12-2019

A Sinking Feeling: The Fate of Concrete Pyramids Deployed in Artificial Reefs in the Texas Gulf of Mexico

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A SINKING FEELING: THE FATE OF CONCRETE PYRAMIDS DEPLOYED IN ARTIFICIAL REEFS IN THE TEXAS GULF OF MEXICO

A Thesis

by

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Submitted to the Graduate College of
The University of Texas Rio Grande Valley
In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2019

Major Subject: Ocean, Coastal, Earth Sciences

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December 2019

ABSTRACT

Moody, Cameron J., Evaluation of Nearshore Artificial Reef Site Materials in the Gulf Of Mexico Off Texas Using Swath Bathymetry and Side Scan Sonar. Master of Science (MS), December, 2019, 60 pp. 9 tables, 26 figures, references, 33 titles

The deployment of 2,611 concrete pyramids in Texas gulf waters represents a significant undertaking. In collaboration with Texas Parks and Wildlife, bathymetric sidescan data was collected at three reefs hit by Hurricane Harvey from 2017 to 2019. All reefs lost significant pyramid height between 2017 and 2019. The pyramids demonstrated greater subsidence in the year when Harvey occurred and minimal subsidence the following year. Pyramids that moved outside the reefs were due to hurricane forces and shrimp trawl activity. Pyramids that remained inside the reef remained at their deployment location for two reefs. The pyramids remaining in the third reef moved into dense clusters due to Hurricane Harvey. The evidence suggests that the pyramids are most affected by extreme weather and trawling activity and otherwise maintain their positions and stabilize their height.

ACKNOWLEDGEMENTS

I would like to thank Dr. Richard Kline, chairmen of my committee, for his support throughout the entire project. His willingness to get his hands dirty and come into the field to work was critical for the completion of this thesis. I would also like to thank my other committee members Dr. Abdullah Rahman and Dr. Juan Gonzalez for lending their feedback and expertise on this project.

I would like to thank Dave Shively and the rest of Texas Parks and Wildlife Artificial Reef Program for their support of this project. The sonar, motion reference unit, software and financial resources they provided allowed this study to go ahead. I would also like to thank the Vollert's captain Skye Zufelt and fellow graduate students Kirsten Lara, Connor Gallagher and Jonathan Truett Cawlfield for helping in both sonar surveys and sediment core collecting. I finally would like to thank Jevon Harding for analyzing the sediment core samples.

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CHAPTER I

INTRODUCTION

Fishing Pressure

Assessments in 2011 place the amount of global fish stocks currently overfished at 28.8% (Bell et al., 2017). Estimates at fishing effort demonstrate that the most intensive fishing activity takes place within the exclusive economic zones of various countries (Kroodsma et al., 2018). Industrial fishing is estimated to occur in over 55% of the global ocean, four times greater than the spatial extent of agriculture (Kroodsma et al., 2018). Despite the global reach and technological advances in locating, catching and preservation, fishing efficiency today has decreased from the 1970s and potentially the 1950s (Watson et al. 2013, Bell et al 2017). This places greater stress on the marine ecosystems as more fishermen have to work longer to get the same amount of fish they would have harvested decades ago.

In conjunction with intentional fishing, many fish end up as by-catch from other fisheries. An example of fishing that causes large by-catch is trawling. Trawling consists of a small mesh net towed through the water or at the bottom with either gears or chains weighting down the net. Trawling is the most widespread anthropogenic activity on the seabed (Oberle et al., 2019). Trawling for Penaeid shrimp species demonstrates the impact trawling can have on a system, representing 1.5% of global catch but contributing greater than 25% of by-catch (McHugh et al., 2016). These impacts combine to deplete ecosystems of their species, and if fishing efforts are not properly managed, lead to a negative cycle that diminishes the fishery and its target population.

One of the more important economic fish species in the Gulf of Mexico is the red snapper (*Lutjanus campechanus*). Red snapper have been commercially fished since the 1840s and are still exploited for both commercial and recreational fisheries (Shipp and Bortone, 2009). Data suggests that the species has been overexploited for at least 30 years, and overexploitation may be occurring throughout the entire Gulf of Mexico (Schwarzkopf et al., 2017). As the fish are substrate oriented, they are concentrated as adults in small areas because much of the western Gulf of Mexico is dominated by muddy bottom (Streich et al., 2017). Areas with muddy bottoms typically have fewer red snapper in comparison to areas with hard substrate (Streich et al., 2017). Reef size and location play important roles in what red snapper are found on the reefs as substrate preference changes with fish age and size (Arney et al. 2017). Recruitment of juvenile fish at reef sites depends on the structures available as well, reducing predation risk while also enhancing feeding prospects (Komyakova et al., 2019). Juvenile snapper mortality is also greatly influenced by shrimp trawling (Gallaway et al 2009). Hard substrate provides the necessary refugee and foraging opportunities at different life stages for red snapper (Streich et al., 2017), however this habitat is limited in the western Gulf of Mexico.

Artificial Reef Usage

Artificial reefs are commonly used to enhance fish populations in coastal areas (Becker et al., 2016; Granneman and Steele, 2015; Stephan et al., 1990, Manoukian et al., 2011, Tassetti et al., 2015). Artificial reefs are any anthropogenic structure that ends up in the marine environment and is utilized as habitat by marine organisms (Lima et al., 2019). Artificial reefs provide reef associated species new habitat they can utilize (Ng et al., 2017), with more complex reefs having a greater abundance of fish (Arney et al. 2017). Enhancing local fish populations to enhance fishing opportunities for anglers has long been the goal for artificial reef programs (Carr and Hixon, 1997). Modern artificial reefs are still developed for this purpose but are also utilized for habitat restoration and species conservation purposes (Lima et al., 2019).

The Texas Parks and Wildlife Department (TPWD) has been active in the construction and maintenance of artificial reefs for over 40 years. In 1976, eleven old cargo vessels were purposely sunk along various points of the Texas Gulf Coast in order to become artificial reefs (TPWD, 1995). The 1989 Texas Parks and Wildlife Artificial Reef Program charged TPWD with the construction and maintenance of artificial reefs along the Texas coastline (Stephan et al., 1990). Even structures that are not placed with the intention of being artificial reefs, such as rigs for hydrocarbon exploitation, are proving to benefit hard substrate-oriented species. Texas Parks and Wildlife helps to convert these structures into artificial reefs with the 'Rigs to Reefs®' program. It is estimated recycled oil production platforms provide 30% of the reef habitat in the Gulf of Mexico (Bull and Love, 2019). Red Snapper living on recycled rigs have been found to have comparable reproductive health to fish living around natural formations (Downey et al., 2018). The comparable reproductive capacities indicate red snapper are growing at healthy rates at artificial reef sites.

With the events of the Deepwater Horizon disaster in 2010, relief money was made available to the affected states to help counteract damage the spill inflicted. Thousands of purpose-built concrete pyramids with a three-meter base and 2.4 meter height have been deployed by TPWD to restore fisheries habitat (Figure 1). 'Atlantic Pods', a smaller (1.5m height, 1.8 m base) four-sided open topped pyramid-like structure demonstrated that upright structures like the pyramids can attract more fish than other concrete designs (Lemoine et al., 2019). The pyramids are hollow and allow for stacking of multiple pyramids atop one another, enabling large numbers to be deployed in quick succession from a single vessel. The pyramids also have openings of various sizes that enable access to the hollow interior, increasing the three-dimensional complexity and vertical relief of the structure compared to donated highway and road construction materials. As of 2018, approximately 2,800 pyramids have been deployed along the Texas coastline into the George Vancouver Reef, Matagorda Nearshore Reef, Shell Reef and the Rio Grande Valley Artificial Reef. The condition and effectiveness of the pyramids, each of which cost an average of $2,500 to build and deploy, in these reefs over time is currently unknown (Shively D., personal communication). If the pyramids lose too much of their height or are displaced outside of reefing areas, they will not directly support Texas Parks and Wildlife's

Figure 1. An example concrete pyramid used to create and expand Texas's artificial reefs.

goal of bolstering recreational and commercial fisheries.

Reef Surveying Tools

As a part of its mission, Texas Parks and Wildlife Artificial Reef Program (TPWD-ARP) needs to monitor and maintain the reef sites it develops (Stephan et al., 1990). Globally, most artificial reef monitoring is conducted using SCUBA surveys (Tassetti et al., 2015). There are issues with using SCUBA surveys for monitoring thousands of pyramids off the Texas coast in multiple reef sites. SCUBA divers have limited bottom time and poor visibility conditions along the Texas coast hamper underwater movement. The ability to assess pyramids and locate any that may have moved or buried by SCUBA survey has been used in other studies (Renchen et al., 2019, Bell and Hall, 1994). These studies however, either worked on smaller reef areas or at much more shallow depths than what the pyramids were deployed at.

With the advancement and refinement of acoustic technologies, new tools are available to survey these pyramids with. One such tool is bathymetric sidescan sonar. Sidescan sonar utilizes sound energy to produce two-dimensional representations of the seafloor (ICES. 2007). Sonars can range from simple devices that utilize a single frequency from an emitter or 'head' or can operate on multiple frequencies. These multi-frequency, or 'multi-beam', sonar heads work on the same principle as a traditional sonar head except they work in tandem with other multiple heads on the unit to transmit and receive sound (Anderson et al., 2007, ICES. 2007). Bathymetric sonars can record in both raster and vector data formats (ICES. 2007). This allows for bathymetric units to produce not only the traditional 2D representation of the seafloor that is common with sidescan units, but also to create 3D representations as well. The proper software can analyze the recordings for changes in volume and depth of a structure (Tassetti et al., 2015).

There are major benefits to using this remote sensing technology as opposed to SCUBA surveys. Utilizing sidescan sonar enables much larger areas to be surveyed with fewer personnel than is feasible with divers due to their limited mobility and productivity depending on environmental conditions. This is especially true in the Gulf of Mexico along Texas, where visibility on the bottom can be a limiting factor (Bollinger and Kline, 2017). While some variables are still better examined with divers, such as fish survey data, locating pyramids over large areas or in limited visibility conditions is better accomplished with a sonar device. While height and location can be precisely measured with sonar, the resolution is too low to determine the orientation or condition of objects like the pyramids.

Objectives and Hypotheses

The objective of this study was to determine the fates of the concrete pyramids deployed in 2017 in three reefs along the Texas coastline by measuring changes in heights and locations using multibeam bathymetric sonar recordings. The utility of reef pyramids is dependent on the amount of the pyramid that remains above the seabed. Pyramid height change is of concern as Red Snapper habitat preference changes with their age (Arney et al., 2017). These pyramids are used in bolstering fisheries numbers for species such as the red snapper. If the pyramids loose too much height, then they will no longer be preferred habitat for red snapper that can be directly exploited by both the recreational and commercial fisheries. Should the pyramids move too much then they would leave the designated reefing area and could provide trawling and navigation hazards. Reef managers trying to maintain Texas's artificial reefs need to understand how well the structures being deposited work and if they need to acquire different structures to continue work. These pyramids have relatively small footprints due to their ability to stack onto one another for transport. While this vastly improves the number of pyramids that can be transported out to a reef site, it might prove to be a detriment if they move, or do not remain above the seafloor. Specific concerns about how the artificial reefs perform at the different reef sites across the state of Texas will be addressed by testing the following hypotheses:

1. The height change of pyramids within reef areas will not be uniform.
2. The majority of pyramids will persist at their deployed heights and locations.
3. Reef sites with different sediment textures will have different changes in pyramid height.

CHAPTER II

METHODS AND MATERIALS

Study Sites

Sonar surveys focused on three artificial reef sites, the George Vancouver Nearshore Reef (BA-336), Brazos Nearshore Reef (A-439) and Matagorda Island Port O'Connor Nearshore Reef (MI-562) (Figure 2). Sediment sampling was conducted in the Rio Grande Valley Reef (PS-1105). Each reef is a Texas Parks and Wildlife nearshore reef site in the northwestern Gulf of Mexico.

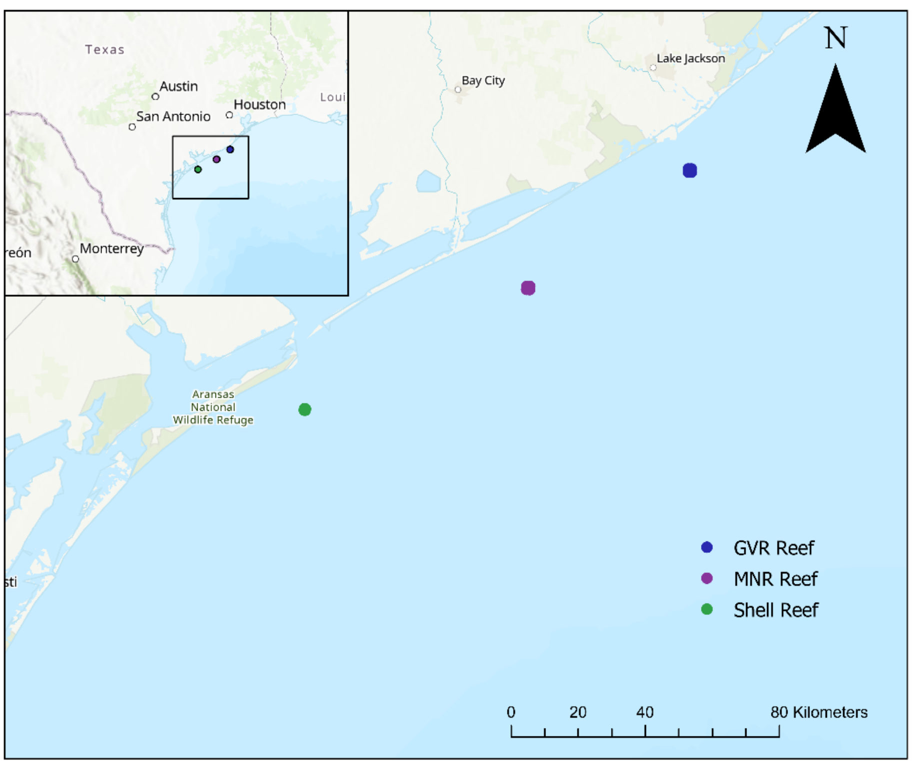

Figure 2. Map of the George Vancouver (GVR blue), Matagorda Nearshore (MNR purple) and Shell (green) reefs.

George Vancouver Nearshore Reef (GVR) is 16 kilometers south of Freeport, Texas. George Vancouver reef was started in 1976 as a part of an early reef building effort (TPWD, 1995). The reef was created by sinking a Liberty Ship cargo vessel in an area with no existing habitat and additional material was added over time. In 2012, 30 pyramids, now known as the Reefman pyramids, were deployed (Figure 3). In 2017, 806 pyramids, were deployed by the Texas Parks and Wildlife Artificial Reef Program (TPWD-ARP) to bolster fisheries after the Deepwater Horizon spill using National Resource Damage Assessment (NERDA) funds (Figure 1). The pyramids were deployed in a square ring around the George Vancouver ship.

Figure 3. “Jailhouse” pyramids that were deployed as a part of the Reefman deployment in 2012

Brazos Nearshore reef, from now on referred to as Matagorda Nearshore reef (MNR), was developed in 2017 by TPWD-ARP using NERDA funding. Matagorda Nearshore reef consists of 1,605 pyramids and is 54.4 kilometers northeast from Port O'Connor, Texas. The pyramids were deployed in a single large square around the center of the reef. No prior material was present at the site and no additional material has been added. Both George Vancouver and Matagorda Nearshore Reefs have an 805 m by 805 m reefing area. Both reefs are also relatively close to the Brazos and Colorado rivers and may receive sediment influx from them. Matagorda is also close to the Lavaca river but is blocked by a barrier island.

Shell reef, a smaller reef 20 kilometers south of Port O'Connor, Texas, is part of the larger MI-562 Matagorda Island Port O'Connor Reef site. It was created in 2017 when 200 pyramids, donated by Shell Oil Company, were deployed in three large groups. Shell reef is close to the Colorado river and is close to the San Antonio, Lavaca and Guadalupe rivers but is directly blocked by barrier islands. Shell reef may have sediment input from these systems. Of special interest is the impact Hurricane Harvey had on Shell reef due to the proximity of the reef to Harvey's path (Figure 4).

Table 1. Summary of each reef that will have pyramid height changes over time analyzed.

	George Vancouver	Matagorda Nearshore	Shell Reef
Year of Creation	1976	2017	2017
Pyramids Deployed in 2017	806	1605	200
Reefing Area size	805 m by 805 m	805 m by 805 m	~ 366 m by 244 m
Distance Offshore to Center	9.8 km	16.3 km	11.6 km
Nearest Port	Freeport TX	Port O'Connor Tx	Port O'Connor Tx
Materials Present	Sunken vessel, concrete cinder blocks, concrete pyramids	Concrete pyramids	Concrete pyramids
Nearby Rivers (* Does not directly drain into Gulf)	Brazos, Colorado	Brazos, Colorado, Lavaca*	Colorado, Lavaca*, Guadalupe*, San Antonio*

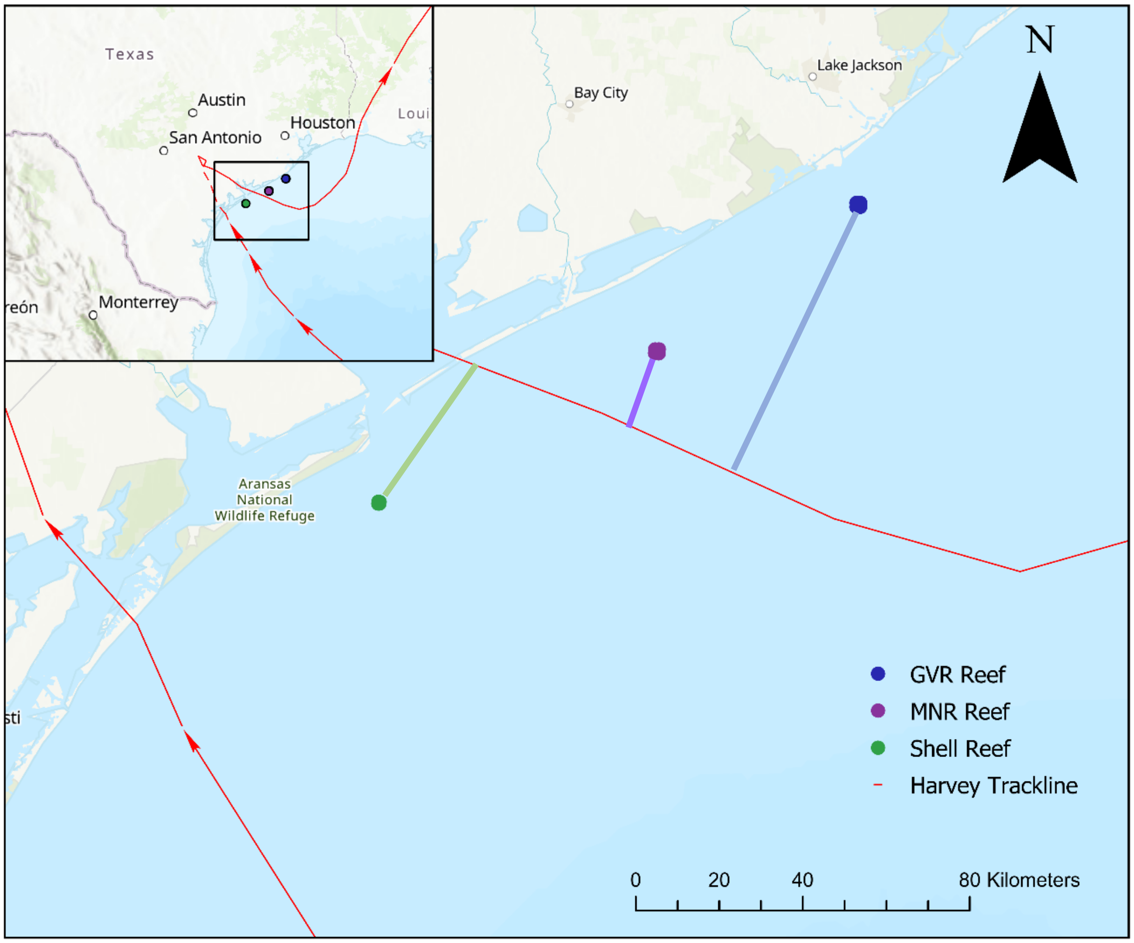

Figure 4. Hurricane Harvey's path relative to the study reef sites. Approximately 39 kilometers (light green) Shell reef (green star). Approximately 19 kilometers (light purple) Matagorda reef (purple star). Approximately 71 kilometers (blue line) for George Vancouver reef (blue star).

The Rio Grande Valley reef is located nine nautical miles northeast of the Port Isabel jetties (Figure 5). The Rio Grande Valley has a variety of concrete and steel materials including sunken vessels, railroad ties and various concrete road construction pieces and purpose built concrete low-profile reefs. In 2018 the reef received an additional 250 pyramids. The only adjacent river system to the Rio Grande Valley reef is the Rio Grande.

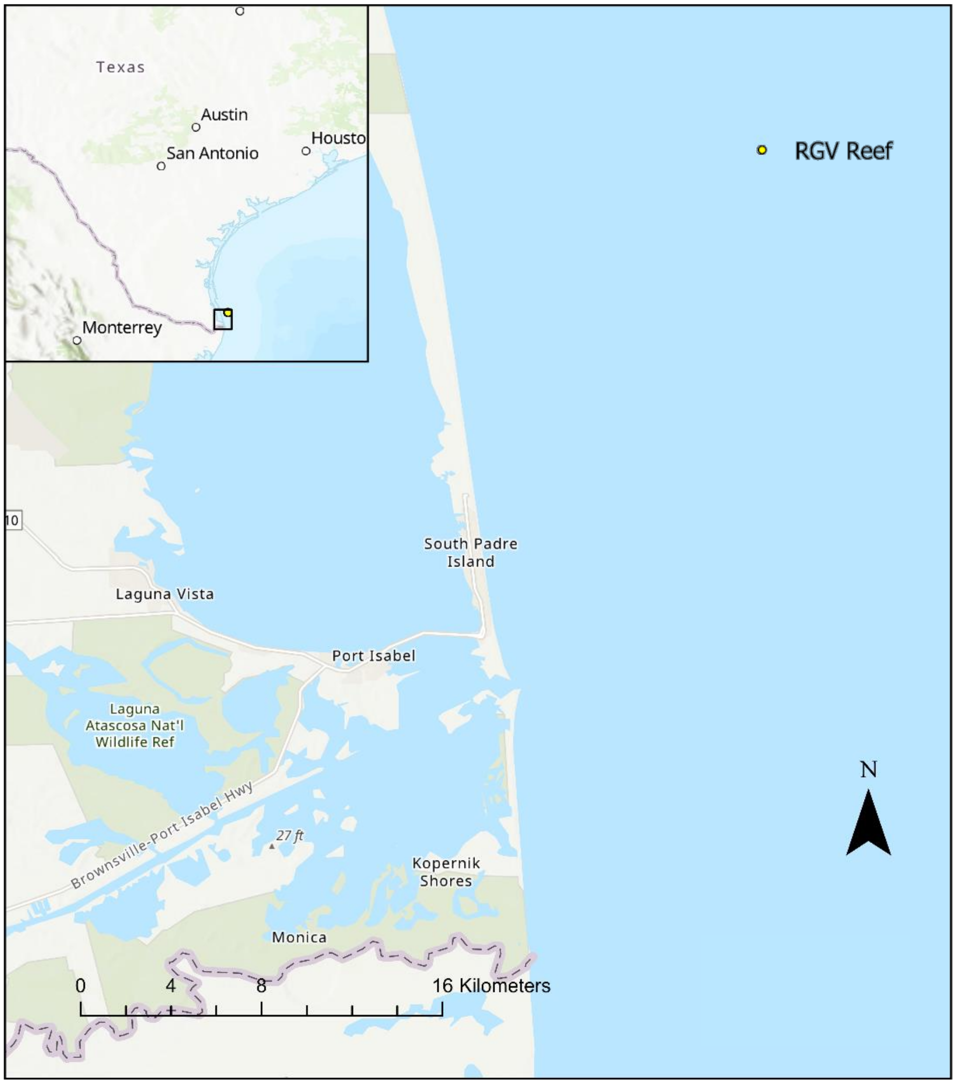

Figure 5. The position of the Rio Grande Valley artificial reef.

Sonar Setup

Figure 6. The RV Vollert in Freeport, Texas with the 6205 mounted and covered for protection.

The Edgetech 6205, a combined multibeam sonar and bathymetry unit, was used for surveys during 2018 and 2019. The 6205 was designed to be able to operate two heads containing ten elements on opposite sides of the device to survey the environment. The sidescan frequencies are paired as either 230 and 550 kHz for higher return signals from targets, or 550 and 1600 kHz for more detailed imagery of those targets. The bathymetric data is recorded in either 230 or 550 kHz depending on which head is in use. For this survey, the sonar was equipped with 230 and 550 kHz elements. The sonar was mounted on a pole that extended 2.4 meters into the water (Figure 6). The mount has a locking mechanism that prevents the sonar from rotating once in position. Data from the sonar is passed via a built-in cable to the topside computer unit (Figure 7).

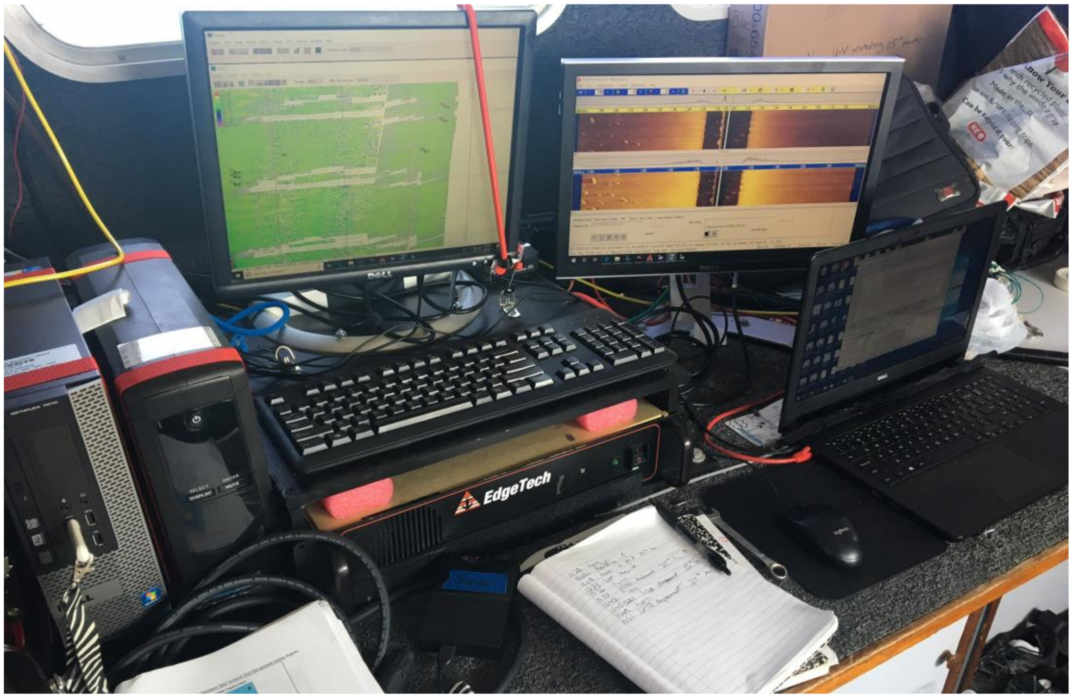

Figure 7. The computer setup within the Vollert used for sonar collection.

The topside unit receives data from a motion reference unit that records the speed of the vessel and changes in its heave, pitch, roll, yaw, and GPS location. The motion reference unit used for these surveys was the Coda® Octopus F180 series. Information was embedded into the sonar data by the topside unit during the recording process. A separate heave file was also recorded separately that was used later in Hypack to correct files in the multibeam editing software MBMAX64. For our surveys, the F180 was calibrated before leaving Port Isabel each year following manufacturer guidelines.

Sonar Surveys

Sonar surveys were conducted in late August 2018 and 2019 on the reef sites. 2017 survey data was obtained from Texas Parks and Wildlife for George Vancouver, Matagorda Nearshore and Shell reefs. All 2018 and 2019 surveys used the 14.6 meter UTRGV research vessel Vollert. Survey speeds were kept at or below 6 knots and an autopilot was used for each survey line. Surveys lines were spaced 36.5 meters apart to ensure full coverage was achieved (Figure 8). Before a survey was conducted, a 'patch test' was recorded to correct the heave, pitch, roll, yaw and GPS latency anomalies in bathymetric data. After the survey was completed, a SonTek® CastAway water column profiler was deployed to record data on variables influencing the speed of sound in water. The data was then downloaded into the Hypack project for the survey. Shell reef was not surveyed in 2018 as it was included into this study in 2019.

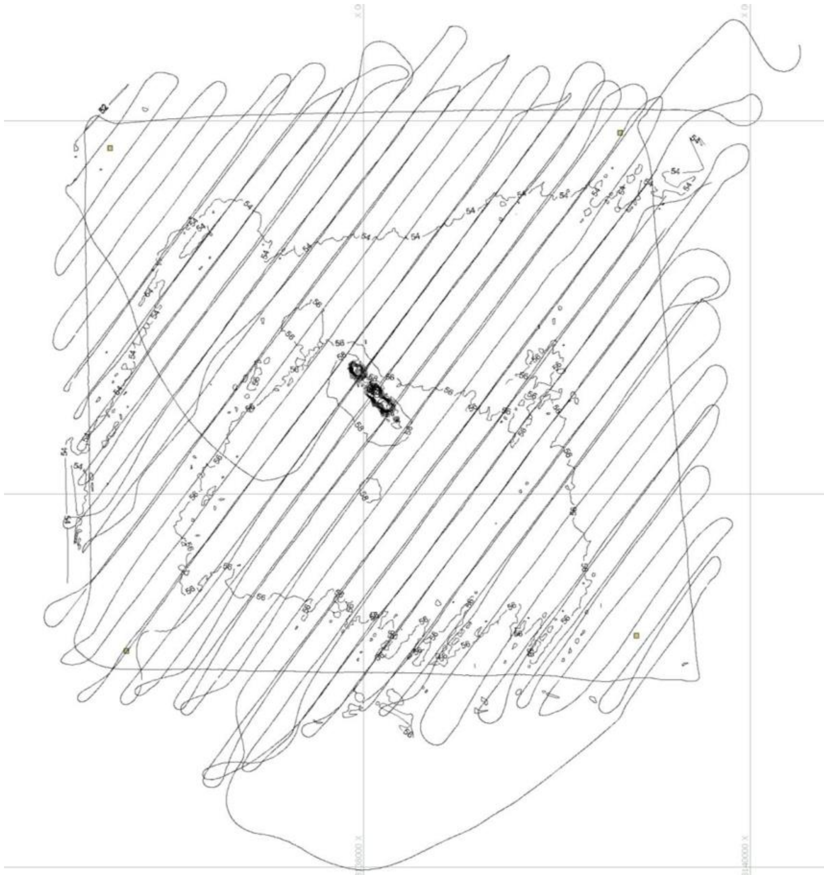

Figure 8. An example of a survey (GVR 2019 shown). A contour map from the same year is below the track lines.

Sonar Analysis

Sonar Data Processing

Survey files were processed in the Hypack multibeam sonar file reading and editing program MBMAX64®. Surveys were loaded and correcting factors were applied. Tide data was taken from the NOAA Tide Gauge Network for the nearest gauge at each site, which was Freeport SPIP 8772471 for George Vancouver and Matagorda Nearshore reefs, Port O'Connor 8773701 for Shell reef and SPI Brazos Santiago 8779749 for Rio Grande Valley reef. Sound velocity data from the CastAway and the heave file from the motion reference unit were also applied. Corrections were calculated using patch test recordings and applied in the order of latency, roll, pitch and yaw on a scale from coarse to fine sensitivity.

Files for 2017 surveys were obtained from Texas Parks and Wildlife for George Vancouver, Matagorda Nearshore and Shell reefs and used to map out the original positions of the pyramids in the reefs. Pyramids added in 2017 to a reef were identified and their positions and depths recorded using the target function in Hypack. Targets were selected by using the cloud viewer and determining the highest point for each individual pyramid present. These target points were then imported into 2018 projects for George Vancouver reef and Matagorda Nearshore reef and used as a basis to identify the pyramids in 2018. The pattern pyramids were found in and the proximity to the 2017 targets was the major factor in determining which pyramids had moved in 2018. This process was then used for 2019 with Shell reef using 2017 positions and George Vancouver and Matagorda Nearshore reefs using both the previous years.

For comparisons between years while ensuring the data was not subject to variations in settings and ocean conditions, data on the surrounding seafloor depth was also recorded for each individual pyramid. This was done by recording three targets on the seafloor surrounding that pyramid while avoiding any sort of scour mark that a pyramid may have developed. Depths at the pyramid tops and the average of the surrounding points were then used to determine how much of the pyramid remained above the surrounding seafloor. These depths were rounded to one decimal place and then compared between years and between reefing areas.

Statistical Analysis. A global and local Moran's I analysis was conducted in ArcGIS pro to determine if there was any preexisting variation in pyramid height changes for George Vancouver and Matagorda reefs. Both the global and local Moran's I tests used inverse distance between pyramids and used 20 meters neighbor distances for the analysis to determine if any pyramids have less or more changes in height.

George Vancouver and Matagorda Nearshore reefs were divided into different zones to analyze changes within each reef (Figure 9). These zones were generated based on the George Vancouver and Matagorda Nearshore reef dimensions in ArcGIS, generating an 11 by 11 grid for George Vancouver and 11 by 10 for Matagorda Nearshore reef for best concentration of pyramids within a zone. Shell reef was not divided into zones because it was deployed in three defined groups. Pyramids were then assigned a number based on their 2017 position within the zone grid. The number designation carried over to the 2018 and 2019 surveys to remain consistent. Shell reef was given an A, B or C prefix to the pyramid number instead.

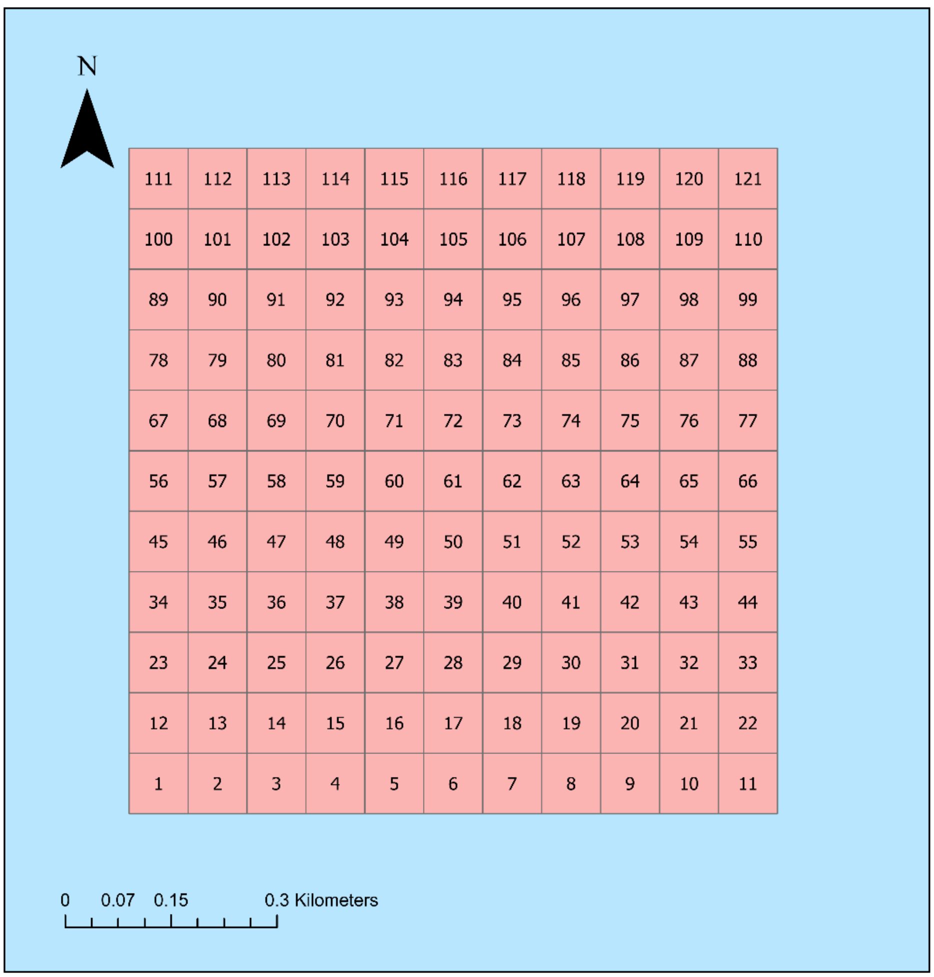

Figure 9. An example of reef zoning using the George Vancouver reef.

George Vancouver had several instances of zones that divided off a small number of pyramids from another zone that they would logically be included in. These pyramids were merged into those zones indicated in table 2.

Table 2. Zones in George Vancouver Reef that were merged for analysis.

Original	Merged Into
2	13
3	14
21	20
26	15
27	16
28	17
29	18
30	19
32	31
37	36
48	47
54	53
59	58
65	64
76	65
78	79
81	82
87	86
101	90
102	91
93	82
94	83
95	84
97	86

Five separate two-factor ANOVAs were used for testing the study's hypotheses. Theses ANOVAs were conducted in SPSS V25 general linear model function with a type 1 model. Three two-factor ANOVA's were conducted using the factors Zone and Year and the interaction Zone * Year, one for each reef. The remaining two-factor ANOVA's were conducted using factors Site and Year and the interaction Site * Year. One of these tests was conducted comparing only George Vancouver and Matagorda Nearshore reefs as they both had three years of data to compare. As Shell reef only had 2017 and 2019 datapoints, the other Site * Time ANOVA was between all reefs and only used heights in 2017 and 2019 for all reefs. Pairwise comparisons were conducted using Tukey HSD tests for year and location comparisons. Pairwise tests with Bonferroni adjustments were used for comparisons of reef zones. Movement of pyramids within a reef was analyzed using the ArcGIS spatial join tool comparing the position of each pyramid in 2017 and 2019.

Overall changes in height were combined for each reef to compare yearly changes in pyramids. Although they were a different model of pyramid, changes in heights of fourteen Reefman pyramids were used as a long-term comparison of changes within George Vancouver Reef. Comparisons of height change over time utilized all year data for all reefs and will include the Reefman pyramids as a seven-year endpoint.

Sediment Surveys and Analysis

In 2019 the Rio Grande Valley artificial reef was used to collect sediment data. Divers collected cores by extracting a 10 by 28 cm sediment push core from the bottom around seven pyramids. The pyramids were chosen due to the distinct profile characteristics they displayed, ensuring that a range of pyramids experiencing minimal to substantial amounts of height change were used for the experiment (Figure 10). At least one core was taken around each pyramid, however when more sediment types were encountered around a pyramid, additional samples were taken. Cores were stored at -20 °C for 24 hours and then thawed and dried. Cores were then manually homogenized to ensure transportation did not artificially separate the different grain sizes. Samples were analyzed following the standard Folk and Ward (1957) protocol for grain size analysis. Fifty-gram samples were taken from each core and dried overnight at 60^{o}C to remove moisture. A column of five sieves, 2mm, 1mm, 500µm, 250µm and 63µm was used (Figure 11).

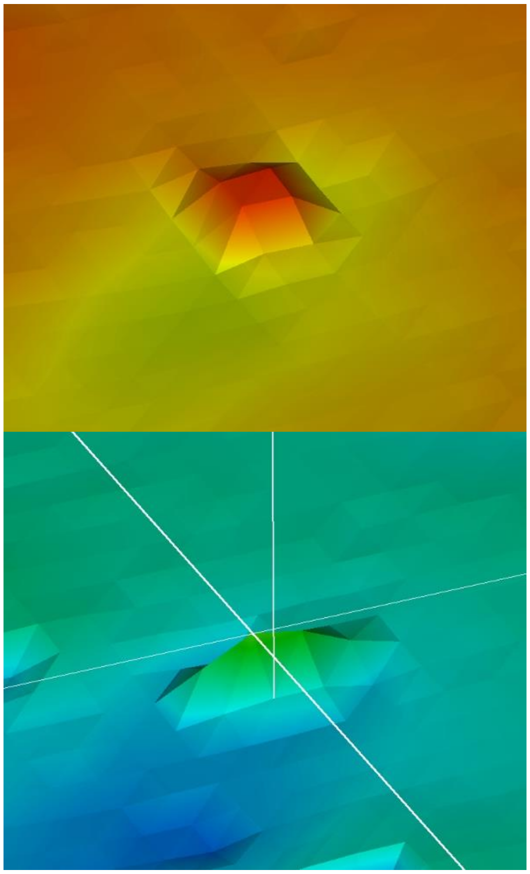

Figure 10. Examples of pyramids that were chosen from the Rio Grande Valley to take cores from. The top is number 58 and the bottom is number 177. Evidence for both suggested that pyramids were subsiding despite being on different sides of the pyramid patches.

Data from sediment grabs were gathered from the Texas General Land Office Texas Coastal Sediment Geodatabase (http://www.glo.texas.gov/land/land-management/gis/) for all four reef sites from the Bureau of Economic Geology and the University of Texas at Austin 1976 Gulf of Mexico and Caribbean Offshore Surficial Sediment Survey (Buczkowski, 1976). This data was compared with the results from the Rio Grande Valley reef core analysis to determine if any patterns between reef type and pyramid height change emerged. Sediment grabs were chosen by proximity to each reef area, the closest grabs in each direction. For all reefs except George Vancouver this resulted in six grabs being used, George Vancouver used seven grabs in total.

Figure 11. Stack of sieves used to run grain size analysis in Rio Grande Valley reef sediment samples.

CHAPTER III

RESULTS

Lost Pyramids

Pyramids disappeared from the reefs over the two-year period (Table 3). Across the three reefs, 168 pyramids out of the 2,443 pyramids could not be relocated in 2019 (6.9%). Loss rates varied across the three different reefs (Figure 12).

Table 3. Summary of loss data for each reef from 2017 to 2019

Site and Year	Total Lost
GVR 2017	0
GVR 2018	4
GVR 2019	8
MNR 2017	0
MNR 2018	19
MNR 2019	82
Shell 2017	0
Shell 2019	78

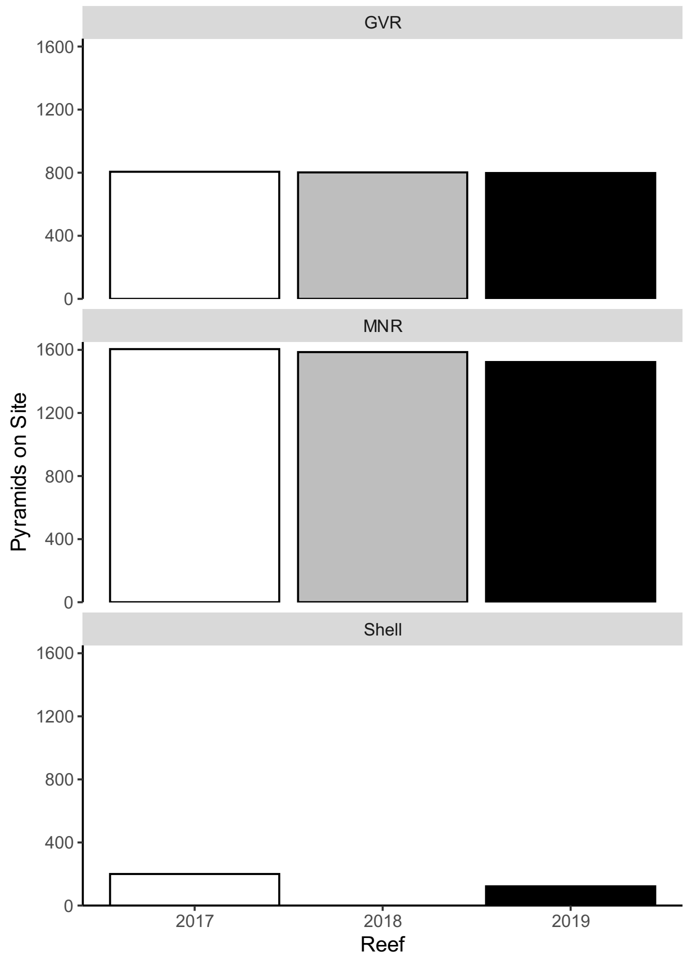

Figure 12. Pyramid counts for each reef (GVR **Top**, MNR **Middle**, Shell **Bottom**) through time (White **2017**, Grey = **2018** and Black = **2019**).

George Vancouver

The pyramid loss at George Vancouver (GVR) was the lowest of the three reefs in terms of both actual number (8 of 806) and percentage (~1%) as of 2019. In 2018 the reef had lost four pyramids. The remaining four were lost in 2019.

Matagorda Nearshore

Matagorda Nearshore (MNR) lost the highest number of pyramids out of the three reefs at 82 pyramids in 2019. This however represents a 5% loss of pyramids over two years. In 2018

Matagorda Nearshore had 1586 pyramids accounted for, representing a loss of 19 pyramids. The remaining 61 pyramids were all lost between 2018 and 2019.

Shell Reef

Shell reef lost 39% of its pyramids, 78 of 200, as of the 2019 survey. As data was not available for 2018, this study was unable to determine whether all 78 pyramids were lost in one event or if a similar pattern to George Vancouver and Matagorda Nearshore occurred.

Pyramid Movement

The majority of pyramids in George Vancouver and Matagorda Nearshore reefs remained within a meter of the coordinates of their original deployment. A few potential sources of movement were found during the study of these reefs, with each reef demonstrating a different scenario. Shell reef had a large number of pyramids moved from their original groups.

George Vancouver

George Vancouver pyramids in 2019 remained on average 0.9 ± 0.2 m within their 2017 location. Pyramids 166, 588 and 232 experienced the greatest disturbance, moving 36.9, 61.6, 108.1 m respectively. These are the only pyramids to have moved over 30 m in George Vancouver, with an additional ten pyramids experiencing greater than three meter displacement. No evidence of trawl scars was found in the survey area in 2018 and only a single large scour was located within the reefing area in 2019 (Figure 13).

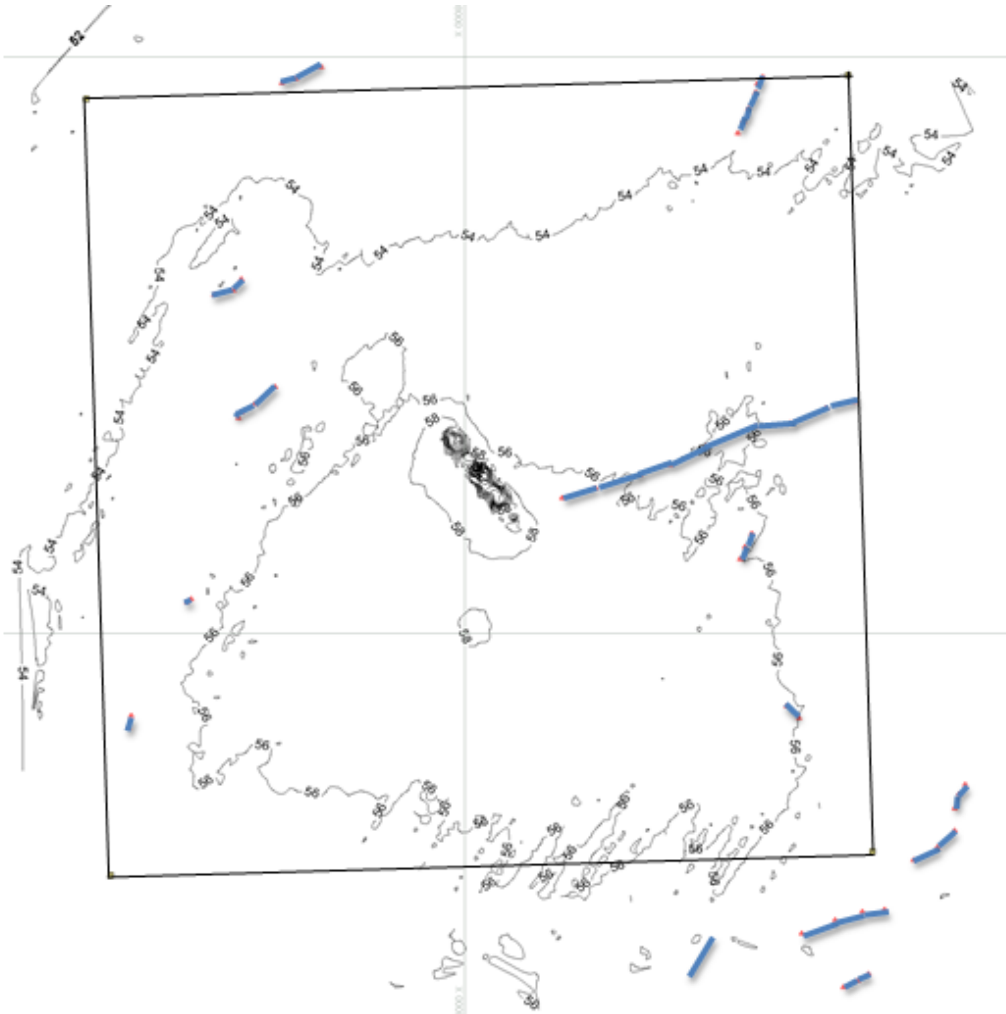

Figure 13. Trawl scars found within and near the George Vancouver reef in 2019. Only one major trawl scar was detected within the reef in 2019.

Matagorda Nearshore

Matagorda Nearshore pyramids in 2019 were relocated an average 1.2 ± 0.1 m from their deployment location in 2017. Five pyramids moved 30.6, 37.1, 41.4, 42 and 67.9 m respectively. 74 pyramids moved between 3 and 30.5 m from their deployment locations. In the 2018 one pyramid was found by following a 518 m trawl mark from the reefing area. 12 trawl scars from shrimping activity were found within the reef in 2019 (Figure 14).

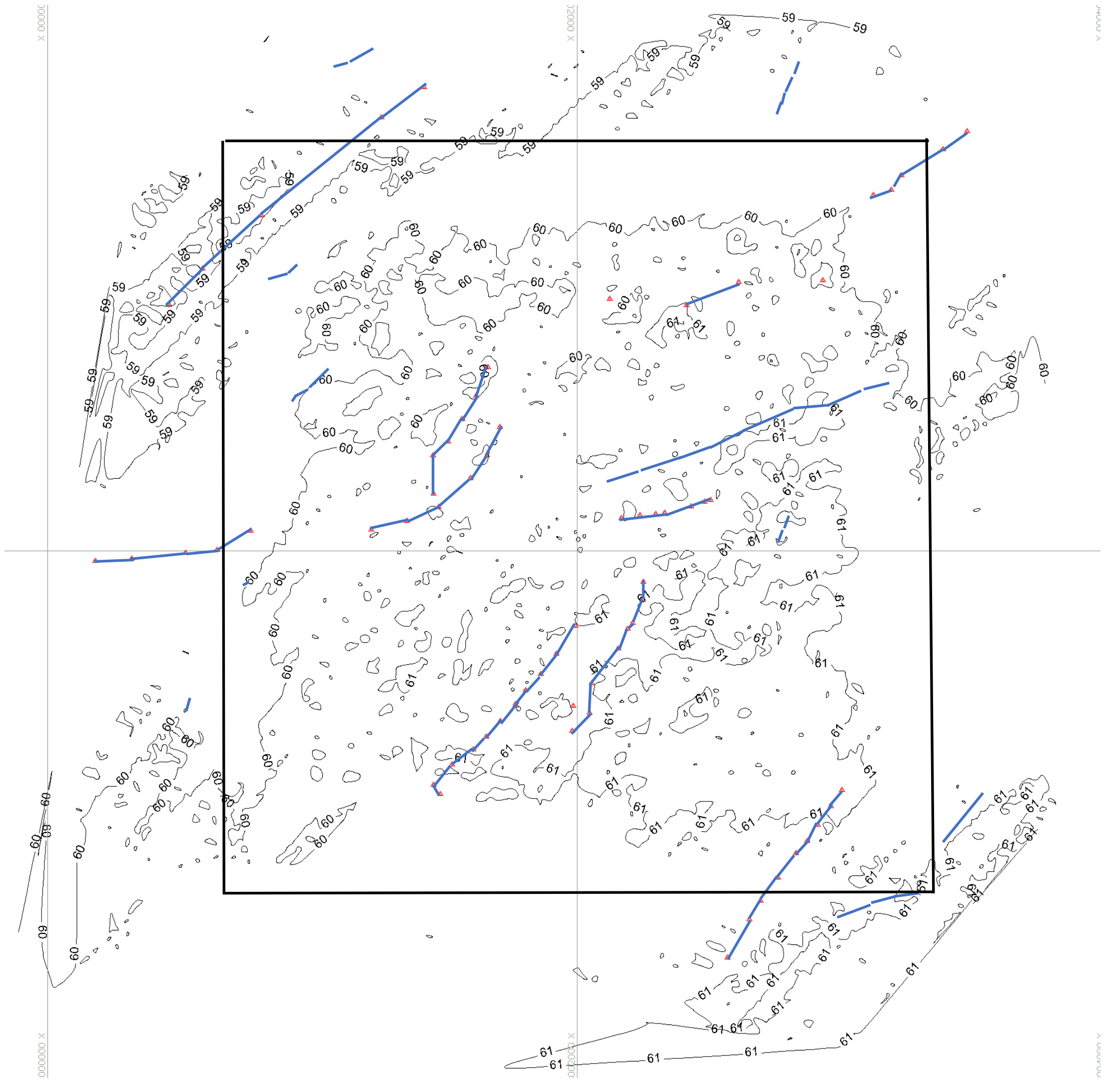

Figure 14. Locations of suspected trawl scars (blue lines) in the Matagorda 2019 survey and within the reef boundaries (black box).

Shell Reef

Individual pyramids could not be tracked due to the extreme disturbance the pyramids experienced during Hurricane Harvey. Comparing the average positions of the groups in 2017 to 2019 found group A moved 47.7 m, B moved 20.8 m and C moved 46.1 m. Pyramids moved differently in each of the clusters but in general were either clumped up into tighter groups or were moved outside of the cluster (Figure 15). Eleven pyramids were relocated from group A, 6.7-104 m from their original group. Nine relocated pyramids from group B, 13.4-69 m from their original group. Fourteen pyramids relocated from group C 38.1-156 m away from their original cluster.

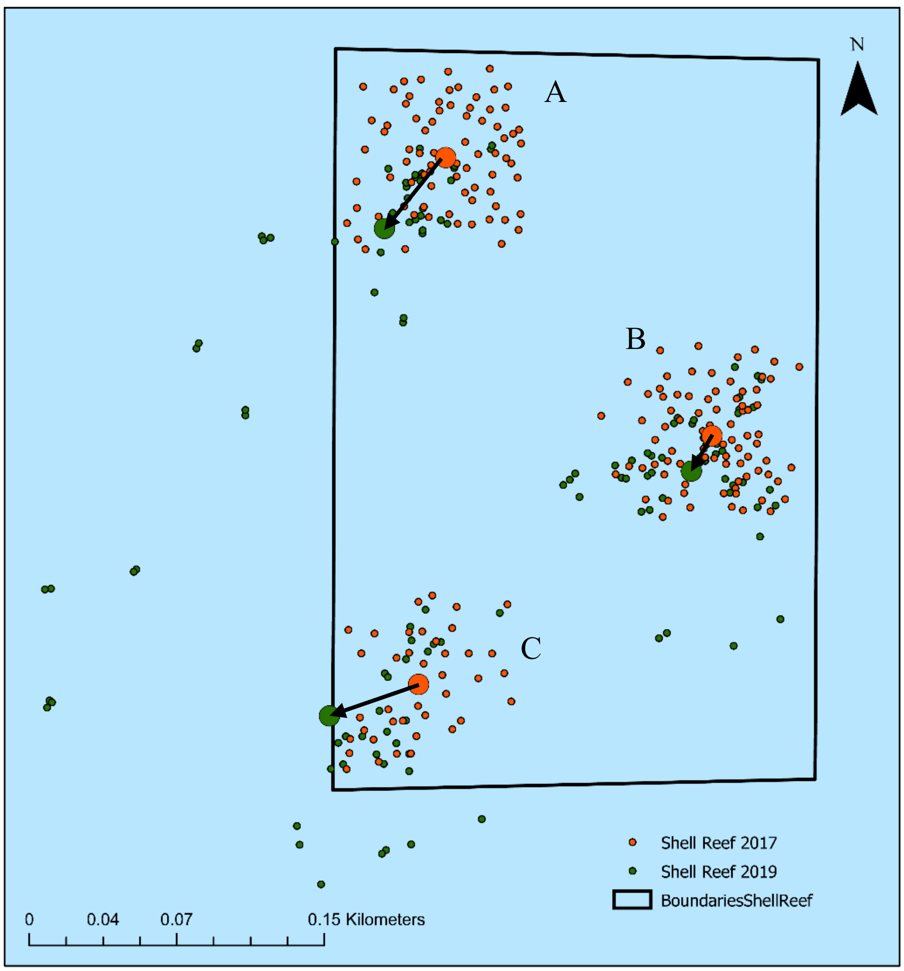

Figure 15. Comparison between the 2017 (Orange) and 2019 (Green) Shell reef pyramid locations. While pyramids were outside Shell reef's borders (Black Box), they were still inside the greater Port O'Connor reefing area.

Pyramid Height

Across the three reef sites, George Vancouver, Matagorda Nearshore and Shell reefs pyramids averaged a height of 2.3 ± 0.01 m in 2017, the year of deployment. In 2018, average pyramid height dropped to 1.4 ± 0.01 m for George Vancouver and Matagorda Nearshore reefs. Shell reef was not surveyed in 2018. Pyramid heights appeared to stabilize in 2019 relative to 2018 at an average value of 1.3 ± 0.01 (Figure 16). The Reefman jailhouse reef pyramids deployed in 2012 at George Vancouver reef averaged 1.3 ± 0.1 m in height, seven years after deployment. Height changes due to the pyramids being pushed onto their sides could not be distinguished from pyramids losing height and remaining upright due to the angle which the sidescan imagery was taken.

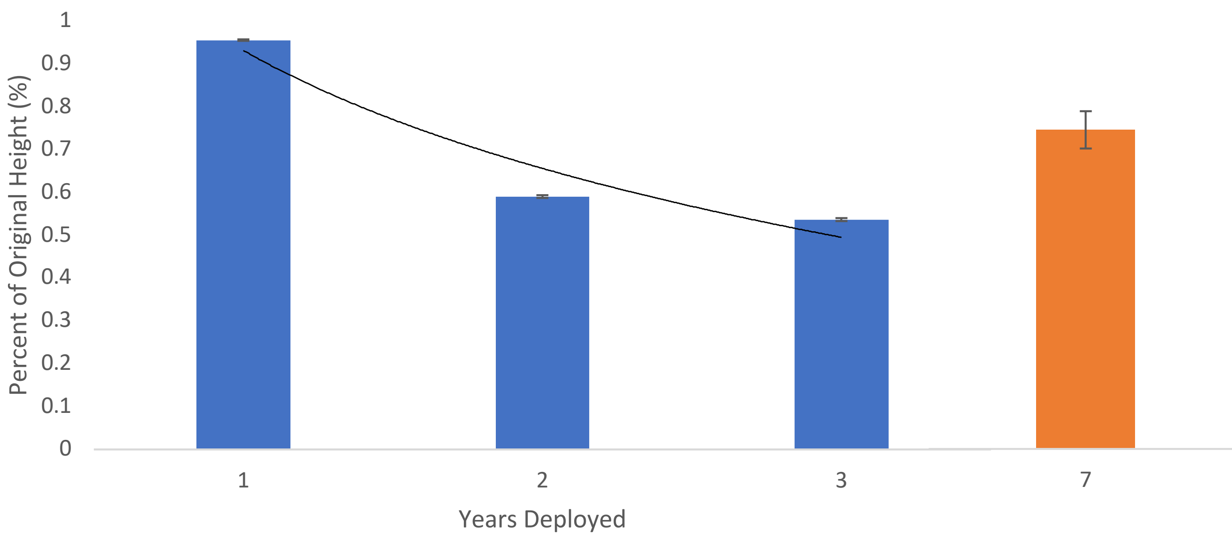

Figure 16. Distribution of heights (% original) at various years of deployment (1,2, 3 and 7-year pyramid heights). Error bars are standard error (0.002%, 0.003%, 0.004% and 0.04%) Blue represents George Vancouver, Matagorda and Shell reef Natural Resource Damage Assessment pyramids. Orange represents the Reefman pyramids in George Vancouver.

Table 4. Summary statistics for height loss over time comparison in Figure 16.

Years Deployed	Average Height (%)	Standard Error (%)
1	95.5	0.00175
2	59	0.00325
3	53.6	0.0035
7	71	0.0415

The following reports results of Height ~ Year * Zone ANOVA's with each specific reef.

George Vancouver

Pyramids deployed in 2017 at the site started with an average height of 2.3 ± 0.01 m. This decreased to 1.5 ± 0.02 m in 2018 and to 1.4 ± 0.01 m in 2019 (Figure 17). A two-way ANOVA (R:0.615), Heights ~ Zone * Year, with a Tukey HSD pairwise test showed that the average heights each year at George Vancouver were significantly different from one another, decreasing over time (F: 1824.956, *p*=0.00, df:2) (Table 5).

Table 5. Tukey HSD results for the time element of the two-way George Vancouver ANOVA analyzing time and zone. All years proved to be significantly different from one another at p<0.05.

(I) Time	(J) Time	Mean Difference (I-J)	Std. Error	*p*
2017	2018	0.86236388737695*	0.01743921253460	.000
	2019	0.92074295540409*	0.01694704889443	.000
2018	2017	-0.86236388737695*	0.01743921253460	.000
	2019	0.05837906802714*	0.01750603076735	.002
2019	2017	-0.92074295540409*	0.01694704889443	.000
	2018	-0.05837906802714*	0.01750603076735	.002

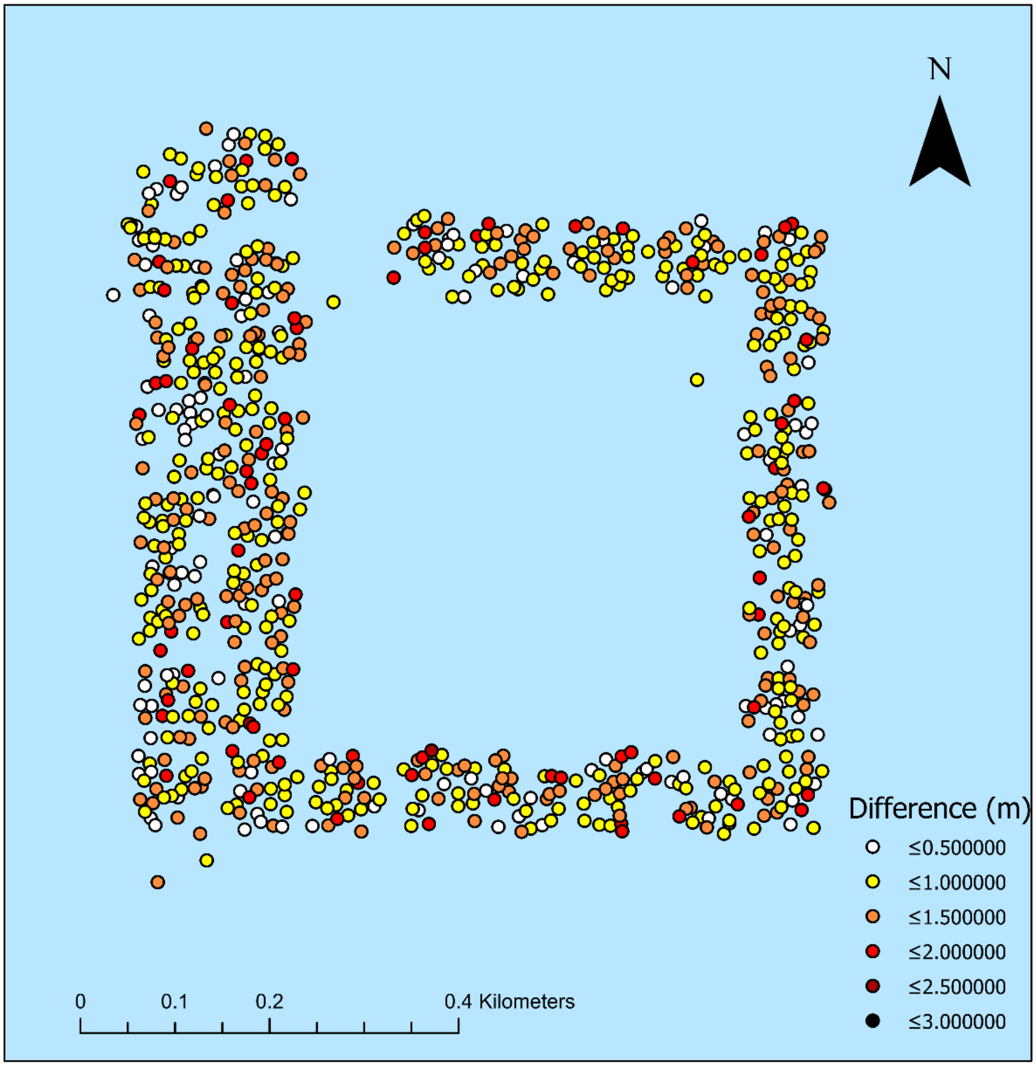

Figure 17. Changes from 2017 to 2019 pyramid heights in George Vancouver Reef. Half meter increment changes are shown.

Matagorda Nearshore

Initial heights after deployment in 2017 averaged 2.3 ± 0.01 m. This decreased in 2018 to 1.4 ± 0.01 m in 2018 and then to 1.2 ± 0.01 m in 2019 (Figure 18). A two-way ANOVA (R:0.670), Heights ~ Zone * Year, with a Tukey HSD pairwise test found the changes in heights between years to be significant, with pyramid height decreasing over time (F: 45549.618, *p*: 0.00) (Table 6).

Table 6. Tukey HSD results for the time element of the two-way Matagorda ANOVA analyzing time and zone. All years proved to be significantly different from one another at a confidence interval of 0.05.

(I) Time	(J) Time	Mean Difference (I-J)	Std. Error	*p*
2017	2018	0.8949922969892*	0.01211304003464	.000
	2019	1.0631146514508*	0.01200385490528	.000
2018	2017	-0.8949922969892*	.039740944995555	.000
	2019	0.1681223544616*	.040235002477398	.000
2019	2017	-1.0631146514508*	.039382726067203	.000
	2018	-0.1681223544616*	.040235002477398	.000

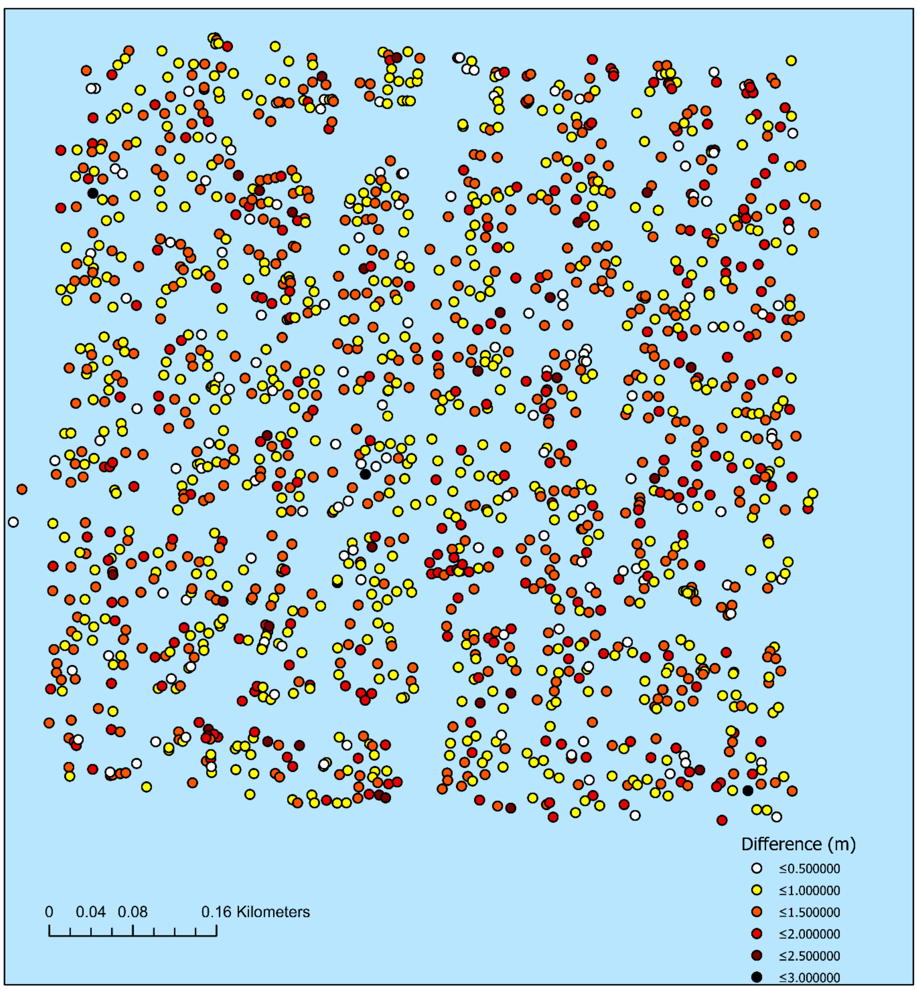

Figure 18. Changes from 2017 to 2019 heights in Matagorda Nearshore Reef. Half meter increment changes are shown.

Shell Reef

Shell reef only had survey data for the years 2017 and 2019. Pyramid height in 2017 averaged 2.4 ± 0.02 m. In 2019 the heights averaged 1.3 ± 0.01 m. Results from a two-way ANOVA (R:0.765), Height ~ Zone * Year, with a Tukey HSD pairwise test comparing pyramid heights in the groups at Shell reef during 2017 and 2019 found that the difference in heights between 2017 and 2019 was significant (F:1037.611, *p*=0.00,).

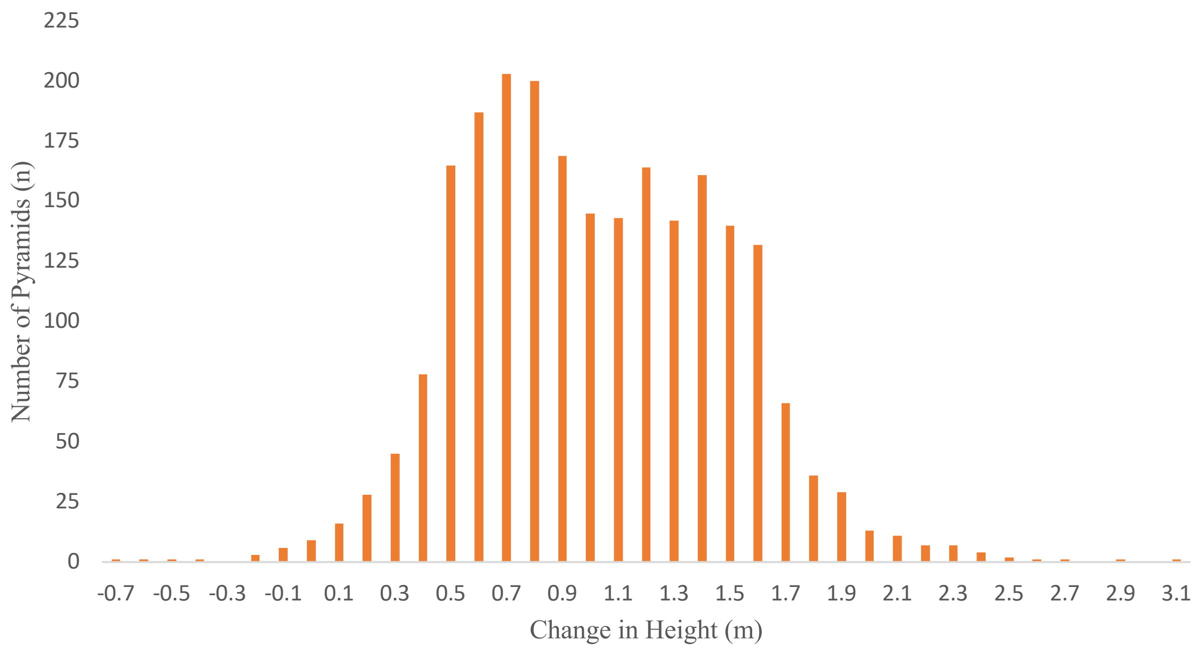

Figure 19. Height changes (orange) for pyramids between 2017 and 2019 in George Vancouver and Matagorda reefs.

Changes Within a Reef

George Vancouver

A global Moran's I test was run in ArcGIS on pyramid height changes from 2017 to 2019. The results indicated that there was clustering present within the reef (Moran's Index:0.040483, z:3.556941, *p*=0.000375). A local Moran's I analysis was conducted to determine where within the reef clusters exist. The analysis found that there was no significant pattern between neighboring pyramids within George Vancouver Reef (Figure 20).

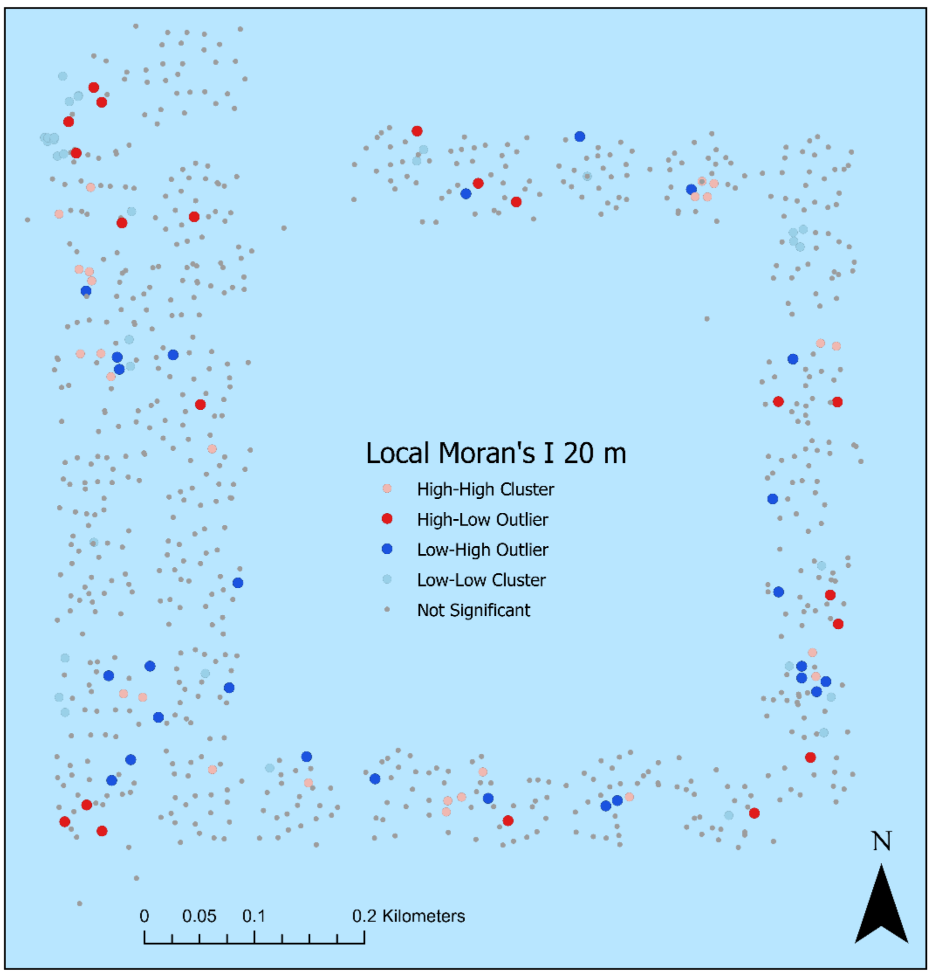

Figure 20. Local Moran's I result for George Vancouver reef, no noticeable patterns in height changes between neighboring pyramids were found. Higher refers to larger changes and lower refers to less changes.

The result of a two-way ANOVA (R:0.615), Height ~ Zone * Year, found that zones had no significant impact on pyramid height (F:0.980, *p*=0.500, df:32). The interaction Zone * Year proved to be significant (F:1.538, *p*=0.004, df:64) although its impact compared to Year was far less (F:1824.956, *p*=0.000, df:2).

Matagorda Nearshore

Like with George Vancouver, both a global and local Moran's I analysis were conducted. The global found that there was clustering (Moran's Index:0.040891, z:2.712743, p=0.006673). The local Moran's analysis found no discernable pattern between neighboring pyramids within

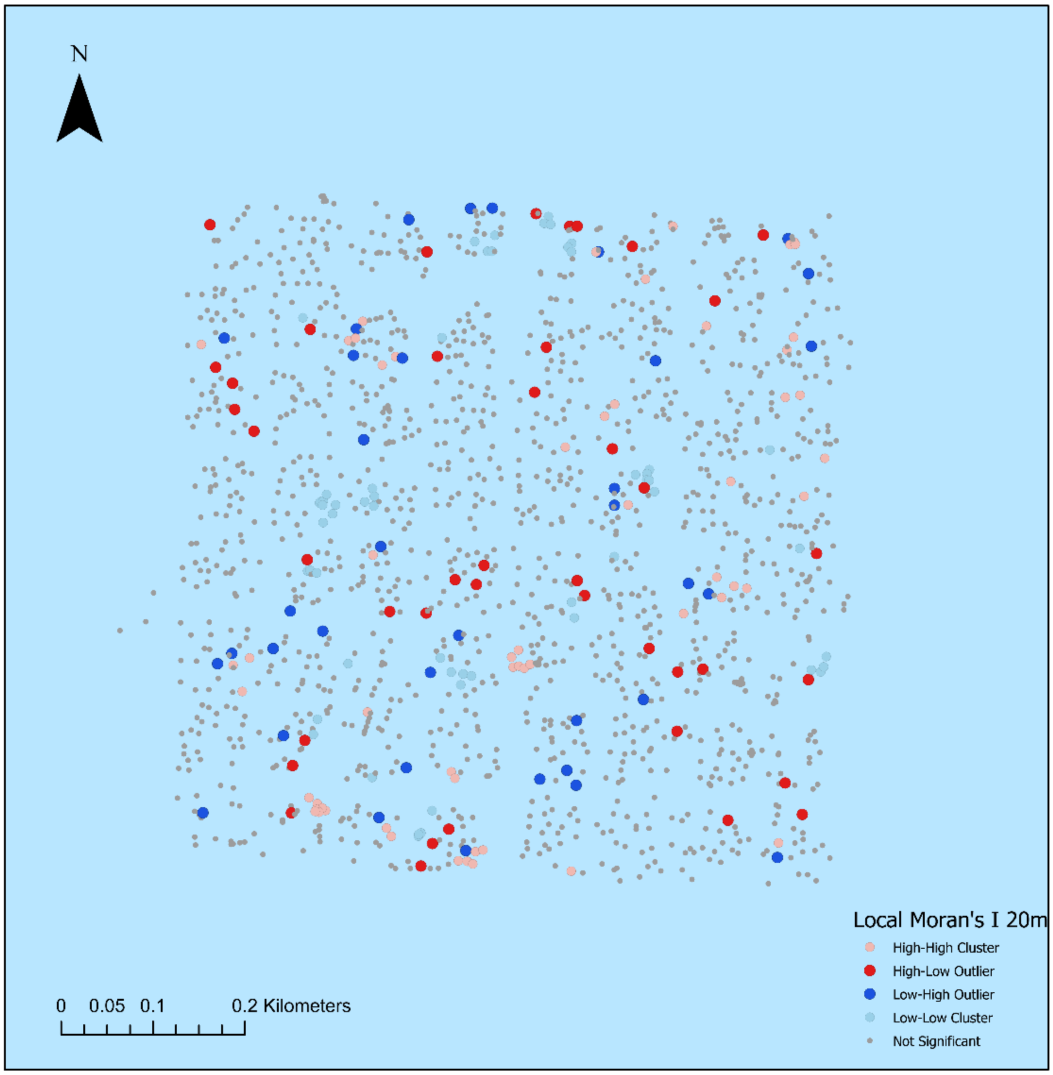

Figure 21. Local Moran's I result for Matagorda Nearshore, no noticeable patterns in height changes between neighboring pyramids were found. Higher is greater changes, lower is less changes.

Matagorda Nearshore reef (Figure 21).

Matagorda Nearshore had no zones that needed merging to properly represent pyramids. The results of a two-way ANOVA, Height ~ Zone * Year, (R:0.670) found the factors Zone (F:2.993, *p*=0.000, df:64) and Time (F:4553.354, *p*=0.000, df:2) (Figure 22) to be significant. However, the interaction of Zone * Year was not significant (F:1.189, *p*=0.076, df:126). A Bonferroni post hoc test was conducted and found that zone 89, 62 and 42 differed significantly from numerous other zones. Zone 89 had an average height in 2019 of 0.8 ± 0.1 m, making it the lowest of the entire reef. Zone 42 had an average height of 1.5 ± 0.1 m and Zone 62 had 1.5 ± 0.1 m, making them the highest zones in the reef. No obvious pattern of pyramid height across the reef could be discerned from this.

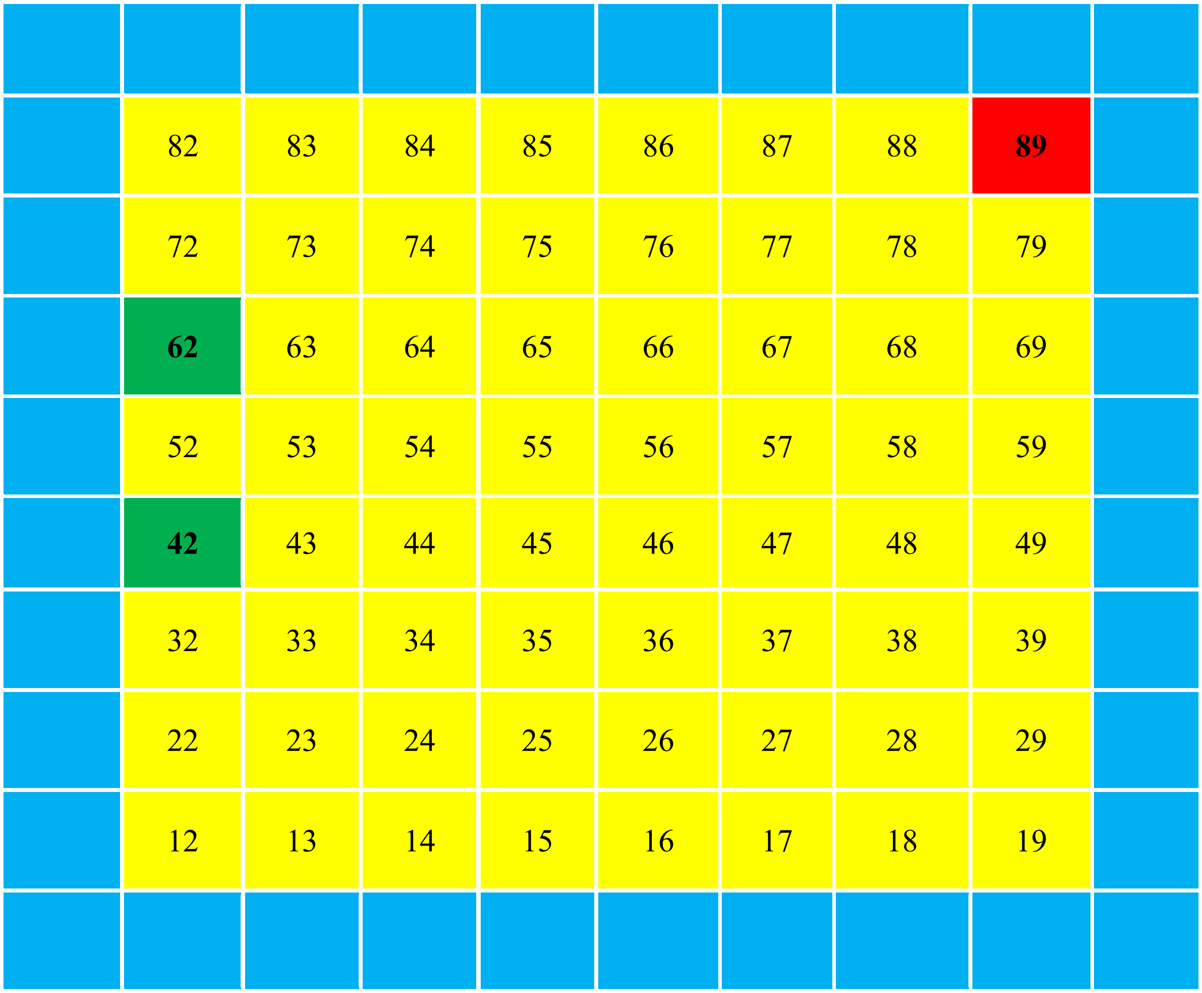

Figure 22. The relationships between zones in Matagorda as of 2019. Significant relationships for zones 89 (0.8 m), 62 (1.5 m) and 42 (1.5 m) in green in comparison to the average value 1.2 m. Yellow zones were not significantly different from average and blue zones are reef buffer area.

Shell Reef

Shell reef had three groups based on the location of pyramid deployment thus, no zones were created for it. A two-way ANOVA, Height ~ Zone * Year, (R:0.765) for Shell reef determined that average height between the two years was significantly different (F:1037.611, *p*= 0.000, df:1). Groups were not significantly different (F:0.993, *p*= 0.372, df:2), nor the interaction between year and group (F:0.853, *p*= 0.427, df:2).

Reef Comparisons

The results for a two-way ANOVA (R:0.718), Height ~ Site * Year, between George Vancouver, Matagorda Nearshore and Shell reefs in 2017 and 2019 found that the height changes were significantly different between reef sites (F:105.386, *p*= 0.000, df:2). Tukey HSD pairwise test for reef site demonstrated that each reef was significantly different from the other two for pyramid height (Table 7).

An ANOVA (R:0.647), comparing Heights ~ Site * Time, was conducted between George Vancouver and Matagorda Nearshore. This comparison used all year data. A Tukey HSD pairwise test found that the reefs were significantly different from each other in pyramid height across time (F:19.024, *p*=0.000, df:1). Reef site by itself again proved significant.

Table 7. Tukey HSD results for an ANOVA of height loss at all reefs from 2017 to 2019. All comparisons proved to be significantly different at a *p* of 0.05.

(I) Location		Mean Difference (I-J)	Std. Error	*p*
GVR	MNR	0.11590200497675*	0.009929480688277	0.000
	Shell	-0.084382953907418*	0.019751086356852	0.000
MNR	GVR	-0.11590200497675*	0.009929480688277	0.000
	Shell	-0.200284958884168*	0.018936660203496	0.000
Shell	GVR	0.084382953907418*	0.019751086356852	0.000
	MNR	0.200284958884168*	0.018936660203496	0.000

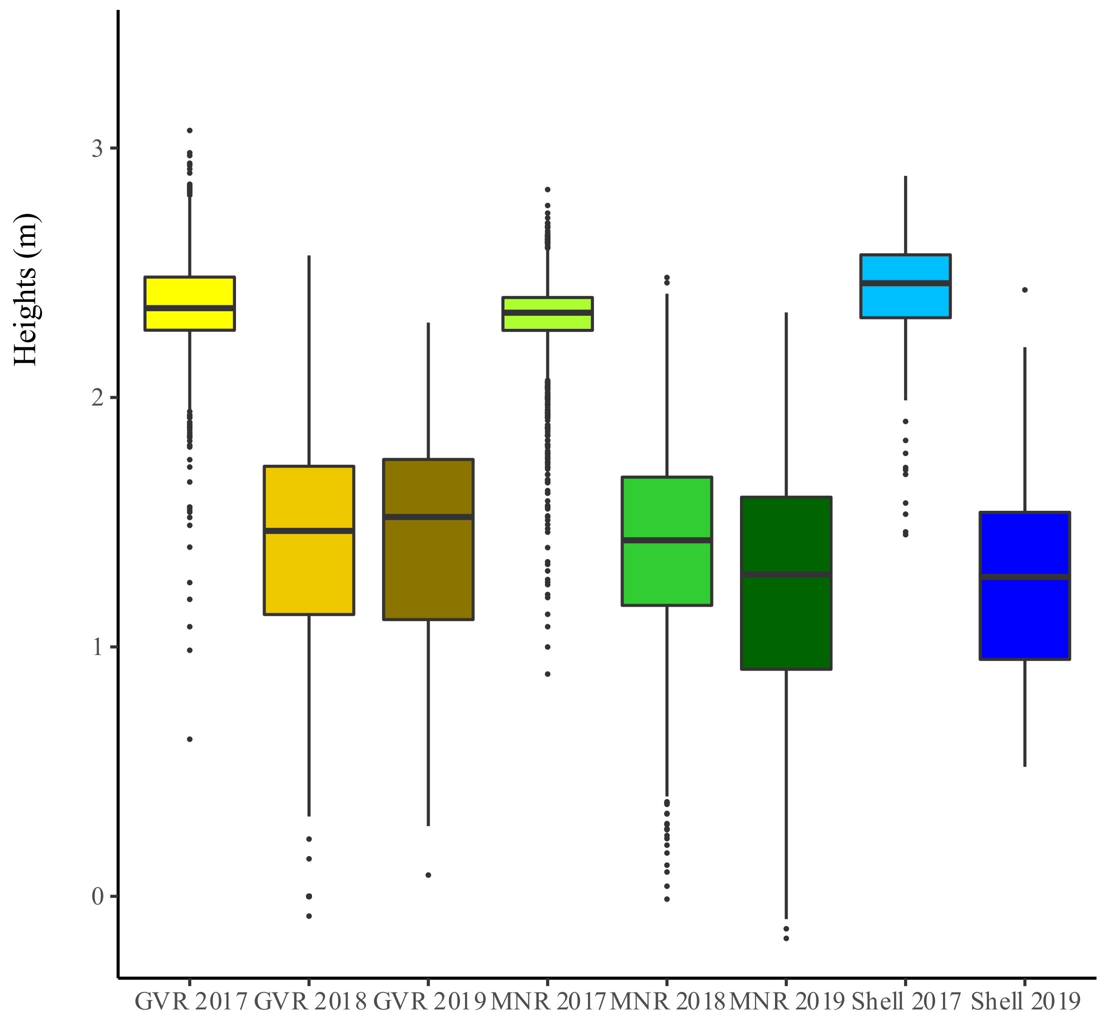

Figure 23. Comparison of pyramid heights (m) between reefs (George Vancouver **yellow**, Matagorda Nearshore **green**, Shell **blue**) over time (**left** 2017, **mid** 2018, **right** 2019).

Table 8. Pyramid Count and Height data from 2017 to 2019.

Reef and Time	Count	Mean	Standard Error
GVR 2017	806	2.3m	0.01 m
GVR 2018	710	1.5m	0.02 m
GVR 2019	793	1.4 m	0.02 m
MNR 2017	1590	2.3 m	0.01 m
MNR 2018	1464	1.4 m	0.01 m
MNR 2019	1511	1.2m	0.01 m
Shell 2017	198	2.4m	0.02 m
Shell 2019	122	1.4 m	0.03 m

Sediment Texture

Ten sediment samples were taken from seven pyramids within the RGV reef. Pyramids were chosen for their positions within the reef due to the observed differences in sediment characteristics within the RGV (Figure 24). Pyramid 67 had three samples taken around it and Pyramid 203 had two taken around it.

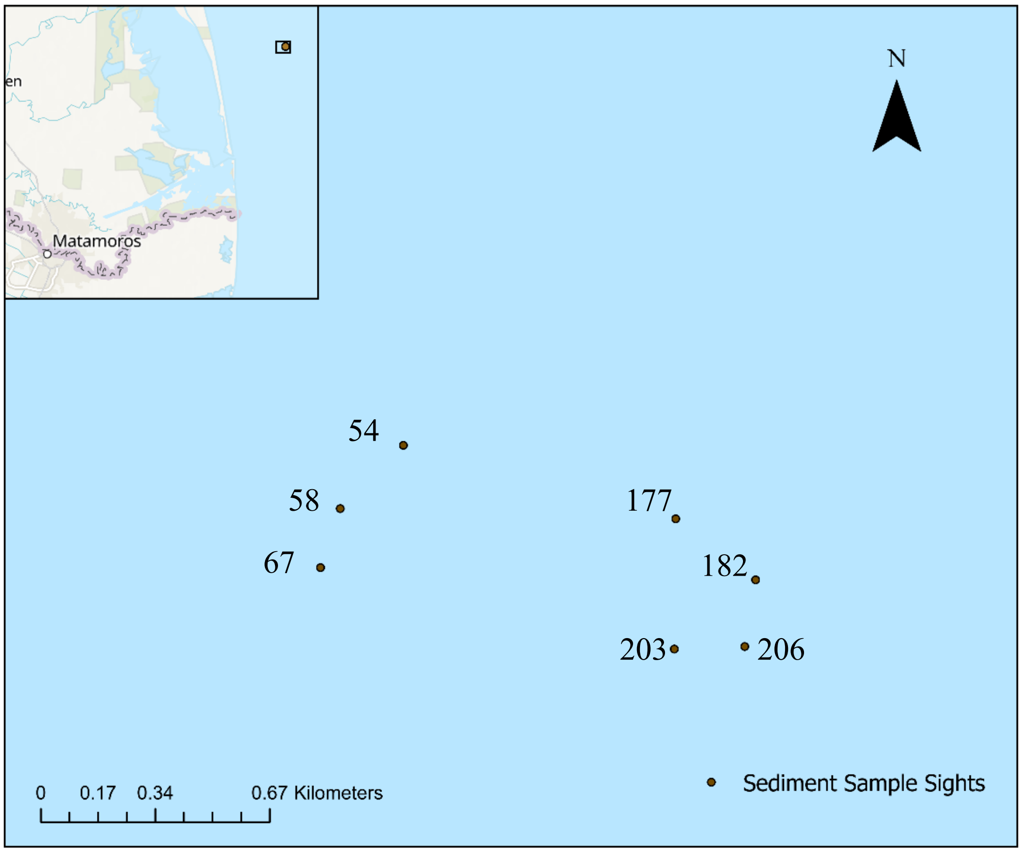

Figure 24. The location of sediment sample sites within the RGV Reef. Sediment samples were taken adjacent to the first pyramid found at the dive site. Target pyramid number is displayed next to each site.

Sediment textures were similar across the reef (Figure 25). Samples typically contained minimal amounts of particles that were retained by 2 mm, 1 mm or 500 µm sieves. All samples were dominated by sediments in the 63um grain sizes (very fine sand), representing 50 to 80% of the sample. The next largest category was the 250 µm for all samples (15 to 46%).

Figure 25. Histogram of sediment grain size. Note that all samples followed a similar pattern and were dominated by the fine sand fraction.

Data were gathered from the Texas General Land Office sediment geodatabase for each reef site (Table 9). The Rio Grande Valley reef has a very different texture to the other reefs as it had far more sand than the other reef sites. In comparison to the Rio Grande Valley Reef 2019 core samples, the Texas Bureau of Economic Geology sediment data for Rio Grande Valley Reef area had more silt and clay and lesser proportion of sand, but was still sand dominated.

Table 9. Comparing the average texture percentages for the Bureau of Economic Geology/University of Texas Austin (TBEG) and the 2019 cores from the Rio Grande Valley reef. The finest sieve used in the Rio Grande Valley 2019 samples was unable to differentiate between silt and clay.

<table>
<tr><th>Site</th><th>Sand</th><th>Silt</th><th>Clay</th><th>Gravel</th></tr>
<tr><td>GVR TBEG</td><td>5%</td><td>64%</td><td>31%</td><td>0%</td></tr>
<tr><td>MNR TBEG</td><td>37%</td><td>48%</td><td>16%</td><td>0%</td></tr>
<tr><td>Shell TBEG</td><td>19%</td><td>53%</td><td>28%</td><td>0%</td></tr>
<tr><td>RGV TBEG</td><td>80%</td><td>13%</td><td>5%</td><td>2%</td></tr>
<tr><td>RGV 2019</td><td>98%</td><td colspan="2">2%</td><td>0%</td></tr>
</table>

CHAPTER IV

DISCUSSION

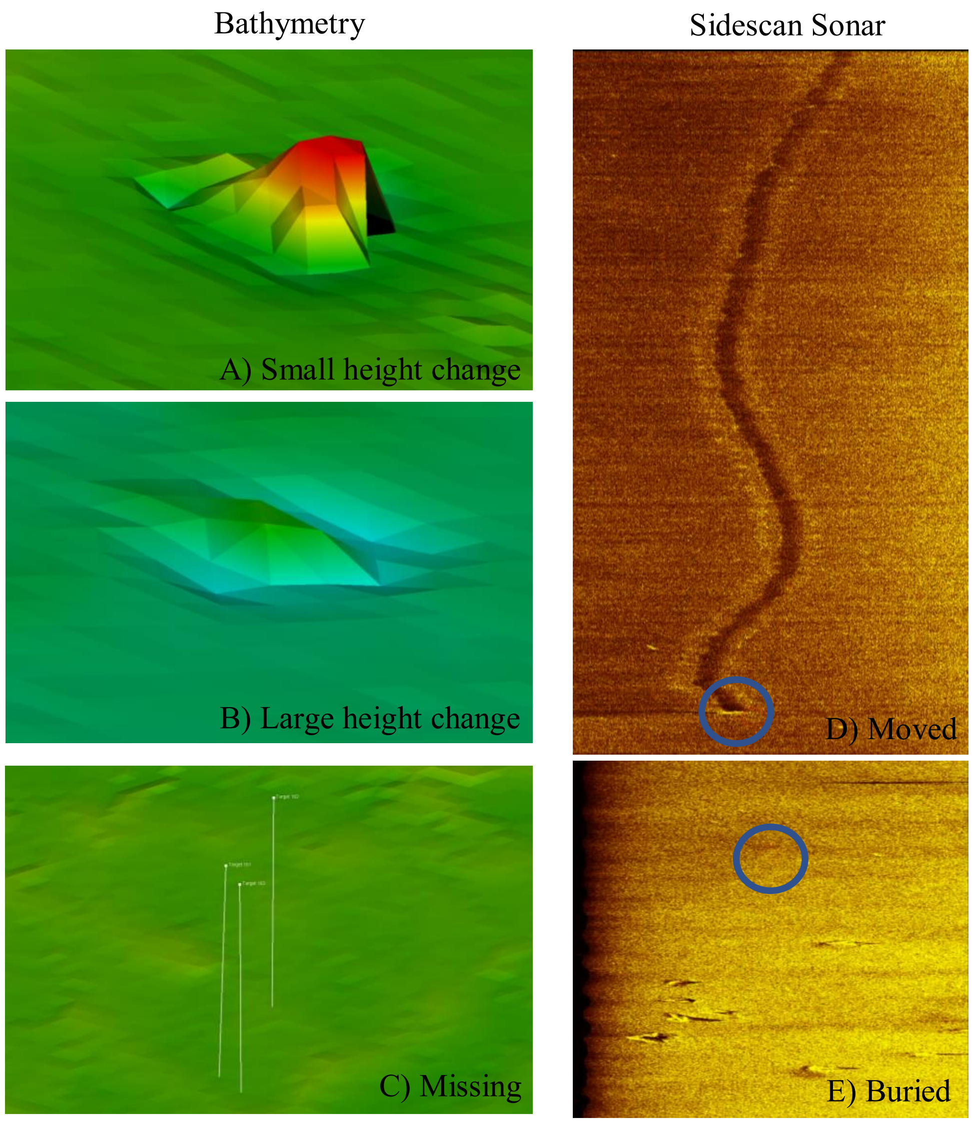

Figure 26. Potential fates of pyramids. Bathymetry: Small height change (A), Large height change (B), missing/buried (C), Sidescan: Moved by trawl fishing activity (D) and missing/buried (E).

George Vancouver

The George Vancouver Reef was the most consistent of the three reefs in terms of pyramid number, height and location. This consistency at the reef site for the two years of the National Resource Damage Assessment (NERDA) pyramids is also reinforced by the persistence of the Reefman pyramids seven years after their deployment. The Reefman pyramids, with a slightly smaller height and a steel bar construction, appear to have performed slightly better than the concrete pyramids. They lost 29% of their original height on average over seven years, however only half of the pyramids deployed were able to be confidently analyzed due to their proximity to similar concrete structures. While a limited representation of their condition, the data suggests that the conditions present at George Vancouver have been consistent enough over time for the Reefman pyramids to perform as hard substrate for up to seven years after deployment.

Pyramid height changes between 2018 and 2019 for the NERDA pyramids demonstrate the likely change in height when no hurricane event occurs. The Cesano-Senigallia artificial reef in the central Adriatic Sea, composed of a combination of 2 cubic meter concrete blocks stacked into pyramid shapes and large metal cages, showed a depth change for materials at 30 cm over a seven year period (Tassetti et al., 2015). However, these concrete block pyramids had a larger footprint and were placed on gravel "mattresses" to help counteract height change (Tassetti et al., 2015). The NERDA pyramids at George Vancouver lost 0.1 m between 2018 and 2019. Since that year had no extreme events occur in the area, this rate of height change is most likely the rate pyramids will continue to change at. While this study cannot directly demonstrate non-hurricane influenced initial year height changes, the data does suggest that the pyramids will stabilize at a certain height and not subside as much. The heights that the pyramids are now residing at are comparable to ‘Atlantic Pods’, four sided pyramid like structures that are 1.1 to 1.5 m tall and 1.6 to 1.8 m at their widest, that demonstrated higher fish abundances, biomasses and species richness when compared to reef balls, concrete pipes and rocky reefs off North Carolina (Lemoine et al., 2019).

The lack of pyramid movement is also important for the longevity of other reefing materials. Pyramids at slightly greater depths have shown no evidence of displacement when a hurricane impacted their area (Renchen et al., 2019, Turpin and Bortone, 2002). If the pyramids had moved much larger distances over the two-year period there would be potential for the pyramids to move and impact the George Vancouver. The hull of the vessel has become less sturdy over time and the archeological survey that was conducted before the NERDA pyramids were deployed that a safety buffer of 50 meters be maintained to prevent and pyramids from hitting and damaging the George Vancouver (Gearhart et al., 2012). The hull of the George Vancouver has already broken into three major sections, the bow, midships and stern, and the stern has already experienced a partial collapse. Additional impacts would speed up the ship’s degradation and lead to a reduction in habitat at the reef. The data from George Vancouver suggests that the concrete pyramids, moving on average one meter from their starting locations, can function as a part of a larger reef with varying structures and be relied on to maintain their position and not harm the interfere with rest of the reef.

Matagorda Nearshore

Along with the height data, movement data at Matagorda is also important to the reef’s continued function. The study identified 79 of 1605 (~5%) pyramids that moved at least three meters from their deployment site. That is higher than the George Vancouver pyramids (13 of

806, ~1.5%) for similar natural conditions. The amount of trawling activity in and around the Matagorda Nearshore reef when compared to George Vancouver reef provides a potential explanation to this difference. When compared over the two-year period, George Vancouver always had fewer trawl marks than Matagorda Nearshore reef, and no direct evidence of a pyramid moving. In 2018, two pyramids were found outside the reefing area in Matagorda Nearshore reef and one of them had been dragged roughly 518 m (Figure 26 D). The large scour where the pyramid was dragged through the mud and the object on the bottom next to it indicate that the pyramid was taken away by a shrimping vessel. The trawl marks are prevalent inside the reef area in 2019 for Matagorda as well.

The trawl marks indicate that Matagorda is near productive shrimp habitat, as imagery from the archeological report conducted in 2013 on Matagorda documented shrimp trawl scars in the area as well (Blackmon & Goldhamer 2014). The consistent presence of shrimp trawl marks within the area indicates regular shrimp trawling in the area (Mérillet et al., 2017). This poses risks to the pyramids as they can be potentially taken outside the reefing area much like the one pyramid identified in 2018. The trawling can also cause resuspension of large amounts of fine substrate that could help bury pyramids (Oberle et al., 2015). The risk however should hopefully decrease over time as more shrimpers learn about the existence of the reef and take measures to avoid losing their nets in the pyramids. George Vancouver has been a reef for over 40 years now (1976-2019), coupled with a rather large vessel that shrimpers must avoid, this may explain the fewer trawl marks within the reef when compared to Matagorda Nearshore reef. Since Matagorda was created in 2017 it is still a relatively new reef, it might not be fully known in commercial fisheries. Time and better communication will both help the reef persist through time and shrimpers from damaging the reef and their nets with pyramid snags.

Shell Reef

Considering the level of exposure to Hurricane Harvey the pyramids in the Shell Reef experienced, analyzing the resulting impact the storm had is very important to future artificial reef development. Of the original 200 pyramids placed in the reef in 2017, only 122 pyramids were found in 2019. This large amount of loss is similar to impacts from Hurricanes Erin and Opal where 26 of 38 reef structures were displaced (Turpin and Bortone 2002). The two larger groups, A and B, lost roughly half their pyramids (42 of 78 and 32 of 81 lost) while most of the group C pyramids were relocated (3 of 39 lost). There is no clear reason why these two sections of the reef lost significantly more pyramids than C. A and B are the northmost and northeastern sections of the reef while C is in the southwest. Harvey impacted the reef from both sides, initially as a major hurricane from the south but then as a tropical storm on the northern side (Blake and Zelinsky 2018). It would stand to reason that C, the section closest to the storm when it was a major hurricane, would have lost the most pyramids. Whatever the reason, Shell reef has had the pyramid deployment fundamentally altered by the storm.

Originally, pyramids at Shell reef were in three large groups with pyramids within each group being close to one another. Hurricane Harvey forced the pyramids to either go outside the deployment area or clump together within the original deployment cluster. Concrete pyramids at the Bell Shoals reef site have been observed being moved hundreds of meters and forced onto their sides by Hurricane Michael (Renchen et al., 2019). There are two issues raised by these pyramids being on their sides when moved outside the reefing area. Pyramids on their sides in general represent a loss of shelter for reef fishes as the large open bottom of the pyramids would enable predators to enter the interior of the structure. While we were unable to confirm if a pyramid in our study was on its side, if the pyramids are on their sides, they will still provide habitat but may not provide as much refuge for reef fish. George Vancouver is the shallowest reef of the three with depths between 16.7 and 18.2 meters. The pyramids were most likely impacted by scouring from the high current speeds during a hurricane, because the wavelength needed to enable surface interaction with upright pyramids on the bottom is calculated at 29.4 meters

The second issue with the pyramids being moved is their movement relative to the reef area boundaries. The pyramids of group A and C were already very close to the western boundary of Shell reef and resulted in many pyramids moved outside the border. Cases of artificial reef materials being moved hundreds of meters after the impact of similar strength hurricanes to Harvey have been documented (Turpin and Bortone 2002). Lighter density materials, such as plastic tetrahedrons, plastic shipping containers and 1.2-meter steel cubes, have been documented off Florida and South Carolina moving hundreds of meters to greater than a kilometer after a storm (Turpin and Bortone 2002, Bell and Hall 1994). While pyramids moved from Shell reef remain within the larger reefing area of the Port O'Connor artificial reef area, pyramids being moved over one hundred meters does serve as a warning to have large reefing areas with pyramids and other similar material placed as centrally as possible to minimize long term displacement.

Pyramids remaining within Shell reef likely experienced one of two scenarios. The first is that the pyramids caused massive scours to form around them when exposed to the forces from Hurricane Harvey and were subsequently topple inside and may become partially buried. The second is that the pyramids were flipped over by Harvey and remain on their sides. The second scenario is more likely to explain the pyramids that were moved outside the deployment clusters that have subsequently lost their height. This has been observed to a more extreme displacement for reefs at depths of 4.5 to 7.6 m in Bell Shoals (Renchen et al., 2019). Pyramids still within the reef clusters are more likely the result of the first scenario, unable to topple over due to adjacent pyramids providing support and thus sinking due to scouring and being partially buried over time. Pyramids have been documented to be stopped by other objects within the reef and stay adjacent to that material (Renchen et al., 2019). Similar material to the pyramids, specifically 3898 kg PVC plastic inside of cylindrical concrete from Reef K off South Carolina, has shown significant burial after being hit by a category four hurricane (Bell and Hall, 1994). The difference in pyramid heights between the 2017 and 2019 surveys was approximately 1.1 meters or roughly 46% of the full height of a pyramid. While this is statistically significant when compared to the data from the other reefs, the changes at functional level are very similar. Pyramids at George Vancouver lost 0.9 meters of height, and Matagorda lost 1.1 meters, with only 0.1 and 0.2 meters of that height being lost between 2018 and 2019. What this indicates is that the direct impact of a major hurricane might cause height changes, displace and bury a large number of pyramids but pyramid height changes in subsequent years are much smaller.

Role of Sediment

An important quality of sands and silts is that sediment particles of this size do not compact to a large extent like organic sediments and fine clays. Due to the lack of compressibility for these soils, a different model for pyramid height change is required. Instead of the pyramid's pressure compacting the sediment and causing the structure to sink into the surrounding sediment, pyramids cause a scour to form underneath them. Pyramids have been documented forming scours after hurricane events like the reefs in this study experienced (Turpin and Bortone, 2002). This can be seen in figure 26 (figure 26 A, B) when comparing a pyramid with high and low levels of height change. The pyramids, along with any hard structure placed on the bottom, disrupt water flow and cause vortexes to form that lead to scour formation (Armono and Wirayuhanto, 2018). Pyramids that have more height change tend to have a scour mark around them. The scour mark forces the pyramid to sink relative to the surrounding seafloor. Turpin and Bortone (2002) have suggested the scouring may prove to be a benefit for the pyramids in terms of maintaining position during future hurricanes. The scouring lowers the pyramid and limits the mobility of the pyramid, preventing them from leaving the reefing area despite the tremendous forces being exerted on them.

This, however, does not explain a pyramid that has changed in height but does not have a scour around them. The likely explanation for this is loose sediment filling in scours that the pyramid formed. Artificial reef structures have been observed to cause an immediate buildup of sediment against the structure with scours forming up to several meters from the structure (Manoukian et al., 2011). Both George Vancouver and Matagorda reefs showed evidence of shrimp trawl marks near the reefing area in 2019. Nearby trawling will loosen sediment that could be carried over to the reef areas (Oberle et al., 2015). The gulf coast of Texas is also known to have intense winter storms. These storms have been observed disturbing loose sediment along the bottom and burying low profile structures and smaller objects up to a meter (Kline R., personal communication). Hurricane Hugo contributed enough fine sediment to reduce visibility at Reef K in South Carolina for the year following the storm, with the initial six weeks having zero visibility three meters below the surface (Bell and Hall, 1994). Hurricane Harvey's sediment input, combined with influence from winter storms, trawling activity and nearby rivers and the Mississippi (Fournier et al., 2019) would provide the sediment necessary for the pyramid scours to be filled.

The three northern reefs differ greatly in composition from the Rio Grande Valley reef based off the sediment grab data and the 2019 core samples. The composition of northern reefs is dominated by silty sediment with variations on the second largest component. Matagorda was secondarily composed of sand and George Vancouver and Shell were secondarily clay based sediments. The critical comparison is between Matagorda and George Vancouver as both were not nearly as affected by Hurricane Harvey as Shell reef in terms of pyramid losses. Matagorda and George Vancouver height changes were significantly different from one another, but the overall pattern was similar. Both reefs started at comparable heights and experienced a large loss in pyramid height the first year while having a much smaller loss the second year. Hard substrate of smaller sizes in the Gulf of Mexico has demonstrated the ability to provide habitat for a number of species including red snapper (Workman et al., 2001). The reefs are still providing habitat for fish communities, have sunk far less from 2018 to 2019 than they have in 2017 to 2018, and Reefman pyramids are still present after seven years. This combined evidence suggests that these pyramids are still performing their role of restoring hard bottom habitat and can continue to do so for years to come.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Pyramid Performance

Pyramid heights across all three reefs surveyed maintained an average height greater than half their original heights. This was true even at Matagorda where height changes (1.2 of 2.4 m remaining) over the two-year period was the greatest. Height loss dramatically decreased after the first year deployed for George Vancouver and Matagorda Nearshore reefs, and the overall height changes between reefs are similar. The majority of pyramids remained in close proximity to their deployment points. Data from the Reefman pyramids suggests that the pyramids should be able to persist for at least a half a decade on site. Data from George Vancouver and Matagorda suggests that the National Resource Damage Assessment (NERDA) pyramids experience very little height change occurs when the pyramids do not experience extreme conditions. Data from the National Data Buoy Center buoy 42019 (https://www.ndbc.noaa.gov/station_page.php?station=42019) and Texas Coastal Ocean Observation Network Matagorda Channel gauge mg0201 (http://cbi.tamucc.edu/TCOON/) indicates that the area the reefs are located in has average wind speeds of 6.7 m/s, average wave heights of 1.2 m, average wave periods of 4.7 s and average currents of 5.1 cm/s. Based off the data for changes between 2018 and 2019, the NERDA pyramids do not experience major height or location changes in the above conditions. Based on the shallowest depths between the three reef sites of 16.5 meters, it would take a wavelength of over 28 meters to have surface conditions influence the tops of pyramids that have not lost any height.

Threats to Pyramid Performance

The greatest threats to concrete pyramids within these reefs are extreme weather events and human disturbance. Shell reef lost 39% of its pyramids and had many pyramids moved outside the reef as a result of Hurricane Harvey hitting it in 2017. Any weather event that would generate waves with a base that could influence the pyramids on the bottom could be a source of pyramid height changes. Human impacts on the reef are primarily the result of shrimp trawling near and within the reefing areas. Matagorda had the highest activity of the three reef sites and has direct evidence of pyramids being moved when caught in fishing nets.

Future Recommendations

In order to maximize the variety of habitats present within current and future reefs, it is recommended to use future pyramids in a supplemental role as in the George Vancouver reef instead of the primary component of the reef like at Matagorda and Shell reefs. This will allow for a larger variety of fish species and life stages to be present at reef sites and better enhance the marine recreational fisheries that utilize these reefs.

To better construct reefs so that they maintain pyramid numbers and heights, several lessons have been drawn from studying the fates of the 2017 pyramids. First, pyramids, or any other relatively small reef material, should have a large distance between the reef area boundary and their initial deployment location. Currently Texas Parks and Wildlife does not have a specific standard process to determine a reef boundary as each one is customized to each reef (Shively D., personal communication). As Hurricane Harvey moved many Shell reef pyramids on average 45.7 meters outside their deployment groups and outside the Shell reef, taking in account the average movement of approximately 67 m pyramids moved can help strategize material placement in future deployments. A potential solution to this may be to place pyramids at greater depths so they are less affected by storm activity. Another solution may be to mix in materials that have been documented to not move, such as culverts and reef balls, with the pyramids to keep pyramids within the deployment area. A final potential solution would be to deploy this design of pyramids in deeper reefs that would be not influenced by storm activity at sites like the Texas Clipper.

Second, reef boundaries must quickly become public knowledge to minimize trawling impact. Matagorda and George Vancouver both displayed trawl marks. The difference is that for George Vancouver only one major scour line can be found in the reefing area while Matagorda had many. Despite being deployed at the same time, pyramids at George Vancouver have not been moved by human activity while Matagorda has had several. The decades-long presence of the George Vancouver hull has likely helped keep shrimpers from getting too close to the pyramids for fear of snagging their nets on the vessel's hull. Matagorda, and future reef deployments, would likely benefit from shrimp boat captains knowing the presence of the reef and the dangers they pose to it and it poses to their equipment. Texas Parks and Wildlife is already working on distributing reef coordinates through actively involving the Texas Shrimper Association in site planning and partnering with Sea Grant to spread awareness of the reef locations (Shively D., personal communication).

Finally, this study did not find a link between sediment texture and pyramid height change. All sites are not dominated by clay and George Vancouver was expanded upon as it was an already existing reef complex despite the high silt proportion. Pyramid performance, however, did not suffer for having a small sand fraction at George Vancouver. Future investigations into pyramid performance should investigate height change data from reefs with distinctly different sediment texture. Further research at the Rio Grande Valley reef would also allow height change comparisons that have not yet been impacted by a hurricane. This would provide a comparison to the height change pattern observed in this study and help separate the effects of sediment characteristics and hurricane impacts.

Texas Parks and Wildlife were aware of the potential impacts of sediment properties on reef development. Since the beginning of the artificial reef program, Texas Parks and Wildlife has geological criteria for reef site selection (Stephan et al., 1990). While the section explicitly states that hard compacted sands are preferred and soft silts and clays are to be avoid, the section does not describe how this information is obtained. This study was able to find data from the Texas General Land Office primarily from sediment grabs and cores from a variety of surveys with different goals and methodologies. This data does not necessarily best describe the sediments at any particular future site due to a lack of fine scale sampling. For future reef sites, a comprehensive analysis of the sediment characteristics could yield important information about the deployment sites.

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