

MANATEE RESPONSE TO ENVIRONMENTAL NOISE

BY

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Abstract

The most pressing concerns associated with conservation of the endangered Florida manatee (*Trichechus manatus latirostris*) include habitat alteration and excessive mortality caused by humans. Whereas considerable research has focused on manatee mortality associated with watercraft collisions, very little attention has been paid to the impacts of noise created by watercraft. Potential effects of environmental noise on the habitat selection, distribution, and behavior of manatees are the foci of this dissertation, the primary goal of which was to understand and predict manatee behavior patterns as a function of environmental noise levels during the non-winter months in the Sarasota Bay area. Manatee behavior was examined in terms of: 1) habitat selection and distribution, 2) activity budget, 3) vocalization usage, and 4) short-term response to playbacks of approaching watercraft.

The initial phase of the study used acoustic modeling and monitoring to relate transmission loss and noise levels in specific manatee habitats to animal distribution. Due to higher levels of transmission loss and lower ambient noise, high-use grassbeds were quieter than low-use grassbeds of equal species composition and density, indicating a correlation between manatee distribution and environmental noise levels. In the morning the presence of boats and their associated noise may also play a dominant role in the timing of grassbed usage.

The degree to which manatees alter their patterns of behavior and vocalization under different environmental noise levels was investigated in the observation phase of the study. Results indicated that elevated environmental noise levels correlate with the overall activity budget of this species. The proportion of time manatees spent

feeding, milling, and traveling in critical habitats was related to noise level. More time was spent in the directed, goal-oriented behaviors of feeding and traveling whereas less time was spent milling when noise levels were highest. Increases in vocalization rate, duration, and source level were most pronounced when calves were present and during behaviors where animals tended to be more dispersed. When noise levels were elevated, manatees increased their call duration during feeding and milling behaviors when calves were present, suggesting that ambient noise levels have a detectable effect on manatee communication and that manatees modify their vocalizations as a function of noise.

The final phase of the study involved a series of playback experiments to test whether the correlations observed in the earlier phases were caused by noise. The speed and degree to which manatees respond to the playback of an approaching boat was assessed in order to better understand patterns observed during the first two phases of the study. Analyses of swim speed, changes in behavioral state, and respiration rate indicated that manatees respond differentially to different categories of boat noise used in the playback study. The most pronounced responses to boat noise playbacks, relative to the controls, were elicited by personal watercraft. Overall, manatees responded to the transient noise of approaching vessels with changes in behavioral state and movements out of the geographical area.

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Preface

This dissertation is written in the format to meet the author guidelines for Aquatic Living Resources.

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Chapter 1. General Introduction

The Florida manatee, *Trichechus manatus latirostris*, is a distinct subspecies of the West Indian manatee and is native to the coastal waterways of the southern Atlantic and Gulf coasts of the United States (Domning and Hayek, 1986). Both recognized subspecies of the West Indian manatee, Florida and Antillean (*T. m. manatus*), have been listed as endangered throughout their range since 1967. With the passage of the Endangered Species Act of 1973, government officials, researchers, and the general public began to take more interest in this species. Manatees have received federal, state, and local protection. This includes the approval of the first recovery plan for the West Indian manatee by the U.S. Fish and Wildlife Service to initiate intensive studies of manatee biology and ecology (U.S. Fish and Wildlife Service, 1980). Since the implementation of the 1980 recovery plan, a large amount of knowledge has been discovered about manatee morphology, physiology, and behavioral ecology (O'Shea et al., 1995).

1.1 Natural History

Manatees are large, bulky mammals with paddle-like front flippers and a round, flat fluke. The skin is described as gray, wrinkled, sparsely haired, and rubber-like (U.S. Fish and Wildlife Service, 2003). Adults average approximately 3.0 m in length but may reach lengths of up to 4.0 m (Reynolds and Odell, 1991). There is little sexual dimorphism in manatees, and it is often hard to tell the sexes apart from surface observations. The average weight of an adult manatee is 1,000 kg. A large

portion of overall weight is attributed to the heavy, massive bones that lack marrow cavities in the ribs or other long bones (Odell, 1982; Romer, 1966). Residing behind bristled upper and lower lip pads are teeth that continuously form at the back of the jaw and move forward as older more distal teeth are worn down from crushing vegetation (Domning and Hayek, 1986). These animals are often considered slow moving creatures, but they can swim at speeds of 6.4 m/sec for short bursts when they are startled or frightened (Gerstein, 2002).

The Florida manatee generally inhabits coastal rivers, estuaries, bays, streams, and lagoons of peninsular Florida and southeastern Georgia. On occasion, animals can range as far north as Rhode Island and as far west as Texas (Reid, 1995). Manatees are rarely found in deep ocean waters, as their herbivorous diet and consumption of fresh water restricts them to shallow, coastal waterways. Seasonal migrations to warm water refuges concentrate manatees in natural warm-water springs and artificial warm-water effluents produced by coastal power plants (Hartman, 1979; Reid et al., 1991; Reynolds and Wilcox, 1986). Manatees seek warm-water refuges during winter months because prolonged exposure to cold water temperatures can result in death. Unusually low metabolic rates and a high thermal conductance lead to energetic stresses in winter when water temperatures drop below 20 degrees Celsius (Irvine, 1983; O'Shea et al., 1995). During non-winter months, manatees are more widely distributed throughout the full extent of their range.

Population growth of the Florida manatee is naturally constrained by the species' life-history traits. Manatees are long-lived animals, have a small litter size, long inter-birth interval, and late age at first reproduction (O'Shea et al., 1995;

Reynolds, 1999). The maximum life expectancy is estimated at 60 years with annual adult survival rates ranging from 90-96% (Lefebvre and O'Shea, 1995; Marmontel, 1995; Reynolds, 1999; Langtimm et al., 2004). Females typically give birth to a single calf after a gestation period of 11-13 months (Boyd et al., 1999). The birth of twins is rare, occurring approximately 1.5% of the time (Lefebvre and O'Shea, 1995; Reynolds, 1999). Births can occur year-round, but more newborns are seen during the non-winter months from May to September compared to the winter months. The average inter-birth interval is two and a half years, and the average age of first reproduction in females is five years of age (Lefebvre and O'Shea, 1995; Rathbun et al., 1995). These life history parameters contribute to the low reproductive potential of the species. This makes manatee populations slow to recover from natural, large-scale die-offs such as abnormally cold weather or red tide outbreaks (Bossart et al., 1998). The combination of life history parameters and behavioral traits that continuously subject manatees to the injurious effects of human activities makes population recovery from both natural and human related mortalities a continuous fight (Reynolds, 1999). Recent increases in manatee population numbers are largely due to extensive conservation and management efforts (Glaser and Reynolds, 2003).

1.2 Sound in Manatee Habitats

Sound is assumed to be the basis of most long range manatee communication (Sousa-Lima et al., 2002). Because sound has the potential to travel long distances in water over short time periods, it provides a reliable way for manatees to communicate beyond visual range in murky coastal waters. Manatees are also dependent on other

types of environmental sound signals to survive in their aquatic habitat. The reflections of surface waves off seawalls and land aid in navigation, whereas noise produced from watercraft warns of an approaching vessel. The issue of how sound travels in the shallow waters of manatee habitats has recently become a topic of interest because of the risk of collision between manatees and boats. The question of whether or not manatees can hear boats approaching in enough time to swim to safety is hotly debated. Understanding more about how sound signals travel through the environment will not only contribute to answering the question of whether manatees can hear boats approaching, but it will also provide information on how the natural communication system of manatees may be impacted by rising levels of background noise and/or transient noise sources in their habitats.

The actual range of effective signal transmission in the noisy, shallow-water areas manatees inhabit depends on the ambient noise levels, acoustic propagation loss characteristics, and frequency and amplitude of the signals being produced. Higher frequencies typically attenuate more quickly than lower frequencies, but in very shallow manatee habitats low frequencies (< 1 kHz) do not propagate as far as higher frequencies (Figure 1.1). This occurs because low frequency sound wavelengths are larger than the water depth, resulting in quick absorption by the sediments. Environmental parameters such as water depth, salinity, temperature, bottom type, and wind speed also affect sound absorption and attenuation. Consequently, sound transmission differs for varying wavelengths in different manatee habitats, and different habitat types may make it easier or more difficult for manatees to detect either conspecific vocalizations or approaching vessels. For example, transmission

loss is greater in seagrass beds than in sandy shoals (Nowacek et al., 2001a), so a manatee may be able to hear a vocalizing manatee or boat approaching from farther away in the shoals. It is entirely possible that both environmental noise and transmission loss are so great in some areas that manatees cannot detect boats until they are only a few meters away. The modeling of acoustic propagation loss and measurement of corresponding ambient noise levels associated with this project addresses whether or not this is a common circumstance.

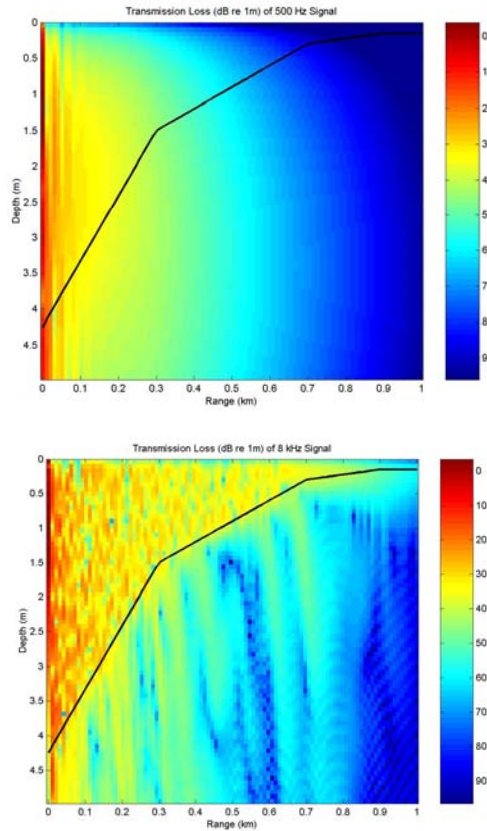


Figure 1.1. Transmission loss as a function of depth and range for a 500 Hz (top) and 8 kHz (bottom) signal. Areas above the black bathymetry line indicate sound propagation in the water column. Below the line indicates sound propagation in the sediment. The model is a representation of sound propagation from a boating channel to the shallow waters of Pansy Bayou in Sarasota, FL. [Water sound speed = 1541 m/s, sediment sound speed = 1664 m/s, sediment density = 1.78 g/cm³, compressional attenuation in sediment = 0.06 dB/km/Hz]

The energy of sound signals traveling through manatee habitats is greatly reduced by both sound absorption and attenuation due to the physical characteristics of the environment. The probability of detecting signals of interest, such as conspecific vocalizations, can also be reduced by masking from other acoustic signals in the environment. Masking, or the obscuring of sounds of interest by interfering sounds at similar frequencies, may hamper an animal's ability to detect a sound signal even when that signal is above the absolute hearing threshold (Richardson et al., 1995). The potential masking by high levels of human generated noise, as well as the cacophony of sounds manatees naturally encounter, provides a constant obstacle to effective vocal communication and the perception of other biologically significant signals. The level of masking is mainly due to noise at frequencies near the signal frequency of interest. Noise at frequencies outside this masking band has little influence on the detection of a signal unless the noise level is very high (Kryter, 1985; Richardson et al., 1995). From the viewpoint of a manatee, any signal of interest must overcome not only absorption and attenuation, but also masking by background noise and myriad broadband and narrowband sounds (Figure 1.2). Some of the major sound components in manatee habitats include high levels of ambient noise (broadband), watercraft (broadband), snapping shrimp (broadband), and fish and marine mammal vocalizations (broadband and narrowband). Whether and how these sounds actually interfere with signal detection is ultimately a function of the specific hearing capabilities of the manatee.

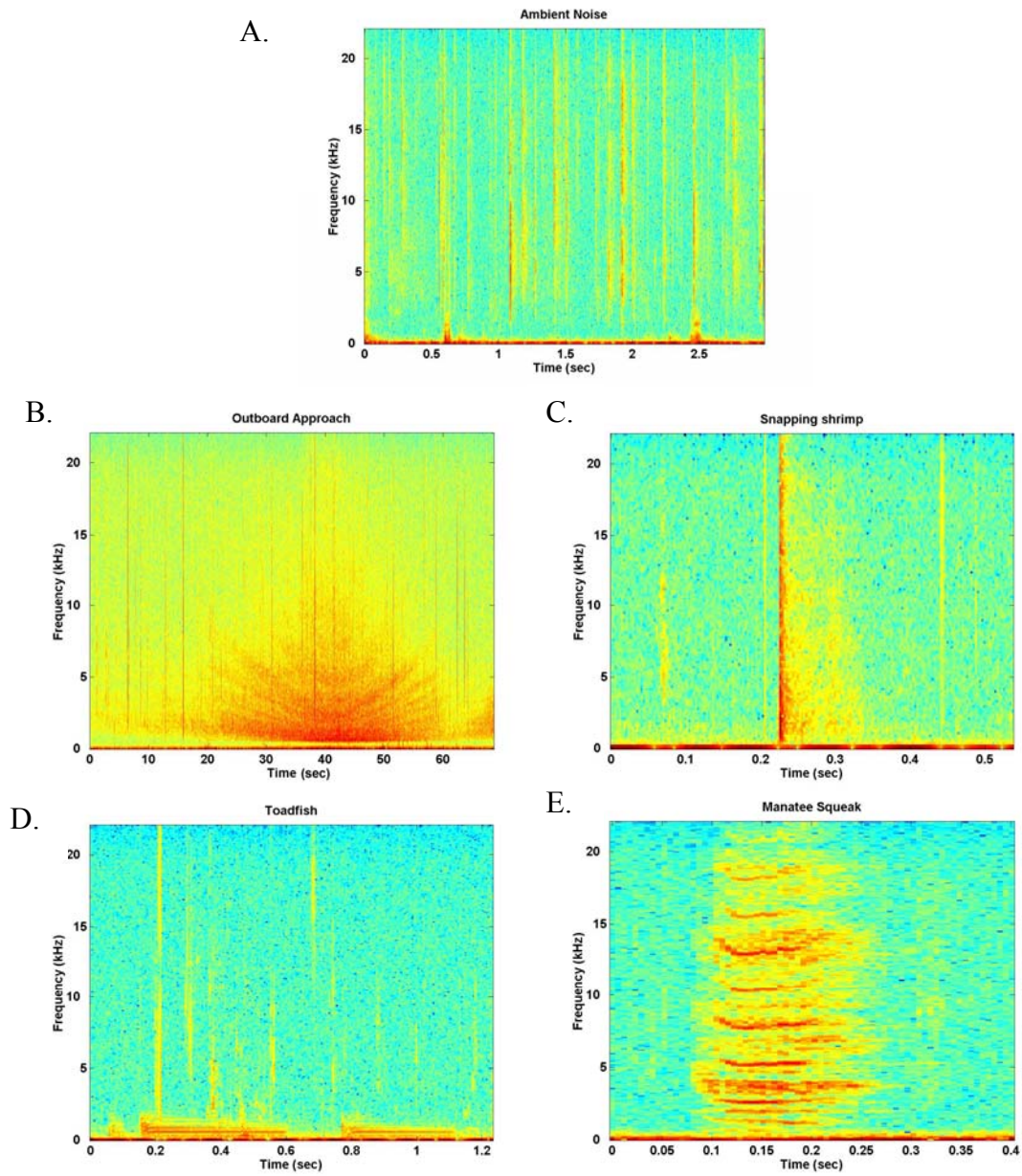


Figure 1.2. Spectrograms of sounds commonly encountered by manatees. A. Background noise dominated by broadband snapping shrimp. B. Outboard motorboat approach. C. Snapping shrimp. D. Toadfish. E. Manatee squeak. All spectrograms were made with a 512 point FFT.

1.3 Manatee Hearing

Electrophysiological and anatomical measurements made on dead manatees suggest that manatees hear best at lower frequencies in the range of 1-6 kHz with an upper limit of approximately 40 kHz (Bullock et al., 1982; Ketten et al., 1992). This range overlaps with the dominant frequencies of manatee vocalizations. The only available behavioral audiogram (Gerstein et al., 1999) reports that the peak sensitivity of hearing is between 16 and 18 kHz with functional hearing limits at 400 Hz and 46 kHz (Figure 1.3). There is a disparity in the available information on manatee hearing, and additional studies are needed to resolve the basic questions of what frequencies manatees hear best. The identification of peak hearing sensitivity and thresholds in manatees is critical for determining whether or not a manatee is reliably detecting boat noise, and at what distance the noise can be detected. For example, Figure 1.4 shows the power spectrum for both distant ambient noise and an approaching outboard motor boat in Sarasota Bay. Boat noise in the frequency range of 1-5 kHz is approximately 10 dB re arb. units²/Hz greater than the received noise level at 15 kHz. Once specific frequencies are targeted, it becomes possible to determine how the sound is absorbed and attenuated between the source and the receiver. More accurate data on hearing thresholds will enable researchers to determine if the received level of biologically relevant stimuli, such as motor noise, can be reliably detected at a specific frequency from a particular distance.

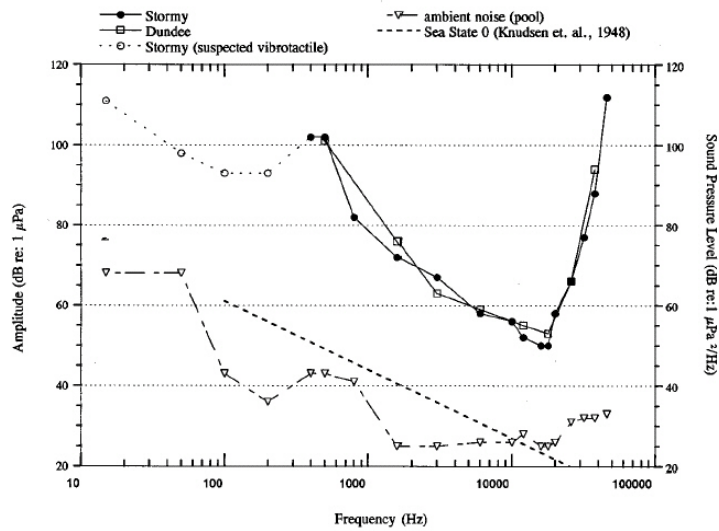


FIG. 4. Underwater audiograms. The audiograms are plotted for Dundee (□) and Stormy (●). Stormy's suspected "vibrotactile" detections below 0.4 kHz are indicated (○, dotted line). The accompanying ambient noise in the pool is plotted in 1-Hz bands and referenced with Sea State 0.

Figure 1.3. Manatee behavioral audiogram reprinted from Gerstein et al. (1999).



Figure 1.4. Background and outboard motor noise recorded near Sarasota Bay at the mouth of Palma Sola Bay on 6/13/02.

1.4 Impact of Human Activities

Human activities have greatly affected the manatee population. Coastal development and continual loss of Florida wetlands has severely reduced the size and quality of manatee habitats, whereas watercraft collisions have become the leading cause of adult mortality (Reynolds, 1995; Ackerman et al., 1995; Marine Mammal Commission, 2005). Watercraft collisions caused 25-30% of manatee deaths from 1976-1996 and remain one of the largest identified causes of death each year (Ackerman et al., 1995; Reynolds, 1999). Reducing the number of adult mortalities is critical for enhancing the recovery of the manatee population, as population modeling indicates that adult deaths have the greatest negative effect on population growth rates (Marmontel, 1993; Eberhardt and O'Shea, 1995). Marmontel et al. (1997) predicted a 10% decrease in adult mortality would lead to population growth, whereas a 10% increase in mortality would drive the species to extinction. The primary management tools aimed at reducing manatee mortality have been establishing boat speed regulation zones and limiting boat access areas. The successful establishment and management of boat speed regulatory zones and manatee sanctuaries depends upon the acquisition of data assessing behavior, habitat-use patterns, and identifying environmental characteristics influencing manatee behavior and habitat selection.

The indirect impacts of human activities are also numerous, and there are undoubtedly others that have yet to be discovered. Traditional migrations have been modified by coastal development or rendered unnecessary by industrially heated waters, and the amount of habitat available to manatees has been drastically reduced (O'Shea et al., 1995). Noise generated by boats has the potential to interrupt the

natural communication of manatees by preventing animals from hearing each other. This may happen because the noise level is too high for quiet manatee vocalizations to be effectively received or because specific frequencies of boat motors mask the frequencies of vocalizations. Activities such as boating and channel dredging also indirectly impact manatees by reducing food availability. Boating causes seagrass scarring that occurs when boat propellers tear and cut up seagrass roots, stems, and leaves, producing a narrow furrow devoid of seagrasses (Sargent et al., 1995). Scarring and erosion caused by boats have resulted in the destruction of more than 6% of Florida's seagrasses (Sargent et al., 1995). Boating and channel dredging further affect seagrasses by increasing the amount of suspended sediments in the water column, which reduces light availability and seagrass production (Reynolds, 1999; Zieman, 1982).

There has been a clear increase in manatee deaths over the past 25 years with a 6% per year exponential increase due to human-related factors between 1976 and 2000 (Ackerman et al., 1995; U.S. Fish and Wildlife Service, 2001). Approximately 31% of all deaths during this time period were documented to be related to human activities. The increase in manatee deaths is partly due to the increasing number of people and boats that share the waterways with manatees (U.S. Fish and Wildlife Service, 2001). Florida's human population increased from 6.8 to 15.7 million (130%) since 1970 and is projected to reach 18 million by 2010 (Florida Office of Economic and Demographic Research, 2000). As the numbers of humans and boats are not likely to decrease in the near future, increased protection of manatees has become critical if the species is to survive. Effective management is dependent on information illustrating

the details of interactions between humans and manatees. More specifically, additional research is needed to fully understand the reactions of manatees to boats, for watercraft collisions are the highest cause of human related manatee deaths.

1.5 Scientific Significance of Dissertation

There was a 10 dB increase in ambient ocean noise from 1950 to 1975 (Urick, 1986). Technological advances in coastal construction, underwater explosives, shipping vessels, sonar, and acoustic telemetry continue to contribute to increases in marine noise. The long and short-term effects these activities have on marine mammals are largely unknown. Constant exposure to high levels of noise can potentially cause behavioral disruptions and physiological stress that may adversely affect the individual and population at large, and specific sound sources have been shown to cause profound behavioral disruption in many marine mammal species. For example, beluga whales stopped feeding and swam rapidly away from approaching icebreakers. They traveled up to 80 km away from productive feeding areas and typically remained there for 1-2 days before returning (Finley et al., 1990). The significance of this reaction takes on even greater importance when models predict that masking of beluga communication signals occur within 14-71 km of icebreakers (Erbe and Farmer, 2000). Bowhead whales show strong avoidance of seismic airgun operations by swimming away from the source, reducing dive durations, reducing time spent at the surface, decreasing number of blows per surfacing, and increasing intervals between successive blows (Ljungblad et al., 1988). Manatees change their behavior and distribution in response to individual boat approaches and high levels of

boating activity (Buckingham et al., 1999; Nowacek et al., 2001b; Nowacek et al., 2004; Provancha and Provancha, 1988).

The aim of this project is to advance the fundamental understanding of manatee behavior and the effects of anthropogenic noise on marine mammals. More specifically, this project provides insight into manatee vocalization usage and habitat selection. The impact of noise on manatees was investigated by relating a quantitative description of the acoustic environment and sound transmission to changes in behavior. Manatees are regularly exposed to high volumes of vessel traffic and other anthropogenic noise producers (Brodie, 1981; Nowacek et al., 2001b; Nowacek et al., 2004; Richardson et al., 1995). Due to physiological requirements, such as food availability and warm water temperatures, manatees may have no alternative but to occupy areas where they are chronically exposed to human activities (Brodie, 1981). The acoustic modeling techniques used in this project quantitatively describe noise, sound transmission, and received levels of biologically relevant sounds in shallow habitats for manatees. This approach provides a template for quantitatively assessing signal detection and the impact of noise sources on other marine mammals in the many different environments that they live.

1.6 Study Site and Subjects

The study area encompasses the near-shore and coastal waters off Sarasota, Florida and extends from Buttonwood Harbor in the north to Siesta Key in the south. The 130-km² estuary includes a system of bays enclosed by barrier islands, harbors, creeks, boat basins, bayous, and residential canals (Koelsch, 2001; Scott et al., 1990).

Water depth in the area ranges from less than 1 meter in the grassflats up to 10 meters or more in the passes and Gulf of Mexico, with an average depth of 4 meters within the barrier islands (Wells et al., 1987). The limits of the study area were Buttonwood Harbor in the north and Philippi Creek in the south (Figure 1.5). Manatees frequent this area on a regular basis during non-winter months from March-November (Kadel and Patton, 1992; Koelsch, 2001; Patton, 1986). Sarasota Bay serves as a summer residence site as well as a stop-over point for migrating manatees (Koelsch, 1997; Rathburn et al., 1990). Currently, once- or twice-monthly aerial surveys are conducted in this region to assess abundance and distribution. Additionally, the Manatee Individual Photo-identification System (MIPS), or scar catalog, is being continually updated for the identification of animals sighted in the area.

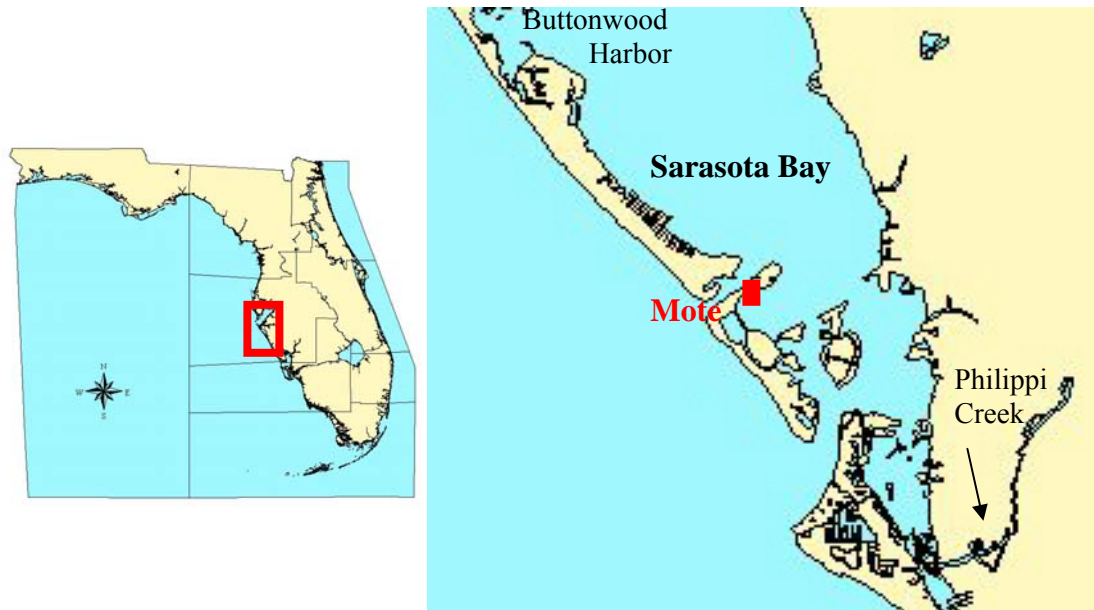


Figure 1.5. Map of the Sarasota Bay study area.

1.7 Dissertation Outline

This dissertation examined the effects of environmental noise on manatees from several different perspectives. Chapter 2 presents results of an ambient noise and sound propagation analysis in which it was determined that noise does influence the habitat selection and geographic distribution of manatees. Transmission loss was modeled and field verified in each habitat studied, and noise recordings were obtained systematically over two six-month field seasons. Chapter 3 describes the relationship between manatee behavior and activity budgets as a function of environmental noise levels. The relationship between manatee vocalization usage and noise level is addressed in Chapter 4. Chapter 5 describes the results of a playback experiment in which recordings of vessel approaches were transmitted to free-ranging manatees. Finally, Chapter 6 is an overall summary of the main dissertation results in the context of manatee conservation and management.

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Chapter 2. Characterizing the Acoustic Environment of Manatee Habitats

2.1 Abstract

The Florida manatee is regularly exposed to high volumes of vessel traffic and other human-related noise because of its coastal distribution. Quantifying specific aspects of the manatee's acoustic environment will allow for a better understanding of how these animals respond to both natural and human-induced changes in their environment. Acoustic recordings and transmission loss measurements were made in two manatee habitats: seagrass beds and dredged habitats. Twenty four sampling sites were chosen based on the frequency of manatee presence in specific areas from 2000-2003. Recordings included both ambient noise levels and transient noise sources. The Monterey-Miami Parabolic Equation (MMPE) model was used to relate environmental parameters to transmission loss, and model outputs were verified by field tests at all sites. Results indicated that high-use grassbeds have higher levels of transmission loss for frequencies above 2 kHz compared to low-use sites of equal food species composition and density. Additionally, high-use grassbeds have lower ambient noise for frequencies below 1 kHz compared to low-use grassbeds of equal species composition and density. This creates a high-use environment where noise above 2 kHz is lower even at the same distance from vessel traffic, due to increased attenuation compared to low-use sites. This also happens to be the range of most efficient sound propagation inside the grassbed habitat and includes the dominant frequencies of manatee vocalizations. The acoustic environment may play a more important role in manatee grassbed selection than seagrass coverage or species composition, as linear regression analysis showed no significant correlation between usage and either total

grass coverage, individual species coverage, or aerial pattern. Additionally, grassbed usage was negatively correlated with concentrated boat presence in the morning hours; no correlation was observed during noon and afternoon hours. This suggests that morning boat presence and its associated noise may play a dominant role in grassbed usage on a daily time scale.

2.2 Introduction

Florida manatees live in shallow coastal habitats that typically range from half a meter to approximately ten meters in depth. The deepest portions of the habitat are utilized most often during travel from one site to another and occur in the Intracoastal Waterway, open bay, and open ocean areas (Koelsch, 1997). When manatees are not traveling, they spend the majority of their time in the shallower waters of seagrass beds, sand bars, and secluded dredged habitats (Marine Mammal Commission, 1986). To better understand how sound may affect manatees in critical habitats, it is necessary to quantify ambient noise levels and the acoustic propagation loss characteristics of these shallow-water regions. Acoustic propagation loss, or transmission loss, is particularly important to characterize because the sonar equation incorporates this term when relating received levels to both source levels and issues of detection (Urick, 1983).

Geographically speaking, shallow water refers to the inland waters of bays and harbors and to coastal waters less than 200 m deep (Etter, 1996). The depth of manatee habitats covers only the shallowest 5% of that range. From an acoustic standpoint, shallow water refers to areas where sound is propagated to distances at

least several times the water depth, under conditions where both the surface and sediment boundaries have an effect on transmission (Urlick, 1983). Shallow water regions form a sound channel in which the sound is trapped between the upper boundary of the surface and lower boundary of the bottom sediments. As sound is propagated through the deep water environment, it is repeatedly reflected from both the upper and lower boundaries. Environmental factors such as surface roughness, depth at the source/receiver, sound speed, and bottom properties all affect sound propagation.

Compared to sound propagation in deep water, the propagation of sound in shallow water is complicated. Characterizing the sound propagation loss in shallow water regions is difficult due to the variability of environmental conditions in space and time, as well as the interactions between the upper and lower boundary layers. In deep water, the medium in which sound travels is more constant in time and space, and boundary layers can be assumed to have minimal or no effect on sound propagation at short ranges. The range of detection in shallow waters is severely limited by high attenuation resulting from repeated interactions with the bottom and by limited water depths, which do not affect the long-range propagation paths available in deep water (Etter, 1996). The challenges associated with characterizing sound propagation and signal detection in shallow water have resulted in numerous theories and mathematical models to integrate acoustic and boundary conditions with transmission loss (Brekhovskikh, 1960; Etter, 1996; Frisk, 1994; Officer, 1958; Urlick, 1983).

The concept of transmission loss relates to conservation of energy. In its simplest form, transmission loss in the far field of a homogeneous unbounded medium is due to spherical spreading and can be defined by:

$$TL = 10 \log (I_o/I_r) = 20 \log (P_o/P_r) \text{ dB re 1 m} \quad (1)$$

where I_o = intensity 1 m from source

I_r = intensity at distance r

P_o = pressure amplitude 1 m from source

P_r = pressure amplitude at distance r

Simple acoustic propagation loss models calculate transmission loss at a specified distance, r , from the source by taking into account acoustic spreading and attenuation properties. Spherical spreading is proportional to r^2 and relates to TL in the following equation:

$$TL = 10 \log (I_o/I_r) + ar = 10 \log r^2 + ar = 20 \log (r) + ar \text{ dB} \quad (2)$$

where a = absorption coefficient

Unfortunately simple transmission loss models are not accurate for bounded, heterogeneous environments like the complex intra-coastal environments that manatees inhabit. Nowacek et al. (2001a) found that frequencies of sound produced by boats are attenuated in manatee habitats to a greater degree than would be predicted by simple transmission loss models. More detailed mathematical models are needed. The theoretical basis underlying all mathematical models of acoustic propagation is the wave equation (Etter, 1996). The wave equation is a partial differential equation that relates acoustic pressure to x , y , z coordinates in space and time. Different groups of models use different approaches to solving the wave equation in relation to transmission loss, and each approach has its associated strengths and weaknesses.

The two dominant groups of models are ray theory and normal mode. Ray-theoretical solutions to the wave equation, or ray-theory models, calculate transmission loss on the basis of ray tracing (National Defense Research Committee, 1946). Multipath expansion techniques expand the acoustic field integral representation of the wave equation for a particular ray path (Weinberg, 1975). Normal mode solutions are derived from an integral representation of the wave equation, which applies cylindrical symmetry in a vertically stratified medium (Etter, 1996; Pekeris, 1948). The normal modes are then additively combined to satisfy initial boundary and source conditions, which will ultimately describe the distribution of sound from the source in space and time. Fast-field models are also based on a derivation of the normal mode approach. Ray theory models are most applicable and practical for high frequency (> 500 Hz), range-dependent environments (acoustic parameters of the medium are a function of range) in both shallow and deep water, whereas normal mode models are most applicable in low frequency (< 500 Hz), range-independent environments (acoustic parameters of the medium are independent of range) for both deep and shallow water (Jensen, 1982).

Parabolic equation (PE) models have been applied to microwave and laser beam propagation since the mid-1940s and were first used in underwater acoustics in 1973 (Hardin and Tappert, 1973). Recently, modified PE models have been used successfully in shallow-water environments (Etter, 1996; Jensen, 1984; Smith, 2001). These models are based on a solution of the parabolic versus elliptic-reduced wave equation, which is used with ray theory and normal mode models. The PE models are most appropriate for use in range-dependent environments and can be used over a

broad frequency band (Collins and Chin-Bing, 1990; Etter, 1996; Jensen, 1982; Orchard et al., 1992; Smith, 2001). The Monterey-Miami Parabolic Equation (MMPE) model (Smith, 2001) was the specific PE model used in this study. The current version of MMPE is a two-dimensional PE model that employs a split-step Fourier algorithm and assumes the surface is a perfect reflector due to a pressure release boundary. Input parameters needed to run the model are: sound speed profile, range-dependent bathymetry contour, sediment properties (sound speed, sound speed gradient, density, compressional attenuation, shear speed, and shear attenuation), source depth, and source type (point or linear array). The MMPE model also allows for an additional bottom layer to be present on top of the deep basement layer to allow for the effect of sediment or grass layers (Smith, 2001).

Making field measurements and using models to determine the transmission loss of a signal in manatee habitats are only two of many elements that must be quantified in order to ultimately answer questions pertaining to signal detection by an animal. Another major factor is noise. As a rule of thumb, a signal must be louder than the background noise level in order for it to be detected. Consequently, a signal with a high source level and low amount of transmission loss may or may not be detected a mere 100 m away depending on how noisy the environment is. The ambient noise levels in coastal waters, bays, and harbors are subject to wide variations compared to the relatively well-defined levels of deep-water ambient noise, and coastal marine mammals must cope with sources of noise that are highly variable in time, frequency, and space (Urick, 1983).

The three primary contributors to coastal noise are watercraft, wind, and biological noise. Because watercraft use and biological noise are higher in coastal areas, noise levels in coastal waters are higher than in deep water far from shore at frequencies above 500 Hz (Urick, 1983). With a firm grasp on both environmental noise and transmission loss levels in a specific habitat at a particular time it then becomes possible to begin to address questions of the range at which a signal can be detected.

This study examines both the ambient noise and transmission loss in the shallow water areas of manatee habitats. The goal of the study is to characterize and compare the acoustic environments of areas used consistently by manatees. Understanding environmental noise levels and how sound is propagated in different manatee habitats is critical in order to more clearly understand the impact of human activities on manatees and the manatee communication system. For example, watercraft collisions have become the leading identified cause of adult mortality (Ackerman et al., 1995; Reynolds, 1995). The question that naturally arises from this is whether or not manatees hear the noise produced from approaching boats in enough time to swim out of harm's way. The root of this question is the detection of sound signals. Quantifying background noise and how sound is propagated in different habitats between the source and receiver provides the necessary information for determining source levels and ultimately the probability of manatees detecting approaching sound sources.

2.3 Methods

2.3.1 *Site Selection*

Sound propagation loss and noise were investigated in two manatee habitats: seagrass beds and dredged habitats. These habitat types were chosen because of their biological importance to manatees. Animals typically feed in grassbeds and rest or socialize in dredged habitats. Habitats used heavily by manatees in the Sarasota Bay area were identified from aerial survey data available from Mote Marine Laboratory for the years 2000-2003. Animals were only sighted outside of grassbeds or dredged habitats in 6.7% of the 38 aerial surveys flown between April and September in the years 2000-2003.

A total of 24 sites was selected for acoustic and environmental sampling: 13 grassbeds and 11 dredged habitats (Table 2.1; Figure 2.1). Grassbed sites were defined by the presence of seagrass within the site, and dredged habitats were areas that had been dredged for human use and were characterized by the presence of a fine sediment layer. There were two selection criteria for site selection. First, animals had to be observed in a site more than once over a 4-year survey period from 2000-2003. Second, the site had to be accessible by the 5.2 m (17') research vessel. The percentage of surveys that animals were sighted in the selected grassbeds ranged from 5.3-78.9%. The percentage of surveys that animals were observed in the dredged habitats ranged from 5.3-39.5% (Table 2.1). The 13 grassbed sites included the five most heavily used grassbeds identified from the aerial surveys, one of which was in a manatee sanctuary (Pansy Bayou Grassbed or Pansy GB). The grassbed sites also included the five least used grassbeds in Sarasota Bay meeting the selection criteria. The 11 dredged habitat sites included the three most heavily used dredged

basins/canals, one of which was in a manatee sanctuary (Pansy Dredged Basin or Pansy DB). The dredged sites also included the four least used dredged habitats in Sarasota Bay meeting the selection criteria.

Table 2.1. Selected grassbed and dredged habitat sites with associated usage patterns. Site identification letters remained consistent throughout the study.

Site	Grassbed	Usage (%)	Site	Dredged Habitat	Usage (%)
A	City Island Grassflats (CIGF)	78.9	C	Pansy DC	39.5
B	Pansy Bayou GB	73.7	W	Buttonwood Canal	23.7
V	Buttonwood Harbor S	44.7	U	Bowlees Creek	15.8
H	S. Sarasota Bay	44.7	K	Cluster	13.2
I	W. Roberts Bay	44.7	M	E. Roberts Bay	13.2
T	Bowlees GB	18.4	L	Phillipi Creek	13.2
N	SE Sarasota Bay	18.4	J	Cocoanut Bayou	10.5
S	Airport GB	15.8	R	Whitacker Bayou	5.3
D	CIGF East	10.5	Q	Hyatt Basin	5.3
F	SW Bird Key	10.5	E	S. Lido Canal	5.3
X	New Pass GB	7.9	P	Harbor Acres	5.3
G	Down South Lido	7.9			
O	E. Sarasota Bay	7.9			

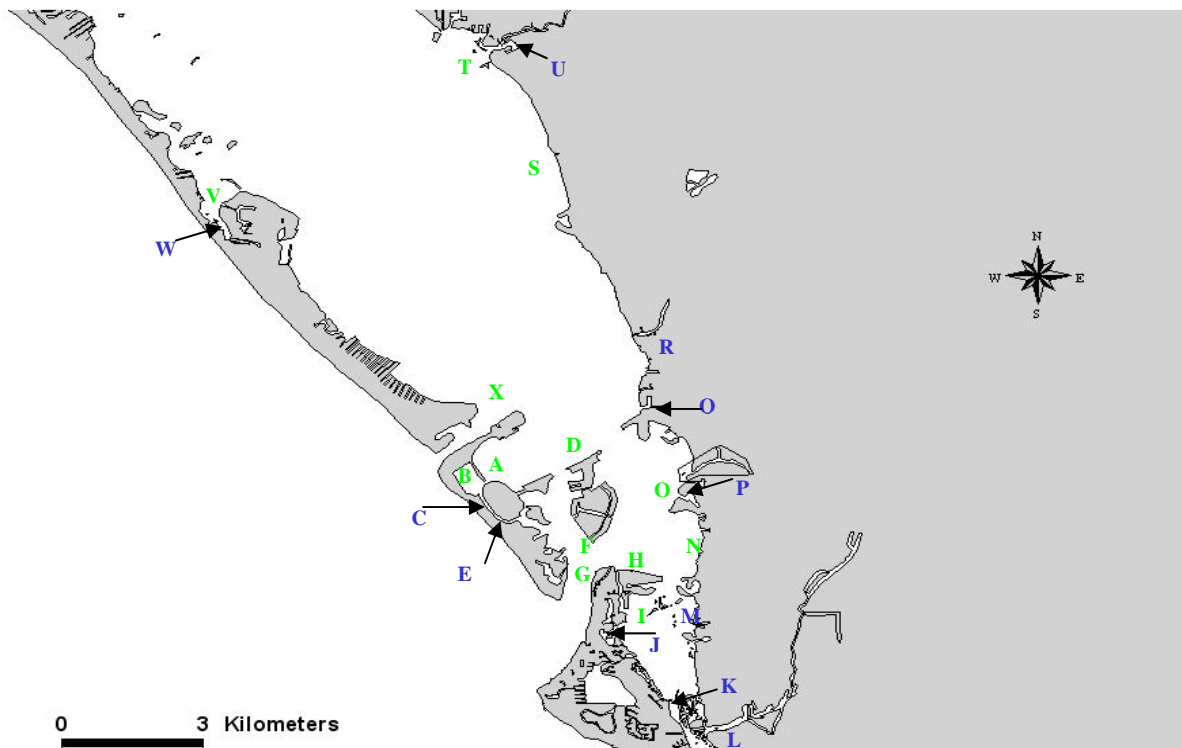


Figure 2.1. Study site map.

2.3.2 *Transmission Loss (TL)*

The Monterey-Miami Parabolic Equation (MMPE) model was used to model the sound propagation loss at sites within the Sarasota Bay area during non-winter months (Smith, 2001). Transmission loss in a seven-octave frequency band was modeled from 250 Hz – 20 kHz over a range of 100 m. Transmission loss was quantified for 8 frequencies: 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 8 kHz, 16 kHz, and 20 kHz. The 20 kHz frequency was chosen as the maximum because this was the maximum frequency output of the broadcasting system used during the field test validations. Initial environmental parameters were collected during the summer of 2003 for application in the MMPE model. A SBE 25 Sealogger CTD was used to monitor salinity, temperature, and sound speed profiles in each site over the course of the season. Each environmental input parameter was averaged for a 6-month time period, and the average sound speed value was used in the MMPE model for each site. The largest difference between the average 6-month sound speed profile and any individual sample within each site was less than 1.5%; therefore the seasonal variation in the sound speed profiles had a negligible effect on model predictions. Bathymetry data were obtained by doing transects across each site. A bathymetry reading was recorded approximately every 10 meters. Sediment properties were obtained from the Sarasota Bay National Estuary Program (Culter and Leverone, 1993). Distribution of sediment grain sizes in each site was identified from Culter and Leverone (1993). The proportion of grain sizes in each site was then used to estimate sediment sound speed, sound speed gradient, density, and compressional attenuation loss from Hamilton (1980).

The modeled transmission loss range in all sites was approximated from the distance between the closest boat channel and the farthest possible manatee position within a given site. A point source at a depth of 0.75 m was used in all models in order to simulate the depth of an outboard motor. A 50 m sediment layer was used in all dredged habitat model runs. The 50 m sediment layer width was chosen because it was the minimum layer width that produced no interaction with the rock layer deep below the sediment layer. In seagrass beds, the transmission loss was modeled with a 0.3 m grass layer on top of a 50 m sediment layer. All grassbed sites were modeled with the same grass layer acoustic properties. These properties were approximated for turtle grass (*Thalassia testudinum*), the dominant seagrass species in the 13 selected grassbed sites. Grass layer velocity (1450 m/s), density (0.90 g/cm³), and attenuation loss (0.17 dB/km/Hz) were derived from grass blade density and physiological and biomechanical properties of turtle grass in Sarasota Bay, FL (Tomasko et al., 1996; Sabol, pers. comm.). Density values were taken directly from measured values, whereas velocity and attenuation loss values were estimated based on the cross sectional ratio of gas-filled lacunae and plant tissue. It was assumed from previous work on the acoustic reflectivity of aquatic vegetation that plant tissue had the acoustic properties of seawater, whereas the lacunae had acoustic properties of air (Kopp, 1998; Sabol et al., 1997; Sabol et al., 2002).

The MMPE model outputs transmission loss in three forms: TL at a single frequency vs. range and depth, TL at a single range vs. frequency and depth, and TL at a single depth vs. frequency and range. All results in this study were based on the output of TL at a single frequency vs. range and depth (Figure 2.2). In order to

compare TL at a specified range and frequency quantitatively between sites, TL was averaged over the depth of the water column at ranges of interest (Figure 2.3). All dB units were converted to intensity before averaging and re-converted back to dB units for final comparisons.

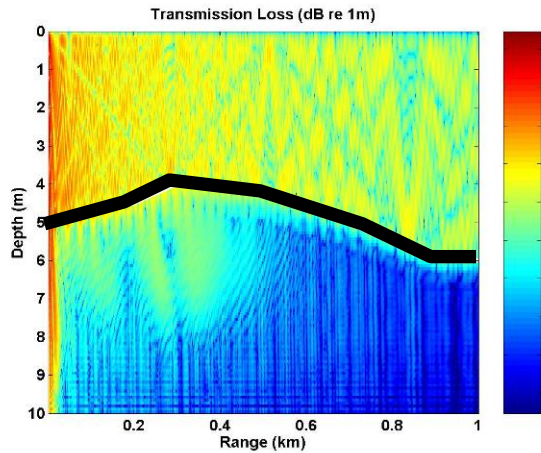


Figure 2.2. MMPE transmission loss output as a function of depth and range for a 4 kHz signal. The black bathymetry line divides the images into water column and bottom sediments with the water occurring above the line and the sediments below.

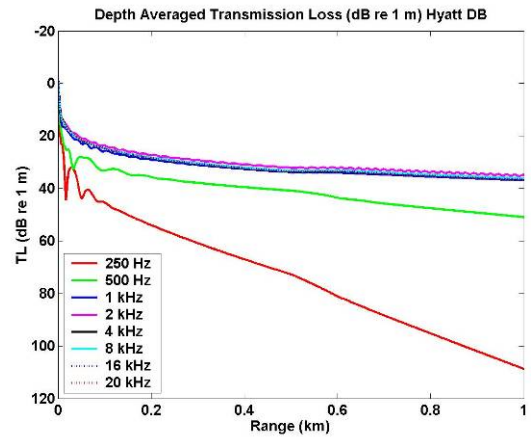


Figure 2.3. Depth averaged transmission loss in a dredged habitat (Hyatt DB). Sound is propagated most efficiently in the dredged habitat at 2 kHz.

A difference technique was used to validate the MMPE model outputs.

Difference techniques measure the distance between the model prediction and field measurements in terms of dB difference at a given range (Etter, 1996). Model accuracy was verified at all sites by recording a broadband signal transmitted from an anchored boat a known distance away. The broadcast signal was a 1 second upsweep spanning 20 Hz-22 kHz. In 2003, the upsweep was introduced by a J-9 underwater transducer, which is capable of producing sounds in the range of 40 Hz – 20 kHz with a source level near 160 dB re 1 μ Pa @ 1 m. In 2004, a Lubell LL916 underwater loudspeaker system was used as a source. This system had a 200 Hz-20 kHz frequency range with an output source level of 180 dB re 1 μ Pa @ 1 m. The upsweep was recorded at a distance of 1 m at each site to obtain a frequency dependent source level for transmission loss determinations. Transmission loss was calculated by subtracting the received levels of signals recorded at a 10 m, 25 m, and 50 m from the

1 m source level at each of the 8 modeled frequencies in all sites. All settings of the broadcasting system remained constant throughout the study. The dynamic range of the recording system was varied to prevent overloading the system. The recording hydrophone was a HTI-99-HF hydrophone with built-in pre-amplifier and had a 2 Hz-125 kHz frequency range and -178 dB re $1\text{ V}/\mu\text{ Pa}$ sensitivity. The recording system was a National Instruments PCMCIA DAQ Card-6062E used in conjunction with a Dell Inspiron 8100. This system had a frequency response of 5 Hz – 250 kHz with a selectable input voltage range. Recording System A refers to the entire recording chain composed of the components described above (hydrophone, DAQ card, and computer). All transmission loss recordings were sampled at a rate of 200 kHz.

2.3.3 *Acoustic Recordings*

2003: Acoustic site sampling was conducted from May through September in 2003.

Acoustic recordings of the 24 selected manatee habitats were made systematically one to two times per week, including weekends and holidays. All identified sites were sampled in succession over the period of a few hours on the same day. The time of day sampling occurred rotated among 3 time periods: 1) morning (07:00-10:30), 2) noon (10:30-14:00), and 3) afternoon (14:00-17:30). The order of site recordings was based on geographical location. Each site was assigned a letter in a counter-clockwise direction around the study area (Figure 2.1). The site at which the sampling regime began each week was selected randomly. Efforts were made to sample each site during each of the three time periods at least once per month (Figure 2.4). This was achieved during the morning and noon time periods, but fewer recordings were made

during the afternoon time period due to late afternoon thunderstorms throughout the season. The above average sampling during the noon hours in some sites is a by-product of where animals were most often encountered. Noise recordings were taken during all animal sightings and focal animal follows (see Chapter 3 in this dissertation). These recordings were made in addition to days devoted strictly to acoustic site sampling. In total, 395 site recordings were made across the 24 sites in 2003.

During the 2003 season recordings at each site were made with recording System A described in section 2.3.2. Ambient noise was recorded at each site for five minutes at a 200 kHz sampling rate.

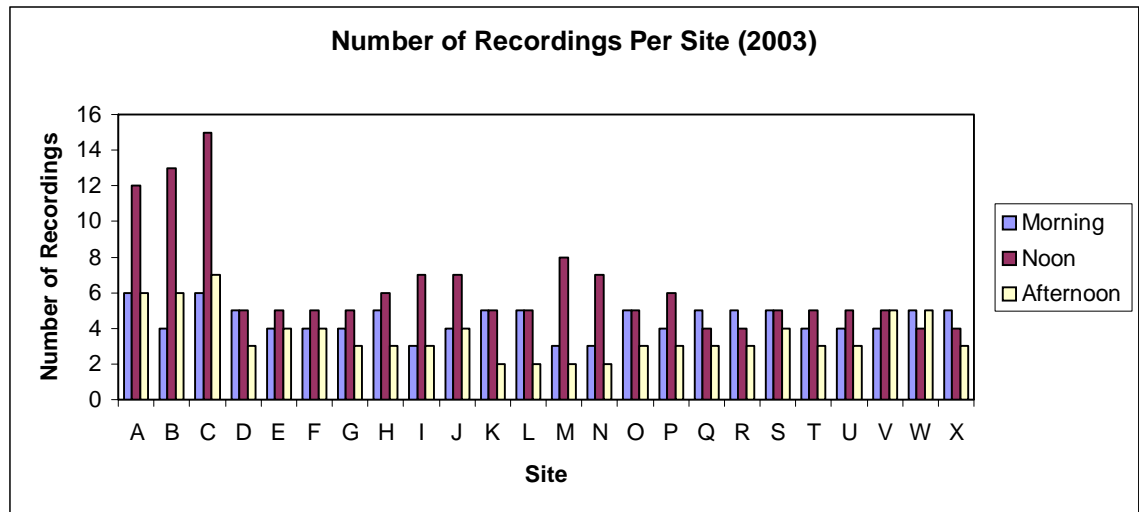


Figure 2.4. Number of recordings made at each site during each time period of the day.

2004: In 2004, a different method for recording ambient noise was implemented. The goal of this sampling regime was to record noise levels in a single site over a longer consecutive period of time compared to 2003 recordings. This would allow for more accurate daily noise patterns to be identified. An Acoustic Rain Gauge (ARG) buoy was deployed for 3-4 days at each site. Each deployment included a minimum of two weekdays and one weekend day. This system consisted of a bottom mounted hydrophone system with a low-noise broadband hydrophone (100 Hz-50 kHz), electronic filter and 2-stage amplifier, TT8 computer processor with 100 kHz A/D sampler, 50 Mbyte memory card, and 51 amp-hour battery package (Nystuen, 2004) (Figure 2.5).

The ARG buoy was programmed to power on and sample at 10 minute intervals. The 10 minute sampling interval was selected in order to preserve the battery pack over the field season and to conserve data storage space. Within each sampling interval, four 10 ms time series were sampled at 5 s intervals over a 20 s time period. This sampling technique was an internally hardwired parameter. A 1024 point Fast Fourier Transform (FFT) (0-50kHz) was then performed on the time series to generate power spectra. The power spectral density (psd) curves for each 10 ms were then processed to identify sound sources present by comparison to stored psd curves of known sources. Data were stored as 200 Hz band averages in 0.1 dB resolution from 0-3 kHz, and 1 kHz band averages thereafter to conserve file space. If any of the four individual psd curves did not trigger a modified sampling regime, the spectra were averaged, stored as a single spectra for the sampling period, and the instrument returned to “sleep” mode. However, if one of two criteria were met during the

analysis of the 4 psd curves, the sampling regime would be modified to a two minute sampling interval instead of ten. The first criterion was a transient rejection. The instrument was programmed to discard the first sampling set and modify its sampling regime if one of the four spectra differed by more than 20 dB, indicating a transient source. If transients were detected in the three consecutive sampling sets, the four psd curves of the last set were stored, and the instrument returned to “sleep” mode. This criterion selected against the inclusion of transient signals, such as clicks from snapping shrimp, in the acoustic record. The second criterion was the detection of sound sources of interest. A modified sampling regime was triggered if the spectra resembled previously stored spectra indicating specific sound sources, and all four spectra were stored for each sampling set. Sampling continued at the two minute interval until the source was no longer present. Sound sources of interest in this study were increased noise levels due to boat traffic and rain.

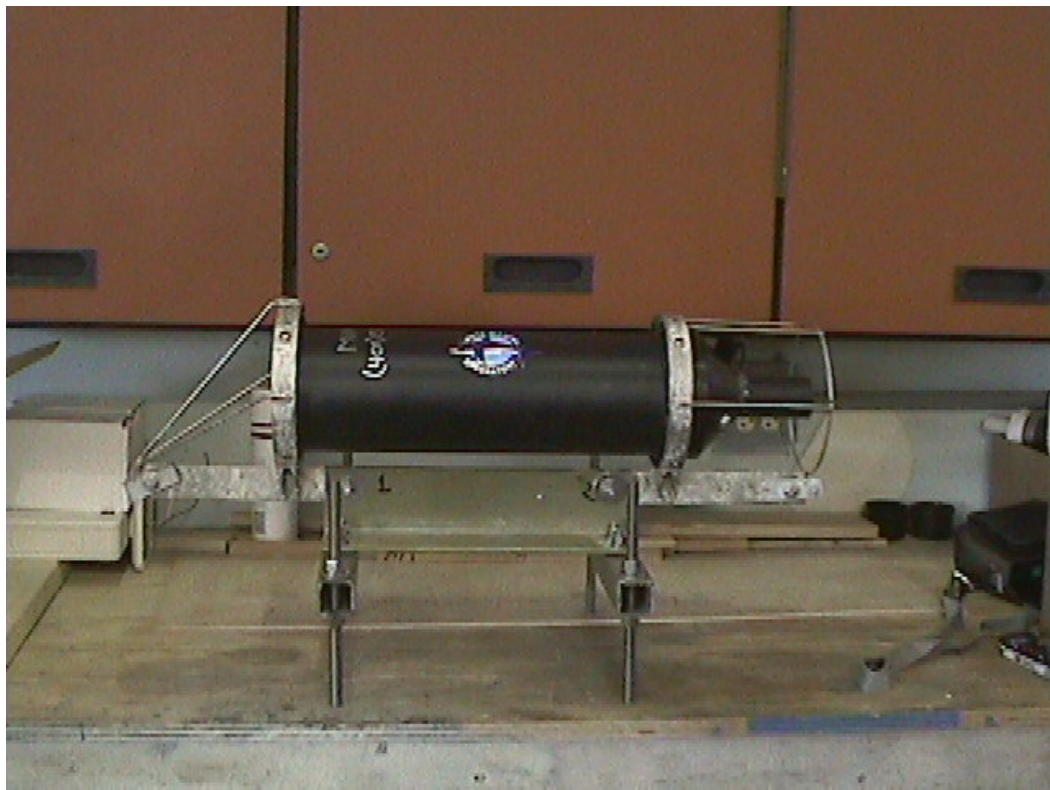
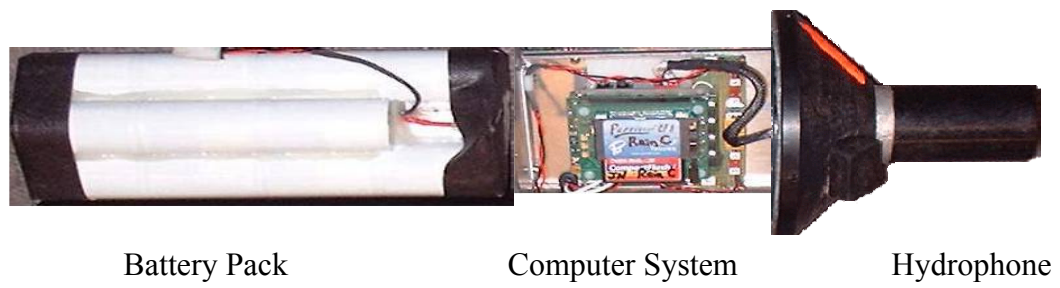


Figure 2.5. Acoustic Rain Gauge (ARG) Buoy. Top image is taken from Nystuen (2004). Top: internal image of ARG. Bottom: picture of mounted ARG.

2.3.4 Noise Level Analysis

2003: Noise levels for each site recording were determined for one-third octave bands at 9 center frequencies: 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 8 kHz, 16 kHz, 32 kHz, and 64 kHz. A one-third octave band pass filter with 30 dB side lobes was created for each of the specified frequencies. One-third octave noise levels were calculated at 4 second intervals and then averaged over the duration of the 5-10 minute site recording to produce an average one-third octave noise level at a specified frequency at a particular time and day. System noise for Recording System A was obtained by suspending the hydrophone in-air and recording in a quiet, dark room. All gain settings were identical to those used in the field. System noise for Recording System A was below all ambient noise levels for all one-third octave bands (Table 2.2).

Table 2.2. One-third octave band system noise levels for the Recording System A.

Center Frequency	dB re 1 μ Pa
250 Hz	24
500 Hz	17
1 kHz	12
2 kHz	7
4 kHz	6
8 kHz	9
16 kHz	15
32 kHz	35
64 kHz	22

2004: Noise levels from each deployment were calculated for one-third octave bands at 8 center frequencies. The stored psd center frequencies sampled with the ARG buoy were not at precise octave intervals, so the center frequencies closest to those analyzed in 2003 were selected: 300 Hz, 500 Hz, 1.1 kHz, 2.1 kHz, 4.6 kHz, 8.5 kHz,

16.3 kHz, 31.9 kHz. For all frequencies the analyzed bandwidth included the center frequencies measured in 2003. An average noise level within each of four time periods was calculated. The time periods were consistent with those used in 2003, with the addition of a fourth night time period: 1) morning (07:00-10:30), 2) noon (10:30-14:00), 3) afternoon (14:00-17:30), and 4) night (17:30-24:00). System noise as a function of frequency for the ARG buoy was less than any ambient noise value obtained throughout the study (Figure 2.6). System noise for the ARG recording system was obtained by operating the ARG buoy in-air in a quiet, dark room.

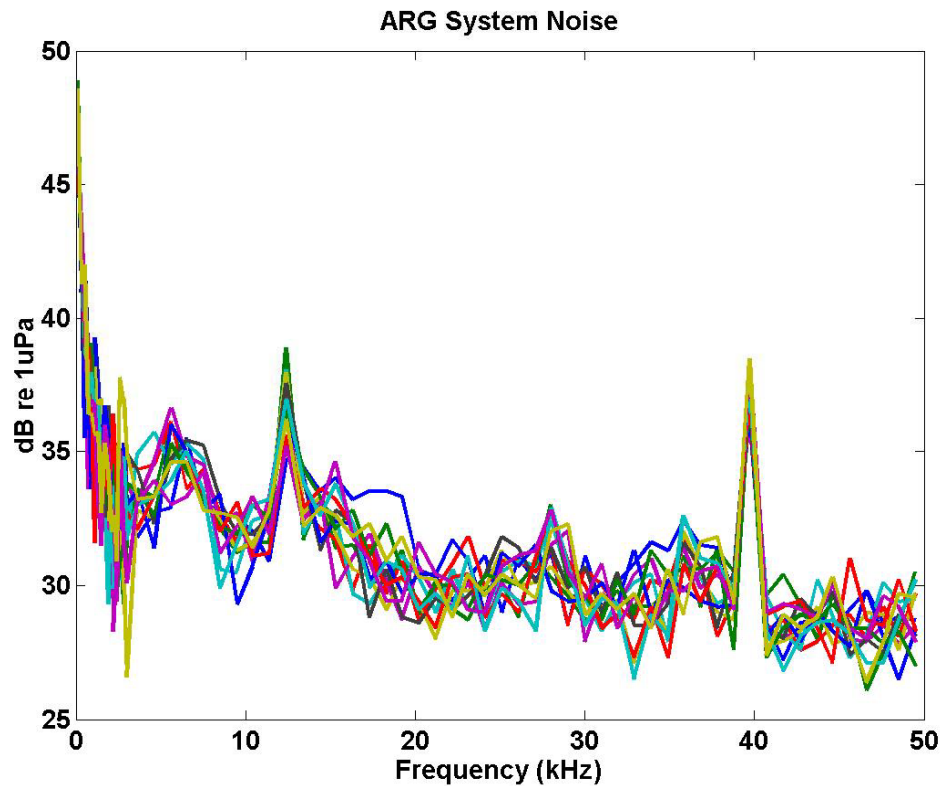


Figure 2.6. System noise of the ARG buoy for all 64 frequencies measured.

2.3.5 Seagrass Habitat Quality Estimates

Seagrass density was estimated for the area's three most prominent seagrass species: turtle grass (*Thalassia testudinum*), manatee grass (*Syringodium filiforme*), and shoal grass (*Halodule wrightii*). In-water estimates were obtained using standard procedures for shoot density and biomass (Tomasko and Dawes, 1989). A 1 m² quadrant, which was divided into 25 equal 20x20 cm squares, was randomly cast six times in each seagrass habitat. The total grass coverage, as well as individual grass species and macroalgae coverage, was evaluated for each quadrant toss. The values were then averaged to determine a final species and total grass coverage percentage for each site.

Seagrass patterns within each site were also estimated from an aerial survey flown on June 16, 2004. Grass patterns were evaluated on a 5-point scale ranging from sparse to dense grass coverage. The categories were: 1) sparse, 2) sparsely patchy, 3) densely patchy, 4) continuous (moderate cover), and 5) dense.

2.4 Results

2.4.1 Transmission Loss (TL)

Initial MMPE model results comparing TL across habitat types supported documented evidence from previous manatee habitat TL experiments which reported higher levels of transmission loss in grassbeds compared to dredged habitats (Nowacek et al., 2001a). Modeled and measured transmission loss was greater in grassbeds than in adjacent dredged basins or canals (Figure 2.7). This pattern was consistent for all frequencies modeled. Model results also indicated that the highest TL occurred at frequencies below 2 kHz, whereas the most efficient frequencies of sound propagation were 2-20 kHz in both grassbeds and dredged habitats (refer to Figure 2.3).

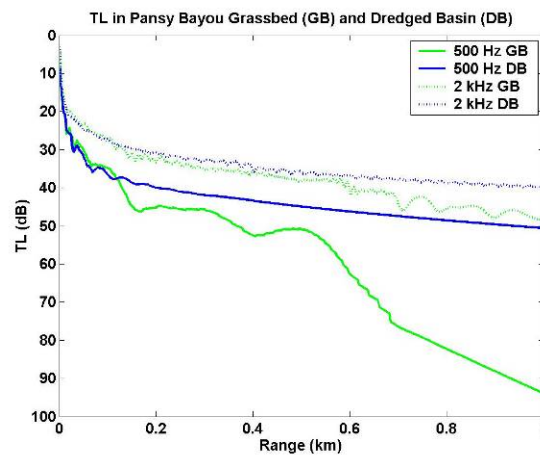


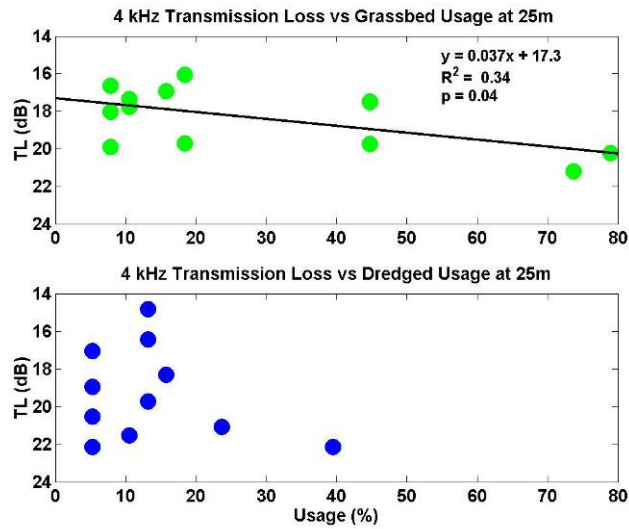
Figure 2.7. Depth-averaged transmission loss in the Pansy Bayou grassbed and dredged basin. Note that transmission loss was greater in the grassbed.

Depth-averaged TL was calculated from the MMPE model outputs at distances of 10 m, 20 m, 25 m, 50 m, 100 m, and 200 m for each of the 8 specified frequencies within each grassbed and dredged habitat site. Regression analyses were performed

within each habitat type and at each frequency and distance in order to determine if TL was significantly correlated with manatee usage.

Usage was defined as the percentage of time manatees were present at a site during aerial surveys from 2000-2003. Results showed a significant correlation between usage and TL in grassbeds at all investigated distances for frequencies from 4-20 kHz (Figure 2.8 and Table 2.3). Sites that were used more heavily by manatees tended to have higher levels of transmission loss. Significance was observed at some distances, but not all, for frequencies of 1-2 kHz. For all significant regressions, R squared values ranged from 0.32-0.71. There was no significant correlation between usage and TL in grassbeds at frequencies below 1 kHz or in dredged habitats at any frequency or distance.

A)



B)

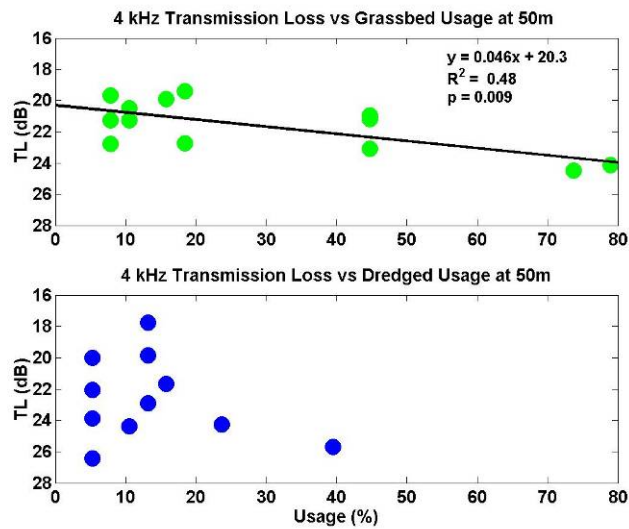


Figure 2.8. 4 kHz Transmission loss at 25m (A) and 50m (B) as a function of manatee site usage in grassbeds and dredged habitats. Solid black regression lines indicate significant relationships.

Table 2.3. Regression analysis p-values for transmission loss and usage comparisons at specified distances and frequencies. Highlighted values show significant relationships.

Grassbeds

Frequency	10m	20m	25m	50m	100m	200m
250 Hz	0.019	0.32	0.70	0.42	0.76	0.63
500 Hz	0.57	0.41	0.79	0.33	0.57	0.78
1 kHz	0.14	0.13	0.23	0.04	0.08	0.04
2 kHz	0.096	0.035	0.04	0.09	0.004	0.001
4 kHz	0.030	0.032	0.04	0.01	0.045	<0.001
8 kHz	0.037	0.037	0.03	0.02	0.037	0.006
16 kHz	0.029	0.025	0.03	0.02	0.016	0.001
20 kHz	0.034	0.033	0.03	0.02	0.015	0.002

Dredged Habitats

Frequency	10m	20m	25m	50m	100m	200m
250 Hz	0.35	0.37	0.10	0.87	0.17	0.30
500 Hz	0.58	0.58	0.74	0.90	0.66	0.54
1 kHz	0.77	0.95	0.80	0.83	0.97	0.67
2 kHz	0.32	0.12	0.14	0.13	0.21	0.27
4 kHz	0.48	0.36	0.39	0.41	0.48	0.61
8 kHz	0.56	0.58	0.51	0.65	0.72	0.85
16 kHz	0.41	0.33	0.35	0.41	0.56	0.68
20 kHz	0.49	0.40	0.42	0.50	0.68	0.76

2.4.2 MMPE Model Evaluation

Transmission loss measurements were made in the field at distances of 10, 25, and 50 m in all sites. Additional measurements at 100 m were made in 2 dredged habitat sites. Model accuracy was evaluated by examining field measurements with respect to model output as a function of range and frequency (Figures 2.9 and 2.10). Figure 2.9 provides an example of how the MMPE model outputs for each model run were viewed in relation to the field measurements. Each MMPE model output was examined on two levels: TL at the depth of the hydrophone and TL depth averaged over the water column as a function of distance. A back of the envelope wave guide

model ($TL=20 \log(r)$) was included for comparison. The MMPE model results were always most accurate at the depth of the hydrophone, and deviations between the model and field measurements were calculated at the hydrophone depth (Figure 2.10).

When deviations between the field measurements and model calculations at the hydrophone depth were averaged over all the sites as a function of habitat type, range, and frequency, results indicated that the MMPE model was most accurate for frequencies from 1-16 kHz (Figure 2.11). In this frequency range, average deviations were predominantly within ± 5 dB. Negative deviation values indicated the model overestimated the TL, and positive values indicated the model underestimated the TL. The frequencies at which the model is most accurate overlaps the dominant frequencies of manatee vocalizations and were used to calculate vocalization source levels and evaluate uncertainty in Chapters 4 and 5.

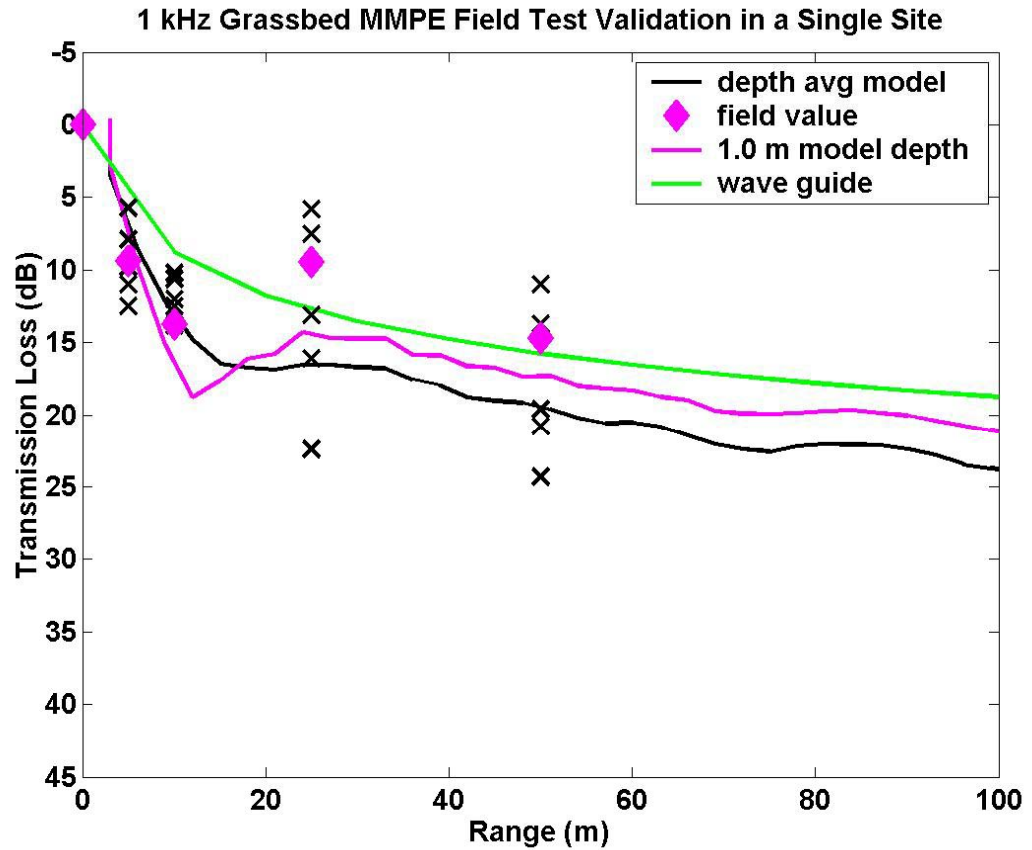


Figure 2.9. MMPE model predictions and field measurements for transmission loss at 1 kHz in a grassbed habitat. The average field value at a specified distance is represented by a diamond. “x” symbols represent the individual measurements from which the average was calculated. The pink colored MMPE model output is the TL at the depth of the hydrophone making the field measurements. The solid black MMPE model output is the depth averaged TL estimated in the water column by the MMPE model over the 100 m range. The back of the envelope wave guide is presented in green for comparison to the MMPE model results.

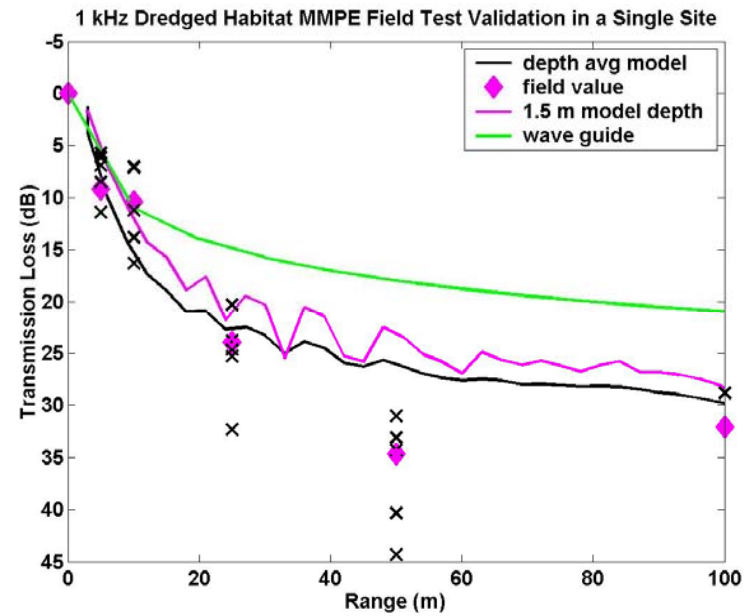
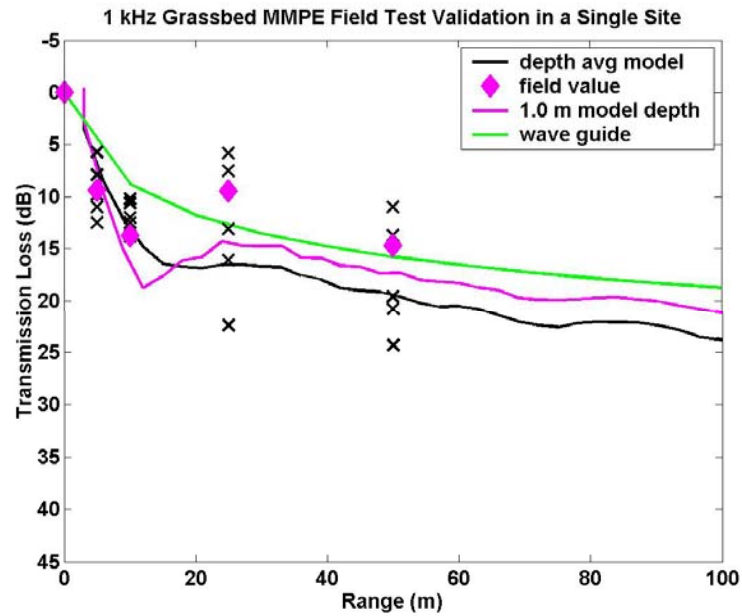


Figure 2.10. Model predictions and field measurements for transmission loss at four frequencies in a grassbed and dredged habitat. Each panel shows the average field value at a specified distance as a diamond and individual measurements as “x” symbols. The designated colored model output is the TL at the depth of the hydrophone making the field measurements. The solid black line MMPE model output is the depth averaged TL estimated in the water column.

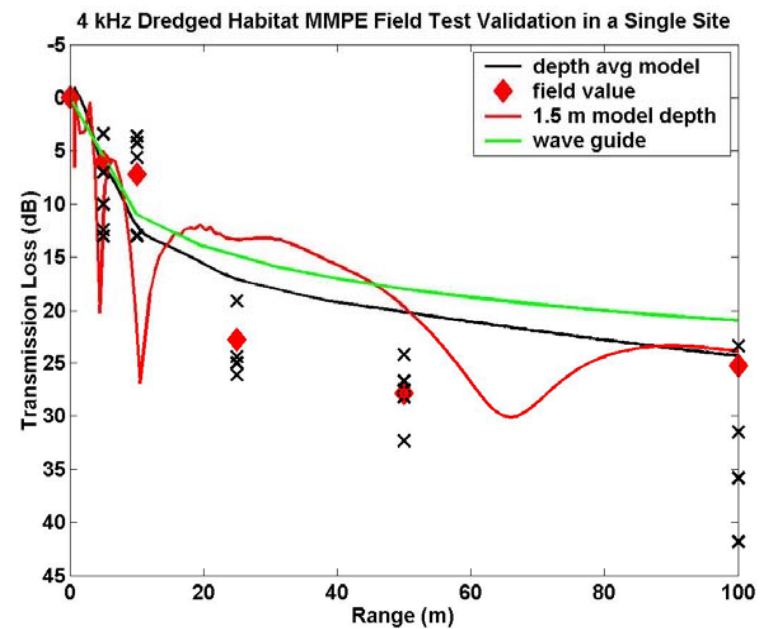
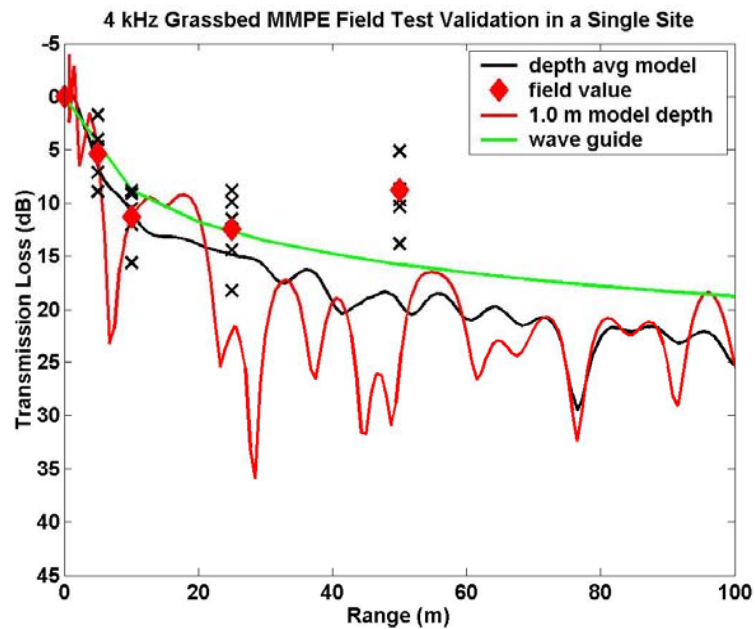


Figure 2.10 cont'd. Model predictions and field measurements for transmission loss at four frequencies in a grassbed and dredged habitat. Each panel shows the average field value at a specified distance as a diamond and individual measurements as “x” symbols. The designated colored model output is the TL at the depth of the hydrophone making the field measurements. The solid black line MMPE model output is the depth averaged TL estimated in the water column.

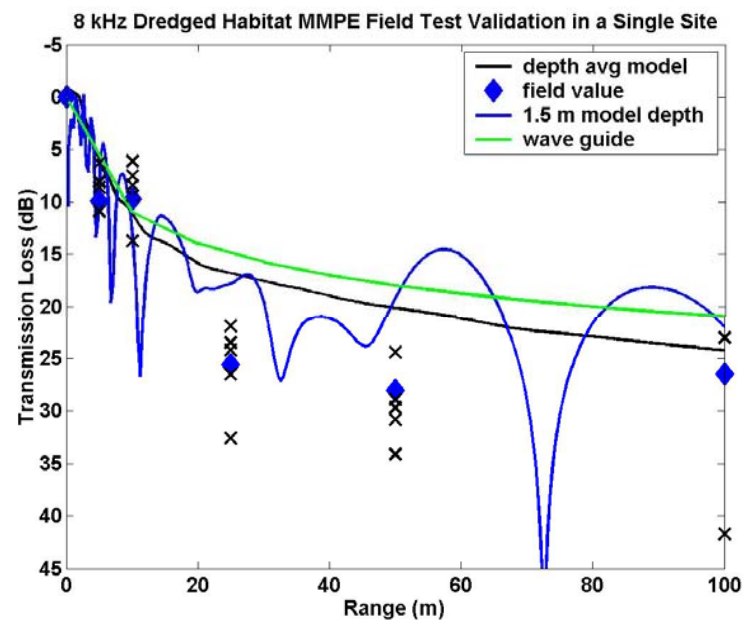
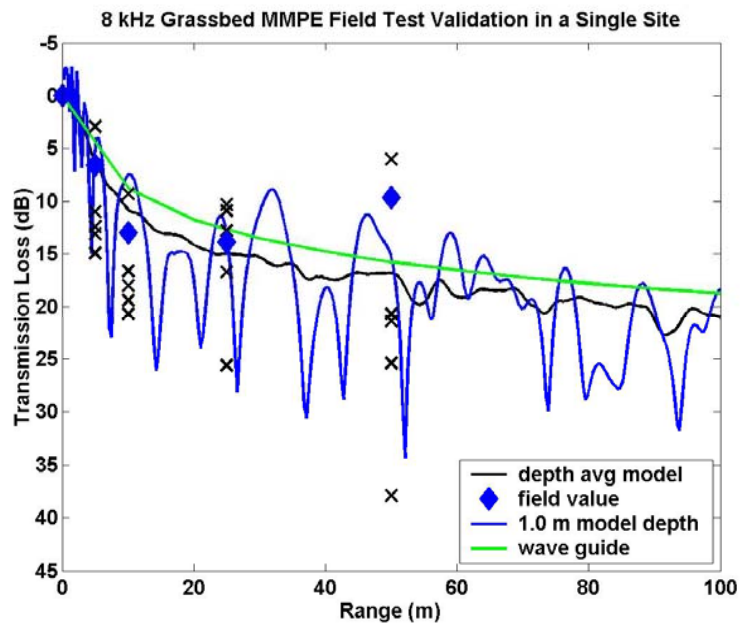
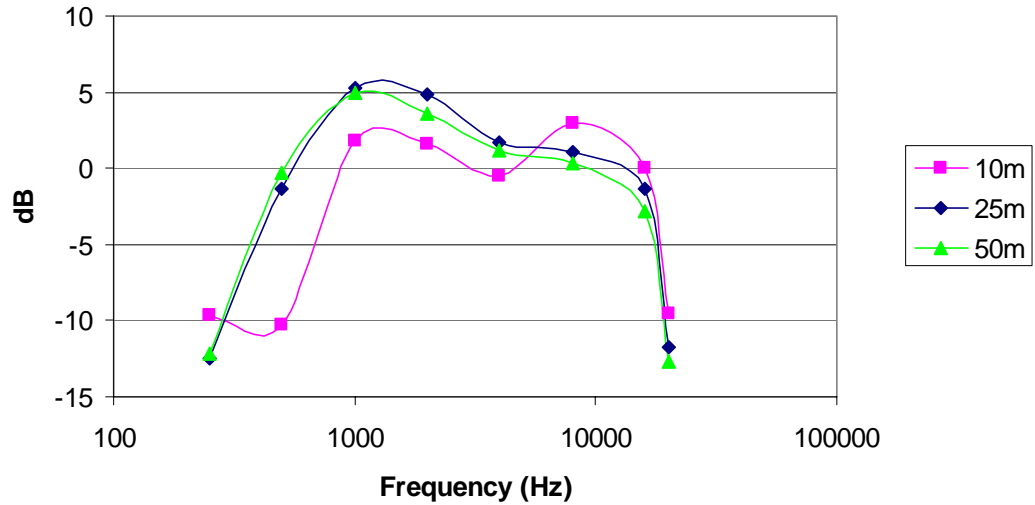


Figure 2.10 cont'd. Model predictions and field measurements for transmission loss at four frequencies in a grassbed and dredged habitat. Each panel shows the average field value at a specified distance as a diamond and individual measurements as “x” symbols. The designated colored model output is the TL at the depth of the hydrophone making the field measurements. The solid black line MMPE model output is the depth averaged TL estimated in the water column.

Grassbed Field Measurement Deviations from Model



Dredged Habitat Field Measurement Deviations from Model

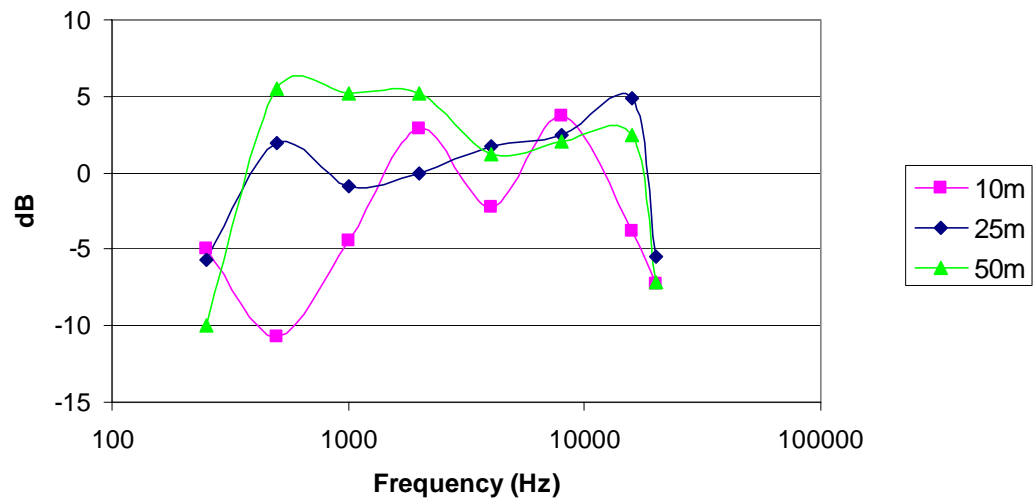


Figure 2.11. Deviations of field measurements from MMPE model predictions at the hydrophone depth for transmission loss in grassbeds (top) and dredged habitats (bottom). Deviations are shown for measurements at 3 specified ranges. Negative values indicate the model overestimated the TL, and positive values indicate the model underestimated the TL.

2.4.3 *Environmental Noise*

2003: Ambient noise was analyzed in 9 one-third octave bands spanning 250 Hz- 64 kHz during three time periods of the day. Analyses were performed to examine patterns both across and within the two habitat types. Overall noise patterns in the Sarasota Bay area differed between grassbed and dredged habitats (Table 2.4). A repeated measure 2-factor (habitat type x time of day) multivariate ANOVA showed that there was a significant habitat interaction for all frequencies except 16 kHz at the 95% significance level (16 kHz: $F = 4.13$, $p = 0.054$). Grassbeds were significantly louder than dredged habitats (average 14 dB louder across observed 1/3-octave bands). There was also a significant time of day interaction within habitat type, but not across habitat types. Post-hoc multiple comparisons showed that for all frequencies noise in the grassbeds was significantly louder in the noon and afternoon compared to morning time periods. In the dredged habitats noise in the morning was significantly less than noise in the afternoon for frequencies below 2 kHz. Above 2 kHz, noise in the morning tended to be the loudest.

Noise levels were also significantly different across the two habitat types, but only at particular time periods of the day (Figure 2.12 and Table 2.4). Post-hoc multiple comparisons of the repeated measure 2-factor, multivariate ANOVA showed a significant habitat x time of day interaction for frequencies 4 kHz and higher ($3.93 < F < 5.49$, $0.03 < p < 0.007$). The emerging pattern was that for frequencies 4 kHz and above, a significant difference existed between the average noise level in the grassbeds and dredged habitats in the afternoon, with the grassbeds having a greater average

noise level in the late afternoon. For frequencies below 4 kHz, there was no significant habitat x time of day interaction.

Table 2.4. Average one-third octave noise levels in grassbeds and dredged habitats as a function of time of day. Morning (7:00-10:30), Noon hours (10:30-14:00), Afternoon (14:00-17:30).

Time of Day	Habitat	Frequency 250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	16 kHz	32 kHz	64 kHz
Morning	GB	73	74	73	73	72	73	74	74	73
	DB	58	58	59	62	73	81	81	77	73
Noon	GB	83	83	83	82	82	82	83	83	83
	DB	63	63	63	63	70	77	76	72	69
Afternoon	GB	85	84	84	84	83	83	84	84	83
	DB	68	68	68	68	69	71	71	70	69

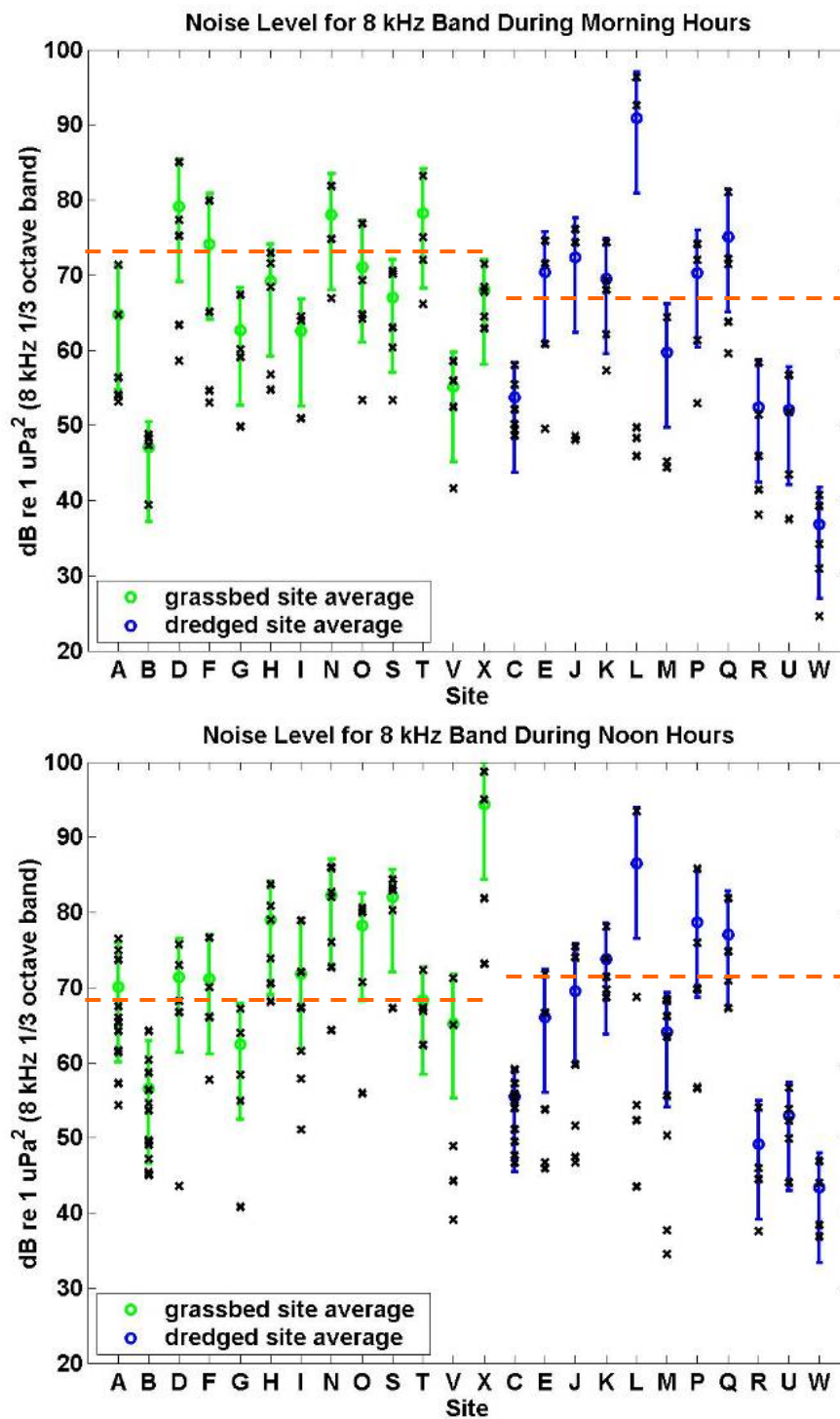


Figure 2.12. Noise levels in grassbeds and dredged habitats reported in one-third octave bands for 8 kHz center frequency. Top panel shows noise during the morning (7:00-10:30), bottom panel shows noise during the noon hours (10:30-14:00). Solid black lines indicate a significant difference in means between grassbed sites and dredged habitats. Dashed red lines represent means that did not significantly differ.

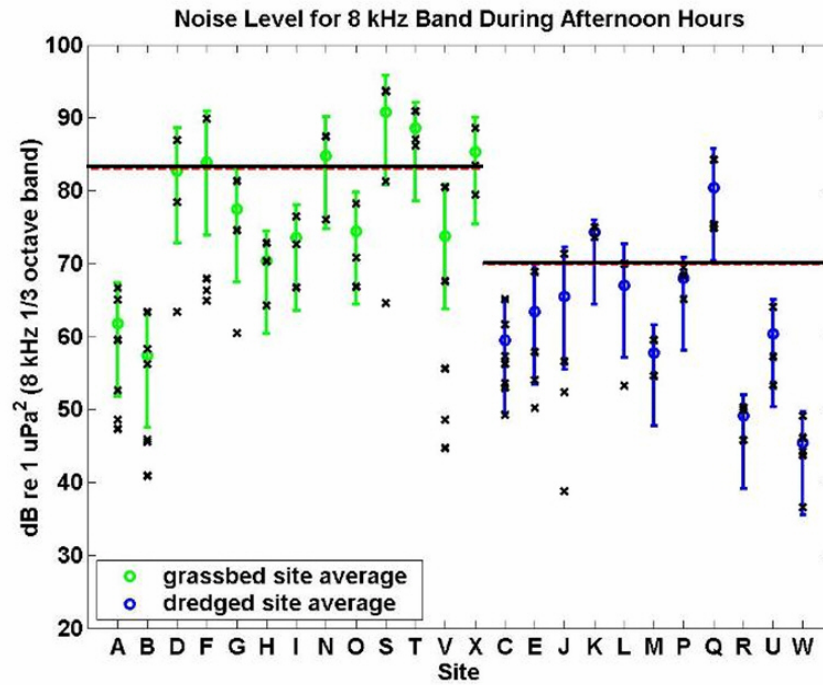


Figure 2.12 cont'd. Noise levels in grassbeds and dredged habitats reported in one-third octave bands for 8 kHz center frequency for noise in the late afternoon (14:00-17:30). Solid black lines indicate a significant difference in means between grassbed sites and dredged habitats.

Regression analyses were performed within each habitat type and at each frequency and distance. Results showed a significant correlation between usage by manatees and noise in grassbeds at all frequencies during the morning and afternoon time periods (Figure 2.13 and Table 2.5). Sites that were used more heavily by manatees tended to have lower levels of noise. For all significant regressions, R^2 values ranged from 0.41-0.49 in the morning and 0.56-0.71 in the afternoon. No significant relationship was observed for grassbeds during the noon hours or for the dredged habitats during any time period.

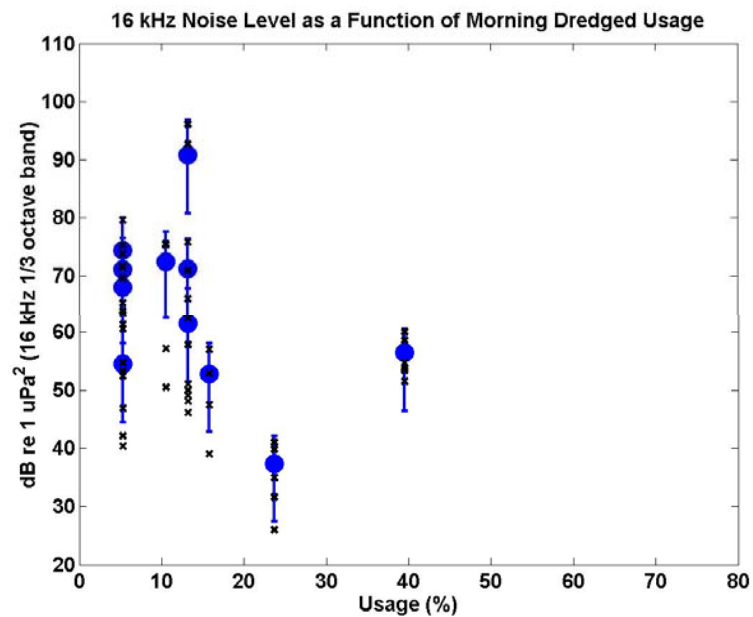
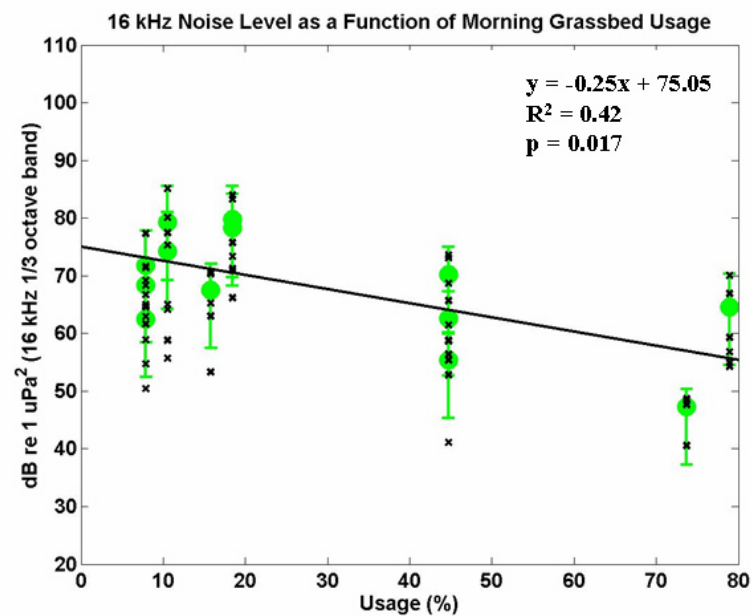


Figure 2.13. 16 kHz noise level during morning as a function of manatee site usage in grassbeds and dredged habitats. The solid black line indicates a significant relationship.

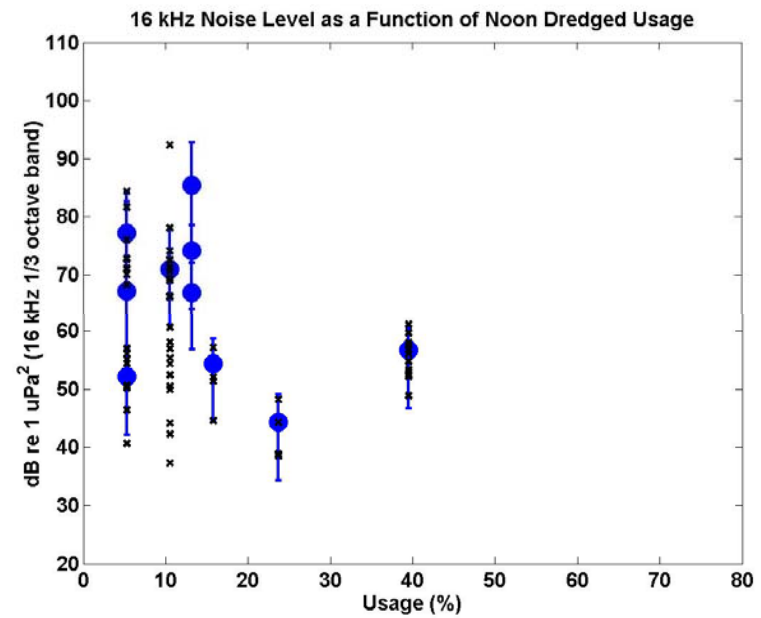
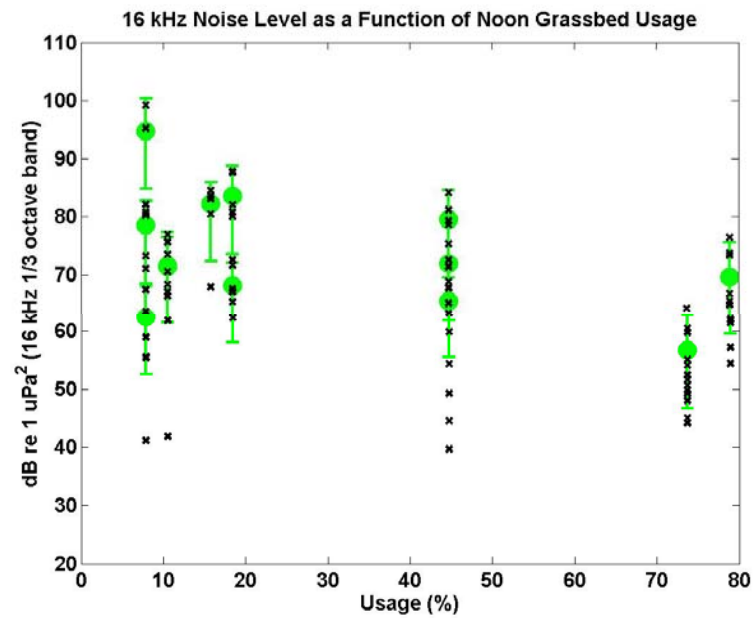


Figure 2.13 cont'd. 16 kHz noise level during noon hours as a function of manatee site usage in grassbeds and dredged habitats. No significant relationships were present.

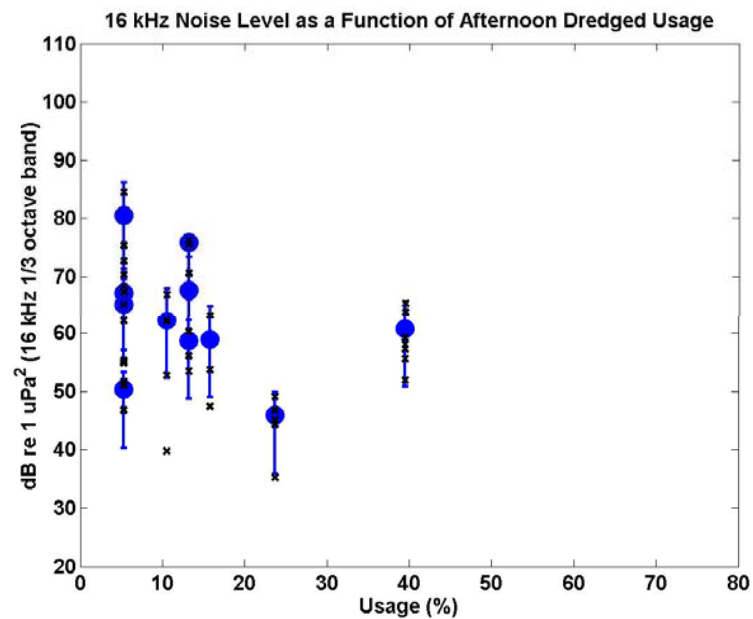
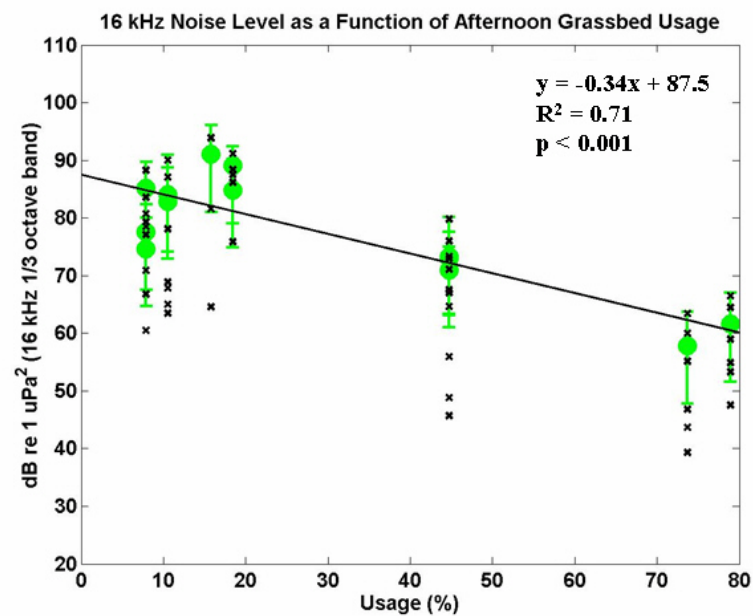


Figure 2.13 cont'd. 16 kHz noise level during afternoon hours as a function of manatee site usage in grassbeds and dredged habitats. The solid black line indicates a significant relationship.

Table 2.5. Regression analysis p-values for ambient noise levels and usage comparisons at specified frequencies during three times of day. Highlighted values show significant relationships.

Grassbeds

Frequency	Morning	Noon	Afternoon
250 Hz	0.008	0.1	< 0.001
500 Hz	0.019	0.14	0.001
1 kHz	0.007	0.12	0.003
2 kHz	0.006	0.1	< 0.001
4 kHz	0.008	0.1	< 0.001
8 kHz	0.017	0.11	< 0.001
16 kHz	0.017	0.11	< 0.001
32 kHz	0.017	0.09	< 0.001
64 kHz	0.008	0.09	< 0.001

Dredged Habitats

Frequency	Morning	Noon	Afternoon
250 Hz	0.31	0.31	0.78
500 Hz	0.41	0.41	0.26
1 kHz	0.24	0.31	0.54
2 kHz	0.23	0.23	0.65
4 kHz	0.15	0.18	0.54
8 kHz	0.15	0.18	0.3
16 kHz	0.19	0.16	0.33
32 kHz	0.19	0.14	0.37
64 kHz	0.25	0.17	0.47

2004: Ambient noise was analyzed at 8 frequencies spanning 300 Hz- 32 kHz during four time periods of the day. Analyses were performed to examine patterns both across and within the two habitat types. Results from this sampling regime showed overall noise patterns in the Sarasota Bay area differed slightly between grassbed habitats and dredged habitats (Table 2.6). A repeated measure 2-factor (habitat type x time of day) multivariate ANOVA showed no overall habitat interaction across time periods of the day, so on average, grassbeds and dredged habitats had similar noise levels. However, there was a significant habitat type x time of day interaction for the lowest two frequencies measured: 250 Hz and 500 Hz ($3.33 < F < 3.99$, $0.01 < 0.02$).

For these two cases, noise in the grassbeds was louder than in the dredged habitats during the morning time period.

Regression analyses were performed within each habitat type and at each frequency in order to determine if ambient noise level was significantly correlated with manatee usage. Results showed a significant correlation between usage and noise in grassbeds at frequencies below 1 kHz during the morning and afternoon time periods (Table 2.7). Correlations were also present in the grassbeds at noon for the lowest frequency and in the dredged basins at frequencies of 500 Hz and below in the morning and afternoon time periods. Sites that were used more heavily by manatees tended to have lower levels of noise. For all significant regressions, R squared values ranged from 0.60-0.70 in the morning and 0.60-0.63 in the afternoon. No significant relationship was observed in either habitat at night or in the dredged habitats during the noon hours.

Table 2.6. Average noise levels in grassbeds and dredged habitats as a function of time of day obtained from ARG measurements. All noise level values are presented in dB re 1µPa. Ranges are presented in parentheses.

Time of Day	Habitat	Frequency	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	16 kHz	32 kHz
Morning	GB		67 (53-79)	62 (52-72)	57 (52-66)	54 (46-71)	52 (37-72)	49 (34-69)	45 (33-64)	41 (31-58)
	DB		65 (57-76)	60 (53-71)	58 (51-69)	55 (41-73)	54 (40-71)	49 (37-64)	46 (33-58)	42 (31-52)
Noon	GB		69 (56-81)	63 (57-74)	57 (44-64)	55 (43-68)	53 (43-66)	48 (41-68)	45 (36-62)	41 (32-57)
	DB		67 (59-81)	62 (55-74)	58 (52-73)	55 (42-72)	54 (41-70)	49 (38-63)	47 (39-55)	43 (34-52)
Afternoon	GB		68 (54-82)	62 (51-76)	55 (44-63)	54 (46-66)	51 (45-66)	47 (38-64)	44 (36-53)	40 (33-56)
	DB		67 (57-81)	62 (54-73)	58 (51-68)	55 (44-68)	53 (40-65)	49 (38-65)	47 (35-66)	43 (33-65)
Night	GB		68 (56-81)	63 (54-72)	55 (46-62)	51 (42-65)	48 (37-67)	45 (32-65)	44 (32-63)	41 (31-51)
	DB		68 (58-79)	62 (55-70)	60 (54-63)	57 (45-65)	54 (40-65)	50 (37-60)	47 (35-56)	43 (33-50)

Table 2.7. Regression analysis p-values for ambient noise levels and usage comparisons at specified frequencies during four times of day. Highlighted values show significant relationships.

Grassbeds

Frequency	Morning	Noon	Afternoon	Night
250 Hz	< 0.001	0.08	0.03	0.27
500 Hz	0.01	0.13	0.05	0.94
1 kHz	0.05	0.12	0.19	0.88
2 kHz	0.41	0.5	0.43	0.53
4 kHz	0.51	0.39	0.44	0.47
8 kHz	0.4	0.54	0.58	0.44
16 kHz	0.23	0.51	0.46	0.3
32 kHz	0.24	0.52	0.62	0.43

Dredged Habitats

Frequency	Morning	Noon	Afternoon	Night
250 Hz	0.01	0.06	0.02	0.07
500 Hz	0.03	0.12	0.04	0.14
1 kHz	0.37	0.56	0.21	0.16
2 kHz	0.64	0.25	0.16	0.2
4 kHz	0.52	0.22	0.11	0.24
8 kHz	0.59	0.14	0.16	0.27
16 kHz	0.26	0.19	0.14	0.18
32 kHz	0.46	0.28	0.3	0.3

The above results indicate that noise effects are pronounced in grassbeds.

Manatee usage is significantly correlated with noise level in the grassbeds for the morning and afternoon time periods. The results of both sampling methods overlap for the lowest two frequency categories (Tables 2.5 and 2.7). Areas that manatees use most tended to be quieter. Two additional questions are raised from this information. One, are the most heavily used areas quietest because they are the most dense, nutritionally productive seagrass beds in the area? Two, are boats the major

contributor dominating the significant results observed in the noise and usage patterns?

2003 vs. 2004: An argument can be made that the observed differences in noise levels and corresponding usage correlations between the two years were due to changes in noise characteristics instead of the different sampling techniques. Noise recordings obtained during all animal observations in 2004 were made with the same recording system (Recording System A) used in 2003. Noise recordings utilizing Recording System A in 2004 were limited to sites in which animals were commonly encountered (Sites A, B, and C). The ANOVA results showed that noise levels in these sites did not differ significantly between 2003 and 2004 (Table 2.8). Based on these results, it can be assumed that the overall noise levels in the bay did not change significantly from 2003 to 2004.

Table 2.8. Average 1/3 octave band noise levels comparisons for 2003 and 2004.

		250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	16 kHz	32 kHz	64 kHz
Site A	2003	66	70	68	65	64	66	65	64	64
	2004	63	63	62	61	61	62	62	62	62
Site B	2003	58	58	60	55	53	54	54	54	54
	2004	54	55	53	53	52	53	53	53	53
Site C	2003	52	54	51	51	52	56	58	58	57
	2004	53	53	52	53	53	55	58	57	56

2.4.4 Seagrass Habitat Quality

Total seagrass coverage and individual seagrass species coverage varied widely among the 13 seagrass habitats sampled (Table 2.8). One hundred percent coverage was seen in four sites ranging in usage from 7.9-44.7%. The two most heavily used grassbed sites (A and B) had a total coverage of 91.3% and 75% respectively. Linear regression analysis showed no significant correlation between usage and either total grass coverage, individual species coverage, or aerial pattern.

Table 2.9. Grassbed quality estimates in relation to % usage. Total coverage of *Thalassia testudinum*, *Syringodium filiforme*, *Halodule wrightii*, and macroalgae values are in % of total quadrant covered by species. Aerial pattern values are based on a 1-5 point scale. The categories were: 1) sparse, 2) sparsely patchy, 3) densely patchy, 4) continuous (moderate cover), and 5) dense.

Site	% Usage	Total Coverage	Thalassia	Halodule	Syringodium	Macroalgae	Aerial Pattern
A	78.9	91.3	75.3	29.3	8	45.3	5
B	73.7	75	46.6	92.2	0	4.7	4.5
D	10.5	100	52.3	34	0	29.3	4.5
F	10.5	100	96.7	38	33.3	2	3.5
G	7.9	100	98.7	16.7	0	76	5
H	44.7	100	83.3	16.7	33.3	9.3	4
I	44.7	84	50	17.3	0	41.3	3
N	18.4	69.3	47.3	46	16.7	12.7	1
O	5.3	98	53.3	28.7	32.7	27.3	3.5
S	15.8	98	96	28	2.7	0.7	4
T	18.4	83.3	78	33.3	0	47.3	4
V	44.7	96	86	34	0	50.7	5
X	7.9	85.7	68.6	30.3	0	24.6	3

2.4.5 Boats

The question of whether boats play a dominant role in the observed noise patterns can begin to be answered by the analyzing the number of boats present in the vicinity of each site during the 2003 acoustic recordings. The number of boats passing within a 1 km radius of the research vessel was documented during each acoustic recording in 2003. A 1 km radius was chosen because manatees have been shown to respond to approaching boats up to 1 km away (Nowacek et al., 2002). A set of single classification ANOVAs showed there was no significant difference in the average number of boats per site as a function of time of day in grassbeds or dredged habitat. However, there was a significant correlation between manatee grassbed usage and the average number of boats passing/ 5-minute time period during the morning hours ($R^2 = 0.409$, $p = 0.018$) (Figure 2.14). There was no significant correlation between number of boats and manatee site usage in grassbeds during the noon or afternoon hours or in dredged habitats at any time of day.

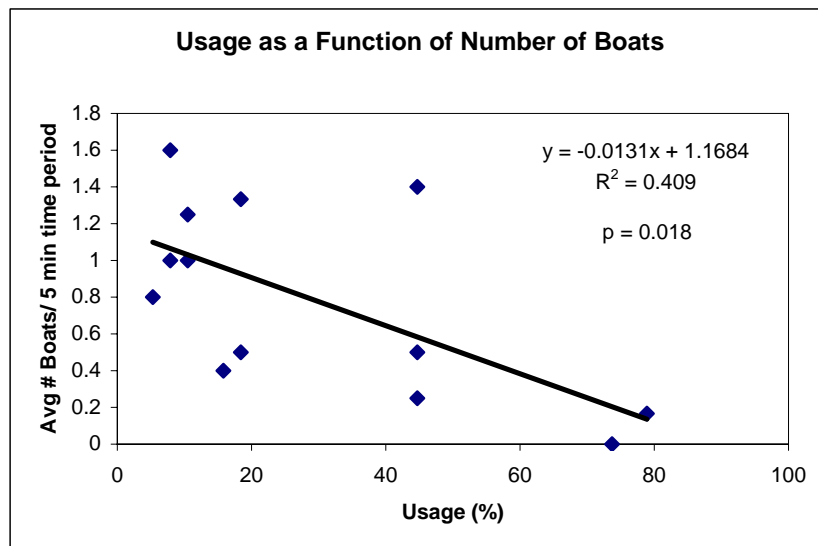


Figure 2.14. Manatee site usage as a function of boat presence in grassbeds.

2.4.6 *Distance Usage Index in Dredged Habitats*

Usage of grassbeds by manatees was shown to be associated with transmission loss, ambient noise levels, grassbed quality, and boat presence in varying degrees throughout the day. However, similar relationships were not statistically significant for usage of dredged habitats. In an effort to explain manatee use of dredged habitats a Distance Usage Index (DUI) was created that relates dredged habitat usage to the distance and usage of the nearest grassbed. The DUI is a unitless index composed of two terms that add together to produce a positive index number (Equation 2.1). The first term is a function of the nearby grassbed usage, distance, and dredged habitat depth. Depth was chosen as a dominant factor because deeper channels and basins were assessable to the manatees during high and low tides, whereas shallow canals had restricted access at low tides. Because deeper channels and basins are available to the manatees at all times, it was more likely animals would be found in these sites; therefore a deeper site would result in a larger term and larger DUI value. The second term is a function of the number of other dredged habitats in a 3 km radius (n) and the potential number of manatees in the immediate area (19). The 3 km radius was selected because it was half the width of the widest distance across the bay and was the upper limit of manatee daily travel based on observation. The potential number of animals in the immediate area (19) was derived from the average number of manatees observed per month during a Sarasota County aerial survey from April- September. The average number of manatees observed was 38 animals with a range of 11-64 animals. A conservative estimate of the possible number of manatees within a 3 km radius of a specific grassbed was $38/2 = 19$. Substituting a value for the possible

number of manatees ranging from 5-100 animals did not impact the significance of the DUI regression analyses, which adds to the robustness of the DUI term.

Equation 2.1

$$\text{DUI} = (\text{GB Usage}/d)(\text{depth}) + (19/n)$$

where GB Usage = usage of nearest grassbed in %

d = distance from edge of nearest grassbed to edge of dredged habitat (m)

depth = average depth of dredged habitat (m)

n = number of dredged habitats within 3 km radius

Regression analysis showed a positive correlation between manatee dredged habitat usage and DUI ($R^2 = 0.79$, $p = 0.00024$ (Figure 2.15). This suggests that dredged habitat usage will be highest when the dredged habitat is in close proximity to a high-use grassbed, when it is the only or one of a few dredged habitats in the vicinity of a specific grassbed, and when the dredged habitat is deep.

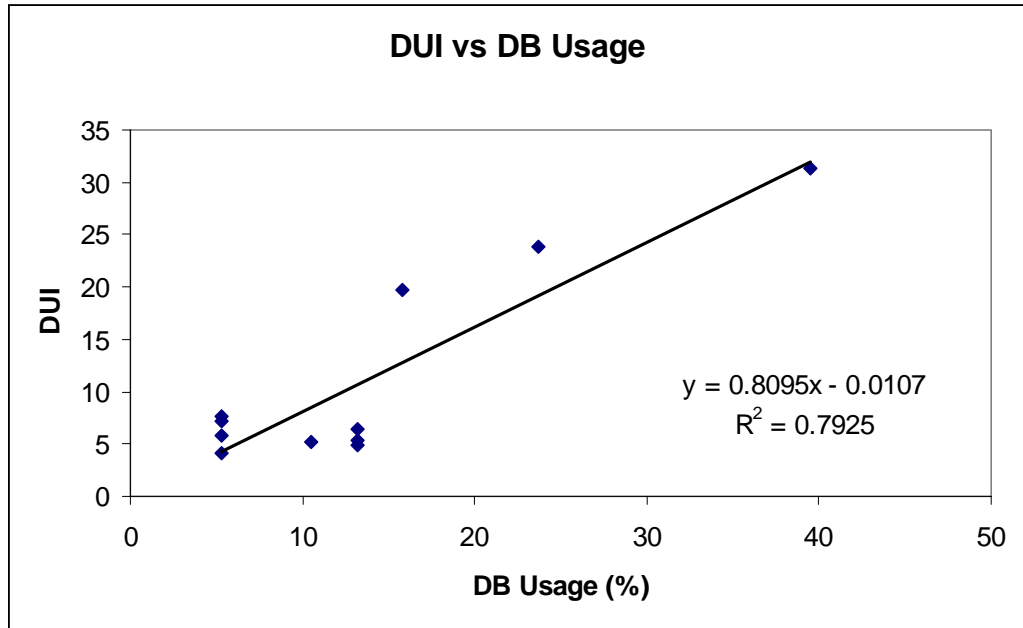


Figure 2.15. DUI as a function of manatee dredged habitat usage.

2.5 Discussion

Manatees live in an acoustic environment that is highly variable in both space and time. Although transmission loss in a specific site shows only small fluctuations due to changes in temperature, water depth, and salinity over periods of days, noise level intensity can change by orders of magnitude in a span of seconds. How changes in ambient noise levels and noise from transient noise sources, such as passing boats, affect manatees is presumably largely due to the level of noise received by the animal. Both model results and transmission loss field experiments showed that TL was greater in grassbeds than in adjacent dredged basins. In addition, the most TL occurred for frequencies below 2 kHz, whereas the least TL was seen for frequencies from 2-20 kHz. From a manatee's point of view this would mean that the sounds traveling through the environment least efficiently in both habitats are the lower frequency sounds, which overlap with dominant boat noise frequencies (Gerstein, 2002; Richardson et al., 1995). Conversely, those frequencies that travel through the environment best are those that overlap with the dominant frequencies of manatee vocalizations (Nowacek et al., 2003). A relatively quiet frequency band has been documented between 1-4 kHz in many terrestrial and ocean environments, and this may be one reason why bird and mammal vocalizations fall in these frequencies (Bradbury and Vehrencamp, 1998). It appears that the manatee communication system has adapted to capitalize on the acoustics of the shallow water habitats they inhabit over evolutionary time. The presence of lower frequency boat noise in manatee habitats is a relatively new pressure on an evolutionary time scale, and its effects are yet to be fully understood.

Knowing that transmission loss is greater in grassbeds than in dredged habitats would theoretically mean that if the same amount of sound were entering a grassbed and a dredged habitat, the sound would be attenuated more quickly in the grassbed, and the grassbed would be quieter. As a whole, this was untrue for grassbeds and dredged habitats in the Sarasota Bay area according to the noise recordings in 2003 and 2004; grassbeds tended to be louder than dredged habitats due to the loud broadband noise produced by snapping shrimp (*Alpheus* and *Synalpheus sp*), which becomes stronger with decreasing depth (Camp et al., 1998; Richardson et al., 1995). The noise level patterns, however, differed greatly between the two years due to the different sampling methods. In 2003, recordings were made with a single hydrophone and processed at a later date. Processing of the 2003 data included all sounds present in the environment without any special weighting or selection. Noise produced by snapping shrimp dominated the shallow habitat noise recordings in 2003; furthermore, the 2003 noise level analysis did not distinguish between the confounding factors of broadband shrimp noise and lower frequency anthropogenic noise. Noise recordings in 2004 were also made from a single hydrophone, but initial processing of the noise spectrum was done in real time. With this processing protocol, transients such as broadband signals produced by snapping shrimp were selected against, so the resulting noise recordings more accurately reflected patterns associated with low frequency anthropogenic noise as opposed to the loud biological signal of snapping shrimp.

By combining transmission loss characteristics and daily noise patterns (both biologic and anthropogenic) with manatee distribution, an interesting two-part picture starts to emerge. Manatee usage of grassbed habitats was highly correlated with

broadband noise, low frequency noise, and high frequency transmission loss. High-use areas were areas of high transmission loss (frequencies > 2 kHz) and low broadband and low frequency noise (frequencies < 1 kHz). This creates a high-use environment where noise above 2 kHz from sources outside the grassbed is attenuated quickly compared to low-use sites. This also happens to be the range of most efficient sound propagation inside the grassbed habitat, and the dominant frequencies of manatee vocalizations (Nowacek et al., 2003). For frequencies below 2 kHz, transmission loss is not correlated with usage, but low frequency noise is, especially during the morning hours. Ultimately, the grassbeds that manatees selected were those that were most quiet due to lower noise below 1 kHz and higher transmission loss above 2 kHz. The selection of dredged habitats was then directed by proximity to high-use grassbeds.

This study benefited from the implementation of two different noise sampling techniques that allowed for the separation of confounding factors associated with the recordings in 2003. Filtering the transient signals out of the acoustic record in the 2004 data set essentially removed the masking effect of the broadband shrimp sound, which allowed for the identification of patterns associated with lower energy, more narrowband anthropogenic noise. Based on the analysis of habitat use and noise recordings in 2003, manatees select grassbed sites that have lower noise levels across a wide range of frequencies. The relationship between usage and noise, however, was only present during the morning and late afternoon time periods. Although snapping shrimp noise is constantly present, these time periods are associated with both sunrise and sunset, which happens to be linked with the small diurnal variation snapping

shrimp exhibit at night (Albers, 1965; Au and Banks, 1998). The 2003 regression results suggest that manatees select the quietest grassbed sites during the peak times of snapping shrimp activity, which implies that manatees select grassbeds with less snapping shrimp noise. The 2004 recordings reduced the presence of the snapping shrimp noise, although they did exhibit a slight diurnal variation associated with this biologic noise source. The analysis of the 2004 data indicated that manatees are selecting grassbed sites that have less low frequency noise, which is most likely attributed to anthropogenic activity. The question of whether shrimp noise or anthropogenic noise is the major force behind the observed manatee distribution patterns can not be answered conclusively with the current data, but it is clear that noise affects manatee habitat selection.

The next logical question is what factor is more dominant in driving the manatee grassbed usage, noise or habitat quality? Dense grassbeds attenuate noise more than sparse grassbeds to create a quiet area near a high traffic zone, yet a sparse grassbed may be located near a less busy boating area but propagate more noise. Dense grassbeds may also complicate the noise and sound propagation by the diversity of fauna living within the habitat (i.e., snapping shrimp, toadfish). Analysis of the seagrass coverage and species composition indicated no correlation between quality, as defined here, and grassbed usage. This suggests that noise and propagation characteristics associated with transmission loss play a more dominant role in habitat selection. This finding contributes to the interpretation of manatee habitat selection and presents a need for clear-cut hypotheses to be experimentally tested in the field. For example, will increasing noise in a high-use grassbed alter use over the course of a

week, month or year? Will decreasing noise in a low-use area increase grassbed use? These questions need to be answered by the conservation managers, for they will be instrumental in directing future management plans.

High-use areas have less low frequency noise at a time when overall noise levels are significantly increasing throughout the bay during the daily night-to-morning transition. It is during this transition period that boat use also increases. There is a concentrated increase of boat use at daybreak associated, for example, with fisherman going out to fish. No concentrated return was observed in the afternoon, as return times appeared widespread possibly due to weather, fishing success, etc. Grassbed usage was negatively correlated with the concentrated boat presence in the morning hours. This suggests that morning boat presence and its associated noise may play a dominant role in grassbed usage on a daily time scale. As Sarasota Bay manatees predominantly use grassbeds to feed (Koelsch, 1997), it can further be extrapolated that the presence of boats in the morning and their associated noise may affect manatee foraging behavior. This result is not unique to manatees, as this pattern has also been observed in another endangered species, the wintering bald eagle (*Haliaeetus leucocephalus*).

Eagle numbers on the Skagit River Bald Eagle Natural Area (SRBENA) in northwestern Washington were negatively correlated with daily boat traffic, and feeding declined exponentially with increased boating activity (Stalmaster and Kaider, 1998). However, early morning boat traffic was most disruptive to eagle feeding behavior. Eagles took longer to return to foraging sites during morning disturbances

than later in the day. One of the recommended management actions resulting from Stalmaster and Kaider (1998) was to prohibit recreational activity in the SRBENA during the first 5 hours of daylight within 400 m of eagles to minimize disturbance of feeding behavior. A management plan focused on areas with high levels of morning boat usage may also be appropriate for manatees.

2.6 Acknowledgements

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Chapter 3. Manatee Behavior in Relation to Environmental Noise

3.1 Abstract

Florida manatees inhabit coastal bays, lagoons, and estuaries because they depend on the aquatic vegetation that grows in shallow waters. These food requirements force manatees to occupy the same areas in which human activities are the greatest. Noise produced from human activities has the potential to affect these animals by eliciting responses ranging from mild behavioral changes to extreme aversion. This study quantified the behavioral responses of manatees to both changing levels of ambient noise and transient noise sources. Results indicated that elevated environmental noise levels do affect the overall activity budget of this species. The proportion of time manatees spend feeding, milling, and traveling in critical habitats changed as a function of noise level. When noise levels were highest, more time was spent in the directed, goal-oriented behaviors of feeding and traveling whereas less time was spent milling. The animals also responded to the transient noise of approaching vessels with changes in behavioral state and movements out of the geographical area. This suggests that manatees detect and respond to changes in environmental noise levels. Whether these changes legally constitute harassment and produce biologically significant effects needs to be addressed by legal and regulatory agencies and will require additional hypothesis-driven experiments and long-term monitoring.

3.2 Introduction

Manatees are sensitive to their environment and their general distribution and habitat selection are dominated by a select set of environmental parameters (Wells et al., 1999). During the winter months, cold water temperatures cause manatees to seek refuge in warmer waters, concentrating manatees into large aggregations within relatively small geographic areas (Craig and Reynolds, 2004). A large portion of the current information about manatees has come from studies conducted at winter aggregation sites (Beck and Reid, 1995; Hartman, 1979; Powell and Rathbun, 1984; Rathbun et al., 1990; Reid et al., 1991). Studying manatee behavior at warm-water aggregation sites is attractive because of the large number of animals present and the potential in some locations of clear water quality compared to the more turbid water manatees frequent outside aggregation sites.

During the non-winter months, manatees disperse widely and are typically seen in small groups. The basic social unit of the Florida manatee is the female and her calf (Reynolds and Odell, 1991). The key features driving habitat selection during warm months appear to be food availability, access to fresh water, and the absence of human waterborne activities (Reynolds, 1999). Absence of human waterborne activities is especially important because females appear to seek calm, quiet waters to give birth (Reynolds and Odell, 1991). Detailed documentation on how the presence and type of human activities affect manatees is minimal but growing at a fast pace. The identification of critical manatee habitats and their associated environmental parameters in the non-winter months is required to direct conservation and management plans. Protection of manatees during warm months has become an

increasing priority, as watercraft-related mortalities are highest during the non-winter months (Ackerman et al., 1995; Florida Fish and Wildlife Conservation Commission, 2000). In addition to watercraft-related mortalities, other human-related manatee mortality involves crushing in flood gates/canal locks, entanglement, ingestion of marine debris, and hunting (Reynolds and Odell, 1991). Koelsch (1997, 2001) conducted one of the few long-term, non-winter studies (in Sarasota Bay), which sets the stage for this study.

Understanding manatee behavior and habitat use patterns will provide insight to the circumstances that put manatees at risk of harmful human activities. Manatees spend six to eight hours a day feeding, and feeding bouts are separated by periods of rest (Reynolds and Odell, 1991). When manatees are not feeding or resting they travel or engage in social activities. Social activities can include mild socialization with other manatees such as mouthing or rubbing. More energetic socialization termed “cavorting” involves rough and tumble behavior often associated with mating herds (Hartman, 1979; Koelsch, 1997). Unlike the usual definition of “play” for most animals, which emphasizes special kinds of social interaction, manatee researchers sometimes use “play” to refer to an interaction between one, or a number of animals, with an inanimate object (Koelsch, 1997; Reynolds and Odell, 1991). Movement activities can be either directed or undirected. Directed movement is associated with traveling, whereas undirected movement is associated with milling (Bengtson, 1981).

The position of animals moving together through the environment has been observed to occur in at least two defined patterns. Adults often swim one behind the other in a follow-the-leader fashion, whereas calves swim parallel to their mother

(Reynolds, 1981a). The parallel swim formation between mother and calf may serve two functions (Reynolds 1981a): a calf may experience the least amount of hydrodynamic drag; and this formation may allow for more effective communication between the mother and calf.

Manatees generally intermittently feed and rest during the day and night, (Reynolds and Odell, 1991). In some areas, such as Matlacha Pass and Blue Lagoon, the frequency of behaviors during the night and day has been observed to differ. In Blue Lagoon, there was an observed absence of body-surfing (riding a current at the surface), cruising, and follow-the-leader activities during the mid day hours (Reynolds, 1981a), possibly an avoidance technique for a high volume of boat traffic. Similarly in Matlacha Pass, feeding was more prevalent during the early morning and late afternoon/early evening. This pattern correlates with time of lower boat traffic and general human activity in the area, but there is no evidence to suggest a cause and effect relationship (Barton and Reynolds, 2002).

In addition to daily behavior patterns, a number of specific behaviors have been linked with specific habitats, whereas other behaviors are seen over many different habitats. Feeding typically occurs in the shallow grassflats of the Florida coast. Manatees are opportunistic feeders that primarily feed on seagrasses, but feeding on mangrove leaves, red mangrove seedlings, overhanging branches, and acorns also occurs (Reynolds and Odell, 1991). In Sarasota Bay grassbeds, manatees typically fed, occasionally milled and traveled, but were never observed playing (Koelsch, 1997). Play in Sarasota Bay has only been observed in the deep water habitats of dredged basins and channels, while open bays, passes, and inlets were

primarily used for traveling. Resting, milling, traveling, and socializing occurred in most habitats including shoals/sand bars, grassbeds, dredged basins, and dredged channels (Koelsch, 1997).

The extent to which environmental factors directly influence manatee behavior has been largely unexplored. A handful of studies examining manatee responses to human activities such as boating and recreational diving have been conducted (Buckingham et al., 1999; Nowacek et al., 2000; Nowacek et al., 2001; Nowacek et al., 2004; O'Shea, 1995; Provancha and Provancha, 1988). The studies addressing how noise may impact wild manatee behavior have been limited to identifiable sound sources associated with the sound incidentally produced by watercraft (Gerstein, 2002; Nowacek et al., 2000; Nowacek et al., 2001; Nowacek et al., 2002; Nowacek et al., 2004; Weigle et al., 1994). Under some circumstances, manatees detect boat presence from up to 1 km away, and they make gross behavioral changes in swim speed and direction at approximately 25-50 m from approaching watercraft (Nowacek et al., 2000; Nowacek et al., 2001; Nowacek et al., 2002; Nowacek et al., 2004). Only one study has explored the impact of naturally occurring ambient noise levels on animal behavior, and this was a masking study done in captivity (Gerstein, 2002). There have been no studies investigating the effect of background ambient noise on wild manatee behavior.

This study examined manatee behavior patterns in association with environmental noise. Noise included measurements of both background and transient anthropogenic noise sources. Manatee responses to environmental noise were examined on two different levels: 1) behavioral state, and 2) energetic expenditure as

determined by changes in respiration. The goals of the study were to determine 1) whether differences in manatee behavioral states within habitat types are associated with noise level and 2) whether energetic expenditure is correlated with and possibly affected by noise level. Understanding the relationship between antropogenic noise levels and behavior is crucial to more clearly understanding the impact of human activities on manatees and manatee habitat selection.

3.3 Methods

A variety of methods were employed in this study. Behavioral observations of manatees occurred in a combination of three contexts: sightings, focal follows, and tagging. Each of these techniques is described below. Vocalizations and ambient noise were recorded continuously throughout all sightings and focal follows from a towed hydrophone system composed of a HTI-99-HF hydrophone with built-in pre-amplifier and internal sound card of a Dell Inspiron 8100 (Recording System B: 20 Hz – 22 kHz with a -178 dB re 1 V/ μ Pa sensitivity at 16 bit resolution). The peak acoustic level of the system was 178 dB re 1 μ Pa, which resulted in a minimum signal detection of 88 dB re 1 μ Pa. An environmental profiling package was also deployed during each sighting and/or follow. Parameters acquired with the profiling package were temperature, salinity, depth, turbidity, and photosynthetically available radiation (PAR). Broadband recordings of ambient noise were made at the beginning and end of each sighting and/or follow with Recording System A (Chapter 2.3.4) at a sampling rate of 200 kHz (2 Hz-100 kHz with a -178 dB re 1V/ μ Pa sensitivity at 16 bit resolution with peak acoustic level at 178 dB re 1 μ Pa). Data were collected on free-ranging animals under the permits issued by the U.S. Federal Fish and Wildlife

Service to the Florida Fish and Wildlife Research Institute (FWRI) (MA773494-7) and to Dr. David Mann of the University of South Florida (USF) (MA051709-0).

Sightings: The term “sighting” in this study is adapted from Wells (1986) and is defined as all individuals at a site, within an approximately 50-100 m radius, at the same time. The technique of collecting information from manatees in a single sighting has been previously used in the field and was implemented in this study to maintain consistency with a previous study (Koelsch, 2001). Daily surveys were conducted by a team of 2-3 observers. Surveys were conducted from either a 6 m center-console outboard motorboat or a 7 m center-console outboard motorboat equipped with a 2 m observation tower. An effort log was recorded to document survey effort. Time spent searching for animals was referred to as “on effort”, while time spent observing animals within a specific sighting was referred to as “on observation”. On effort survey times decreased on days when aerial surveys were conducted, as the aerial observers communicated animal locations to the on-water observation vessel. At the initial sighting of manatees, the group behavior was recorded, the outboard motor was turned off and raised, and a small electric trolling motor was lowered in order to approach the manatees without disturbing them. Manatees have shown to be indifferent towards human presence with the use of a trolling motor (Koelsch et al., 1995).

The following parameters were recorded during each sighting: time, GPS location, habitat type, number of animals, size class of animals, gender (if possible), initial behavior of animals, and animal entrances/exits from the observation group. Photographs of each individual were taken for later identification of unidentified

animals. The length of each sighting ranged from 30-180 min. The number of sightings/daily survey ranged from 0 – 4.

Focal Follows: Focal animal sampling provided the opportunity to obtain repeated behavioral observations of one individual. The average duration a focal manatee has been followed in the Sarasota Bay area was 95 minutes (Koelsch, 1997). The durations of focal follows in this study ranged from 30-135 minutes. Focal animals were selected from available adults and subadults within a single sighting. First priority was given to females with calves, as reproducing females are the most valuable size and gender class for population maintenance (Marmontel et al., 1997). After females with calves, focal animals were selected according to the following (listed in order of decreasing priority): adult females without calves, adult males, and subadults. Animal selection was facilitated by the long-term photo-identification catalogue maintained by Mote Marine Laboratory personnel.

Four sampling regimes (instantaneous, four minute interval, continuous, and intermittent) were implemented during a focal animal follow.

1) Instantaneous sampling was used to record the time of each surfacing associated with breathing. Ventilation statistics were calculated from this data set. This sampling regime was also used to record the time and distance of each opportunistic vessel approach.

2) Four minute interval sampling was used to obtain general behavioral data and habitat type. Time sampling was recorded at four minute intervals based on the average submergence time for adults and subadults over all observed behaviors (Reynolds, 1981a). Data collected at each interval were:

Time

during a temporary capture/release period and remained on the animals for periods of days to years. Satellite fixes and tracking signals from the radio tag allowed for repeated and extended focal follows of one individual. Because of the floatation in the transmitter housing, the tag essentially hovered above the animals and was not an accurate indicator of animal depth. All tag deployments were performed for funded state research projects separate from this study and authorized under the FWRI permit MA773494-7 issued by the U.S. Federal Fish and Wildlife Service.

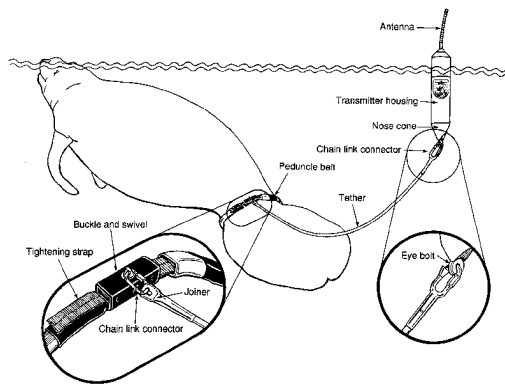


Figure 3.1. Schematic of radio tag assembly used on Florida manatees (adopted from Reid et al., 1995).

3.4 Results

Over the course of the study 653 hours were spent on effort surveying manatee habitats for animals. Time “on observation” totaled 152 hours over the two 6-month summer field seasons in 2003 and 2004. There were 128 sightings, 47 untagged focal follows, and 3 tagged follows completed during this time period.

3.4.1 Sightings

Behaviors noted at the time of initial sighting indicated that the dominant behavior in the grassbeds was feeding, whereas resting and milling/playing were the dominant behavior in the dredged habitats (Figure 3.2). The proportion of sightings in which the initial behavior was recorded as socializing, travel, or mill/play was not significantly different between the two habitat types. The average environmental noise levels recorded in association with the five behavior categories are reported in Table 3.1. An ANOVA was performed and results showed that there was a significant interaction between noise level and behavioral state ($df=122$, $p = 0.024$). Post-hoc multiple comparisons via the GT2-method (Hochberg, 1974) revealed the noise levels present

when animals were feeding was significantly louder than when the animals were resting for all frequencies analyzed. Noise levels during feeding were also louder than during social behaviors for 7/9 frequencies tested. The two frequencies that were not significant (2 kHz and 16 kHz) were only slightly below the 95% significance level (0.056 and 0.067, respectively).

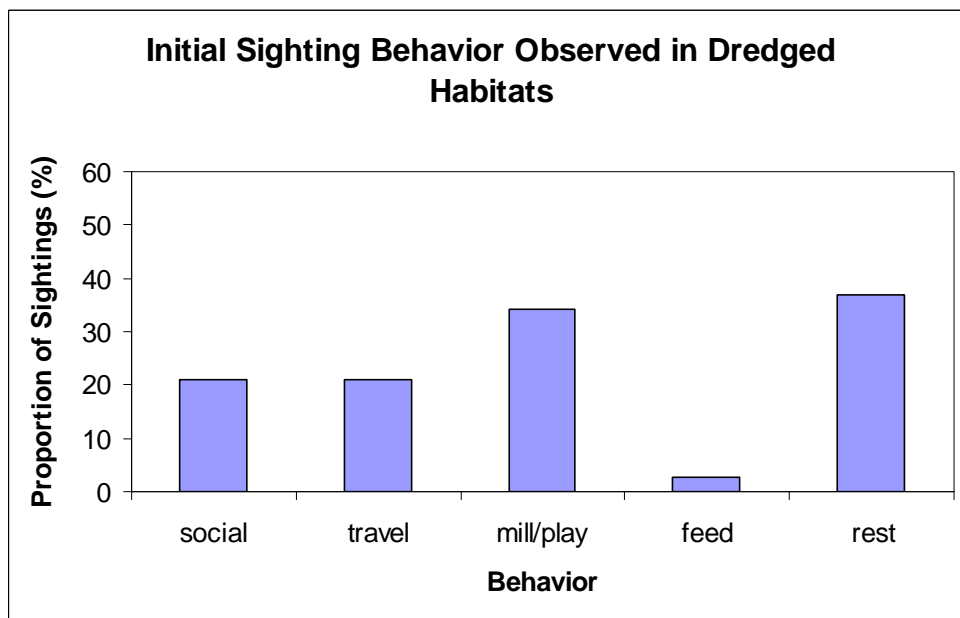
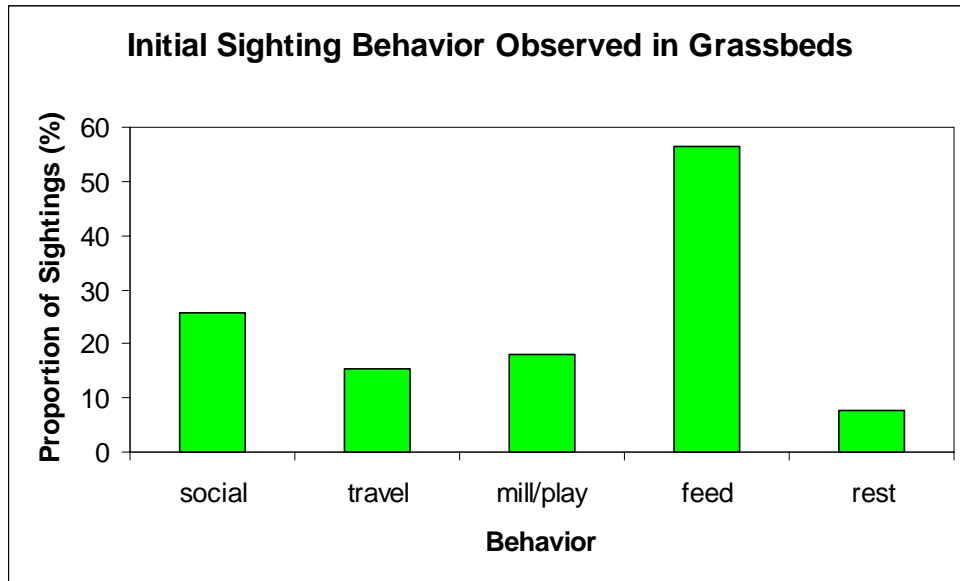


Figure 3.2. Distribution of behavior recorded during initial sightings in grassbeds (top) and dredged habitats (bottom).

Table 3.1. Average noise levels (dB) in 1/3 octave bands during designated behaviors.

	Feed (n=43)	Social (n=25)	Mill (n=15)	Travel (n=15)	Rest (n=25)
250 Hz	61.7	55.1	56.7	54.4	50.3
500 Hz	62.4	56.1	57.1	55.9	51.2
1 kHz	61.5	54.7	56.5	54.6	49.5
2 kHz	60.3	54.3	55.5	51.8	49.2
4 kHz	60.2	53.9	55.5	52.9	50.7
8 kHz	60.9	55.0	57.3	55.7	53.8
16 kHz	61.4	55.7	58.8	56.8	55.5
32 kHz	61.1	55.2	58.6	56.9	55.1
64 kHz	60.9	55.1	58.0	56.6	54.2

3.4.2 *Focal Follows*

Focal follows provided the opportunity to examine the proportion of time a manatee spent in a particular behavioral state over the course of the follow. In grassbeds, manatees spent approximately 40% of their time feeding, 10% resting, 10% socializing, 20% traveling, and 20% milling (Figure 3.3). In dredged habitats more time was spent resting and less feeding (0% feeding, 45% resting, 15% socializing, 15% traveling, 5% playing, and 20% milling). Before the proportion of time spent in a specific behavioral state could be related to the environmental noise level, it was necessary to determine whether or not the proportion of time spent in a behavioral state changed due to the presence of one or more calves in the sighting group. Results of ANOVA tests showed no significant interaction between calf presence and proportion of time spent in each behavioral state (Figure 3.3). Consequently, focal follows containing calves in the immediate group were pooled with those follows without calves in further analyses.

Environmental noise levels were related to the proportion of time spent within behavioral states separately for grassbeds and dredged habitats because the dominant

behaviors within each habitat types were not the same. Regression analyses showed that the proportion of time spent feeding in all grassbeds increased with increasing noise for the nine frequencies tested ($r^2 = 0.18-0.23$, $p = 0.006-0.023$), whereas the proportion of time spent milling decreased with increasing noise levels for the nine frequencies tested ($r^2 = 0.13-0.18$, $p = 0.02-0.04$) (Figure 3.4). There was no significant correlation between noise level and the proportion of time spent socializing, resting, or traveling in grassbeds at any frequency. A similar pattern was observed for dredged habitats. The proportion of time manatees spent traveling significantly increased with increasing noise for all frequencies ($r^2 = 0.21-0.25$, $p = 0.004-0.03$), whereas the proportion of time spent milling decreased with increasing noise levels for all frequencies ($r^2 = 0.15-0.33$, $p = 0.006-0.04$) (Figure 3.4). There was no significant correlation between noise level and the proportion of time spent socializing or resting in dredged habitats at any frequency.

The rate and variability of ventilation were also examined in addition to the proportion of time spent in each behavioral state. Average ventilation rate was calculated from instantaneous ventilation rates within each behavioral category (Table 3.2). An ANOVA test was performed separately within each habitat type to determine if there was an interaction between ventilation rate and behavioral state. The ANOVA results from both habitats showed no significant interaction between ventilation rate and behavioral state (grassbeds: $df = 92$; $p = 0.35$; dredged habitats: $df = 63$; $p = 0.26$). A multi-variate ANOVA also showed no significant interaction between ventilation rate and noise level in any behavioral state, at any frequency, within either habitat type.

Variability of ventilation was calculated from the time series of surface breaths recorded continuously throughout each focal follow. Within each behavioral state the absolute value of variation in time (s) between two successive breaths was summed over three consecutive breaths to produce a single variability value. Average ventilation rate was calculated by averaging the single variability values within each behavioral state for each follow (Table 3.3). Similar to ventilation rate, separate ANOVAs were performed within each habitat type to determine if there was an interaction between ventilation variability and behavioral state. Results from the grassbeds showed no significant interaction between ventilation variability and behavioral state ($df = 82$; $p = 0.25$), whereas results from the dredged habitats showed the variation in ventilation was greater during rest compared to all the other categories ($df = 52$; $p = 0.04$). Again, a multi-variate ANOVA also showed no significant interaction between ventilation variability and noise level in any behavioral state, at any frequency, within either habitat type.

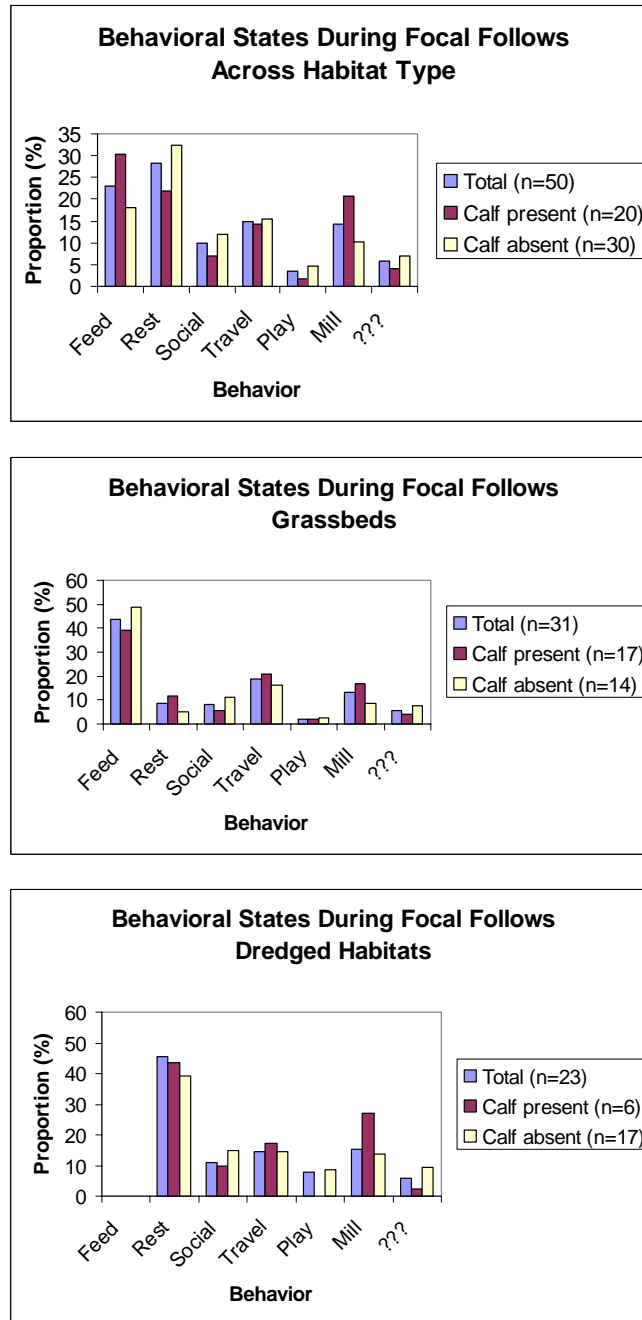
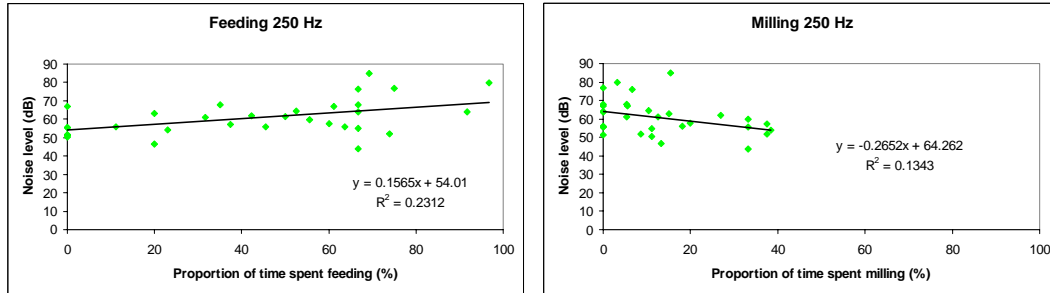


Figure 3.3. Distribution of behavior associated with calf presence in a group for all follows (top), follows in grassbeds only (middle), and follows in dredged habitats only (bottom). The “???” category in each panel represents the proportion of time the behavior was not identifiable or when the animal was obstructed from view.

Grassbeds



Dredged Habitats

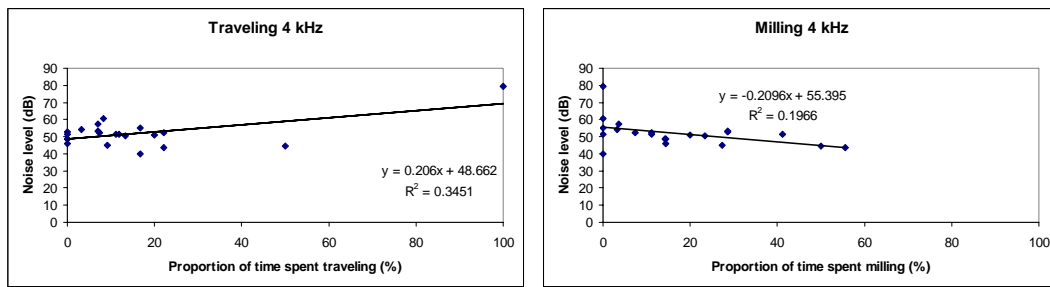


Figure 3.4. Regression plots for noise level and the proportion of time spent in a specified behavior. The top panel provides an example in grassbeds at 250 Hz. The bottom panel provides an example in the dredged habitats at 4 kHz. In both habitats the positive correlation is associated with directed behaviors on the left (feeding and traveling). The negative correlation on the right is associated with the undirected behavior of milling.

Table 3.2. Average ventilation rate associated with each behavioral category in the two habitats.

			Avg. Ventilation Rate (breaths/min)
Grassbeds	Behavior	n	
	Feed	26	1.20
	Rest	10	1.20
	Social	8	1.44
	Travel	24	1.13
	Play	2	0.98
	Mill	23	1.04
Average =			1.17
Dredged Habitats	Rest	18	1.50
	Social	11	0.99
	Travel	15	1.15
	Play	4	1.32
	Mill	16	1.43
Average =			1.28

Table 3.3. Average ventilation variability associated with each behavioral category in the two habitats.

			Avg. Ventilation Variability (s)
Grassbeds	Behavior	n	
	Feed	25	107.29
	Rest	8	135.92
	Social	7	116.71
	Travel	21	143.42
	Play	2	80.25
	Mill	20	136.19
Average =			119.96
Dredged Habitats	Rest	16	303.35
	Social	8	150.06
	Travel	10	248.56
	Play	4	147.91
	Mill	15	182.35
Average =			206.45

3.4.3 *Opportunistic Vessel Approaches*

Focal follows also provided the opportunity to document the focal manatee's response to opportunistic vessel approaches. Whenever possible, vessel speed, engine type, and closest point of approach of the watercraft were recorded. Within the sampling regime of the focal follow protocol, it was possible to determine the manatee's reaction to the vessel approach from behavioral changes, abandonment of the immediate area, and changes in swim speed and ventilation. All opportunistic approaches occurred in the grassbed habitats. There were 35 vessel approaches to within 100 m of the focal animal over the course of 16 focal follows (Figure 3.5). Over 70% of the approaches were within 50 m of the focal animal. Of the seven instances that vessels approached to within 25 m of the focal animals, behavioral changes were seen in 6/7 approaches, animals left the area in 2/7 approaches, and 1/7 showed an increase in swim speed (Figure 3.6). There were 19 approaches within 50 m of the focal animal, and the predominant response was a change in behavior. In all instances where there was an observed change in behavior, the change was always to either a traveling or milling behavioral state.

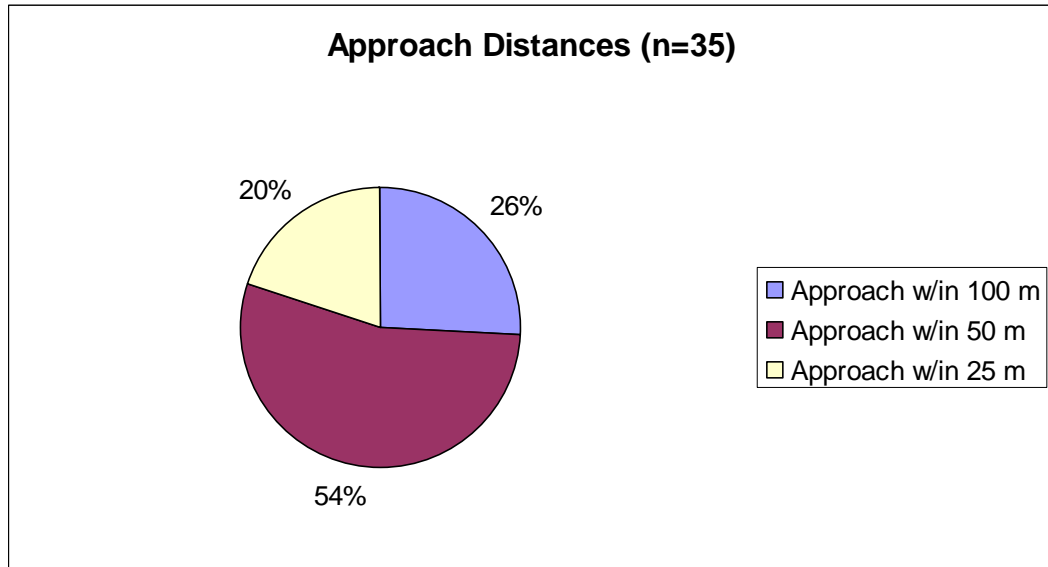


Figure 3.5. Distribution of vessel approach distances.

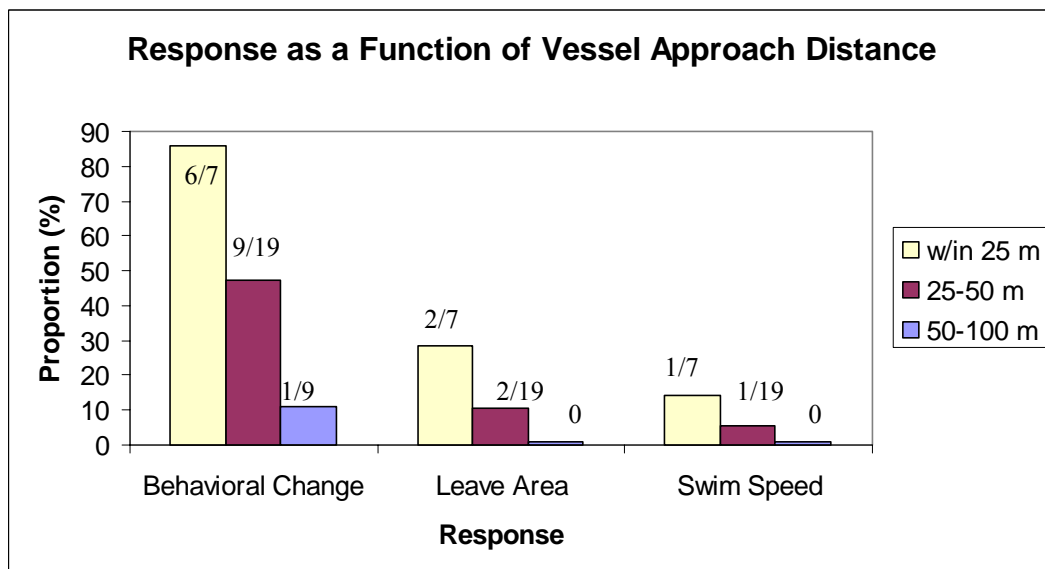


Figure 3.6. Distribution of response as a function of approach distance.

Motorboats with outboard engines dominated the observed vessel approaches (69%). Personal watercraft (PWC) accounted for 28% of the approaches, and motorboats with inboard engines accounted for the remaining 3%. Of the 43% of the animals that responded to vessel approaches with a behavioral change, 63% of those changes were in response to outboard motors, whereas only 37% of the behavioral changes were elicited by PWCs (Figure 3.7). However, of the 11% of the animals that responded by abandoning the area, 75% were due to PWC approaches whereas only 25% were due to outboard motor approaches. Manatee behavioral reactions to vessel approaches are more thoroughly investigated in Chapter 5 through a series of controlled playback experiments.

The last measure of response to the opportunistic vessel approaches was a change in the variability of ventilation. The absolute time differences between the 3 consecutive breaths preceding the approaches were summed for comparison to the ventilation variability value calculated from the 3 consecutive breathes following the approach. Three breaths were chosen to most accurately reflect the variability in breathing patterns observed to occur in groups on three: one long duration submergence followed by two short duration submergences. Pooled across behaviors, engine types, and approach distance to achieve a sample size of adequate statistical power ($n=21$), the mean ventilation variability value prior to approaches was 125 s compared to a 200 s value following the approach. A paired t-test indicated that the increase in ventilation variability was significant, which suggests that the vessel approaches have an effect on the animals' ventilation.

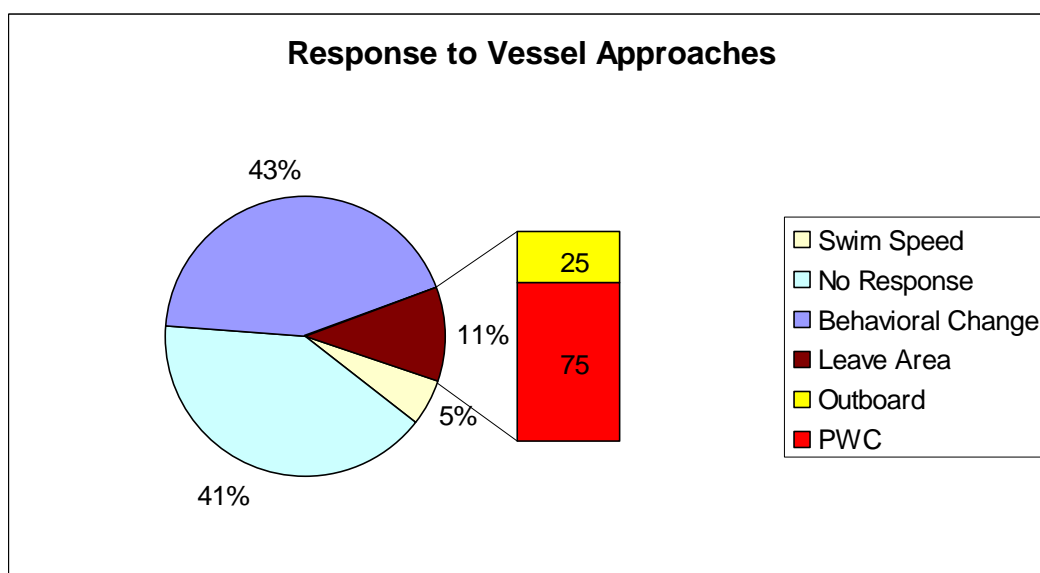
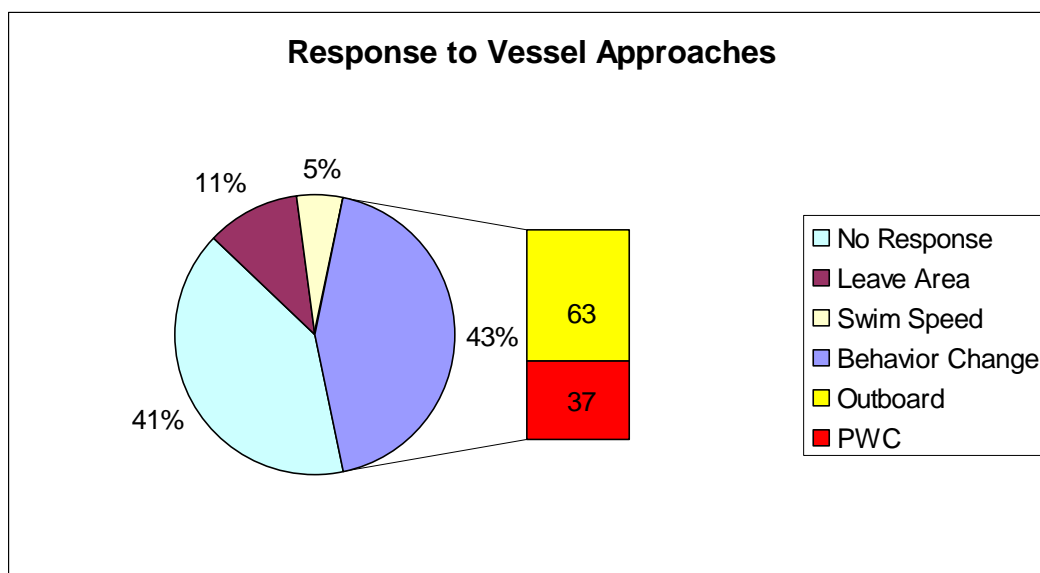


Figure 3.7. Distribution of response as a function of type of vessel approach.

3.5 Discussion

Mammals and birds physically react to noise in one of three ways – approach, maintain position, and avoid (Bowles, 1995). Approaching a noise source often indicates attraction, whereas avoiding the source often represents an aversion. If an animal maintains its position relative to the noise source, the response is more ambiguous. For example, the animal could be tolerating the noise, unable to hear the noise, or physiologically reacting with an internal stress response not indicated by physical movement. Ultimately, each of these reactions has the potential for negative effects. Attraction to noise can have negative consequences because it puts an animal in closer vicinity of potentially dangerous human activities. For example, grey and common seals are attracted to fishing activities that corral prey. This then puts them at risk for net entanglement, shooting, trapping, and poisoning (Anderson and Hawkins, 1978). Tolerance is dangerous because habituation to traffic noise has the potential to make animals more vulnerable to vehicle collisions, as could be the case with manatees. Aversion comes in many forms from short-term behavioral responses to changes in habitat use, mating success, communication, and quality of parental care (Bowles, 1995). Many of these responses are cumulative and have the potential to affect entire populations.

“The proportion of mammals and birds responding to noise varies greatly depending on previous experience, season, group size, age/sex, motivational state, reproductive condition, terrain, weather, and other natural factors” (Bowles, 1995). Results from this study show that manatees react to environmental noise with both tolerance and aversion depending on behavioral state, habitat type, and noise source.

Due to physiological requirements such as food availability and warm water temperatures in winter, manatees may have no alternative but to occupy areas where they are chronically exposed to human activities and attendant noise. Tolerance and habituation have become important survival responses as the areas where these animals are sheltered or not exposed to human activities shrinks as a result of population growth and coastal development.

Due to the impossibility of direct avoidance or attraction to changes in ambient noise level, tolerance was the dominant response attributed to ambient noise level differences by default. Tolerance, however, was not passive. Although the animals were not able to respond with physical movement towards or away from background noise, they were able to change behaviors and shift activity budgets to compensate for the noise. The ambient noise levels associated with manatee feeding behaviors were significantly higher than levels encountered during both resting and socializing behaviors. The feeding (high noise) vs. resting (low noise) dichotomy can be most easily explained by the natural habitat characteristics with which these behaviors are most dominant. Feeding is the dominant behavior in extremely shallow grassbeds where noise is loudest due to snapping shrimp and other physical parameters affecting sound propagation (Chapter 2). Resting, however, is the dominant behavior in the deeper more sheltered dredged habitats that tend to be quieter (Chapter 2). The feeding (high noise) vs. social behavior (low noise) dichotomy, on the other hand, can not be explained by a natural difference in habitat type because socializing occurs in essentially the same proportion in both the grassbed and dredged habitats.

How much or little a manatee chooses to feed or socialize at any specific time may be a direct response of the animal to the noise in its environment. One explanation is that manatees selectively socialize at times when ambient noise levels are lower in order to maximize the distance vocal signals travel while minimizing the effort needed to vocalize. This explanation can be tested by examining vocalization rates and source levels in relation to noise level, which is addressed in Chapter 4. If vocalization rate and/or source levels increase in response to elevated noise levels, socializing during periods of lower noise may be a strategy to minimize vocalization effort. A second explanation is that when noise levels are high, manatees in grassbeds focus on feeding and reduce the proportion of time spent engaging in other activities in an effort to reduce overall feeding time in the noisy environment. In order to test the second hypothesis, a study would need to be conducted in which individual manatees were followed for long enough to quantitatively compare noise and the proportion of time the animal spent in each behavioral state over its complete duration in the grassbed habitat. The overall activity budgets in grassbeds as a function of noise could then be compared. The focal follows in this study were not long enough to observe an animal's entire stay in a grassbed.

The focal follows in this study were suggestive, however, of the hypothesis that when noise levels are high, manatees in grassbeds focus on feeding and reduce the proportion of time spent engaging in other activities in an effort to reduce overall time required to feed in the noisy environment. In grassbeds, the proportion of time spent feeding increased with increased noise levels, whereas the proportion of time spent milling decreased with increased noise levels. This supports this idea that during high

noise manatees engage in more directed, goal-oriented behaviors such as feeding and less undirected behaviors like milling. A larger proportion of time feeding would allow a manatee to meet its nutritional requirements and leave the area more quickly than would interspersing feeding bouts with milling, socializing or resting.

An analogous pattern was seen in the dredged habitats. The proportion of time spent traveling increased with increased noise levels, whereas the proportion of time spent milling decreased with increased noise levels. Again, directed, goal-oriented traveling behavior increases with noise and undirected milling behavior decreases with elevated levels of noise. Caribou in Alaska exhibited a similar shift in activity budget in response to noise produced by military jet aircraft overflights (Murphy et al., 1993). Caribou that had been recently overflown spent less time lying down and more time either feeding or traveling. The shift in activity budget was most pronounced during the post-calving season.

Noise tolerance is a likely explanation accounting for the absence of any relationship between ventilation rate or variability and ambient noise level. The only significant respiration-related relationship identified was that of ventilation variability and behavioral state in the dredged habitats. Ventilation variation was significantly greater during resting behaviors compared to all others. This was attributed to the patterned breathing sequences of resting manatees. Resting manatees submerged for 3-5 minutes. This long submersion was then followed by 2-4 quick breaths before the initiation of another long submersion. The breathing behavior during other behaviors was less stereotyped. The average breathing rate (1.17 breaths/min) in this study was also found to be much lower than the 4 minute average reported by Reynolds (1981b).

The difference is most likely due to the fact that many of the areas of Blue Lagoon where the Reynolds study was conducted were very quiet, allowing for longer periods of undisturbed submersions (Reynolds, pers. comm.). This clearly illustrates a need to investigate the effect of ambient noise levels on the breathing patterns of manatees in other areas. If natural breathing rates can be different among geographical areas, it stands to reason that other behaviors and responses can also be affected.

Where tolerance appears to be the primary response to ambient noise, avoidance was most visible when specific noise sources approached the manatees. Behavioral change was the dominant response to vessel approaches within 50 m. This is consistent with the responses reported by Nowacek et al. (2001, 2004). In instances where animals left a geographical area in response to an approaching vessel in his study, the predominant vessel type eliciting this response was the PWC. Last, the ventilation variability was significantly higher directly following an approach than before. These behavioral changes indicate that vessel approaches disturb manatees, and a series of controlled experiments need to be conducted in order to determine whether this disturbance truly constitutes harassment (Chapter 5). Vessel approaches have the potential to increase the activity of the animals by causing them to travel away from the direction of noise and affect the breathing patterns. Consequently, metabolic rate may potentially be affected by the increased activity and can, in turn, deplete energetic reserves, which can have severe effects for the individual and population at large (Bowles, 1995).

3.6 Acknowledgements

Special thanks are extended to the staff in the Manatee Research Program at Mote Marine Laboratory for their support of this study in so many ways. This study would not have been possible without the aid of numerous Mote interns, the sharing of knowledge and time from the staff, and the unending encouragement. Thank you to David Mann and FWRI for allowing this project to be conducted under their permits.

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Chapter 4. Manatee Vocalization Usage in Relation to Environmental Noise

4.1 Abstract

Elevated environmental noise levels have the potential to interfere with the acoustic communication system of manatees by masking signals containing biologically important information. Communication theory recognizes several ways a sender can modify its acoustic signal to compensate for noise. These include increasing the source level of a signal, its repetition, its duration, or shifting frequency outside of the noise band. To test whether manatees can modify their vocalizations to compensate for noise, vocalization usage and structure were examined in terms of vocalization rate, duration, frequency, and source level. Results imply that manatees do increase their vocalization energy expenditure, or vocalization effort, as a function of behavior and calf presence. Increases in vocalization rate, duration, and source level were most pronounced when calves were present and during behaviors where animals tended to be more dispersed, which may suggest a cohesion function. In conditions of elevated noise levels, manatees increased call duration during feeding and milling behaviors when calves were present, suggesting that ambient noise levels do have a detectable effect on manatee communication and that manatees modify their vocalizations as a function of noise.

4.2 Introduction

Vocalizations are assumed to form the basis of most long range communication in manatees (Sousa-Lima et al., 2002). Sound has the potential to travel long distances in water over short time periods, providing a reliable way for

manatees to communicate beyond visual range in murky coastal or riverine waters. The actual range of effective acoustic communication in the noisy, shallow-water areas inhabited by manatees depends on the acoustic propagation loss characteristics of the area and the frequency and amplitude of the vocalizations being emitted.

Manatee vocalizations were initially described as squeaky with a ragged sounding component (Schevill & Watkins, 1965). Schevill and Watkins (1965) reported that the vocalizations were not particularly loud, registering only 10-12 dB above the background noise at 3-4 meters in a vegetation-choked canal on the east coast of Florida. These calls ranged in duration from 0.15-0.5 seconds and were composed of 2 or more frequencies not harmonically related. A second type of vocalization described by Schevill and Watkins (1965) contained harmonics where the second harmonic was often more intense than the first. Schevill and Watkins (1965) described the fundamental frequency of manatee vocalizations to be mostly between 2.5-5 KHz, but possibly as low as 600 Hz or as high as 16 kHz. Spectrograms of a manatee squeak and harmonic call from Schevill and Watkins (1965) are pictured in Figure 4.1.

A representative selection of spectrograms from Nowacek et al. (2003) is presented in Figure 4.2. The power spectrum in Figure 4.3 illustrates the variation in level of a short segment from a typical manatee vocalization as a function of frequency (Nowacek et al., 2003).

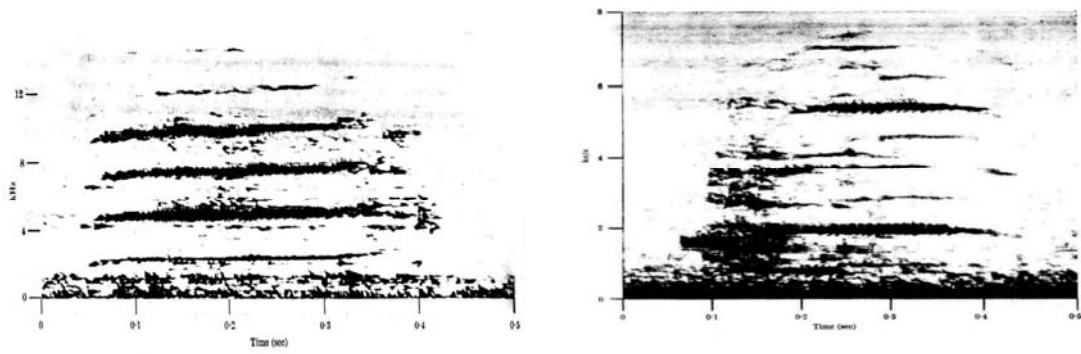


Figure 4.1. Manatee vocalizations reproduced from Schevill and Watkins (1965). The left image is an example of a harmonic vocalization. Note how the second harmonic is stronger than the first. On the right is a manatee squeak vocalization.

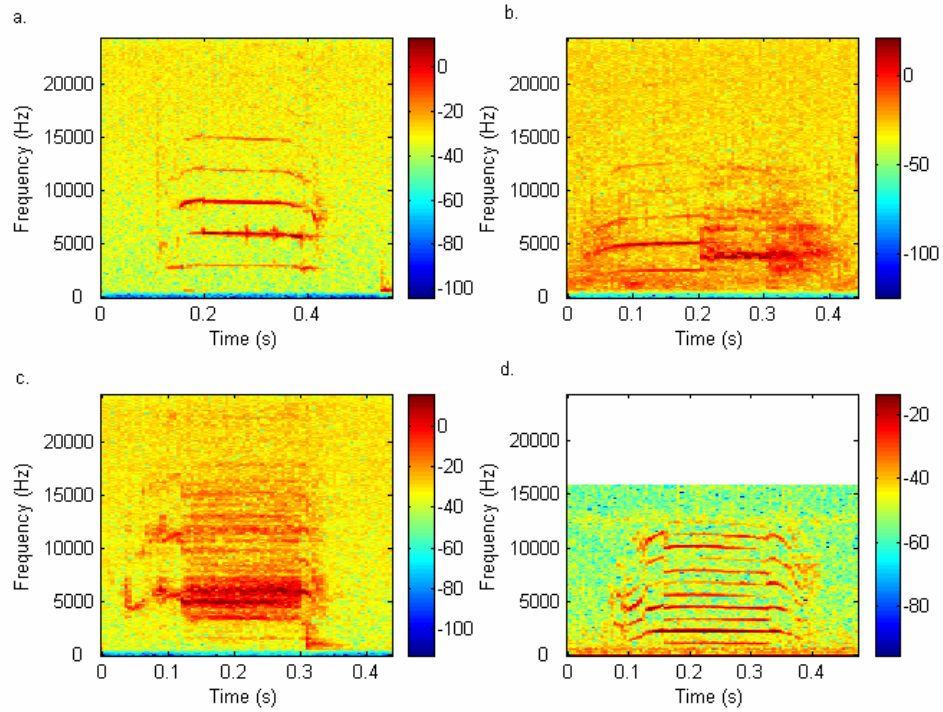


Figure 4.2. Manatee vocalization spectrograms reprinted from Figure 1 of Nowacek et al. (2003). The scale bar shows relative sound levels in decibels. Spectrogram a). typical tonal harmonic vocalization (FL), b). tonal vocalization transitioning to less tonal (FL), c). broader-band harmonic vocalization (FL), d). typical harmonic vocalization (Belize).

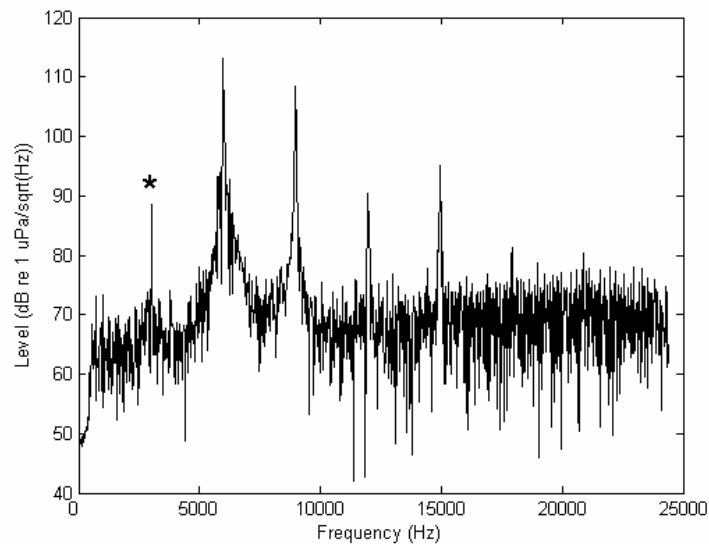


Figure 4.3. Manatee vocalization power spectrum reprinted from Figure 2 of Nowacek et al. (2003). The power spectrum was constructed using a 2048-point FFT of a 2048-point segment from the middle of the segment shown in Figure 4.2a. The * indicates the fundamental frequency.

Since the first descriptions of manatee vocalizations in 1965, little progress has been made in understanding the structure, function, and use of manatee vocalizations compared to the in-depth studies of acoustic communication in other marine mammal species. Evans and Herald (1970) and Sonoda and Takemura (1973) recorded vocalizations from West Indian and Amazon manatees (*Trichechus inunguis*), respectively. Both studies described the vocalizations as squeaks, squeals, and chirps similar to those of Schevill and Watkins (1965). Hartman (1979) and Reynolds (1981) were the first to associate vocalizations with particular behaviors. Manatees were reported to vocalize while socializing and feeding, when startled, and to maintain contact between a female and her calf. Reynolds (1981) noted the variability of calls from the same solitary animal at the same location on different days. On one day, the animal was silent for 152 minutes, whereas on the other day it vocalized constantly for 31 minutes. Except for mother-calf pairs, animals in herds were not reported to be more vocal than single animals. The increase in observed vocalizations between a female and her calf may allow the mother and calf to maintain contact.

The most recent information regarding West Indian manatee vocalizations comes from studies by Bengtson and Fitzgerald (1985), Nowacek et al. (2003), and Phillips et al. (2004). Bengtson and Fitzgerald (1985) measured the vocalization rates of wild manatees during different activities to examine the importance of vocalizations during certain behaviors. Manatees were reported to vocalize more during social activities and milling than during feeding, traveling, or resting. Vocalization rates also increased in response to manatees being startled or excited during social interactions. Rates ranged from approximately 0.25 calls/manatee per 5 minute period during

feeding to 4.75 calls/manatee per 5 minute period during social cavorting, defined as intense social interactions (Bengtson and Fitzgerald, 1985). The mean call rate per individual was calculated for each behavioral category when an individual was alone or when individuals in a group of manatees were behaving similarly. These rates compare well with the calculations of 1-2 vocalizations per five minute period reported by Phillips et al. (2004).

Nowacek et al. (2003) compared vocalization rates between two West Indian populations in Florida and Belize at 1.29 and 0.09-0.75 calls/minute, respectively. Average received level of the peak frequency of calls at each of the two sites was reported at about 100 dB re 1 μ Pa (Nowacek et al., 2003). Additionally, source levels from tagged manatees in Belize were estimated at 106-115 dB root mean square (rms) re 1 μ Pa at 1 m (Nowacek et al., 2003). Phillips et al. (2004) reported a similar mean source level of approximately 112 dB rms re 1 μ Pa at 1 m. Localizations were obtained from time of arrival differences at four hydrophones located within Homosassa Springs. Source levels were then calculated based on the location of the source. Whether or not call structure or source level changes during different behavioral contexts has not yet been documented. Bengtson and Fitzgerald (1985) noted that calf presence may have raised calling rates.

Three of the four studies describing West Indian manatee vocalizations allude to the presence of two different vocalization types: tonal harmonic calls and broader-band, less tonal calls (Schevill and Watkins, 1965; Bengtson and Fitzgerald, 1985; Nowacek et al., 2003). However, this differentiation is not acoustically quantified, and authors combined all call types in their rate and source level analyses. The

identification of two acoustically distinct categories of manatee vocalizations may provide some insight into the role of manatee vocalizations, as the functions of manatee vocalizations are still unclear. It has been suggested that vocalizations function to establish and maintain contact between individuals (such as the female-calf pair) and play a role in greeting or identifying individuals (Hartman, 1979). The presence of individually stereotyped vocalizations in the repertoire of captive Amazonian manatees provides evidence in support of the idea that manatee vocalizations function to establish and maintain contact between individuals (Sousa-Lima et al., 2002).

There is still much to learn about the structure, context, and function of manatee vocalizations. Most studies of manatee vocalizations were conducted in clear waters at winter aggregation sites or in captive environments. Manatees seem to be able to visually detect objects in clear water from distances of tens of meters, but sound has been used to explain how animals communicate over longer distances or when visibility is reduced. How several male manatees manage to find an estrous female hundreds of meters away all at the same time has been suggested to result from sound production by the female (Reynolds and Odell, 1991). In turbid waters the visibility is often less than 5 meters, so manatees may need to rely more heavily on vocalizations to maintain contact with animals among a group, defined as all animals within an approximate 50-100 m radius. As manatees disperse from the clear waters of some winter aggregation sites into the more turbid waters of coastal Florida in warm months they may need to rely more on acoustic communication; thus, vocalization rates and structure may change during the summer months.

Vocalization usage also has the potential to be affected by environmental noise level. Overlapping frequencies of noise and vocalizations may mask significant signal information within manatee calls, consequently reducing effective communication. The impact of noise may therefore become even more crucial to the acoustic communication system during the summer months when the visual mode of communication is reduced due to high turbidity. Increasing the source level of a vocalization, its repetition rate, its duration, or shifting frequency outside that of the noise band are several ways an animal can compensate for noise (Richardson et al., 1995; Turnbull and Terhune, 1993). In order to accurately quantify the effect of noise on manatee vocalization usage, it is first necessary to investigate the effect of behavior and calf presence on vocalization use. Although other social factors may affect vocalization usage, these two factors were chosen for analysis because they have already been identified as factors affecting vocalization use (Bengtson and Fitzgerald, 1985). The initial objective of this study was to determine how vocalization rate, source level, and/or structure vary as a function of behavioral state or calf presence. Only after a basic understanding of vocalization use pattern in summer habitats was obtained could the question of how ambient noise and human activities are affecting the acoustic communication system of manatees be addressed.

4.3 Methods

Vocalizations and ambient noise were recorded continuously throughout all sightings and focal follows from a towed hydrophone system (Recording System B: 20 Hz – 22 kHz with a -178 dB re 1 V/ μ Pa sensitivity at 16 bit resolution. A detailed

description of Recording System B appears in Chapter 3.3). The peak acoustic level of the system was 178 dB re 1 μ Pa, which resulted in a minimum signal detection of 88 dB re 1 μ Pa. System noise for Recording System B was obtained by suspending the hydrophone in-air and recording in a quiet, dark room. All gain settings were identical to those used in the field. The system noise of Recording System B was dominated by discretization noise and was well below the minimum detectable signal (Oppenheim et al., 1999) (Figure 4.4). Only vocalizations emitted at times when the trolling motor was off were used in the analyses. This was done in order to eliminate any indirect response of the animals to the motor following them during observation periods. However, vocalization selection and analysis were not designed to account for reactions to prolonged exposure to the trolling motor during periods of observation or to transitions of the trolling motor being turned on an off.

Broadband recordings of ambient noise were made at the beginning and end of each sighting and/or follow at a sampling rate of 200 kHz (Recording System A: 2 Hz-100 kHz with a -178 dB re 1V/ μ Pa sensitivity at 16 bit resolution with peak acoustic level at 178 dB re 1 μ Pa. A detailed description of Recording System A is in Chapter 2.3.4). Noise levels were calculated in nine 1/3 octave bands as described in Chapter 2. System noise for Recording System A was below all ambient noise levels at all 1/3 octave bands (Tables 4.1 and 2.2). Data collection on free-ranging animals was performed under the permits issued by the U.S. Federal Fish and Wildlife Service to the Fish and Wildlife Research Institute (FWRI) (MA773494-7) and to Dr. David Mann at the University of South Florida (USF) (MA051709-0).

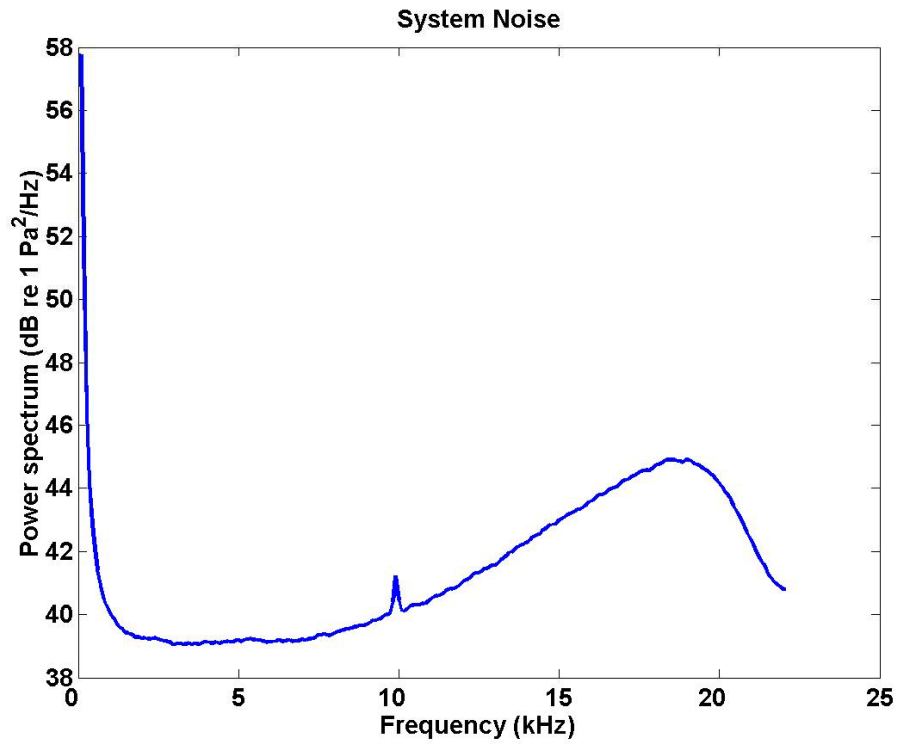


Figure 4.4. Power spectrum of system noise for Recording System B. A 512 point FFT size was used to calculate the power spectrum. Note: system noise is calculated as the integral of this curve.

Table 4.1. One-third octave band system noise levels for Recording System A.

Center Frequency	dB re 1 μ Pa
250 Hz	24
500 Hz	17
1 kHz	12
2 kHz	7
4 kHz	6
8 kHz	9
16 kHz	15
32 kHz	35
64 kHz	22

4.3.1 Behavioral States

Analysis of vocalizations included only those produced when an entire group of manatees being observed was engaged in the same behavior or only a single animal was being observed. This is consistent with the methodology of Bengtson and Fitzgerald (1985). An additional criterion for inclusion in the behavior analysis was that the recording lasted a minimum of 20 minutes. This criterion eliminated 10 of the 99 recordings from analysis. The 20 minute time period was selected because it was the minimum amount of time needed to accurately approach a group and determine behavior, number of animals, and calf presence. Both the number of manatees and behavior classification are potential sources of error in the recordings. The number and behavior of manatees may have been misidentified in turbid waters although the number of animals obtained from the observation vessel compared well with simultaneous aerial survey counts. No discrepancies occurred for groups of five animals or less. In 13 comparisons, the maximum difference between the aerial survey and on-water counts was 2 animals for groups with a minimum of six individuals and ranging from 6-20 total animals. The on-water counts underestimated the number of manatees present in all comparisons. Another possible source of error was that animals nearby or approaching the observation group could have introduced vocalizations while in a different behavioral state.

4.3.2 Vocalization Rate

The number of vocalizations used from each recording was determined by the following protocol. The protocol was implemented to account for the context

dependent usage of vocalizations during different behavioral states. All vocalizations identified within a randomly chosen 20 minute time period during the same behavioral state were included in rate analyses. Vocalizations continued to be identified in 20 minute time periods within the same behavioral state until the behavioral state changed or the recording ended. Because of the great number of vocalizations produced during social interactions, a separate criterion was applied. For social behaviors only, if more than 200 vocalizations were obtained within the 20 minute time period, no further vocalizations were identified from that behavioral state on a single recording. Even though vocalizations were calculated in 20 minute blocks, vocalization rate was presented per manatee per five minute period to maintain consistency with previous studies (Bengtson and Fitzgerald, 1985; Phillips et al., 2004). Vocalization rates calculated from consecutive 20 minute time periods within the same behavioral state from the same recording were averaged to produce a single rate value per behavioral state for each recording.

4.3.3 Vocalization Structure

Vocalizations included in the vocalization structure analysis were subjected to the same selection criteria as those for the vocalization rate analysis. Subsets of these vocalizations were selected for structure analysis based on the following additional criteria: 1) a clear start and end to the vocalization was identified, 2) there were no overlapping signals, and 3) more than 3 harmonics were visible on a 512 point fast Fourier transform (FFT) spectrogram. Parameters measured were duration, minimum frequency, maximum frequency, frequency range, and frequency of peak energy. All

parameters were measured by hand from a 512 point FFT spectrogram. Absolute level of the signal was not used as part of the structure analysis.

4.3.4 Source Level

Vocalizations included in the source level analysis were subjected to the same selection criteria as those for the vocalization rate analysis. A subset of these vocalizations was selected for source level analysis based on the following additional criteria: 1) distance from a single animal or compact group of animals to the hydrophone was specified, 2) a clear start and end to the vocalization was identified, and 3) there were no overlapping signals. A band pass filter was constructed and applied to each vocalization from minimum and maximum frequency points selected by hand. An rms received level was then calculated over the duration of the vocalization. Final source level calculations were obtained by adding a transmission loss component which was specific to each animal distance and geographical site. Average transmission loss values within each manatee habitat were determined from the MMPE model in Chapter 2.

4.4 Results

Over the course of the study, 103 hours of vocalization recordings were obtained during 128 sightings, 47 focal follows of untagged manatees, and 3 follows of tagged manatees. Of the total recordings only 77 hours were reviewed. These were the hours when the manatees were observed either as a single animal or all animals within the observation group were engaged in the same behavior. The total number of

hours actually used in the vocalization analyses was 62.5. The number of usable hours in each behavioral category, as well as the number of vocalizations identified is outlined in Table 4.2.

Table 4.2. Behavior category breakdown of hours and identified vocalizations.

Behavior	Behavior hrs	Usable hrs	Total vocalizations	Trolling motor off (%) of total	Trolling motor on (%) of total
Social	20	14.5	3083	2668	415
Mill	10.5	10	677	580	97
Rest	23	18	935	887	48
Feed	23.5	20	1326	1083	243
Total	77	62.5	6021	5218 (86.7)	803 (13.3)

4.4.1 Vocalization Rate

Average vocalization rates ranged from 1.04-4.39 vocalizations/manatee/5 minute period (Table 4.3). These values correspond well to the rates of 0.25-4.75 and 1-2 vocalization/manatee/5 minute period previously reported by Bengtson and Fitzgerald (1985) and Phillips et al. (2004), respectively. A single factor ANOVA within each behavioral state using the recording as the unit of analysis showed that there was a significant calf presence interaction within the social ($F= 9.81$, $p = 0.002$, $df = 18$) and resting behavior categories ($F= 8.41$, $p = 0.003$, $df = 19$). Vocalization rates were greater when one or more calves were present during social and resting behaviors (Table 4.3). There was no significant calf interaction for the feeding and

milling behaviors. There was also no significant behavior interaction across all behavior categories. Consequently, all vocalization rates within the feeding and milling behavior categories were pooled for further noise analyses. Two sets of noise regression analyses (calf absence and calf presence) were run for the social and resting behavior categories in order to be consistent with the previous ANOVA results.

Table 4.3. Summary table of mean vocalization rates organized by behavior and calf presence. Rate units are vocalizations/animal/5 minute period.

	Combined total		Calves absent		Calves present	
	n	mean	n	Mean	n	mean
Social	2817	2.55	1276	2.03	1541	4.39
Mill	578	2.49	185	2.32	393	2.75
Rest	885	1.53	261	1.04	624	2.70
Feed	1149	1.63	478	1.10	671	2.47

Regression analyses were performed at each of the nine ambient noise frequencies analyzed in order to determine if manatee vocalization rates were significantly correlated with ambient noise level. Results showed no significant correlation between vocalization rate and one-third octave noise levels during any behavior at any third octave band.

4.4.2 *Vocalization Structure*

A preliminary analysis was done in order to determine if manatee vocalizations can be classified into two distinct vocalization types. The tonal harmonic calls previously described by Schevill and Watkins (1965), Bengtson and Fitzgerald (1985), and Nowacek et al. (2003) were designated chirps (Figure 4.5a). The broader-band, less tonal calls were designated squeaks (Schevill and Watkins, 1965; Bengtson and

Fitzgerald, 1985; Nowacek et al., 2003) (Figure 4.5b). Five traditional structure parameters were measured for each vocalization: duration, frequency range, minimum frequency, maximum frequency, and frequency of peak energy. A series of Bonferroni corrected t-tests showed that chirps and squeaks are acoustically different based on the five parameters measured (Table 4.4). Chirps are longer in duration, have a broader frequency range, and are higher in frequency compared to the more raspy sounding squeaks. These results indicate that chirps and squeaks are two distinct vocalization types, so they were analyzed separately for patterns associated with behavior, calf presence, and ambient noise.

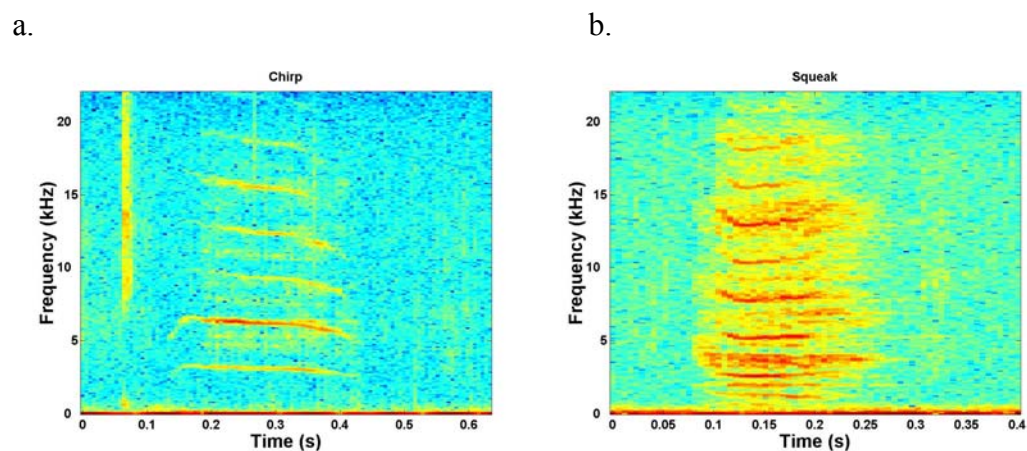


Figure 4.5. Spectrogram a.) chirp and b.) squeak.

Table 4.4. Summary table of the average parameter values and Bonferroni corrected p values for chirps and squeaks.

	Chirps	Squeaks	t stat	p-value
Sample size	1168	375		
Duration (ms)	221.8	198.4	4.47	<0.001
Freq. range (Hz)	15033	12776	9.28	<0.001
Min. freq (Hz)	1804	1358	9.7	<0.001
Max. freq. (Hz)	18026	14135	11.02	<0.001
Peak freq. (Hz)	5097	3341	11.63	<0.001

The acoustic features of squeaks appeared consistent across behaviors and group composition (Table 4.5a). A single factor multivariate ANOVA showed a significant interaction among behavior categories within the squeak vocalization type ($F = 11.92$, $p < 0.0001$, $df = 372$), and post-hoc multiple comparisons revealed that squeaks made only during resting behaviors were shorter in duration than those made during any other behavior. There were no significant interactions between behavior category and frequency range, minimum/maximum frequency, or frequency of peak energy. Similarly, ANOVA results showed no significant interaction of calf presence for any of the five measured parameters of squeaks (Table 4.5b).

Table 4.5. Summary table of the acoustic features of squeaks for the five parameters measured. a). Average values separated by behavior. The highlighted cell indicates a significant difference from other values in the parameter row. b). Average values separated by behavior and calf presence.

a).

	Social	Feed	Rest	Mill
Sample size	247	38	53	35
Duration (ms)	196	250	166	197
Freq. range (Hz)	12607	12744	13005	12599
Min. freq. (Hz)	1344	1404	1521	1262
Max. freq. (Hz)	13847	14148	14526	13862
Peak freq. (Hz)	3335	3301	3527	2944

b).

		Social	Feed	Rest	Mill
Sample size	Absent	167	27	15	15
	Present	78	11	38	20
Duration (ms)	Absent	196	274	181	173
	Present	196	192	160	215
Freq. range (Hz)	Absent	11872	13365	12768	15077
	Present	13842	11222	13099	10742
Min. freq. (Hz)	Absent	1338	1527	1025	1215
	Present	1357	1100	1717	1298
Max. freq. (Hz)	Absent	13211	14892	13793	16292
	Present	15200	12322	14816	12040
Peak freq. (Hz)	Absent	3471	3596	2967	2942
	Present	3045	2578	3748	2946

Regression analyses for each of the five structure parameters were performed at the nine ambient noise frequencies analyzed to determine if the structure of manatee squeaks varied as a function of ambient noise level. Based on the non-significant behavior and calf presence interactions for the frequency range, minimum frequency, maximum frequency, and frequency of peak energy parameters, all squeak vocalizations were pooled across behaviors and group composition for the noise

analysis. Two separate regressions were run for the duration parameter. Squeaks emitted during feeding, milling, and socializing were pooled, and those emitted during resting behaviors were analyzed separately. Results showed no significant correlation between squeak structure and noise level for any behavior at any frequency.

The acoustic features of chirps varied much more than those of squeaks across both behavior and group composition (Table 4.6). An initial single factor ANOVA showed a significant interaction across behavior categories for the duration parameter ($F = 13.42$, $p < 0.0001$, $df = 1158$). Post-hoc multiple comparisons showed that chirps were longer in duration during feeding and milling compared to resting and socializing. The ANOVA results also showed that the frequency range of chirps was greater during feeding compared to the other behaviors ($F = 14.70$, $p < 0.0001$, $df = 1158$). Minimum frequency was significantly greater during milling and resting compared to socializing and feeding, and the same was seen for maximum frequency (minimum frequency: $F = 6.21$, $p = 0.0004$, $df = 1158$; maximum frequency: $F = 16.14$, $p < 0.0001$, $df = 1158$). Finally, the frequency of the spectral peak energy across complete chirps was significantly less for feeding compared to the other behaviors ($F = 4.28$, $p = 0.005$, $df = 1158$). Overall, chirps made while manatees fed were the longest and lowest in frequency with the most narrow frequency range. Chirps made while manatees milled and rested were higher in frequency compared to feeding chirps with milling chirps lasting longer than resting chirps. Chirps emitted during social behaviors tended to be short with frequency parameters overlapping those of the other behaviors.

Two factor ANOVA results also showed a significant overall calf presence x behavior interaction across behavior categories. Post-hoc multiple comparisons showed no effect of calf presence during social behaviors across all five acoustic parameters (Table 4.6b). For feeding, resting and milling, the effect of calf presence was less clear. Chirp durations were longer when calves were present during feeding and milling behaviors, but not during resting. The frequency range and maximum frequencies were also decreased when calves were present during feeding, but significantly increased during rest. No significant effect of calf presence was observed in the peak frequency parameter for any behavior.

Regression analyses were performed for each of the five acoustic parameters at the nine ambient noise frequencies analyzed in order to determine if the structure of manatee chirps varied as a function of ambient noise level. Chirp durations were pooled across the resting and socializing behaviors because there were no significant behavior or calf interactions. Durations were also pooled across the feeding and milling behaviors, but separated for calf presence. Regression analysis indicated that chirp durations increased as a function of elevated ambient noise levels for frequencies 16 kHz and greater during feeding and milling only when calves were present (16 kHz: $p = 0.02$; 32 kHz: $p = 0.02$) (Figure 4.6). Pooling of chirps for the remaining four acoustic parameter regressions was directed by the behavior and calf presence interactions observed in Table 4.6. In summary, there were no correlations between noise level and frequency range, maximum frequency, or frequency of peak energy of chirp vocalizations across behaviors and calf presence. There was a significant correlation between noise level and minimum chirp frequency during resting

behaviors when calves were present. For noise levels in the 8-64 kHz band, minimum chirp frequency decreased as noise levels increased (Figure 4.7).

Table 4.6. Summary table of the acoustic features of chirps for the five parameters measured. a). Average values separated by behavior. The highlighted cells indicate significant similarities and differences from other values in the parameter row. b). Average values separated by behavior and calf presence. Highlighted cells show the combinations that were significantly different due to calf presence.

a).

	Social	Feed	Rest	Mill
Sample size	699	179	200	81
Duration (ms)	210	256	219	244
Freq. range (Hz)	15139	13390	15785	15829
Min. freq. (Hz)	1741	1792	1984	1900
Max. freq. (Hz)	16880	15182	17770	17729
Peak freq. (Hz)	5240	4433	5088	5196

b).

		Social	Feed	Rest	Mill
Sample size	absent	374	75	44	45
	present	325	104	156	36
Duration (ms)	absent	212	226	204	208
	present	208	277	223	289
Freq. range (Hz)	absent	15065	14318	14542	16114
	present	15224	12720	16135	15472
Min. freq. (Hz)	absent	1713	1875	1702	1776
	present	1772	1732	2063	2054
Max. freq. (Hz)	absent	16778	16193	16245	17891
	present	16997	14453	18200	17526
Peak freq. (Hz)	absent	5325	4803	5329	5003
	present	5142	4166	5020	5438

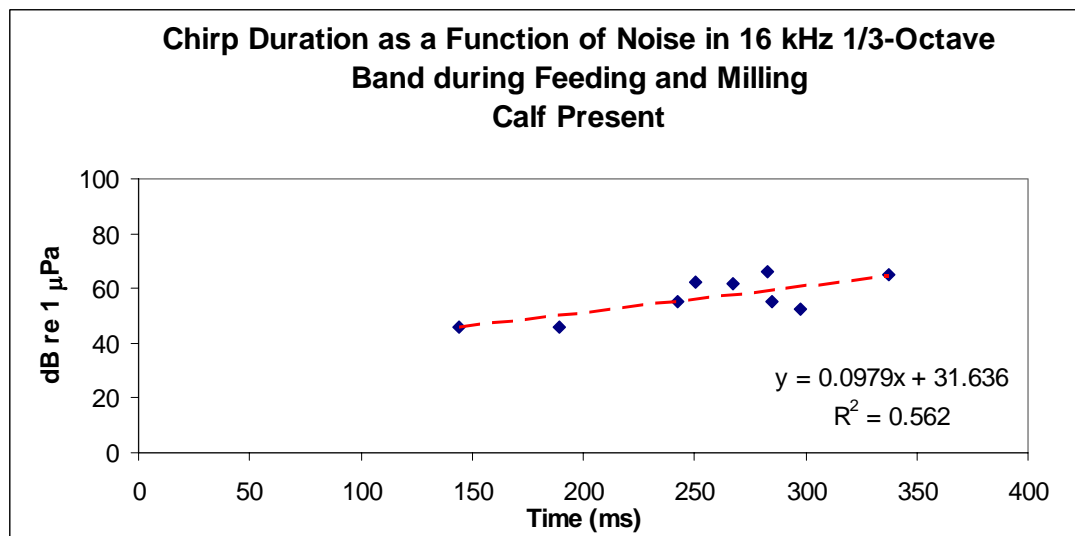
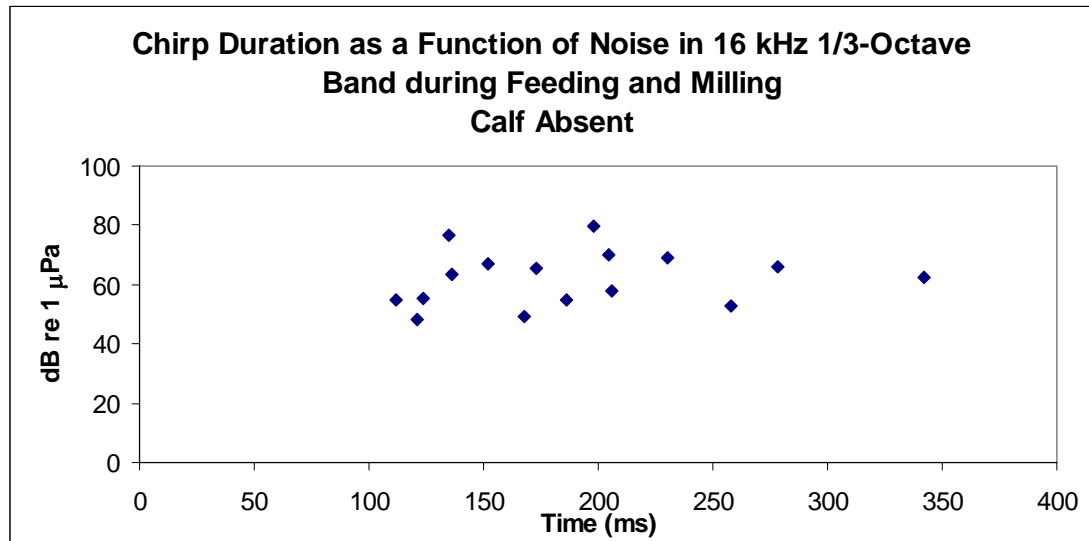


Figure 4.6. Regression plots of chirp durations as a function of 16 kHz noise in 1/3-octave bands. Top panel: calf absent. Bottom panel: calf present, dashed line indicates a significant correlation.

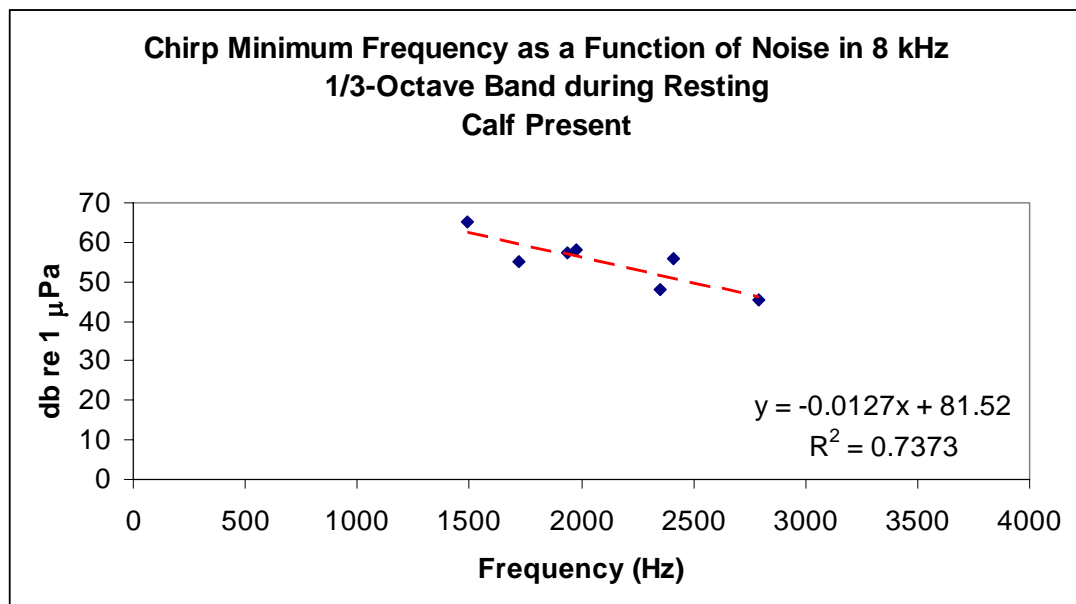
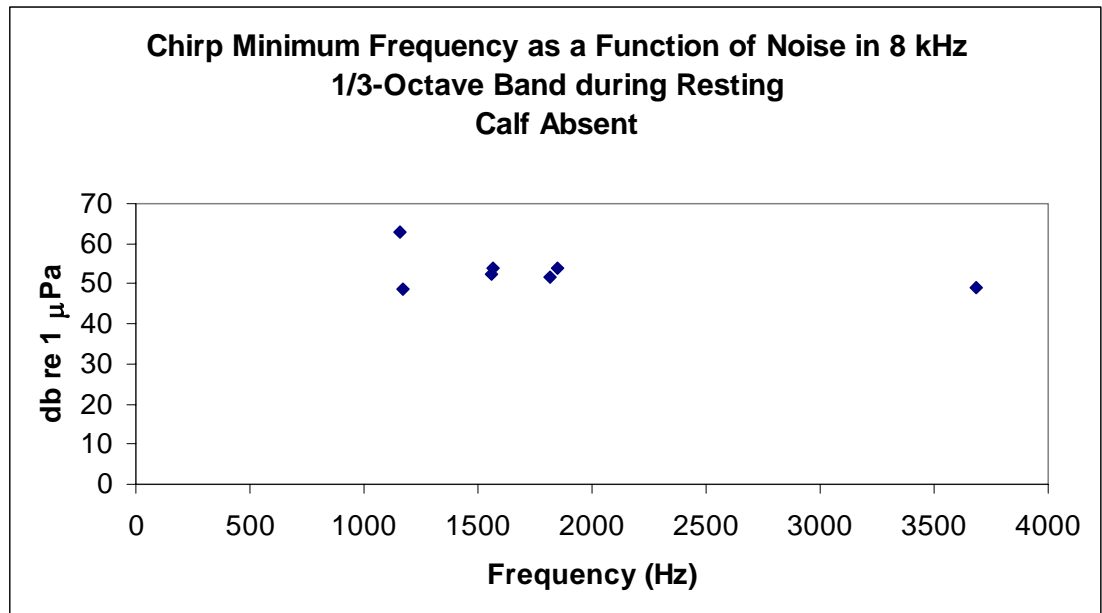


Figure 4.7. Regression plots of chirp minimum frequency as a function of 8 kHz noise in 1/3-octave bands. Top panel: calf absent. Bottom panel: calf present, dashed line indicates a significant correlation.

4.4.3 *Source Level*

Source levels obtained in this study overlapped with the range of source levels previously reported (90-138 dB rms re 1 μ Pa) (Nowacek et al., 2003; Phillips et al., 2004). However, the majority of source levels obtained in this study were greater than the means of 100 and 112 dB re 1 μ Pa previously reported (Figure 4.8). This is possibly due to the fact that the selection for source level calculations in this study of vocalizations were those that showed the clearest contours on spectrogram plots. Quieter vocalizations tended to appear less sharp, masked by background noise, and were eliminated from further analysis. Source levels reported here therefore reflect a sample that was biased to represent relatively high signal to noise levels for manatee vocalizations, which is likely also biased for high source levels. An alternative explanation as to why this study obtained greater source levels is that vocalizations emitted during the summer season in very turbid waters may be louder than those emitted in less turbid waters or during the winter season. Source levels of Florida manatees reported by Nowacek et al. (2003) were obtained from a spring in Crystal River, FL, and those levels reported by Phillips et al. (2004) were obtained during the late winter/early spring season in Homosassa Springs Wildlife State Park.

Comparison of source levels for chirps and squeaks across behavioral categories showed no significant difference (chirp mean = 122.4 dB, n = 1168; squeak mean = 121.6 dB, n = 375) (Figure 4.8). A two factor ANOVA also showed no significant behavior x calf presence interaction for squeak vocalizations, which allowed all squeaks to be pooled for a single noise regression analysis. Regression analyses were performed at the nine ambient noise frequencies analyzed in order to

determine if squeak source level was a function of ambient noise level. There were no significant correlations of squeak source level and noise at any frequency (Figure 4.9).

Analyses of chirp source levels were not as straightforward as the squeak analyses. An initial single factor ANOVA revealed a significant interaction for behavior x source level among chirps ($F = 6.35$, $p = 0.0003$, $df = 1158$). Post-hoc multiple comparisons showed that the source levels of chirps emitted during resting were greater than those emitted during socializing, feeding, or milling. A two factor ANOVA then showed a significant behavior x calf presence interaction for chirp source levels ($F = 13.42$, $p < 0.0001$). Post-hoc multiple comparisons showed that chirp source levels were not significantly affected by calf presence during social behaviors, but chirp source levels did increase when calves were present during feeding and resting behaviors (Table 4.7). Appropriate pooling across behaviors and group composition based on ANOVA results was maintained through the noise regression analyses. Regression analyses were performed at the nine ambient noise frequencies analyzed in order to determine if chirp source level was a function of ambient noise level. The only significant correlation of source level and noise was observed for noise bands of 250 Hz-4 kHz at rest when a calf was present. When calves were present, chirp source levels increased with decreasing noise levels during resting behaviors (Figure 4.10).

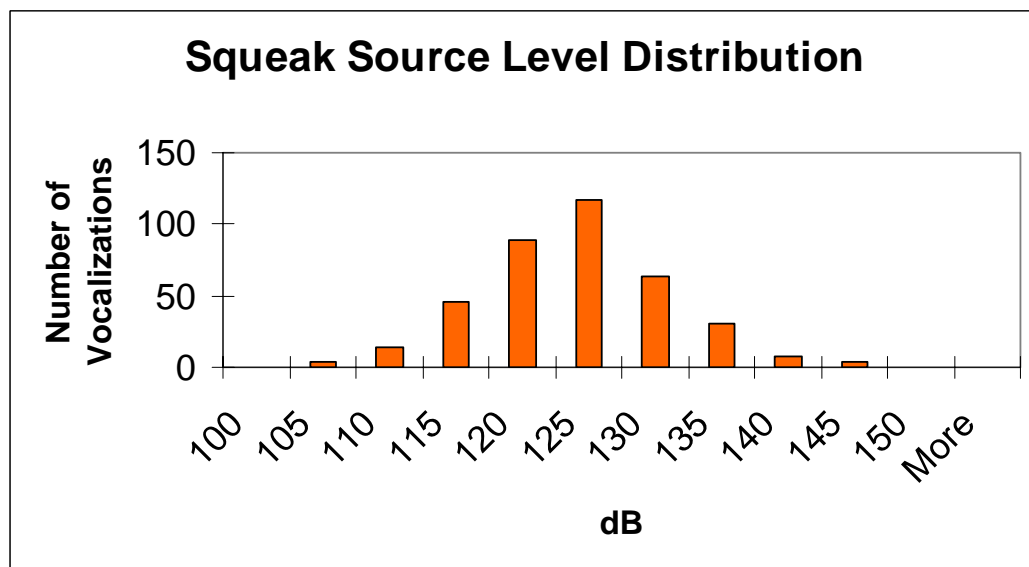
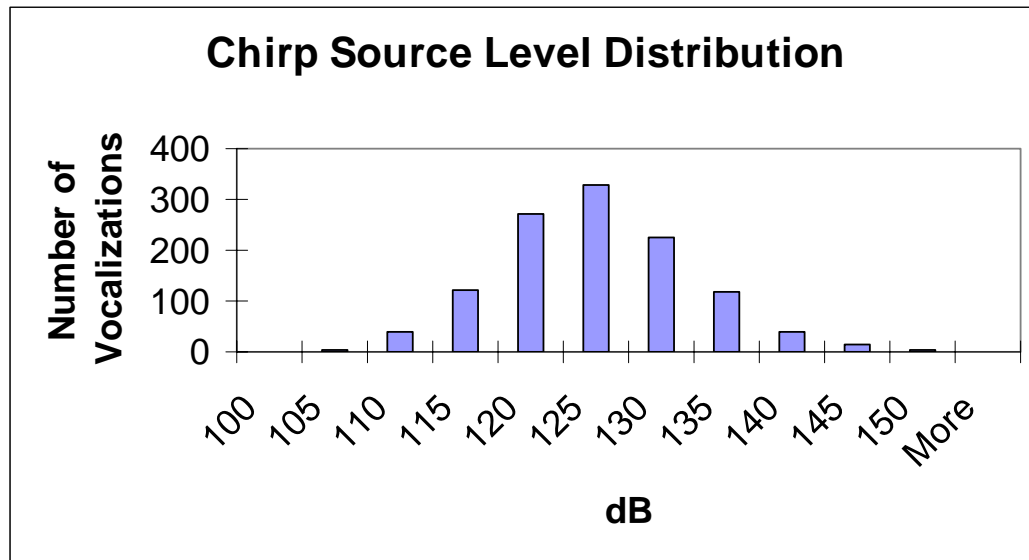


Figure 4.8. Maximum source level distributions for top: chirps and bottom: squeaks.

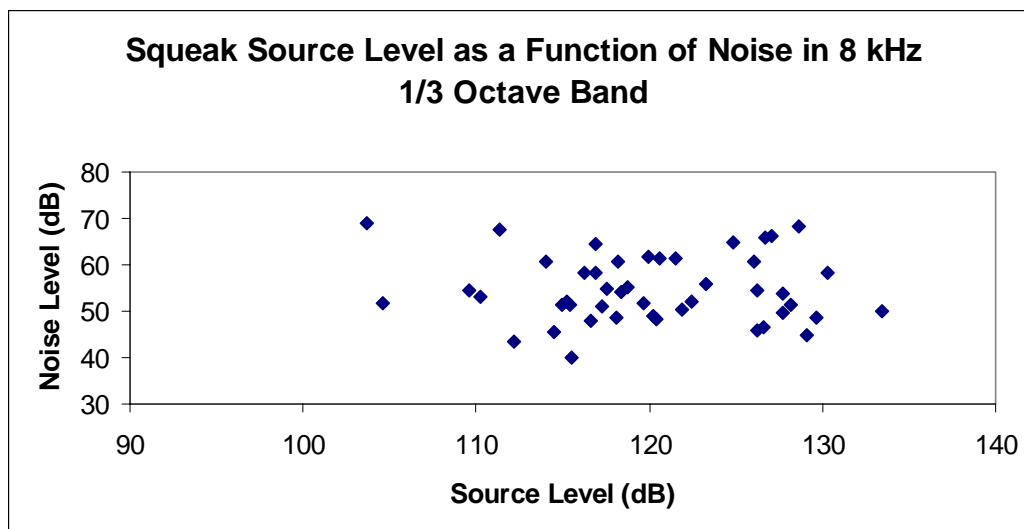


Figure 4.9. Regression plot of maximum squeak source level as a function of 8 kHz noise in 1/3-octave bands.

Table 4.7. Average chirp source levels as a function of behavior and calf presence. The yellow highlighted cell indicates a significantly greater source level for resting compared to other behaviors in the row. Pink highlighted cells indicate significant difference in source level as a function of calf presence. Source levels increased with calf presence.

		Social	Feed	Rest	Mill
Source level (dB)	total	122 (699)	121 (179)	124 (200)	122 (81)
	absent	122 (374)	118 (75)	119 (44)	125 (45)
	present	122 (325)	124 (104)	125 (156)	118 (36)

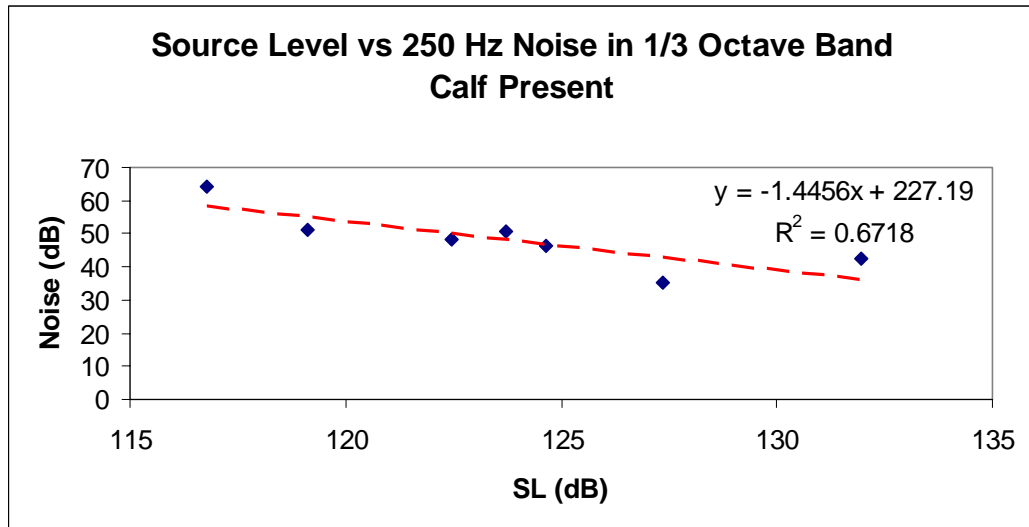


Figure 4.10. Regression plot of chirp source level as a function of 250 kHz noise in 1/3-octave bands. The dashed line indicates a significant relationship. The Bonferroni corrected p-value = 0.02.

4.5 Discussion

The structure and usage of manatee vocalizations appears to be more complex than suggested by prior studies (Bengtson and Fitzgerald, 1985; Hartman, 1979; Nowacek et al., 2003; Phillips et al., 2004; Reynolds, 1981b; Schevill and Watkins, 1965; Sousa-Lima et al., 2002). The average range of vocalization rates (1.0-4.4 vocalizations/manatee/5 minute period) and maximum source levels (105-150 dB re 1 μ Pa) determined in this study were consistent with those reported in previous studies. One of the biggest differences between the results of this study and prior studies is that in this study the two acoustically distinct types of vocalizations, chirps and squeaks, were analyzed separately instead of pooled. Chirps are tonal, longer in duration, higher in frequency, and have a broader frequency range compared to the more raspy squeaks. Chirp structure across behaviors and group composition was also more variable than squeak structure. This raises questions associated with discriminating the potential functions of each vocalization type.

This data set was rich enough to provide additional insight into vocalization structure and usage as a function of behavioral state, group composition (calf absence or presence), and environmental noise levels. The many different vocalization patterns observed in this study in association with behavior, calf presence, and noise can best be explained by the concept of vocalization effort. Animals are predicted to behave in a manner to maximize the success of vocal communication while minimizing the costs of vocalizing (Bradbury and Vehrencamp, 1998). Common costs associated with vocalizing are increased exposure to predators and parasites, increased energy expenditure, and time that otherwise would be available for other activities.

From the perspective of the manatee, increased energy expenditure is most salient because they currently have no natural predators other than humans, their food source is stationary vegetation, and manatees are able to vocalize while engaged in other activities. Increasing the energy involved in vocalizing is most likely to increase the range of effective communication; therefore, it stands to reason that manatees only increase their vocalization effort when the benefits of effective vocal communication outweigh the cost of increased energy expenditure. Some benefits of effective communication include maintaining mother-calf contact, maintaining group contact, and signaling intentions.

Manatee vocal effort was quantified by changes in vocalization structure and usage, which fell into two broad categories: 1) increasing effort through an increase in emitted sound output and 2) increasing effort by shifting vocalization frequencies. For signals used in long-distance communication, it is usually assumed that selection should favor increased signal amplitude at the receiver. This can be accomplished by increasing the signal amplitude at the source and by decreasing the loss of signal amplitude during transmission (Ryan, 1986; Ryan and Brenowitz, 1985). Increasing sound output is accomplished by increasing vocalization rate, duration, and/or source level. Shifting vocalization frequencies to bands with less noise or interference has the potential to decrease the loss of signal amplitude during transmission, thus increase the range of effective communication. However, frequency shifting may also incur additional energetic costs. It has been argued that shifting vocalizations to higher frequencies increases vocal effort because it takes more energy to produce high frequency sounds that are closer in wavelength to the size of the sound-producing and

resonating structures (Ryan, 1986). This has been demonstrated for frog and cricket species and is “probably true in many if not all animals “ due to the mismatch between wavelength of the sounds produced and the radiating structures involved in coupling the sound to the environment (Ryan, 1986). Neither the amount of energy used in producing a single call or the exact location and size of the sound producing organs has been documented in manatees, but it is possible that manatees exhibit a similar energetic cost of shifting to higher frequencies. Excessive increases in vocalization effort could potentially affect the energy budgets of this species on both short-term and long-term time scales.

Manatees exhibited marked changes in vocalization effort by increasing sound output and frequency shifting as a function of behavioral state and calf presence. Vocalization rates were greatest during social and resting behaviors when one or more calves were present. Chirp durations were also longest when calves were present during feeding and milling behaviors, and source levels were greatest during resting and feeding behaviors when calves were present. Differences in frequency were only observed within chirp vocalizations. Overall, chirps were higher in both minimum and maximum frequencies during milling and resting behaviors. By contrast, the frequency of peak energy was significantly lower for chirps during feeding. When calves were present, maximum chirp frequencies also decreased. Differences in chirp frequency characteristics suggest that more vocal effort is expended during milling and resting, and less energy is utilized during feeding. It appears that manatees predominantly increase vocalization effort, as evidenced by increases in sound output, when one or more calves are present. Increased output effort may aid in more

effective communication geared towards maintaining mother-calf contact. When the two components of vocalization effort are surveyed in combination, a pattern of tradeoffs emerge within specific behaviors. For example, manatees increase vocal effort with increases in sound output during feeding, yet this is countered by a reduction in vocal effort associated with low chirp frequencies. These findings are the first to suggest that manatees do alter their vocalization effort, as indicated by changes in usage and structure, based on behavior and group conditions, but more extensive studies are needed to provide clear details of how these changes relate to energetic expenditure.

Whether most marine mammals can adjust the frequencies, duration, rate, and source levels of their various call types to increase communication range in the presence of noise has not been extensively studied (Richardson et al., 1995). Animals can potentially increase the effective range of communication calls by increasing the vocalization rate rather than emitting single brief sound, as a rapid sequence of brief sounds is more detectable amidst background noise. This has been demonstrated with the echolocation clicks of odontocetes and the short tone pulses emitted by harbor seals (*Phoca vitulina*) (Au, 1993; Johnson, 1991; Turnbull and Terhune, 1993). There is also evidence that toothed whales can shift the dominant frequencies of echolocation signals from ranges of elevated noise toward ranges with less noise (Au, 1993; Lesage et al., 1993; Romanenko and Kitain, 1992; Turl et al., 1991). Source level increases in response to elevated noise levels have been documented in beluga whales (*Delphinapterus leucas*), which suggests these animals exhibit a Lombard

vocal response similar to humans, monkeys, bats, cats, and birds (Scheifele et al., 2005).

When the effort of manatee vocalization was examined in relation to ambient noise levels, results showed that as noise levels in the frequency range of 16-64 kHz increased, manatees increased the duration of chirp vocalizations during feeding and milling when calves were present. Manatees engaged in feeding and milling behaviors do tend to separate more than when resting or socializing, so it is possible that manatees need to increase vocal effort to compensate for higher noise levels at these times. The patterns observed during resting were inconsistent. Source levels increased with decreasing noise in the frequency range of 250 Hz-4 kHz, indicating an increase in vocal effort with a reduction in noise. Minimum frequency was also found to decrease with increasing noise level, indicating a decrease in vocal effort with an increase in noise. This pattern may indicate that manatees wait until it is quiet to vocalize while resting, consequently minimizing vocalization effort during periods of high noise. Noise levels in Sarasota Bay are at a minimum during the morning hours (Chapter 2), so if this theory is correct, manatees in Sarasota Bay should have greater vocalization rates, source levels, and minimum frequencies during the morning hours. The data from this study can neither support nor dispute this theory. Although the results pertaining to the question of whether or not manatees alter their vocalization usage as a function of noise level are inconsistent, the increased vocalization effort exhibited during feeding and milling behaviors at times of elevated noise conditions suggests ambient noise levels do have a detectable effect on manatee communication and that manatees are able to modify their vocalizations as a function of noise.

4.6 Acknowledgements

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Chapter 5. Characterizing Manatee Responses to Playbacks of Approaching Vessels

5.1 Abstract

One of the most pressing concerns associated with the endangered Florida manatee is mortality and serious injury due to collisions with watercraft. Watercraft collisions are the leading identified cause of manatee mortality, resulting in 25 to greater than 30% of deaths each year. The primary management tools aimed at reducing manatee mortality have been establishing zones where boat speed is regulated and limiting boat access in certain areas. The successful establishment and management of boat speed regulatory zones and manatee sanctuaries depends upon the acquisition of data assessing behavior patterns, habitat-use patterns, and identification of environmental characteristics influencing manatee behavior and habitat selection. Detailed information on manatee distribution, behavior patterns, and habitat-use during non-winter months is sparse compared to the amount of knowledge and number of studies at winter aggregation sites. Acoustic playback experiments were conducted to assess the behavioral responses of manatees to watercraft approaches in shallow-water environments during the non-winter season. Playback stimuli were constructed to simulate a vessel approach to approximately 10m in seagrass habitats. Stimulus categories were 1) silent control, 2) approach with outboard at idle speed, 3) planing outboard approach, and 4) fast personal watercraft approach. Analyses of swim speed, changes in behavioral state, and respiration rate indicate that the animals respond differentially to the playback categories. The most pronounced responses, relative to the controls, were elicited by the personal watercraft. All subjects showed a visible response to the personal watercraft stimuli, and the most common response (68%) was

a fast swim directly away from the playback vessel towards deeper water. An increase in ventilation variability occurred in response to both planing outboard and personal watercraft approaches. Quantitative documentation of response during playbacks provides data that may be used as the basis for future models to predict the impact of specific human activities on manatees and other marine mammal populations.

5.2 Introduction

Watercraft pose a threat to manatees. A pressing question is how to minimize both the lethal and non-lethal impacts on manatees while permitting watercraft to operate. Carcass recovery programs have provided a great amount of information associated with the lethal effects of manatee-boat interactions (Wright et al., 1995), but information regarding the non-lethal effects of watercraft interactions is lacking. The non-lethal impacts of boating on the physical health of manatees, as well as an indirect impact on food availability and communication are controversial topics unsupported by adequate empirical data. Identifying specific environments or behaviors that put manatees at a greater risk for boat collisions and quantifying manatee reactions to varying speeds and motor types of approaching vessels are necessary steps towards achieving the overall goal of minimizing the negative, non-lethal impacts of boats and the noise they make.

Manatees most commonly encounter relatively small boats: outboard or inboard/outboard leisure boats, personal watercraft (PWC), and fishing trawlers (Gorzelany, 2004). Less frequently, manatees encounter larger tugboats and ships near deeper shipping channels. Noise produced from boats falls into two major

categories: cavitating and non-cavitating noise. Non-cavitating noise originates from a combination of propeller singing and other propulsion machinery. Hull interactions with the water (e.g. hull slapping, waves, etc.)are also a source of non-cavitating noise. Cavitating noise is associated with propeller rotation. When propellers rotate at fast speeds tiny bubbles form and then collapse. The collapsing of each bubble produces a broadband sound. Propeller cavitation is usually the dominant noise source of boats traveling at high speeds, whereas non-cavitating noise is more dominant at idle and slow speeds (Ross, 1976). In general cavitating noise is higher in frequency than non-cavitating noise. Noise associated with PWC is unique in that the propeller is not directly exposed to the water, but housed inside the hull. This not only enables PWCs to travel into very shallow areas, but it also produces a different acoustic signature compared to outboard motors.

The sounds produced by watercraft span a wide range of frequencies ranging from 10 Hz – 20,000 Hz, but the dominant noise spectra are typically below 2000 Hz. The estimated 1/3-octave source levels at 1 m for small boats are 120-160 dB re 1 μ Pa @ 1 m (Figure 5.1) (Gerstein, 2002; Richardson et al., 1995). When measured from approximately the same distances, planing PWC are 9 dB quieter than planing motorboats within the same habitat type (Buckstaff, 2004).

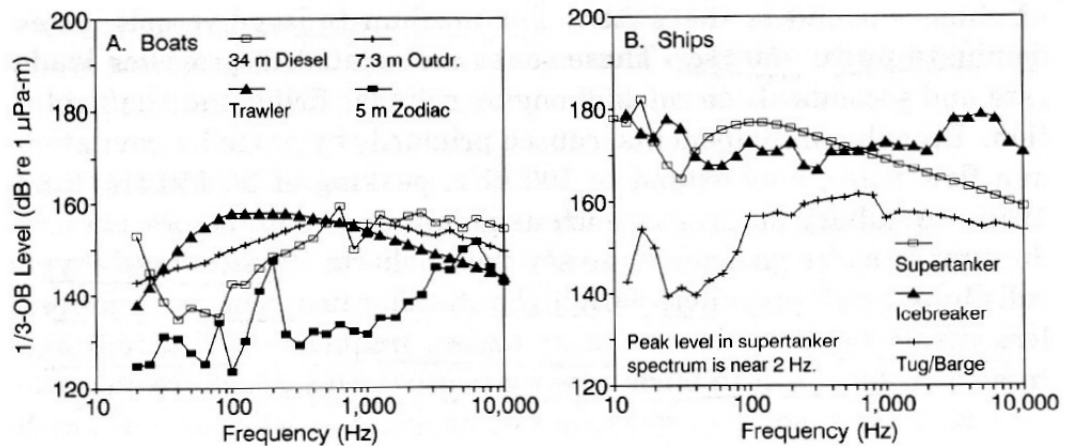


Figure 5.1. Estimated 1/3 – octave source levels of underwater noise at 1 m for examples of boats and ships. This image is reproduced from Figure 6.5 in Richardson et al., 1995.

5.2.1 Detection of Sound

Do manatees hear the noise produced from approaching boats in enough time to swim out of harm's way? The core of this question is rooted in the detection of sound signals. What frequencies are manatees capable of hearing, and how loud does the sound need to be at those frequencies? Despite the controversy concerning the frequency of peak hearing sensitivity, physiological, anatomical, and behavioral studies indicate that manatees should be able to detect approaching boats (Gerstein, 2002; Ketten et al., 1992; Nowacek et al., 2000; Nowacek et al., 2004). This is confirmed by field studies in which manatees were observed to respond to approaching boats (Nowacek et al., 2000; Nowacek et al., 2004; Reynolds, 1981a; Weigle et al., 1994). Quantitative responses to boat approaches were documented by Nowacek et al. (2000, 2004). Manatees detected boat presence from up to 1 km away and made gross changes in behavior at approximately 25-50 m from approaching watercraft. Specifically, animals increased their swimming speed and movement was

made towards deeper channel waters in response to boat approaches. Boat distance from the manatees, water depth at the boat, and water depth at the manatees all had a significant effect on swimming speed, whereas the type of boat or boat speed had no significant effect.

5.2.2 Localization of Sound

Accurate detection of an approaching boat is only part of the problem for a manatee. In order to swim out of the direct path of the boat, the manatee must accurately localize the boat and respond accordingly. Similar to the debate on the frequency of best hearing, localization capabilities of manatees are still being investigated. Based on inner ear structure, Ketten et al. (1992) reported that manatees lack the directional hearing capabilities compared with most mammals. However, in a study conducted by Gerstein (1999a) a manatee demonstrated equal localization of sounds originating from the left or right side, and accuracy improved with higher frequencies during psychoacoustic testing. The manatee also demonstrated good overall localization of both low and higher frequency sounds, suggesting it may utilize both time of arrival cues and intensity difference cues for localizing brief sounds. Localization was best at $\pm 45^\circ$ relative to head on (Gerstein, 1999a). Directional hearing may be enhanced by the lipid composition in the zygomatic process of the squamosal bone by providing a channel for sound conduction similar to the function of the intramandibular fat body in bottlenose dolphins and other odontocetes (Ames et al., 2002).

The physical characteristics of sound in shallow water further complicate localization of sound sources for manatees. Compared to deep water, sound simply

does not travel efficiently through shallow water environments (Medwin and Clay, 1998). With respect to the sound source, higher frequencies have shorter wavelengths and are therefore more directional than lower frequencies. High levels of sound reverberation in shallow water combined with the omnidirectional characteristic of low frequency sound produced by boats makes localization difficult for even the most accurate localization techniques. It is interesting to note that bottlenose dolphins (*Tursiops truncatus*), which have excellent localization capabilities, have been hit by boats in shallow water (Buckstaff, 2004; Wells and Scott, 1997).

5.2.3 *Disturbance by Boats*

Manatees that do manage to avoid collisions with watercraft still need to cope with the indirect effects of boats. There were approximately 943,872 boats registered with the state of Florida from 2003-2004, and numbers are expected to increase as the human population increases along the coast (Florida Department of Highway Safety and Motor Vehicles, 2005). Boats produce noise over the same frequencies as manatee vocalizations. Motor noise can potentially mask communication signals of which manatees depend for survival. For example, if efficient communication is reduced by boat noise, females may lose contact with their calves or other members of a group, which could affect survival of the calves.

Heavy vessel traffic may also cause manatees to expend more energy than they normally would and cause them to leave optimal habitats (Reynolds, 1999). Manatees significantly increase swim speed and move from shallow waters to deeper channels during boat approaches (Nowacek et al., 2001a). Manatees also reduce their use of

critical habitats with chronic boat disturbance (Buckingham et al., 1999; Provancha and Provancha, 1988). For example, high levels of human activity in Kings Bay (a winter thermal refuge) influenced manatee distribution, which resulted in an increase of their use of needed warm-water sanctuaries in the southern portion of the bay (Buckingham et al., 1999). Data for the Buckingham et al. (1999) study were collected during aerial surveys, and manatee counts were correlated with number of boats in the area. Disturbance was inferred from the number of boats, but noise levels were not recorded.

Disturbances created by boats could affect time and energy budgets that could result in sickness and death if manatees were to leave warm-water refuges during cold weather (O'Shea et al., 1995; Reynolds, 1999). It is conceivable that the presence of high noise levels generated by human activities may put manatees more at risk when they move to areas that seem quieter. For example a manatee in a deep boating channel may experience high levels of noise due to the large number of boats and low sound transmission loss in a deep channel. If the animal were to move to a seemingly quieter area to feed in a grassbed 5 meters away, the noise level would be less because of the higher transmission loss that attenuates approaching boat noise (see Chapter 2). In this case manatees could be moving to areas in which they are more at risk for collisions. However, manatees typically move from shallow water to deeper channels in response to direct boat approaches (Nowacek et al., 2000). The example described above illustrates movement in the opposite direction, so the example would only apply when animals are freely moving from one habitat to another during daily activities and being influenced by direct boat approaches. These results clearly indicate the need for

playback experiments to further illuminate the varying degree of manatee responses to direct vessel approaches.

5.2.4 Playbacks

In this study, response time and degree of response were evaluated for the playback of sounds simulating approaching vessels. Responses were categorized based on changes in behavioral state, orientation, direction of movement, ventilation rate, and fluke stroke rate. The playback study was designed to address the question of whether differences in manatee responses to the approaching boat noise recordings were related to engine type and/or vessel speed. It was assumed that manatees would respond to the playback of boat approaches in a similar way that they responded to direct boat approaches by increasing swim speed and moving towards deeper channel waters (Nowacek et al., 2001a; Nowacek et al., 2004). Avoidance behaviors such as these are not unique to manatees, as these behaviors have also been elicited by cetaceans in response to approaches to motorized watercraft (Buckstaff, 2004; Janik and Thompson, 1996; Kruse, 1991; Nowacek et al., 2001b). At the present time, it is unclear whether or not manatees discriminate among different types of vessel approaches.

“The playback of natural and synthetic sounds has been used as an experimental technique with diverse groups of animals to gain insight into the biological significance of the sounds (frogs, birds, primates, and humans; (Hauser, 1996). The purpose of playbacks is to broadcast a sound and observe the animals untrained, naturally occurring responses to particular stimuli, as opposed to trained responses. The intention of a playback study is to mimic the natural presentation of a stimulus in such a way that the recipient's response reveals something about how the animal perceives and categorizes the signal (Hopp and Morton, 1998). Simple playbacks focus on the presence or absence of a response to the stimuli presented. By analyzing the pattern of responses, the features of the sounds essential for eliciting a response are identified. More complex playbacks measure variations in the magnitude or

intensity of responses to specific stimuli in order to make inferences about how animals perceive variation and discriminate between different sounds” (Miksis, 2000).

5.3 Methods

5.3.1 *Stimulus Recordings*

All stimulus recordings were made by a single hydrophone suspended from a recording vessel anchored in a seagrass habitat adjacent to a boating channel (Figure 5.2). The recording system (Recording System B) had a frequency response of 20 Hz – 22 kHz with a -178 dB re 1 V/ μ Pa sensitivity at 16 bit resolution, and the peak acoustic level of the system was 178 dB re 1 μ Pa. For each stimulus the sound was recorded as a vessel approached the recording hydrophone from approximately 500-1000 m away at a constant speed. The vessel approached to exactly 10 m of the recording hydrophone and continued away at a constant speed for another 500-1000 m. This method allowed for received levels at 10 m distance to be calculated (Table 5.1). Acoustic recordings of vessel approaches were made at two boat speeds: idle and full-throttle planing.¹ Multiple exemplars from each category were recorded in order to ensure the generality of results and avoid pseudo-replication. Two exemplars were recorded for idle approaches. One vessel had a 115 hp, 4-stroke outboard motor, and the other vessel had a 110 hp, 4-stroke outboard motor. The same vessels were used to record two exemplars during a planing approach. Four exemplars were made using personal watercraft (PWC). Two separate 4-stroke PWCs were used to produce two planing approach recordings from each vessel for a total of four exemplars. Each PWC was recorded at 2 planing speeds: 25 mph and 40 mph (Table 5.1).

¹ Stimulus recordings were made in accordance with U.S. Fish and Wildlife permit MA071799-0 issued to Jennifer Miksis at the University of Rhode Island for the purpose of conducting playback experiments with Florida manatees.

The duration of all stimulus exemplars, regardless of stimulus category, was edited to three minutes to ensure the same length for each exemplar. This was done to control for the amount of time the playback subject was exposed to any sound coming from the playback system. Three minute durations were chosen based on the longest audible approach sequence, which was the slow moving idle approach. For the idle approaches, 45 seconds of ambient noise preceded and followed the onset and offset of the stimulus signal, resulting in a total exemplar duration of three minutes. For planing and PWC approaches ambient noise preceding and following the stimulus signal was appropriately truncated to produce a final stimulus duration of three minutes. The amount of noise added prior to the stimulus onset was equal to that added after the signal offset. A silent control of three minutes was also constructed.

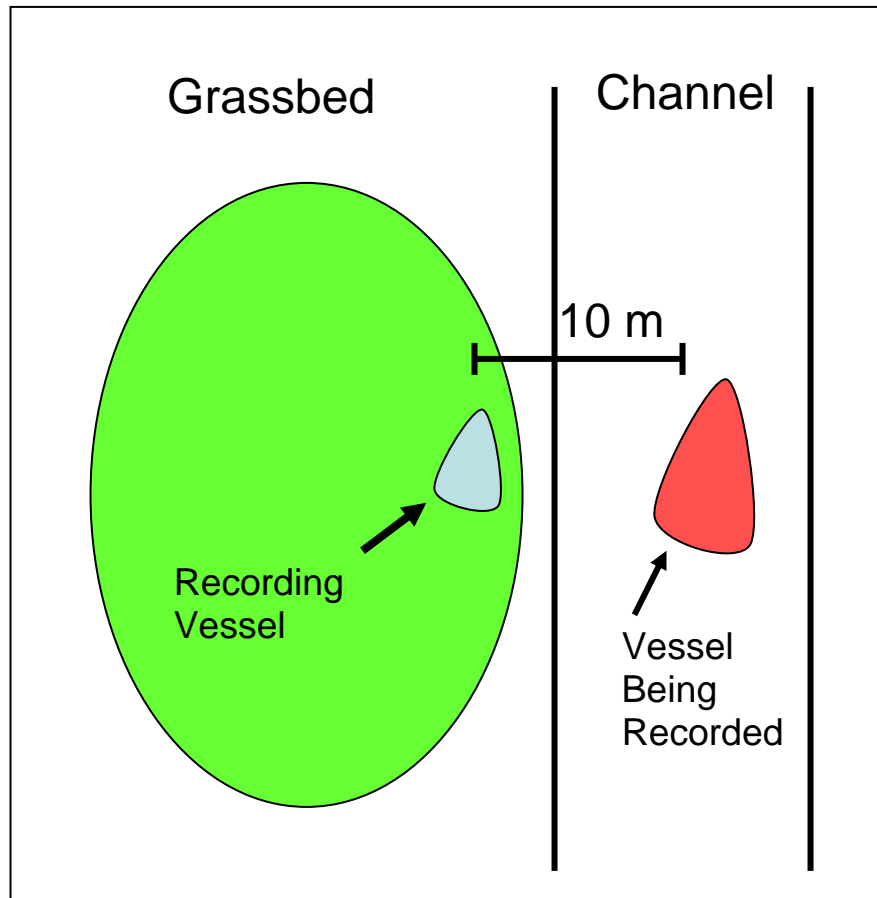


Figure 5.2. Schematic depicting vessel placement for playback stimulus recordings.

Table 5.1. Characteristics of playback stimuli.

Category	Exemplar	Received Level @ 10 m	Speed (miles/hr)	Motor Size
Idle	1	150 dB	5	115 hp
	2	151 dB	5	100 hp
Planing	1	168 dB	35	115 hp
	2	163 dB	35	100 hp
PWC	1	166 dB	40	1235 cc
	2	158 dB	25	1235 cc
	3	157 dB	25	1235 cc
	4	162 dB	40	1235 cc

5.3.2 Playback Categories

Clear differences among the stimulus groups allow for potential acoustic discrimination among the three playback categories by a manatee. The stimulus categories differ not only in their acoustic envelopes, or overall amplitude shape, but also in their frequency characteristics (Figure 5.3). The idle approaches had the longest stimulus duration, but smallest stimulus amplitude (Figures 5.3a and 5.3b). The planing approaches had a sharper rise time and greater amplitude than the idle approaches, but with a shorter acoustic envelope. The planing approaches also had a more gradual onset compared to the abrupt offset. The acoustic envelope of the PWC approaches was the smallest with the sharpest rise time and approximate equal peak amplitude as the planing approaches.

The differences in frequency parameters were most evident in the spectrograms of Figure 5.3c. The idle approaches lacked a clearly defined broadband peak at the closest point of approach, and the U shaped bands indicated the Beta effect of sound during the approach and retreat. The planing and PWC approaches had a clear broadband peak at the closest point of approach.

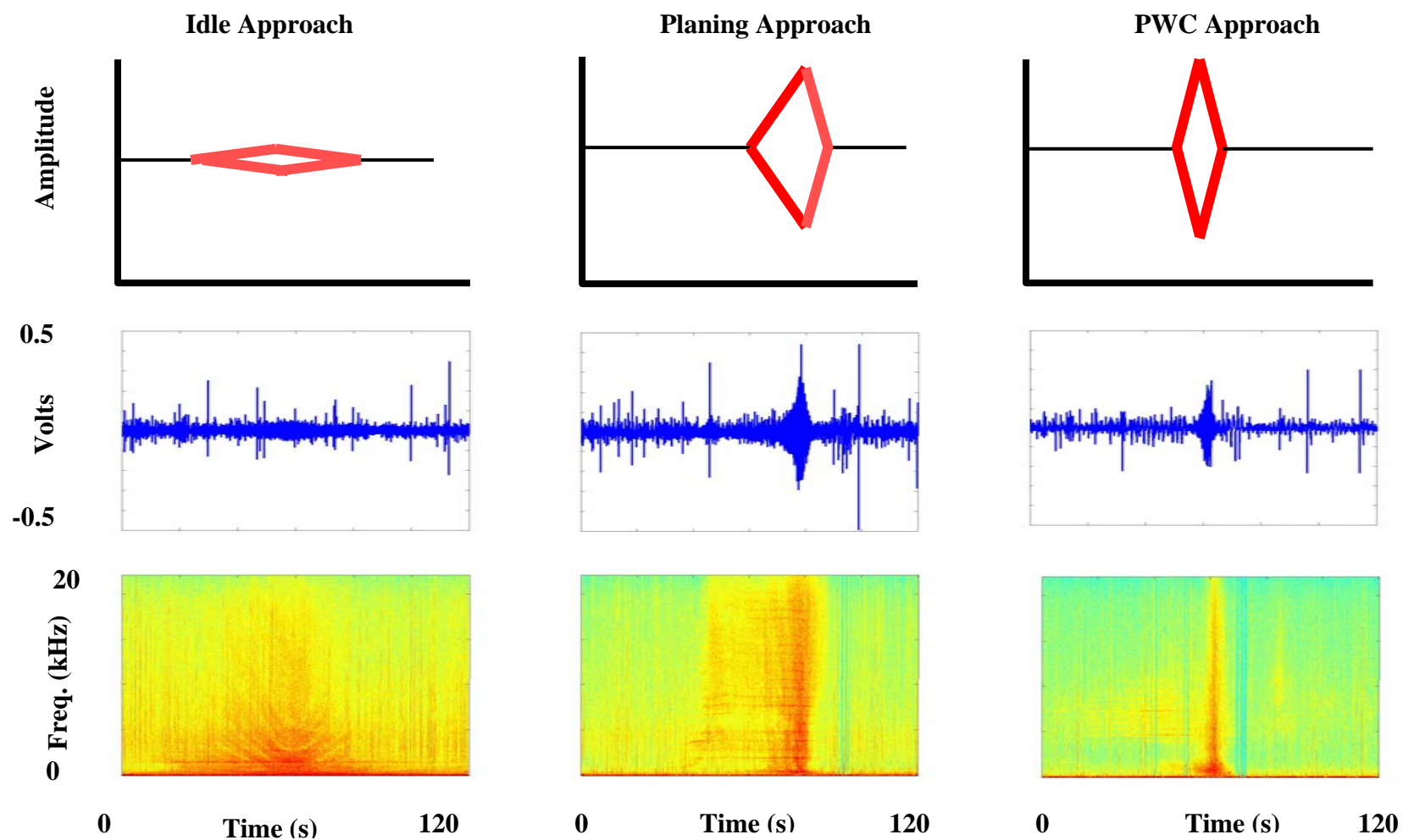


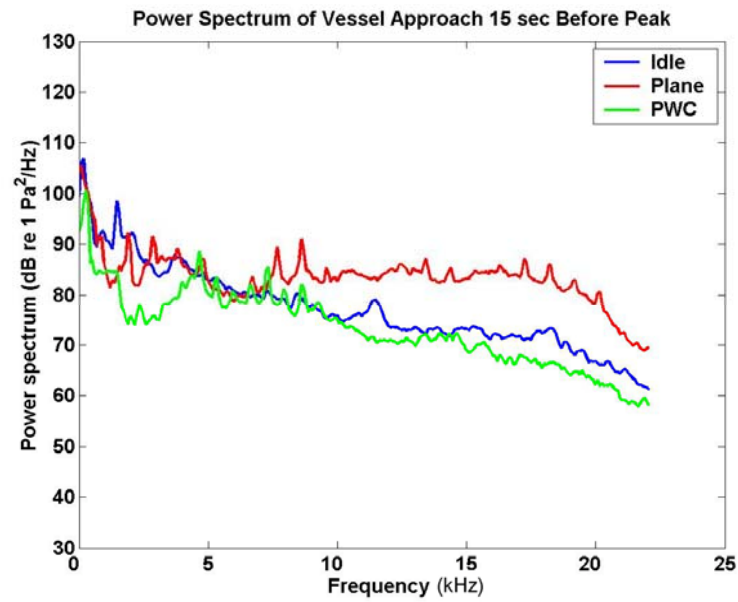
Figure 5.3. Playback categories aligned in time. Top row shows the acoustic envelope difference among the categories. The middle row shows the raw time series of a single exemplar within each category. The bottom row shows the corresponding spectrograms for each exemplar.

This was preceded by a strong tonal, harmonic signal. In the PWC approaches, the tonal component of the approach was vastly reduced compared to the planing approaches, and the broadband peak of the PWC approach was also much narrower. Figure 5.4 further illustrates the difference in frequency spectra among the playback categories. Fifteen seconds prior to the peak of approach, the PWC was approximately 10 dB quieter than both the idle and planing signals at 2-3 kHz (Figure 5.4a). The magnitude of the idle and planing approaches was similar up to approximately 6 kHz. Above 6 kHz, the planing approach became about 10 dB louder than both the idle and PWC signals. Fifteen seconds prior to the peak of approach, the planing approach transmitted the loudest signal in the higher frequencies. The planing approach was also clearly the loudest at the peak of approach by about 10 dB (Figure 5.4b), with the exception of the PWC being the loudest between 2-3 kHz. The idle approach was the quietest at all frequencies during the peak of approach.

To get a better idea of what the manatees detected during the vessel approaches, the power spectra of approaches were weighted by the only available manatee hearing thresholds as measured by Gerstein et al. (1999b) (Figure 5.5). Prior to the closest point of approach (Figure 5.5a), planing signals were most salient above the background noise. The idle approach was above both the hearing threshold and noise floor for frequencies of approximately 2 kHz, whereas the PWC signature was either at or below detectable levels. At the closest point of approach (Figure 5.5b), both the planing and PWC signals were well above threshold levels for all except the very lowest frequencies. The idle approach signal was loudest at approximately 2 kHz

at the closest point of approach, but this level is 5 dB quieter than the planing and PWC levels.

a.



b.

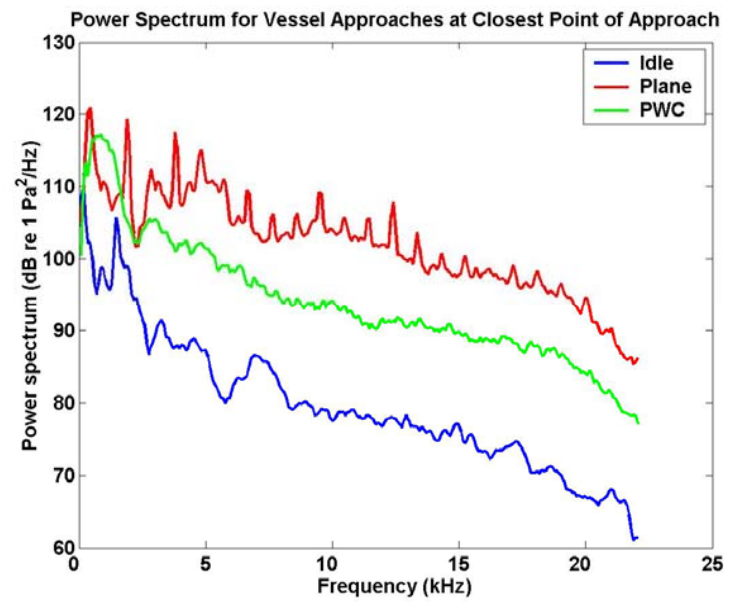
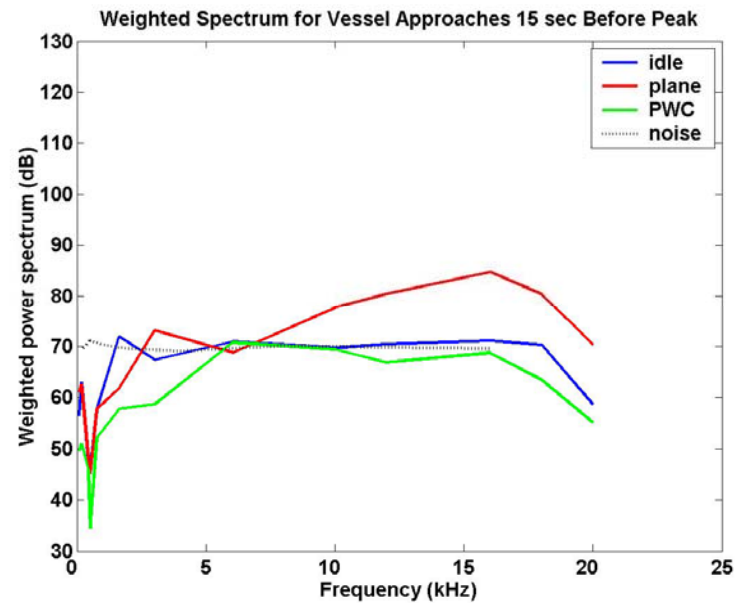


Figure 5.4. Power spectra of vessel approach stimuli: a) the comparison of 2 second clips measured 15 seconds before the closest point of approach. b) the comparison of 2 second clips taken at the closest point of approach.

a.



b.

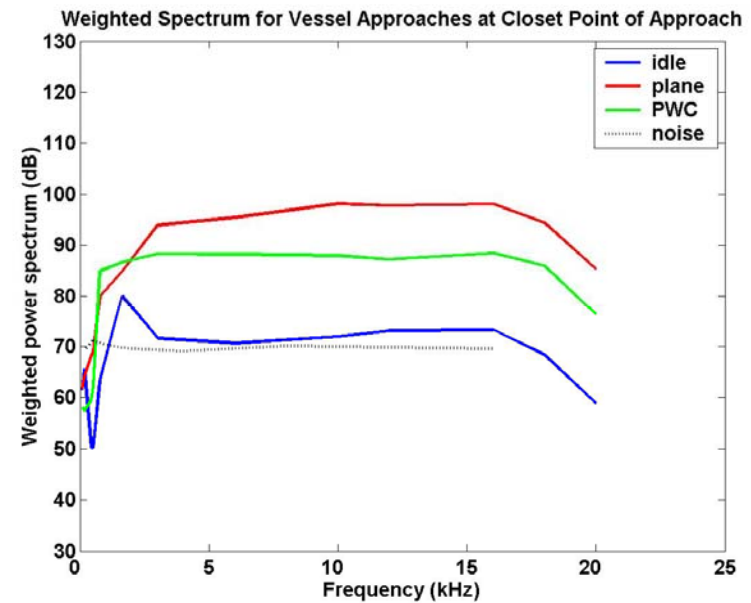


Figure 5.5. Spectra of vessel approaches weighted by the manatee hearing thresholds and smoothed in frequency plotted with ambient noise levels. a) comparison of 2 second clips measured 15 seconds before the closest point of approach. b) comparison of 2 second clips taken at the closest point of approach.

5.3.3 *Playback Experiments*

5.3.3.a Playback Constraints

The playback protocol was constrained by the guidelines of U.S. Fish and Wildlife permit MA071799-0 issued to Jennifer Miksis at the University of Rhode Island. The maximum number of playback takes authorized by the permit was 70 wild manatees per year; 50 of these individuals could be a target subject for one playback series a year and 20 animals could be tested up to 3 times per year. All playbacks had to be performed within a single habitat type from a boat using a trolling motor. Total exposure could not exceed a 10 minute cumulative duration, and projected levels could not exceed recorded levels. Playback experiments were to be terminated if non-targeted animals entered the immediate area, or if the manatees were eliciting distress responses defined as repeated tail fluking in the vicinity of the playback vessel.

5.3.3.b Playback Protocol

All playbacks were conducted in grassbed habitats, as grassbeds were where all significant usage correlations with vessel noise were observed in Chapter 2. Restricting playbacks to one habitat type also eliminated a variable in the statistical analysis, which helped to increase the sample size within each playback category. Additionally, playbacks were only performed with animals that were initially feeding or resting. During these two behaviors the animals were relatively stationary compared to traveling, milling, or social behaviors; therefore, deviations from original behaviors were more easily observed and quantified. Restricting playbacks to two specific behavioral states also served to reduce the number of categories of analysis for statistical purposes, thus increasing the degrees of freedom for each test.

The goal was for the playbacks to simulate a boat approaching a manatee to 10 m when the playback vessel was between 2-25 m from the animal. Transmitted levels were adjusted so that the animal had a consistent 10 m received sound level regardless of distance to the playback vessel. In order to make the playbacks more realistic, the same logistical set-up was used for each playback (Figure 5.5). The playback vessel was always positioned between the playback subject and the closest boating channel to simulate a boat approaching from deeper water and from the direction that a majority of boats would be traveling.

During playback experiments, the focal animal (occurring as a single animal or in a pair) was observed for a minimum of 20 minutes before and after the exposure of the playback stimuli. During this time the subject was either identified from previously catalogued animals or photographed for later identification. Playbacks were only conducted in instances where no other animals were observed within a visual radius during the 20-minute pre-exposure period. Pre and post-stimulus observation included 4 minute interval sampling of focal animal course, heading, distance to boat, and behavioral state. Continuous recording of ventilation rate and vocalization rate was maintained. Vocalizations were recorded with a hydrophone deployed from the playback vessel. If the animals fled the area during the pre-exposure period or during exposure to the playback stimuli, they were not pursued or chased.

Five minutes prior to the playback of any stimulus, the research vessel was anchored within 25 m of the focal animal and the sound source was deployed. A Lubell transducer was used to playback the boat noise stimuli. This stationary system

was capable of producing sound of approximately 180 dB re 1 μ Pa at 1 m in the frequency range of 240 Hz – 20 kHz. Response due to multiple boat interactions was avoided by only performing a playback when no other vessel had entered the area for a 15 minute period prior to the start of playback session. Each playback session consisted of 4 playback stimulus presentations presented 5 minutes apart. The five minute stimulus presentation was chosen based on the knowledge that bottlenose dolphins in Sarasota Bay encounter a passing vessel every six minutes (Buckstaff, 2004). Manatees would encounter a similar or shorter boat encounter frequency depending upon the number of recreational vessels in grassbeds at any particular time. One stimulus from each of the 4 categories (control, idle, plane, PWC) was presented in random order. If the focal animal moved outside of a 25 m radius before the presentation of the last stimulus, the research vessel re-anchored closer to the animal and the remaining playback stimuli were presented followed by a 20 minute post-stimulus observation period. In an effort to avoid pseudoreplication, defined as generalization from a study due to an animal responding to or learning from a single exemplar (Kroodsma, 1989), no manatee was a playback subject more than twice, and no animal ever received the same exemplar more than once.

During the playback session, observations included point sampling of focal animal course, heading, distance to boat, ventilation, and behavior. Visually observed responses to the playback stimuli generally fell into four categories: 1) investigate boat, 2) slow swim, 3) rolling dive, and 4) fast swim. Animals investigating the boat swam directly to the boat and interacted with the boat in some way. Slow swims were characterized by the animals changing position relative to the playback vessel without

any visible wake or fluke prints. Rolling dives were identified by the arching of the manatee's back and entire fluke leaving the water prior to a dive. Last, fast swims were characterized by a visible wake and destructive fluke prints, often accompanied by a mud cloud stirred up from the bottom. Two retreating behaviors were also observed: 1) retreat to deep water and 2) pass by boat on the way to deep water. Direct retreats were characterized by the animal increasing distance from the playback vessel in the direction of deeper water (Figure 5.6a). Passing by the boat on the way to deep water was a separate classification because the animal had to initially approach the playback vessel before retreating to deeper water (Figure 5.6b).

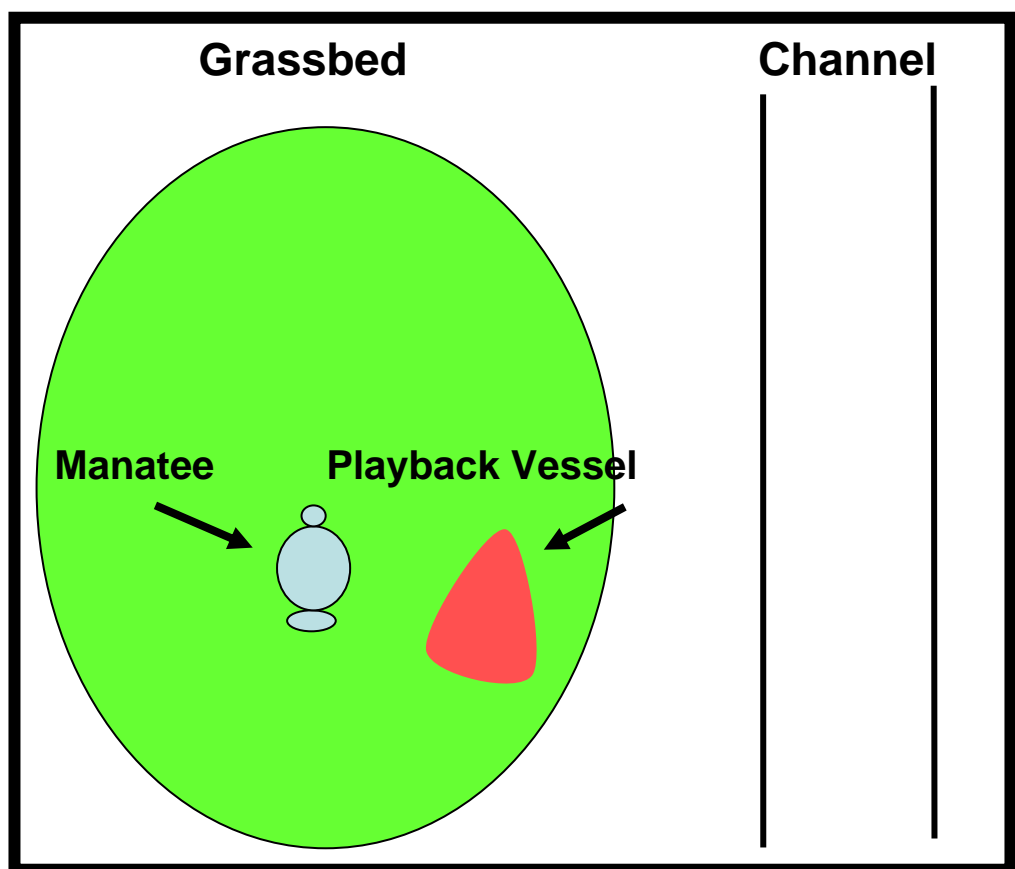
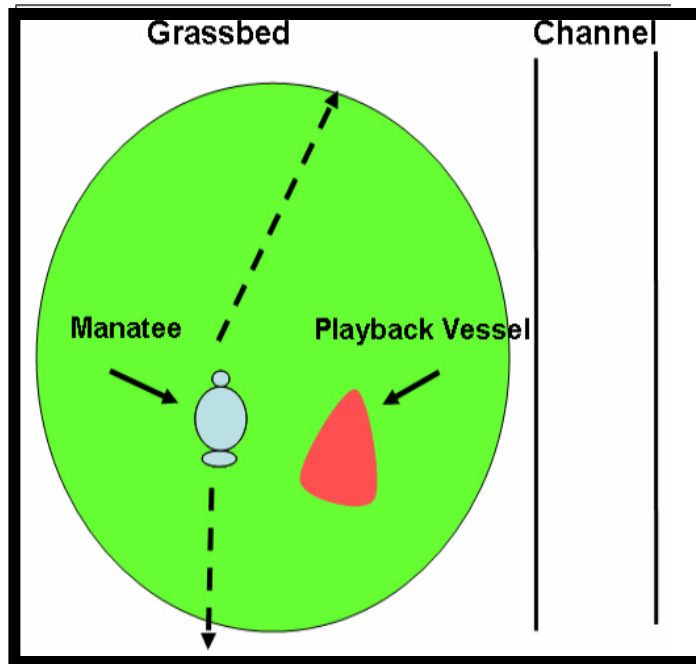


Figure 5.6. Schematic showing playback set-up.

a)



b)

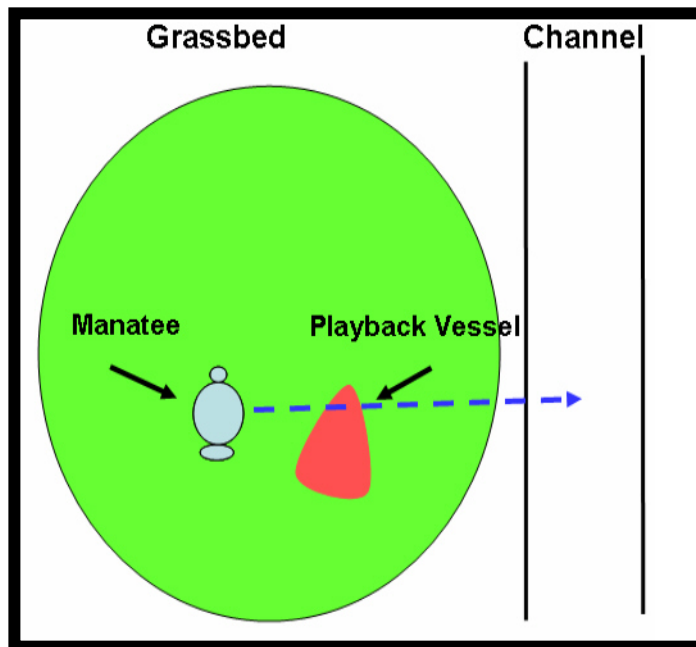


Figure 5.7. Schematics showing potential manatee paths of responses. a) represents a direct approach to deep water while avoiding the playback vessel. b) represents a response where the animal initially approaches or passes the boat in order to retreat to the deep water beyond the playback vessel.

5.4 Results

Manatees showed a marked visible response to the playback stimuli compared to the silent control (Figure 5.7). Seventeen out of 21 animals (81%) showed no visible response to the silent control. The frequency of no response was significant at the 95% significance level based on a binomial distribution ($p < 0.001$). This indicated that the control was operating effectively. Thirteen out of 20 animals (65%) showed no response to the idle approach, whereas 35% showed some type of visible response (i.e. slow swim, approach boat, fast swim, etc.). This response rate was not significant. During the planing approaches there was a significant visible response rate of 63% ($p = 0.002$). Of the 12 animals that showed a visible response to the planing approach, two abandoned the area. All animals showed a visible response to the PWC approach ($p < 0.001$). Four of the 20 animals that responded (20%) left the area.

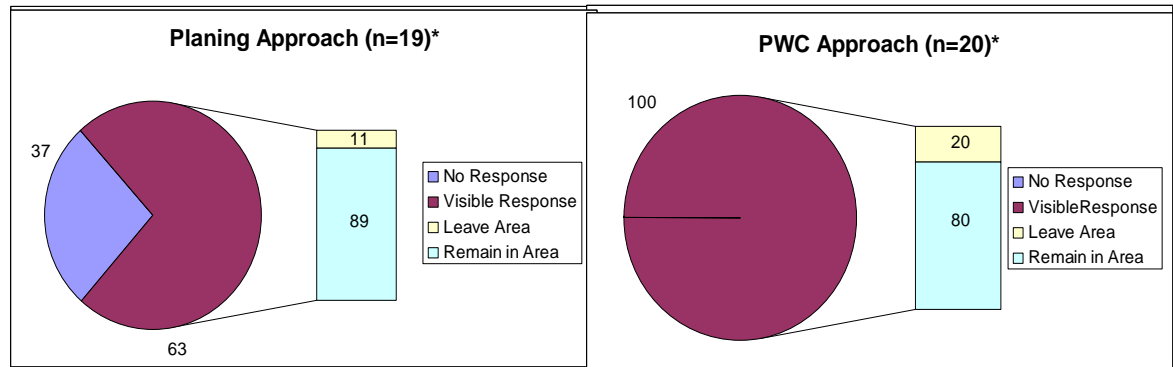


Figure 5.8. Manatee response to the 4 playback categories. Asterisk (*) indicates significance at the 95% significance level based on a binomial distribution.

An analysis of response orientation and heading of those animals that did show a visible response to the playback stimuli revealed a striking pattern (Figure 5.8). Of the four animals that did respond to the control, all four investigated the boat. Seven animals out of 20 responded to the idle approach. Of the seven, four (57%) retreated directly to deep water, two (29%) passed by the playback vessel on the way to deeper water, and one animal (14%) retreated from the playback vessel to shallow water. During the planing and PWC approaches, the number of animals retreating directly to deep water increased whereas the number of animals passing by the boat decreased. In general, manatees tended to respond to all approaches by retreating to deep water. The frequency of animals retreating directly to deep water increased in response to an increase in speed of the approaching vessel.

Behavioral analysis of the retreating animals showed a graded response in behavior associated with playback category (Figure 5.9). No animals retreated during the controls, so this category was not included in the analysis. The frequency of

animals retreating with a slow swim decreased from 71% in response to the idle approach to 37% for the planing approach to finally 16% in response to the PWC approach (Figure 5.9a). Analysis of frequency using a RxC G-test for independence revealed that the frequency of the slow swim response was dependent on playback category ($0.01 < p < 0.025$) (Sokal and Rohlf, 1995). Similarly, the increase seen in the frequency of fast swim response was dependent upon playback category ($0.01 < p < 0.025$). No animals responded to the idle approach with a fast swim, where as 37% and 68% responded to the planing and PWC approaches, respectively (Figure 5.9b). There was slight decrease in the frequency of rolling dive responses to the PWC approaches, but this decrease was not significant pattern.

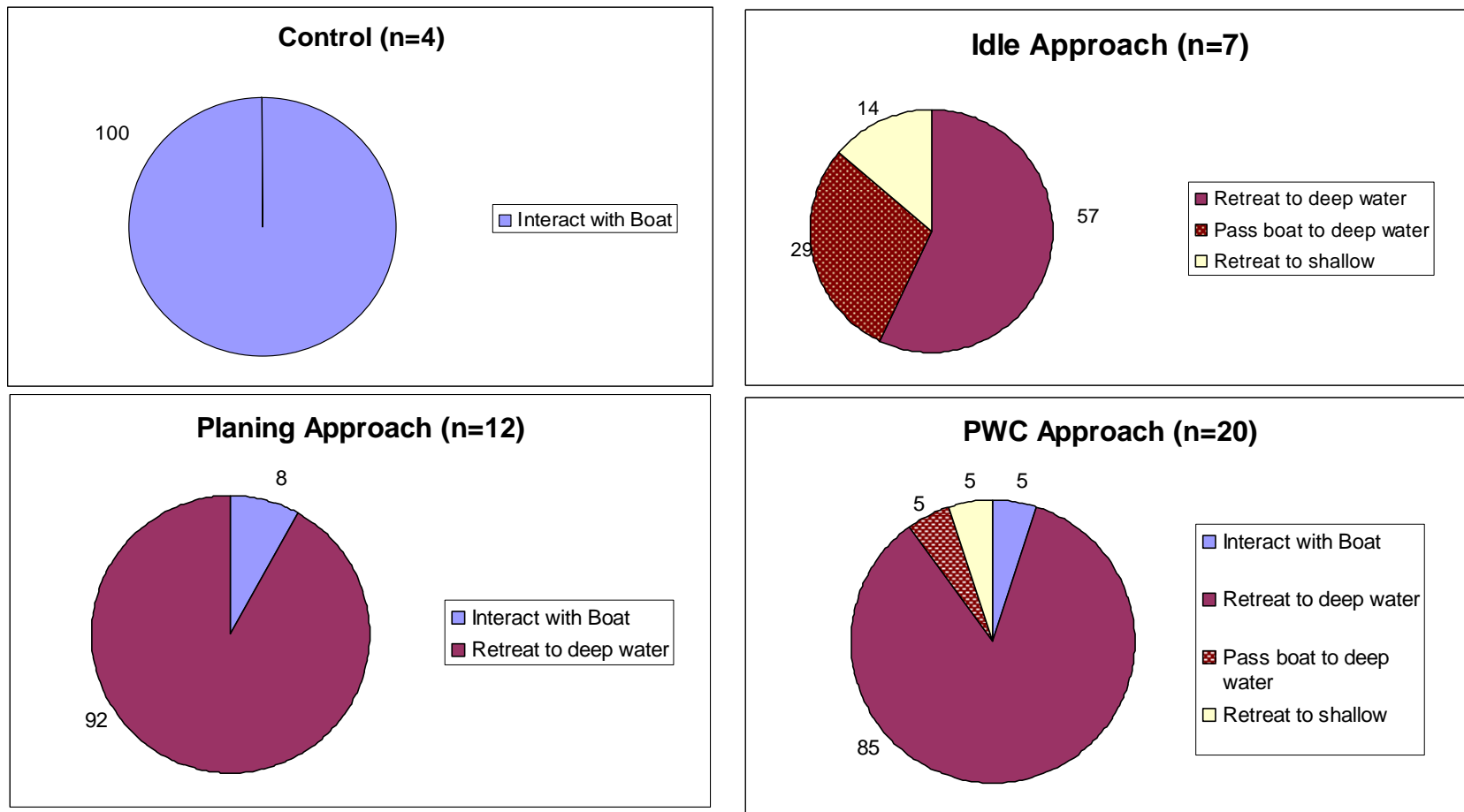
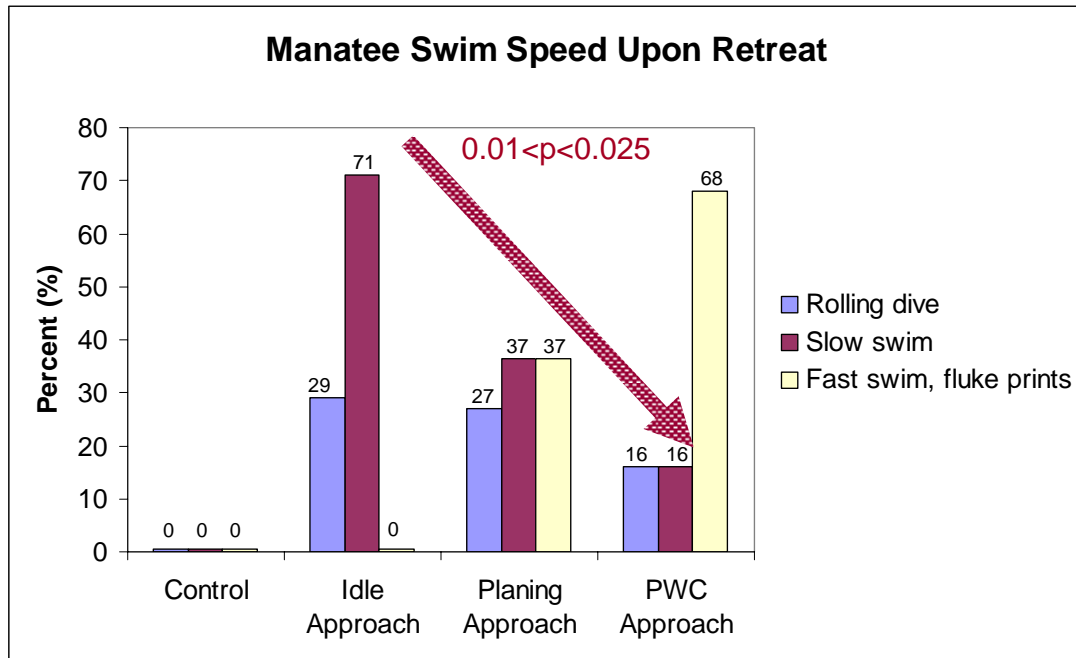


Figure 5.9. Changes in manatee course and heading in response to the playback categories.

a)



b)

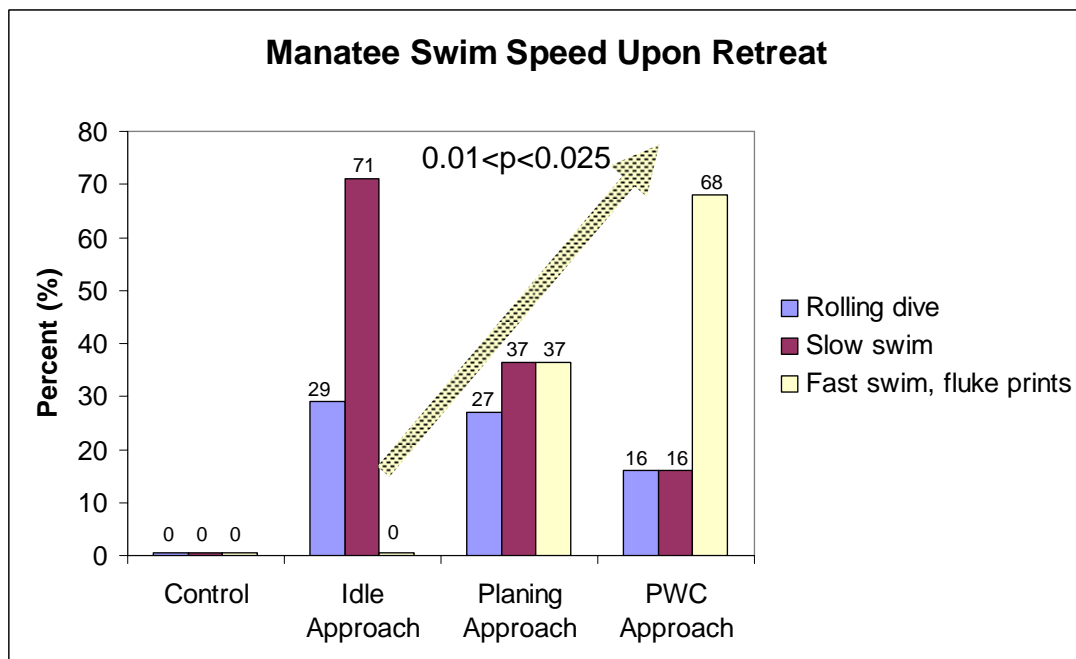


Figure 5.10. Behavioral response of retreating manatees to the playback categories. There is no response for the controls because no animals retreated during control presentations. a) shows the significant decrease in the slow swim response associated with playback category. b) shows the significance increase in fast swim responses associated with playback category.

In addition to behavioral responses, there was also a respiratory response to the playback stimuli. Variability of ventilation was calculated from the time series of visually observed surface breaths recorded continuously throughout the playback experiments (Figure 5.10). Post-stimulus variation was calculated by adding the absolute values of the difference in time between breaths for the 3 consecutive breaths following the stimulus onset (variability post-stimulus = $|t_0 - t_1| + |t_1 - t_2| + |t_2 - t_3|$). Higher values of post-stimulus variability indicated a larger variability in ventilation. Pre-stimulus variation was calculated in a similar manner. Variability was calculated for triads of 3 consecutive breaths preceding the first stimulus. The triad values were then averaged to produce a pre-stimulus variability value (variability pre-stimulus = $\{\Sigma(|p_0 - p_1| + |p_1 - p_2| + |p_2 - p_3|)\}/n$). A paired t-test showed no significant difference between ventilation variability for the pre-stimulus period and response to the control ($p = 0.73$), so the pre-stimulus and control variabilities were pooled for further analyses. An ANOVA on the post-stimulus variabilities showed a significant overall effect of stimulus type ($F(3,82) = 3.14, p = 0.03$) (Figure 5.11). Post-hoc multiple comparisons indicated an increase in variability between the pre-stimulus/control period and both planing and PWC responses. No other comparisons were significant. This suggests that the manatees were responding to the planing and PWC approaches in a similar manner with an increase in ventilation variability.

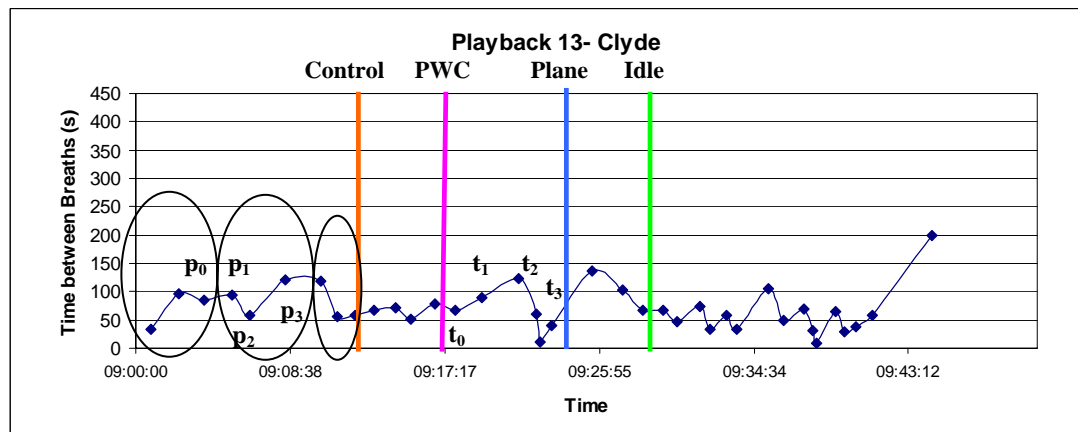


Figure 5.11. Time series of breaths during a playback session. The colored vertical lines represent the onset of the playback stimulus. The circles during the pre-stimulus period represent the grouping of triads for variability calculations. The marked breaths following the PWC presentation represent the consecutive breaths used in the post-stimulus variability calculations.

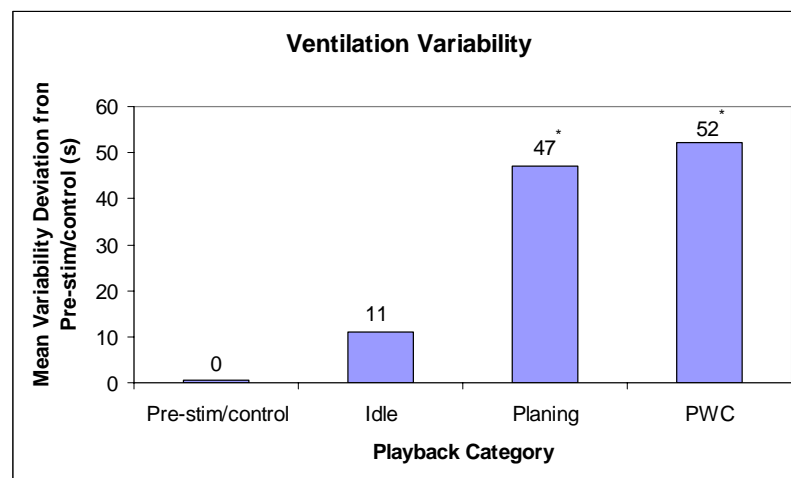


Figure 5.12. Mean deviation from pre-stimulus/control variability for each playback category. The asterisk (*) indicates categories that differed significantly from the pre-stimulus/control values.

5.5 Discussion

The most pronounced responses to the playback stimuli, relative to the controls, were elicited by the personal watercraft. Significant behavioral and physiological responses were also seen in response to planing boat approaches, indicating that fast moving vessel approaches do have an effect on manatee behavior. Fast moving vessel approaches resulted in the disruption of feeding activity, an increase in energy expenditure inferred from swim speed changes, and in some cases a short-term avoidance of the feeding area. Avoidance reactions to approaching vessels are not unique to manatees, as disturbance responses to motorized vehicles have been documented in both marine and terrestrial species. In the marine environment, avoidance to motorized watercraft had been reported in manatees, cetaceans and pinnipeds [manatees: (Buckingham et al., 1999; Nowacek et al., 2004; Provancha and Provancha, 1988); cetaceans: bottlenose dolphins (Buckstaff, 2004; Hastie et al., 2003; Janik and Thompson, 1996; Nowacek et al., 2001b), killer whales (Kruse, 1991), Hector's dolphins (Bejder et al., 1999), and beluga whales (Finley et al., 1990); pinnipeds: walruses (Fay et al., 1984), and harbor seals (Reijnders, 1981)]. Documented disturbances include increases in vocalization rate, increases in swim speed, longer dive durations, decreased interanimal distance, increased breathing synchrony, and displacement from haulout sites. Terrestrial animals [bighorn sheep (MacArthur et al., 1979), white-tailed deer (Richens and Lavigne, 1978), caribou (Murphy et al., 1993), and penguins (Culik et al., 1990)] were also found to elicit avoidance behaviors in response to road vehicles, snowmobiles, and aircraft.

The most interesting aspect of the results was that the manatees showed the ability to discriminate and differentially react to the two different engine types and speeds simulated in the playback experiments. Findings reported by Nowacek et al. (2001a, 2004) showed that a generalized response by manatees to approaching boats involved turning toward or into deep water without specific regard to boat type, boat speed, distance from the manatee, the kind of habitat the boat was operating in, or the kind of habitat occupied by the manatee. Increases in swim speed were most prevalent in shallow water grassbeds when boats approached between 0-9 m (Nowacek et al., 2004). This study also showed manatees reacting to simulated vessel approaches within 10 m with an increase in swim speed and directed movement toward the closest deep water. The findings here differed from the previous study, however, because boat type and boat speed in this study appear to have a significant effect on swimming speed. This effect was not detected by Nowacek et al. (2004) due to differences in study design and categorization of visible responses. This study differentiated between responses based on two different changes in swim speeds and the presence of rolling dives, which indicate deeper dives. Results presented here show that the manatees responded to slower idle approaches with a greater number of slow swim responses and a larger number of retreat paths that intersected with the playback vessel. In contrast, responses to fast approaching outboard motorboats or PWCs elicited a significantly greater frequency of response for fast swim speeds and retreat paths that avoided the playback vessel. Because playback experiments only introduce a single mode of acoustic information (compared to potentially bi-modal acoustic and visual information of directed vessel approaches) the acoustic information available to

the animal prior to the closest point of approach can be used to explain how the animals may be discriminating and ultimately reacting to the different playback categories.

Fifteen seconds prior to the closest point of approach, the planing approaches were approximately 10 dB louder than the idle and PWC approaches for frequencies from 6-22 kHz. Similarly, the idle approach was approximately 12 dB louder than both the planing and PWC approaches at 2 kHz. Therefore, the slower rise times of the idle and planing approaches provide more information to the animals 15 seconds prior to arrival compared to the PWC approach. It is possible the manatees can extract the necessary information from these acoustic cues relating to speed, direction, and boat type in order to execute the most energetically favorable response.

The most energetically favorable response to any approach would be to minimize locomotor costs by not moving at all. If a change in location is necessary, a response at swim speeds at or near the minimum cost of transport (COT) would be most efficient. It is often found that birds and mammals swim underwater at or near the speed of minimum COT (Lavvorn et al., 2004; Ropert-Coudert et al., 2001; Williams et al., 1993). Manatees generally cruise at speeds of 2-6 mph, although they have been recorded at speeds of 15 mph for short bursts (Hartman, 1979). Speeds of 2-6 mph would have been classified into the slow swim response in this study, so it appears that manatees responding to idle and many planing approaches acquire enough prior information to execute an energetically efficient response. The PWC acoustic signatures 15 seconds prior to arrival do not provide as much acoustic information compared to the idle and planing approaches.

The high rise time signal associated with PWC approaches does not differ greatly from ambient noise levels until 5 seconds before the peak, so it is possible that the manatees do not perceive these approaches in enough time to execute an energetically favorable response. Consequently, faster, less efficient responses are necessary to retreat from a possible PWC collision. An alternative explanation is that the sharp rise time associated with the PWC approach elicits a startle response which causes manatees to retreat from the sound source without evoking a higher level of cognitive analysis. Avoidance responses to the high rise time signals have also been observed in sharks. Myrberg et al. (1978) reported that a silky shark (*Carcharhinus falciformis*) withdrew 10 m (33 ft) from a speaker broadcasting a 150-600 Hz sound with a sudden onset and a peak sound pressure level of 154 dB re 1 μ Pa. These sharks also avoided a pulsed attractive sound when its sound level was abruptly increased by >20 dB.

Regardless of the specific acoustic characteristic of the fast vessel approaches eliciting fast swim responses, these signals cause manatees to increase their swim speed. Is it possible that multiple reactions could have a long-term effect at the individual or population level? Swimming speed, as well as breathing rates and heart rate, have been used to estimate the energetics of free-ranging marine mammals (Hind and Gurney, 1997; Kshatriya and Blake, 1988; Sumich, 1983; Williams et al., 1992). A simple model describing the energetic demands of a free-ranging animal in a thermally neutral environment states that total energetic cost = basal metabolic cost + locomotor cost + feeding cost (Costa and Williams, 1999; Williams et al., 2004). Assuming that manatees respond at maximum speeds and that the maximum aerobic

energy used during locomotion can reach 4-11 times resting levels in marine mammals (Elsner, 1986; Williams et al., 1993), consistent responses to vessel approaches have the potential to have significant effects on the manatee energy budget. This effect is further compounded by the fact that in many cases manatees are disrupted during feeding and abandon feeding areas, which reduces their energy intake.

Consistent with this study, most playbacks measure visual or vocal responses to the sound played. Behaviors most typically measured are orientation or movement relative to the sound source, vocalizations made in response to the playback, and/or previously defined behaviors or displays such as aggressive or sexual displays. Less frequently used, but possibly more objective, responses are changes in heart rate [birds (Davis, 1986; Diehl, 1992): humans (Brown et al., 1976): chimpanzees (Berntson and Boysen, 1989): dolphins (Miksis et al., 2001)] and hormone levels (Dufty, 1982). Neither quantitative swim speed nor fluke rate or amplitude were measurable in this study. More accurate measurements of both swimming characteristics and physiological responses during playback responses are necessary in order to determine the degree to which repeated exposure to vessel approaches are affecting the manatee energy budget. Technological advances in tag construction and measurement sensors may soon allow for the recording of these critical parameters (Johnson and Tyack, 2003).

In summary, the playback technique presented here allows for the investigation of numerous questions associated with manatee disturbance source, threshold level, etc. without the risk of injury associated with the unpredictable behavior of wild animals during directed vessel approaches. This methodology has identified that

vessel approaches, especially by PWCs and fast approaching watercraft, are a cause of manatee disturbance. Manatees were also shown to hear and respond to boats approaching at idle speeds. Much more information is needed to determine how to minimize this disturbance in order to meet the criteria for species downlisting as outlined in the Florida Manatee Recovery Plan (U.S. Fish and Wildlife Service, 2003).

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Chapter 6. Summary and Conclusions

6.1 General Summary

Human activity can disturb manatees, and the growing magnitude of waterborne activity in the coastal waters of Florida increases the likelihood for both direct and indirect conflicts between humans and manatees (Ackerman et al., 1995; Buckingham et al., 1999; Gerstein, 2002; Gorzelany, 2004; Nowacek et al., 2002; Provancha and Provancha, 1988; U.S. Fish and Wildlife Service, 2003). The amount of noise introduced into the environment as a byproduct of human activity is of particular interest because of the potential impacts to marine life. The main goal of this work was to understand and predict manatee behavior patterns as a function of environmental noise levels. The study took place in Sarasota Bay, FL during the summer months when animals were dispersed from their winter aggregation sites. As few previous studies have focused on the behavior of these animals outside winter aggregation sites (Koelsch, 2001; Nowacek et al., 2004; Reynolds, 1981), this work is a major contributor to the information available on manatee behavior during the non-winter months. Each of the four data chapters in this dissertation examines a different facet of how noise impacts manatee behavior. Chapter 2 was devoted to how environmental noise levels and the amount of signal transmission loss affect manatee distribution and habitat selection. Chapter 3 examined how differences in manatee activity budgets related to noise. Chapter 4 investigated the use of vocalizations as a function of noise, and Chapter 5 described a series of playback experiments in which manatees were exposed to recordings of approaching watercraft.

The objective of Chapter 2 was to quantify the acoustic environment of manatee habitats and how it related to animal distribution. The first step in understanding manatee response to environmental noise was to develop a general understanding of sound levels and sound transmission in specific manatee habitats. A total of 24 sites, 13 grassbeds and 11 dredged habitats, was examined. Noise levels were recorded systematically during two 6-month seasons, and transmission loss was modeled and verified in each site. Data showed that grassbeds used most often are quieter due to higher levels of transmission loss and lower noise levels compared to low-use grassbeds of equal species composition and density. Dredged habitat use was a function of the geographical proximity to high-use grassbeds, but not a function of environmental noise levels. Patterns of manatee habitat selection indicated that they may be selecting grassbeds based on the level of morning noise, which is associated with the amount of morning boat traffic. Consequently, morning boat presence and its associated noise may be playing a dominant role in grassbed usage on a daily time scale.

Chapter 3 was devoted to understanding manatee behavior patterns and how they were affected by both ambient noise and identifiable transient noise sources. Behavior, group composition, physical environment parameters, and noise were measured simultaneously for tagged and non-tagged manatees during sightings and focal follows. The proportion of time manatees spend feeding, milling, and traveling in critical habitats changed as a function of noise level. When noise levels were highest, more time was spent in the directed, goal-oriented behaviors of feeding and traveling while less time was spent milling. Whereas changes in activity budget

appeared to be the primary response to ambient noise, avoidance was the most visible response when specific noise sources approached the manatees. Behavioral change and an increase in ventilation variability were the dominant responses to vessel approaches within 50 m. In instances where animals left a geographical area in response to an approaching vessel, the predominant vessel type eliciting this response was the PWC.

Chapter 4 examined the use of vocalizations in relation to noise. Vocalization rate, structure, and source level were first analyzed as a function of behavioral state and calf presence. Increases in vocalization rate, duration, and source level were most pronounced when calves were present and during feeding and milling behaviors when animals tended to be more dispersed. A second level of analysis related vocalization usage to environmental noise levels. Increased vocalization effort was exhibited during feeding and milling behaviors at times of elevated noise conditions, which suggests ambient noise levels do have a detectable effect on manatee communication and that manatees are able to modify their vocalizations as a function of noise.

The playback experiments in Chapter 5 were designed to validate the pattern of behavior observed in response to approaching watercraft in Chapter 3. Manatees were exposed to recordings from four different categories: 1) silent control, 2) outboard motorboat approaching in idle, 3) outboard motorboat approaching on plane, and 4) fast PWC approach. Manatees responded to the transient noise of approaching vessels with changes in behavioral state and movements out of the geographical area, which suggests that manatees detect and respond to changes in environmental noise levels. Analyses of swim speed, changes in behavioral state, and respiration rate indicate that

the manatees respond differentially to playback categories of boat noise and that the most pronounced responses to boat noise playbacks, relative to the controls, were elicited by the personal watercraft. Overall, manatees responded to the transient noise of approaching vessels with changes in behavioral state and movements out of the geographical area.

6.2 Conclusions

The major conclusion emerging from this work is clear. Environmental noise is perceived by and affects manatees. This is the common thread weaving through each of the data chapters, and it documents that manatees detect and respond to both ambient noise changes and transient boat noise. Responses were seen through habitat selection and distribution, changes in activity budget, changes in vocalization patterns, and direct responses to the sound of approaching watercraft. Whereas the majority of findings emphasized the connection between noise and human activities, natural noise sources such as snapping shrimp, wind and waves also contributed to the observed patterns.

The effects of human generated noise on manatee behavior are best understood by realizing that manatees exhibit a wide range of tolerance to humans, and numerous intrinsic and extrinsic variables affect manatee response to specific human disturbances. Here noise has been shown to disturb manatees. Disturbance, or a detectable change in behavior, can occur at a number of different levels ranging from mild aversion to mortality (Bowles, 1995). Disturbance due to noise affected grassbed selection and distribution, which has the potential to reduce foraging areas and limit food intake, increase activity level and associated energy costs, and cause manatees to

leave optimal habitats (Reynolds, 1999). Over the long term this could lower the carrying capacity of particular sites and lead to higher mortality and lower survival and reproduction rates, although these effects have not been documented (Stalmaster and Kaider, 1998).

Noise disturbance also disrupted the normal manatee activity budget. This could cause an increase in energy expenditure and consequent need for a greater amount of food (Reynolds, 1999; Stalmaster and Kaider, 1998). With the documented reduction in the area of Florida seagrass habitats due to scarring and habitat alteration (Sargent et al., 1995), a disturbance that results in greater food intake may have devastating effects on the manatee population in the future. Conversely, elevated noise levels may affect the metabolic level of manatees resulting in a decrease of food consumption. A series of studies by Lagardère (1980; 1982) demonstrated the effects of ambient noise (20-1,000 Hz) on the growth, reproduction, and metabolic level of shrimp (*Crangon crangon*). Results showed delayed growth, decreased reproduction, and decreased food uptake indicative of a stress response in elevated noise conditions (Lagardère, 1982; Lagardère and Régnault, 1980). The observed increase in traveling during periods of elevated noise levels argues for an accompanying increase in energetic expenditure, but the increase in feeding in association with elevated noise levels does not necessarily imply greater ingestion of food. It is unclear how consistent an animal's rate of food uptake is in conjunction with changing noise levels.

The observed increase in vocalization activity in an effort to compensate for masking during periods of elevated noise similarly lends itself to the argument of increased energetic output and resulting consequences for both the individual and

population. The energetic cost of converting metabolic to acoustic energy is inefficient, ranging from 0.5-5% efficiency in most animals (Bradbury and Vehrencamp, 1998; Ryan, 1986); long-term increases in vocal activity could have serious repercussions at the population level. A related concern is that the masking of vocalizations by noise causes a decrease in the effective range of communication (Richardson et al., 1995). This could have significant effects on manatee reproduction and survival. For example, any interference that affects the effective communication between a mother and calf could jeopardize the calf's survival by causing permanent separation. Additionally, a decrease in effective communication during mating behaviors could result in lower reproductive success or the production of less fit offspring.

The experimental portion of this study illustrates the need for carefully planned, hypothesis-driven research to clearly show the link between behavioral changes and noise. Playback results revealed a clear response by manatees to the sound of approaching watercraft, solidifying a cause-effect relationship. Differences in the degree of response suggest that manatees can differentiate between the speed and type of approaching vessel. The combination of these relationships with the behavioral correlations established in the observational portion of the study provides conservation and management agencies with evidence to predict the impacts of specific human activities. Future research demonstrating cause-effect relationships between environmental noise and manatee behavior, distribution, reproduction, and survival will be instrumental in directing conservation efforts.

6.3 Suggestions for Future Research

Due to the largely observational nature of the present study, hypothesis-driven experiments are needed to validate many of the correlations and implications presented in this work. The captive environment provides the ideal opportunity to perform controlled masking experiments and studies investigating the physiological effects of noise. Captive research will also be critical to providing the much needed information on manatee hearing abilities and sound production mechanisms.

Suggestions for future captive studies are outlined below:

- 1) Additional hearing studies are needed in order to clarify discrepancies in the hearing abilities of manatees presented in prior studies (Bullock et al., 1982; Gerstein et al., 1999; Ketten et al., 1992). An evoked potential study has already been initiated (Mann et al., 2004), and the presentation of detailed results is imminent. This is a necessary first step in then being able to identify critical bands of hearing important to masking issues and frequencies most sensitive to human generated noise.
- 2) Following the definition of the critical ratios and critical bands of manatee hearing, behavioral studies are needed to identify the degree of masking to which manatee vocalizations are subjected. With carefully designed experiments, it may even be possible to separate the masking of signal detection from signal comprehension. Similar behavioral studies are also needed to evaluate the level of sensitization and habituation of manatees to ambient noise level changes as well as transient noise sources.

3) Correlations of vocalization structure with noise level suggest that the observed increase in vocalization effort is indicative of an increase in energy expenditure. Anatomical studies of manatee sound production mechanisms are needed in order to determine how the size of the sound-producing and resonating structures relates to the wavelength of vocalizations, for the argument has been made that shifting vocalizations to higher frequencies increases vocal effort because it takes more energy to produce high frequency sounds that are closer in wavelength to the size of the sound-producing and resonating structures (Ryan, 1986). Only then can it be determined whether or not shifting vocalizations to a higher frequency incurs additional costs to manatees, as it does in frogs and crickets (Ryan, 1986).

4) Correlations of vocalization rate and source level with noise suggest that the observed increase in vocalization effort is indicative of an increase in energy expenditure. To support this implication, it is necessary to determine how the amount of acoustic energy in a single call relates to the amount of aerobic and anaerobic energy used in producing the vocalization. How that energy input changes in relation to noise levels can then be tested experimentally.

5) Lagardère (1980; 1982) demonstrated the effects of ambient noise on the growth, reproduction, and metabolic level of shrimp (*Crangon crangon*). A similar study investigating the link between physiology and noise would be instrumental in evaluating the impact of noise on manatees. The suggested research will provide

information about the physiological effects a manatee may experience when exposed to chronic noise over a long period of its life cycle, and how these may affect growth and reproduction. Experiments investigating the effect of ambient noise and transient noise sources should be conducted. Conscientious combinations of noise sources may also be able to address the cumulative effects of various noise sources. Results of captive studies could then be extrapolated to wild animals based on environmental noise levels and exposure to human activities.

6) Stress affects adrenal steroid hormones by raising cortisol levels, and elevated cortisol levels have been shown to indirectly affect heart rate (Sapolsky, 1996).

Environmental stress has also been shown to increase irritability in humans and rodents, which has led to increases in agonistic behaviors and suppressed food intake (Anthony and Ackerman, 1955; Sackler et al., 1959; Sapolsky, 1996). Monitoring cortisol levels, heart rate, aggression, and food intake during captive noise experiments has the potential to provide indisputable evidence that noise is impacting manatees by inducing stress.

Whereas captive studies are ideal, and in some instances necessary, for conducting certain types of experiments, results may not always be accurately extrapolated to wild animals due to vastly different living conditions. For example, noise of captive facilities may have different effects on the hearing abilities of captive animals compared to the environmental noise to which wild animals are exposed. Animals may also react differently to the same stimulus presented in captivity and in

the wild. When possible, field studies should be conducted to validate results from captive studies. Similar results give strength to the conclusions of the theories being tested in both environments. There are also instances for which the hypothesis being tested can only be addressed in the field. Noninvasive research techniques must be used with wild marine mammals in order to comply with federal protection laws, and this limits the type of research that can be conducted in the field. Studies involving manatees is further constrained due to their endangered status. Nevertheless, there are specific studies that can be conducted to further investigate the effect of noise on manatees that comply with the established protection laws. These are outlined below.

7) Long-term observational and post-mortem studies combined with current advances in tag technology and genetics may soon make it possible to investigate the effect of noise on reproductive success and survival (Ackerman et al., 1995; Garcia-Rodriguez et al., 2000; Johnson and Tyack, 2003). Do animals exposed to lower noise levels over their life span have greater survival rates and reproductive success? Do animals with greater amounts of scarring have poor hearing abilities? Are animals that have previously been hit by a boat more likely to be hit again? Tracking of parents and offspring over consecutive years may provide answers to these questions. The effect of noise on conception and pregnancy in the wild has not been addressed in wild marine mammals due to logistical obstacles, but technological advances may make this information obtainable in the future.

8) Results from this study were obtained from the observation of manatees during non-winter months. Factors such as seasonal behavior patterns, seasonal environmental patterns, and seasonal limitations on geographical distribution due to physiological constraints may have a substantial cumulative effect on how manatees respond and are ultimately affected by both ambient and identifiable components of coastal ocean noise. Comparative studies are necessary to elucidate the seasonal effects of noise exposure.

9) The successful application of the playback technique used in this study provides a model for future studies investigating response of manatees to specific noise sources. There are endless possibilities to the questions that can be answered with this technique. For example, is an animal with large amounts of scarring more or less likely than a less scarred animal to respond to the playback of approaching watercraft? Experiments designed to utilize the natural differences in ambient noise levels while experimentally introducing human generated noise sources also have the potential to answer questions on the cumulative effects of noise exposure.

10) The focus of noise in this study was overall background noise and human generated noise, specifically watercraft. However, these are only two of many sound sources contributing to coastal marine noise. Snapping shrimp were present in all recordings made in seagrass habitats, and data hint at a relationship between manatee usage and the amount of snapping shrimp noise in the morning and afternoon periods. In evaluating manatee distribution in relation to noise for the purpose of management

decisions, it is crucial to understand the role of natural biological noise in habitat selection. More detailed research examining the relationship between the amount of snapping shrimp noise and manatee grassbed usage is needed to verify a significant interaction.

11) Habitat selection and corresponding distribution are subject to numerous factors of which environmental noise is just one. Significant relationships between noise level and manatee grassbed usage were shown in Chapter 2. The role of seagrass quality on selection was addressed by examining the species composition and amount of seagrass coverage in grassbed site, but no significant relationship emerged. Further research testing the hypothesis of whether increasing noise in high-use grassbeds alters site use over time should be done to validate the noise vs manatee usage relationships observed here. Similarly, will decreasing noise in a low-use area increase grassbed use? Analogous experiments investigating the effects of other factors that may influence habitat selection, such as human activity level, wind exposure, current strength, etc., should also be explored.

The above suggestions for future research all focus on the short-term effects of noise on a single individual or group of animals. Long-term impacts of observed short-term effects are generally unknown. Also unknown are how the short-term impacts at the individual level relate to long-term effects at the population or species level. The National Research Council has identified one of the basic scientific challenges pertaining to this issue as using short-term observations at the level of the individual to

predict effects on populations (National Research Council of the National Academies, 2005). This process necessitates more controlled long-term studies on the growth, physiology, energetics, reproduction and survival of manatees to chronic exposure of continuous and intermittent sound upon which to base a model. The development of such a predictive model would be two-fold. It would have the potential to identify the point at which the cumulative effects of human activities impact a population and to identify the activities that pose the greatest risk.

6.4 References

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Appendix A Acronyms and Abbreviations

ANOVA	analysis of variance
ARG	Acoustic Rain Gauge buoy
COT	cost of transportation
CTD	conductivity, temperature, and depth meter
dB	decibel
DB	dredged basin
DC	dredged canal
DUI	distance-usage index
FFT	fast Fourier transform
GB	grassbed
MMPE	Monterey-Miami Parabolic Equation
NN	nearest neighbor
PAR	photosynthetically available radiation
PE	parabolic equation
psd	power spectral density
PWC	personal water craft
rms	root mean square
TL	transmission loss

Appendix B Introduction to Acoustics

The following information serves to provide an introduction to the acoustic terms used in this dissertation.

Sound is waves of energy that travel through air or water as vibrations of the fluid particles. The vibrations produce a sinusoidal pattern of pressure fluctuations. Frequency is the rate of the pressure fluctuations measured in cycles per second or hertz. One thousand hertz is equal to one kilohertz. The fundamental measure of sound is acoustic intensity. This is the amount of energy per unit time (power) traveling through a unit area. Sound intensity is equal to the sound pressure squared divided by the acoustic impedance of the medium (ρc):

$$\text{Intensity} = \frac{\text{Pressure}^2}{\rho c}$$

where ρ = fluid density
 c = speed of sound

The difference between two intensities is measured on a logarithmic scale in decibels (dB). Intensity differences are often a comparison between a reference intensity (I_{ref}) measured 1 m from a sound source and a signal intensity (I) measured some distance from the source:

$$\text{Sound Intensity Level (dB)} = 10 \log (I/I_{\text{ref}})$$

Intensity is proportional to pressure (P) squared, and the sound pressure level (SPL) is given by

$$\text{Sound pressure level (SPL)} = 20 \log (P/P_{\text{ref}})$$

Underwater sound is detected by an underwater microphone called a hydrophone. This instrument senses pressure fluctuations and converts them to voltage fluctuations.

Hydrophones used to measure the pressure of sound 1 m from a source is conventionally referred to as the source level (SL) and is expressed as $SL = XX \text{ dB re } 1\mu\text{Pa at } 1 \text{ m}$. Using a hydrophone, received level (RL) of sound can also be calculated as follows:

$$\text{Received level (RL)} = 20 \log (P_{\text{measured}}/P_{\text{ref}})$$

Sound varies with frequency, and an animal's response to a sound is dependent on the level of sound at frequencies within its hearing bandwidth, or range of frequencies. Sound or noise levels are typically presented in either octave bands or 1/3-octave bands with a specified center frequency. An octave is a factor of two in frequency, whereas the 1/3-octave bandwidth is approximately 23% of its center frequency from $x(2^{-1/6})$ to $x(2^{1/6})$.

The reception of sound also varies with motion. The Doppler effect is caused by echoes from a moving source bouncing off a moving target and producing a frequency shift of the echo. The shift in frequency (Δf) is characterized by the following equation:

$$\text{Shift in frequency } (\Delta f) = (2vf)/c$$

where v = difference in velocity between source and receiver
 c = speed of sound

Waveguide invariants, also known as the Beta effect, are observed when a moving source passes a stationary recording element in shallow water. Interference patterns, or striations, characterizing this effect are often seen on spectrograms and change slope direction prior to and following the closest point of approach.

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