hickey 2003). Target strength (TS) is an acoustic measure of fish size (MacLennan and Simmonds 1992) and can be used under certain conditions both to estimate length-frequency relationships of ensonified fish and to estimate relative fish density. Volume backscattering strength can be scaled by TS to derive estimates of both fish density and biomass (Simmonds and MacLennan 2005).

My ultimate goal was to use horizontal-aspect split beam acoustics to quantify fish biomass and distribution in shallow estuarine waters of Louisiana. In doing so, it was necessary to develop a methodology and determine the potential effect of non-nektonic scatterers on acoustic estimates. Therefore, I quantified the acoustic scattering attributed to non-nektonic sources (e.g. plankton and suspended solids) in Barataria Bay, LA, and considered their contribution to the overall observed scattering in the estuary. Additionally, I developed a method to quantify fish biomass associated with hard and soft bottom habitats in a Louisiana estuary. I tested the null hypotheses that observed acoustic scattering was not attributed to fish and that acoustic biomass estimates did not vary with salinity or habitat type within the estuary.

2.2 METHODS AND MATERIALS

2.2.1 Study Area

Barataria Bay (Figure 2.1), part of the Barataria-Terrebonne estuarine complex, is characterized as an interdistributary estuarine-wetland system with an area of approximately 4,100 km^2 and an average depth of 2.3 m (Conner and Day 1987). I recognized two main types of subtidal habitat in Barataria Bay; hard (oyster reef) bottom and soft bottom (sand/mud) habitat.

Survey stations were established adjacent to the Barataria Bay Navigation Channel, along a north-south salinity gradient at sampling sites established for a Louisiana Department of Wildlife and Fisheries long-term fisheries monitoring program. Survey stations and their measured salinity (March 2004) included Fisherman's Point (FP; low salinity, 2.9 ‰), Manila Village (MV; mid-salinity, 12.8 ‰), Queen Bess Island (QB; high salinity, 25.3 ‰), and Grand Terre Island (GT; high salinity, 26.0 ‰) (Figure 2.1). Each survey station contained adjacent areas of hard and soft bottom substrates identified by reflectance intensity from a mosaic generated during a recent side scan sonar survey (Allen et al. 2005). An exception was the GT station, which did not contain significant shell habitat, therefore a corresponding hard bottom station was established nearby at QB due to its abundance of oyster shell habitat, geographic proximity (<3 km), and similar salinity level (25.6 ‰). Acoustic equipment was deployed during daylight hours at both habitat types at each survey station.

2.2.2 Acoustic Array

Acoustic backscattering data were collected with a Biosonics DE-X digital echosounder equipped with two 420 kHz elliptical split-beam transducers (Table 2.1)

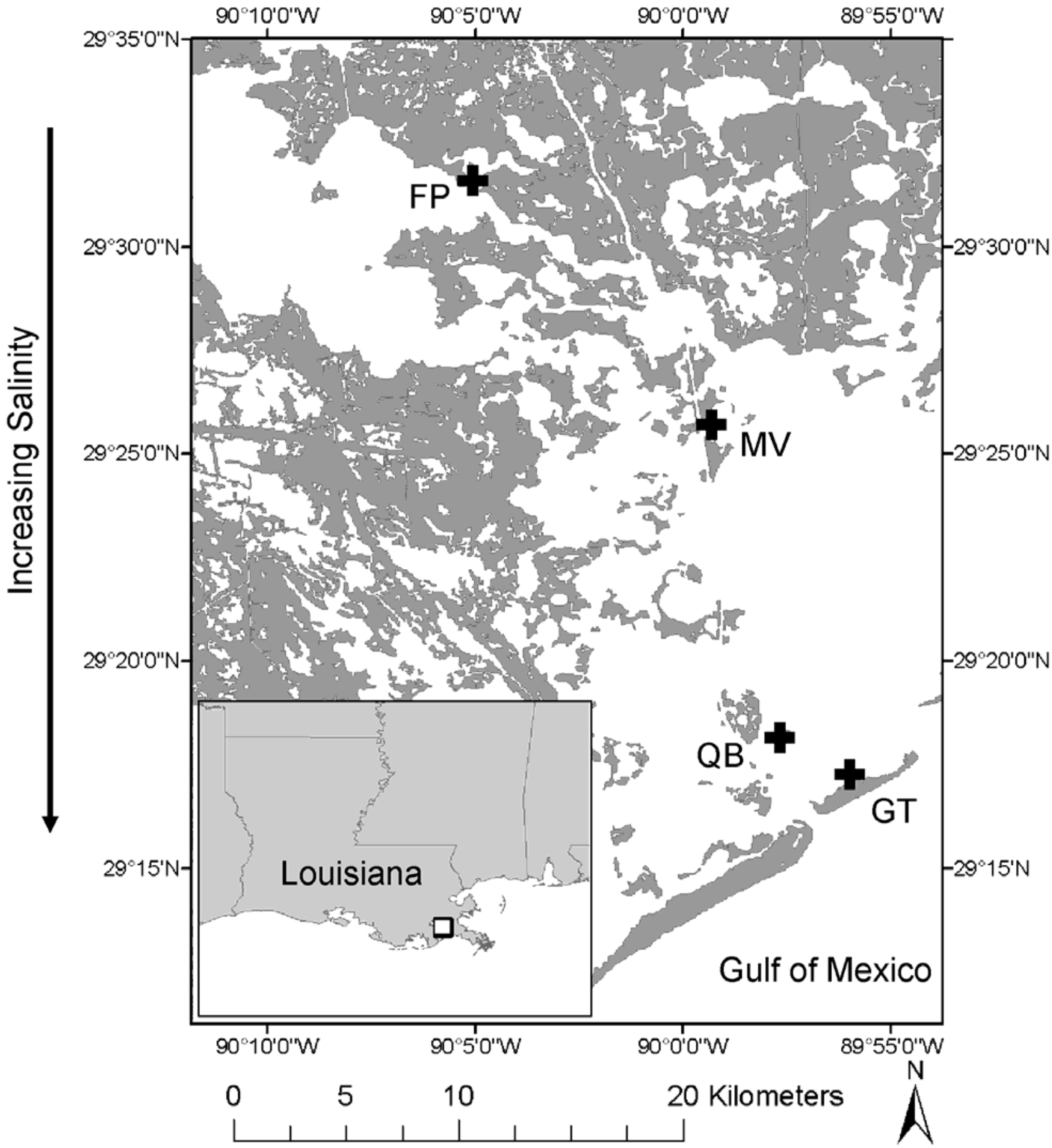

Figure 2.1. Sample stations located in Barataria Bay, LA in the northern Gulf of Mexico. Land is characterized by gray shading and water by open areas. Survey stations are identified and correspond to current Louisiana Department of Wildlife and Fisheries monitoring stations: Fisherman's Point (FP), Manila Village (MV), Queen Bess Island (QB) and Grand Terre Island (GT). Scale bar represents distances of larger regional map.

Table 2.1. Echosounder, transducer, and analysis parameters used in analyses. Experiment 1 refers to exclosure net experiment. Experiment 2 refers to the settings used in analyses of effects of salinity and habitat type on fish biomass and size distribution in Barataria Bay, LA.

Sonar system parameters		
BioSonics DE-X split beam echosounder:	Experiment 1	Experiment 2
Operating frequency	420 kHz	420 kHz
Pulse duration	0.4 ms	0.4 ms
Pulse rate, per transducer	5 Hz	5 Hz
Transducer parameters		
2-way beam angle (ψ)	-24.47 dB	-24.47 dB
Collection threshold	-75 dB	-75 dB
Major-axis beam width	6.2 º	6.2 º
Minor-axis beam width	2.4 º	2.4 º
Echoview analysis parameters		
Analysis thresholds		
S_v	-70 dB	-60 dB
TS		-55 dB
Single target detector		
Pulse length determination level		6 dB
Minimum normalized pulse length		0.6
Maximum normalized pulse length		1.7
Maximum beam compensation		12 dB
Maximum standard deviation of:		
minor-axis angles		0.8
major-axis angles		0.8

calibrated by the standard sphere method (Foote et al. 1987). Elliptical transducers were selected for this study to maximize the horizontal sampling distance and increase the ensonified volume. Acoustic data were visualized and stored on a laptop computer running BioSonics Acquisition Program (4.1). Approximate acoustic resolution of single targets was 0.3 m following $R = c\tau/2$ (Simmonds and MacLennan 2005), where c=speed of sound in water (1500 m/s) and τ is pulse length duration (0.4 ms). Transducers were multiplexed at a sample rate of 10 Hz with an effective sample rate of 5 Hz per transducer. Water temperature, salinity, and depth were measured (YSI, Model 85) and recorded for correct calculation of sound speed and absorption coefficients. The echosounder, computer, and power source were placed in a water resistant topside box and secured on the deck of a 7 m modified pontoon boat (see Chapter 1). Transducers were mounted to a remotely controlled platform as described in Chapter 1.

2.2.3 Identification of Scattering Sources-Experiment One

I developed an *in situ* method for excluding targets from the ensonified water volume to quantify the potential effects of acoustic backscattering by non-nektonic and non-biological sources. An exclosure net (Figure 2.2) was constructed of 2 mm nylon mesh to exclude all scatterers >2 mm (e.g. fish and invertebrates) and to allow all potential scatterers <2 mm (e.g. plankton and suspended solids) to pass through. The collapsed net was deployed in the water, opened, and anchored. The exclosure net was deployed at the GT survey station (Figure 2.1) on 26 October 2004 and 16 August 2005. During the first deployment, transducer one (T_1) was placed directly inside the net yielding an effective sampling distance within the net of approximately 4 m; however, during the second deployment, T_1 was placed directly outside the net yielding a sampling

distance of 5 m within the net (Figure 2.2). During both deployments, T_1 was positioned to ensonify the water volume inside the net in addition to the water volume beyond the net wall. Transducer 2 (T_2) was placed in open water next to the net to quantify scattering from all possible targets distributed throughout the water column near the net (Figure 2.2).

Data were collected for 2 hours yielding approximately 36,000 pings per transducer. Raw acoustic data were imported and visualized in Echoview 3.4 (SonarData Pty Ltd.) with an S_v analysis threshold of -70 dB (Table 2.1). Prior to echo integration, a grid was applied to the data establishing 5 min x 5 m analysis cells. Estimates of the volume backscattering coefficient (s_v), the linear counterpart of S_v (S_v=10* $\log_{10}$ (s_v)) used for all calculations involving S_v (MacLennan et al. 2002), were derived in Echoview following standard echo integration techniques (MacLennan and Simmonds 1992). Integration reports were generated for each analysis cell in Echoview and exported into SAS (v 9.0, SAS Institute 2003) for further analysis. Nomenclature of acoustic variables (e.g S_v, s_v, TS, σ_{bs}) follows MacLennan et al. (2002).

2.2.4 Fish Biomass and Length Estimation- Experiment Two

The acoustic array was deployed over discrete hard and soft bottom habitats to quantify relative changes in habitat-specific acoustic fish biomass, fish size distribution, and mean fish size in Barataria Bay. Habitat type was identified in the field by viewing real-time positional data overlaid upon side scan imagery of Barataria Bay in ArcPad (Allen et al. 2005). Habitat type was further verified by poling with an aluminum sounding pole to ensure that habitat specific data were collected (Allen et al. 2005). Monthly surveys were conducted from June 2003 to May 2004, excluding November and

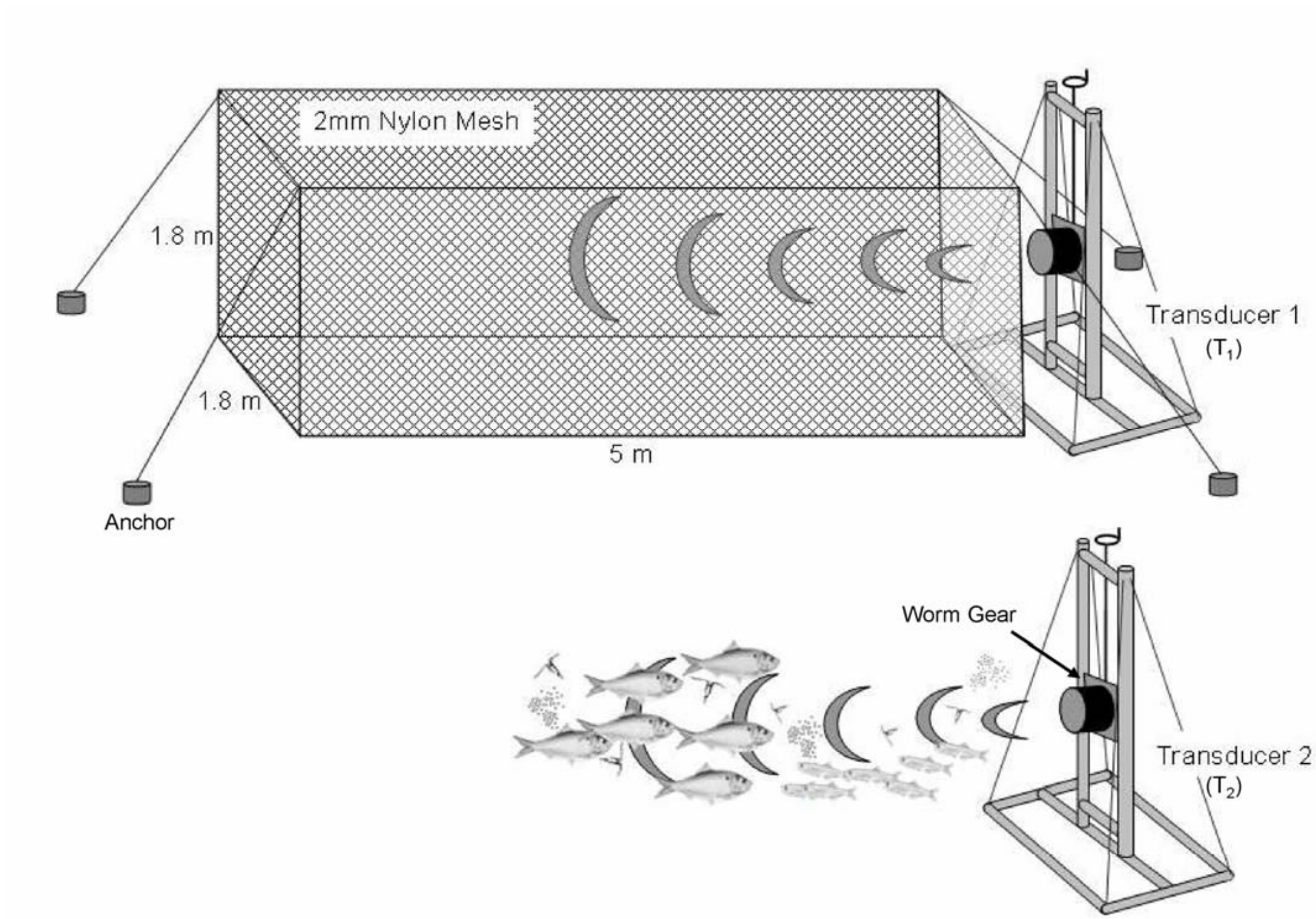

Figure 2.2. Diagram of exclosure net used for excluding targets greater than 2 mm in size (e.g. zooplankton and suspended sediments). Transducer placement is indicated by transducer 1 (T_1) and transducer 2 (T_2); T_1 ensonified the water volume inside the net (plankton and suspended solids) and T_2 ensonified the water column adjacent to the net (fish, plankton, and suspended solids). The net was deployed and anchored with weights on the bottom. Transducers platforms were equipped with a worm gear for manipulating transducer position.

December 2003 (inclement weather and equipment malfunction); data from the March 2004 survey are presented here to describe a technique for acoustically assessing differential habitat use of estuarine fish in ultra-shallow water (<2 m).

2.2.4.1 Echoview Setup and Integration

Acoustic data were organized and pre-processed in Echoview for quality control. Data were edited to exclude unwanted reverberation (entrained air and surface/bottom scatter) using the schools module that allows for fine scale object selection within the echogram. Sound speed and absorption coefficients were calculated in Visual Acquisition and entered in Echoview to account for the effects of temperature and salinity on the acoustic data.

A filtering technique was developed using the virtual echogram module in Echoview to enhance acoustic signals that were susceptible to inappropriate thresholding due to low signal-to-noise ratios (Figure 2.3). A 7x7 convolution matrix with coefficient (i,j)=1 for all (i,j) was applied to the thresholded TS echogram. The role of the 7x7 convolution was to broaden and enhance peaks in the data corresponding to the strongest targets in the TS echogram. The convolution spreads the data laterally in x and y dimensions, encompassing data surrounding the maximal peaks that would otherwise be removed by the threshold. Instead of using a threshold directly, a bitmap was created corresponding to all values in the convoluted data that exceeded a -60 dB threshold. The resulting bitmap was then applied to the original S_v data through the mask operator, providing an S_v echogram for echo integration analyses with corresponding “0” bitmap values removed (Figure 2.3). The success of this filtering method is dependent upon appropriate thresholding and is adequate for use in data analysis at relatively short

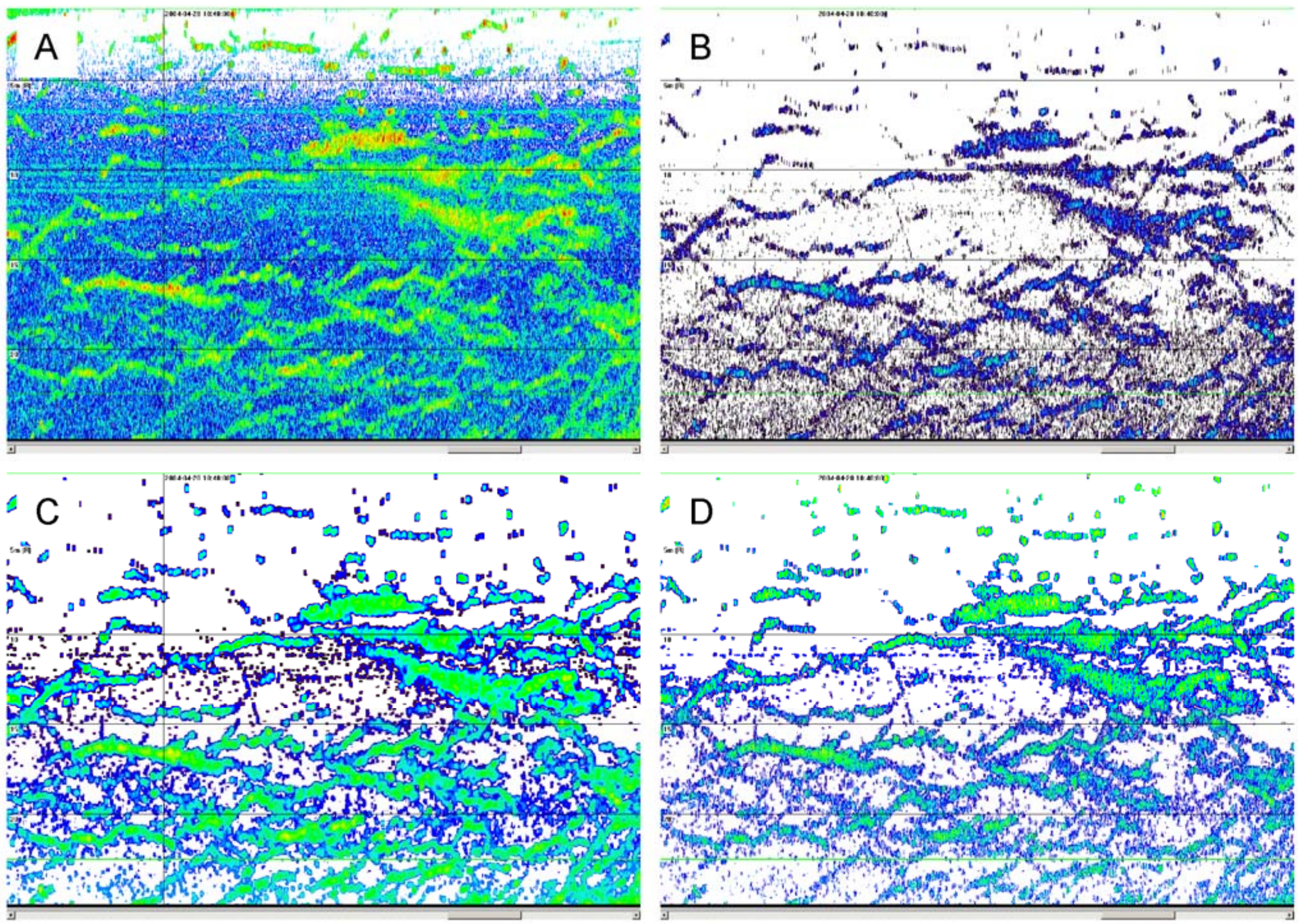

Figure 2.3. Analysis filter, developed with the virtual variable module in Echoview. Figure illustrates performance of filter with 3 minute sample echograms of each variable. A) unthresholded S_v, B) thresholded target strength echogram, C) target strength convolution echogram, and D) final S_v mask echogram used for generating integration reports.

integration ranges (<30 m) common in shallow water surveys. The method utilizes a key property of the TS raw data: that the 40 log R spreading correction present in TS raw data (as opposed to 20 log R spreading correction present in S_v raw data) correctly accounts for spreading loss for individual targets, yielding above-threshold values in the TS data where there may have been below-threshold values in the S_v raw data.

A 5 min x 5 m grid was applied to acoustic data in Echoview and an analysis threshold of -60 dB was applied for biomass calculations. Indices of biomass (S_v) were generated by habitat type for each survey station along the salinity gradient. Integration reports were calculated for each cell in Echoview and exported into SAS for further analysis.

Weighted means of S_v were generated in SAS by weighting s_v within each cell by the actual number of acoustic samples recorded. Weighting was necessary to account for slight variability in sample size observed within each cell, and to ensure the computed s_v reflected the true contribution of scatterers relative to sample size.

2.2.4.2 Fish Biomass Calculations

It is often preferable to describe acoustic data with units that are more convenient and interpretable than the decibel (dB). Consequently, acoustic data were used to derive estimates of relative biomass (g m^{-3}). A series of algorithms based upon the widely used function of the relationship of fish weight W (g) to standard fish length SL (cm),

$$W = a * SL^b, \quad \text{Equation (2.1)}$$

were employed where the coefficients a and b are fitted from the length-weight relationship of the fish community. We used an averaged SL-W relationship based on the mixed species assemblage from gill net and push trawl catches with parameters

a=0.0174 and b=2.9628, yielding a TS per unit weight (TS_w; described in detail in Simmonds and MacLennan 2005) for the fish community (Figure 2.4):

$$TS_w = -4.45 * \log_{10} SL - 47.95. \quad \text{Equation (2.2)}$$

Transformation of TS_w yields an equivalent acoustic backscattering cross-section per unit weight (σ_{bsw}) used to scale s_v for deriving volumetric estimates of fish biomass (g m^{-3}) within each analysis cell, via:

$$\text{Fish Biomass}_{cell} = s_{v\ cell} / \sigma_{bsw\ cell}. \quad \text{Equation (2.3)}$$

2.2.4.3 Target Strength

Reports for TS were generated in Echoview for single targets within each analysis cell identified by the split-beam single target detection algorithm. Targets fulfilling single target criteria (Table 2.1) with a TS above -55 dB were accepted. The single target algorithm was tuned to accept targets with echo envelopes between 0.6 and 1.7 times the pulse length with a maximum beam compensation of 12 dB. For each target identified in Echoview, a TS value was provided and an estimate of the backscattering cross section (σ_{bs}) for each target was calculated in SAS via the following:

$$TS = 10 * \log_{10} (\sigma_{bs}) \text{ (MacLennan et al. 2002).} \quad \text{Equation (2.4)}$$

The variable, σ_{bs}, the linear equivalent of TS, was used for all calculations involving TS, including all statistical analyses. Given the mixed species assemblages found in estuarine systems (Subrahmanyam and Coultas 1980; Hoese and Moore 1998; Rozas and Minello 1998; Gelwick et al. 2001), and lack of horizontal-aspect information on the relationship of TS and SL for estuarine fish, I used the relationship defined in Frouzova et al. (2005):

$$TS = 24.71 * \log_{10} (SL) - 64.92. \quad \text{Equation (2.5)}$$

Frequency distributions of TS, based upon acceptance criteria, were collated into 3 dB

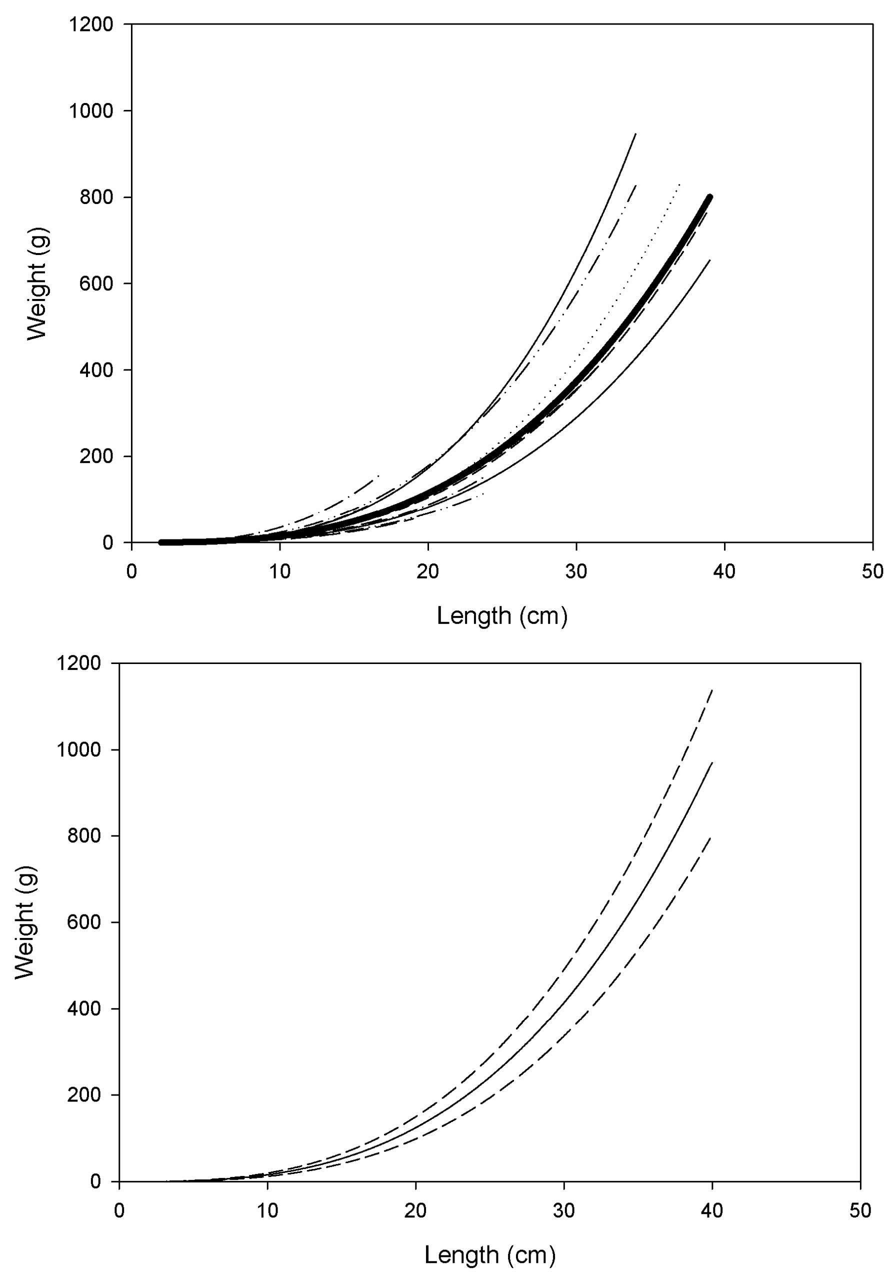

Figure 2.4. Length-weight relationship estimated from common estuarine fishes sampled in Barataria Bay, LA. Top panel illustrates length-weight relationships for each species. An averaged fish community length-weight relationship is represented by the bold solid line. Species used for averaged relationship include: *Brevoortia patronus, Anchoa mitchilli, Cynoscion nebulosus, Cynoscion arenarius, Dorosoma petenense, Menticirrhus americanus, Micropogonias undulatus, Sciaenops ocellatus, Arius felis, Pogonias cromis, Mugil cephalis, Mugil curema, Lagodon rhomboides, Leiostomus xanthurus, Membras martinica, Alosa chrysolecuas, Bairdiella chrysoura*. The lower panel represents the averaged fish community length-weight relationship with a 95% confidence interval, illustrated by broken lines. Parameters for length-weight relationship (Equation 2.1) are a=0.0174 and b=2.963.

bins for each cell and were used to compare fish length data from gill net and push trawl samples by converting SL into TS following equation 2.5. Although the TS-SL relationship proposed by Frouzova et al. (2005) was derived for an assemblage of European freshwater fishes (cyprinids, salmonids, and percids ranging in length from 7.2 to 71 cm), we adopted its use for the mixed assemblage due to the lack of horizontal-aspect acoustic information available on estuarine fishes. The body morphologies of those fish were assumed to be similar to those found in the estuarine waters in this study.

2.2.4.4 Gill Nets and Push Trawls

Gill nets and push trawls were deployed concurrently with acoustic surveys to identify fish community composition associated with habitat type and to derive fish length distributions. Fish SL was then converted to TS following Equation (2.2). Gill nets were fished for two hours adjacent to the acoustic beam over each habitat type. The gill nets used were 46.5 m in length and consisted of five 9.3 m panels with unstretched mesh sizes ranging from 1.905 to 3.175 cm. Samples were sorted by species; individual SL (mm) and W (g) were recorded. Catches with greater than 50 individuals of the same species were sub-sampled; total abundances, total W, and SL of the 50 sub-sampled fish were recorded (MacRae 2006).

Push trawls were used to capture the smaller fish that the gill nets did not sample effectively. Directly following acoustic data collection, transducer platforms were retrieved and a 1 m^2 push trawl with 1 cm mesh and 0.5 cm cod end was deployed from the bow of the pontoon boat. Three 100-m habitat-specific transects were conducted at an approximate speed of 2 m s^{-1}; position was verified by visualizing real-time positional data in ArcPad. Fish collected were bagged, placed into an ice slurry and later frozen.

Samples were sorted by species; individual SL (mm) and W (g) were recorded. Catches with greater than 50 individuals of the same species were sub-sampled; total abundances, total W, and individual SL of the 50 sub-sampled fish were recorded.

2.2.5 Data Analysis

2.2.5.1 Experiment One

Acoustic data collected in the net experiment were classified into two regions based upon position relative to the transducer face: data collected within the first 5 m were classified into the <5 m region; all data collected beyond 5 m were classified into the >5 m region (Figure 2.2). This classification scheme provided for comparisons of acoustic scattering between T_1 and T_2 within the <5 m region, corresponding to the volume of water within the exclosure net. For each analysis cell in the <5 m region, s_v values from T_1 (enclosure containing plankton and abiotic scatterers) were subtracted from T_2 (open-water containing, fish, plankton, and abiotic scatterers) to calculate a corrected estimate of s_v (Boswell and Wilson 2004) to illustrate the magnitude of ambient noise. Following subtraction, s_v was converted into S_v.

Three-way analysis of variance (ANOVA; SAS Institute Inc., 2003, Proc Mixed, α=0.05) was used to test the null hypothesis that no differences existed in s_v among surveys, transducers, and analysis regions. Prior to ANOVA testing, the dependent variable was transformed $\log_{10}((s_v \times 10e^9) + 1)$ to minimize heteroscedasticity. The datasets from the two surveys were combined due to the lack of a significant difference (p=0.208) between experiments. A one-way ANOVA was performed on the transformed dependent variable, s_v, to test the hypothesis that scattering in the <5 m region within T_1 did not differ from either the <5 m region in T_2 or the corrected estimate. The

distribution of the residuals was approximately normal; however, an abundance of low values attributed to the reduced acoustic scattering within the <5 m region in T_1 approximated a bi-modal distribution. Given that the high degrees of freedom (df= 222) and the distribution of residuals were approximately normally distributed, I relied upon the robustness of the ANOVA procedure for correctly detecting significant differences (Underwood 1981) in scattering between T_1, T_2, and the corrected estimates. *Post-hoc* comparisons were conducted on significant effects with Tukey's HSD test at a significance level of α=0.05.

2.2.5.2 Experiment Two

A two-way ANOVA was used to test for differences in mean acoustic biomass (g m^{-3}) and mean σ_{bs} (main effects: site and habitat, Table 2.2) between survey stations and habitat types. Biomass estimates were $\log_e$ (biomass) transformed and σ_{bs} estimates were $\log_{10}$ (σ_{bs}) transformed prior to analysis to satisfy the assumptions of the ANOVA. The null hypothesis that neither mean acoustic biomass nor σ_{bs} differed across site or habitat type was tested. Tukey's HSD *post-hoc* tests (α=0.05) were used to test for differences in means of significant main effects. Variability in TS-frequency distributions were compared with the Kolmogorov-Smirnov (KS) two sample test (Sokal and Rohlf 1995) and the median test (Zar 1996) in SAS. Statistical tests were reported as significant at α= 0.05.

Table 2.2. Analysis of Type III fixed effects (Proc Mixed) on mean acoustic biomass ($\log_e$ biomass) and mean backscattering coefficient ($\log_{10} \sigma_{bs}$) by habitat type (oyster shell vs. sand/ mud) and survey station (FP, MV, GT/QB). Data collected during March 2004 in Barataria Bay, LA.

	Mean Acoustic Biomass		Mean σ_{bs}	
Source of Variation	F Value	Pr > F	F Value	Pr > F
Habitat	1.58	0.175	7.06	0.008
Station	22.49	<.001	10.14	<.001
Habitat* Station	15.19	<.001	0.91	0.405

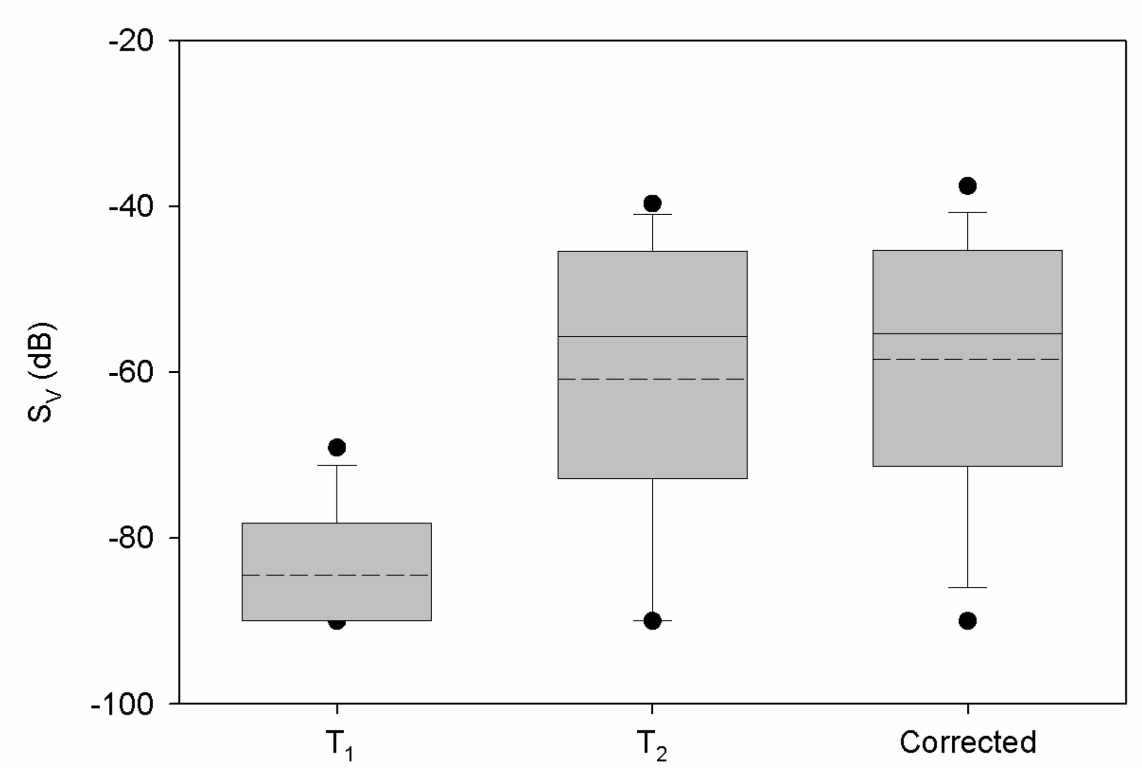

Figure 2.5. Comparison of mean S_v (dB) collected during exclosure net experiments. Data represent mean S_v collected within the <5 m analysis region for T_1 and T_2. Corrected value illustrates effect of background noise on estimates of S_v in T_2. Solid line represents mean while dotted line represents median. Whiskers represent 5 and 95% limits around mean.

2.3 RESULTS

2.3.1 Scattering Sources

Scattering within the exclosure net was dramatically less than that observed in the corresponding volume in T_2 (open water column). Mean S_v in the <5 m region of T_1 (inside the net) was significantly less ($p<0.001$) than the same regions in T_2 and the >5 m region of T_1 (Figure 2.5). *Post-hoc* comparisons of mean S_v suggested that no difference ($p=0.628$) existed between the <5 m region of T_2 (-60.7 dB) and the corrected estimate of S_v (-59.6 dB); however, S_v in the <5 m region (-84.3 dB) of T_1 was significantly ($p<0.001$) less. Given that S_v values in the <5 m region in T_1 were significantly lower than in T_2, I conclude that scattering observed in the water column (T_2) was attributable to nekton. Furthermore, low scattering within T_1 suggests that scattering from non-nektonic sources (e.g. zooplankton and suspended sediments) can be considered negligible.

2.3.2 Biomass Estimates

Mean acoustic biomass collected during the March 2004 survey varied with salinity and habitat type. A significant interaction ($p<0.001$) between mean biomass was observed in relation to habitat type and salinity (Figure 2.6); oyster shell habitat supported higher biomass at MV, and lower biomass were observed at GT/QB. Overall, mean acoustic biomass was highest at the low salinity station (FP, 0.92 ± 0.15 g m^{-3}) and showed a decreasing trend with increasing salinity, decreasing from 0.54 ± 0.15 g m^{-3} at MV to 0.29 ± 0.11 g m^{-3} at GT and QB (Figure 2.6). *Post-hoc* multiple comparison tests indicated that biomass associated with the shell habitat was greatest at lower salinity stations (Figure 2.6, FP and MV), and lowest at the highest salinity station (QB).

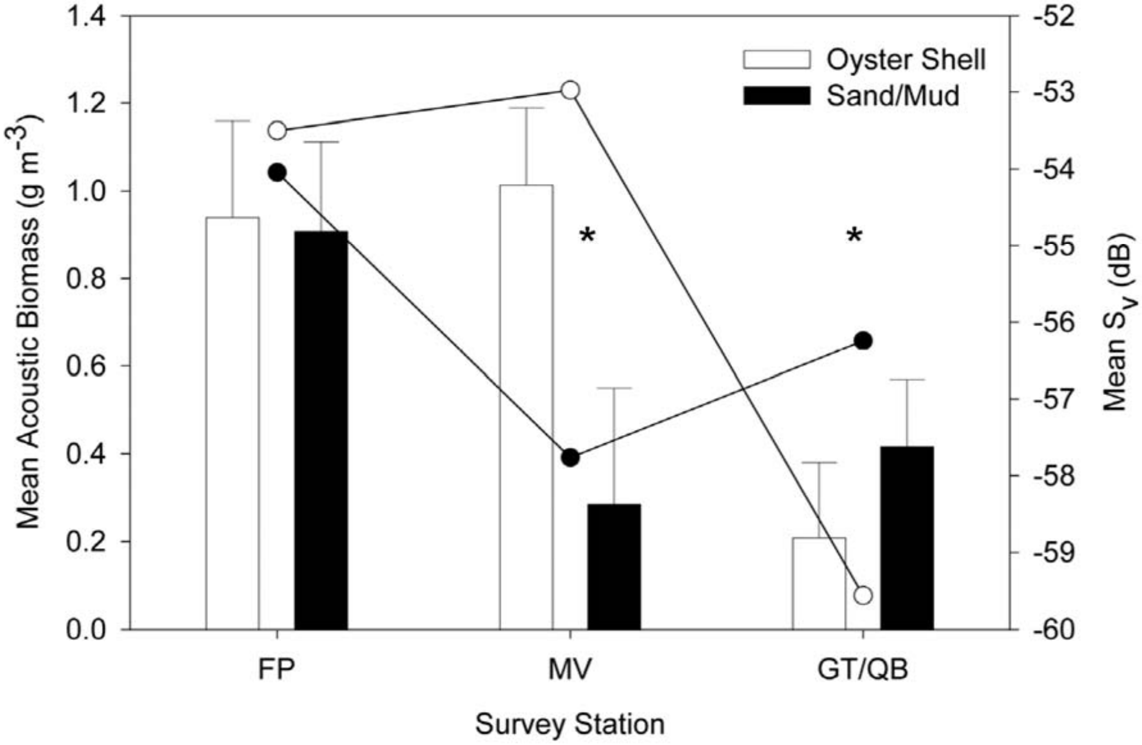

Figure 2.6. Mean acoustic biomass (g m^{-3}) and mean S_v by survey stations and habitat types in Barataria Bay, LA. Mean acoustic biomass is represented by bars and mean S_v is represented by circles with lines. Oyster shell habitat is denoted by open bars and circles, while sand/mud habitat is represented by filled bars and circles. Asterisks indicate significant differences (ANOVA, α=0.05) from Tukey's *post-hoc* pairwise comparisons.

Similarly, soft bottom habitats supported higher biomass at FP, with significantly (p=0.001) lower biomass at both MV and GT stations.

2.3.3 Target Strength Distributions

The greatest variability in TS distributions was seen across salinity levels, although slight differences were observed between habitat types at the low salinity station, FP. Target strength distributions at FP varied significantly between habitats (median test, p=0.006; KS test, p=0.036); however, differences were not observed between habitats at the other survey stations. The overall effects of salinity and habitat on TS distributions were evaluated by collapsing frequency distributions over survey station and habitat type. A significant difference was observed when comparing TS distributions across survey stations, with GT/QB having a greater proportion of smaller fish and a smaller proportion of larger fish than at MV (Figure 2.7; median test, p=0.004; KS test, p=0.035). No other differences were observed in TS distributions among survey stations, indicating that fish length distributions did not differ among the other stations. Additionally, no difference in TS distributions were observed between habitat types (Figure 2.8; median test, p=0.242; KS test, p=0.791).

Fish SL data collected with the push trawls, converted into TS following equation 2.5, showed moderate concordance when compared with collected TS data as illustrated in Figures 2.7 and 2.8, however little concordance was observed between collected TS data and gill net data. Comparisons of TS distributions generated from fish SL data illustrate the presence of consistent peaks (-53, -51, -49, and -39 dB) across sites and between habitat types. Although the peaks were not as dramatic in the acoustic TS data, the distributions were generally coincident with converted fish SL data. Cumulative TS-

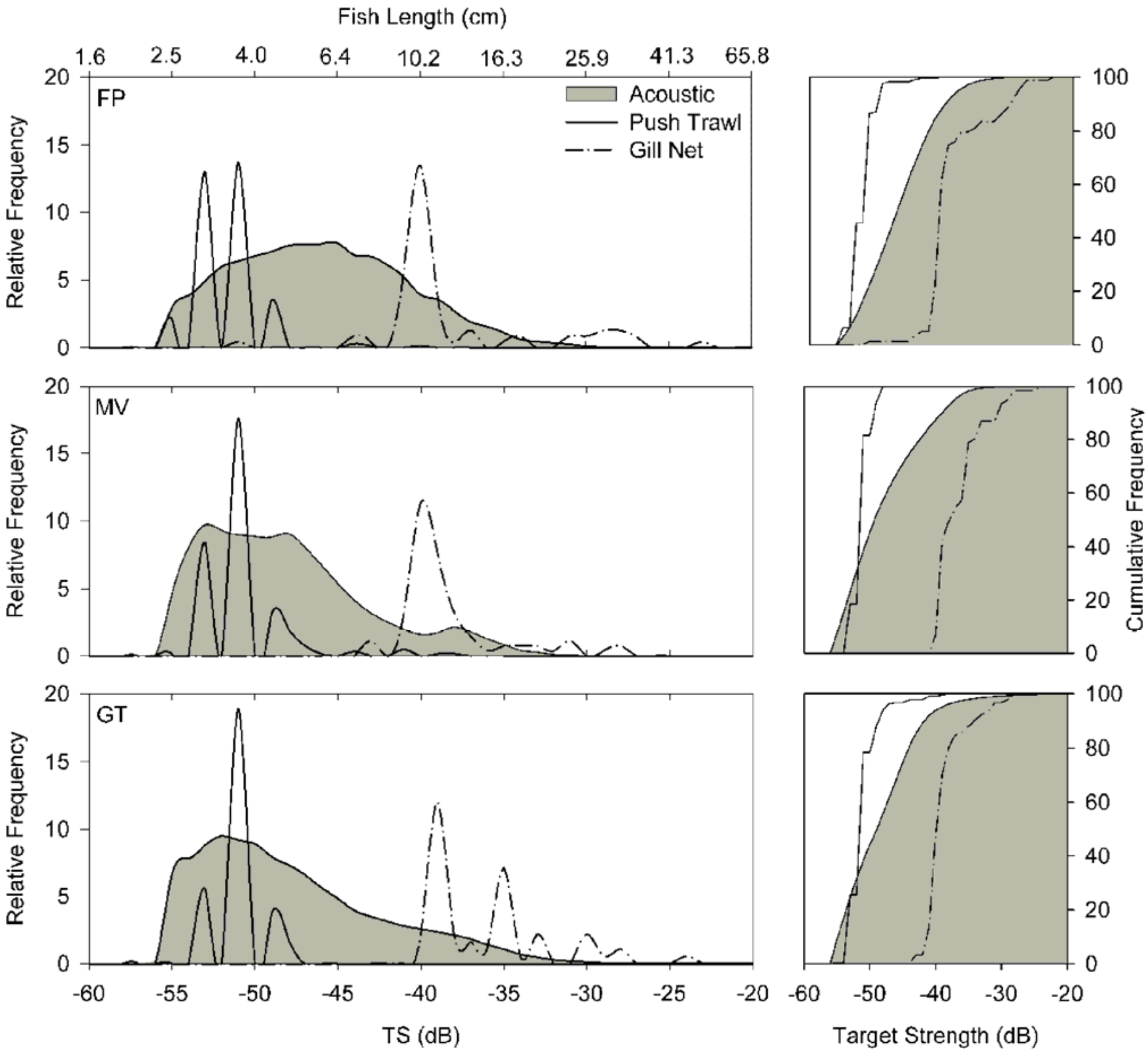

Figure 2.7. Target strength (TS) frequency distributions by survey station along a salinity gradient in Barataria Bay, LA. Right-hand panels represent cumulative frequency distributions of target strength data. Filled areas represent TS data from acoustic surveys and lines represent standard length (SL) frequency from gill net and push trawl collections. SL data from collections were converted to TS following the TS-SL relationship $TS=24.71 * \log_{10}(SL)-64.92$ proposed by Frouzova et al. 2005. Estimated SL along upper x-axis was derived for both distributions in each panel following Frouzova et al. 2005. X-axes are represented in $\log_{10}$ scale.

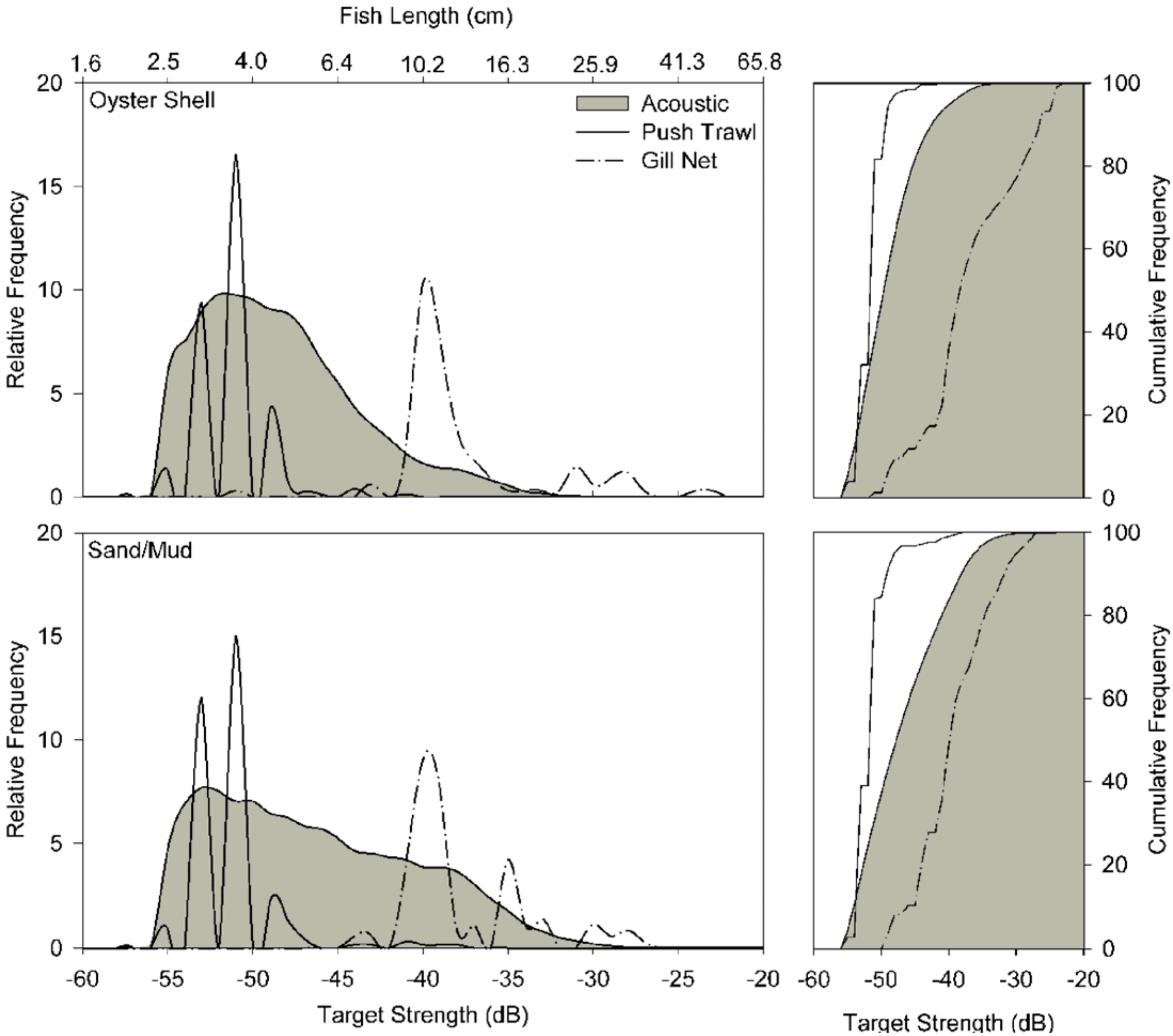

Figure 2.8. Target strength (TS) frequency distributions by habitat types. Right-hand panels represent cumulative frequency distributions of target strength data. Filled areas represent TS data from acoustic surveys and lines represent standard length (SL) frequency from gill net and push trawl collections. SL data from collections were converted to TS following the TS-SL relationship TS=24.71 * $\log_{10}$ (SL)-64.92 proposed by Frouzova et al. 2005. Estimated SL along upper x-axis was derived for both distributions in each panel following Frouzova et al. 2005. X-axes are represented in $\log_{10}$ scale.

frequency distributions (Figures 2.7 and 2.8) indicate that the majority of scattering (>70%) observed was attributed to targets less than -47 dB.

2.3.4 Mean Target Strength Estimates

Generally mean TS, and therefore mean fish size, was greatest over shell habitat and decreased with increasing salinity (Figure 2.9). The largest mean fish size (-37.9, SE bounds:-37.2,-38.7) was observed at FP. Slightly smaller mean fish sizes were observed at MV (-38.7 dB, SE bounds:-38.0,-39.5), although not significantly different from FP ($p = 0.775$). The smallest mean size targets, which varied significantly from FP and MV ($p < 0.004$), were seen at GT/QB (-41.5 dB, SE bounds:-41.0, -42.1). Based on single target detections, larger fish were observed consistently over oyster shell habitat ($p = 0.008$; Figure 2.9b) across the salinity levels. Larger fish observed at FP (-37.7 dB, SE bounds:-36.7, -39.0) and MV (-37.2 dB, SE bounds:-36.4, -38.3), compared to QB (-40.2 dB, SE bounds:-39.4, -41.3). Sand/mud habitats supported smaller fish and illustrated a decreasing trend in fish size with increasing salinity (Figure 2.9b).

2.3.5 Push Trawl and Gill Net Catch

Bay anchovy and Gulf menhaden abundance consistently dominated push trawl catches, whereas Gulf menhaden dominated gill net catches (Tables 2.3 and 2.4). Bay anchovy were not captured in the gill nets due to their small size. Combined datasets of both gear types reflected consistently higher numerical abundance of bay anchovy (> 65%) and Gulf menhaden (> 25%) as compared to abundances of all other species captured.

2.4 DISCUSSION

Acoustic surveys have proven to be effective tools for estimating fish abundance and density in various aquatic habitats (Simmonds and MacLennan 2005). Acoustics serve as a non-invasive sampling technique and may allow for the direct estimation of acoustic fish biomass, size frequency, and distribution. Based on the results presented herein, I am

encouraged in the use of acoustics for indexing fish biomass and size distributions within the ultra shallow waters of coastal Louisiana. However, I recognize that environmental conditions present the greatest constraint for successful data collection. Shallow water environments are commonly influenced by entrained air (Kubecka 1996; Mouse and Kemper 1996; Kubecka and Wittingerova 1998; Boswell and Wilson 2004), and at times suspended sediments, due to environmental conditions. Thus, considerations for the effects of bubble-induced noise must be taken into account. Although an effective measure to remove effects of entrained air and other noise from the acoustic record has been presented, I conclude that, in Barataria Bay, it is not feasible to analyze data collected in the presence of winds greater than 6 m s^{-1}, due to the overwhelming effects of air entrainment experienced during windy conditions.

Results from the exclosure net experiments provide evidence that the predominant source of observed scattering at survey stations in Barataria Bay can be considered nektonic in nature. Accounting for the analysis thresholds employed, scattering from zooplankton and suspended sediments were considered negligible. I believe that observed scattering is attributable to fish, as behavior observed in the echograms is consistent with highly mobile targets. Whereas other studies (Burwen and Fleischman 1998; Daum and

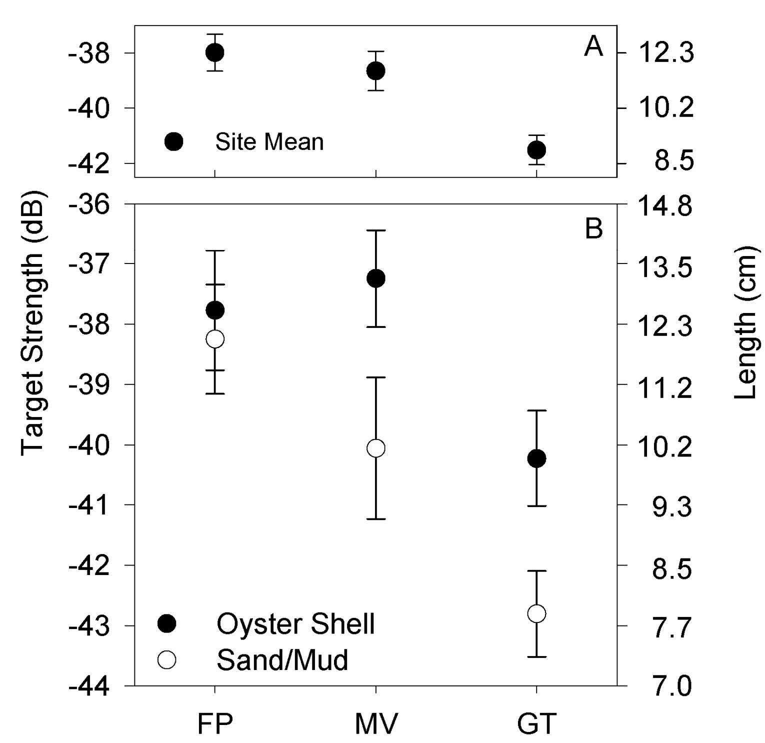

Figure 2.9. Mean target strength (TS) by survey station and habitat type in Barataria Bay, LA. Panel (A) effect of salinity level on mean TS. Panel (B) effect of habitat type on mean TS by survey station. Secondary y-axis represents estimated fish standard length (SL) following the relationship TS=24.71 * $\log_{10}$(SL)-64.92 (Frouzova et al. 2005).

Table 2.3. Percent species abundance of catch from push trawl and gill net collections by habitat type for fishes collected during March 2004. Only four most dominant species are shown for each gear type.

	Push Trawl			Gill Net		
Station	Species	Count	Percent	Species	Count	Percent
Sand/Mud	*Anchoa mitchilli*	200	93.9	*Alosa chrysoleucas*	2	1.7
	Brevoortia patronus	5	2.4	*Arius felis*	7	5.9
	Cynoscion arenarius	1	0.5	*Brevoortia patronus*	99	83.9
	Membras martinica	4	1.9	*Dorosoma petenense*	2	1.7
Oyster Shell	*Anchoa mitchilli*	224	88.9	*Arius felis*	8	7.1
	Brevoortia patronus	23	9.1	*Bairdiella chrysoura*	29	25.7
	Membras martinica	4	1.6	*Brevoortia patronus*	61	54.0
	Micropogonias undulatus	1	0.4	*Cynoscion nebulosus*	4	3.5

Table 2.4. Percent species abundance of catch from push trawl and gill net collections by survey station for fishes collected during March 2004. Only four most dominant species are shown for each gear type.

	Push Trawl			Gill Net		
Station	Species	Count	Percent	Species	Count	Percent
FP	*Anchoa mitchilli*	200	85.8	*Alosa chrysoleucas*	3	3.8
	Brevoortia patronus	27	11.6	*Arius felis*	7	8.9
	Membras martinica	2	0.9	*Brevoortia patronus*	60	75.9
	Micropogonias undulatus	2	0.9	*Dorosoma petenense*	3	3.8
MV	*Anchoa mitchilli*	206	96.3	*Arius felis*	4	4.4
	Brevoortia patronus	1	0.5	*Bairdiella chrysoura*	27	29.7
	Cynoscion nebulosus	1	0.5	*Brevoortia patronus*	53	58.2
	Membras martinica	6	2.8	*Cynoscion nebulosus*	4	4.4
GT	*Anchoa mitchilli*	18	100	*Arius felis*	4	6.6
				Bairdiella chrysoura	3	4.9
				Brevoortia patronus	47	77.0
				Scomberomorus maculatus	2	3.3

Osborne 1998) deal with unidirectional current flows, where fish and other targets generally traveled in one apparent direction, the survey stations in this study experience microtidal flows. Thus, targets observed in the acoustic record are likely to be motile organisms.

Although Guillard et al. (2004a) reported the underestimation of schooling fish, as a result of avoidance of their moored vessel, I observed the passing of many schools both in the field and on the echograms. The effects of avoidance by fish were likely reduced due to the deployment of the transducers on the platforms approximately 12 m from the vessel. However, from a stationary position, fish detection is often reduced as compared to mobile surveys given the reduced survey coverage (Guillard et al. 2004a; Simmonds and MacLennan 2005). Thus, my estimates of biomass and abundance are considered to be conservative.

Calculation of biomass based on acoustic estimates requires acknowledgement of fundamental assumptions, i.e. an overall fish length-weight relationship must be assumed, particularly for a mixed species assemblage where little acoustic information is available. Furthermore, TS estimates for surveyed species should be available. However, in acoustic surveys, these values are not always logistically feasible to obtain, and must be estimated based upon knowledge of the fauna. When parameters must be estimated without empirical data, biomass values may still be useful for comparisons on a relative scale, particularly in the case of the horizontal-aspect where the TS response can be described as a stochastic variable and can vary with fish orientation and condition (Simmonds and MacLennan 2005). Guillard et al. (2004b) suggested that the derivation of fish biomass estimates should be avoided due to the high degree of variability

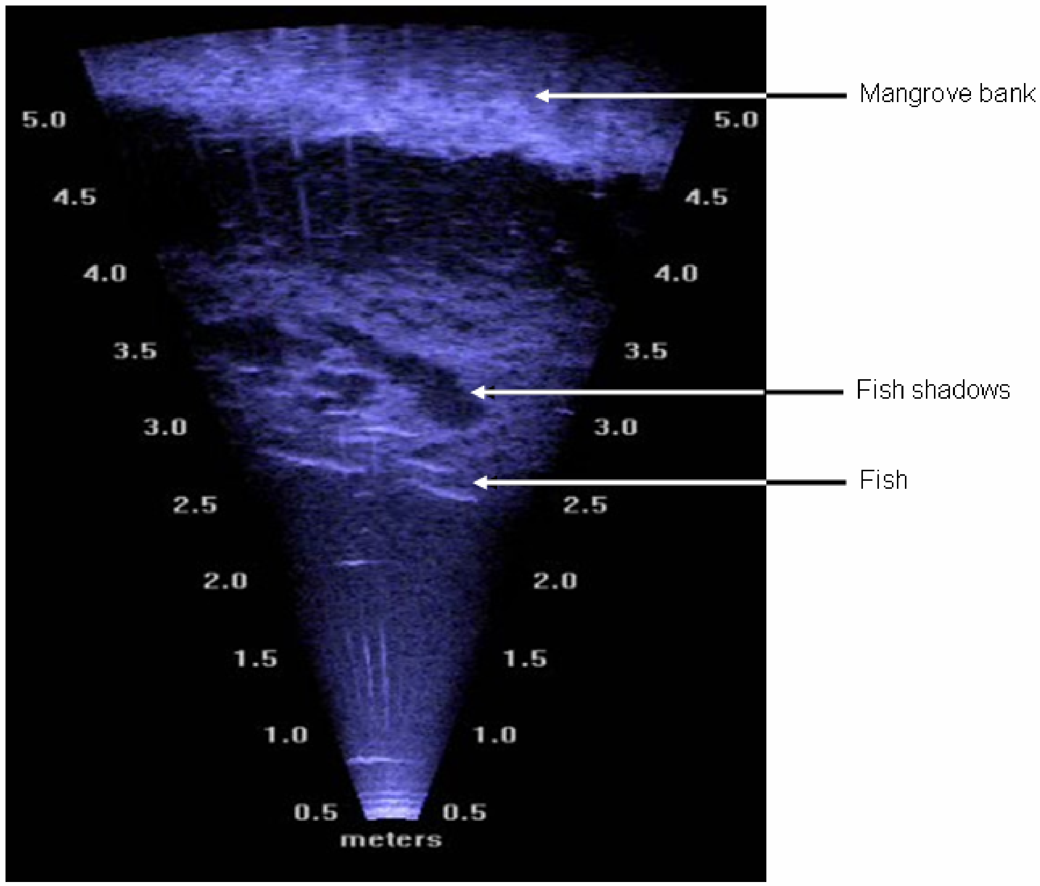

Figure 2.10. Image of acoustic video obtained from dual-frequency identification sonar (DIDSON) collected in tidal channel near Barataria Bay, LA. Perspective is bird's eye-view with increasing range from DIDSON unit. Mangrove bank edge can be seen at a range of 4.5 m. Image depicts individual fish swimming along the mangrove bank. In addition to individual fish, acoustic fish shadows are illustrated.

experienced in fitting fish length data to an empirical TS equation (e.g. Love 1971; Foote 1987), particularly for a mixed assemblage. However, the derived metrics presented in this paper are useful when used as a relative index (Yule 2000) for comparing magnitudes of fish biomass, while acknowledging the inherent variability in horizontally derived TS measurements. As more data become available, particularly through integration of dual frequency identification sonar (DIDSON, Figure 2.10) data and the incorporation of mixture models in analyses (Burwen and Fleischman 2003), I will be better able to incorporate the response of TS on fish orientation relative to the transducer.

Cumulative target strength-frequency distributions suggest that the majority of acoustic data is likely due to low-scattering fish. Based on gill net and push trawl data, the majority of acoustic backscattering data collected during this study may be attributable to bay anchovy (*Anchoa mitchilli*) and Gulf menhaden (*Brevoortia patronus*), each of which consistently comprised greater than 65 and 25 % of the catch, respectively, at all stations. The dominance of bay anchovy and Gulf menhaden in Gulf coast estuarine systems throughout the year has been well documented (Thompson and Forman 1987; Rozas and Reed 1994; Rozas and Zimmerman 2000; Jones et al. 2002). Past studies within Barataria Bay (Thompson and Forman 1987; Jones et al. 2002) and nearby Terrebonne-Timbalier Basin (Rozas and Reed 1994) reported bay anchovy as the most abundant and frequently occurring fish species throughout Barataria Bay, while Gulf menhaden were also consistently ranked as one of the most abundant species.

Distributions of TS (Figures 2.6 and 2.7) show similarities in ranges across stations and between habitat types, although slight differences are apparent (e.g. MV vs. GT/QB) and may be due to a difference in the distribution of schooling fish. Preliminary

analyses of recent tank experiments suggest that the TS for bay anchovy (n=15; SL=45-65 mm) can range from -55 and -47 dB and from -48 to -38 dB for Gulf menhaden (n=85; SL=70-100 mm; Boswell unpublished data), for various orientations in the horizontal aspect. Although the peaks observed in the converted push trawl and gill net catch data (Figures 2.6 and 2.7) exhibit strong similarities to the expected TS response from bay anchovy and Gulf menhaden, the acoustic data cannot be explicitly decomposed into a species composition. However, given knowledge of the fish community present during the spring, it is possible that the large proportion of targets seen at GT/QB may be attributed to the greater presence of schooling anchovy, whereas fewer anchovy were caught in the less saline parts of the bay during this survey. Interestingly, an increase in the proportion of Gulf menhaden was observed coincident with decreases in anchovy abundance. These trends loosely follow the predicted TS values of each species. However direct interpretation is not recommended due to the large variability in the TS response with fish orientation. Additionally, without direct observation of these species, it is difficult to describe their contribution to the overall scattering on a species-specific level. In response to this inadequacy, I have recently developed an integrated approach, through the combined use of split-beam and multibeam sonar, for acquiring high resolution species specific data as it pertains to habitat use and fish distribution in shallow coastal waters.

I have demonstrated the utility of hydroacoustics as a tool for quantifying changes in fish biomass and size distributions in ultra shallow waters (<2 m) that may be useful in the evaluation of essential fish habitat. Furthermore, I have suggested a standardized method for habitat specific sampling through the combined use of geo-referenced habitat

mapping and spatially explicit acoustic sampling which may enhance efforts for evaluating EFH in estuaries. The underlying premise of my effort was to use acoustics to enhance the resolution of information available for evaluating EFH and to develop a reliable method for quantifying changes in fish distribution associated with estuarine habitats. The ultimate objective is to augment sampling practices to enhance the current level of understanding of the relative importance of estuarine habitats. My results have led to an increased understanding and identification of the proper collection and analysis parameters needed for use of acoustics in turbid ultra-shallow waters. Information presented will aid in the future endeavors as specific criteria for successful acoustic sampling are identified and refined.

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CHAPTER 3: SIDE-ASPECT TARGET STRENGTH MEASUREMENTS OF BAY ANCHOVY (*ANCHOA MITCHILLI*) AND GULF MENHADEN (*BREVOORTIA PATRONUS*) DERIVED FROM *EX-SITU* EXPERIMENTS

3.1 INTRODUCTION

The conversion of acoustic backscattering into a reliable measure of fish length remains problematic in shallow coastal waters due to the lack of information on the side-aspect acoustical scattering properties of fishes present. The importance of accurate target strength (TS, in dB) data, the proxy for fish length, cannot be understated, as acoustic estimates of fish abundance rely directly on TS as a parameter to properly scale echo integration estimates into meaningful measures of fish abundance (Foote 1991; MacLennan and Menz 1996; Ona 2003).

To achieve reliable estimates of fish abundance and distribution, it is commonplace to incorporate TS–fish length relationships, derived by empirical or *in situ* methods, to describe acoustically surveyed fishes (Simmonds and MacLennan 2005). Love (1971; 1977) and Foote (1987) derived general TS-fish length relationships based on pooled acoustic data of several common fishes. Although useful (Frouzova et al. 2005; Hartman and Nagy 2005), these relationships are generalized models and do not apply to specific species nor all possible orientations. It is inappropriate to pool data from different species to formulate TS equations (McClatchie et al. 1996; Fleischer et al. 1997), given that the relationship between TS and fish length varies greatly by species and is dependent upon several factors such as swimbladder morphology, fish behavior, physiological condition, and orientation (Ona 1990; MacLennan and Simmonds 1992; Rose and Porter 1996).

Ideally TS estimates should be derived *in situ* where fish can be surveyed and monitored in natural settings (Brandt et al. 1991; Rudstam et al. 1993; Simmonds and MacLennan 2005). Some previous studies have been successful at *in situ* identification of scattering sources because either the study systems were dominated by few species (Burwen and Fleischman 1998; Daum and Osborne 1998), or acoustic data could be directly related to catch data (Foote and Traynor 1988). However, *in situ* methods are not generally suitable in the shallow, turbid, and biologically-heterogeneous systems characteristic of places like coastal Louisiana. Furthermore, the schooling behavior of resident target species confound single target measures as a result of the low spatial separation of individuals observed during survey periods.

To make use of acoustic data it is important to identify the potential sources of acoustic scattering. In coastal estuarine waters of the northern Gulf of Mexico two dominant species, bay anchovy (*Anchoa mitchilli)* and Gulf menhaden (*Brevoortia patronus*), hereafter referred to as anchovy and menhaden, are known to comprise the majority of annual biomass (Thompson and Forman 1987; Rozas and Reed 1994; Rozas and Zimmerman 2000; Jones et al. 2002). Anchovy and menhaden share a wide geographic distribution (Hoese and Moore 1998), and are of great ecological importance in many estuarine systems (Allen et al. 1995; Kneib 1997). To date there are no data concerning the side-aspect acoustic properties of either anchovy or menhaden.

I conducted tank experiments on tethered individuals to derive species-specific side-aspect TS-length and TS-weight relationships and to compare predicted values to side-aspect equations proposed by Love (1977) and Frouzova et al. (2005). Distributions of TS from tethered individuals were also compared to the TS distributions to free

swimming individuals in a tank to infer the potential biases between the two methods and to determine a TS threshold level for both species to be applied in shallow water acoustic surveys. Finally, because pulse duration can have important consequences for target separation and selection, I consider the effects of pulse duration on TS distributions of tethered and free swimming individuals.

3.2 METHODS AND MATERIALS

3.2.1 Fish Collection

Target strength measurements were collected during June 2005 in a 3.1 m diameter fiberglass tank (1.5 m water depth) at the Louisiana Universities Marine Consortium (LUMCON) Laboratory in Cocodrie, LA. Anchovy (TL 4.7-6.1 cm) and menhaden (TL 5.1-7.7 cm) were collected from surface waters with a 1 m^2 push trawl in nearby Terrebonne Bay, LA and transported to LUMCON in an aerated tank. Fish were transferred into a filtered, aerated holding tank and allowed to acclimate for two days prior to acoustic experiments. Tank temperatures (mean= 24.5º C ± SE 0.4) and salinity (mean= 20.1 ‰ ± SE 0.2) were monitored and maintained throughout the study.

3.2.2 Acoustic Data Collection

Target strength data were collected with a BioSonics DE-X digital echosounder (see Table 3.1 for parameter settings) equipped with a 420 kHz split-beam transducer (2.4º x 6.2º, half-power beam width) calibrated with a 17 mm tungsten carbide calibration sphere, following the standard sphere method (Foote et al. 1987). Acoustic data were collected and stored to a laptop computer with BioSonics Visual Acquisition (4.1) at a threshold of -70 dB and a sample rate of 5 Hz, resulting in approximately 9000 TS measures for each tethered individual. The BioSonics DE-X system was parameter-

plexed, allowing for sequential operation at multiple pulse durations. In this study, two pulse durations, 0.4 and 0.1 ms, were used alternatively to evaluate the effect of pulse duration on TS. The pulse duration settings were chosen based upon collection parameters used in current field surveys (see Chapter 2). The transducer was placed at mid-water depth along the tank wall (Figure 3.1) and positioned to ensonify the water volume horizontally across the tank.

A frame (Figures 3.1 and 3.2) constructed of 1.75 mm diameter fiberglass rods was mounted onto a 36-tooth rotating sprocket, allowing fish to be ensonified at 10º increments (Lilja et al. 2000). The axis of rotation of the frame was centered in the beam by hanging a calibration sphere within the center of the frame and monitoring its angular position with BioSonics Visual Acquisition 4.1, ensuring that ensonified fish were positioned within the axis of the acoustic beam. Acoustic data were collected in the empty tank to measure noise levels from the tank walls and reverberation. A clearly defined tank wall was apparent in the echogram (> -30 dB), and background noise associated with the tank was below -65 dB. Additionally, data were collected on the frame and tether, which was detectable at angles (50, 60, 120, and 130º, Figure 2). However, the magnitude of backscatter was not considered significant (<-65 dB).

3.2.3 Tethered Fish

Anchovy (n=15) and menhaden (n=14) were anesthetized in an 18 ‰ ice slurry for 2 min. Individuals were immediately tethered in an upright position in the center of the frame with four 4-lb monofilament lines, two lines into the jaw and two into the tail. Small knots were tied through the jaw and monofilament loops were used to secure the tail of each individual within the frame. Fish were rotated about their dorso-ventral axis

Table 3.1. Echosounder, transducer, and analysis parameters used in target strength experiments for bay anchovy and Gulf menhaden.

Sonar system parameters	
BioSonics DE-X split beam echosounder:	
Operating frequency	420 kHz
Pulse duration	0.1 and 0.4 ms
Pulse rate, per transducer	5 Hz
Transducer parameters	
2-way beam angle (ψ)	-24.47 dB
Collection threshold	-70 dB
Major-axis beam width	6.2 º
Minor-axis beam width	2.4 º
Echoview analysis parameters	
Analysis threshold	
TS	-60 dB
Single target detector	
Pulse length determination level	6 dB
Minimum normalized pulse length	0.5
Maximum normalized pulse length	1.7
Maximum beam compensation	6 dB
Maximum standard deviation of:	
minor-axis angles	0.9
major-axis angles	0.9

within the beam while being ensonified for 90 sec at each 10º increment. Measurements began from the lateral perspective and rotated 180º, with the head ensonified at 90º, resulting in 19 positions for each individual. Following the rotation, each individual was ensonified at a tail-on perspective. Individual wet weights (W, g) and total lengths (TL, cm) were recorded.

3.2.4 Free Swimming Fish

A 1-m diameter circular net (Figure 3.2), modeled after that of Nielsen and Lundgren (1999), was constructed of 1-cm extruded nylon mesh and placed in the fiberglass tank (described above) to concentrate free swimming individuals within the acoustic beam. The acoustic equipment and collection settings were the same as in the tethering experiment. During the experiments, individuals of each species (anchovy, n=30, 4.5-7.1 cm; menhaden, n=30, 4.9-8.2 cm) were placed within the net for 12 hours to measure the TS of swimming individuals at each pulse duration setting. A slight current was introduced to help orient the fish within the tank. A video camera was placed over the net enclosure to monitor the change in fish orientation throughout the experiments. Qualitative reviews of the video data showed that fish were assuming some degree of natural schooling behavior during the experiments and showed no indication of avoidance of the acoustic beam.

3.2.5 Data Analysis

Acoustic data collected from both the tethered and free swimming fish were visualized and analyzed in Echoview 3.50 (SonarData, Pty. Ltd.). Prior to calculating means, all TS values were converted to the arithmetic form, termed the acoustic backscattering cross-section ($\sigma_{bs} = 10^{(TS/10)}$) (MacLennan et al. 2002). Means were

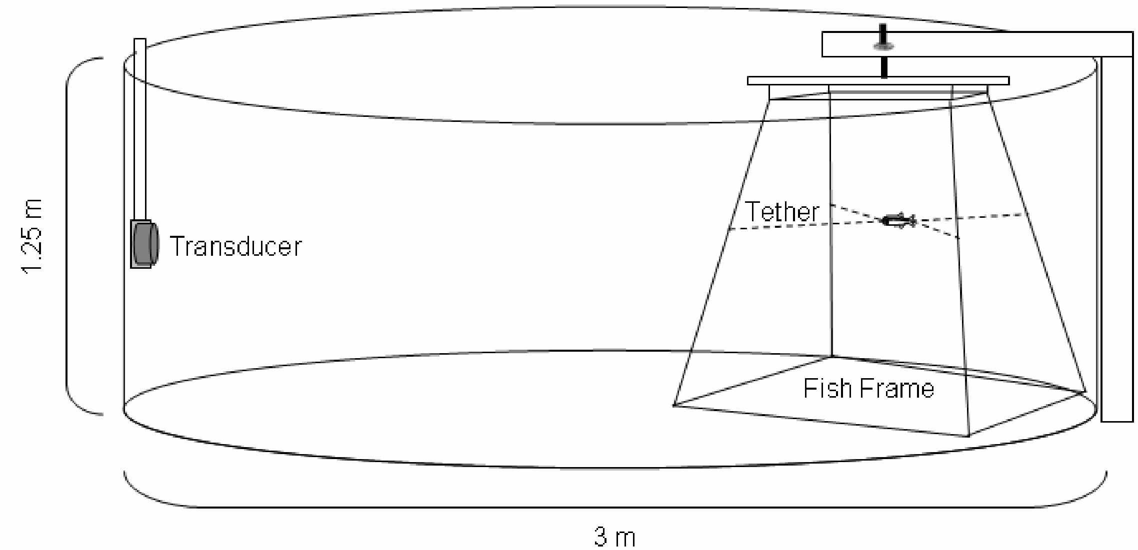

Figure 3.1. Experimental tank setup, including transducer placement along tank wall and frame used for tethering bay anchovy and Gulf menhaden individuals. Frame is mounted onto an indexed sprocket and frame is rotated about its central axis, note transducer is aimed in a side-looking orientation. During experiments with free swimming fish, the frame was removed and a 1 m diameter circular net was positioned in place of the frame.

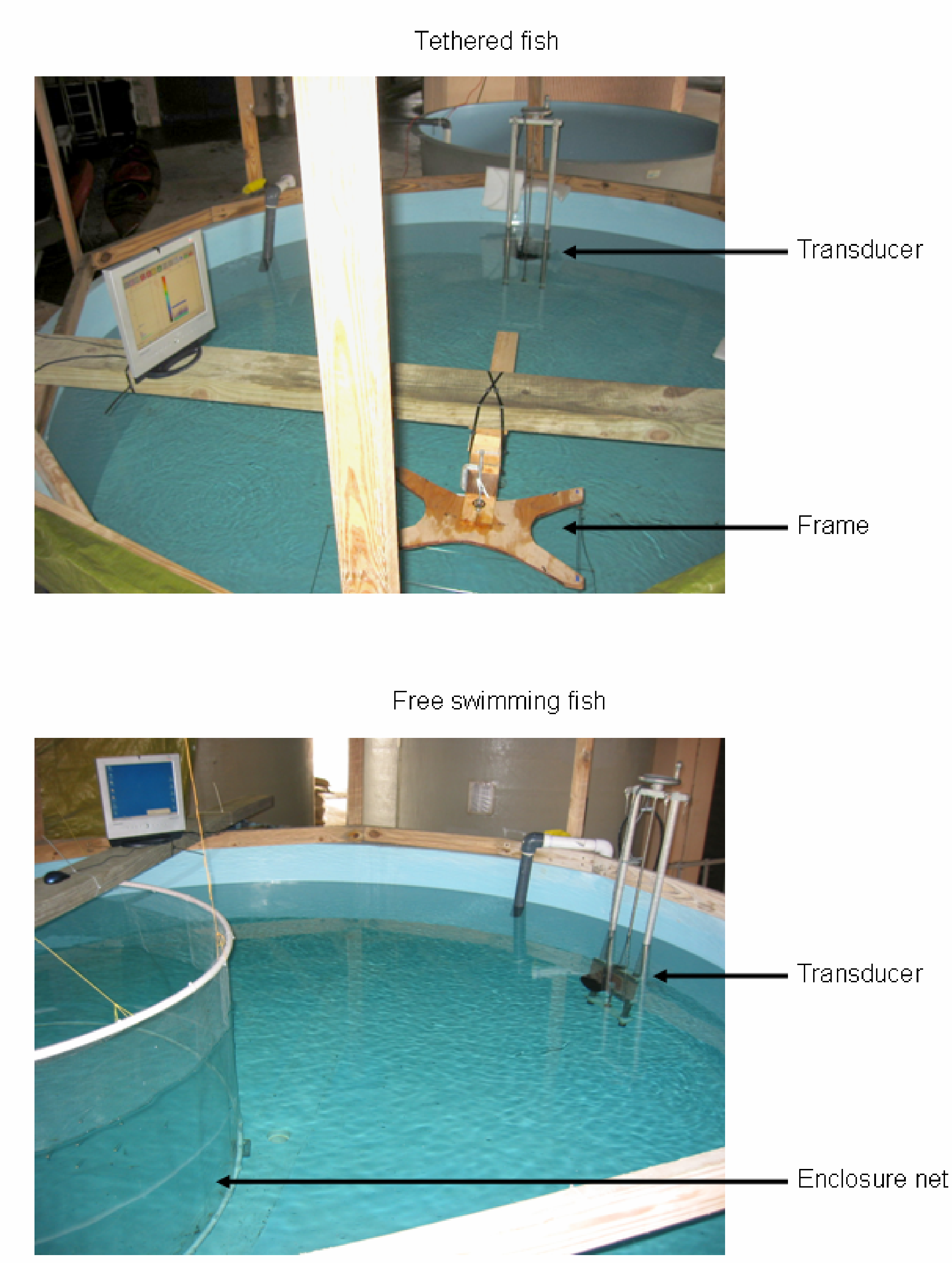

Figure 3.2 Images of tank setup, including fish frame used in tethering experiments (upper) and enclosure net used for free swimming experiments (lower). Throughout both experiments, transducer placement did not change.

transformed back into TS ($TS=10 * \log_{10} \sigma_{bs}$), whereas, standard errors are reported in the arithmetic form in the text and in the logarithmic form in all graphics.

3.2.5.1 Tethered Fish

Three angular regions (head/tail, oblique and, lateral; Figure 3.3) based on orientation were established for describing the TS responses by fish position relative to the acoustic beam. Analysis of variance (ANOVA, Proc GLM, alpha=0.05) was conducted in SAS 9.0 (SAS Institute, 2003) to test for effects of pulse duration on the variability of mean TS. Tukey's HSD *post-hoc* tests (alpha=0.05) were conducted on all pairwise comparisons. Variability in TS-frequency distributions were compared with the Kolmogorov-Smirnov (KS) two sample test (Sokal and Rohlf 1995) and the median test (Zar 1996) in SAS.

Simple linear regression models were used to describe the relationship between both TL and TS and W and TS by orientation. Regression analyses were conducted on anchovy, menhaden, and pooled datasets of both anchovy and menhaden combined. The TS-TL relationship was modeled with the equation $TS= a * \log_{10} L + b$. Two models were fitted to the data; model I, in which the slope (a) and the y-intercept (b) parameters were estimated, and model II, the standard form (Foote 1987), in which the slope parameter (a) was fixed at 20 and the intercept (b_{20}) was estimated.

The best fit models (pulse duration= 0.4 ms) for each species and pooled data from both species were compared to predicted values from $TS_{lateral}= 24.71 * \log TL_{cm}- 64.92$ (Frouzova et al. 2005) and $TS_{lateral} = 24.1 \log10 TL_{cm} - 61$ (Love 1977).

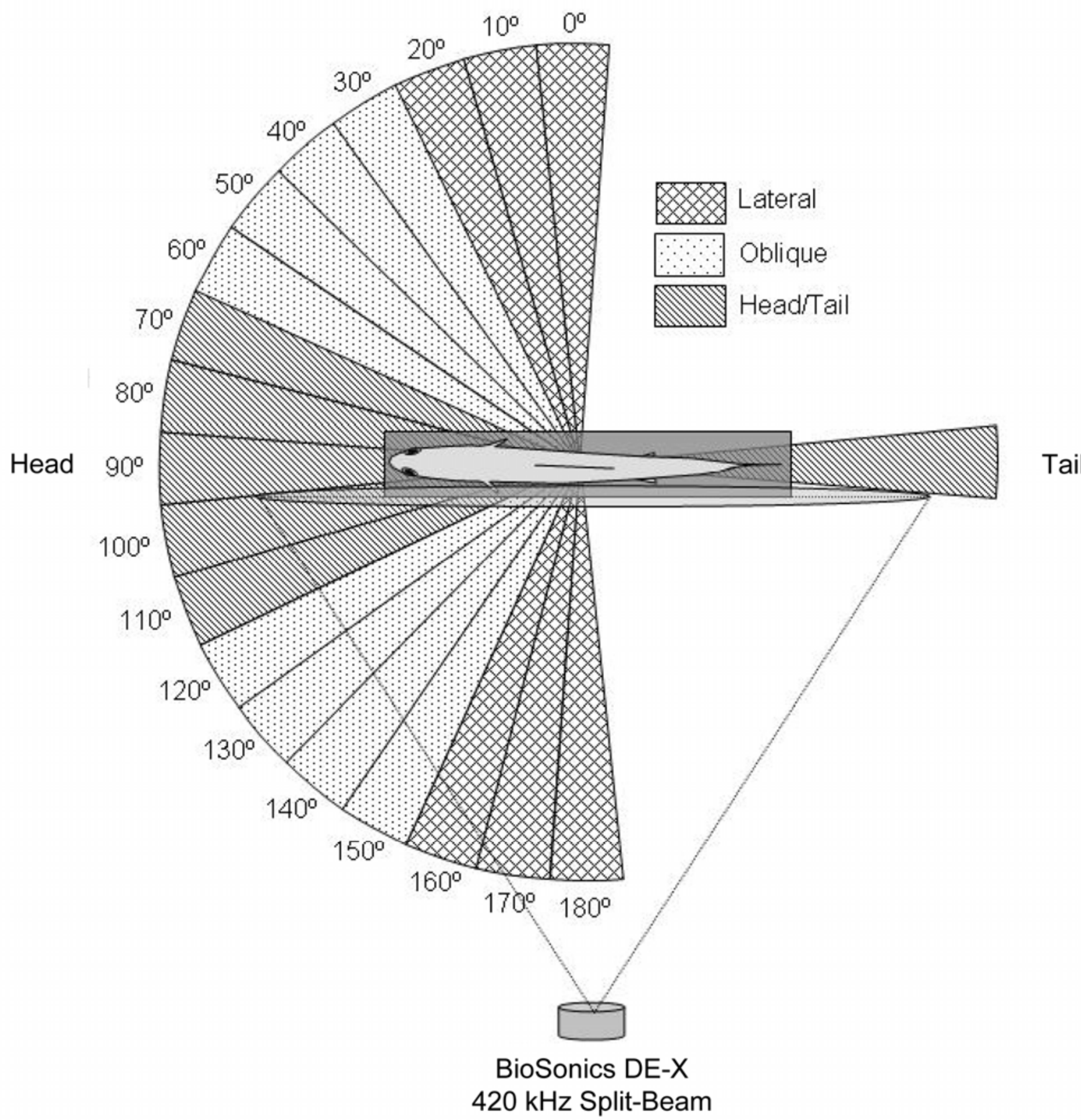

Figure 3.3.Angular positions and analysis regions used for tethered bay anchovy and Gulf menhaden. Fish were ensonified in a side-looking orientation. Fish were rotated about their dorso-ventral axis within the beam. TS measurements began at the lateral perspective and fish were rotated 180°.

3.2.5.2 Free Swimming Fish

Fish tracks of individuals consisting of at least five consecutive targets were identified from single targets that satisfied the criteria (Table 3.1) of the split-beam single target operator in Echoview. A mean TS value for each accepted fish track was generated in Echoview and data were analyzed in SAS. Frequency distributions of TS for each species at both pulse durations were generated for comparison to distributions of tethered individuals and were tested with the Kolmogorov-Smirnov (KS) two sample test (Sokal and Rohlf 1995) and the median test (Zar 1996).

3.3 RESULTS

3.3.1 Tethered Fish

Target strengths measured from tethered individuals appeared consistent throughout the experiments and the TS frequency distributions from each ensonified position approximated a normal distribution. Target strengths measured from tethered individuals varied with position and pulse duration for both species. Typical TS responses with fish orientation and pulse duration are illustrated in Figure 3.4 for a 5.8 cm anchovy and a 5.4 cm menhaden. Overall menhaden had significantly higher TS at both pulse durations (0.1 ms = -49.5 dB, SE bounds:-49.2,-49.8; 0.4 ms = -47.6 dB, SE bounds:-47.4,-47.8; $p<0.001$) than anchovy (0.1 ms = -52.7 dB, SE bounds:-52.0,-53.3; 0.4 ms = -50.1 dB, SE bounds:-49.7,-50.4; $p<0.001$). For both species, pulse duration had a significant effect ($P<0.001$; ANOVA) on overall mean TS. Mean TS was greater at the 0.4 ms level than at the 0.1 ms, irrespective of fish orientation.

Target strength increased as fish were rotated from a head-on to a lateral position with respect to the axis of the acoustic beam (Figures 3.5- 3.10). The lateral orientation

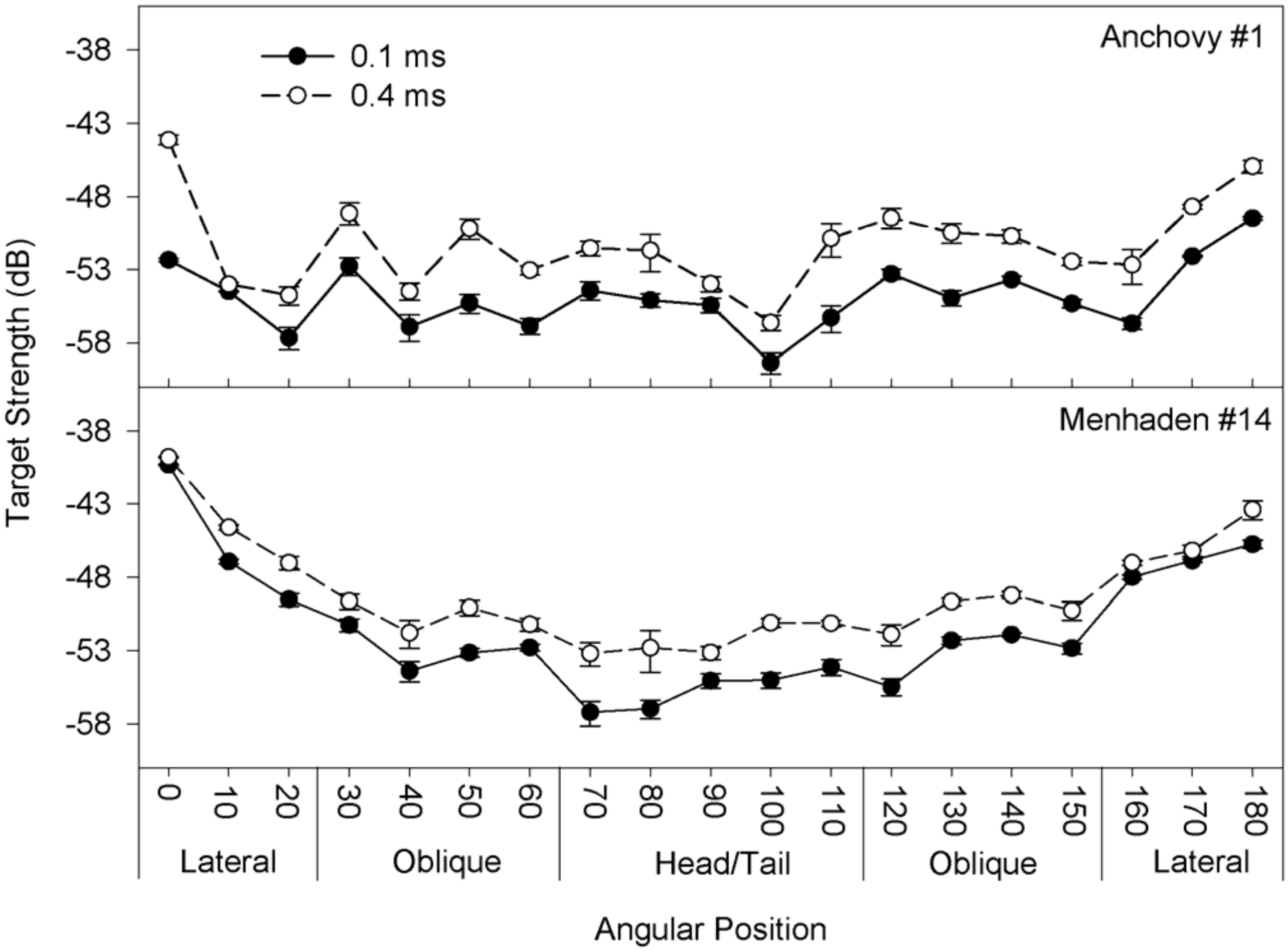

Figure 3.4. Target strength distributions by angular position for (A) anchovy #1 (5.8 cm) and (B) menhaden #14 (5.4 cm). Effect of collection pulse duration on TS is illustrated by solid and dashed lines. Orientation labels are below angular position and correspond to regions used in data analysis to describe effects of horizontal fish orientation on TS. Error bars represent standard error.

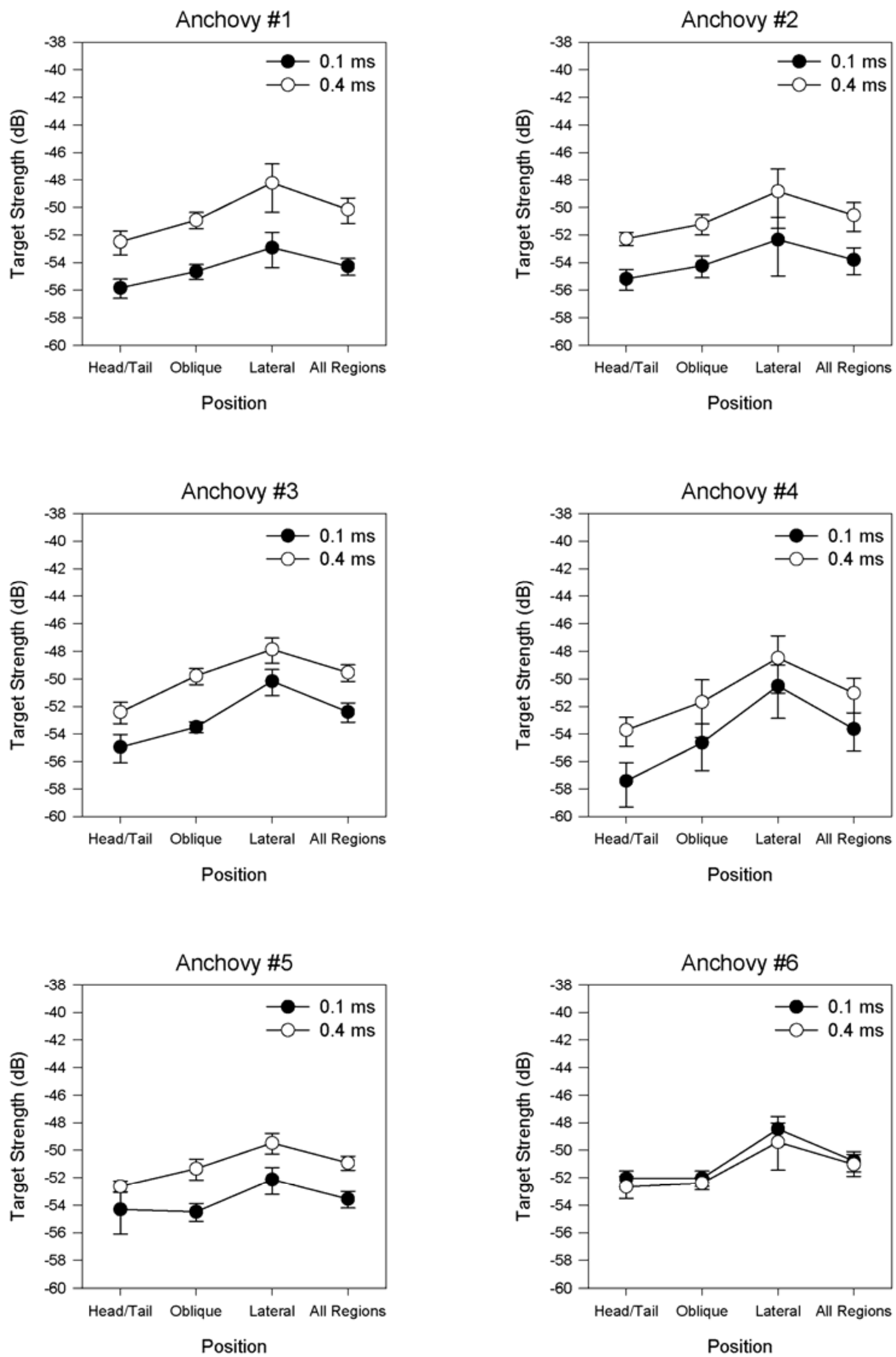

Figure 3.5 Positional target strength distributions of tethered bay anchovy (*Anchoa mitchilli*) individuals. Target strength distributions are illustrated for each pulse duration (0.1 and 0.4 ms) for bay anchovy #1-#6.

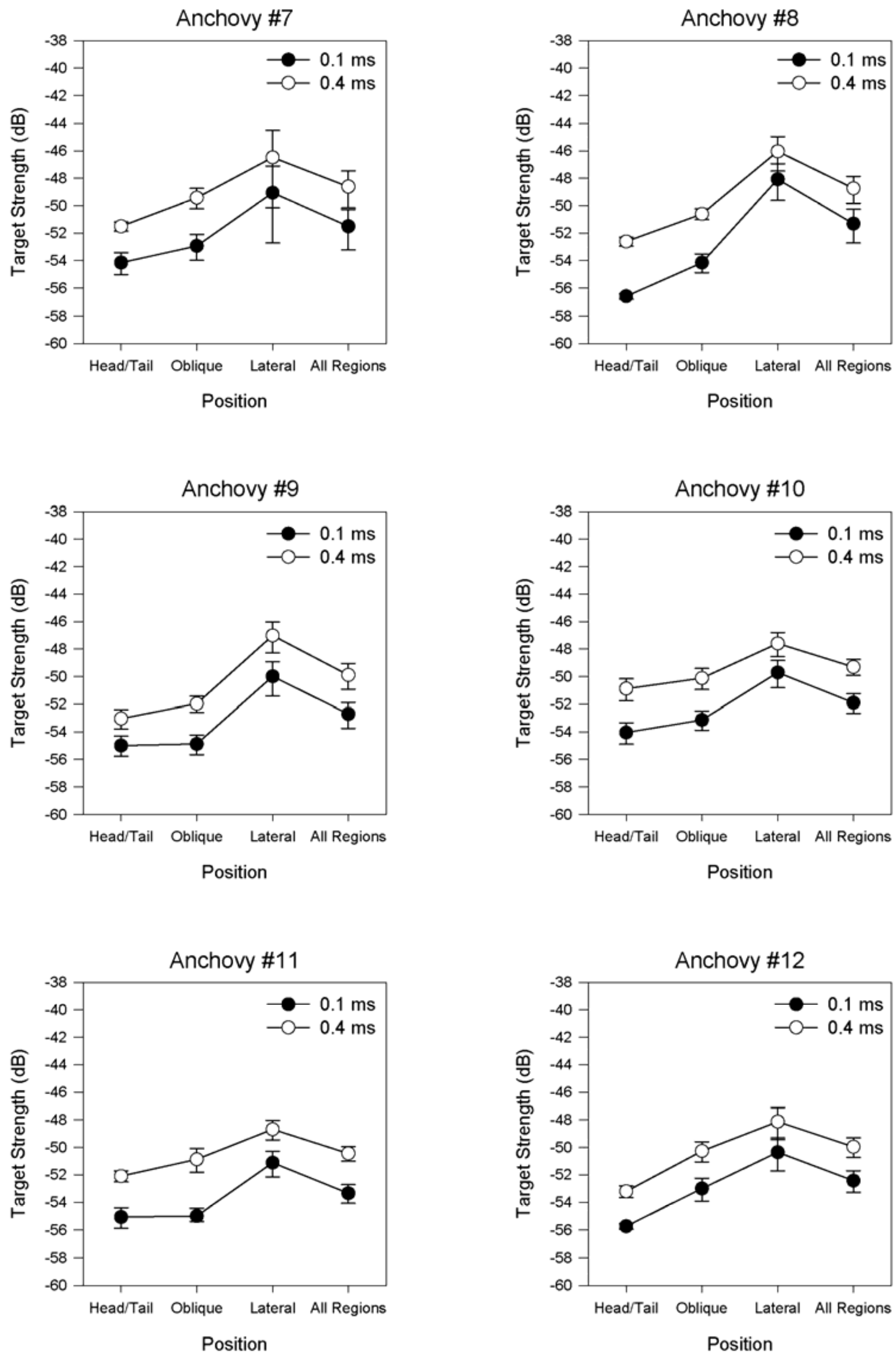

Figure 3.6 Positional target strength distributions of tethered bay anchovy (*Anchoa mitchilli*) individuals. Target strength distributions are illustrated for each pulse duration (0.1 and 0.4 ms) for bay anchovy #7-#12.

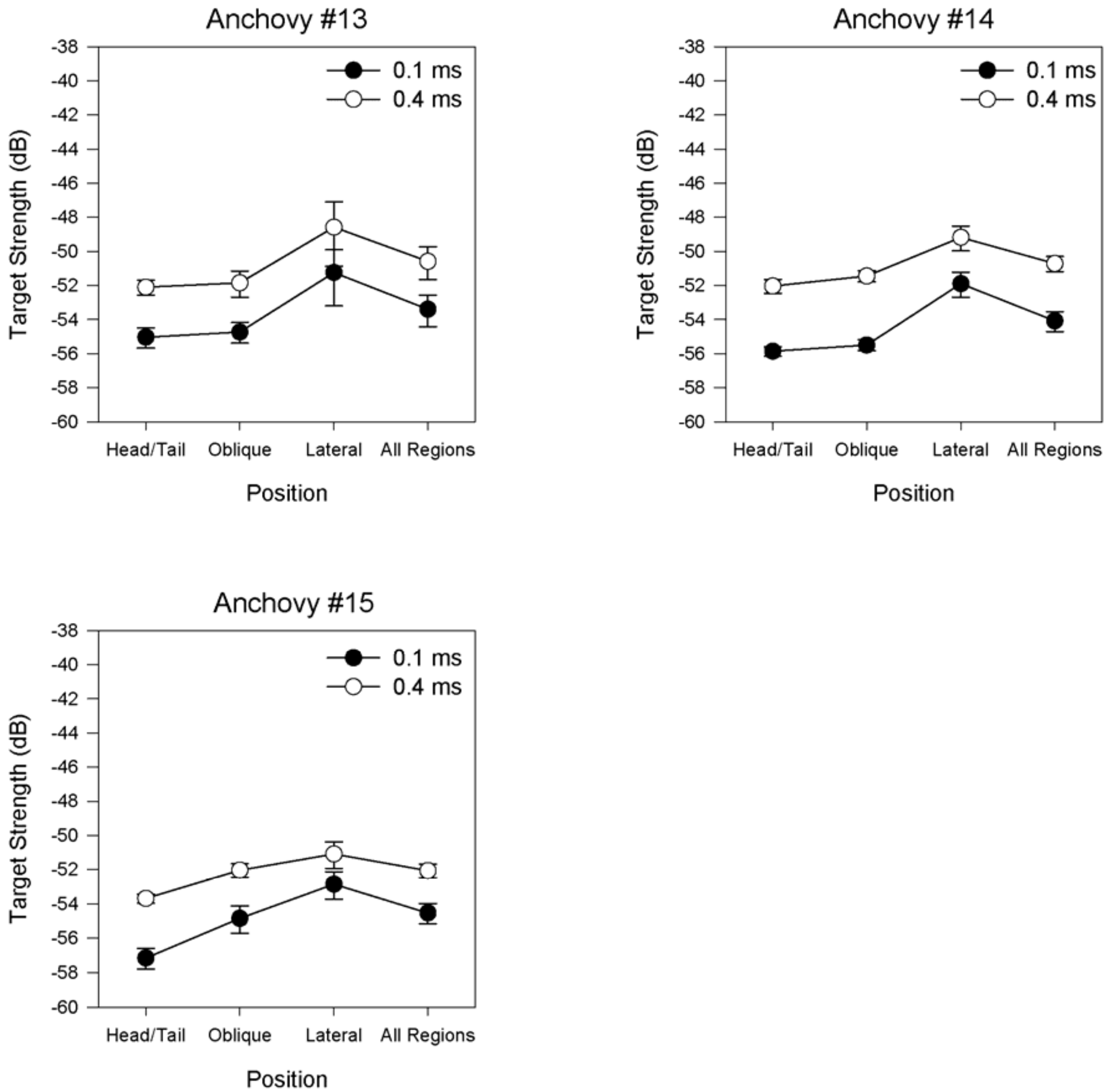

Figure 3.7 Positional target strength distributions of tethered bay anchovy (*Anchoa mitchilli*) individuals. Target strength distributions are illustrated for each pulse duration (0.1 and 0.4 ms) for bay anchovy #13-#15.

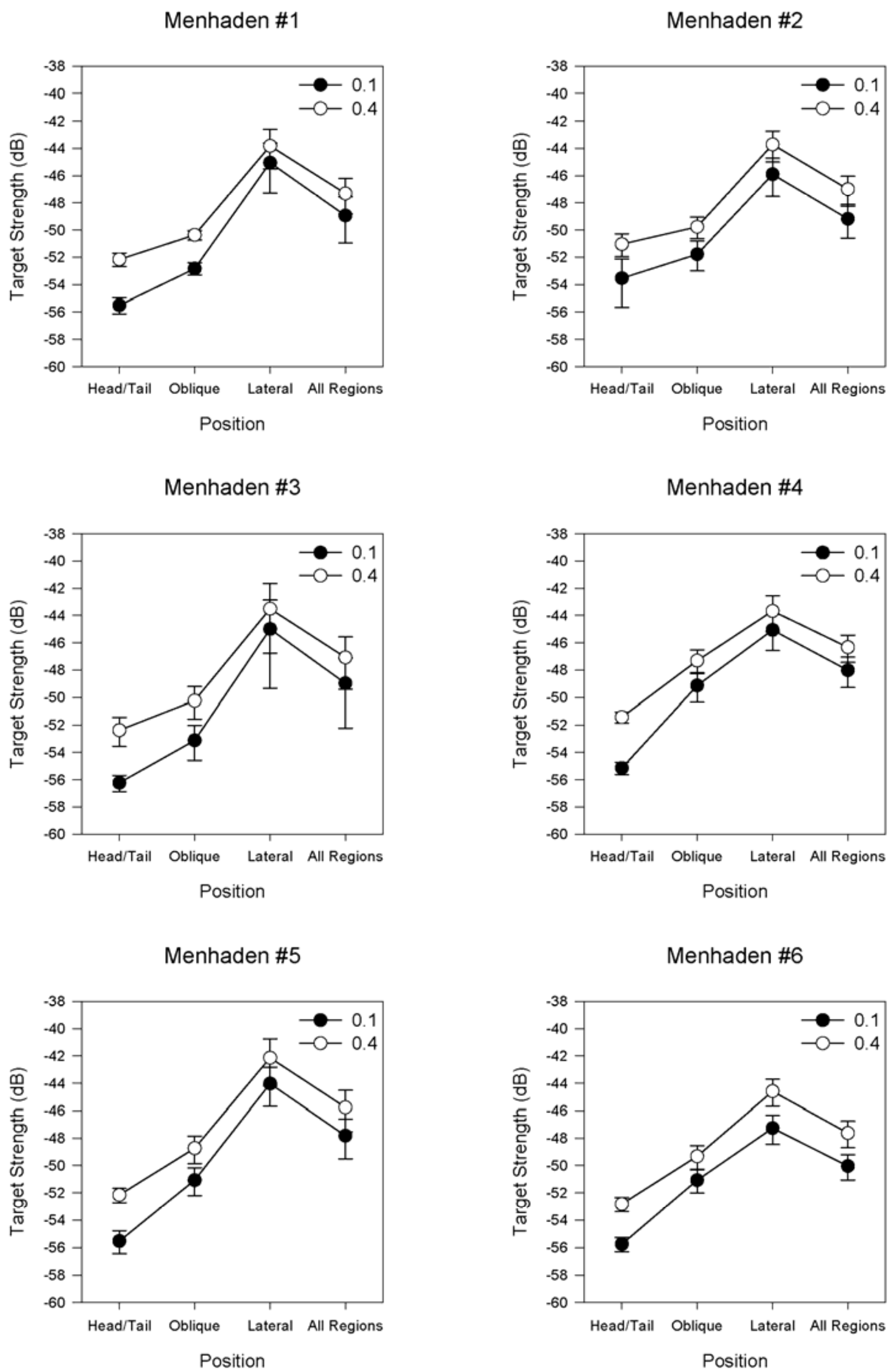

Figure 3.8 Positional target strength distributions of tethered Gulf menhaden (*Brevoortia patronus*) individuals. Target strength distributions are illustrated for each pulse duration (0.1 and 0.4 ms) for Gulf menhaden #1-#6.

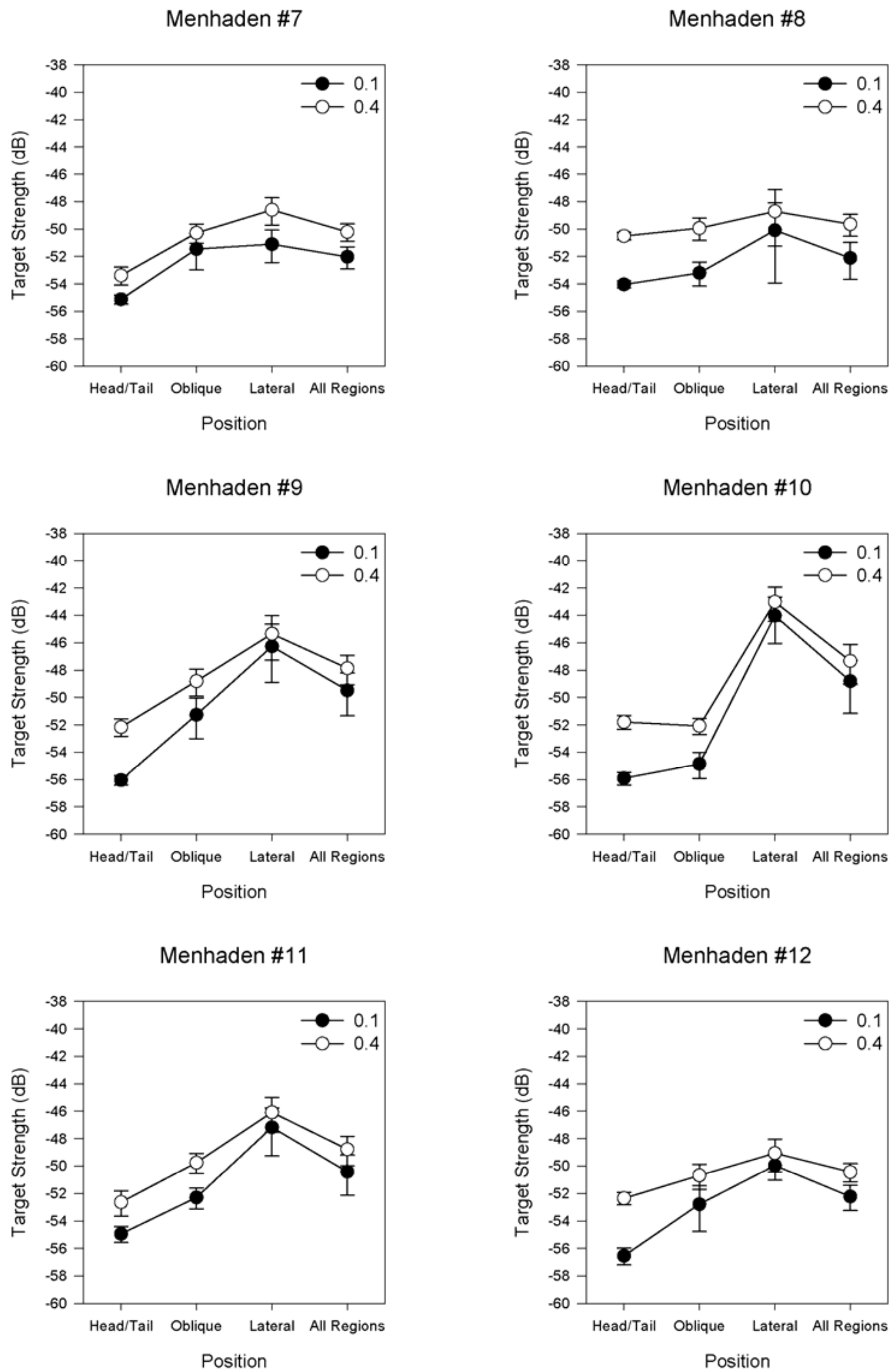

Figure 3.9 Positional target strength distributions of tethered Gulf menhaden (*Brevoortia patronus*) individuals. Target strength distributions are illustrated for each pulse duration (0.1 and 0.4 ms) for Gulf menhaden #7-#12.

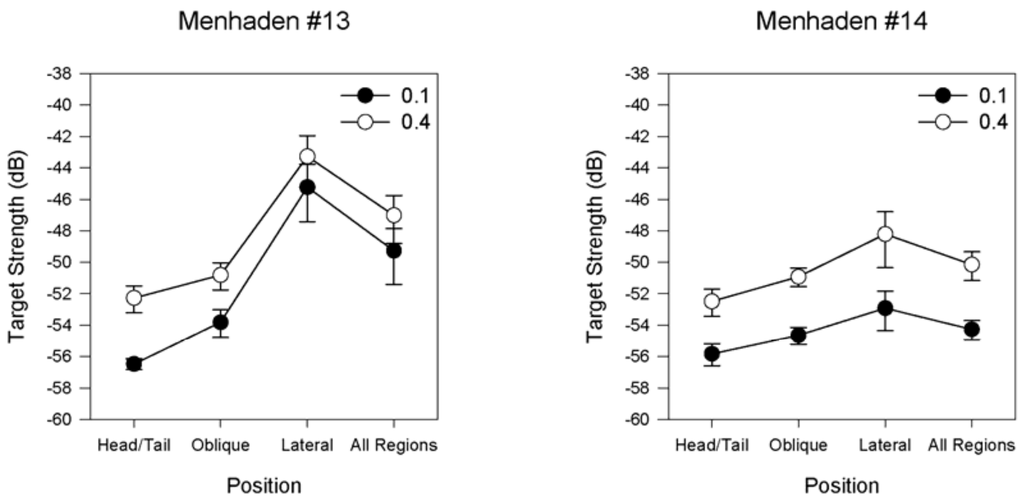

Figure 3.10 Positional target strength distributions of tethered Gulf menhaden (*Brevoortia patronus*) individuals. Target strength distributions are illustrated for each pulse duration (0.1 and 0.4 ms) for Gulf menhaden #13 and #14.

had a considerably higher mean TS value than the other orientations. Menhaden had a greater lateral perspective TS than anchovy at both pulse durations ($p<0.001$); however, at other orientations, menhaden and anchovy had similar, lower, TS responses. Mean TS pooled from all orientations differed from the other orientations (head/tail, oblique, and lateral) by less than 2 dB for anchovy and less than 4 dB for menhaden. Greatest differences between both species and pulse durations were observed when comparing the lateral and head/tail region, with differences ranging from 4.1 to 4.3 dB and 7.3 to 9.1 dB for anchovy and menhaden, respectively.

Target strength frequency distributions differed significantly between pulse durations within species (median test, $p<0.001$; KS test, $p<0.001$; Figure 3.11) and between species (median test, $p<0.05$). Target strength frequency distributions (Figure 3.12) derived for each species and orientation from tethered individuals approximated a normal distribution; however, TS distributions from the head/tail and oblique regions had a narrower range than that of the lateral region for both species.

Linear relationships between TS and $\log_{10}$-TL were derived for the lateral region and the combination of all regions for anchovy, menhaden, and both species combined (Figure 3.13 and 3.14). Coefficients for the fitted regressions for anchovy and menhaden at 420 kHz are listed in Table 3.2. Model II, the standard form of the TS- log length relationship ($TS=20 * \log_{10} L - b_{20}$), provided a better fit for the data in most cases. Model II provided a better fit in all cases for anchovy, whereas model I provided more predictive power at the 0.4 ms pulse duration for menhaden. Similarly, analyses with model I of the pooled data from anchovy and menhaden provided a better fit at the 0.4 ms pulse duration as compared to model II.

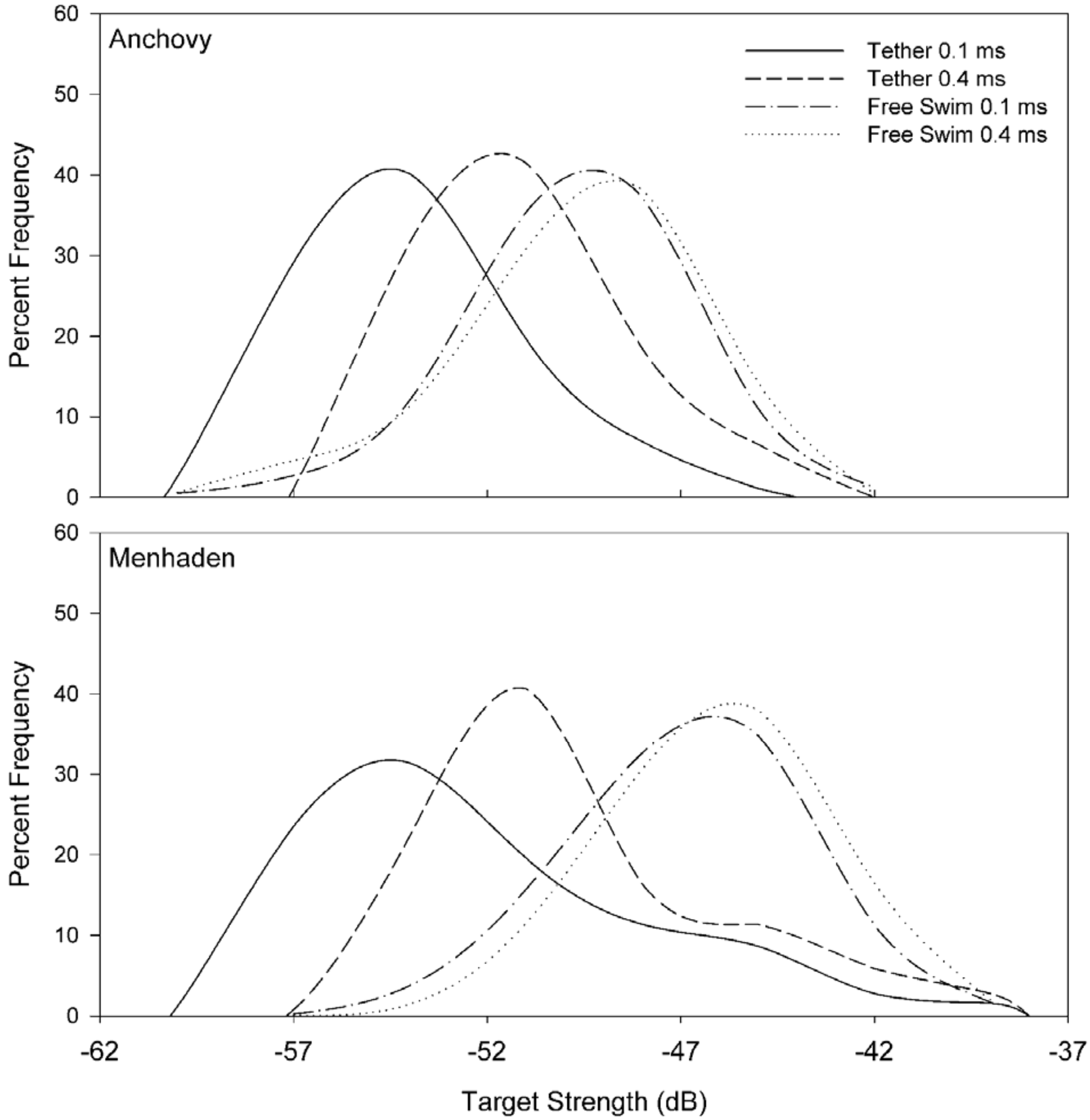

Figure 3.11. Comparisons of TS-frequency distributions for tethered and free swimming individuals by pulse duration collected at 420 kHz. Upper panel: bay anchovy (*Anchoa mitchilli*); tethered individuals: n=15, 4.7-6.1 cm and free swimming individuals, n=30, 4.5-7.1 cm. Lower panel: Gulf menhaden (*Brevoortia patronus*); tethered individuals: n=14, 5.1-7.7 cm and free swimming individuals: n=30, 4.9-8.2 cm.

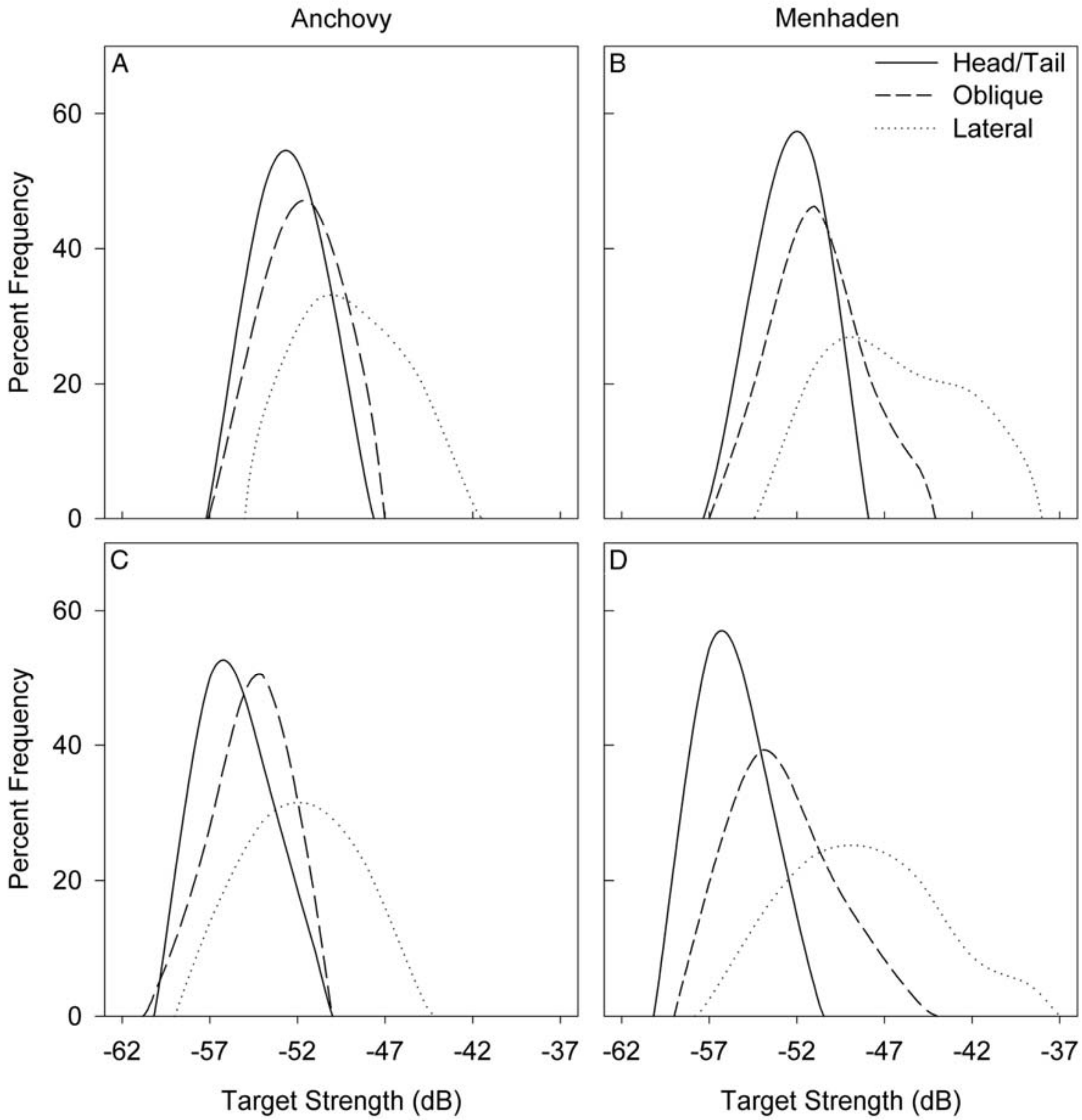

Figure 3.12. Target strength-frequency distributions for bay anchovy (*Anchoa mitchilli*, 4.7-6.1 cm) and Gulf menhaden (*Brevoortia patronus*, 5.1-7.7 cm) at 420 kHz by ensonified region. Panels (A) and (B): pulse duration =0.4 ms; panels (C) and (D): pulse duration =0.1 ms.

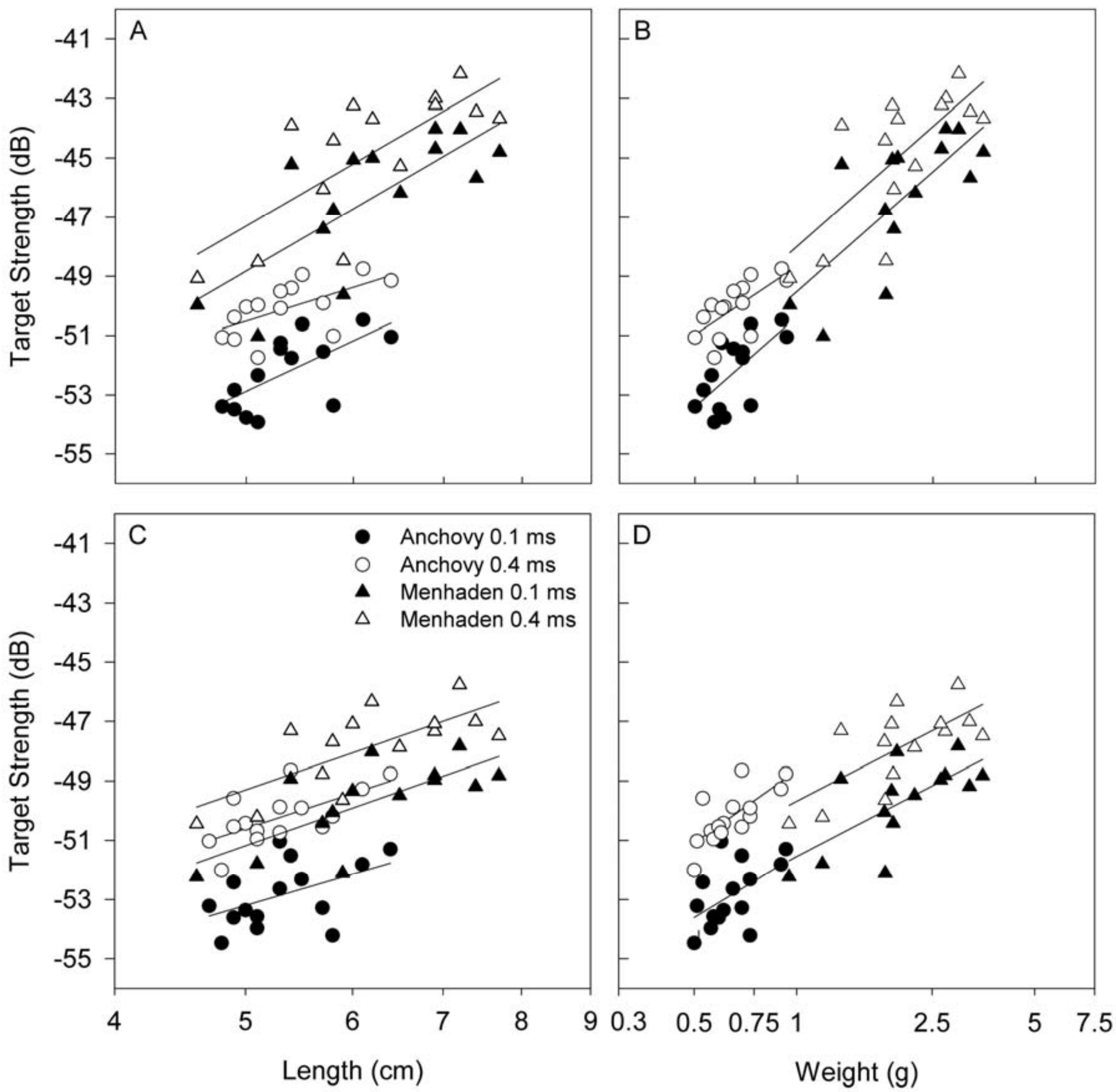

Figure 3.13. Regressions of TS-length and TS-weight for bay anchovy (*Anchoa mitchilli*, 4.7-6.1 cm) and Gulf menhaden (*Brevoortia patronus,* 5.1-7.7 cm) at 420 kHz by pulse duration level. Each panel illustrates least squares fit through data points for each pulse duration level. (A) lateral, length; (B) lateral, weight; (C) all regions, length; (D) all regions, weight. See Table 3.2 for regression coefficients.

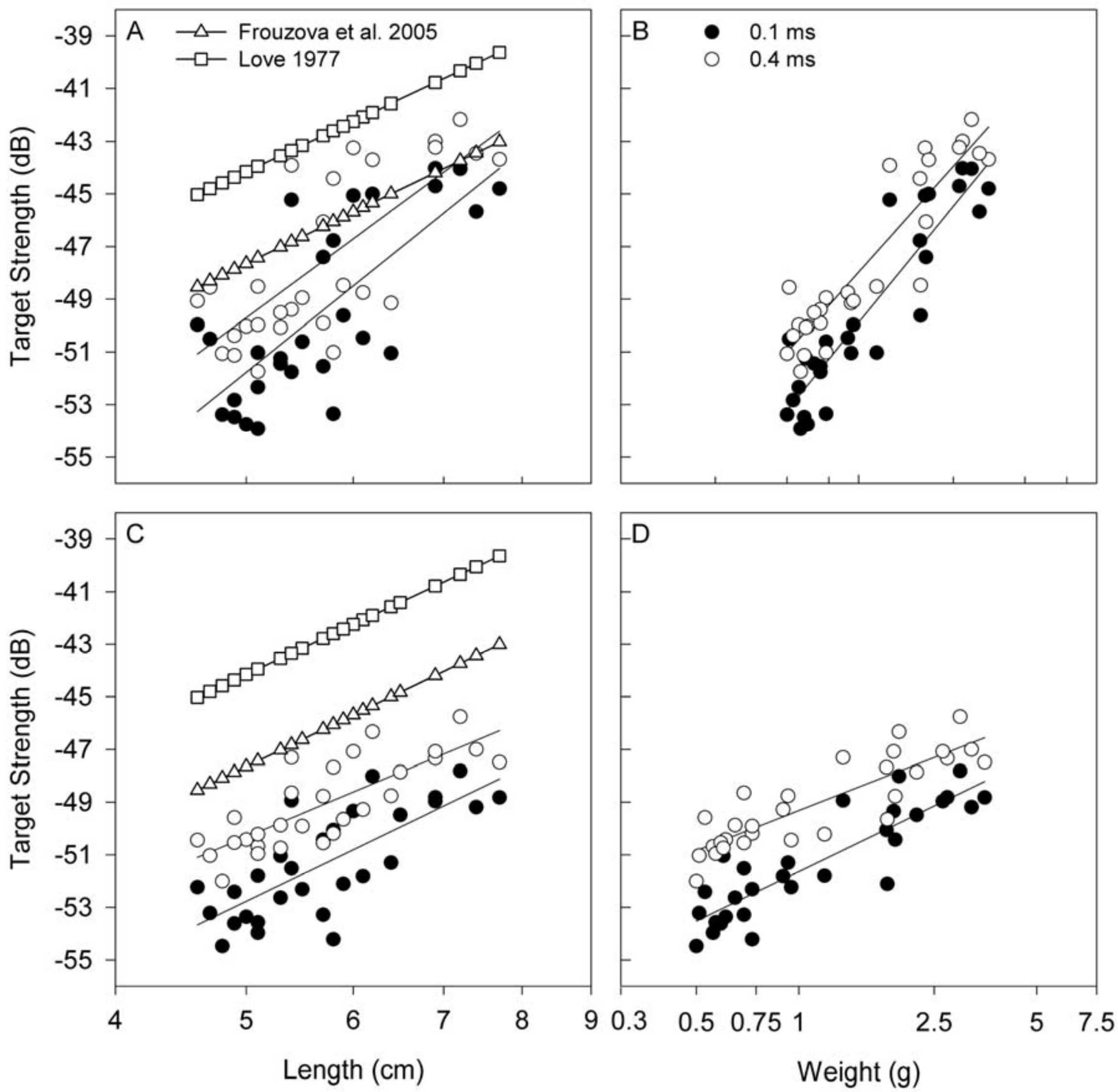

Figure 3.14. Regressions of TS-length and TS-weight for pooled data from bay anchovy (*Anchoa mitchilli*, 4.7-6.1 cm) and Gulf menhaden (*Brevoortia patronus,* 5.1-7.7 cm) at 420 kHz. Each panel illustrates least squares fit through data points for each pulse duration level. (A) lateral, length; (B) lateral, weight; (C) all regions, length; (D) all regions, weight. See Table 3.2 for regression coefficients.

Table 3.2. Target strength (TS) regression coefficients estimated from ex situ tank experiments on bay anchovy (*Anchoa mitchilli*) (n=15, 4.7-6.1 cm; 0.5 – 0.93 g) and Gulf menhaden (*Brevoortia patronus*) (n=14, 51-77 cm; 0.71 – 3.52 g). Regressions analyses of TS (dB) to total fish length (TL, cm) and wet weight (W, g) were fitted following TS= a $\log_{10}$ TL + b and TS= a $\log_{10}$ W + b for the lateral region and all regions at 420 kHz at two pulse durations. Parameter estimates for the standard form regression (TS= 20 $\log_{10}$ TL + b_{20}, Foote 1987) and corresponding correlation coefficients are included.

			Length (TL)				Weight (W)		
Species	Pulse duration	Orientation	A	b	b_{20}	R^2 / R^2 b_{20}	a	b	R^2
Bay anchovy	0.4 ms	lateral	19.5	-62.4	-62.8	0.38 /0.40	10.4	-46.3	0.47
		all	11.6	-59.0	-65.4	0.05 /0.15	6.5	-49.4	0.07
	0.1 ms	lateral	17.2	-63.3	-65.3	0.22 /0.29	9.1	-49.0	0.27
		all	8.6	-59.6	-67.9	0.02 /0.12	4.6	-52.5	0.03
Gulf menhaden	0.4 ms	lateral	26.1	-65.6	-60.8	0.54 /0.32	10.0	-48.0	0.52
		all	9.9	-56.8	-64.8	0.03 /0.14	3.7	-50.2	0.03
	0.1 ms	lateral	26.3	-67.3	-62.3	0.53 /0.31	10.0	-49.5	0.51
		all	8.9	-58.5	-67.2	0.02 /0.10	3.4	-52.4	0.02
Anchovy/ Menhaden Combined	0.4 ms	lateral	32.0	-70.9	-61.8	0.64 /0.25	7.3	-47.0	0.71
		all	14.5	-60.8	-65.0	0.09 /0.18	3.4	-50.0	0.11
	0.1 ms	lateral	35.9	-75.9	-63.9	0.59 /0.18	8.9	-49.1	0.76
		all	14.9	-63.7	-67.5	0.07 /0.13	3.8	-52.6	0.10

Comparisons of TS measures from anchovy and menhaden with predicted TS values from the side-aspect relationships proposed by Frouzova et al. (2005) and Love (1977) showed that both equations overestimated TS. On average, the model by Frouzova et al. (2005) overestimated TS by 1.9 dB and 1.3 dB for anchovy and menhaden, respectively, while the model of Love (1977) overestimated TS by 5.6 dB and 3.4 dB for anchovy and menhaden, respectively.

Regression coefficients for the TS to $\log_{10}$-W relationships for anchovy, menhaden, and the combination of anchovy and menhaden are provided in Table 3.2. The relationship between lateral TS and log-weight for anchovy, menhaden, and both species combined showed modest fit, however the relationships for all orientations were poorly fitted (Table 3.2; $r^2 < 0.11$).

3.3.2 Free Swimming Fish

Anchovy fish tracks (n=880) and menhaden fish tracks (n=1308) were identified in the acoustic data from individual fish swimming within the net. Menhaden had a significantly ($P<0.001$) higher mean TS at both pulse durations (0.1 ms = -45.8 dB, SE bounds:-45.7,-46.2; 0.4 ms = -45.2 dB, SE bounds:-45.1,-45.3) than did anchovy (0.1 ms = -49.1 dB, SE bounds:-49.0,-49.2; 0.4 ms = -49.3 dB, SE bounds:-49.2,-49.4). Species differences in mean TS between pulse durations were not significant for anchovy ($p=0.971$) although differences were significant for menhaden ($p<0.0001$).

Target strength distributions were not different between pulse durations within species for free swimming fish (median test, $p>0.2402$; KS test, $p>0.129$); however, I found significant differences in distributions (Figure 3.11) between species (median test, $p<0.0001$; KS test, $p<0.001$). Menhaden at the 0.4 ms pulse duration had a higher TS

(-45.2 dB, SE bounds:-45.1,-45.3) than anchovy at 0.1 ms pulse duration (-48.8 dB, SE bounds:-48.6,-49.0).

3.3.3 Tethered Fish vs. Free Swimming Fish

Mean TS measures of free swimming individuals were between 0.8 and 3.7 dB higher than the corresponding mean TS generated from the tethered individuals for both species and both pulse durations. Target strength frequency distributions of free swimming individuals overlapped frequency distributions from tethered fish (Figure 3.11). Based on regional (head/tail, oblique, lateral) TS frequency distributions from tethered individuals (Figure 3.12), the majority of scattering observed in the free swimming individuals may be the result of the predominance of measures from the lateral orientation in both species.

3.4 DISCUSSION

3.4.1 Target Strength Model Comparisons

The goal of acoustic surveys is to describe fish distribution, by estimating abundance or biomass through the scaling of echo integration data. Typically a generalized equation (Love 1977; Foote 1987; Frouzova et al. 2005) is used to estimate fish length from TS data (Simmonds and MacLennan 2005). However, biases can be introduced in the application of these equations. For example, if an echo integration value typical of a stationary acoustic survey in Barataria Bay, LA (S_v= -53 dB; Chapter 2) and a mean fish length of 6 cm were adopted, the resultant density estimate following the regression relationship presented here for both species combined at all orientations would be 0.063 fish m^{-3} (pulse duration= 0.4 ms). In this example, Frouzova et al.'s (2005) equation would underestimate acoustic fish density by approximately 30% (0.044 fish m^{-}

^{3}) and Love's (1977) equation would underestimate acoustic fish density by 60% (0.022 fish m^{-3}) relative to my model. When considered on an average survey scale in terms of water volume sampled, Frouzova et al.'s and Love's relationships would greatly underestimate anchovy and menhaden fish density by 437 fish 10,000 m^{-3} and 224 fish 10,000 m^{-3}, respectively; as compared to my predicted density estimate (631 fish 10,000 m^{-3}). Peltonen and Balk (2005) reported vast differences (850,000 tons) in estimated biomass of herring in the Baltic Sea based upon the proper selection of TS-length equations. Thus, the potential variability associated with selection of an appropriate TS-L relationship highlights the importance of careful selection and use of TS-length relationships during data analysis.

The TS-TL relationships presented in this paper are derived from a small sample size for both species. However, for the size ranges presented, the relationships should be representative of the expected TS response (Lilja et al. 2000; Gauthier and Rose 2001; Hartman and Nagy 2005). Based on the results in this study, and given the ubiquitous distribution of both anchovy and menhaden in Louisiana estuaries, I recommend the use of the following TS-TL relationships for the pooled data from both species at 0.4 ms ($TS_{lateral} = 32 * Log_{10}\ TL - 70.9$; $TS_{all\text{-}angles} = 20 * Log_{10}\ TL - 65$) as they provided the most realistic predicted values and explained more variability in the data than did the individual species-specific models (see Table 3.2).

3.4.2 Effects of Orientation on Target Strength Estimates

Lateral orientations had consistently greater TS values, particularly in menhaden, than the head/tail, oblique, and pooled data from all regions. Kubecka and Duncan (1998) reported a similar finding for European freshwater fishes with the mean all-aspect

TS intermediate to other orientations. It is well known that fish orientation can influence TS distributions of individuals (Love 1977; Foote 1991; Simmonds and MacLennan 2005). This is particularly true for side-looking aspects (Kubecka and Duncan 1998; Frouzova et al. 2005) where large variations can exist in the cross-sectional area of the target and variations in scattering are largely a function of swimbladder shape relative to the acoustic axis (Medwin and Clay 1998). Additionally, it is understood that fish condition and physiological changes (Ona 1990; Hazen and Horne 2003), both of which vary spatially and temporally, can have measurable effects on the scattering strength of an organism (Rose and Porter 1996).

For the size ranges used in this experiment, orientation did not significantly influence TS values, particularly for anchovy, whose greatest average difference between pooled data from all regions versus any one particular region (head/tail, oblique, and lateral) was 1.9 (0.1 ms) and 1.7 dB (0.4 ms). This suggests that when averaging over all possible orientations, we can expect that the maximum difference in the average TS will not be greater than 2 dB for anchovy and 3.5 dB for menhaden, assuming that fish must be ensonified at all angles for the resultant averaging effect to be useful (Yule 2000).

I propose that when taking into account the complex hydrological characteristics of estuarine systems in Louisiana, where currents are generally neither uniform nor uni-directional, the probability of ensonifying an individual fish in shallow estuarine waters at any horizontal aspect is likely to be equal. Based on the results of this study, it would be appropriate to adopt a TS-TL relationship which accounts for all possible angles in the horizontal aspect. This is true for fish that exhibit highly aggregative behavior and are highly mobile, like anchovy and menhaden.

3.4.3 Effects of Pulse Duration on Target Strength Measurements

I modeled the effect of pulse duration on TS in an effort to understand the potential role of using pulse duration as a discriminatory variable for separating echoes from anchovy and menhaden in estuarine waters. It is impractical to utilize multiple frequencies due to the influence of acoustic noise in shallow waters (<2 m) which can be amplified in lower frequencies (120–200 kHz). For both methods, tethered and free swimming anchovy and menhaden could be clearly separated by mean TS between pulse durations. For example, tethered menhaden had much higher TS at 0.4 ms than did anchovy at 0.1 ms, supporting my assertion for the potential use of pulse duration as a discriminatory variable. In addition to measured differences in mean TS, preliminary discriminant function analyses of tank data support the utility of pulse duration as a time dependent variable for separating echoes from anchovy and menhaden with 80% correct classification. Recent integration of dual-frequency identification sonar (DIDSON) into my survey design has further enhanced the ability to use pulse duration as a discriminatory variable by providing a better ‘visual’ resolution of species differences.

3.4.4 Target Strength Distributions

Distributions of TS from the head/tail and oblique regions showed a narrower range than the lateral region for both species and furthers understanding of the effects of increasing surface area on TS estimates. As the orientation of the swim bladder becomes more perpendicular with respect to the acoustic beam, TS increases. The fact that the lateral TS distribution for menhaden was much wider and more pronounced than the corresponding distribution for anchovy is likely due to species-specific fish morphology and more specifically swim bladder shape (Boswell unpublished data) and volume.

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CHPATER 4: ACOUSTIC ESTIMATES OF FISH BIOMASS, DENSITY, AND SIZE DISTRIBUTIONS ASSOCIATED WITH ESTUARINE HABITATS

4.1 INTRODUCTION

Links between coastal wetlands and fishery production have been well documented (Boesch and Turner 1984; Conner and Day 1987; Herke et al. 1992; Houde and Rutherford 1993; and Mitsch and Gosselink 1993). In particular, estuarine systems have been shown to serve as nursery habitat to many transient and resident fishes, including important commercial and recreational species. The U.S. Congress recognized the importance of protecting habitats that are critical to fish life history in the Sustainable Fisheries Act (SFA) of 1996. The Act identifies essential fish habitat (EFH) as those waters and substrates necessary for spawning, breeding, feeding, or growth to maturity and mandates that EFH be identified for federally managed species (Benaka 1999). Because estuarine habitats are highly variable and complex, the dependence of fish upon these available habitat types is not well understood (Able 1999; Minello 1999). We cannot effectively manage and protect these habitats without sound scientific knowledge of the functional dependence of all life history stages of fishes on available habitat. Furthermore, the high rate of land loss and habitat degradation occurring in coastal Louisiana (Dahl 2000; Raynie and Beasley 2000; Barras et al. 2003) further emphasizes the need for understanding the relative importance of habitat to fishes and their forage base.

Hydroacoustics has been widely accepted as a method for enhancing fisheries assessments and has been gaining momentum as a survey technique in shallow water environments. Despite the many benefits of acoustics (e.g. non-invasive, rapid data collection, high resolution spatio-temporal data, and large sample volume), fundamental

challenges are encountered when conducting acoustic surveys in shallow waters. In many shallow water surveys, horizontal beaming has been chosen over vertical beaming to increase sample volume and maximize detection of fishes. Shallow water surveys are often susceptible to bubble-induced noise due to physical and environmental conditions (Frouzova et al. 1998). Additionally, in shallow waters horizontal acoustic range is a function of water depth; interfaces of the sediment and the surface elicit scattering that can influence scattering from nearby targets. However, performance may be optimized when care is taken to aim the acoustic beam to maximize sampling range in shallow waters (Pedersen and Trevorrow 1999).

Most studies utilize acoustics as a complementary sampling technique to efficiently estimate fish abundance and density while relying on direct biological sampling to gain information on the composition of the surveyed fish community (Mackinson et al. 1994; Yule 2000; Simmonds and MacLennan 2005). Attempts have been made to standardize acoustic data to net catches and to use selectivity indices from nets to partition acoustic data (Hansson and Rudstam 1995; Bethke et al.1999). However, little effort has been put into the integration of acoustic and net data in shallow waters. A probable explanation for this paucity of research is the lack of species-specific acoustic information and bias in fish length estimation, given the functional dependence of acoustic scattering on fish orientation from a horizontal aspect.

In a cooperative effort to understand and evaluate EFH for fishes associated with estuarine habitats, I conducted hydroacoustic surveys to quantify changes in habitat-specific fish biomass, density, and size distribution in the ultra-shallow waters (<2 m) of Barataria Bay, LA. I tested the null hypotheses that: 1) seasonal differences in habitat-

specific biomass, density, and fish size distributions could not be detected; and 2) seasonal differences in fish biomass, density, and size distribution would not vary across a salinity gradient. In addition, traditional net sampling was incorporated (MacRae 2006) to compare with acoustically derived size distributions to assess the feasibility of a multi-gear sampling approach.

4.2 METHODS AND MATERIALS

4.2.1 Study Area

The Barataria Bay complex, located in southeastern Louisiana, is characterized as an interdistributary estuarine-wetland system bordered by the natural levees of the Mississippi River to the east and the abandoned Bayou LaFourche distributary to the west. The Barataria Basin is one of the largest estuaries in the northern Gulf of Mexico and encompasses an area of approximately 4,100 km^2 with an average depth of 2.3 m (Conner and Day 1987). The basin is characterized by two dominant substrate types: hard-bottom (oyster shell/reef) and soft-bottom (sand/mud). The areal extent of each has been partially documented with side scan sonar as described by Allen et al. (2005).

Survey stations were located along a north-south salinity gradient at sampling stations established for the Louisiana Department of Wildlife and Fisheries (LDWF) long-term fisheries monitoring program. Stations were located at Fisherman's Point (FP; oligohaline), Manila Village (MV; mesohaline), Queen Bess Island (QB; polyhaline), and Grand Terre Island (GT; polyhaline) (Figure 2.1). Each site was characterized by the presence of adjacent hard and soft-bottom substrate, identified from side scan sonar mosaics (Allen et al. 2005). As the GT station did not contain significant shell habitat, a corresponding hard-bottom station was established at nearby QB (MacRae 2006).

4.2.2 Acoustic Array

Acoustic fish biomass, density, and size distributions were estimated with a BioSonics DT-X digital echosounder equipped with two BioSonics 420 kHz elliptical split-beam transducers (2.4º x 6.2º half-power beam widths) calibrated with the standard sphere method (Foote et al. 1987). Data were collected at a -75 dB threshold and a pulse width of 0.4 ms with the BioSonics Acquisition Program (4.1) (see Table 4.1 for parameter settings). Approximate acoustic resolution of single targets was 0.3 m following $R = c\tau/2$ (Simmonds and MacLennan 2005) where c=speed of sound in water (1500 m/s) and τ is pulse length duration (0.4 ms). Transducers were multiplexed at a sample rate of 10 Hz with an effective sample rate of 5 Hz per transducer. Acoustic data were collected for 1 hour at each habitat at each station. Standard environmental variables (water temperature, salinity and dissolved oxygen) were recorded with a calibrated hand-held environmental monitor (YSI, Model 85) at each station.

Each transducer was mounted horizontally on an aluminum platform with a remote pitch control to manipulate transducer angle and optimize acoustic range to accommodate fluctuations in water levels and environmental conditions. Transducers were manually adjusted to mid-water depth (approximately 0.9 m) and transducer pitch, relative to the water surface, was adjusted for optimum range and data quality. The minimum effective sampling depth of the platform was 0.5 m, yielding a minimum sampling range of approximately 15 m.

A series of fixed-location horizontal acoustic surveys were conducted to quantify relative changes in acoustic fish biomass, density and fish size distribution associated with hard (oyster shell) and soft (sand/mud) bottom habitats. A GPS unit, interfaced with

Table 4.1. Echosounder, transducer, and analysis parameters used in analyses.

Sonar system parameters	
BioSonics DE-X split beam echosounder:	
Operating frequency	420 kHz
Pulse duration	0.4 ms
Pulse rate, per transducer	5 Hz
Transducer parameters	
2-way beam angle (ψ)	-24.47 dB
Collection threshold	-75 dB
Major-axis beam width	6.2 º
Minor-axis beam width	2.4 º
Echoview analysis parameters	
Analysis thresholds	
S_v	-60 dB
TS	-55 dB
Single target detector	
Pulse length determination level	6 dB
Minimum normalized pulse length	0.6
Maximum normalized pulse length	1.7
Maximum beam compensation	12 dB
Maximum standard deviation of:	
minor-axis angles	0.8
major-axis angles	0.8

a personal computer, provided real-time position with respect to the side scan mosaic, enabling acoustic backscattering data to be collected over discrete habitat types. Monthly surveys were conducted from June 2003 to May 2004, excluding November and December 2003 due to inclement weather and equipment malfunction. Occasionally during the study, weather conditions prevented data collection at some stations. Table 4.2 provides dates for which data were successfully collected. Acoustic sampling gear were deployed during daylight hours at both habitat types at each survey station concurrently with both experimental gill nets (MacRae 2006) and push trawl collections.

4.2.3 Echoview Setup and Integration

Raw acoustic data were imported, organized and pre-processed in Echoview 3.50 (SonarData Pty Ltd.) with an acoustic volume backscattering strength (S_v, in dB) analysis threshold of -70 dB (Table 4.1). Data were edited to exclude unwanted reverberation (entrained air and surface/bottom scatter) with the School Detection Module in Echoview. Sound speed and absorption coefficients were calculated in Visual Acquisition and entered in Echoview to account for the effects of temperature and salinity on acoustic data. Prior to echo integration, a grid was applied to the data establishing 5 m x 5 min analysis cells. Estimates of the volume backscattering coefficient (s_v), the linear counterpart of S_v ($S_v = 10 * \log_{10}(s_v)$) used for all calculations involving S_v (MacLennan et al. 2002), were derived in Echoview following standard echo integration techniques (MacLennan and Simmonds 1992). Integration reports were generated for each analysis cell in Echoview and exported into SAS (v 9.1, SAS Institute 2006) for further analysis. Nomenclature of acoustic variables follows MacLennan et al. 2002.

Table 4.2. Survey dates. '+' indicates where data were successfully collected and '-' indicates where data were not collected.

		Station					
Date	Season	FP-Mud	FP-Shell	MV-Mud	MV-Shell	GT-Mud	QB-Shell
6-2003	Summer	-	-	+	+	+	+
7-2003	Summer	+	+	+	+	+	+
8-2003	Fall	+	+	+	-	+	+
9-2003	Fall	+	+	+	+	-	-
10-2003	Fall	+	+	+	+	+	+
11-2003	NA	-	-	-	-	-	-
12-2003	NA	-	-	-	-	-	-
1-2004	Winter	+	+	+	+	+	+
2-2004	Winter	-	-	+	+	+	+
3-2004	Spring	+	+	-	-	+	+
4-2004	Spring	-	-	+	+	+	+
5-2004	Spring	-	-	+	+	-	-

One limitation of shallow water surveys is the susceptibility to bubble-induced noise from entrained air under windy conditions (Kubecka and Wittingerova 1998; Knudsen and Sægrov 2002). Occasionally I detected high levels of noise in the acoustic record for which a filtering technique was necessary. The filter was implemented in Echoview using the Virtual Echogram Module to enhance acoustic signals relative to background levels. A series of virtual echograms were applied to reduce the effect of backscattered noise generated from entrained air by selecting for data that consistently exceeded background levels (Figure 4.1).

The original Sv data was resampled at 300-400 pings in the horizontal dimension and at 5-10 m in the vertical dimension with no threshold imposed. The resampling operation involved calculating a specified percentile, usually 83%, of the Sv sample values in each bin and applying that value as the resampled Sv value for the bin. The result was a 'noise' echogram consisting of a spatially-smoothed measure of Sv defining the boundary between background noise and biological scattering signal. In each case the specified percentile was tuned by visual examination. In parallel, the original Sv data were also subjected to a 7x7 matrix median filter which effectively smoothed the echogram, spatially enhancing areas of significant backscatter signal and spatially diminishing areas of low backscatter signal. The purpose was to remove the effects of inter-sample variation on all scales smaller then the expected scale of the biological backscatter. The 'noise' echogram was then subtracted from the median-filtered echogram via a subtraction operator, yielding an echogram in which all values exceeding the corresponding samples from the 'noise' echogram were given positive values and all others assigned negative values. The final "processed" echogram was created by applying

a 7x7 convolution matrix with coefficient (i,j)=1 for all (i,j) to the results of the minus operation. Finally a mask was applied to the original Sv echogram based on all of the positive samples in the 'processed' echogram. The use of a mask allows the original data to be preserved where the various conditions in the processed echogram are effectively met.

Thus, the method used to generate the 'processed' echogram can be assumed to provide a definition of undesirable noise, and the final masked echogram will consist of only valid biological data, with undesirable noise excluded. The success of this filtering method is not dependent upon appropriate thresholding and has been determined adequate for use in data analysis at integration ranges >20 m, typical of side-looking data collected in shallow waters (<2 m) of coastal Louisiana.

4.2.4 Target Strength

Target strength (TS) reports were generated in Echoview from single targets identified using the single-beam single target detection algorithm. Due to a limitation of the masking echogram in Echoview, the single-beam single target operator was used for target selection rather than the split-beam operator. Furthermore, only targets that corresponded to accepted data from the masked S_v echogram were accepted for processing. Targets in the masked echogram that fulfilled both single target criteria (Table 4.1) and had TS above -55 dB were accepted. The single target algorithm was tuned to accept targets with echo envelopes between 0.6 and 1.7 times the pulse duration with a maximum beam compensation of 12 dB. For each target identified in Echoview, a TS value was provided and an estimate of the backscattering cross-section (σ_{bs}) for each target was calculated in SAS with the following:

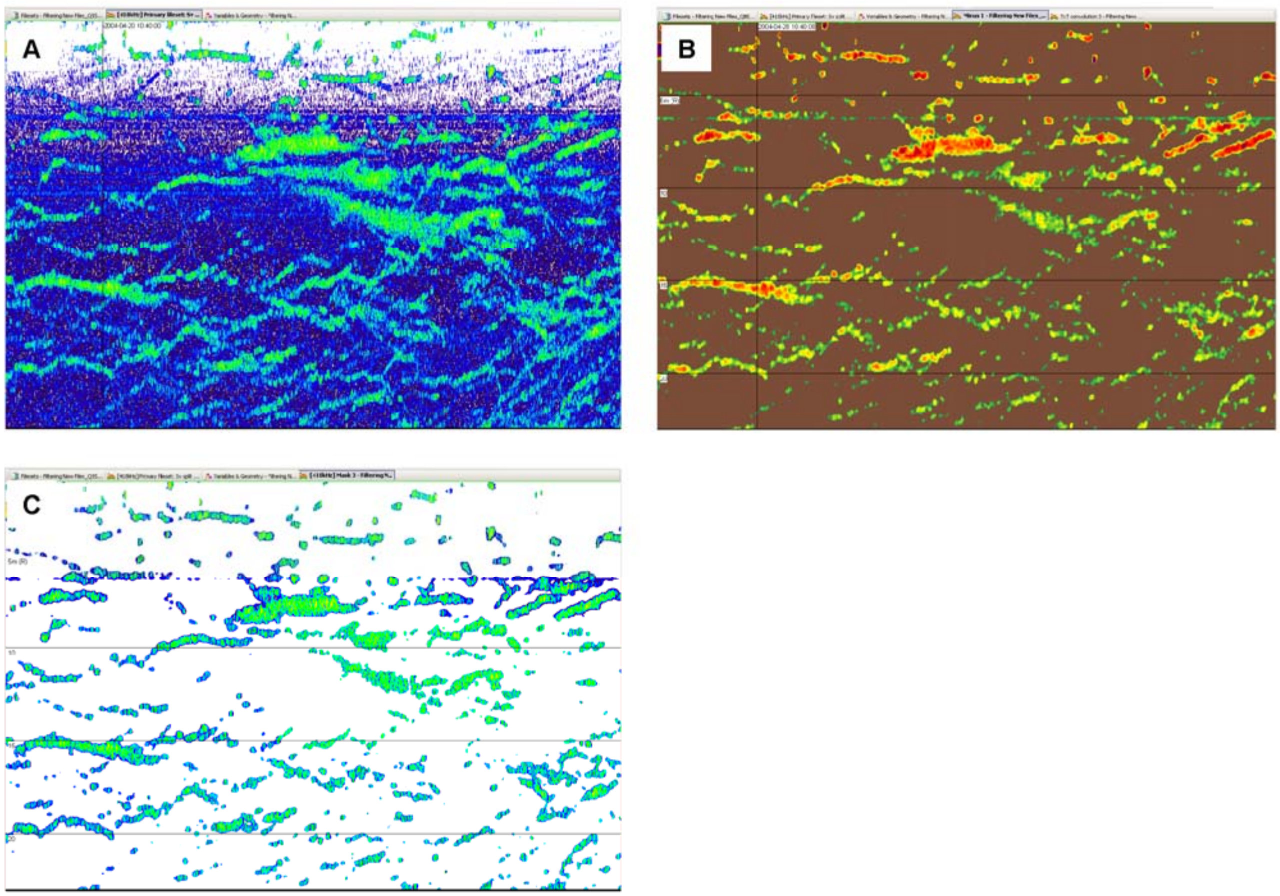

Figure 4.1. Analysis filters developed in Echoview to remove background noise from survey data. Panels A-C illustrate the performance of the filter technique. (A) Represents the unthresholded S_v echogram, simulating raw, unfiltered data. (B) 'Noise' echogram. Resampled S_v data removed from raw data via subtraction operator to remove background noise. (C) 'Processed' echogram of data that consistently exceed background data. The x-axis represents elapsed time and y-axis represents distance from transducer face, distance increases in negative y direction.

$TS=10 * \log_{10}(\sigma_{bs})$ (MacLennan et al. 2002), Equation (4.1)

where σ_{bs} is the linear equivalent of TS and was used for all calculations involving TS and all statistical analyses. Given the mixed species assemblages found in estuarine systems (Subrahmanyam and Coultas 1980; Hoese and Moore 1998; Rozas and Minello 1998; Gelwick et al. 2001), and the lack of horizontal-aspect information on the relationship of TS and standard length (SL) for estuarine fish, we used the relationship defined in Frouzova et al. (2005) to estimate SL from TS:

$TS=24.71 * \log_{10}(SL)-64.92.$ Equation (4.2)

Target strength frequency distributions, based upon acceptance criteria were used to compare fish SL (cm) data from gill net and push trawl samples by converting SL into TS with equation (4.2). Although the TS-SL relationship proposed by Frouzova et al. (2005) was derived for an assemblage of European freshwater fishes (cyprinids, salmonids, and percids ranging in length from 7.2 to 71 cm), I adopted its use for the mixed assemblage in Barataria Bay due to the lack of horizontal-aspect acoustic information available for estuarine fishes. The body morphologies of the European fish (referenced above) were assumed to approximate the potential body morphologies of those found in the estuarine waters in this study.

4.2.5 Fish Biomass Calculations

Fish biomass (g m^{-3}) was estimated from acoustic data by converting σ_{bs} into SL (cm)following equations (4.1) and (4.2). By converting σ_{bs} into an estimate of SL, the weight (W, in g) per unit SL can be derived (MacLennan and Simmonds 1992; Hedgepeth et al. 1996) with the widely known function:

$W= a * SL^b.$ Equation (4.3)

The coefficients a and b were fit from the SL-W relationship of the fish community. I used an averaged SL-W relationship based on the mixed species assemblage from net catches with parameters a=0.0174 and b=2.9628, yielding a TS per unit weight (TS_w) for the fish community (Figure 2.4),

$$TS_w = -4.92 * \log_{10} SL - 47.33. \qquad \text{Equation (4.4)}$$

Transformation of TS_w yields an equivalent acoustic backscattering cross-section per unit weight (σ_{bsw}) used to scale s_v within each analysis cell, with:

$$\text{Fish Biomass}_{cell} = s_{v\ cell} / \sigma_{bsw\ cell}. \qquad \text{Equation (4.5)}$$

4.2.6 Gill Nets and Push Trawls

Gill nets and push trawls were deployed contemporaneously with acoustic surveys to identify the fish community composition associated with habitat type and to derive fish length distributions. Of the ten monthly surveys conducted, four (February- May 2004) surveys included both push trawl and gill net comparisons. Gill nets were fished for two hours adjacent to the acoustic beam over each habitat type (MacRae 2006). Experimental gill nets were 46.5 m in length and consisted of five 9.3 m panels with unstretched mesh sizes of 1.27, 1.91, 2.54, 3.18 and 3.8 cm. Total abundances, total W(g), and SL (cm) were recorded for each species. Individual SL and W were recorded and catches with greater than 50 individuals of the same species were sub-sampled for SL and W (MacRae 2006). Fish SL were converted to TS with equation (4.2).

Push trawls were used from February to May 2005 to capture the smaller fishes (<7 cm) that the gill nets did not effectively sample (MacRae 2006). Directly following acoustic data collection, transducer platforms were retrieved and a 1-m^2 push trawl (1 cm mesh and 0.5 cm cod end) was deployed from the bow of the pontoon boat. Three 100 m

habitat-specific transects were conducted at an approximate speed of 2 m s^{-1}. Fishes collected were bagged, placed in an ice slurry and later frozen. Total abundances, total W (g), and SL (cm) were recorded for each species. Individual SL and W were recorded and catches with greater than 50 individuals of the same species were sub-sampled for SL and W.

Length distributions from both gill nets and push trawls were combined at each station and habitat type for comparison with the acoustic data. Standard lengths from Gulf menhaden (*Brevoortia patronus*) less than 9 cm and all bay anchovy (*Anchoa mitchilli*) were converted into TS with an equation derived from tank measurements (see Chapter 3). The equation,

$$TS=20* \log (SL) -65, \qquad \text{Equation (4.6)}$$

was fit from pooled data of bay anchovy and Gulf menhaden at a side-aspect and incorporates all horizontal-aspects relative to the transducer as suggested by Kubecka (1994). Target strengths for all other fish were estimated with equation (4.2).

4.2.7 Data Analysis

Data were grouped into seasons (winter, spring, summer, and fall) as shown in Table 4.2. Attempts were made to designate surveys into seasons based upon solstice dates. However, I combined data from surveys that did not represent true seasonal designations to account for missing data (Table 4.2), thus balancing the statistical design and to conforming to assumptions of parametric analyses. A three-way ANOVA was used to test for seasonal differences in mean acoustic biomass (g m^{-3}) and mean acoustic fish density (fish m^{-3}) (Factors: season, station, and habitat; Table 4.2). Biomass and fish density estimates were ($\log_e * x$) transformed prior to analysis to satisfy the assumptions

of homogeneity of variance. The null hypothesis was that no difference in mean acoustic biomass or mean acoustic fish density would be detected across season, station, or habitat type. A similar analysis was conducted for TS. Prior to analysis, TS was converted into the linear form following $\sigma_{bs} = 10^{(TS/10)}$ and then $\log_e(\sigma_{bs})$ transformed to satisfy the assumptions of normality. For all three ANOVA models, the residuals were approximately independently and normally distributed, with less than 20 observations appearing as outliers. Therefore, I relied on the robustness of the analysis and the large sample size (n=2866) to detect differences. Tukey's honest significant difference *post-hoc* test was used to test for differences in means among main effects. Variability in TS-frequency distributions by station and habitat were compared with the Kolmogorov-Smirnov (K-S) two sample test (Sokal and Rohlf 1995) and the median test (Zar 1996). All statistical tests were reported as significant at $\alpha=0.05$ and all means and standard errors reported are least squares means (LSMeans).

4.3 RESULTS

4.3.1 Biomass and Density

Mean acoustic biomass varied significantly as a function of season, station, and habitat, in addition to their interactions (Table 4.3). Oyster shell habitats supported higher biomass (0.36 ± 0.02 g m^{-3}; $p<0.001$) than soft-bottom habitats (0.27 ± 0.02 g m^{-3}) when pooled across season and survey station. Mean acoustic biomass was highest at GT/QB (0.36 ± 0.02 g m^{-3}) and lowest at FP (0.28 ± 0.02 g m^{-3}), although significant differences were only detected between GT/QB and MV ($p=0.035$) based upon LSMeans comparisons. Seasonal biomass estimates increased from 0.14 ± 0.02 g

Table 4.3. Analysis of Type III fixed effects (Proc Mixed) on mean acoustic biomass ($\log_e$ biomass) by habitat type (oyster shell vs. sand/mud) and survey station (FP, MV, GT/QB) in Barataria Bay, LA.

	Mean Acoustic Biomass		Mean TS		Mean Fish Density	
Source of Variation	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F
Season	62.7	<0.0001	26.3	<0.0001	49.4	<0.0001
Station	4.0	<.0177	3.7	<.0249	7.0	0.0009
Habitat	12.4	0.0004	42.3	<0.0001	7.2	0.0072
station*habitat	13.2	<0.0001	42.3	<0.0001	13.9	<0.0001
season*station	39.1	<0.0001	19.5	<0.0001	19.1	<0.0001
season*habitat	16.7	<0.0001	3.8	<0.0134	11.4	<0.0001
season*station*habitat	17.4	<0.0001	17.7	<0.0001	5.2	<0.0001

m^{-3} during the summer to 0.74 ± 0.05 g m^{-3} during the spring (Figure 4.3), with fall (0.26 ± 0.02 g m^{-3}) and winter (0.35 ± 0.02 g m^{-3}) being intermediate. Throughout the study, biomass was higher over oyster shell than adjacent sand/mud habitat, with the exception of the winter season (Figure 4.5) when an abundance of schooling fish, mostly bay anchovy and Gulf menhaden, increased biomass estimates over the sand/mud habitat.

Season, station, habitat, and their interactions significantly explained variation in fish density (Table 4.3). Seasonal fish density (fish 100 m^{-3}) estimates closely followed trends in fish biomass (Figures 4.4 and 4.6). However, in contrast to biomass estimates, fish density did not increase with increasing salinity. Rather, density was lowest at MV ($p<0.05$) with no differences between FP and GT/QB ($p=0.92$). In addition, fish density was significantly higher over sand/mud habitat (9.6 ± 0.6 fish 100 m^{-3}; $p=0.007$). *Post-hoc* comparisons of the station*habitat interaction indicate that the MV shell habitat was much lower than the other stations. When coupled with higher biomass estimates, this suggests that the lower density estimates associated with the MV oyster shell habitat were due to the detection of larger individuals. Increases in density were much more pronounced over the sand/mud habitat during the winter and spring seasons as compared to oyster shell habitat (Figure 4.5).

4.3.2 Mean Target Strength Estimates

Mean TS, and therefore mean fish size, was greatest over shell habitat (-45.2 dB, SE bounds:-45.0,-45.5) as compared to sand/mud habitat (-46.7 dB, SE bounds:-46.6,-46.9) and increased moderately with increasing salinity from -46.4 dB (SE bounds:-46.2,-46.7; FP) to -45.7 dB (SE bounds:-45.5,-46.0;GT/QB). For both habitat types, mean TS

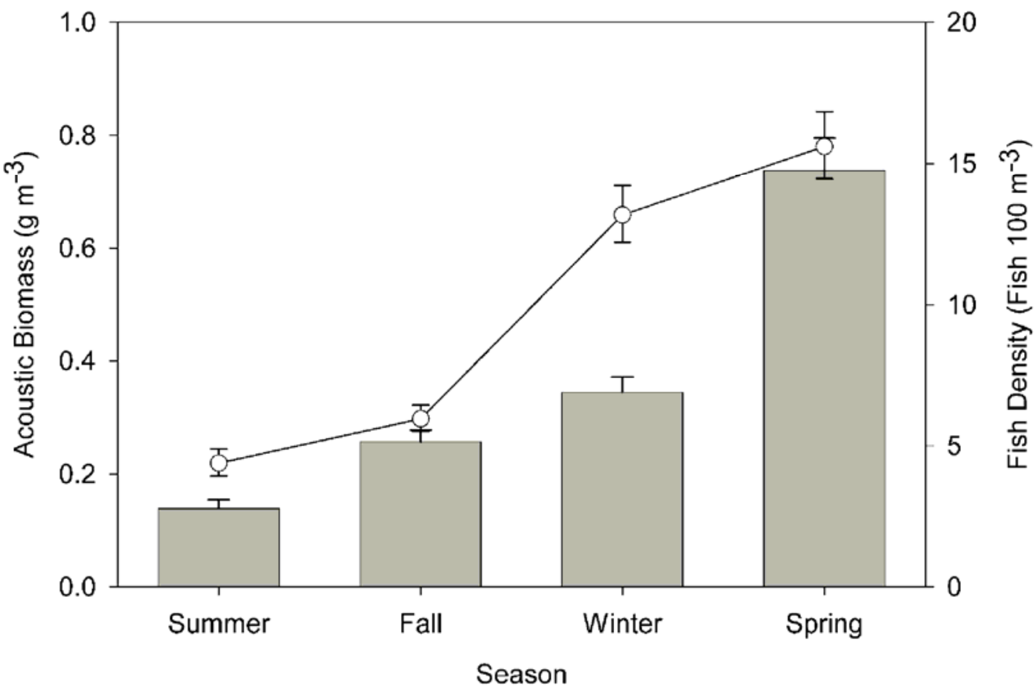

Figure 4.2. LSMeans of seasonal biomass (bars) and fish density (line) pooled across station and habitat type. Error bars represent standard error.

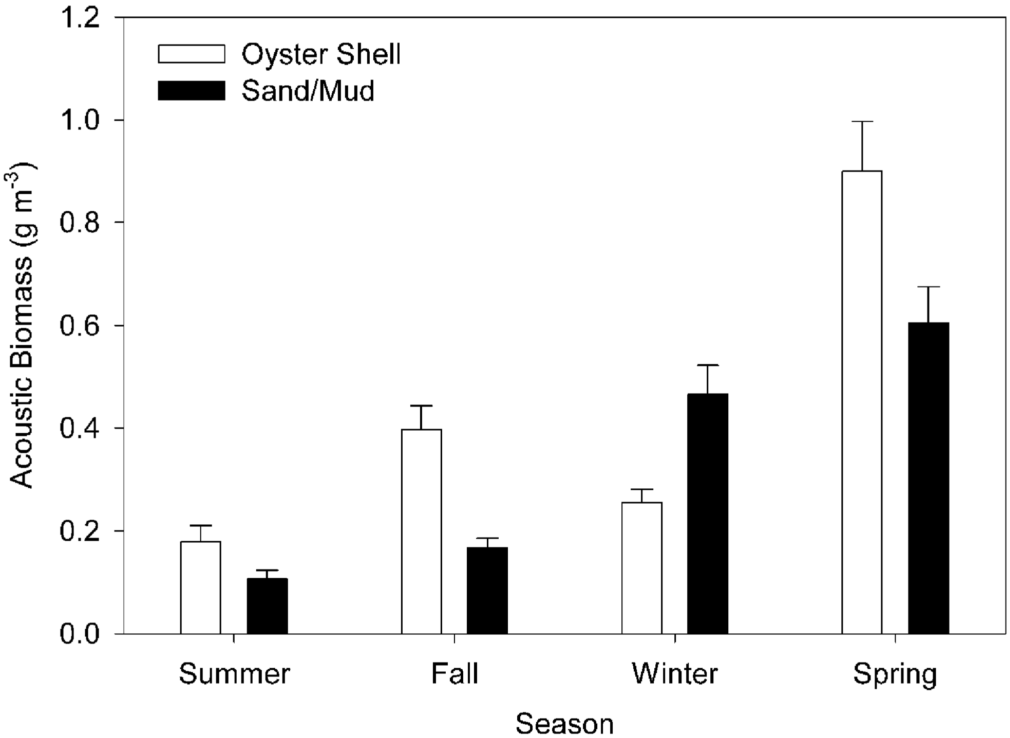

Figure 4.3. LSMeans estimates of seasonal biomass by habitat type in Barataria Bay. Error bars represent standard error.

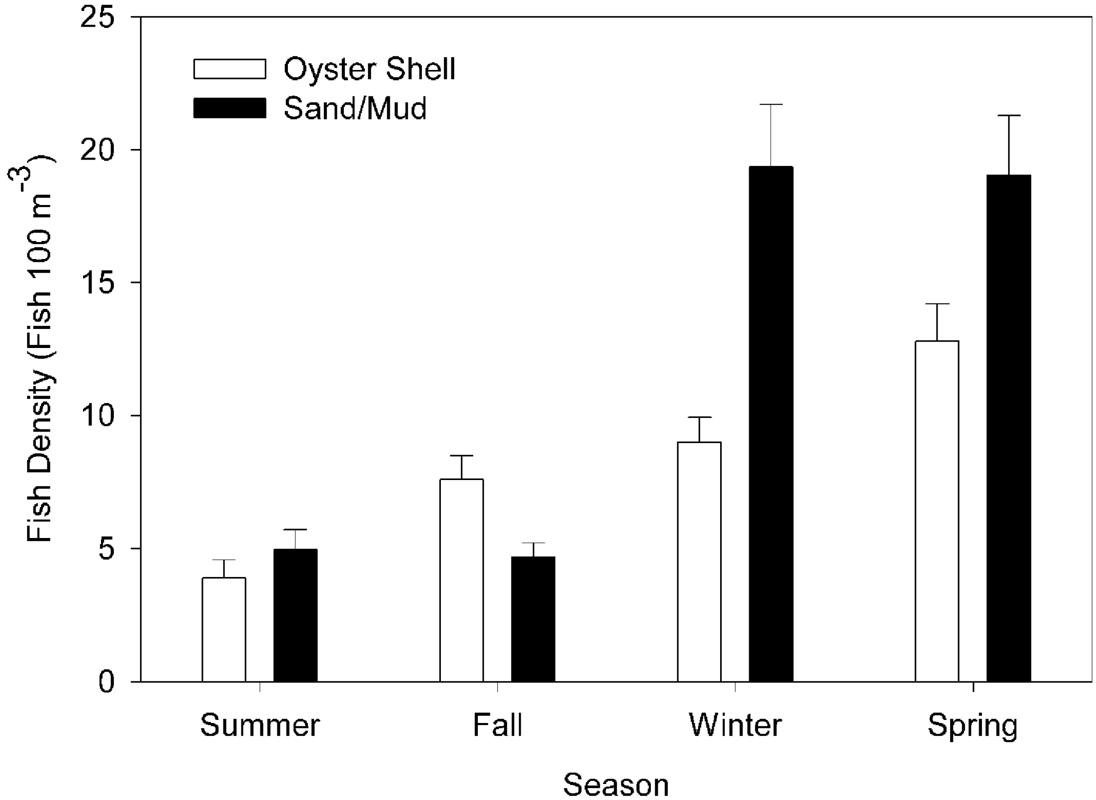

Figure 4.4. Seasonal fish density estimates (Fish 100 m^{-3}) by habitat type. Error bars represent standard error.

increased from summer (oyster shell, -45.4; sand/mud, -47.6) to fall (oyster shell, -44.4; sand/mud, -45.6), decreased from fall to winter (oyster shell, -47.0;sand/mud,-47.4), and subsequently increased from winter to spring (oyster shell, -44.1; sand/mud,-46.1) (Figure 4.6). Overall, larger fish were more associated with oyster shell habitat (-45.2 dB, SE bounds:-45.0,-45.4; $p<0.001$) than compared with sand/mud habitat (-46.7 dB, SE bounds:-46.5,-47.0), with the greatest separation in fish sizes occurring at MV between oyster shell (-44.2 dB, SE bounds:-43.9,-44.5) and sand/mud habitat (-47.2 dB, SE bounds:-47.0,-47.5). Fish size was generally smallest at FP. However, during the spring season the largest mean size individuals were found at FP with GT/QB supporting the smallest mean size individuals (Figure 4.7).

4.3.3 Target Strength Distributions

Overall no difference was observed in TS distributions (K-S test, $p=0.999$; median test, $p=0.483$) between habitat types, although significant differences were observed between habitats within months during March (K-S test, $p=0.004$; median test, $p=<0.001$) and April 2004 (median test, $p=0.012$). Differences in TS distributions between habitats during March were attributed to differences between habitats at the GT/QB stations, with an increase in the number of smaller individual fishes at the oyster shell than at the sand/mud habitat. Conversely, differences in TS distributions during April were driven by the same stations, although a higher percentage of smaller individuals occurred over sand/mud compared to the oyster shell habitat. A significant difference was observed when comparing TS distributions across survey stations, with GT/QB having a greater proportion of smaller fish than at FP (K-S test, $p=0.038$; median concordance when compared with monthly TS data; however, similarities in trends are

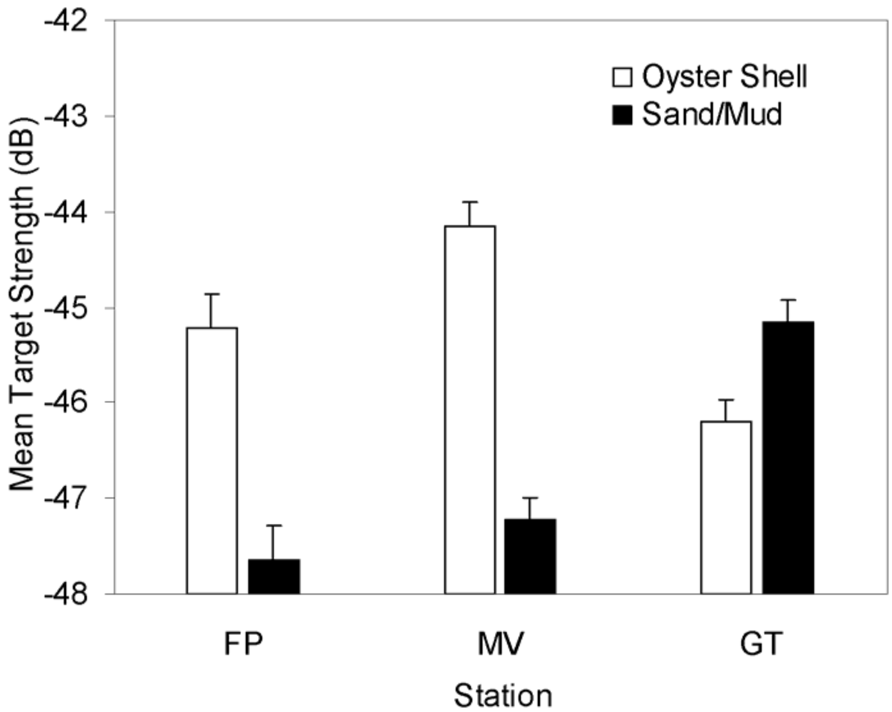

Figure 4.5. Seasonal estimates of LSMeans for TS pooled across station by habitat; empty bars are oyster shell and solid bars are sand/mud. Error bars represent standard error.

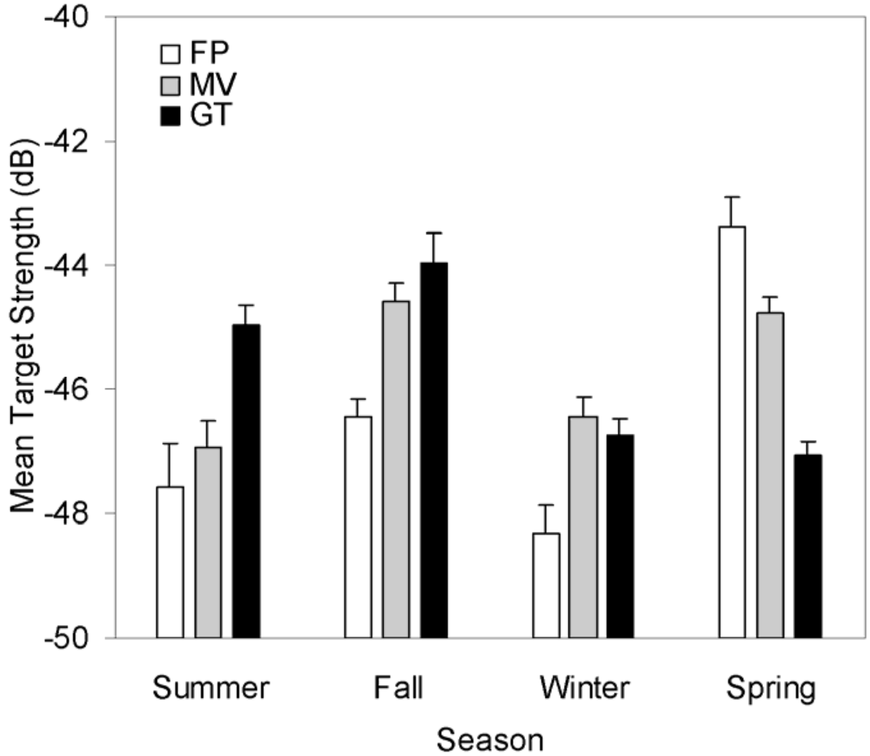

Figure 4.6. LSMeans of TS by survey station in Barataria Bay, LA. FP=empty bars, MV=gray bars, and GT/QB= black bars. Error bars represent standard error.

test, $p<0.005$), with MV not differing from either. However, it should be noted that only one survey from FP was included in this analysis due to missing data (Table 4.2).

Fish SL data, converted into TS with equations (4.2) and (4.7), showed moderate less obvious when pooled across seasons for both station and habitat (Figures 4.7 and 4.8). Considerable overlap (>10 dB) was observed between TS distributions of converted push trawl and gill net data (Figures 4.7 and 4.8).

4.3.4 Push Trawl and Gill Net Catch

Bay anchovy consistently dominated push trawl catches, whereas gill net catches were dominated by Gulf menhaden at all stations (Tables 4.4 and 4.5). As a result of the selective nature of gill nets, bay anchovy were not captured because of their small size. Combined datasets from both gear types reflected consistently higher proportional abundances of bay anchovy (> 65%) and Gulf menhaden (> 25%) when compared to abundances of all other species captured (see MacRae 2006).

4.4 DISCUSSION

Fish biomass, density, and TS in Barataria Bay varied significantly by season, salinity, and habitat type, with higher salinity and oyster shell habitat supporting the highest biomass and the largest individuals. Inspection of the echograms generated from the surveys suggests that schooling fish are likely influencing biomass and density estimates. For example, the increase in fish biomass over sand/mud habitat during the winter and spring season is at least partly a result of the detection of schooling fish, which is further supported by high density values and smaller individuals associated with corresponding habitat types during each of these periods. In the biologically heterogeneous system characteristic of coastal Louisiana, many small-bodied schooling

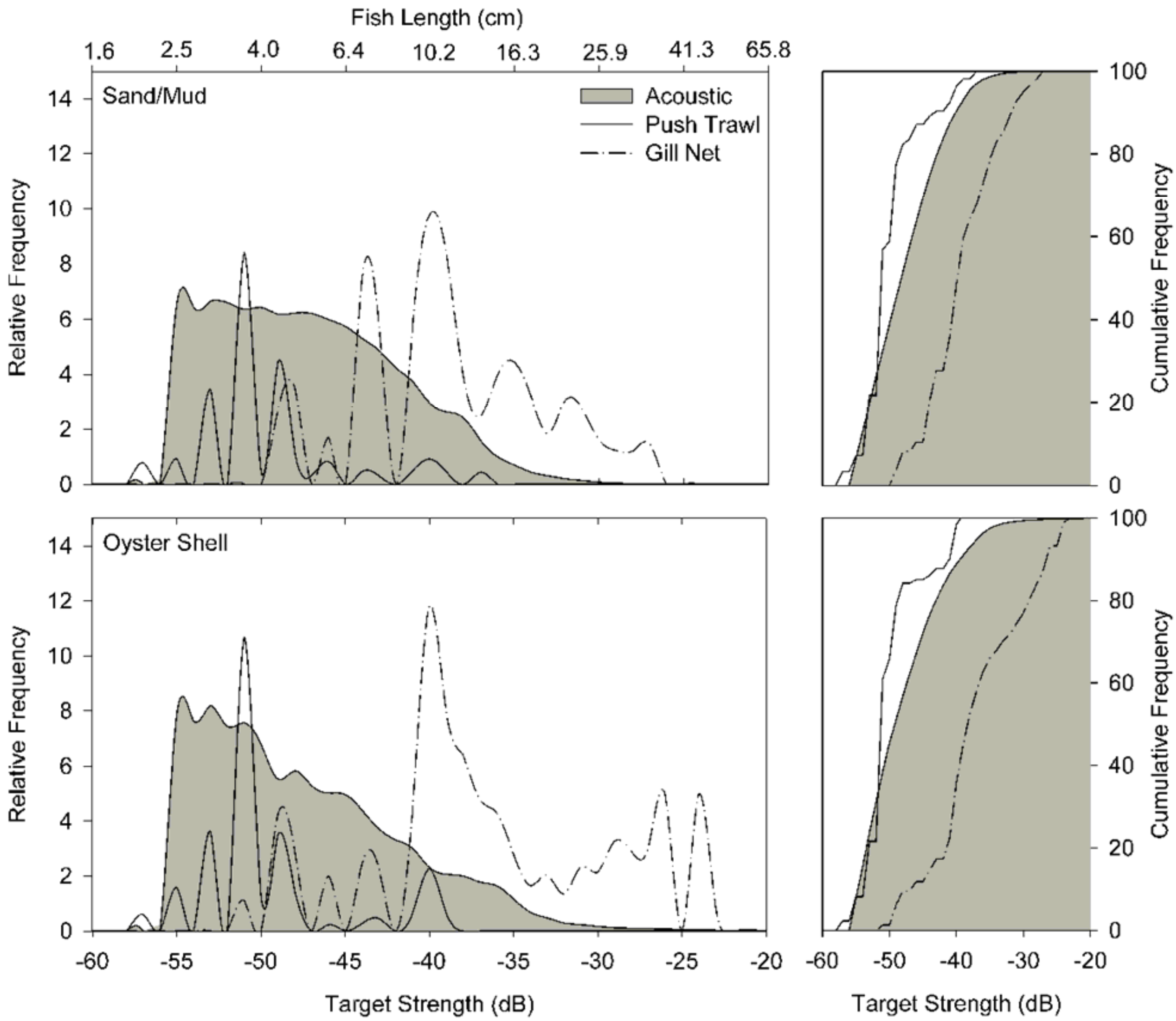

Figure 4.7. Target strength frequency distributions by habitat type. Right-hand panels represent cumulative frequency distributions of target strength data. Filled area represents measured TS distribution from acoustic data and lines represent estimated TS distributions derived from push trawl and gill net catches in Barataria Bay, LA. Estimated fish length is along upper x-axis. The x-axes are represented in $\log_{10}$ scale.

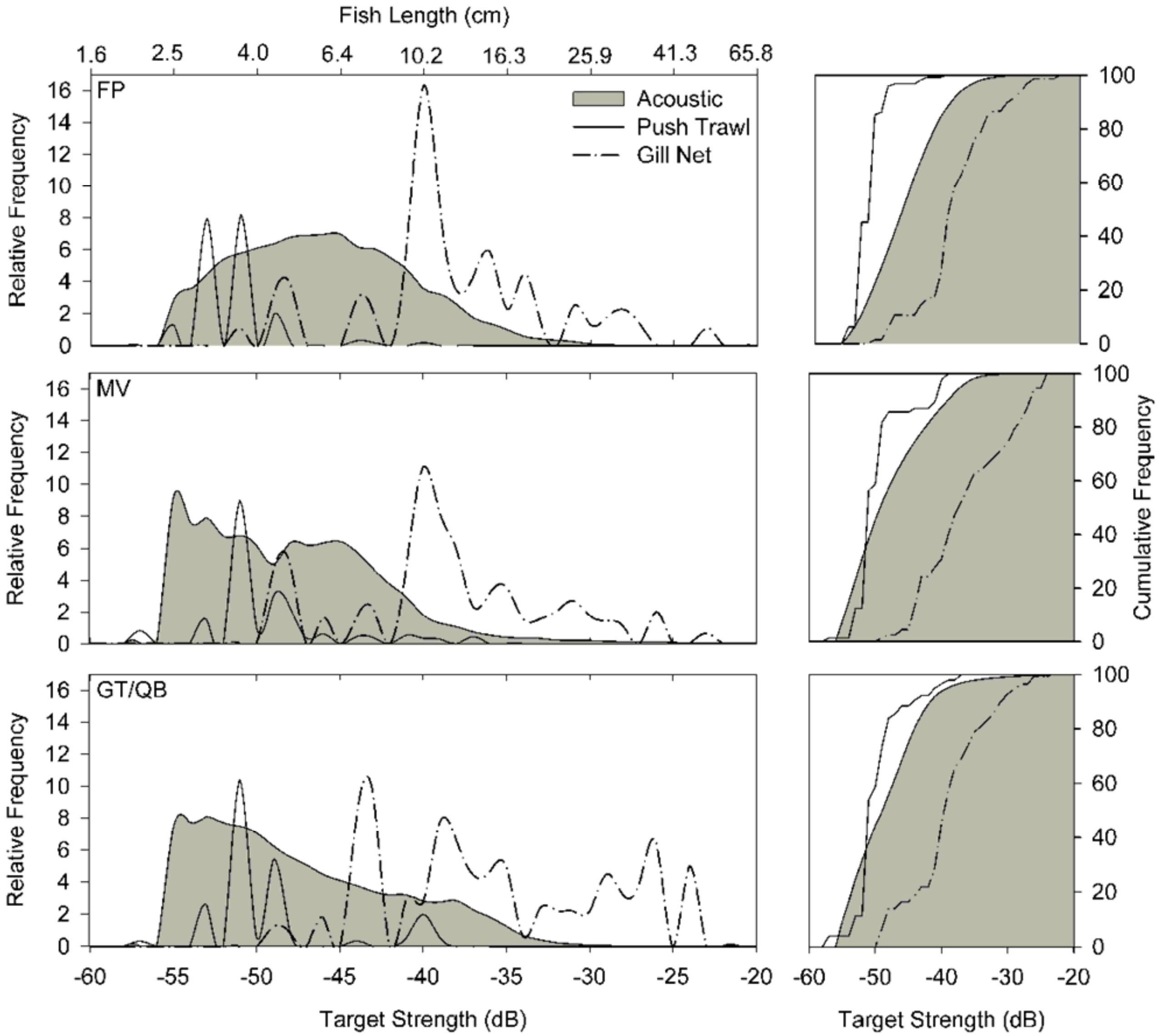

Figure 4.8. Target strength frequency distributions by survey station, pooled across habitats. Right-hand panels represent cumulative frequency distributions of target strength data. Filled area represents the measured TS distribution from acoustic data and lines represent estimated TS distributions derived from push trawl and gill net catches in Barataria Bay, LA. Estimated fish length is along the upper x-axis. The x-axes are represented in log_{10} scale.

Table 4.4. Percent species abundance of catch from push trawl and gill net collections by habitat type. Only the four most dominant species are shown for each gear type.

	Push Trawl			Gill Net		
Station	Species	Total Count	Total Percent	Species	Total Count	Total Percent
Sand/Mud	*Anchoa mitchilli*	354	80.8	*Brevoortia patronus*	232	50.7
	Cynoscion arenarius	19	4.34	*Cynoscion arenarius*	25	5.5
	Membras martinica	25	5.7	*Leiostomus xanthurus*	67	14.6
	Sphoeroides parvus	13	3.0	*Micropogonias undulatus*	59	12.9
Oyster Shell	*Anchoa mitchilli*	253	76.6	*Arius felis*	29	7.9
	Brevoortia patronus	23	6.9	*Bairdiella chrysoura*	35	9.6
	Cynoscion arenarius	25	7.6	*Brevoortia patronus*	214	58.5
	Membras martinica	14	4.2	*Micropogonias undulatus*	22	6.0

Table 4.5. Percent species abundance of catch from push trawl and gill net collections by survey station. Only the four most dominant species are shown for each gear type.

Station	Push Trawl			Gill Net		
	Species	Total Count	Total Percent	Species	Total Count	Total Percent
FP	*Anchoa mitchilli*	200	85.8	*Alosa chrysoleucas*	6	3.5
	Brevoortia patronus	27	11.6	*Arius felis*	13	7.6
	Membras martinica	2	0.9	*Brevoortia patronus*	131	76.2
	Micropogonias undulatus	2	0.9	*Micropogonias undulatus*	6	3.5
MV	*Anchoa mitchilli*	203	67.7	*Arius felis*	16	6.0
	Cynoscion arenarius	44	14.7	*Bairdiella chrysoura*	32	12.0
	Membras martinica	10	3.3	*Brevoortia patronus*	166	62.4
	Sphoeroides parvus	24	8.0	*Cynoscion nebulosus*	16	6.0
GT	*Anchoa mitchilli*	204	86.8	*Brevoortia patronus*	149	38.6
	Gobiosoma bosc	1	0.4	*Cynoscion arenarius*	23	6.0
	Membras martinica	27	11.5	*Leiostomus xanthurus*	67	17.4
	Sphoeroides parvus	3	0.4	*Micropogonias undulatus*	67	17.4

species are present (e.g. *Anchoa mitchilli*, *Brevoortia patronus*, *Membras martinica*, *Leiostomus xanthurus*) and were likely contributors to the scattering observed during the study. It has been suggested that extended survey intervals, from 4 hours to 4 days, may help to reduce variations in biomass and density as fish behavior and temporal variation can significantly influence estimates (Comeau and Boisclair 1998). This is particularly important when the objective is to evaluate habitat use by fishes.

Fish biomass and density estimates are useful when used as a relative index for following changes in fish distributions (Yule 2000). However, I recognize that biomass estimates should not be interpreted explicitly because of the functional dependence on both S_v and TS. The calculation of acoustic biomass may be inherently biased because S_v is a measure of all scattering within a volume of water, not specific to individual fish or size ranges. Furthermore, TS is a measure of the scattering length of a target and can vary with orientation and fish condition. Thus, the conversion of TS into an estimate of L, and ultimately unit weight, relies upon the proper selection and fit of TS-L and W-L relationships. In our study, we estimated the W-L relationship for the individuals known to inhabit the estuary, and all species-specific W-L relationships received equal weighting regardless of their presence during the study. As such, this may have resulted in inherently biased biomass estimates. That notwithstanding, the use of acoustic biomass estimates should be viewed as a metric for acoustically assessing temporal and spatial changes in fish biomass distributions (McClatchie and Dunford 2003) and further supports the need for identification of the acoustic properties of common estuarine fishes.

In this study I was able to use acoustics to detect differences in biomass and density between habitat types. However, significant differences were not observed from

the analyses of concurrent gill net catches (MacRae 2006). The lack of concordance between the two gear types is potentially due to gear selectivity inherent with traditional collection techniques (Hubert 1996). As stated earlier, the gill nets did not effectively sample the smaller sized individuals, which according to the push trawl catches and TS distributions presented, may have accounted for a significant fraction of the observed acoustic scattering. Given the considerable overlap in TS distributions of push trawl (upper end of distribution) and gill net data (lower end of distribution), there is compelling evidence of our ability to more effectively sample the fish community than with only a single gear type. Furthermore, results from single gear surveys may provide misleading results (Browne 1981; Jackson and Harvey 1997).

It is important to note, that although biases are likely present with each net collection gear, potential sampling bias may also exist with the acoustic gear. The gill net and push trawl gear were designed to characterize a particular component of the fish community and when combined, provide a more complete picture of the species composition and the length distributions of fishes in Barataria Bay. In contrast, the acoustic gear was incorporated to describe the fish community, and was assumed to be free of bias. Figures 4.7 and 4.8 both show TS distributions from gill net data that exceed measured TS values. Further, cumulative frequency distributions indicate that a majority of scattering is due to smaller fishes. Two possible explanations are provided: 1) proportionally, the larger fish are less likely to be ensonified in the acoustic volume as compared to smaller pelagics; and 2) the ability to ensonify benthic-associated fishes, generally larger fish captured in the gill nets (e.g. black drum, *Pogonias cromis*; and red

drum, *Sciaenops ocellatus*; hardhead catfish, *Arius felis*), is reduced given the conical shape of the beam and the inability to survey along the sediment water interface.

Given the presumed ecosystem function of oyster reefs and their importance to fishes (feeding, reproduction, recruitment, refugia) it is not surprising that overall fish biomass estimates were higher than adjacent soft-bottom habitats (Jordan et al. 1996; Coen et al. 1999; Harding and Mann 2001; Lehnert and Allen 2002). An overall increase in habitat-specific fish biomass associated with oyster shell may be indicative of increased habitat value and thus could imply habitat selection or preference by fishes. There is compelling evidence to suggest that oyster habitats, while limited in spatial extent, may be considered important to estuarine fishes (Cohen et al. 1999; Lehnert and Allen 2002). Although few in number, some studies have directly compared diversity and abundance between oyster reef and soft-bottom habitats (see Cohen et al. 1999; Lehnert and Allen 2002). Lehnert and Allen (2002) found that oyster habitat supported both higher diversity and abundance of nekton and benthic communities when compared to surrounding soft-bottom habitats. An increase in biomass and density associated with oyster habitat can be attributed to the complex three-dimensional substrate which organisms utilize for settlement, feeding, and refugia (Cohen et al. 1999; Coen and Luckenbach 2000; Mann 2000; Peterson et al. 2003). Although an association between fish and oyster habitat has been illustrated, based on fish distribution data (Avre 1960; Dame 1979; Coen et al. 1999; Lenihan et al. 2001; Lehnert and Allen 2002), the relative habitat value to fishes is not clear.

Information provided in this study addresses the first two levels of information required for the designation of EFH (Level 1- fish distribution; Level 2- relative density

and abundance). When considering that estuarine habitats exist as a mosaic of discrete habitats that can be utilized by various mobile species (Bell et al. 1991; Posey et al. 2000; Lehnert and Allen 2002), efforts for identifying or isolating essential habitats may be misdirected. Furthermore, Hubert (1992) suggested that habitat selection is assumed to be driven by resources available and the immediate needs of an individual and may not necessarily represent habitat as essential. Therefore it may be more prudent to place efforts on understanding habitat function within a multi-species fish-life-history context. For example, efforts could be expanded to a more appropriate scale whereby ecosystem benefits are incorporated rather than the traditional approach of focusing on a species-specific EFH approach.

In this study I have demonstrated that acoustics can be a useful tool for assessing changes in fish distributions in the shallow waters of Barataria Bay. Although direct comparisons between acoustic metrics and gill net catch statistics were not conducted, it is probable that by filtering the acoustic data to mimic the size selective nature of the gill nets, a useful approach for the integration of both gears may be developed. Certainly the use of acoustics should be viewed as a complimentary survey technique to traditional collection methods given the high resolution (spatial and temporal) data and ease of collection (Mackinson 2004). I are confident in the abilities to detect changes in fish distribution across discrete habitat types and salinity gradients and argue that further development of this method will result in a robust tool for assessing differential habitat use of fishes in estuarine habitats.

To make effective management use of the concept of EFH, a universal standard must be developed and, although the level of information afforded through acoustic and

traditional sampling (e.g. gill nets, trawls, traps, etc.) does not satisfy the classification criteria of EFH (Level 3- growth, reproduction, and mortality; Level 4- production rates), it will help to establish a baseline for comparisons within and between estuarine systems. Clearly a need exists for the further development of acoustics as a tool for generating estimates of fish distribution in estuarine waters, particularly when it is well known that estuaries play a critical role as nursery habitat and serve as refugia for many fishes (Boesch andTurner1984; Minello 1999; Zimmerman et al. 2000). Through the proper development and use, acoustics could be useful for quantifying estuarine flux and for assessing production potential for habitats thought to be necessary for optimal fish survival and growth. Furthermore, acoustics will complement sampling efforts for evaluating habitat importance, particularly in efforts for evaluating EFH. Lastly, acoustics could be useful for identifying and monitoring ecosystem reference points to evaluate change and in standardizing methods for ecosystem based management approaches.

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CHAPTER 5: HYDROACOUSTIC ASSESSMENT OF SEASONAL CHANGES IN FISH BIOMASS, DENSITY AND SIZE DISTRIBUTION AT A SHALLOW WATER ARTIFICIAL REEF IN THE NORTHERN GULF OF MEXICO

5.1 INTRODUCTION

Approximately 4,000 petroleum platforms currently stand in the continental shelf waters of the northern Gulf of Mexico (NGOM) (Pulsipher et al. 2001). These structures serve as artificial reefs and provide complex hard structure in an otherwise largely structureless soft bottom environment. Upon the cessation of their production of petroleum products, platforms can be decommissioned and retired as artificial reefs via the Louisiana Artificial Reef Program Rigs to Reefs initiative. It is believed that artificial reef structures influence the fish community both by increasing and improving the available complex habitat important for feeding and refuge (Grossman et al.1997) and by enhancing and concentrating resources (Stanley and Wilson 2000). Although the addition of complex structure likely provides benefits to the fish community, it has been shown to increase opportunity for exploitation of fishery resources (Bohnsack 1989; Bohnsack et al. 1994; Grossman et al. 1997) and has become a topic of discussion among fishery managers (Steimle and Meier 1997).

The Freeport Sulphur Mine Artificial Reef (FSMAR), located 11 km southeast of Barataria Bay, LA, in the NGOM (Figure 5.1; 29º 11’ 13” N, 89º 53’ 20” W), may be the world’s largest intentional artificial reef (130 m^2). It is composed of more than 29 metal structures, ranging from support platforms to a power plant facility, including 2.4 km of bridgework. The mine was decommissioned in the early 1990’s and through a cooperative agreement between the State of Louisiana and the Freeport Sulphur Company, the structure was converted into a shallow water (15 m) artificial reef. During

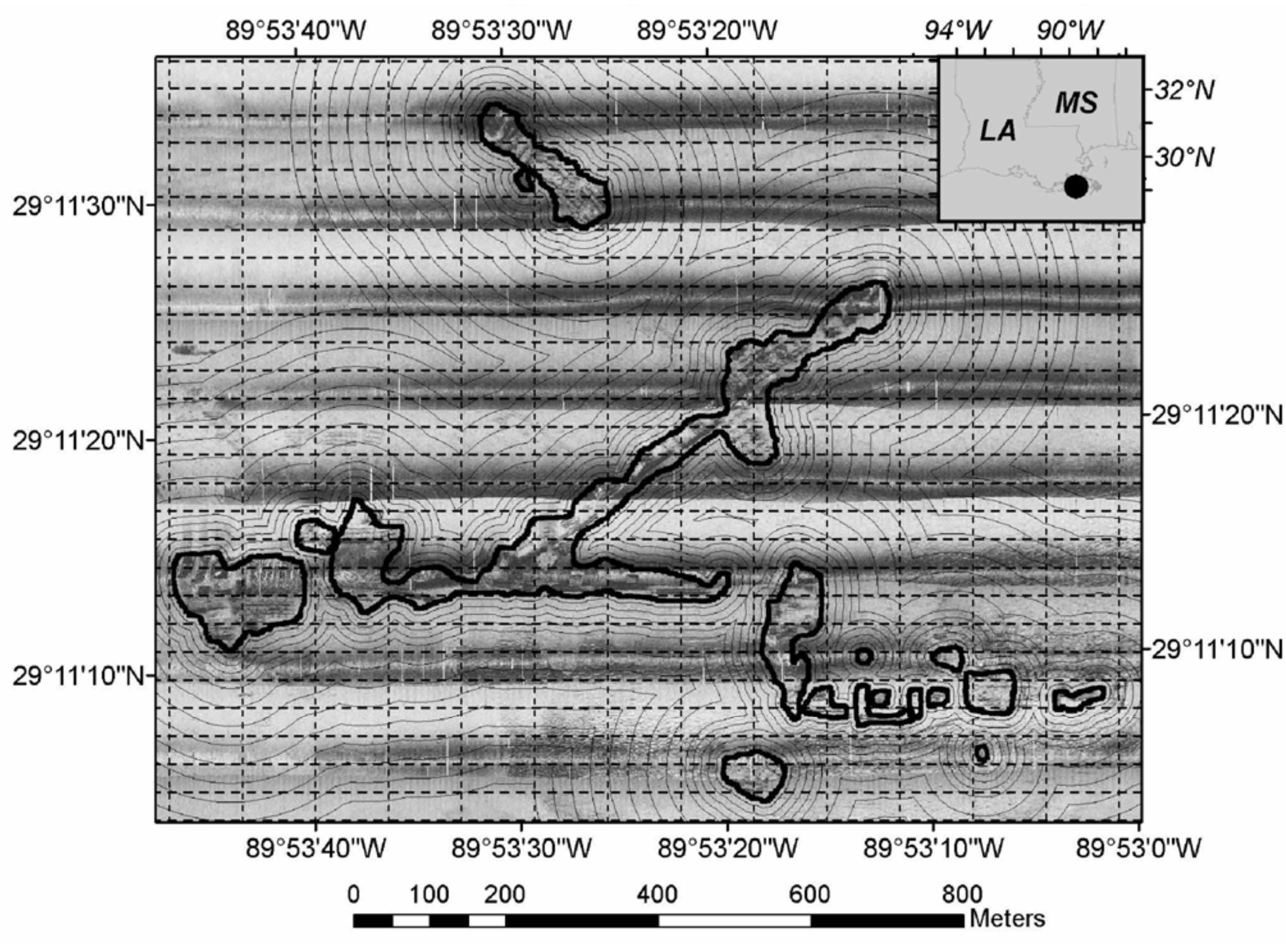

Figure 5.1. The FSMAR, located off Grand Isle, LA in the northern GOM. Map shows position of concentric buffer distance zones placed around the reef structure. The first buffer includes the reef structure and areas out to 1 m. Buffer zones 2-6 are spaced at 10 m intervals and include distances from buffer 1 out to 50 m. Buffer zones 7-14 are spaced at 25 m intervals and include distances from buffer 6 out to 250 m. Buffer zones 15 and 16 are spaced at 250 m intervals and represent distances from 250 m to 1000 m away from the reef. Broken lines overlaid on image represent transect lines, vertical transect was conducted in September 2003 and horizontal transect was conducted in October 2003. Datum: NAD83. Projection: UTM Zone 15. Map modified from original produced by John Chance and Associates.

the decommissioning process, all superstructures were removed and the remaining components were cut off at a depth of 7 m from the water's surface and placed next to the remaining structure.

The FSMAR has historically been heavily exploited by recreational anglers and sport divers due to its close proximity to coastal fishing ports and diverse fauna. Anecdotal evidence suggests that the FSMAR is characterized by both estuarine and marine fishes. The implications of an artificial structure of this magnitude in shallow waters are currently unknown; however, knowledge of effects of the unique attributes of this reef on the distribution of fishes may prove useful for designing future deployments of artificial structures in coastal waters.

Effective fishery management decisions concerning the use of artificial reefs in the management of fishery resources depends on quantitative data on spatial and temporal variations in biomass, abundance, and community composition (Bortone et al. 1997); however, fishery independent data are often difficult to obtain, particularly at decommissioned oil and gas platforms (Stanley and Wilson 1996). Traditional net sampling methods are not effective, much less safe, for sampling areas of high relief and structural complexity. Traditionally, visual census techniques have been employed for identifying and enumerating the faunal communities (Hastings et al. 1976; Gallaway et al. 1981; Bortone et al. 1986; Rooker et al. 1997) associated with artificial and natural reefs; however, these techniques are often compromised by poor visibility (Fabi and Sala 2002) and can be biased by diver impact on fish behavior (Stanley and Wilson 1997).

Hydroacoustics has been used as a tool both for deriving relative unbiased estimates of fish abundance and describing community structure in the NGOM (Stanley

and Wilson 1996; 1997; 1998; 2000). The use of hydroacoustics as a tool for surveying fishery resources in a variety of ecosystems has been widely accepted (Luo and Brandt 1993; Lima and Castello 1995; Burwen and Fleischman 1998; Fabi and Sala 2002; Simmonds and MacLennan 2005). This technology offers many benefits, some of which include reduced sampling effort, non-invasive sampling, and acquisition of high resolution spatio-temporal data (Simmonds and MacLennan 2005). However, in spite of the many advantages, species specific estimates are often confounded by a lack of validation. Consequently, it is necessary to supplement acoustic surveys with some form of qualitative and quantitative species-specific sampling (e.g. video or diver census techniques).

Acoustic volume backscattering strength (S_v) and target strength (TS) are the two primary output variables used for acoustically describing the surveyed fish community. S_v is a logarithmic expression of the integration of acoustic energy scattered from targets within a unit-volume of water (MacLennan et al. 2002); it is often considered a proxy for fish biomass (Simmonds and MacLennan 2005) that, when available, can be indexed with biological biomass data to enhance comparisons (Swartzmann and Hickey 2003). TS is an acoustic measure of the reflected echo energy, which is related to target size by species-specific relationships (Simmonds and MacLennan 2005). Such equations can be used to project length-frequency relationships of ensonified targets. Many algorithms have been presented in the literature relating fish length from various orientations to acoustic energy from a single target (Love 1971; McCartney and Stubbs 1971; Love 1977; Foote 1979; Williamson and Traynor 1984; Fleischer et al. 1997; Burwen and Fleischman 1998; Warner et al. 2002). As such, TS-length relationships can be useful for

deriving estimated fish length-frequency distributions for the surveyed community. Furthermore, with sufficient data on length and weight relationships of ensonified targets, S_v and TS can be used to derive volumetric estimates of fish biomass (g m^{-3}) (Gunderson 1993; Simmonds and MacLennan 2005, see Chapter 2).

The purpose of this study was to describe the seasonal and spatial distribution of acoustic fish biomass and size distribution associated with the FSMAR using hydroacoustics. We hypothesized that the unique character of the FSMAR, in addition to seasonal effects, water depth and distance from the reef, would have an influence on the fish community. Furthermore, we sought to identify where in the spectrum of surveyed artificial habitats, within the NGOM, the FSMAR lies with respect to acoustic fish biomass. Ultimately we sought to gain knowledge on the role that this unique inshore artificial reef complex plays in the distribution of the fish community and to consider its management value for creation of similar structures in shallow coastal waters.

5.2 METHODS AND MATERIALS

5.2.1 Survey Description and Collection Parameters

Acoustic data were collected at FSMAR during ten mobile surveys conducted from July 2003 to March 2005 (Table 5.1). Surveys were done at an average vessel speed of 5.5 knots along pre-designated track lines. The sampling grid consisted of both north-south and east-west transect lines with 80 m spacing (Figure 5.1); the direction of travel was dependent upon sea-state conditions.

Acoustic backscattering data were collected with a 420 kHz split-beam transducer, a BioSonics DE-X scientific echosounder (see Table 5.2 for parameter

Table 5.1. LSMeans of S_v, TS, and fish density of FSMAR by survey dates aboard R/V Percy Viosca. Surveys with data included in the analyses are indicated by "+". Dates of surveys in which data were not included in the analyses represented by "-". Estimated fish density was calculated following Equation 2. Standard error bounds for both S_v and TS are shown, with upper and lower limits.

			Volume Backscattering Strength (S_v)		Target Strength (TS)		Estimated Fish Density
Survey Date	Season	Included in Analysis	Mean (dB)	Standard Error	Mean (dB)	Standard Error	(Fish m^{-3})
16 July 2003	Late	-	-	-	-	-	-
19 August 2003	Late	+	-57.8	-56.8, -59.0	-43.9	-43.8, -44.0	0.04
18 September 2003	Late	+	-54.5	-54.0, -55.1	-45.2	-44.5, -46.0	0.11
8 October 2003	Late	+	-50.9	-50.5, -51.4	-37.5	-37.3, -37.8	0.06
18 March 2004	Early	+	-63.6	-63.3, -63.9	-47.8	-47.6, -48.0	0.04
19 May 2004	Early	+	-63.0	-62.7, -63.3	-50.9	-50.7, -51.1	0.45
1 September 2004	Late	+	-64.1	-63.5, -64.8	-52.8	-52.5, -53.1	0.01
23 February 2005	Early	+	-55.6	-55.2, -56.1	-48.5	-48.3, -48.7	1.60
1 March 2005	Early	+	-62.5	-62.1, -63.0	-44.8	-44.6, -45.0	0.01
25 April 2005	Early	-	-	-	-	-	-

settings), and a personal computer used both to run acquisition software and to store acoustic data. The transducer was mounted in a downward orientation on a towfish pulled approximately 3.5 m behind the vessel. The towfish was positioned approximately 0.75 m below the water surface; after accounting for the near-field zone (~1.25 m), no data were available for the upper 2 m of the water column. Acoustic data were collected with BioSonics Acquisition Program 4.1. The acoustic system was calibrated with a standard reference sphere (BioSonics 2003) both at the manufacturer's facility and in the tank facility at the Louisiana Department of Wildlife and Fisheries (LDWF) Lyle S. St. Amant Marine Biological Laboratory.

5.2.2 Echoview Configuration

Post-processing of raw acoustic data was conducted in Echoview 3.1 (Sonar Data Pty.). In Echoview, analysis thresholds on both S_v and TS echograms were applied and sound speed coefficients were integrated to compensate for temperature and salinity effects on sound attenuation. Following the parameter configuration (Table 5.2), echograms were visually inspected either for bad data regions (gas bubbles, unfavorable towfish behavior, cavitation) or for corruptions in data integrity (sudden changes in speed or loss of GPS signal). To prevent anomalously high values, the bottom detection algorithm was applied to exclude the sea floor and the reef structure from the analysis. The bottom detection line was manually edited adjacent to the reef to ensure that fish over and around the reef structure were not excluded from the analyses. Prior to integration, a grid was applied to the data establishing 1 m x 2 m (vertical x horizontal) analysis cells. To maintain consistency in symbols and names of acoustic variables (e.g. s_v, S_v, TS, σ_{bs}), I have adopted the nomenclature proposed by MacLennan et al. (2002).

Table 5.2. Echosounder, transducer, and analysis parameters used for this study.

Sonar system parameters	
BioSonics DE-X split beam echosounder:	
Operating frequency	420 kHz
Pulse duration	0.4 ms
Pulse rate	10 Hz
Transducer parameters	
Source level	224.2 dB
Receive sensitivity	-53.8 dB
2-way beam angle (ψ)	-24.47 dB
Collection threshold	-75 dB
Major-axis beam width	6.2 º
Minor-axis beam width	2.4 º
Echoview analysis parameters	
Analysis thresholds	
S_v	-65 dB
TS	-55 dB
Single target detector	
Pulse length determination level	6 dB
Minimum pulse length	0.6
Maximum pulse length	1.7
Maximum beam compensation	12 dB
Maximum standard deviation of:	
minor-axis angles	0.8
major-axis angles	0.8

5.2.3 Echo Integration

Estimates of volume backscattering coefficients (s_v), the linear counterpart of S_v used for all calculations involving S_v (MacLennan et al. 2002), were derived in Echoview following standard echo integration techniques (Simmonds and MacLennan 2005). Integration reports were generated in Echoview for each analysis cell and exported into SAS 9.0 (SAS Institute 2003) for further processing. Weighted means of S_v were generated in SAS by weighting s_v within each cell by the actual number of acoustic samples recorded within that cell. This was done to account for slight variability in sample size observed within the cells and to ensure that the computed s_v reflected the true contribution of scatterers relative to sample size.

5.2.4 Target Strength

Reports for TS were generated for single targets identified with the split-beam single target detection algorithm within each 1m x 2 m (vertical x horizontal) analysis cell in Echoview. Targets fulfilling single target criteria with TS greater than -55 dB 3 cm standard length (SL), based on the model by McCartney and Stubbs (1971) were accepted. The single target algorithm was tuned to accept targets with echo envelopes between 0.6 and 1.7 times the pulse length with a maximum beam compensation of 12 dB (Table 5.2). For each target identified in Echoview, a minimum, mean, and maximum TS value was calculated. An estimate of the backscattering cross section (σ_{bs}) for each individual target was calculated for each cell in SAS following:

$TS=10*\log_{10}(\sigma_{bs})$ (MacLennan et al. 2002). Equation (5.1)

σ_{bs}, the linear equivalent of TS, was used for all calculations involving TS, including all statistical analyses. Given the mixed species assemblage often associated with artificial

reefs (Rooker et al. 1997; Wilson et al. 2006), the relationship defined in McCartney and Stubbs (1971) was used for TS as a function of SL (in cm), given below:

$$TS=24.5* \log_{10}(SL)-66.84. \quad \text{Equation (5.2)}$$

5.2.5 Fish Density

Fish density was calculated as the mean s_v divided by the mean σ_{bs} of a known volume of water given the relationship:

$$\text{Fish density (Fish m}^{-3}) = s_v / \sigma_{bs} \quad \text{Equation (5.3)}$$

Analyses of output from Echoview produced useful density estimates; however, they are only used as a relative index given the nature of the fish density calculation (e.g. mean biomass scaled by mean fish size). In some cases, an s_v value was generated, but no σ_{bs} value was generated for the same volume of water due to detected targets failing the single target criterion imposed in the single target detection algorithm. In such cases, the mean σ_{bs} value for surrounding cells was used based on the assumption that mean fish sizes within adjacent cells would be similar (Wilson et al. 2006). Comparisons of fish density estimates over the reef, and off the reef were not included for the March 2005 survey due to a corruption in the spatial (GIS) information.

5.2.6 Data Analysis

Data from two of the ten completed surveys were removed from the analysis dataset due to poor data quality as a result of unfavorable weather conditions (July 2003 and April 2005). Surveys conducted during the first half of the year (January- June) were categorized as Season='Early' in the analyses and surveys conducted during the second half of the year (July- December) were categorized as Season='Late'.

Estimates of the distribution of S_v, with respect to proximity of the artificial reef structure, were derived by incorporating a GIS into the analysis of hydroacoustic data. A series of variously spaced buffer zones were created around the reef structures to analyze fish distribution in relation to the horizontal distance from the structure (Figure 5.1). The buffer zones included the reef structure and extended out to 1000 m. Buffer zone intervals were 10 m (1-50 m), 25 m (50-250 m) and 250 m (250-1000 m) with the first buffer zone incorporating the reef and surrounding areas out to 1 m. In addition to horizontal stratification, acoustic data were binned into five depth intervals (1-3, 3-6, 6-9, 9-12, and 12- bottom m), with the last depth bin including infrequent samples to depths greater than 15 m.

The probability of detecting a fish (Presence =1) was modeled with logistic regression (alpha=0.05, Proc Logistic; SAS Institute 2003) to test for differences both in fish detection across seasons and in the vertical and horizontal position within the water column. Results were reported from odds ratio estimates provided in SAS. Independent variables included in the analysis were season, depth, and distance. In order to simplify the model and enhance its interpretability, a base model that included all levels of depth (14 levels) and distance from the reef (16 levels) by season was fit. Results from the base model showed that fish detection increased greatly at 6–9 m water depth and was greatest within the first 30 m of the reef as compared to distances greater than 30 m. Therefore, depth and distance were further stratified into three levels each. Depth had three levels corresponding to water depths above the reef (2-6m), at the top of the reef (6-10 m) and depths below the top of the structure (10-16m). Distance had three levels, 0-30 m from the reef, 30-100 m, and distances greater than 100 m from the reef. The significant

model used for analysis contained the independent variables season, depth, and distance (Table 5.3).

Analysis of variance (ANOVA, Proc Mixed; SAS Institute 2003) was used to test for differences in s_v by season, depth and distance from the reef. Due to the great number of sampling zeros (68 %) in the data and to conform to the constraints of parametric statistics, only observations where presence=1 were included in the analysis. The dependent variable, s_v, was transformed with a $\log_{10}((s_v *10e^9)+1)$ transformation to approximate the normal distribution. Given the high degrees of freedom associated with the test (Table 5.3) and that the distribution of residuals were approximately normally distributed; we relied upon the robustness of the ANOVA procedure for detecting significant differences. The independent variables included in the significant model (alpha=0.05) were season, depth, and distance in addition to all logical interactions (Table 5.4). *Post-hoc* comparisons were conducted on significant effects with Tukey's HSD test at a significance level of alpha=0.05.

TS data were analyzed following the ANOVA model described above with the dependent variable σ_{bs}, which was transformed with a $\log_{10}((\sigma_{bs} *10e^9)+1)$ transformation to test for differences in mean target size by season, depth and distance from the reef. As with the previous ANOVA, residuals were approximately normally distributed and therefore the robustness of the ANOVA was relied upon for detecting significant differences. The independent variables included in the significant model (alpha=0.05) were season, depth and distance, in addition to logical interactions (Table 5.4). *Post-hoc* comparisons were conducted on significant effects with Tukey's HSD test at a significance level of alpha=0.05.

Table 5.3. Logistic regression table of Type III fixed effects model for the dependent variable Presence, derived from acoustic data collected at FSMAR from July 2003 to March 2005. Logistic regression modeled the probability of Presence=1. The Wald Chi-square value and probability (P) of a greater Chi-square are provided for each model effect. Significance levels are (α=0.05).

Type 3 Analysis of Effects		
Effect	Wald Chi-Square	P
Season	3358.83	<.001
Depth	2476.66	<.001
Distance	2760.31	<.001

Table 5.4. Results of type III fixed effects analysis of variance for spatio-temporal effects on fish distribution at FSMAR from July 2003 to March 2005. The F-value and probability (P) of a greater F are provided for each model effect. Table includes model results for the dependent variables mean s_v and mean σ_{bs}. Significance levels are (α=0.05).

	Mean s_v		Mean σ_{bs}	
Effect	F-value	P	F-value	P
Season	703.64	<.001	222.63	<.001
Depth	105.43	<.001	5.79	0.003
Distance	77.82	<.001	6.54	0.002
Season x depth	41.20	<.001	6.23	0.002
Season x distance	65.70	<.001	14.08	<.001
Season x depth x distance	36.88	<.001	2.92	0.003

5.3 RESULTS

5.3.1 Fish Presence

The probability of detecting a fish was approximately 2.5 times greater during the first half of the year (early season) than during the latter half (late season). Additionally, as water depth increased, the probability of detection increased by a factor of 2.8, from the surface (2-6 m) to depths corresponding to the reef structure (>6 m). With increasing distance from the reef, (>30 m), the probability of detection generally decreased by a factor of 2.

5.3.2 Acoustic Fish Biomass

Estimates of least squares means (LSMeans) of S_v indicated that the proxy of acoustic fish biomass was significantly greater ($p<0.001$) during the late season (-57.4 dB, SE bounds:-53.4,-60.2) than during the early season (-61.2 dB, SE bounds:-55.7,-59.4). It is important to note that a 3 dB difference in S_v is equivalent to a difference of a factor of two in observed acoustic scattering. Overall, mean S_v was greatest (-58.2 dB, SE bounds:-53.7,-58.9) at depths corresponding to the reef structure (>6 m, Figure 5.2a) and distances within 30 m of the structure (-57.7 dB, SE bounds:-53.2,-58.7; Figure 5.2b). Acoustic estimates of biomass within 30 m of the reef area varied significantly by season and by depth (Figure 5.3). During the early season S_v at the 2-6 m depth interval was not different with distance from the reef ($p>0.05$); however, biomass at distances greater than 30 m from the reef decreased significantly ($p<0.001$) with depth as compared to the 0-30 m interval (Figure 5.3a).

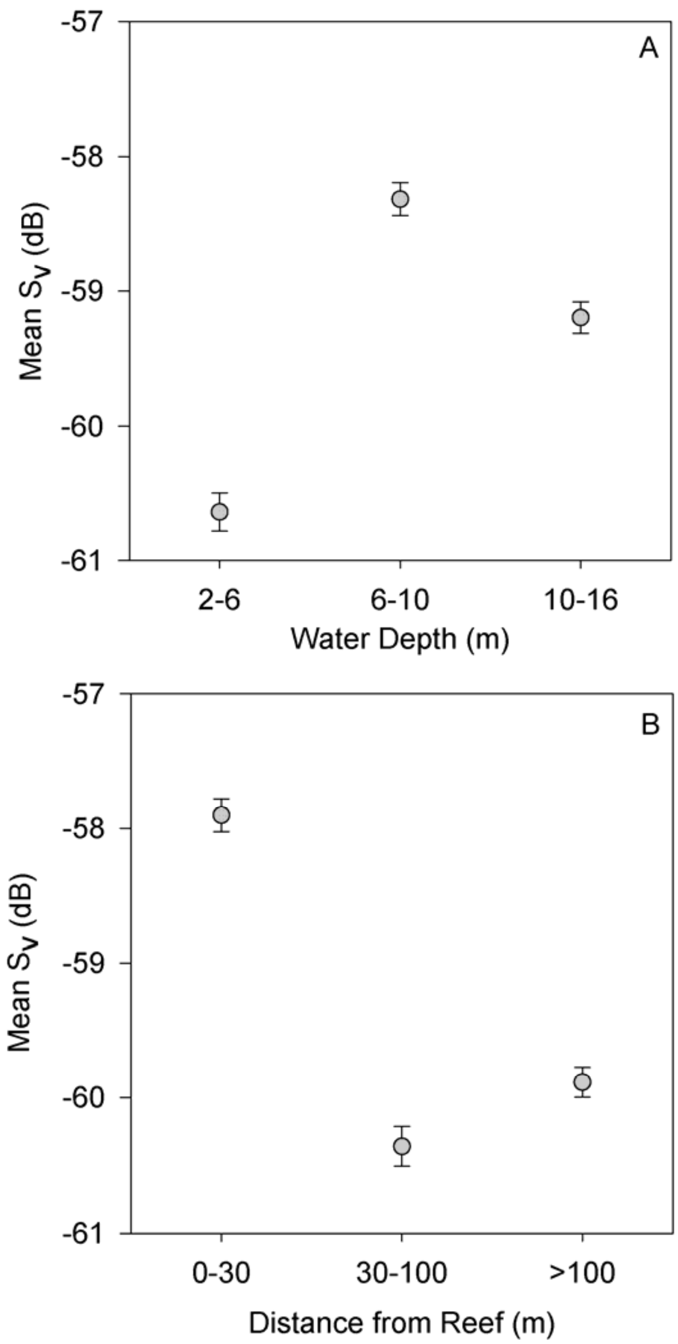

Figure 5.2. LSMeans of acoustic proxy of fish biomass (S_v) collected at FSMAR from August 2003 to March 2005. (A) By water depth interval. Depth interval 6-10 m corresponds to the top of the reef structure. (B) By distance from the reef. The first category, 0-20 m, includes the reef. Error bars represent standard error of LSMeans estimates.

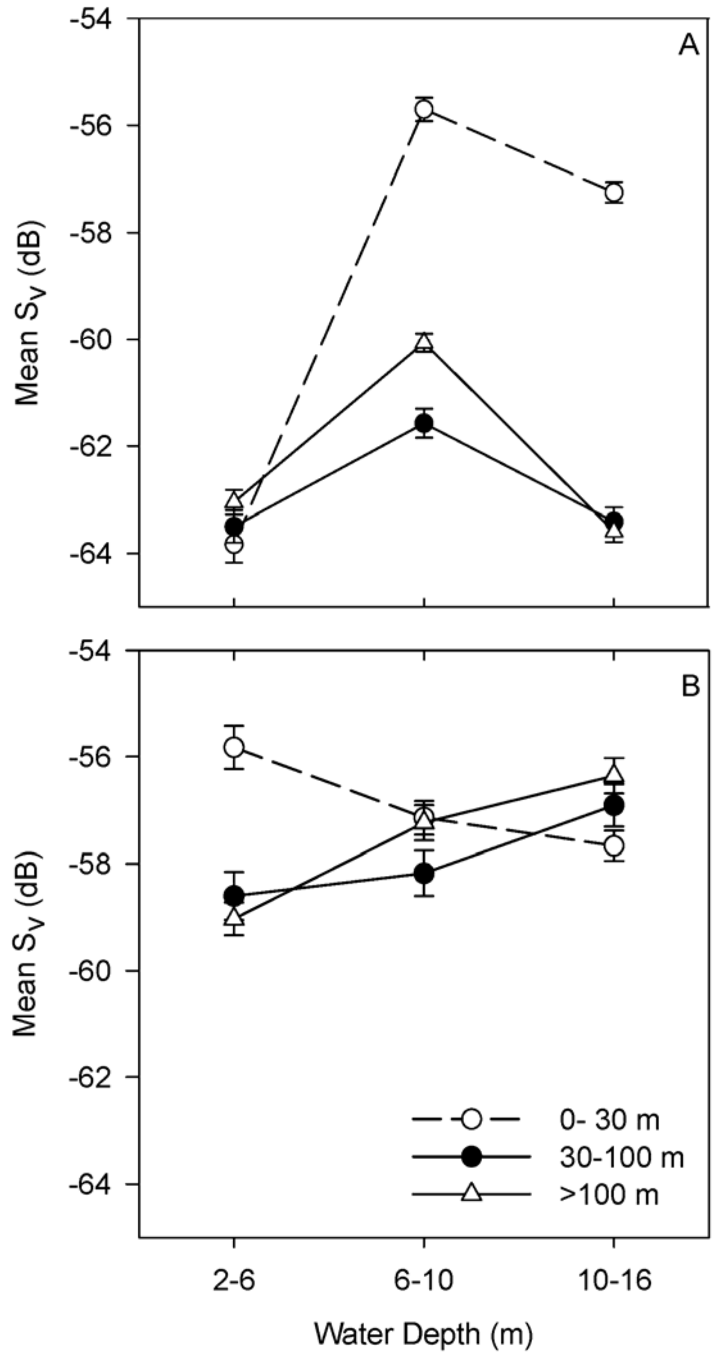

Figure 5.3. LSMeans of acoustic biomass (S_v) by water depth interval, season, and distance from the reef structure. (A) Mean Sv during the early season. (B) Mean S_v during the late season. Note that depth bin 6-10 m corresponds to the top of the reef structure. Error bars represent standard error of LSMeans estimates.

Near the reef, mean S_v was significantly different than at greater distances in the upper water column ($p<0.001$), although as depth increased, the magnitude of the difference was greatly diminished (Figure 5.3b) regardless of distance from the reef. During the late season there was no apparent peak in acoustic biomass at depths near the reef structure (>6 m) as was seen in the early season.

In both seasons, mean S_v was significantly ($p<0.014$) greater within 30 m from the reef than at greater distances from the reef structure (Figure 5.4). Mean S_v at distance from the reef was consistently higher during the late season (Figure 5.4) with an S_v at 0-30 m of -56.9 dB (SE bounds:-56.0,-58.2) gradually decreasing to -57.5 dB (SE bounds:-56.5,-58.7,) at distances greater than 100 m. The decrease in S_v with distance was much more pronounced during the early season with S_v decreasing from -58.9 dB (SE bounds:-57.9,-60.3) within 30 m from the reef to -62.2 dB (SE bounds:-60.6,-64.7) at distances greater than 100 m from the reef (Figure 5.4).

5.3.3 Target Strength

LSMeans of TS, the acoustic proxy for fish length, was significantly greater during the late season (-44.8 dB, SE bounds:-44.0,-45.7) than during the early season (-49.8 dB, SE bounds:-47.9,-53.3; $p>0.001$), corresponding to an estimated SL of 9 cm and 5 cm (Equation 5.2), respectively. Figure 5.5 illustrates the effect of depth and distance on mean TS of detected targets; little fluctuation in TS is evident within the early season (Figure 5.5a) with increasing distance or depth. Conversely, TS estimates varied significantly by depth and distance in the late season (Figure 5.5b). No significant ($p>0.269$) increase in TS was associated with the reef during the early season, although during the late season, somewhat larger individuals were detected at both depths

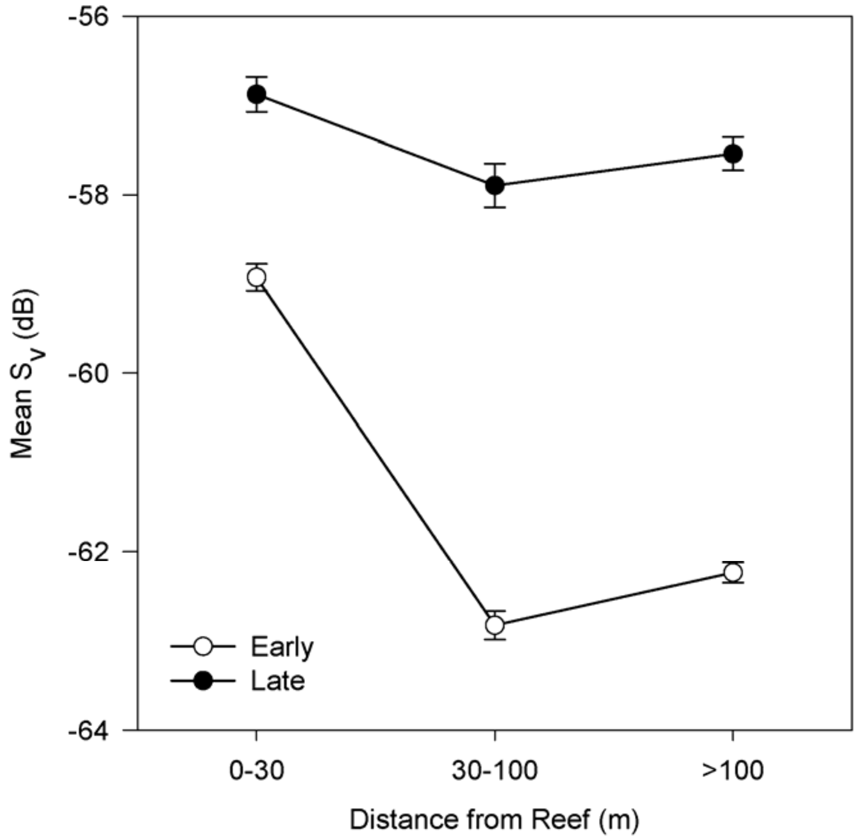

Figure 5.4. LSMeans of acoustic biomass (S_v) by season with distance from the reef structure. Empty circles represent biomass during early season whereas filled circles correspond to the late season estimates. Note that interval 0-20 m includes the reef structure. Error bars represent standard error of LSMeans estimates.

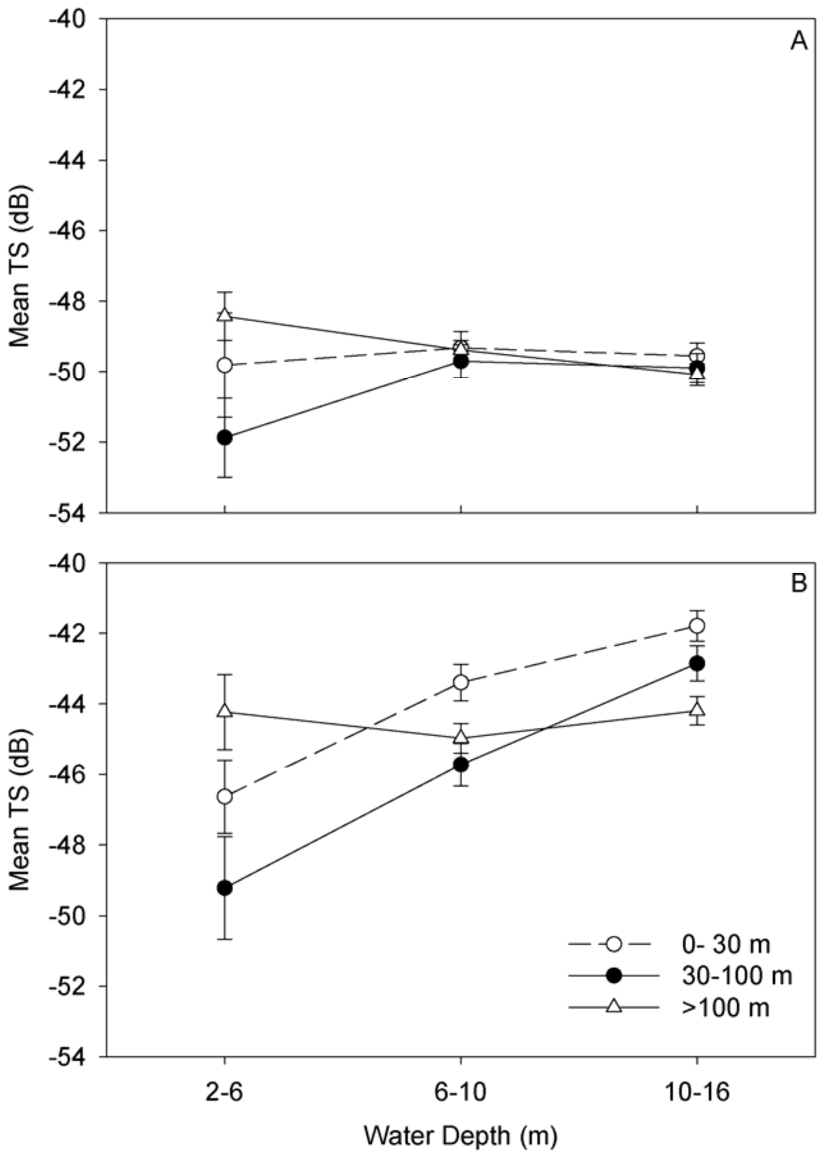

Figure 5.5. LSMeans of target strength by water depth interval, season, and distance from the reef structure. (A) Mean target strength during the early season. (B) Mean target strength during the late season. Note that depth bin 6-10 m corresponds to the top of the reef structure. Error bars represent standard error of LSMeans estimates.

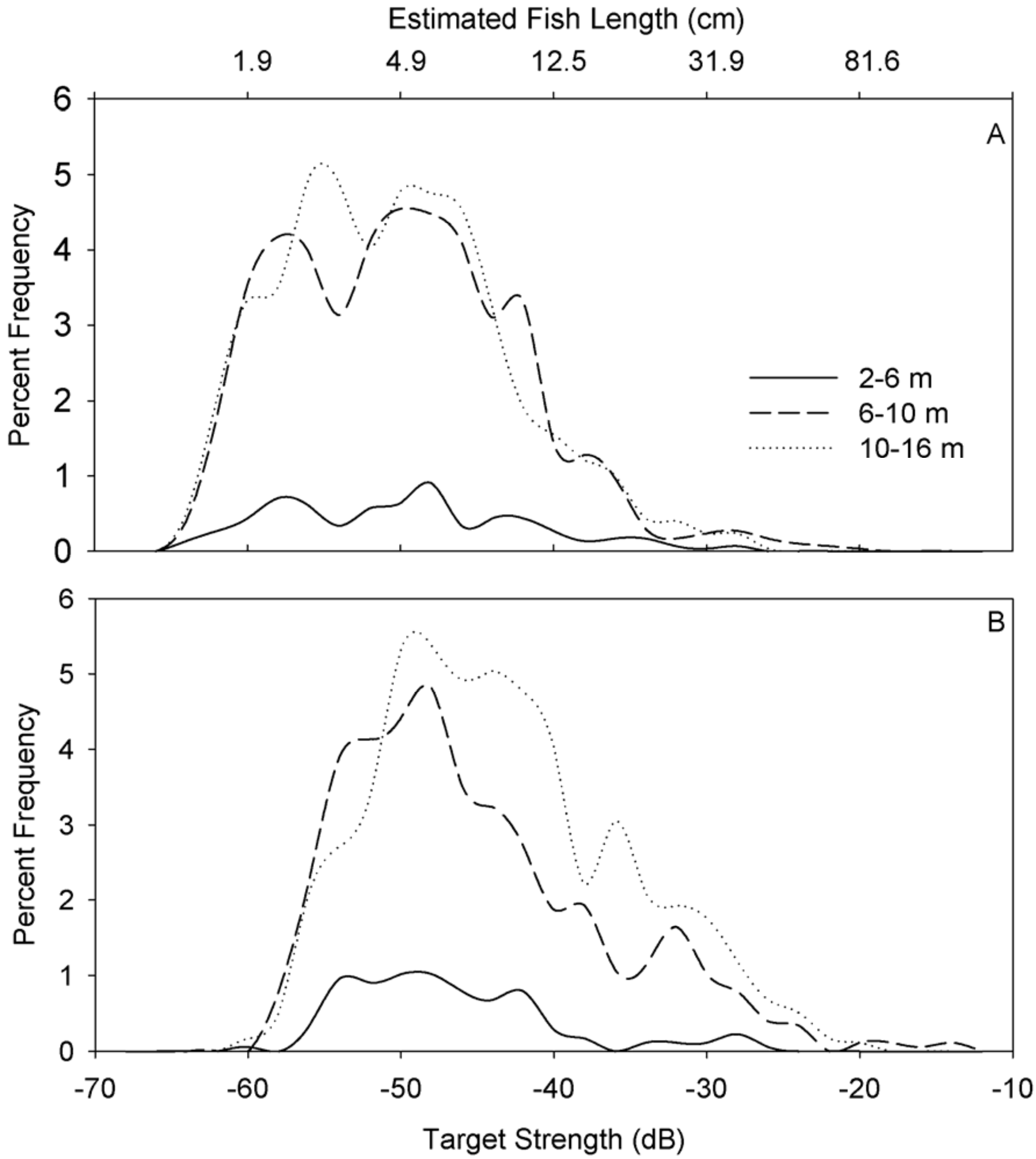

Figure 5.6. Target strength-frequency distributions of single targets identified with the single target detection algorithm in Echoview by season and water depth. (A) Target strength distribution during the early season. (B) Target strength distribution during the late season. Frequency distributions are cumulative by season (e.g. curves sum to 100 % for each season). Secondary X-axis represents the estimated standard fish length based on Equation 2 (McCartney and Stubbs 1971). X-axes are represented in $\log_{10}$ scale.

associated with the reef (>6 m) and at distances closer to the reef (0-30 m, Figure 5.5b). TS observed at intermediate distances (30-100 m) was generally lower (-50.5 dB, SE bounds:-50.0,-51.3 and -45.9 dB, SE bounds:-45.7.-46.1) than at both proximate (0-30 m) distances (-49.6 dB, SE bounds:-49.1,-50.1 and -43.9 dB, SE bounds:-43.0,-45.1) and distances greater than 100 m (-49.3 dB, SE bounds:-4734,-52.6 and -44.5 dB, SE bounds:-43.4,-45.9) during early and late seasons, respectively.

The number of detected targets was lowest in the upper water column (<6 m) and increased with depth during both seasons (Figure 5.6). TS frequency distributions (cumulative within each season and sum to 100%) were relatively similar between seasons (Figure 5.6), although a greater abundance of weaker scattering targets (TS≈ -64 to -55 dB; 1.3 to 3.1 cm) were observed during the early season (Figure 5.6a). Peaks in TS-frequency distributions during both seasons occurred between -48 and -49 dB, corresponding to individuals with estimated SL of approximately 5 cm (McCartney and Stubbs 1971).

5.3.4 Fish Density

Large differences in fish density at depth and distance from the reef were observed between seasons (Figure 5.7). Throughout the early season fish density was much higher (2.88 fish m^{-3}) near the reef structure (Figure 5.7b) than with increasing distance from the structure (<0.11 fish m^{-3}). Conversely, in the late season, fish density was consistently low at all distances from the reef structure. As depth increased, estimates of fish density within the late season decreased from 0.36 fish m^{-3} at the surface to 0.15 fish m^{-3} at depths greater than 10 m (Figure 5.7a), whereas fish density during the

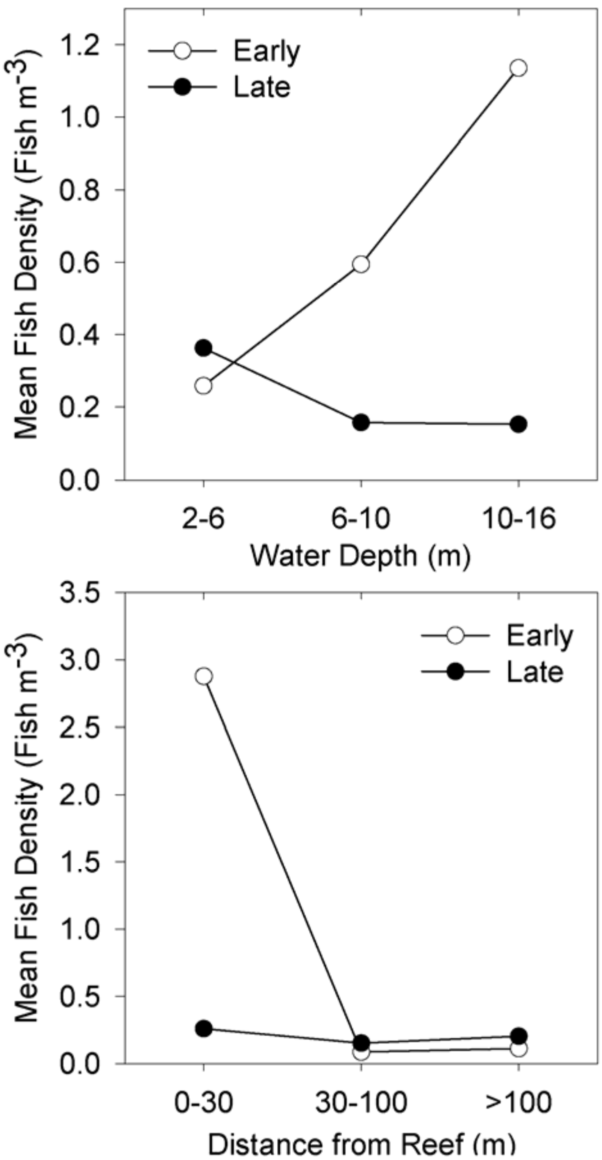

Figure 5.7. Estimated fish density (Fish m-3) at FSMAR from August 2003 to March 2005, by season. (A) Density by water depth interval. (B) Density by distance from the reef structure. Note that depth bin 6-10 m corresponds to the top of the reef structure.

early season was lowest (0.26 fish m^{-3}) at the upper depth and peaked (>0.59 fish m^{-3}) at depths coincident with the reef.

5.4 DISCUSSION

This was our first attempt at using hydroacoustics at a shallow water artificial reef and we believe this study has further demonstrated the utility of this sampling approach.

To date, both mobile and stationary hydroacoustic surveys have been employed to describe the distribution of fish biomass and density associated with artificial (Stanley and Wilson 1996; 2000; Wilson et al. 2003) and natural habitats such as the West Flower Garden Banks (WFGB) (Wilson et al. 2003) and Sonnier Bank (Wilson et al. 2006), in the deeper waters (>30 m) of the NGOM. Copious high resolution data have been collected in association with deeper water habitats in the NGOM; however, to our knowledge, this is the first report of an acoustic survey at a shallow-water artificial reef of this size and character in the NGOM. Consequently, no previous data exist on the effects of large artificial habitats on the distribution of fishes in the shallow coastal waters of the NGOM to which we can compare our results.

Our observations at the FSMAR are consistent with the findings of Stanley and Wilson (1996; 1997; 2000) and Wilson et al. (2003) in terms of the patterns of fish distribution associated with complex artificial reef structures. They reported that fish were more likely to be distributed either over or near the surveyed structure than in the surrounding open water areas. Stanley and Wilson (1997) reported the average horizontal distance of influence (area of influence in Stanley and Wilson 1997) of a standing oil and gas platform to be 16 m. Although buffer zones within the first 50 m from the FSMAR were set at 10 m intervals, significant declines in both fish biomass and

density were observed beginning at distances greater than 30 m in most cases, thereby further supporting the localized distance of influence of artificial reef structures. Based on the analyses presented herein, we define the distance of influence of the FSMAR to be the distance (30 m) at which acoustic fish biomass drops to a consistent background level.

The distance of influence at the FSMAR is a function of water depth and configuration of the reef. Previously surveyed habitats in the NGOM were characterized by deeper water (>30 m) and structures composed of single units; unlike the FSMAR which is composed of one main structure and several smaller clusters located anywhere from 50 to 250 m away from the main structure. In addition, the layout of the FSMAR is far more complex than the general rectangular shape of the other habitats surveyed. Excluding the WFGB, the footprint of previously surveyed habitats did not exceed 1,800 m^2, as compared to the FSMAR, which exceeds 130,000 m^2. Together with its unique shape, shallow water environment, and expansive areal extent, the FSMAR undoubtedly has a profound effect on the distribution of fishes in the inshore waters and may explain the greater distance of influence observed at the FSMAR.

The FSMAR is in close proximity to the Barataria Bay-Terrebonne Bay estuarine complex, further distinguishing the FSMAR from other previously surveyed habitats within the NGOM in terms of the fish community associated with this unique habitat. Stanley and Wilson (2000) and Wilson et al. (2006) reported that the top-to-bottom vertical profile of standing platforms attracts and holds large numbers of surface-oriented, pelagic fish species, such as blue runner *Caranx crysos* and Bermuda chub *Kyphosus sectatrix*, not normally associated with the inshore FSMAR. Many species of reef-

associated fish commonly found offshore in large numbers (gray triggerfish *Balistes capriscus*, red snapper *Lutjanus campechanus*, and Atlantic creolefish *Paranthias furcifer*) (Rooker et al. 1997; Stanley and Wilson 2000) are not expected at an inshore site such as FSMAR. Based on our knowledge of the inshore fish fauna along the Louisiana coast and video footage captured following the decommissioning process, we expect that the FSMAR is largely inhabited by common nearshore fishes (grey snapper *Lutjanus griseus*, Atlantic spadefish C*haetodipterus faber*, lane snapper *Lutjanus synagris*, Spanish mackerel *Scomberomorus maculatus*) and estuarine fishes (spotted seatrout *Cynoscion nebulosus*, Gulf menhaden *Brevoortia patronus*, red drum *Sciaenops ocellatus*, sheepshead *Archosargus probatocephalus*). Limited ROV video surveys coupled with newly developed dual-frequency identification sonar (DIDSON, Figure 2.10) technology are planned for future efforts. Each would be beneficial in identifying the seasonal changes in composition of the fish community as well as relative changes in species abundance associated with the FSMAR.

Estimates of S_v at FSMAR varied with season, water depth, and distance from the reef. Early season surveys were conducted during February and March, times of potentially high recruitment of juveniles (Ditty and Truesdale 1984; Akin et al. 2003). We attribute the generally smaller sizes in the early season to these recruitment events. The early season fish density estimates (Figure 5.7a) associated with the reef structure, in addition to the observed TS distribution (Figure 5.6a), suggests that the biomass is largely comprised of smaller individuals. A peak in the TS distribution in Figure 6a at -58 dB corresponds to individuals of approximately 2.3 cm SL (McCartney and Stubbs 1971) which represents newly recruited individuals. Furthermore, due to the proximity of

FSMAR to Barataria Pass and Quatre Bayou Pass, it is expected that the fish community is highly influenced by both nearshore and estuarine species, both of which could be contributing to the increase in biomass over the reef.

In order to make acoustic biomass estimates comparable and useful as indices of relative changes in fish distribution, comparisons should be made with other reef systems to help illustrate the importance of artificial reefs as complex habitat essential to fish communities. Often researchers prefer to describe acoustic data with units that are more convenient and interpretable than the decibel (dB). Therefore, acoustic data are used to derive estimates of relative biomass (g m^{-3}) through a series of algorithms based on the widely used function of the relationship of fish weight w (g) to standard fish length SL (cm)

$$w = a * L^b \qquad \text{Equation (5.4)}$$

where the coefficients a and b are fitted from the length and weight relationship of the fish community. The slope of the length to weight relationship in our survey areas, based on knowledge of the fauna, approximated that reported by Fabi and Sala (2002) in which they derived a TS per unit weight (TS_w) for Mediterranean reef associated fishes of

$$TS_w = 0.69 * \log_{10} SL - 56.38. \qquad \text{Equation (5.5)}$$

Transformation of TS_w yields an equivalent acoustic backscattering cross-section per unit weight (σ_{bsw}) that can be used to scale s_v to derive volumetric estimates of fish biomass (g m^{-3}) following equation (5.3).

Calculation of biomass based on acoustic estimates requires acknowledgement of fundamental assumptions, i.e. fish length-weight relationships must be assumed, particularly for a mixed species assemblage and TS estimates for surveyed species should

be available. However, in acoustic surveys, these values are not always logistically feasible to obtain and must therefore be estimated given knowledge of the fauna. In the event that the parameters must be estimated without empirical data, biomass values may still be useful for comparisons on a relative scale. Given the above considerations, we calculated a mean biomass of 1.03 g m^{-3}, corresponding to a mean S_v of -55.7 dB, during the early season at distances within 30 m of the reef and 6-10 m water depth. Compared to biomass at distances greater than 100 m (0.38 g m^{-3}, -60.1 dB) for the same water depths, associated biomasses are indeed greater than background levels. It should be noted that these estimates are based on coefficients derived from Mediterranean reef associated fishes and should at this point be tenuously used for relative comparisons as acoustic data for the fishes in the NGOM are currently unavailable.

Mean S_v and TS were both greater during the late season than during the early season; however, the estimated fish density was lower during the second part of the year (Figure 5.7). A probable explanation for this is the consistent biomass and target size seen with depth and across distance intervals as compared to the early season where dramatic shifts were observed in biomass distributions (Figures 5.3a and 5.4). The decrease in fish density during the late season could be attributed to the effects of fishing mortality, emigration of adult and sub-adult fishes, and the development of hypoxic conditions along the Louisiana coast. The FSMAR, like much of the NGOM, experiences hypoxic conditions (Rabalais et al. 2002) down to levels of 0-0.5 mg L^{-1} during the summer (N. Rabalais, pers. comm.); however, the temporal extent of hypoxic conditions is unknown. Nevertheless, it is plausible that fish associated with the FSMAR

respond to the unfavorable conditions and move off the reef during some part of the late season.

The overall mean S_v observed at FSMAR is similar to those at other standing platforms previously surveyed with hydroacoustics in the NGOM (Wilson et al. 2003, Wilson et al. 2006). While the biomass we found at FSMAR (-59.8 dB) was less than that reported from several standing platforms (-57.9 dB) which occupy the entire water column, S_v at FSMAR was considerably higher than that found over natural hard bottoms in the NGOM. At Sonnier Bank biomass was (-66.4 dB) and the WFGB (-67.5 dB) and at other artificial reef sites, both partially removed (-68.9 dB) or toppled (-69.8 dB) (Figure 5.8).

Although fish densities associated with artificial reefs are generally variable in time (Bohnsack et al. 1991), estimates from this study are comparable to those generated from previous work in the NGOM (Stanley and Wilson 1996). Stanley and Wilson (1996) reported monthly means ranging from 0.04 to 0.50 fish m^{-3} with the highest densities occurring within 9 m of the platform. Fabi and Sala (2002) observed a significant 'time of day' effect on the density distribution of fish over an artificial reef with greatest densities occurring in the early morning and a subsequent and lower peak in the late afternoon. Unfortunately, the temporal resolution of this study was too low to comment on any diel effects. However, it should be noted that differences in the density or abundance of fishes observed with acoustic studies may be influenced by the physical and behavioral variability on TS, an important parameter for calculating acoustic fish density. Many studies have shown the stochastic properties of TS with regard to fish condition and orientation (reviewed in Simmonds and MacLennan 2005).

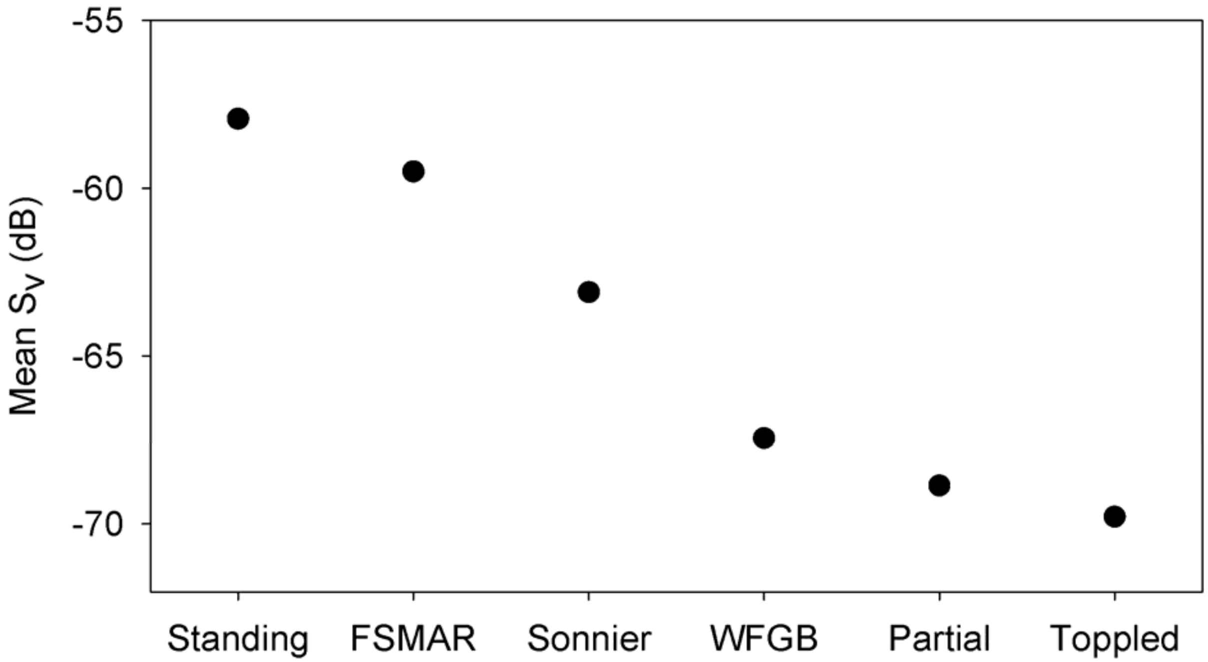

Figure 5.8. Mean acoustic biomass across previously surveyed habitats in the northern Gulf of Mexico. Plotted data are from standing oil and gas platforms, toppled oil and gas platforms, partially removed oil and gas platforms, West Flower Garden Banks (WFGB) were summarized in a previous study by Wilson et al. 2003. Data from Sonnier bank were reported by Wilson et al. 2005.

This information will be useful for future planning of permit areas and may make the deployment of future reefs more effective. As previously discussed, the distance of influence and water depth may be particularly important components for the establishment of a successful artificial reef within a fisheries management context. Moreover, reef size and spacing (Bohnsack et al. 1994), in addition to reef configuration as shown in this paper, are likely to be important factors contributing to the development of a healthy faunal community. During planning stages, considerations should be made for proximity of structures, and should be dependent upon the management objective, i.e. fisheries enhancement. However, when dealing with large structures such as oil and gas production platforms, financial and logistical challenges may supersede biological priorities. The inclusion of these data, in addition to the described survey method, may assist managers and perhaps help to close the information gap for making effective management use of retired oil and gas production platforms as artificial reefs.

The fishery benefits and ecological impact of shallow water artificial reefs is still poorly studied. Emphasis needs to be places on understanding the role of these unique shallow water habitats with respect to the life history stages of fishes that utilize them. Although artificial reefs are useful fisheries management tools, there is a lack of information on many levels hindering a clear and objective management strategy. Furthermore, to make effective use of artificial reefs for either enhancing fisheries production or concentrating fishery resources for exploitation, efforts must be directed toward assessing the true value of this artificial habitat and its contribution within a fish life history context.

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GENERAL SUMMARY AND CONCLUSIONS

The objectives of this study were to address the potential for using hydroacoustics for quantifying changes in fish biomass, density, and length distributions associated with relevant sub-tidal estuarine habitats, with the impetus for utilizing acoustic technology to assist in the identification of essential fish habitat (EFH). Given the paucity of information, lack of research, and ample opportunity for its application, I sought to develop a method for the integration of acoustic technology in shallow estuarine research. This study presents methods for the successful application of hydroacoustic technology in shallow waters and highlights some of the potential shortcomings of a single-gear approach at identifying EFH.

Chapter 1 described a platform developed for deploying an acoustic array over various sub-tidal estuarine habitats. The platform was used for two years in Barataria Bay and provided the ability to consistently manipulate the transducer position in the water column to achieve optimum range and data quality. Throughout the study, I was able to utilize the platform to deploy a traditional BioSonics transducer and a dual-frequency identification sonar for assessing fish behavior and distribution associated with estuarine habitats.

The results of Chapter 2 illustrate the feasibility of the use of hydroacoustics and limited traditional net sampling to quantify changes in habitat-specific fish biomass and size distribution. A filter was developed and imposed on the acoustic data to remove the acoustic bubble-induced noise generated from entrained air, a common challenge in shallow water surveys, thus facilitating extraction of accepted target information from noisy data. A series of exclosure net experiments were conducted and suggest that

observed scattering is of nektonic origin and influence of scattering from sediments and plankton in this area are considered negligible. Mean acoustic fish biomass during March 2004 varied significantly with salinity and habitat type. Oyster shell habitat supported larger individuals than adjacent soft-bottom habitats. Additionally, I observed moderate concordance in length distributions between gear types, with the gill net and push trawl gears encompassing the observed acoustic length distributions, although the majority of scattering was attributed to the presence of small fishes.

In Chapter 3 I present target strength-length and target strength-weight relationships developed for bay anchovy (*Anchoa mitchilli*) and Gulf menhaden (*Brevoortia patronus*) and discussed their utility for the length ranges used. I recommend the use of a target strength-length relationship which incorporates all fish orientations and is derived from pooled data of both bay anchovy and Gulf menhaden [$TS_{lateral}=32 * \log_{10}(SL_{cm})-70.9$]. The development of reliable target strength-length and target strength-weight relationships, and the subsequent inclusion of these relationships into analysis of acoustic data, will provide a means for quantifying abundances of bay anchovy and Gulf menhaden. Furthermore, information on the predicted lateral-aspect target strength values will for bay anchovy and Gulf menhaden will enhance our resolution of species-specific population estimates.

Chapter 4 further illustrates the use of acoustics for monitoring changes in habitat-specific acoustic fish biomass, density, and size distribution. Similar to Chapter 2, a novel filtering technique was developed and implemented in the analyses of acoustic data. The filtering technique presented in this chapter utilized a resampling technique rather than a threshold based filter as described in Chapter 2. The improved filter is more

suitable to a range of sampling distances rather than the constrained threshold approach. Although the filter performed well for removing acoustic noise, I identified a threshold for wind speed (> 6 m s^{-1}) above which acoustic data collection was limited by environmental conditions and which the data were too corrupted to be useful. I found that seasonal acoustic mean biomass, density, and fish size varied significantly with salinity level and habitat type. Analyses suggested that fish biomass was greatest over oyster shell habitat and both biomass and density increased throughout the survey from summer 2003 through the following spring 2004. Overall acoustic fish length distributions did not differ by habitat type whereas slight differences did exist along the salinity gradient. This could be a result of similarly sized mobile fish visiting each habitat within a salinity level; whereas fish communities may actually differ along the salinity gradient (MacRae 2006). Efforts to compare acoustically derived estimates of abundance and biomass to metrics derived from gill nets (catch per unit effort, abundance, and biomass) were unsuccessful and likely a result of the selective nature of the survey gear.

The adaptability of the acoustic technique was examined in Chapter 5 through mobile acoustic surveys at the Freeport Sulphur Mine Artificial Reef (FSMAR). The surveys were conducted to describe the seasonal and spatial distribution of acoustic fish biomass and size distribution associated with the FSMAR. In addition, I examined where in the spectrum of surveyed artificial habitats, within the northern Gulf of Mexico (NGOM), the FSMAR lies with respect to acoustic fish biomass. Results indicated that the horizontal distance of influence of the structure on the fish community is approximately 30 m. These findings further support the notion that artificial reefs do

play a role in the distribution of fishes in the relatively featureless NGOM. It is also noted that the water depth and expansive horizontal configuration of the reef likely play a role in the extended area of influence when compared to other studies in the NGOM which estimated the area of influence at approximately 16 m. Additionally, it was reported that fish density and biomass estimates were significantly influenced by the reef structure. These results suggest that the distance of influence and water depth may be particularly important components for the establishment of a successful artificial reef within a fisheries management context. Moreover, reef size and spacing (Bohnsack et al. 1994), in addition to reef configuration are likely factors that contribute to the development of a healthy faunal community.

The need exists for improved application and integration of sampling technologies to better understand and appreciate the role of biological and physical processes that influence fish abundance and distribution estimates. Integration of these disciplines (traditional net sampling and hydroacoustics) will aid in the proper design, analysis, and interpretation of fishery abundance assessments and may enhance management efforts. For estuarine habitats, appropriate efforts should be put forth to understand the function and relative value of habitats deemed important at an ecosystem level rather than focusing on a species-specific approach. Furthermore, the narrow species-specific approach to EFH is likely not suitable for managing fishery resources in estuarine systems.

VITA

Kevin was born at the U.S. Naval base in Portsmouth, Virginia, on 26 April 1976. He spent his childhood fishing and sailing on Galveston Bay, Texas, and it was during this time that he developed a keen interest in the outdoors and became particularly fond of the many fascinating aspects of the marine world. Kevin attended Texas A&M University and received a bachelor of science degree in marine fisheries management. While a student at Texas A&M, Kevin also worked for the Texas Parks and Wildlife Department where he initiated his career in fisheries science. However, after graduation Kevin and his wife, Piper, moved to California where he became involved in neuroscience studying the electrophysiological properties of Drosophila neuronal cells, with a particular focus on the cells responsible for learning and memory. While in California, Kevin accepted an opportunity to serve as an observer in the National Marine Fisheries Service Hawaii Long-Line Fishery Observer Program. It was that experience where Kevin rekindled his interest in fishery science and then subsequently accepted a position as a graduate student at Louisiana State University, studying under Charles A. Wilson. Following graduation, Kevin will assume as post-doctoral researcher position within the Coastal Fisheries Institute studying under Dr. James H. Cowan.