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West Indian Manatee (Trichechus Manatus) Habitat Characterization Using Side-Scan Sonar

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ABSTRACT

WEST INDIAN MANATEE (*TRICHECHUS MANATUS*) HABITAT CHARACTERIZATION USING SIDE-SCAN SONAR

by

Mindy J. McLarty

Chair: Daniel Gonzalez-Socoloske

ABSTRACT OF GRADUATE STUDENT RESEARCH

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School of Arts and Sciences

Title: WEST INDIAN MANATEE (*TRICHECHUS MANATUS*) HABITAT CHARACTERIZATION USING SIDE-SCAN SONAR

Name of researcher: Mindy J. McLarty

Name and degree of faculty chair: Daniel Gonzalez-Socoloske, Ph.D.

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In this study, the reliability of low cost side-scan sonar to accurately identify soft substrates such as grass and mud was tested. Benthic substrates can be hard to classify from the surface, necessitating an alternative survey approach. A total area of 11.5 km^2 was surveyed with the sonar in a large, brackish mangrove lagoon system. Individual points were ground-truthed for comparison with the sonar recordings to provide a measure of accuracy. Five substrate types were identified: Dense seagrass, sparse seagrass, mangrove soil, mangrove soil with rock, and silt. A zoned benthic substrate map was created from the sonar recordings. Dense seagrass was most accurately identified. Sparse seagrass had the lowest accuracy. A bathymetric map was also created from the sonar recordings. Manatee sighting locations were overlaid on these maps to

preliminarily assess habitat use. Most manatee sightings occurred in areas 2–6 m deep and characterized as mangrove soil.

Andrews University

College of Arts and Sciences

WEST INDIAN MANATEE (*TRICHECHUS MANATUS*) HABITAT

CHARACTERIZATION USING SIDE-SCAN SONAR

A Thesis

Presented in Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Mindy J. McLarty

April 2017

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APPROVAL BY THE COMMITTEE:

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Date approved

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LIST OF ABBREVIATOINS

GPS	Global Positioning System
IUCN	International Union for Conservation of Nature
KML	Keyhole Markup Language
KMZ	Keyhole Markup Language Zipped
QGIS	Quantum Geographic Information System
SD	Secure Digital

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CHAPTER 1

INTRODUCTION

The mammalian Order Sirenia has four extant species distributed between two families. Family Trichechidae contains three species while Family Dugongidae has only one species. The trichechids include the Amazonian manatee (*Trichechus inunguis*), the West African manatee (*Trichechus senegalensis*), and the West Indian manatee (*Trichechus manatus*). The West Indian manatee is further split into two subspecies, the Antillean manatee (*T. m. manatus*) and the Florida manatee (*T. m. latirostris*) (Domning & Hayek, 1986). Family Dugongidae is comprised of a single living species, the dugong (*Dugong dugon*) (Deutsch, Self-Sullivan, & Mignucci-Giannoni, 2008; Keith Diagne, 2015; Marmontel, de Souza, & Kendall, 2016; Marsh, O'Shea, & Reynolds III, 2011).

Manatees are fully aquatic mammals and specialized for this lifestyle. Their forelimbs are paddlelike flippers and they lack hind limbs. Their tails are rounded flukes and movement is powered by dorsal-ventral undulations (Kojeszewski & Fish, 2007). The lungs are long, unlobed, and oriented horizontally (Domning & Buffrénil, 1991). Sirenians' bones are especially heavy and dense, acting as ballast for their large lungs (Domning & Buffrénil, 1991). Manatees have very sensitive vibrissae and their bodies are covered in bristle-like hairs that are tactilely receptive, making them exceptionally adept at interacting with their environment by touch (Bachteler & Dehnhardt, 1999; Bauer et al., 2012; Reep, Marshall, & Stoll, 2002; Reep, Marshall, Stoll, & Whitaker, 1998; Reep, Stoll, Marshall, Homer, & Samuelson, 2001). Their eyesight is relatively good, but they are partially color blind, seeing blues, greens, and grays (Griebel & Schmid, 1996). Manatees are seemingly quiet creatures, but will communicate with each other using chirps and squeals (Hartman, 1979; O'Shea & Poché, 2006). Manatees have very good hearing and are able to hear sounds above the water as well as beneath it (Hartman, 1979). Special adaptations for hearing, including a fused contact between the periotic and squamosal bones and enlarged zygomatic processes that are spongy and oil-filled, may help localize sound and possibly act as a low-frequency resonator (Ketten, Odell, & Domning, 1992). Manatees exhibit good localization abilities at frequencies between 200 Hz and 35–40 kHz, including recreational boat engines and manatee vocalizations (Colbert, Gaspard, Reep, Mann, & Bauer, 2009).

Sirenians are herbivores, therefore their distribution is restricted to relatively shallow coastal areas where plants may be found. Dugongs are found throughout the marine areas of the Indo-Pacific region and manatees are found on both sides of the Atlantic Ocean (Marsh et al., 2011). All extant Sirenians are sensitive to cold and thereby restricted to the tropics and subtropics. Amazonian manatees are an entirely freshwater species, endemic to the major waterways of the Amazon River Basin (Denkinger, 2010; Marmontel et al., 2016). West African manatees are found in western Africa from Mauritania in the north to Angola in the south along the coasts and in larger rivers (Keith Diagne, 2015; Powell, 1996; Silva & Araújo, 2001). West Indian manatees span a broad range across 25 countries from the United States, along Central America and the Greater Caribbean region, south to Brazil (Deutsch et al., 2008). The Florida subspecies of the West Indian manatee is found in the United States, with occasional individuals found in the Bahamas and one record of a cow and calf from Cuba (Alvarez-Alemán, Beck, & Powell, 2010). The Antillean subspecies is found throughout the rest of the West Indian manatee's range. Manatees need a patchwork area of seagrass beds, freshwater sources, and sheltered areas for rest and calving (LaCommare, Self-Sullivan, & Brault, 2008). If their range is far enough north, as is the case for the Florida manatee, they will also need warm water refuge sites during the colder, winter months (Laist & Reynolds, 2005; Shane, 1984; Stith et al., 2011). Manatees are most often found in water depths of 2-6 m, sometimes down to 10 m (Castelblanco-Martínez et al., 2013; Lefebvre, Reid, Kenworthy, & Powell, 2000; Olivera-Gómez & Mellink, 2005).

West Indian manatees have a broad diet consisting of more than 108 genera of freshwater and saltwater plants and algae (Alves-Stanley, Worthy, & Bonde, 2010; Gonzalez-Socoloske, 2013; Hartman, 1979; Ledder, 1986; Lefebvre et al., 2000; Reynolds III, 1981). Seagrasses are an important component of the manatee diet in marine areas. Studies suggest that *Halodule wrightii*, *Syringodium filiforme*, and *Thalassia testudinum* are the most important seagrass species for West Indian manatees in the Caribbean (Aleman, 2011; Lacommare, 2011; Lefebvre et al., 2000). Manatees also feed on many species of terrestrial plants and algae and floating vegetation. Anecdotal evidence suggests that manatees will eat sponges or steal fish from fishermen's nets if given the chance. However, it is thought that this type of behavior is exhibited by manatees under some type of physiological stress and is not widespread (Courbis & Worthy, 2003; Powell, 1978).

All manatee species are listed as vulnerable by the IUCN (Deutsch et al., 2008; Keith Diagne, 2015; Marmontel et al., 2016). The Florida and Antillean subspecies are individually listed as endangered (Deutsch, 2008; Self-Sullivan & Mignucci-Giannoni, 2008). Habitat loss and hunting have had major negative impacts, leading to a decline in all species. In the United States, aggressive conservation actions have increased the numbers of the Florida manatee, which is now considered to have a stable population (Runge, Langtimm, Martin, & Fonnesbeck, 2015). Most studies done on manatees have been with the Florida manatee, owing to the easy access to this subspecies. Less is known about the other manatee species and subspecies as their range falls within countries with limited access or dangerous political situations.

Humans are the manatee's main threat. In some areas, hunting has played a role in reducing population numbers (Domning, 1982; Morales-Vela, Saldivar, & Mignucci-Giannoni, 2003; O'Shea, Correa-Viana, Ludlow, & Robinson, 1988). Manatees can provide a lot of meat and their hides make tough leather. Hunting pressures are most notable in developing countries, though unlawful in most places. Human coastal use is the most prevalent threat to manatees currently (Bossart, 2011; Castelblanco-Martínez et al., 2009; Gonzalez-Socoloske, Taylor, & Rendon Thompson, 2011; Marsh et al., 2011; Mignucci-Giannoni et al., 2000; O'Shea, Moore, & Kochman, 1984; Rommel et al., 2007; Waycott et al., 2009). Boat traffic in coastal areas can be very high, such as in Florida where boat strikes on manatees are a common occurrence, often resulting in manatee fatalities (Runge et al., 2015). Noise pollution from boats can mask certain call frequencies, effecting manatees' ability to communicate with each other (Chavarría, Castro, & Camacho, 2015). It has also been shown that manatees avoid feeding in areas with high levels of ambient noise (Miksis-Olds, Donaghay, Miller, Tyack, & Nystuen, 2007). Fishing in areas frequented by manatees raises the risk of a manatee becoming entangled in fishing gear and drowning or a trapped manatee being taken opportunistically by a fisherman (Adimey et al., 2014; Deutsch et al., 2008; Gonzalez-Socoloske et al., 2011).

Development along coastlines is detrimental to manatees as well. Coastal development often destroys the native ecosystem or at least disrupts it. Manatees depend on these coastal systems for their survival. Mangrove forests offer shelter and seagrass beds are commonly found near these areas as well. Seagrasses are an important dietary component of West Indian manatees (Alves-Stanley et al., 2010; Lefebvre et al., 2000), thus loss of seagrass coverage reduces forage quantity for these animals. Worldwide, seagrasses are declining, mostly caused by poor water quality and human activity such as dredging (Waycott et al., 2009). Access to freshwater sources and warm water refuges can be blocked. Runoff from coastal cities can pollute the surrounding waterways, causing an increase in disease among aquatic organisms (Bossart, 2011). Manatees may also eat trash which can be fatal (Attademo et al., 2015; Guterres-Pazin, Rosas, & Marmontel, 2012). Tourism involving swimming with manatees is becoming increasingly popular, which could disturb the manatees overwintering in warm water refugia (Sorice, Shafer, & Ditton, 2006).

The present status of the Antillean manatee population in Cuba is not well understood. Historical accounts of manatees in Cuba suggest a thriving and abundant population (Aleman, 2011). However, hunting, which is now illegal and carries a stiff penalty, has dramatically decreased their numbers (Aleman, 2011). Pressures from habitat degradation and loss have furthered the decline. Manatees also occasionally become entangled in fishing gear, usually resulting in drowning. Conservation efforts in

Cuba are currently focused on education and protecting habitat (Aleman, 2011). It is therefore vital to continue to collect information on the manatee population and their habitat use to better inform management authorities to ensure that the proper areas are being protected.

Cuba is an important stronghold for Antillean manatees in the Greater Caribbean. Minimal coastal development and extensive seagrass beds provide ideal locations for manatees. However, not all areas appear to be used equally. Surveys are currently being conducted to determine which features of a habitat are most valuable to manatees in Cuba. These surveys include seagrass sampling as well as measuring the abiotic factors such as water temperature and salinity. This study will contribute to this body of knowledge by providing a substrate map and manatee usage patterns for the San Pedro lagoon system on Isla de la Juventud, an area already identified as important to manatees. Identifying these patterns and the habitat parameters best suited for manatees will help identify other areas that could be potentially productive and thus should be protected. Very little is known about the health and size of the manatee population in Cuba due to the difficulty of conducting research and the inaccessibility of some regions. The current studies are critical to establishing a baseline as the shifting geopolitical climate could bring major foreign investment and coastal development. Protecting good habitat will be very important to the survival of the Cuban population of Antillean manatees.

Chapter 2 describes the use of side-scan sonar to identify benthic substrates and bathymetry in areas with poor water visibility. The San Pedro lagoon system is entirely surrounded by mangroves. The system consists of two large lagoons and three small lagoons. The lagoons are connected by channels that tend to be much deeper on average than the lagoons. There are two entrances to the system from Siguanea Gulf and a number of islands within the lagoons and channels. Water visibility in much of the system is very limited due to the high amount of dissolved tannins. A Humminbird® side-scan sonar unit (Johnson Outdoors Inc., Racine, WI) was used to map the benthic substrates and bathymetry. This information was then used to determine substrate type and coverage as well as the bathymetric profile.

Chapter 3 examines patterns of manatee sightings from an 8-year data set within San Pedro and compares this to the previously characterized benthic substrates and water depths in those areas. Manatees are known to commonly use this area, but the reasons are not well understood. By surveying the benthic substrates and bathymetric profile, manatee use patterns may be more clearly identified.

CHAPTER 2

MANATEE HABITAT CHARACTERIZATION USING SIDE-SCAN SONAR

Introduction

Examining submerged substrates in a time and cost effective manner has been a challenge for researchers. Areas of interest often have poor water visibility, limiting bottom visibility and identification from the surface. Traditional sonar units are expensive and large, thereby restricting access by most researchers and usefulness in smaller, shallower bodies of water; however, side-scan sonar is useful in these types of situations. Commercially available, low cost units, such as those used by sport fishermen, may be a remedy for this problem.

Side-scan sonar utilizes multiple beams to cover a larger horizontal area than traditional downward facing-beam sonar. Although side-scan sonar still has a down-beam (to record bathymetric data), it also has two beams angled laterally to create a fan-shape. Humminbird® (Johnson Outdoors Inc., Racine, WI) sells side-scan sonar units that can create up to 180° of coverage in a swath up to 146 m wide. The sonar beams are converted into an image that is viewed in real-time on the sonar's console and can be played back on a computer using software such as ReefMaster (ReefMaster Software Ltd., West Sussex, UK). Submerged objects can then be identified. Objects raised off the bottom, such as logs or a sunken boat, cast sonar shadows as these objects block the sonar beam. The shadows can help indicate the size and location of submerged items relative to the boat.

The Humminbird® (Johnson Outdoors Inc., Racine, WI) sonar unit is comprised of three pieces. The console is the control unit with a display screen that can display many different types of real-time data and images and also play back previous sonar tracks and navigation paths. The transducer emits the sonar beams and feeds into the console. It is mounted about 15 cm below the surface, ideally directly to the boat's stern though it can be mounted on a bracket that can be secured to the boat. The GPS antennae connects to the console to facilitate a more accurate geographical fix. The console is powered by an external 12V battery.

Studies done by Kaeser and Litts (2008, 2010) demonstrated that substrates could accurately be identified using a Humminbird® side-scan sonar (Johnson Outdoors Inc., Racine, WI) unit in a small, freshwater stream. Substrates encountered in this system were rocky and sandy. These studies found that substrates could be correctly identified with an accuracy of 77% (Kaeser & Litts, 2010). Garner et al. (2016) used side-scan sonar to identify boulders and bedrock crevices to help facilitate population surveys of a freshwater gastropod. This method greatly reduced the time needed to complete the survey by focusing efforts on areas likely to contain colonies of the target organisms. Various studies have demonstrated that side-scan sonar can be used to detect submerged animals. Gonzalez-Socoloske and colleagues (Gonzalez-Socoloske, 2007, 2013; Gonzalez-Socoloske & Olivera-Gomez, 2012; Gonzalez-Socoloske, Olivera-Gomez, & Ford, 2009) demonstrated that side-scan sonar could be successfully used to detect manatees in both freshwater and marine habitats. Subsequent studies have confirmed this ability in other locations (Arévalo-González, Castelblanco-Martínez, Sanchez-Palomino, Lopez-Arevalo, & Marmontel, 2014; Castelblanco-Martínez, dos Reis, & de Thoisy, 2017). McCarty (2014) demonstrated the use of side-scan sonar to detect alligator gar and Flowers and Hightower (2013) demonstrated the use of this technology to identify Atlantic sturgeon. Additionally, Gonzalez-Socoloske and Olivera-Gomez (2012) determined logs, rocks, and softer substrates, such as underwater vegetation, could also be identified using side-scan sonar. Bottom contour and texture as well as depth can also be deduced from the sonar data, suggesting that this technology may be useful in categorizing benthic habitat at a resolution much greater than was possible before.

In Cuba, manatees inhabit mangrove coastlines and lagoons. Manatees are known to use the San Pedro lagoon system of Siguanea Gulf on Isla de la Juventud (Alvarez-Alemán, Angulo-Valdés, Alfonso, Powell, & Taylor, 2016). The water in these regions is heavily tannin stained and visibility is greatly reduced over large areas. Little is known about the substrates present or how these substrates might influence manatee use. To characterize the benthic environment, a Humminbird® side-scan sonar unit was used to image the bottom and then maps were created of substrate type and depth profile.

Methods

Study Site

The study site was located in Siguanea Gulf, Isla de la Juventud, Cuba (Fig. 1). The area consists of two large lagoons and three smaller lagoons, interconnected by a network of natural channels. There are two entrances to the lagoon system from Siguanea Gulf, separated by a large mangrove island. There are numerous other small mangrove islands, mostly concentrated in the channels and in very shallow areas where clumps of a few trees have taken root. There is a freshwater inflow from a wetland at the extreme eastern end of the lagoon system. The surveyed area is entirely surrounded by mangroves.

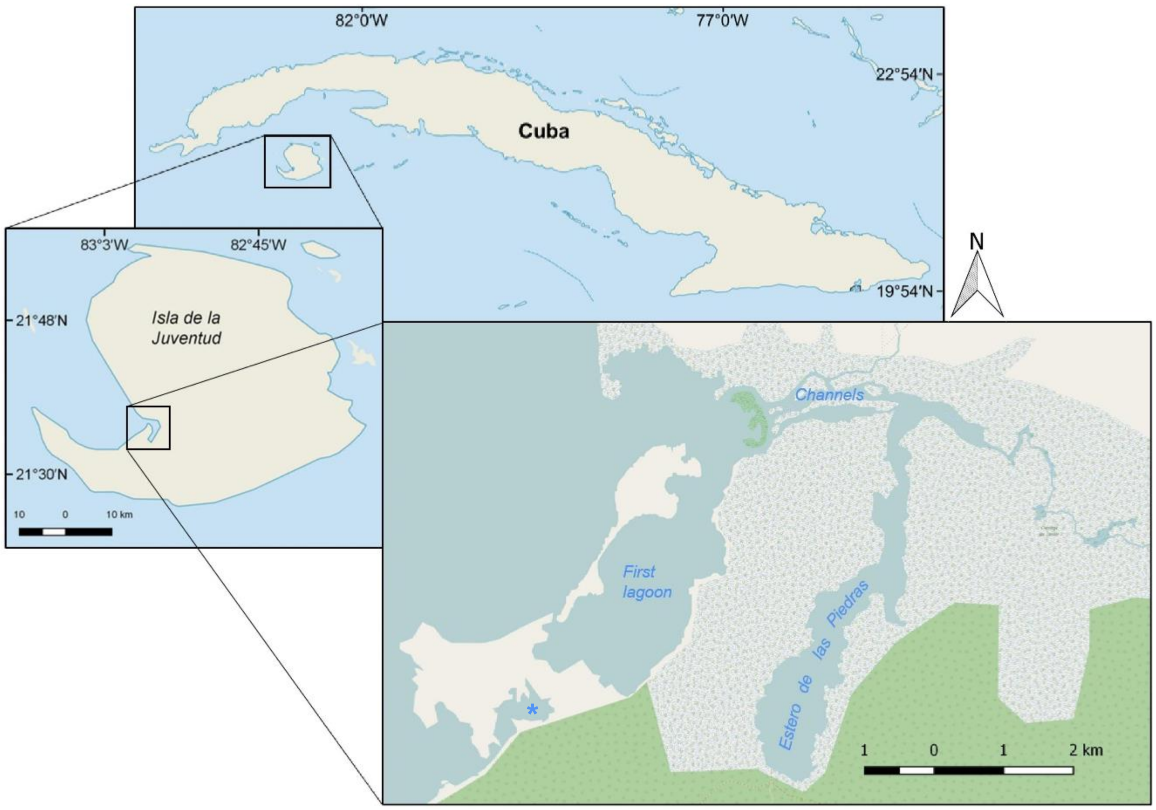


Figure 1. Study site on Isla de la Juventud, Cuba. Light blue areas are water. Blue thatched and white areas are mangrove wetlands. Green thatched areas are dry forest. *Unnamed small lagoon to the south of the first lagoon. Base map taken from OpenStreetMap® (© OpenStreetMap contributors).

Sonar Data Collection

Sonar imagery was collected over two summer seasons (June-August, 2015-16) using a Humminbird® 999ci HD SI side-scan sonar unit (Johnson Outdoors Inc., Racine, WI). The sonar unit was rear-mounted on a small boat with an outboard engine. Tracks were run at a width of 37 m with each track overlapping the previous track by 3-5 m (Fig. 2). In larger areas, tracks were run parallel to each other with the longest, straightest lines as possible, using a rectangular pattern (Fig. 2B). In narrower areas, such as channels, tracks were run parallel to the shoreline, then a zig-zag pattern was used. When time and fuel supplies allowed, the edges of each area were taken as a separate track. Tracks can only be recorded when the transducer is moving. Areas with a water depth of less than ~0.4 m were not surveyed as these were inaccessible to the boat and therefore also deemed inaccessible to manatees. Boat speed was kept at 6–8 km/h. Tracks were saved to an SD card in .DAT and .SON formats.

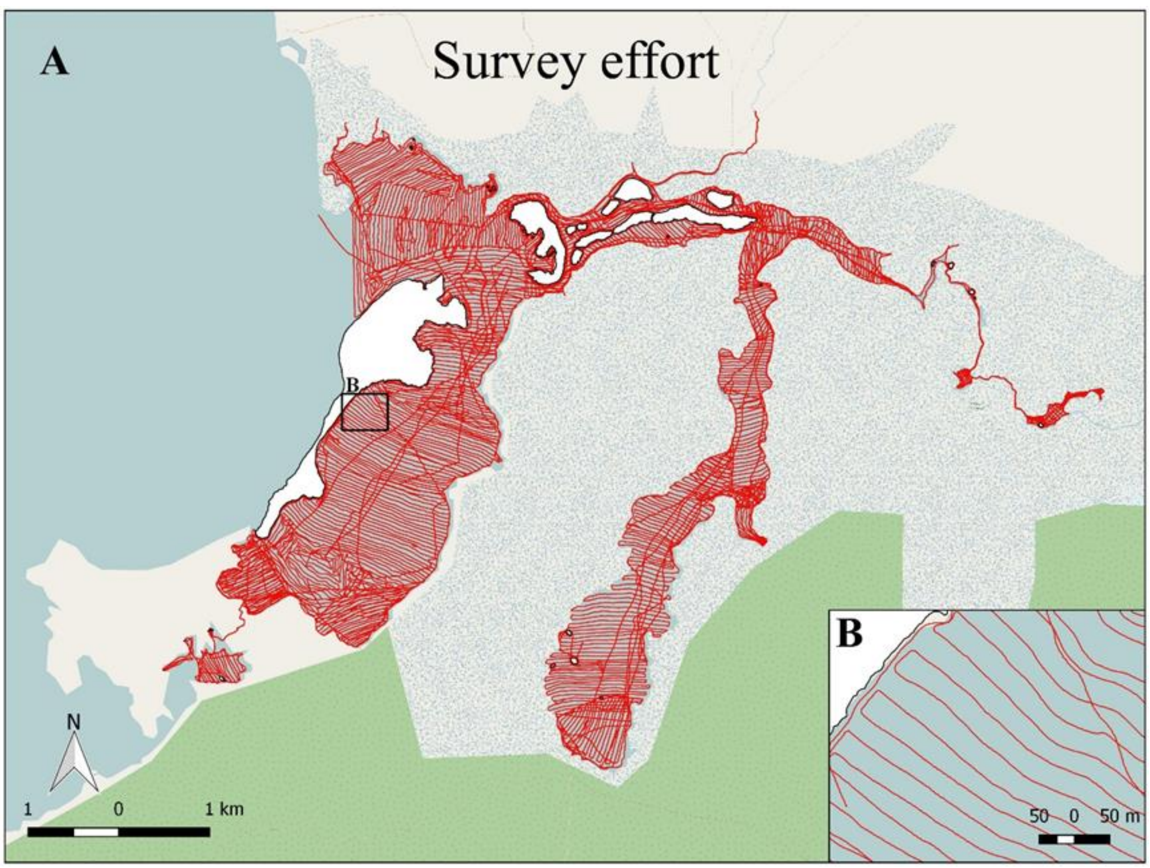


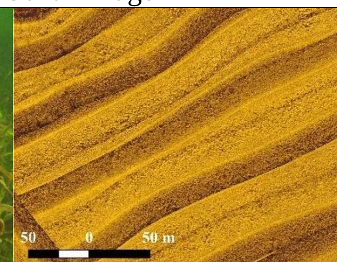
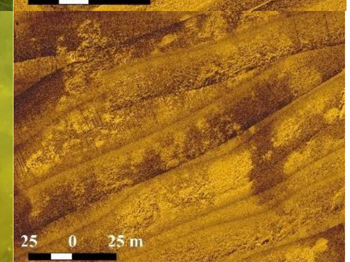
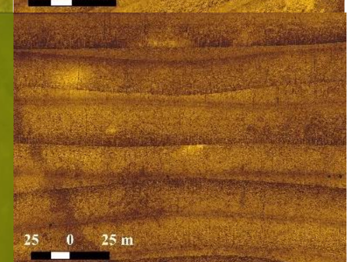
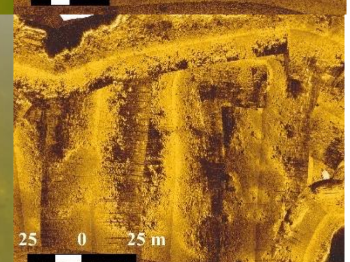
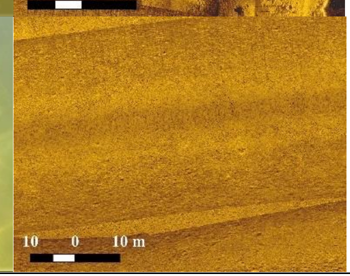
Figure 2. Survey effort in the San Pedro lagoon system. Inset: Close-up of sonar survey pattern. Base map taken from OpenStreetMap® (© OpenStreetMap contributors).

Substrate Mapping

The side-scan sonar recordings were imported into ReefMaster (ReefMaster Software Ltd., West Sussex, UK). Each track was examined separately and the contrast and brightness adjusted as needed before being compiled into a “New Sonar Mosaic”. The tracks were then trimmed to provide the best coverage and least amount of noise. The resulting complete mosaic was exported as a .mbtiles file and imported into QGIS (Quantum GIS 2.18.3). The substrates were characterized into six categories: dense seagrass (>50% coverage of seagrass), sparse seagrass (20–50% coverage of seagrass), mangrove soil, mangrove soil and rock, silt, and unknown (Table 1). A shapefile layer was created for each substrate type within QGIS. Polygons were drawn around each substrate type patch manually to create a patchwork map. Substrate classifications were determined by the dominate substrate in that patch. To validate the sonar images, 38 areas were ground-truthed opportunistically by recording videos using a GoPro video camera concurrently with sonar recordings (26 areas) or snorkeling using a GoPro or Canon PowerShot D30 waterproof camera (12 areas). Videos taken during sonar tracks were 13-70 s long, averaging 44 s. GPS points were taken at the starting and ending points of each video taken during a sonar track, resulting in 26 pairs of points. After the sonar images were categorized by substrate, the videos were reviewed and the substrates present in each clip determined. These visual characterizations were then compared with the sonar categorization. Accuracy was determined by the percent of substrates identified correctly.

Table 1

Description of substrate types with examples of each substrate and corresponding sonar image

Substrate	Description	Example	Sonar Image
Dense seagrass	Seagrass coverage greater than 50%		
Sparse seagrass	Seagrass coverage between 20% and 50% or patchy seagrass		
Mangrove soil	Substrate consisting of mud and partially decomposed organic debris		
Mangrove soil with rock	Rocky outcrops covered with a thin layer of mangrove soil and/or a mix of mangrove soil and rocky patches		
Silt	Smooth, muddy substrate		

A point was determined to be correct if the visual and sonar classifications matched. In the case of videos taken during sonar tracks, the start and end points were considered to be separate points and classified individually. This method yielded a total of 64 ground-truthed points (Fig. 3).

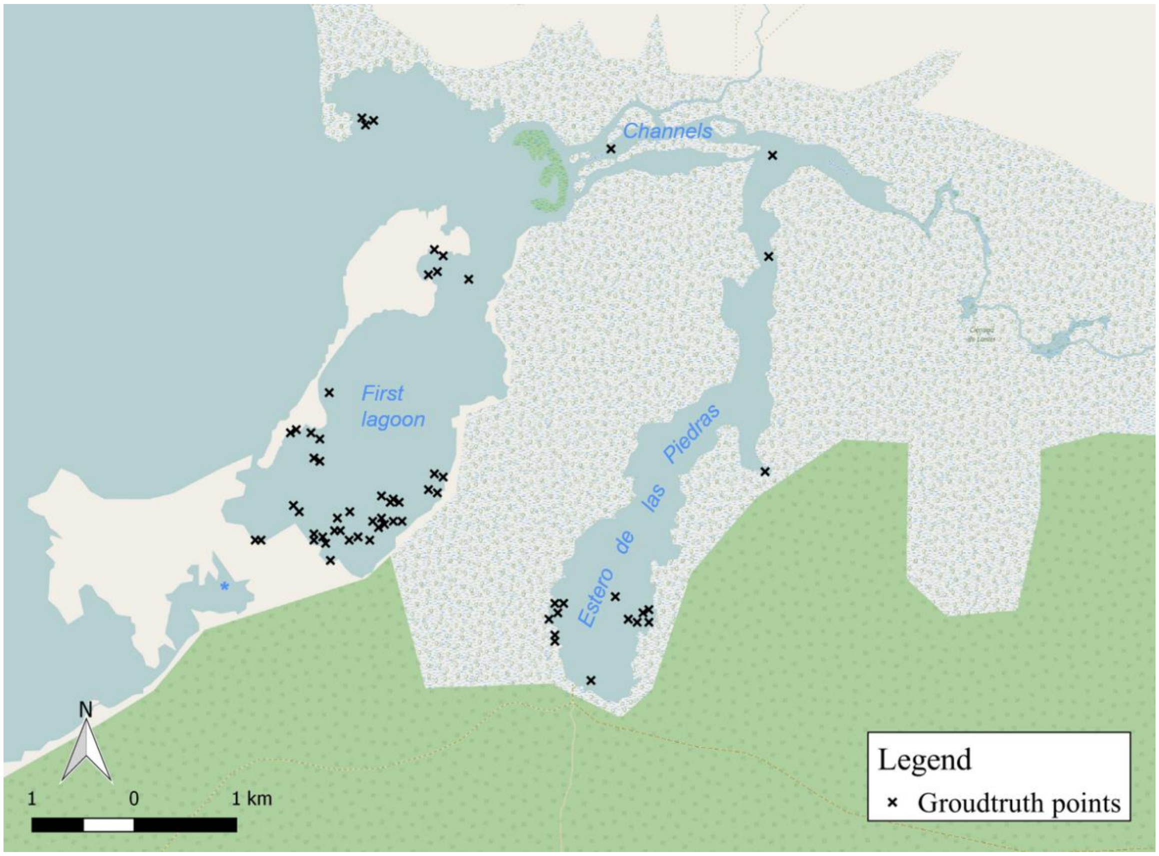


Figure 3. Points used for ground-truthing. *Unnamed small lagoon to the south of the first lagoon. Base map taken from OpenStreetMap®
(© OpenStreetMap contributors).

Bathymetric and 3D Mapping

Sonar tracks were downloaded from the sonar unit into ReefMaster. Tracks were reviewed and those with excessive noise (black linear artifacts, smearing, or poor recording quality) were discarded. Individual tracks were then added to a “New Project” to produce a map covering the whole study area. Shoreline and island map boundaries were created by exporting the side-scan sonar mosaics in KML format into Google Earth. The “Path” function was used to trace around the edges of the shoreline and islands using the mosaic images as a guide. Each path was saved as a KMZ file and imported into ReefMaster. The paths were added to the map as “Map Boundaries”. The path bordering the lagoon system was designated as the “Shoreline” and the paths around each island were designated as “Islands” with a “Closed Loop”. The max interpolation was set to 50 m and the major contour lines set to 0.5 m with the minor contour lines displayed at 0.125 m. The map can be displayed as a bathymetric map or a 3D map by toggling between the two modes within ReefMaster.

Results

A total of 11.55 km^2 were mapped using side-scan sonar. The depth was relatively shallow overall with deeper areas in the channels (Fig. 5, 6, Table 2). Mangrove soil and dense seagrass were the most common substrate types. Sparse seagrass, silt, and mangrove soil with rock were present over small areas. Less than 1% of the area could not be definitively identified (Fig. 6–8, Table 3).

After comparing the video recordings to the characterized map, it was determined that the overall characterization was 70% accurate (Table 4). Accuracy ranged from 43–90% correct. Dense seagrass had the highest accuracy, followed by mangrove soil with rock. Sparse seagrass had the lowest accuracy (Fig. 9). No areas classified as unknown were ground-truthed.

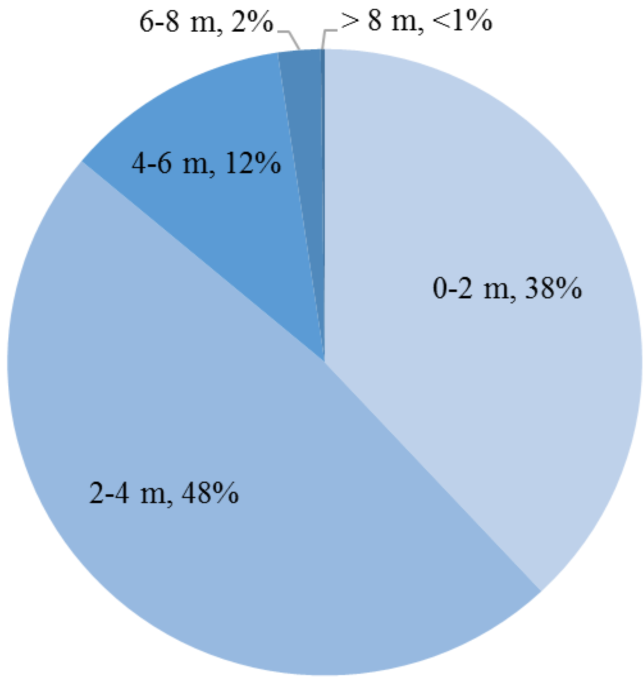


Figure 4. Water depth ranges by percentage of surface area.

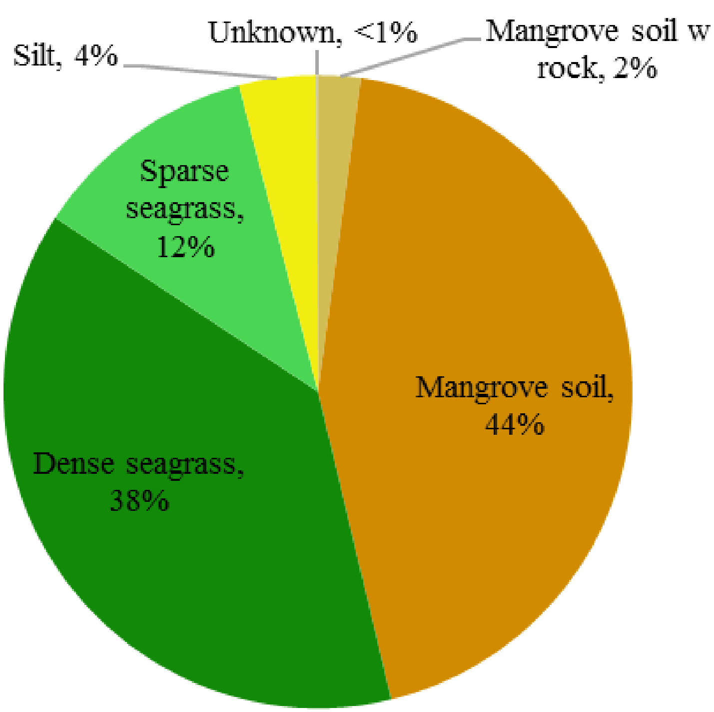


Figure 5. Substrate types by percentage of area covered.

Table 2

Depths, surface area, and percentage of the total area in each depth range

Depth range (m)	Surface area (m^2)	Surface area (km^2)	Percentage total area
0–2	4,403,586	4.40	38%
2–4	5,543,459	5.54	48%
4–6	1,328,898	1.33	11%
6–8	251,336	0.25	2%
>8	24,072	0.02	<1%

Table 3

Substrate type by area and percentage of the total area covered by each substrate type

Substrate	Area (m^2)	Area (km^2)	Percentage total area
Mangrove soil	5,514,175	5.51	44%
Dense seagrass	4,755,855	4.75	38%
Sparse seagrass	1,461,989	1.46	12%
Silt	494,722	0.49	4%
Mangrove soil w rock	272,945	0.27	2%
Unknown	11,099	0.01	<1%

The first lagoon contained a mixture of all sediment types, with a much higher coverage of seagrass than the second lagoon (Estero de las Piedras). The second lagoon was almost entirely mangrove soil or mangrove soil with rock. There was a small area of dense seagrass, but no sparse seagrass or silt. The deeper, narrow channels were covered by silt or mangrove soil. The small lagoons were covered entirely by mangrove soil, except for the small lagoon to the south of the first lagoon which had some areas of sparse seagrass.

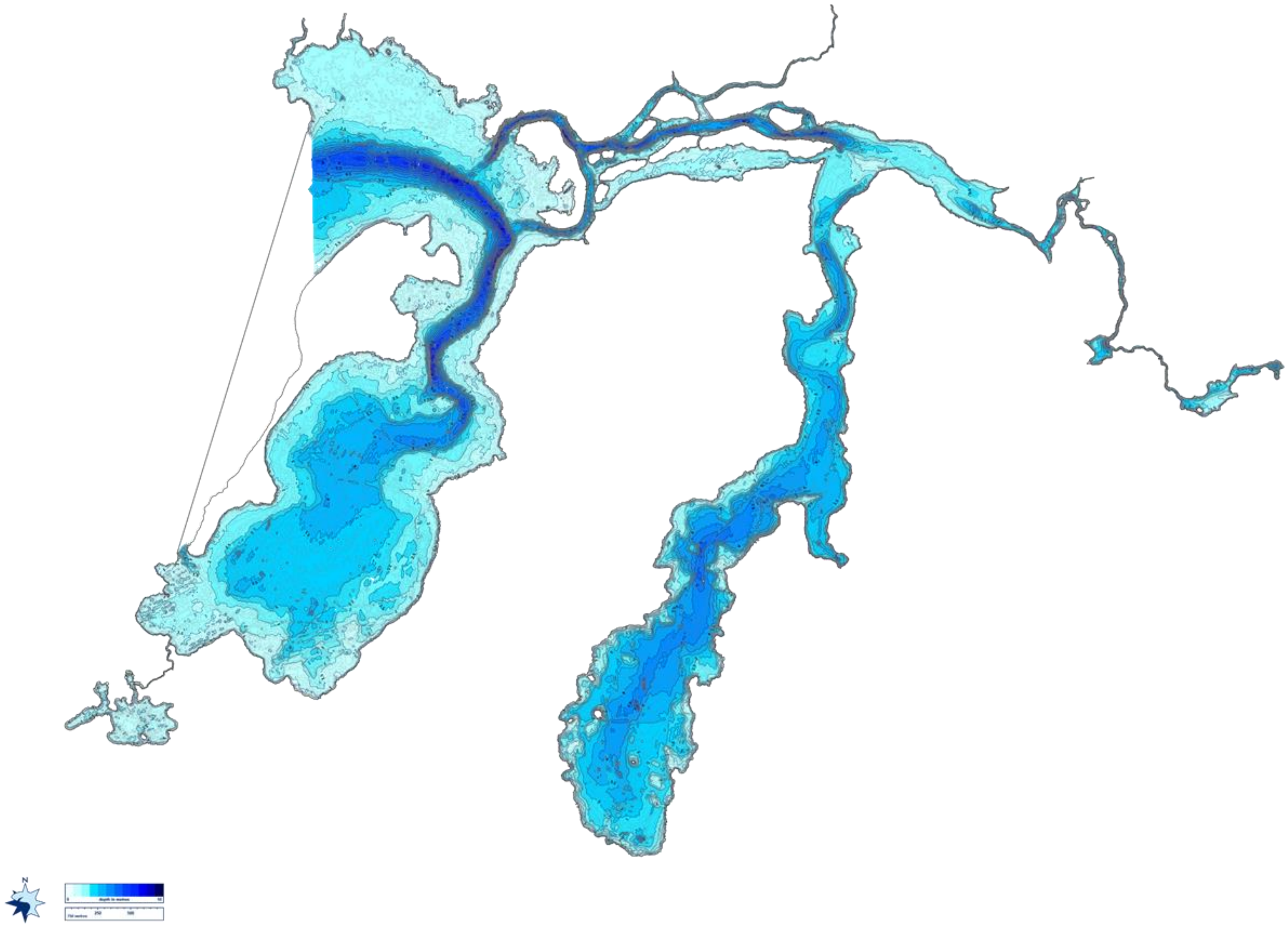


Figure 6. Bathymetric map of the San Pedro lagoon system.

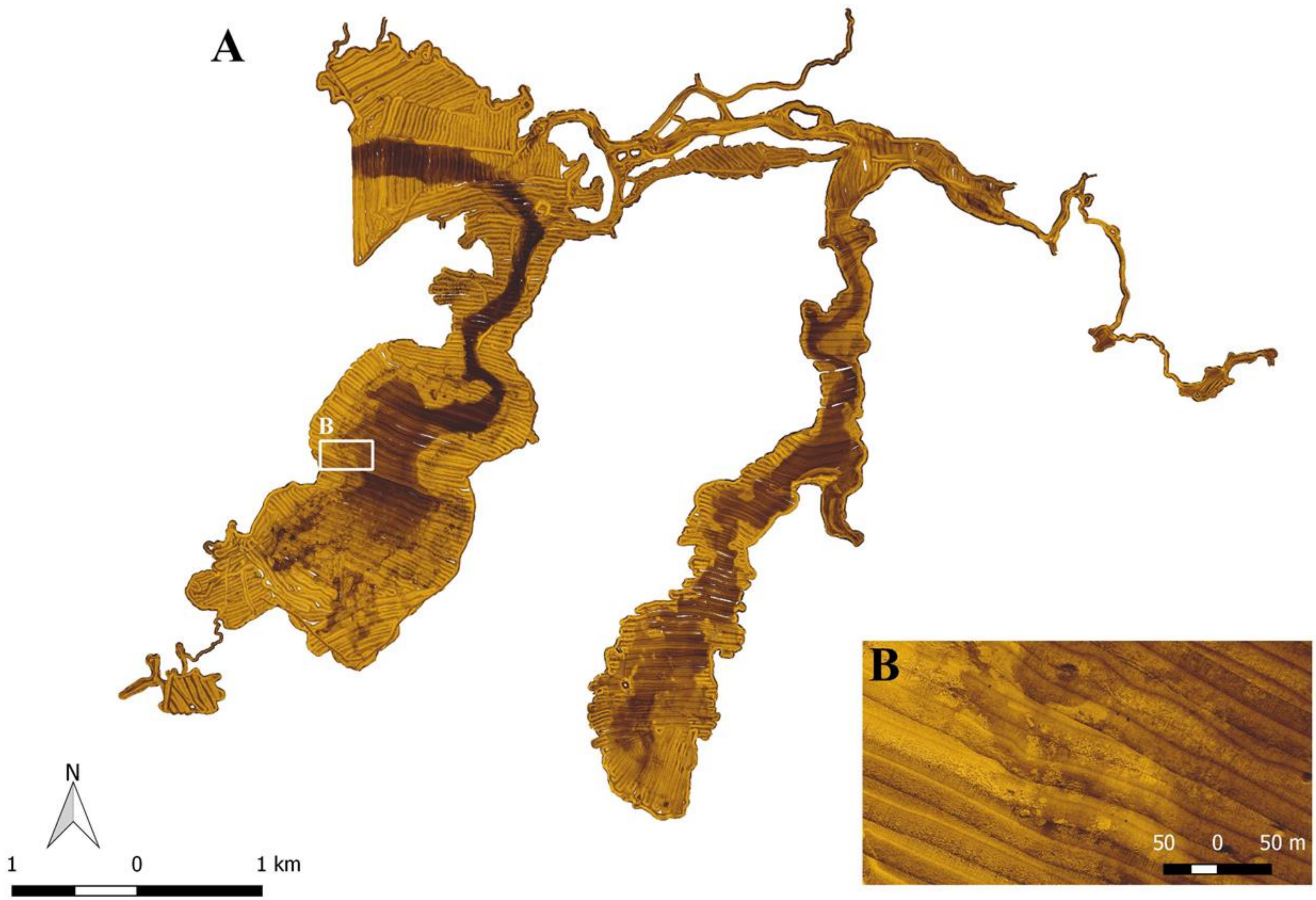


Figure 7. A) Sonar mosaic of the San Pedro lagoon system. B) Close-up of sonar tracks.

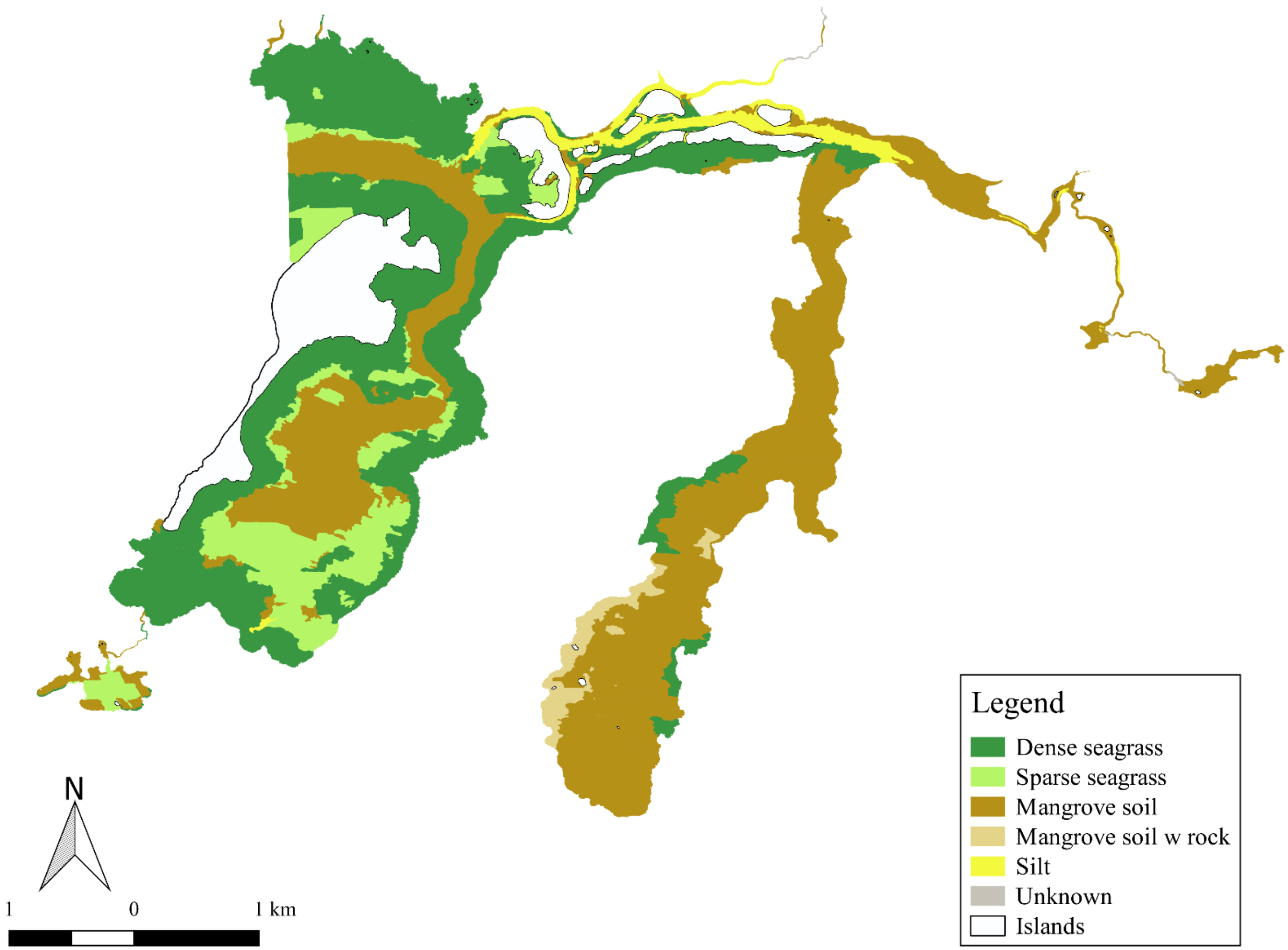


Figure 8. Benthic substrate map of the San Pedro lagoon system

Table 4

Correct classifications of substrate type

Substrate type	Correct classifications	Percent correct
Dense seagrass	26 out of 29	90%
Sparse seagrass	3 out of 7	43%
Mangrove soil	11 out of 21	52%
Mangrove soil with rock	4 out of 5	80%
Silt	1 out of 2	50%
Overall	45 out of 64	70%

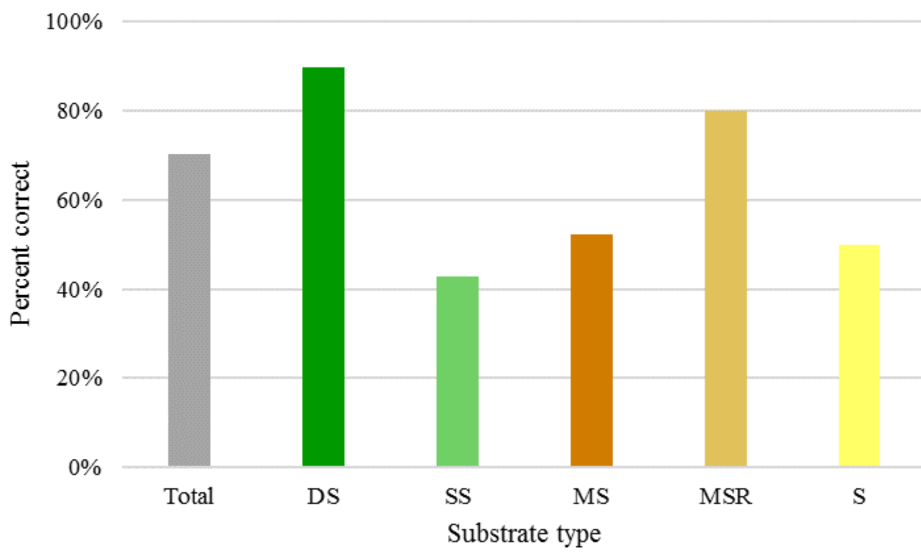


Figure 9. Percentage of substrate types classified correctly. DS = Dense seagrass; SS = Sparse seagrass; MS = Mangrove soil; MSR = Mangrove soil with rock; S = Silt

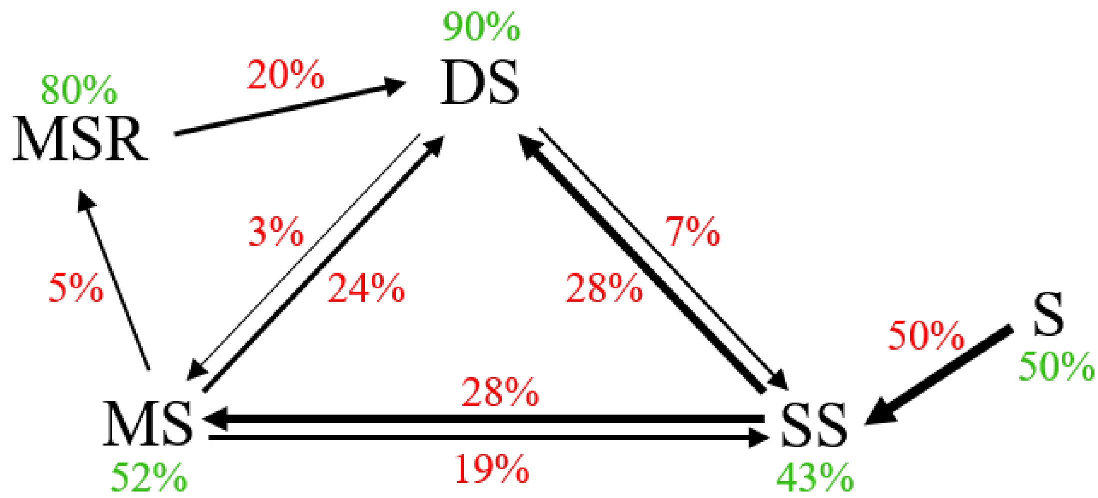


Figure 10. Substrate classification accuracy and misidentification. Green numbers are correct classifications; red numbers are incorrect classifications. Incorrect classifications are shown as a percentage of the observed substrate that was misidentified as the substrate the arrow points towards. Arrow thickness corresponds to the percentage value.

Discussion

As demonstrated by this study, side-scan sonar can be used to successfully identify benthic substrates. This is an important tool in areas with poor water visibility. The lagoons in San Pedro look very similar from the surface. All of them are brackish lagoons surrounded entirely by mangroves, but the benthic compositions are very different. The first large lagoon has a lot of area covered by seagrass, whereas the second large lagoon is almost entirely mangrove soil. The small lagoon to the south of the first lagoon has some areas of sparse seagrass. The other small lagoons do not. The deeper channels also appeared similar from the surface, but most of these channels were covered by silt. The very narrow channels were still classified as mangrove soil. The silty channels were wider and seemed to be in an area with a stronger current. One channel area was much shallower and wider with clearer water and contained a dense seagrass bed.

The substrate characterization was 70% accurate, overall. Dense seagrass had the highest accuracy at 90%. Dense seagrass has a distinctive sonar signature, making it relatively easy to identify. Sparse seagrass proved the most difficult to classify accurately (43%, 7 points). Sparse seagrass was equally misidentified as dense seagrass and mangrove soil. Silt had an accuracy of 50%. Silt has a very distinctive sonar signature, however, only two ground-truthed points were in silt areas. The misidentified point was classified as sparse seagrass. Mangrove soil was also difficult to identify correctly (52%, 21 points). This substrate type can vary significantly in depth, generating several different sonar signatures very similar in appearance to other substrate types. Mangrove soil with rock had an accuracy of 80% with five ground-truthed points. While dense seagrass had the highest accuracy, this substrate was also the substrate that accounted for most of the misidentifications of the other substrates. Classification as dense seagrass included 28% of misidentified sparse seagrass, 24% of misidentified mangrove soil, and 20% of misidentified mangrove soil with rock. Mangrove soil was mostly misidentified as seagrass with a small percentage misidentified as mangrove soil with rock (Fig. 10). Seagrass and mangrove soil can look very similar on the sonar recording, making it difficult to tell these substrates apart.

The San Pedro lagoon system also varies greatly in depth. The first large lagoon was shallower overall with clearer water in most places. The second large lagoon was deeper and narrower with fewer access points to the rest of the area. Most of the channels were deep and narrow, with the exception of the one channel containing the dense seagrass bed. The deepest point in this lagoon system was in the channels (10.3 m). The minimum depth of 0 m was interpolated by the software as the boat was not able to access areas shallower than ~0.4 m.

Side-scan sonar does have limitations. Soft substrates are more difficult to classify than hard substrates as the sonar signature can be more ambiguous and not as clearly defined. Mangrove soil can be particularly difficult to classify. This soil type can vary in depth from very shallow, which can resemble silt, to deep, which has a feathery appearance much like seagrass. Additionally, differentiating seagrass by density can be challenging. However, seagrasses of different heights produce different sonar signatures, possibly lending itself to easier identification by height. While it is not possible to differentiate between grass species by their sonar signatures, relative heights could help with identification of seagrasses. Scanning large areas is very time consuming as track widths must be relatively narrow in order to obtain an image resolution suitable for classifying substrates. However, using this technology facilitates faster data collection than if substrates were classified manually in the field by diving or snorkeling.

Some of the identification errors could be explained by GPS margin of error as some misidentified points were on the boundary between substrate types. This study was limited by the number of ground-truthed points and the areas ground-truthed. This was due to limited time and fuel supplies as well as a camera malfunction that prevented recording for several days. In the future, random points will be generated for the surveyed area and more ground-truthing will take place.

To the best of my knowledge, this is the first complete benthic substrate characterization of a mangrove lagoon system in the Greater Caribbean. It is also the first study to utilize low-cost side-scan sonar in a brackish system over a large area.

Recommendations

Ideal conditions for side-scan sonar use are a calm water surface and little or no wind and current. Sunny days are preferable as this contributes to the ease of ground-truthing from the surface. However, useful data can still be collected in choppy conditions, though chop higher than ~0.3 m will significantly increase the noise in the data. In choppy conditions, the tracks should run parallel to the wave motion if collecting primarily bathymetric data. For cleaner tracks of sonar imagery, the tracks should run perpendicular to the wave motion. Running tracks perpendicular to the wave motion causes the boat to roll. This creates a slight smearing effect in the sonar images, but is more dramatically seen in the bathymetric profile where the roll is evident in the bottom topography. Running tracks parallel to the wave motion causes the boat to move up and down, greatly increasing the noise in the sonar images. However, this type of motion has less of an effect on the bathymetric data than a side-to-side roll. For best results, water surface conditions should be as flat as possible and sonar data should not be collected in choppy conditions greater than 0.30 m.

The engine on the boat should produce as little vibration as possible. The propeller shaft should be short to avoid blocking the sonar beam. The transducer’s cord should be secured, preferably with brackets to the hull of the boat, to avoid the cord dragging into the water and tangling in the propeller. The angle of the transducer should be adjusted to be parallel with the ground when the boat is in motion. The boat driver should be able to see the sonar console while in motion. Viewing the map screen is the easiest way to make sure the tracks are aligned correctly and cover the appropriate area. The side-scan image screen should be frequently checked to monitor image quality.

Boat balance and vibration both greatly influence image quality. Each boat balances differently, but weight should be distributed so the boat remains as evenly balanced as possible. This can be achieved by adding people or counterweights to the boat. Vibration should be limited as much as possible. A good engine will reduce much of this problem. Mounting the transducer directly to the hull of the boat also decreases issues caused by vibration.

Using a GoPro or similar type camera to record videos while running the sonar transects works well to capture real-time images of the benthic substrates. However, in areas with heavily tannin stained or turbid water, the depths at which the GoPro can be used will be greatly limited. Bright sunlight increases the visibility for the camera. Ideally the GoPro should be held just below the surface and angled slightly down and back.

CHAPTER 3

PRELIMINARY ASSESSMENT OF HABITAT USE BY MANATEES

Introduction

West Indian manatees are large herbivores, requiring sizeable amounts of forage. Their diet is relatively broad, composed of submerged, floating, and terrestrial vegetation that is within the manatees' reach. In Cuba, seagrasses of the genera *Thalassia, Syringodium,* and *Halodule* are the major components of manatee diet (Aleman, 2011). Manatees need beds of such grasses to support their dietary needs. Feeding areas range between 1 and 5 m in depth with an average depth of 2 m (Lefebvre et al., 2000). Manatees also require fresh water for drinking periodically and will take advantage of both artificial, such as an irrigation hose, and natural sources, such as springs or rivers (Marsh et al., 2011). Manatees avoid areas with fast moving or turbulent water. Sheltered areas with low water movement seem to be favored by resting manatees and mothers with newborn calves (Bacchus, Dunbar, & Self-Sullivan, 2009; Gannon, Scolardi, Reynolds, Koelsch, & Kessenich, 2007). Additionally, cows and calves are often found in areas near seagrass beds (Gannon et al., 2007). Manatees also prefer areas with lower ambient noise, anthropogenic or natural, selecting habitats with lower environmental noise and avoiding high traffic boating areas (Miksis-Olds et al., 2007).

Previous surveys to determine manatee habitat use have relied on a combination of aerial surveys (Lefebvre et al., 2000; Morales-Vela, Olivera-Gómez, Reynolds III, & Rathbun, 2000; Olivera-Gómez & Mellink, 2005; Wright et al., 2002), point surveys (LaCommare et al., 2008), telemetry (Castelblanco-Martínez et al., 2013; Lefebvre et al., 2000), and opportunistic, anecdotal, and historical sightings (Cummings et al., 2014; Jiménez, 2005) to determine manatee presence. After manatee locations were identified, various habitat characteristics were measured and habitat use was correlated to these factors. Morales-Vela et al. (2000) classified habitat types at their study sites in Mexico as rivers, lagoons, coast, cays, and Turneffe Atoll. Manatees used all areas, but the fewest were seen around Turneffe Atoll. Lefebvre et al. (2000) determined that feeding manatees in Florida and Puerto Rico use shallow, sheltered, near-shore seagrass beds. Wright et al. (2002) found that manatees use habitats, defined as open ocean, Intracoastal Waterway, sounds and bays, rivers and creeks, and marinas, with different frequency in North Carolina and Virginia, though most sightings were in more sheltered areas and away from marinas. Sighting frequency throughout the area was effected by water temperature with fewer sightings in the colder months. Cummings et al. (2014) also found that manatee habitat use is affected by water temperature in the United States. Olivera-Gómez and Mellink (2005) used transects to determine aquatic vegetation cover near manatee sightings in Chetumal Bay, Mexico, and also characterized these areas by depth, slope of bottom, shelter from wind and waves, salinity, and distance to freshwater sources. Manatee use of areas within the study site was most strongly influenced by depth and distance to freshwater and was also influenced by vegetation cover. LaCommare et al. (2008) used point surveys to determine manatee habitat use in the Drowned Cayes area of

Belize. Habitats were classified as lagoon, channel, channel edge, seagrass bed, cove, and reef. Average depth and the presence of seagrass and resting holes was also noted. It was determined that the probability of spotting a manatee was highest on the seagrass beds and lowest on the reef. Castelblanco-Martínez et al. (2013) used telemetry data to identify hotspots of manatee use in Mexico and Belize. Points were then sampled in these areas to determine depth and benthic substrate which was categorized as either soft or hard. Manatee activity was concentrated near estuarine and coastal habitats in shallow waters with soft substrates. Jiménez (2005) compared manatee sightings from study sites in Nicaragua and Costa Rica to water depth and temperature (taken with a traditional sonar at equal intervals along a transect), water visibility and current (taken at discreet points), waterway width (measured from maps and aerial photographs or *in situ* in narrow areas), and emergent and floating vegetation cover (presence and estimated cover taken at regular intervals along the edges of each waterway). Manatees tended to use areas with clear, warm water that also had higher vegetation cover, greater depths, and slower currents and were more often found in wider areas than narrower areas.

The San Pedro lagoon system on Isla de la Juventud, Cuba, shares many of the same characteristics with these other study sites and is known to be an important area for manatees, though the reasons for this are not well understood (Alvarez-Alemán, Angulo-Valdés, Alfonso, Powell, & Taylor, 2016). The lagoon system is surrounded by mangroves and contains large seagrass beds, soft sediment areas, sheltered areas, freshwater sources, warm, shallow water and has minimal tidal changes. This preliminary study compares manatee sightings to depth and benthic substrates, categorized as dense seagrass, sparse seagrass, mangrove soil, mangrove soil with rock, silt, and unknown.

From previous studies, it is predicted that most manatee sightings would be in seagrass beds and areas with softer substrates (seagrass, mangrove soil, or silt) and most frequently in water depths of 2–4 m ±1 m. An ongoing project by the Centro de Investigaciones Marinas from the University of Havana has collected data on manatee sightings through the use of boat transects and fixed observation points where abiotic factors are also measured (unpublished data). Pairing these data with the spatial data from chapter 2 can provide a more complete picture of manatee use patterns within the San Pedro lagoon system.

Methods

Spatial data from chapter 2 was used for bathymetric and habitat characterization maps. This map and the bathymetric map were then overlaid with records of manatee sightings in the San Pedro lagoon system between 2007 and 2014. Sightings were recorded during boat transects, while at fixed observation points (Fig. 11), and opportunistically during other activities (unpublished data). Observers were researchers from the University of Havana and volunteers through Operation Wallacea. The distribution was then analyzed for patterns. A one sample chi-square test was used to examine significant differences of manatee sightings by substrate type and water depth range, which was controlled for area. Water depths were divided into five ranges (0.0–2.0 m, 2.0–4.0 m, 4.0–6.0 m, 6.0–8.0 and >8.0 m) to provide even intervals for the range of depths found in the San Pedro lagoon system (max depth 10.3 m).

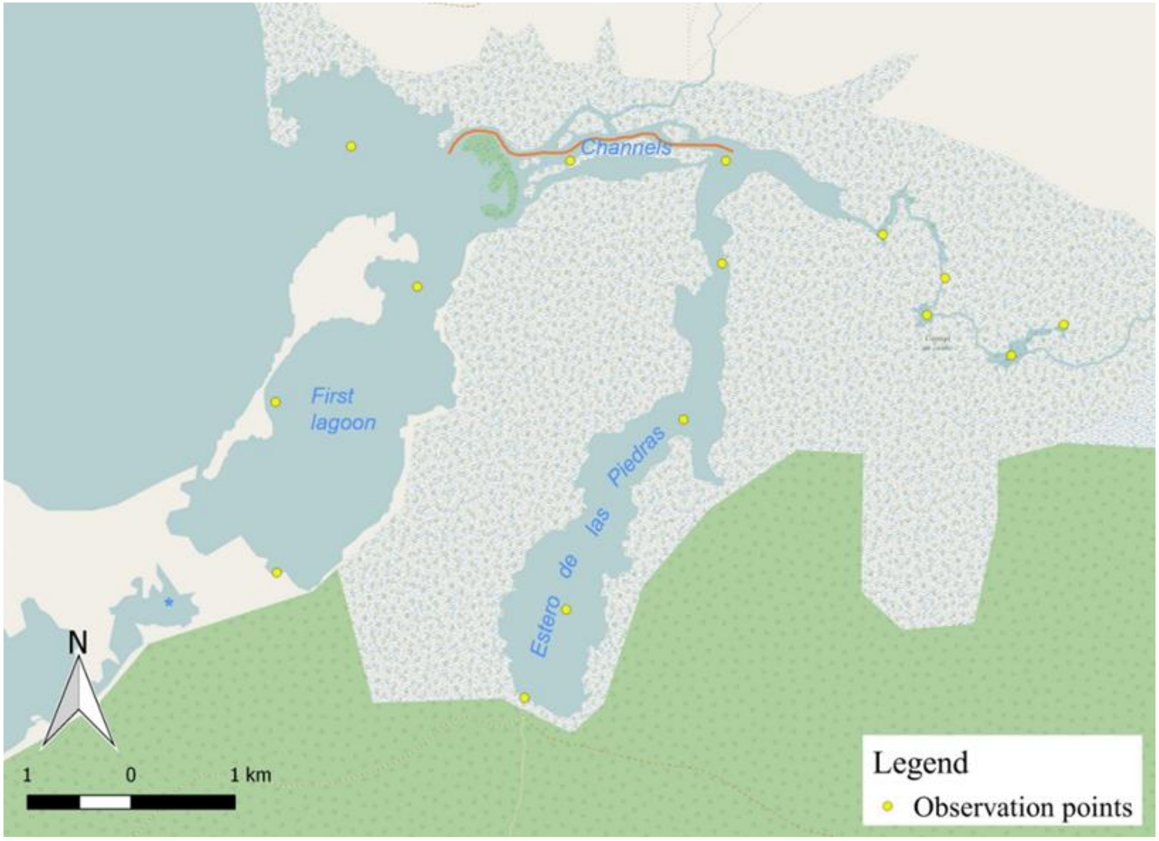


Figure 11. Fixed observation points within the San Pedro lagoon system used for point surveys of manatee presence and collection of abiotic environmental factors. Orange represents route taken by survey boat between the first lagoon and Estero de las Piedras. *Unnamed small lagoon to the south of the first lagoon. Base map taken from OpenStreetMap® (© OpenStreetMap contributors).

Results

There were 95 georeferenced sightings of manatees between 2007 and 2014. Most sightings were in areas characterized as mangrove soil. Areas characterized as silt also had a high number of sightings. There were only a few sightings in areas characterized as dense seagrass. No manatees were spotted in areas characterized as sparse seagrass, mangrove soil with rock, or unknown substrate (Table 5, Fig. 12). Manatees were seen most frequently in areas ranging in water depth of 2–6 m. Only 1 sighting was recorded in an area over 8 m deep (Table 6, Fig. 13). There was a significant difference in the number of manatee sightings between the different substrate types ($\chi^2(5) = 130.59$, $p < 0.001$). There was a significant difference in the number of manatee sightings between the different depth ranges ($\chi^2(4) = 169.62$, $p < 0.001$).

Table 5

Number of manatee sightings by characterized substrate type

Substrate	Number of sightings	Expected number of sightings*	Difference
Dense seagrass	10	36.1	-26.1
Sparse seagrass	0	11.4	-11.4
Mangrove soil	63	41.8	21.2
Mangrove soil w/rock	0	1.9	-2.1
Silt	22	3.8	18.2
Unknown	0	0.08	-0.08

*Expected values based on proportion of substrate type found in the study site

Table 6

Number of manatee sightings by water depth range

Depth range (m)	Number of sightings	Expected number of sightings*	Difference
0.0–2.0	6	36.1	-30.1
2.0–4.0	36	45.6	-9.6
4.0–6.0	38	11.4	26.6
6.0–8.0	14	1.9	12.1
>8.0	1	0.2	0.8

*Expected values based on proportion of water depths found in the study site

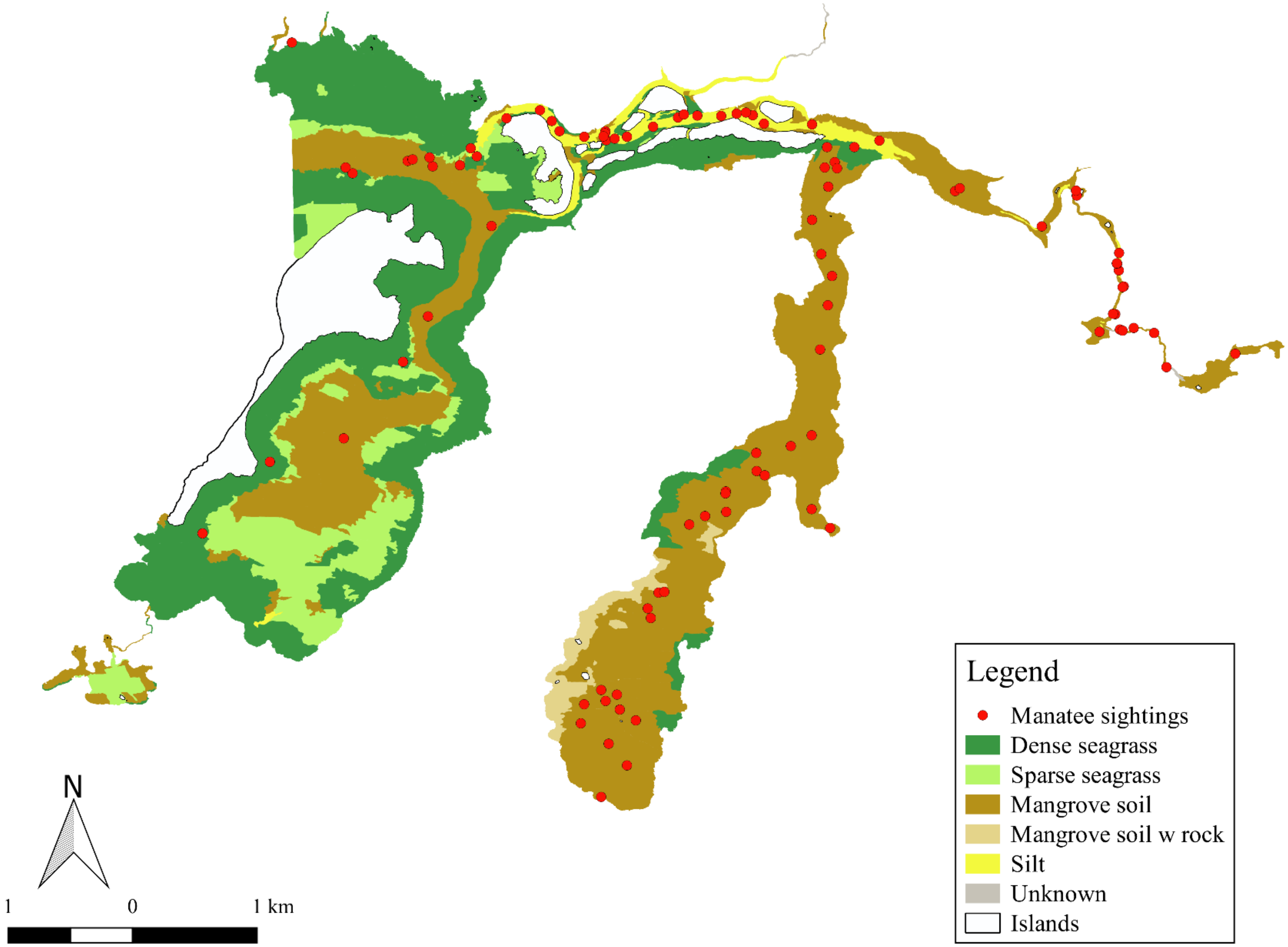


Figure 12. Manatee sightings by substrate type.

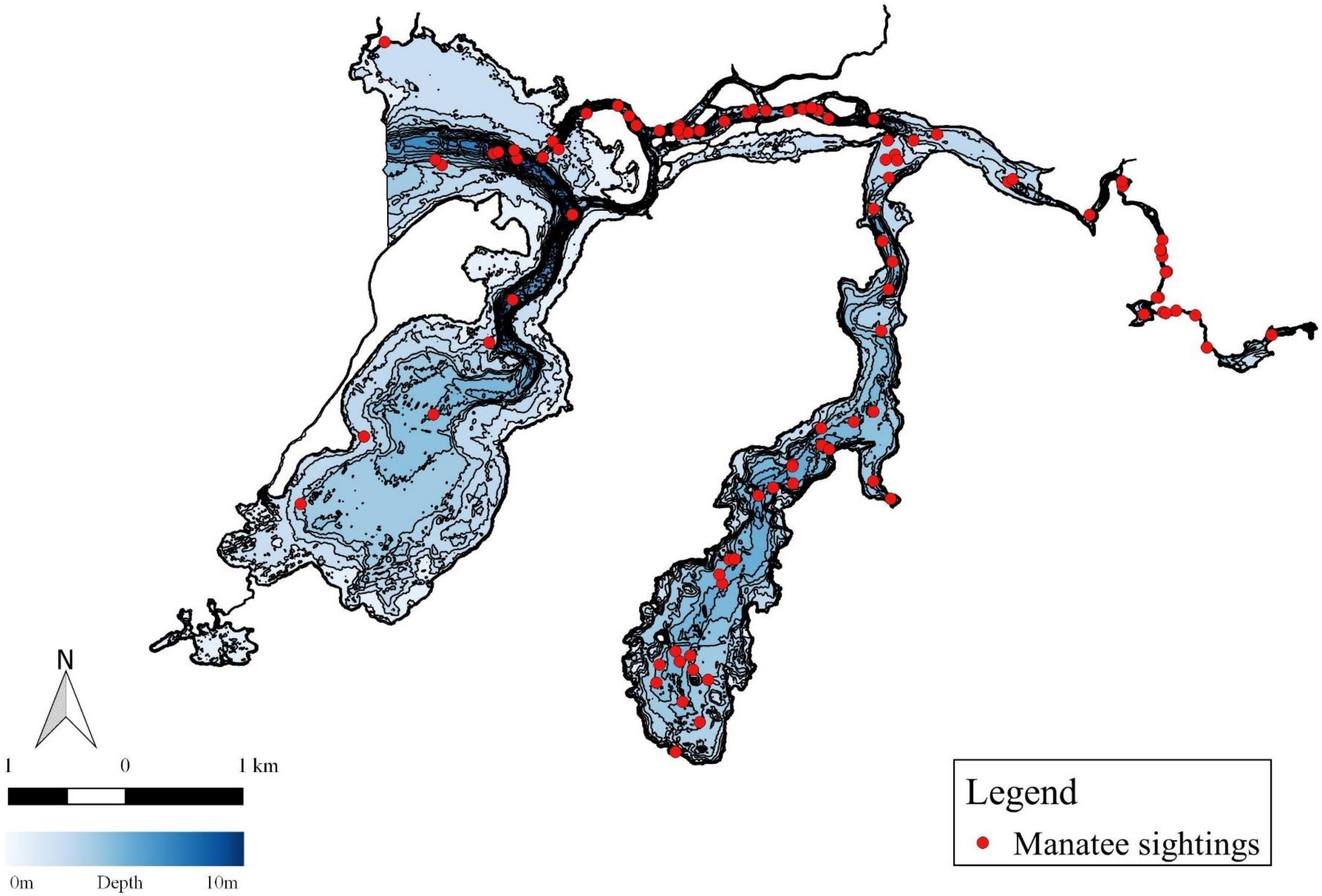


Figure 13. Manatee sightings by water depth.

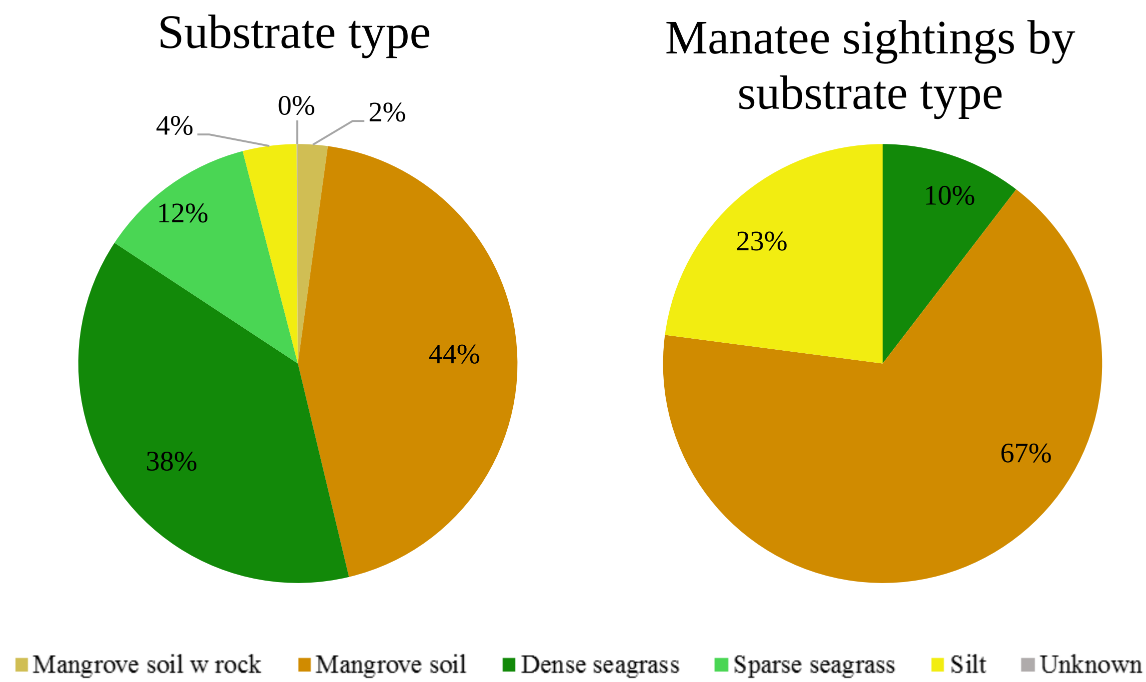


Figure 14. Comparison of substrate coverage (left) and manatee sightings by substrate type (right).

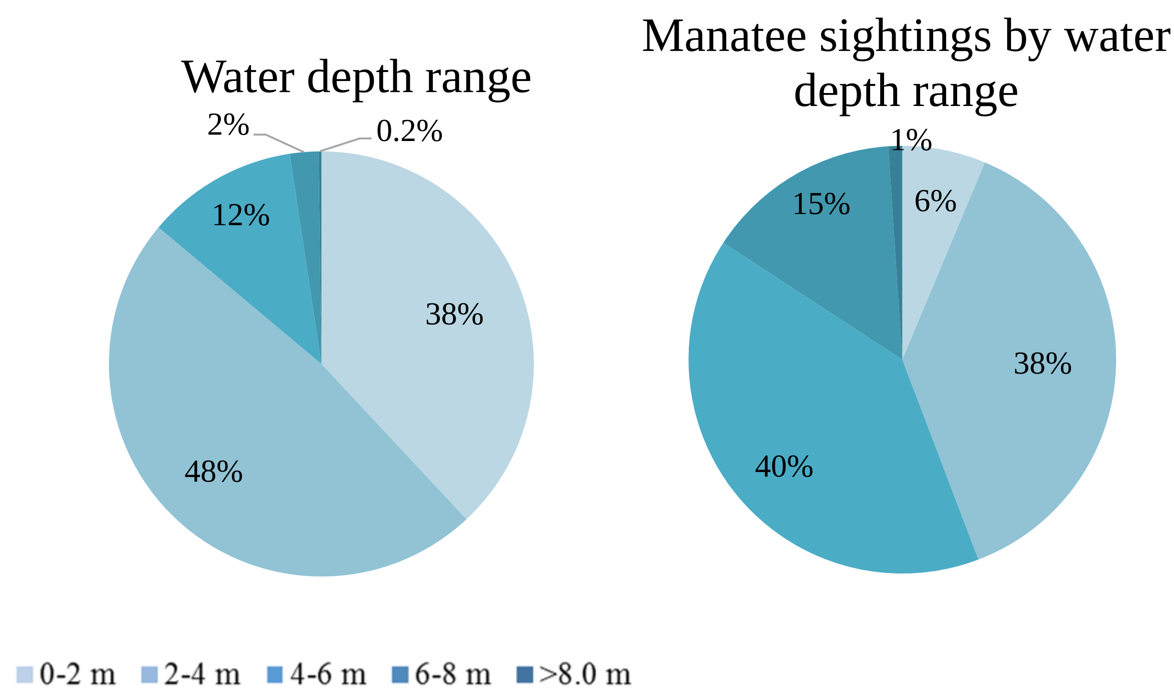


Figure 15. Comparison of water depth range (left) and manatee sightings by water depth range (right).

Discussion

Manatees were most commonly sighted in depths of 2–6 m (Fig. 15). There were very few sightings in areas with depths shallower than 2 m and only 1 sighting in areas with depths greater than 8 m. The prediction that manatees would be seen in areas with water depths of 2–4 m ±1 m was correct and the result was statistically significant. There were many more sightings in water depths of 4–6 m than expected when scaled for area. There were also a lot less sightings than expected in water depths of 0–2 m. This aligns with previous studies in which manatees were observed most commonly at depths of 2–6 m, but also observed at depths down to 10 m (Castelblanco-Martínez et al., 2013; Olivera-Gómez & Mellink, 2005), and feeding at depths between 1 m and 5 m, with an average depth of 2 m. (Lefebvre et al., 2000).

All manatee sightings were in areas with soft substrates, which was predicted and is similar to the results of Castelblanco-Martínez et al. (2013). In the San Pedro lagoon system, most of the manatee sightings were in mangrove soil areas (Fig. 14). Only 10% of sightings were made in seagrass areas though seagrass covers 50% of the surveyed region. This could indicate that while there are extensive areas of seagrass within this lagoon system, the forage quality is low or the seagrass species composition is less favorable to the manatees in this region as manatees were much more likely to be seen in seagrass areas in other studies (Jiménez, 2005; LaCommare et al., 2008; Olivera-Gómez & Mellink, 2005). Manatees may also be using these areas outside of survey times, such as at night. A large proportion of the sightings were made in mangrove soil and silt areas, 90% of sightings combined. These two substrates cover 48% of the area. Many of the sightings were along the route the survey boat always takes between the fixed observation points. Most areas of dense seagrass were in areas too shallow for the survey boat as these were areas of clear water that facilitate plant growth. This likely artificially skewed the records to include a much higher incidence of manatees in mangrove soil and silt areas as this is where the observers spent more time. A lack of sightings in seagrass areas may also indicate that the San Pedro lagoon system is used for purposes other than feeding, such as shelter and resting. However, it may be that observations took place outside of foraging times as these sightings were taken only during the day and often by volunteer observers with limited training over a relatively short period of the day. Longer surveys, radio telemetry, and side-scan sonar could all be utilized to help determine use patterns within the San Pedro lagoon system. Radio telemetry would add valuable data about the nocturnal movements of these animals, something that would be impossible for an observer to detect.

The San Pedro lagoon system appears to be an important site for manatees. It contains a patchwork of habitats, including seagrasses and freshwater sources. It also provides shelter and is relatively shallow. There was a significant difference in the distribution of manatee sightings between the different water depths and substrate types, showing an apparent preference for shallower water in areas characterized as mangrove soil.

CHAPTER 4

CONCLUSION

Characterizing submerged habitat has been and continues to be a challenge to researchers. Traditional sonar units are large, cumbersome and expensive. This limits the availability and usefulness of such sonar systems to most researchers. However, small, affordable side-scan sonar units, such as those manufactured by Humminbird®, offer a tangible solution. These units are particularly useful in the detection of submerged manatees and other larger animals (Arévalo-González et al., 2014; Castelblanco-Martínez et al., 2017; Flowers & Hightower, 2013; Gonzalez-Socoloske, 2007, 2013; Gonzalez-Socoloske & Olivera-Gomez, 2012; Gonzalez-Socoloske et al., 2009; McCarty, 2014) and the characterization of their benthic habitats (Gonzalez-Socoloske & Olivera-Gomez, 2012; Kaeser & Litts, 2008, 2010) as these areas tend to be difficult to access and water visibility is usually very poor.

Hard substrates and large objects are easily identified as the sonar signature of these features are very distinct. Soft substrates can be more difficult to differentiate, but can still yield valuable results. Loose soils and substrates, such as the mangrove soil found throughout much of this system, can mimic other substrates such as seagrass, increasing the likelihood of errors. Sparse, but evenly distributed, seagrass is more difficult to identify than clumps of dense seagrass as it can also look very similar to mangrove soil. Seagrass could probably be much more easily separated by height than by density, especially if distribution remains even. However, a trained observer should be readily able to tell most substrate types apart.

Training is very important not only for the sonar analyst, but also the sonar operator and the boat driver. The sonar imagery is best when the tracks are as long and straight as possible. Rapid and frequent turning smears the image, rendering it almost useless. Noise is easily introduced, but also easily eliminated if the problem can be quickly identified and corrected. Balance is very important on a boat running sonar as is minimizing the effects of the propeller's disturbance. Learning to recognize and respond appropriately to such situations is essential to collecting clean sonar data.

Manatees are cryptic animals and wary of humans in much of their range due to hunting. This makes studying manatees a challenge. Studying their habitat also proves a challenge as many areas are very remote or in regions of geopolitical instability. However, establishing good population estimates and identifying key habitat characteristics can go a long way to helping preserve these unique animals. Utilizing imagery produced by side-scan sonar with mapping and analysis software such as ReefMaster and QGIS gives researchers a powerful tool to identify patterns and establish baselines for population and behavior.

APPENDIX A

RAW DATA FOR CHAPTER 2

Table 7. Ground-truthing points and substrate observation and classification.

Point number	Video file	Latitude	Longitude	Observed substrate[a]	Classified substrate[b]
WP006	GOPR0074	N 21°33'44”	W 82°57'22”	MS	MS
WP007	GOPR0074	N 21°33'44”	W 82°57'19”	MSR	MSR
WP008	GOPR0075	N 21°33'42”	W 82°56'50”	MS	MS
WP009	GOPR0075	N 21°33'41”	W 82°56'52”	MS	MS
WP010	GOPR0076	N 21°33'41”	W 82°57'21”	MS	MSR
WP011	GOPR0076	N 21°33'39”	W 82°57'24”	MSR	MSR
WP012	GOPR0077	N 21°33'39”	W 82°56'57”	MS	MS
WP013	GOPR0077	N 21°33'39”	W 82°56'57”	MS	MS
WP014	GOPR0078	N 21°33'38”	W 82°56'54”	MS	DS
WP015	GOPR0078	N 21°33'38”	W 82°56'50”	MSR	DS
WP016	GOPR0079	N 21°33'34”	W 82°57'22”	MSR	MSR
WP017	GOPR0079	N 21°33'32”	W 82°57'22”	MSR	MSR
WP018	GOPR0081	N 21°34'04”	W 82°59'04”	DS	DS
WP019	GOPR0081	N 21°34'04”	W 82°59'02”	DS	DS
WP020	GOPR0082	N 21°34'07”	W 82°58'37”	DS	DS
WP021	GOPR0082	N 21°34'07”	W 82°58'35”	MS	MS
WP022	GOPR0083	N 21°34'10”	W 82°58'17”	SS	SS
WP023	GOPR0083	N 21°34'10”	W 82°58'14”	DS	DS
WP024	GOPR0084	N 21°34'09”	W 82°58'20”	SS	DS
WP025	GOPR0084	N 21°34'08”	W 82°58'22”	DS	DS
WP026	GOPR0085	N 21°34'05”	W 82°58'41”	DS	DS
WP027	GOPR0085	N 21°34'06”	W 82°58'44”	DS	DS
WP028	GOPR0086	N 21°34'04”	W 82°58'44”	DS	DS
WP029	GOPR0086	N 21°34'03”	W 82°58'40”	DS	DS
WP030	GOPR0087	N 21°34'04”	W 82°58'32”	MS	SS
WP031	GOPR0087	N 21°34'05”	W 82°58'29”	SS	SS
WP032	GOPR0088	N 21°34'04”	W 82°58'25”	SS	MS
WP033	GOPR0088	N 21°34'05”	W 82°58'29”	DS	SS
WP037	GOPR1861	N 21°34'38”	W 82°58'52”	DS	DS
WP038	GOPR1861	N 21°34'39”	W 82°58'50”	DS	DS
WP039	GOPR1862	N 21°34'24”	W 82°58'00”	DS	DS
WP040	GOPR1862	N 21°34'25”	W 82°58'03”	DS	DS
WP041	GOPR1863	N 21°34'38”	W 82°58'45”	DS	DS
WP042	GOPR1863	N 21°34'36”	W 82°58'42”	SS	MS
WP043	GOPR1864	N 21°34'19”	W 82°58'02”	DS	DS
WP044	GOPR1864	N 21°34'20”	W 82°58'05”	DS	DS
WP046	GOPR1866	N 21°34'29”	W 82°58'42”	MS	SS
WP047	GOPR1866	N 21°34'30”	W 82°58'44”	MS	MS
WP048	GOPR0127	N 21°34'13”	W 82°58'49”	DS	DS
WP049	GOPR0127	N 21°34'15”	W 82°58'51”	DS	DS
WP050	GOPR0128	N 21°34'17”	W 82°58'17”	DS	SS

Table 7 - *Continued*.

WP051	GOPR0128	N 21°34'16”	W 82°58'15”	SS	SS
WP052	GOPR0129	N 21°34'16”	W 82°58'18”	S	SS
WP053	GOPR0129	N 21°34'18”	W 82°58'21”	SS	DS
WP054	GOPR0130	N 21°34'11”	W 82°58'21”	DS	DS
WP055	GOPR0130	N 21°34'10”	W 82°58'24”	MS	SS
WP056	GOPR0131	N 21°34'13”	W 82°58'32”	MS	SS
WP057	GOPR0131	N 21°34'11”	W 82°58'36”	MS	DS
WP133	GOPR0069	N 21°35'34”	W 82°58'00”	MS	DS
WP134	GOPR0069	N 21°35'36”	W 82°58'03”	MS	DS
WP135	GOPR0070	N 21°35'29”	W 82°58'02”	DS	DS
WP136	GOPR0070	N 21°35'28”	W 82°58'05”	DS	DS
Point 8	GOPR0142, GOPR0143, GOPR0144, GOPR0145	N 21°33'58”	W 82°58'38”	DS	DS
Point 9	GOPR0146, GOPR0147, GOPR0148	N 21°34'51”	W 82°58'39”	DS	DS
Point 10	GOPR0149, GOPR0150	N 21°35'27”	W 82°57'51”	DS	MS
Point 11	GOPR0151, GOPR0152	N 21°36'06”	W 82°57'00”	S	SS
Point 12	GOPR0161	N 21°36'06”	W 82°56'08”	MS	DS
Point 13	GOPR0155	N 21°35'34”	W 82°56'09”	MS	MS
Point 15	No video, field observation	N 21°33'46”	W 82°57'01”	MS	MS
Point 16	MVI_1524, MVI_1525, MVI_1526, MVI_1528	N 21°33'19”	W 82°57'15”	MS	MS
Extra point[c] 1	No video, field observation	N 21°34'25”	W 82°56'10”	MS	MS
Extra point[c] 2	GOPR0133	N 21°36'19”	W 82°58'28”	DS	DS
Extra point[c] 3	GOPR0135	N 21°36'16”	W 82°58'26”	DS	DS
Extra point[c] 4	GOPR0136	N 21°36'18”	W 82°58'23”	DS	DS

[a]Observed substrates from videos taken during side-scan sonar transects and snorkeling
[b]Substrate classification based on analysis of side-scan sonar recordings
[c]Extra points taken opportunistically by snorkeling while survey boat was stopped for other activities
DS=dense seagrass, SS=sparse seagrass, MS=mangrove soil, MSR=mangrove soil with rock, S=silt

Table 8. Water depth and surface area in the San Pedro lagoon system.

Mapped Area (m^2)	11,559,358		
Max Depth (m)	10.28		
Min Depth (m)	0		
Average Depth (m)	2.65		
Lower (m)	Upper (m)	Cumulative Area (m^2)	Individual Area (m^2)
0	0.5	11551351	267205
0.5	1	11284146	349020
1	1.5	10935126	1557675
1.5	2	9377451	2229686
2	2.5	7147765	1701579
2.5	3	5446186	1167067
3	3.5	4279119	1575146
3.5	4	2703973	1099667
4	4.5	1604306	672782
4.5	5	931524	359694
5	5.5	571830	157316
5.5	6	414514	139106
6	6.5	275408	110556
6.5	7	164852	70898
7	7.5	93954	45193
7.5	8	48761	24689
8	8.5	24072	14340
8.5	9	9732	5030
9	9.5	4702	3024
9.5	10	1678	1431
10	10.5	247	247

Table 9. Areas of substrate polygons used for substrate map

Substrate type	Total number of polygons	Area (m^2)
Dense seagrass	44	24,122
		52,130
		39,637
		39,887
		65,148
		5,942
		305
		289
		3,619
		1,892
		318,620
		467,421
		52,782
		45,579
		5,534
		59,998
		7,167
		12,987
		1,132
		4,121
		1,872
		109,502
		50,182
		6,424
		991
		6,007
		3,111
		1,760
		347,289
		31,666
		801,163
		1,457
		3,037
		2,648
		692
		686
		1,086
		11,549
		580,884
		4,044
		174,400
		425,043

Table 9 - *Continued*.

		21,066
		960,984
Sparse seagrass	30	1,331
		2,020
		529
		29,236
		2,084
		8,231
		49,920
		32,873
		18,413
		2,972
		52,372
		35,092
		17,415
		58,759
		47,671
		3,743
		8,593
		39,279
		707,731
		949
		88,844
		5,850
		65,206
		35,116
		12,763
		9,413
		11,387
		5,373
		1,720
		107,104
Mangrove soil	65	85,371
		5,361
		65,095
		32,493
		466,142
		41,036
		9,780
		724,658
		3,499
		106,235
		277,204
		873,044

Table 9 - C*ontinued*.

57,692
18,152
193,934
22,875
1,657
2,708
13,988
2,962
807
49,834
18,740
6,544
2,678
105,083
4,866
297,981
3,938
8,822
3,499
7,831
958
4,258
1,653
3,975
2,989
1,743
10,647
6,831
4,240
25,268
68,495
11,049
35,170
11,557
15,045
19,465
5,722
1,197,246
3,711
1,828
4,777
2,902
2,268
50,325

Table 9 - *Continued*.

		14,398
		6,131
		8,527
		24,216
		47,773
		7,866
		2,383
		14,866
		381,384
Mangrove soil with rock	8	25,519
		174
		165
		915
		8,753
		1,816
		213,323
		22,280
Silt	15	10,458
		24,770
		5,543
		3,001
		1,205
		183
		1,206
		423,265
		7,424
		1,720
		3,021
		3,091
		413
		450
		8,972
Unknown	5	3,562
		1,824
		1,069
		3,684
		960

APPENDIX B

RAW DATA FOR CHAPTER 3

Table 10. Manatee sightings in the San Pedro lagoon system

Date*	Latitude	Longitude	Number of individuals
11/27/2007	N 21° 34’ 50”	W 82° 58’ 17”	3
12/23/2007	N 21° 35’ 53”	W 82° 55’ 07”	1
01/09/2008	N 21° 35’ 29”	W 82° 54’ 54”	1
05/08/2008	N 21° 35’ 22”	W 82° 54’ 57”	1
05/08/2008	N 21° 35’ 29”	W 82° 54’ 55”	1
05/10/2008	N 21° 35’ 10”	W 82° 58’ 02”	1
05/11/2008	N 21° 36’ 06”	W 82° 56’ 04”	1
12/23/2008	N 21° 36’ 07”	W 82° 57’ 09”	1
01/17/2009	N 21° 35’ 18”	W 82° 54’ 55”	3
01/17/2009	N 21° 35’ 18”	W 82° 54’ 52”	1
06/28/2009	N 21° 36’ 05”	W 82° 57’ 44”	1
07/02/2009	N 21° 36’ 08”	W 82° 57’ 07”	2
07/04/2009	N 21° 36’ 01”	W 82° 57’ 47”	3
07/04/2009	N 21° 36’ 02”	W 82° 58’ 01”	5
07/05/2009	N 21° 33’ 44”	W 82° 57’ 10”	1
07/06/2009	N 21° 36’ 01”	W 82° 57’ 54”	2
07/21/2009	N 21° 36’ 10”	W 82° 57’ 09”	2
07/21/2009	N 21° 36’ 03”	W 82° 57’ 55”	2
08/03/2009	N 21° 36’ 12”	W 82° 56’ 28”	1
08/04/2009	N 21° 35’ 38”	W 82° 54’ 56”	2
08/04/2009	N 21° 36’ 09”	W 82° 57’ 09”	1
01/12/2010	N 21° 33’ 30”	W 82° 57’ 08”	2
01/12/2010	N 21° 33’ 36”	W 82° 57’ 15”	1
01/12/2010	N 21° 33’ 42”	W 82° 57’ 09”	1
01/12/2010	N 21° 33’ 39”	W 82° 57’ 05”	1
01/12/2010	N 21° 33’ 41”	W 82° 57’ 15”	3
01/12/2010	N 21° 33’ 17”	W 82° 57’ 10”	2
01/12/2010	N 21° 35’ 22”	W 82° 54’ 57”	1
01/12/2010	N 21° 35’ 33”	W 82° 54’ 56”	1
01/12/2010	N 21° 35’ 54”	W 82° 55’ 38”	1
01/12/2010	N 21° 36’ 14”	W 82° 56’ 45”	1
01/12/2010	N 21° 36’ 13”	W 82° 56’ 50”	1
01/13/2010	N 21° 36’ 12”	W 82° 57’ 23”	2
01/13/2010	N 21° 36’ 10”	W 82° 57’ 21”	3
06/26/2010	N 21° 36’ 06”	W 82° 56’ 12”	1
06/29/2010	N 21° 36’ 13”	W 82° 57’ 35”	1
06/30/2010	N 21° 34’ 10”	W 82° 56’ 55”	1

Table 10 – *Continued*.

06/30/2010	N 21° 34’ 03”	W 82° 56’ 57”	1
06/30/2010	N 21° 35’ 24”	W 82° 56’ 11”	1
07/09/2010	N 21° 35’ 45”	W 82° 55’ 16”	1
07/10/2010	N 21° 35’ 18”	W 82° 54’ 55”	1
07/10/2010	N 21° 36’ 00”	W 82° 56’ 12”	1
07/12/2010	N 21° 36’ 14”	W 82° 56’ 35”	1
07/17/2010	N 21° 36’ 14”	W 82° 56’ 39”	1
07/19/2010	N 21° 34’ 25”	W 82° 58’ 54”	2
07/19/2010	N 21° 36’ 03”	W 82° 57’ 43”	1
07/19/2010	N 21° 33’ 25”	W 82° 57’ 03”	1
07/19/2010	N 21° 35’ 08”	W 82° 54’ 43”	1
07/21/2010	N 21° 33’ 37”	W 82° 57’ 01”	1
07/21/2010	N 21° 36’ 15”	W 82° 57’ 26”	1
07/23/2010	N 21° 34’ 41”	W 82° 56’ 30”	1
07/23/2010	N 21° 34’ 51”	W 82° 56’ 16”	1
07/24/2010	N 21° 36’ 08”	W 82° 57’ 15”	1
08/14/2010	N 21° 36’ 02”	W 82° 56’ 09”	1
08/14/2010	N 21° 35’ 55”	W 82° 56’ 11”	2
08/16/2010	N 21° 35’ 13”	W 82° 56’ 13”	1
08/16/2010	N 21° 34’ 36”	W 82° 56’ 38”	1
02/09/2011	N 21° 36’ 07”	W 82° 55’ 58”	1
02/09/2011	N 21° 35’ 38”	W 82° 56’ 13”	1
07/09/2011	N 21° 35’ 35”	W 82° 54’ 56”	3
07/09/2011	N 21° 35’ 05”	W 82° 54’ 56”	3
07/22/2011	N 21° 36’ 14”	W 82° 56’ 49”	1
07/23/2011	N 21° 35’ 22”	W 82° 57’ 55”	1
03/02/2012	N 21° 36’ 33”	W 82° 58’ 31”	1
06/30/2012	N 21° 35’ 12”	W 82° 54’ 25”	2
07/04/2012	N 21° 36’ 08”	W 82° 57’ 03”	1
07/07/2012	N 21° 34’ 40”	W 82° 56’ 28”	2
07/29/2012	N 21° 34’ 31”	W 82° 56’ 38”	1
07/29/2012	N 21° 35’ 17”	W 82° 55’ 01”	1
11/04/2012	N 21° 36’ 02”	W 82° 57’ 59”	1
11/04/2012	N 21° 33’ 43”	W 82° 57’ 06”	1
03/19/2013	N 21° 36’ 14”	W 82° 56’ 31”	1
03/19/2013	N 21° 34’ 48”	W 82° 56’ 21”	4
03/19/2013	N 21° 35’ 59”	W 82° 58’ 15”	2
06/28/2013	N 21° 34’ 30”	W 82° 56’ 43”	1
07/05/2013	N 21° 36’ 08”	W 82° 57’ 10”	1

Table 10 – *Continued*.

07/20/2013	N 21° 35’ 32”	W 82° 56’ 10”	2
07/20/2013	N 21° 34’ 44”	W 82° 58’ 36”	1
07/23/2013	N 21° 34’ 31”	W 82° 56’ 16”	3
10/02/2013	N 21° 36’ 11”	W 82° 56’ 15”	1
10/02/2013	N 21° 35’ 54”	W 82° 55’ 07”	1
10/03/2013	N 21° 34’ 46”	W 82° 56’ 30”	1
10/03/2013	N 21° 35’ 17”	W 82° 54’ 47”	1
06/28/2013	N 21° 34’ 30”	W 82° 56’ 43”	1
07/13/2013	N 21° 34’ 27”	W 82° 56’ 11”	1
07/13/2013	N 21° 34’ 36”	W 82° 56’ 38”	3
07/13/2013	N 21° 34’ 27”	W 82° 56’ 47”	2
07/13/2013	N 21° 34’ 10”	W 82° 56’ 54”	1
07/13/2013	N 21° 34’ 06”	W 82° 56’ 58”	2
07/13/2013	N 21° 36’ 11”	W 82° 56’ 57”	1
07/18/2014	N 21° 35’ 45”	W 82° 57’ 39”	1
07/20/2014	N 21° 36’ 00”	W 82° 56’ 09”	2
07/21/2014	N 21° 36’ 15”	W 82° 56’ 33”	1
07/21/2014	N 21° 35’ 47”	W 82° 56’ 15”	1
07/30/2014	N 21° 35’ 55”	W 82° 55’ 37”	1

*****Date format: mm/dd/yyyy

REFERENCE LIST

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