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Differences in Erosion Rates and Elevation Among Natural, Living and Hardened Shorelines in Mississippi, and Alabama

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Differences in Erosion Rates and Elevation Among Natural, Living and Hardened Shorelines in Mississippi, and Alabama

by

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ABSTRACT

Shoreline erosion is a phenomenon that currently threatens both natural ecosystems and human settlements along the coast. With trends showing gradual sea level rise as a result of climate change, erosion is becoming an increasing threat to these communities. This research aims to provide more insight into the relationship between shoreline morphology and three shoreline protection techniques: natural marsh, living shoreline, and hardened structures. Six sites along the Alabama and Mississippi coast that had all three shoreline types were evaluated to determine what the average erosion rate and slope was for each shoreline. Erosion rates were calculated by image analysis and georectification over a period of ~30 years using historical imagery available on Google Earth Pro. Slopes were calculated from shoreline elevation change profiles measured in the field along duplicate transects laid perpendicular to the shore. Both wave fetch exposure and shoreline treatment type were found to have an effect on shoreline retreat. As wave exposure increased so did the shoreline's erosion rate across all sites. Between the three treatment types hardened shorelines were the most resistant to erosion while natural shorelines were the most susceptible. The data also suggests that the implementation of living elements at a shoreline helped to slow erosion after construction. Analysis of elevation data showed that fetch energy did not affect the slope as much as shoreline type. The highest slopes were found at hardened shorelines, while the gentlest slopes were found on living shorelines. This research provides coastal managements with a better understanding of the dynamics of shoreline stabilization and with construction options to better protect shorelines. **Keywords: erosion, elevation change, natural, living, and hardened shorelines.**

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LIST OF ABBREVIATIONS

AL	Alabama
ANOVA	Analysis of variance
AZ	Alonzo Landing, AL
CW	Camp Wilkes, MS
DSAS	Digital Shoreline Analysis System
GB	Grand Bay NERR, MS
HC	Hancock County Marsh Project at Heron Bay, MS
HS	Hardened shoreline/s
LS	Living shoreline/s
MHHW	Mean higher high water level
MHW	Mean high water level
MLW	Mean low water level
MS	Mississippi
NOAA	National Oceanic and Atmospheric Administration
NS	Natural shoreline/s
OS	Ocean Springs Inner Harbor, MS
SPSS	Statistical Package for the Social Sciences
SW	Swift Tract Project at Bon Secour Bay, AL
USGS	United States Geological Survey

CHAPTER I: INTRODUCTION

Shoreline morphology is heavily influenced by the physical energy that hits the shore, sediment replenishment, and sea-level rise (Davis, 1997). Along the shores of the Gulf of Mexico these factors have caused erosion rates to steadily increase in the past few decades (Davis, 1997), potentially in response to rising sea levels. Understanding how shorelines interact with these driving factors is increasingly becoming a global concern, as approximately 10% of the human population resides in places that are considered threatened by loss of shoreline (Bilkovic & Mitchell, 2013). In Alabama (AL) and Mississippi (MS) specifically, residents rely on the ~1287.5 km of shoreline for both recreation and economic purposes (Bryars *et al.*, 2016). The focus of my study is to provide information and insight on the relationship between shoreline morphology, as measured by elevation change and long-term erosion rates, and shoreline type. I did this by comparing three different shoreline protection techniques in AL and MS: natural marsh, living shoreline, and hardened structures (bulkheads and seawalls).

Literature Review

Erosion and Geomorphology

In AL and MS, shorelines can be classified as stretches of land located along coastal areas, bays, and streams heavily influenced by tidal currents (Bryars *et al.*, 2016). One of the most prominent threats to coastlines is erosion resulting in sediment removal and shoreline retreat. Factors that drive coastal erosion can include sea level change, sediment supply, and the amount of wave or wind energy acting on the shore (Davis, 1997). A main cause of erosion is an insufficient amount of natural sediment replenishment under increased energy conditions. Along the Gulf Coast, shorelines

experience longshore transport of sediment as a result of tidal currents, where sediment naturally progresses along the shore from a source to a sink (Davis, 1997). To avoid a net loss of sediment coastlines must experience deposition of sediment to replace what was lost from longshore drift, with replacement sediments often coming from rivers and streams (Davis, 1997). If the amount of sediment gained does not equal the amount lost through longshore currents, then the shoreline will experience erosion (Davis, 1997). Many factors can disrupt the influx of sediment, such as human activities, offshore currents, dams on rivers, and other structures that obstruct natural water flow (Bryars *et al.*, 2016). Sea level rise can also influence erosion rates, because as water levels rise, more of the shoreline will be vulnerable to erosion through wave action. The coasts of AL and MS currently experience a rate of 4.5 mm/yr local relative sea level rise (NOAA, 2020) while eustatic (global) sea level rise is slightly less at ~3.6 mm/yr (Lindsey, 2021). The rate of erosion is also influenced by the amount of physical energy the shoreline experiences (Davis, 1997). The northern Gulf Coast, in comparison to many shorelines around the world, experiences low wave energy except when tropical storms, cold fronts, and hurricanes occur (Davis, 1997). On average, the annual wave height of the area is <0.75 m, reaching up to an average 3 m during storm surges (Davis, 1997). In areas where fetch distance is shorter, like in back bays, maximum wave height can be as small as 30-60 cm. In summary, shoreline erosion rates depend on how much wave energy a shoreline experiences, and how well that shoreline can retain its sediment (Bryars *et al.*, 2016).

The long-term result of erosion is change to the shoreline's geomorphology and its new interaction with wave action (Bryars *et al.*, 2016). The shoreline's morphology

can be described based on both the shoreline's actual slope, between the mean high water (MHW) and mean low water (MLW) levels, and its upland slope occurring above mean higher high water level (MHHW) (Bryars *et al.*, 2016). Both slopes in combination can affect the vegetation present, the ecosystem functions supported, and the erosion rates occurring along the shoreline (Bryars *et al.*, 2016). For example, along vegetated shorelines gradually sloped banks tend to have more vegetation than cut banks with steep slopes (Duhring, 2008). In addition, if the shoreline has a gentler slope, it is more likely to have larger and hardier plants nearer the water (Eleuterius and Christmas, 1973). The vegetation success at gentler slopes is thought to be possible because there is more suitable area for vegetation to settle and establish rhizome systems (Bryars *et al.*, 2016). The erosion the bank experiences is also related to its slope. The more gradual the shoreline slope, the more surface area the bank has, which means the higher its dissipation capacity is for wave energy (Bryars *et al*., 2016). Milder slopes also provide better drainage, as the shore has more time to capture sediment from runoff than steeper banks (Bryars *et al*., 2016). The interaction of slope and erosion rate differs among natural shorelines with vegetated marsh shorelines being more stable than steeper beach shorelines. Constructed hardened shorelines often result in increased sediment erosion rates as a result of wave energy refraction from the extremely steep slope.

1. Natural Shorelines

In MS, the natural vegetation along the shore consists of several species of grasses, rushes, and sedges that exhibit zonation, which can be further influenced by the morphology of the shoreline edge and other physical factors (Eleuterius and Christmas, 1973). For example, salinity is a key factor in determining the vegetation of the shore as

certain species prefer different salinities and can only handle a certain level of regular tide immersion (Eleuterius and Christmas, 1973). The vascular plant species mainly seen in MS coastal areas include *Juncus roemerianus* Scheele (Black needle rush), *Spartina alterniflora* Loisel (Smooth cordgrass), *Spartina patens* (Aiton) Muhl (Saltmarsh hay), and *Sagittaria lancifolia* L. ssp. Media (Micheli) Bogin (Bulltongue arrowhead), with varying levels of abundance dependent on the prevailing salinity (Eleuterius and Christmas, 1973). For example, in areas with higher salinity *J. roemerianus* and *S. alterniflora* endure as opposed to other, less salt tolerant species (Eleuterius and Christmas, 1973). Some plant species have also been shown to be affected by wave exposure. The amount of wave exposure, which can be measured by fetch distance, has the potential to affect the rate of sediment transport from one part of the shore to another causing the slope of the shore to change (Bryars *et al*., 2016). This can affect the composition of the vegetation along the shoreline, as gentler slopes allow for vegetation to have more area to establish roots (Bryars *et al*., 2016).

In AL many of the same species of grasses line the shoreline with similar stressors acting on the vegetation. For example, AL's shores are also dominated by *Spartina* spp. and *J. roemerianus* (Swann, 2008). These plant species also exhibit zonation based on salinity and wave energy in this area (Roland & Douglas, 2005). Similar to MS, researchers in AL found that areas with low wave energy were more prone to have vegetation along its banks (Roland & Douglas, 2005). In both AL and MS, natural shorelines have been found to be more successful at reducing erosion when vegetation is present (Bryars *et al*., 2016). The vegetation mitigates wave energy that hits the shore by providing a buffer for that force before it hits the sediment. The deeper and denser the

root system of the vegetation the more the shoreline can limit the amount of sediment lost before it is deposited elsewhere (Bryars *et al.*, 2016). Denser and taller stems of the emergent plants help to further reduce erosion by trapping suspended sediments, resulting in net sediment deposition.

For both states, naturally vegetated shorelines provide essential support to surrounding ecosystems. These marsh habitats in the Gulf of Mexico support upwards of "80 species of fish, 60 species of birds, and many reptile, mammal, and invertebrate species" (Swann, 2008). The health of the marsh vegetation is a key factor in the survival of these species, as it provides essential services like protection from predation, stable food sources, and nursery areas (Franco *et al*., 2010). For example, Franco *et al*. (2010) found that the same species of fish living off unvegetated banks had lower growth rates and higher mortality rates then their neighbors living along shorelines with natural vegetation. Without these natural ecosystems native species that are economically important to the area, like shrimp and crabs, can become stressed, which can lead to negative effects on fisheries catch (Bryars *et al.,* 2016).

2. Living Shorelines

An alternate shoreline protection strategy that has become more popular in recent years are living shorelines. Living shorelines are man-made additions to a preexisting shoreline; their purpose is to protect against erosion without hindering the natural processes of that environment (Bryars *et al*., 2016). The type of structural addition is dependent on the habitat's needs and the original biota of the area, as different kinds of living shorelines provide different services to the environment (Davis *et al*, 2006). The addition of these components enhances the natural 'living' function and can not only

prevent erosion but also provide other ecosystem services to nearby surroundings (Swann, 2008). For example, the addition of living shorelines that have a structural element, like oyster reefs, provides a substrate and home for several species while protecting the shoreline from wave action (Davis *et al*, 2006). In contrast, living shoreline additions that consist of planting extra vegetation are better for nursey functions, which could increase the productivity of the area (Davis *et al*, 2006). It is important to note that living shorelines also have their own limitations, because they need to be implemented correctly to succeed. For example, some studies have found that the installation of plants to a shoreline is more successful in places "where regular high tides do not reach the upland bank", which could be due to the plants' lack of tolerance to immersion (Duhring, 2008). Shoreline additions have also been shown to be more successful when planted on a gentle stope with dense vegetation (Duhring, 2008).

Recently, researchers have begun to investigate the use of "hybrid" structures which use a mix of hardened and living shoreline elements to protect the banks from wave energy without destroying important ecosystems (Allen, 2013). An example of this approach would be the use of a sill, a hard structure placed parallel to the shore that just breaches the water level, with extra vegetation planted behind it (Allen, 2013). This method has shown success in the past when compared to hardened structures, like bulkheads, after being exposed to a Category 1 hurricane (Gittman *et al*., 2014). It was found that shorelines with a sill element experienced less damage to the structure after the storm than the bulkheads, which had collapsed causing major shifts in the surrounding sediment (Gittman *et al*., 2014). The hybrid and vegetated shoreline, in comparison, both

showed no obvious sediment change and saw full vegetation recovery within the year (Gittman *et al.*, 2014).

When implemented correctly, living shorelines have the potential to lessen erosion rates, as they are designed to heighten the natural protection features of a shore (Bryars *et al*., 2016). One way to do that is to add marsh vegetation, like *S. alterniflora* and *J. roemarianus*, which have extensive rhizome systems that extend through the ground (Bryars et al., 2016). These specialized root systems create a strong holdfast in the ground, allowing the marsh grass to resist being uprooted from wave energy (Bryars et al., 2016). These roots, because of their thickness and extensiveness, are able to trap sediment and stabilize the shoreline against erosion (Bryars *et al.*, 2016). Their rhizomes, along with the vegetations' ability to naturally adjust vertically makes the addition of natural vegetation to shorelines preferable, as the marsh grass can mitigate wave energy and adjust to sea level rise (Bryars *et al*., 2016). In MS and AL, contractors are urged to try and achieve an 8:1 - 10:1 slope to maximize rehabilitation success of vegetation and sediment capture (Bryars *et al.*, 2016). This slope range allows for vegetation at the foot of the bank to absorb the majority of the wave energy while the stretch of vegetation behind it can absorb the rest (Bryars *et al.*, 2016). Hybrid living structures, like oyster reefs, can also be used to prevent erosion by creating sturdy structures to provide habitat while absorbing wave energy before it hits the shore (Bryars *et al.*, 2016). In some areas the addition of marsh sill designs, another living hybrid design, has shown to lower wave energy hitting the shore by 90% (Bryars *et al*., 2016).

3. Hardened Shorelines

A hardened shoreline is defined as a shoreline that has been reinforced with a vertical structure meant to armor the existing shoreline and protect it from erosion by halting or impeding wave action (Bryars *et al.*, 2016). Common examples of this approach used in the coastal areas around the Gulf of Mexico are bulkheads, revetments, groins, sills, and breakwaters (Allen, 2013). This type of armoring has been shown to be preferred by the majority of homeowners and has been installed by many cities to protect highways and other critical infrastructure (Smith *et al*., 2017). The Mississippi Department of Marine Resources states that "hardened structures are used most effectively in areas of high wave energy to prevent erosion to the land just behind the structure" (Allen, 2013). Once installed, hardened shorelines change the original geomorphology of the area, which can cause shifts to wave energy and result in sediment movement in the area (Bryars *et al*., 2016). For example, research has shown that while a hardened structure will protect the shoreline directly behind it, the surrounding areas will experience a higher rate of erosion (Fletcher *et al.,* 1997). By looking at aerial photos taken over 49 years, it was found that beaches with a heightened rate of erosion were adjacent to the strips of beach protected by a hardened structure (Fletcher *et al*., 1997). This loss of sediment occurs because the area's natural process of wave movement is altered with the introduction of a hardened structure (Allen, 2013). This can cause sediment that is naturally supposed to accumulate down current to replenish another part of the shore to settle offshore, or to accumulate around the hardened structure (Allen, 2013). Research shows that the installation of a hardened structure can cause the loss of intertidal habitat for native plant and animal populations from both direct and indirect

destruction because of its role as a barrier between super-tidal and sub-tidal shoreline functions (Bilkovic and Mitchell, 2013). This study reported that the bulkhead caused a decrease in the immediate area's invertebrate diversity and caused increased turbidity in the area, which could further negatively affect the wider area's invertebrate population (Bilkovic and Mitchell, 2013).

Objectives

The focus of this study is to provide information and insight on the relationship between shoreline morphology and three shoreline protection techniques: natural marsh, living shoreline, and hardened structures. Shoreline morphology was measured by determining the long-term erosion rates of the sites surveyed, and measuring the elevation change along replicate transects. It is expected that of the three treatment types, natural shorelines will be the most vulnerable to erosion and that erosion rates will increase with fetch distance. Erosion rates are also expected to lessen as shoreline slope decreases and becomes gentler like at living shorelines. Shoreline slope is thought to be affected by both fetch distance and shoreline type; with steeper slopes found at high exposure natural sites and at hardened shorelines. Specific null hypotheses (Ho) tested in my research to determine these relationships between morphology and protection strategy are: 1.) Ho – There are no significant differences in erosion rate among sites or shoreline types. 2.) Ho - There are no significant differences in erosion rate among sites with different fetch distances. 3.) Ho – There are no significant differences in shoreline slope between sites or shoreline types. 4.) Ho - There are no significant differences in shoreline slope among sites with different fetch distances. 5.) Ho – Erosion rates and shoreline slope have no direct relationship to each other.

CHAPTER II: METHODOLOGY

Study Locations

This study occurred at six different sites along the coast of AL and MS. Each of the six sites has a hardened (HS), living (LS), and natural shoreline (NS) segment. In total there were 18 different shoreline segments to compare to each other for erosion distances and slope profiles. The relative wave energy at the sites was determined using maximum fetch distance as a proxy of exposure. Two of the sites were classified a priori as having long wave fetch, two represented medium wave fetch, and the remaining two represented short wave fetch distances. The high energy (long fetch) sites are the Swift Tract Project at Bon Secour Bay in AL and the Hancock County Marsh Project at Heron Bay in MS. The medium energy (medium fetch) sites are Camp Wilkes in MS and Alonzo Landing in AL. The two low energy (short fetch) sites are Ocean Springs Inner Harbor and Bayou Heron, Grand Bay National Estuarine Research Reserve both located in MS (Figure 1). There were two types of data collected at each site, (1) shoreline erosion rates and (2) shoreline slope, both of which are potentially influenced by fetch distance.

Figure 1. Map of the six study site locations in AL and MS. Two sites each represent high, medium, and low wave energy respectively. Each site has three shoreline types (natural marsh, living shoreline, and hardened shoreline).

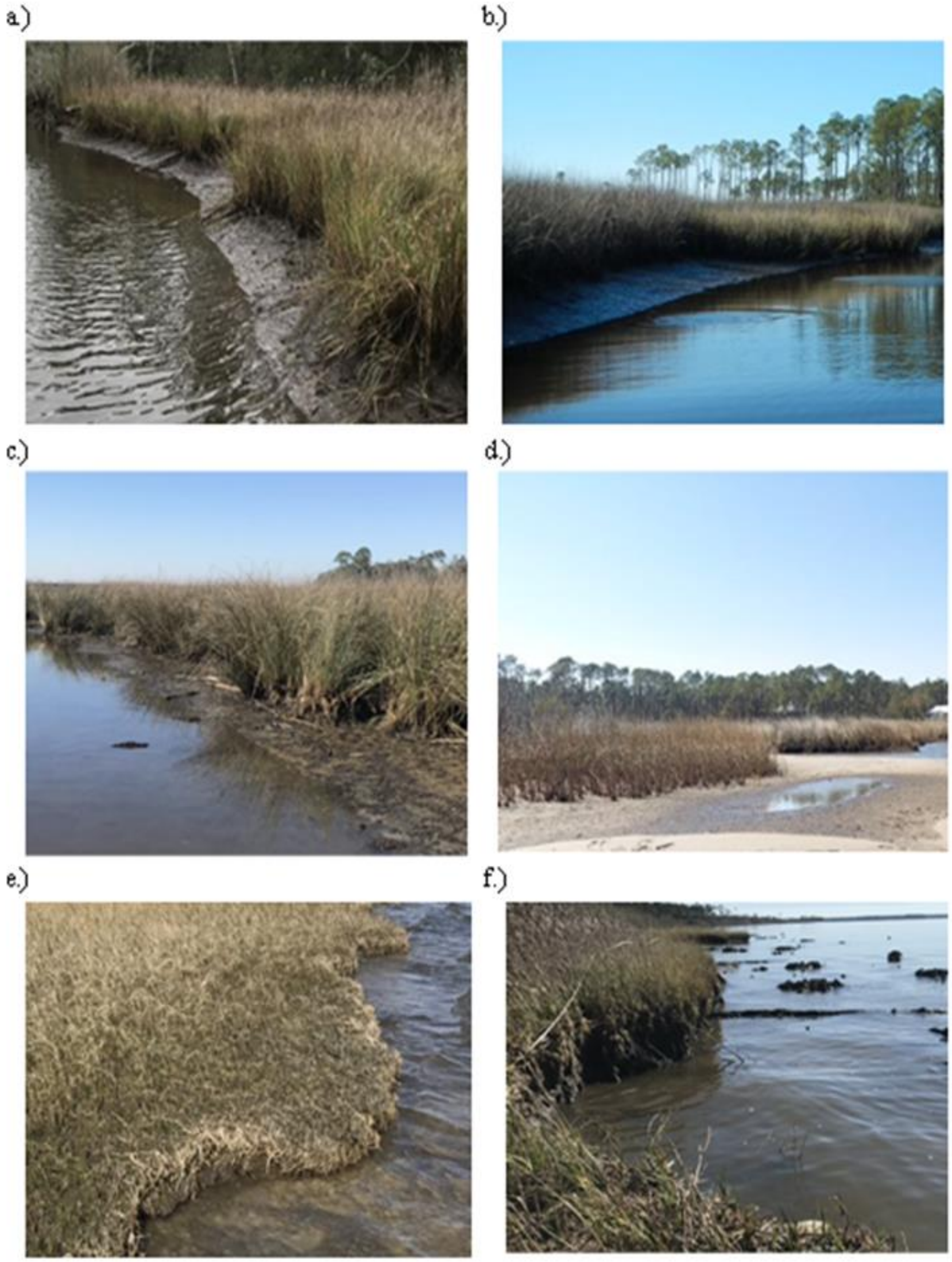

Figure 2. Images of the Natural Shorelines (NS) were taken either on the day of elevation surveying or on previous fieldwork days. Panels are a.) Ocean Springs, b.) Grand Bay, c.) Camp Wilkes, d.) Alonzo Landing, e.) Hancock County, f.) Swift Tract.

Figure 3. Images of the Living Shorelines (LS) were taken either on the day of elevation surveying or on previous fieldwork days. Panels are a.) Ocean Springs, b.) Grand Bay, c.) Camp Wilkes, d.) Alonzo Landing, e.) Hancock County, f.) Swift Tract.

Figure 4. Images of the Hardened Shorelines (HS) were taken either on the day of elevation surveying or on previous fieldwork days. Panels are a.) Ocean Springs, b.) Grand Bay, c.) Camp Wilkes, d.) Alonzo Landing, e.) Hancock County, f.) Swift Tract (picture is of a similar shoreline to the site studied).

Shoreline Erosion Rate Determination

Image Analysis and Georectification

In order to determine how erosion rates varied among the three shoreline types at the six sites, historical imagery was used to measure shoreline retreat over a span of ~30 years. This imagery was obtained from Google Earth Pro, which allowed the maps to be annotated to measure the shoreline retreat through time. To begin, the sites were geolocated and GPS coordinates of both ends of the surveyed shoreline were recorded. The distance of the surveyed shorelines varied from ~100 m–110 m to ~40 m–60 m depending on the site (G. Spellmann, pers comm.). This range was due to physical constraints when surveying the shoreline, and the varying lengths of the living and hardened components at each of the sites. Once the site was geolocated, a tracing of the shoreline in that year was drawn using the path tool for each of the four desired years at each of the 18 shorelines. The four years chosen in this study were 2019, 2011, 2005, and 1992. The years 1992 and 2019 were chosen because they were the earliest and latest years available for the majority of the sites in the Google Earth database. The years 2011 and 2005 were used as intermediate time point markers to determine if erosion rates differed depending on the 'decade'. The 'decade' was the span of time between each image and not a 10-year period. Some decade lengths varied for certain sites either because the image was too blurry to discern where the shoreline was located, the image had cloud-cover obscuring the shoreline, or the year's image was not available in the database. For instance, at the Hancock County Marsh site the year 1989 was used because there was no 1992 image available. At the Swift Tract and Grand Bay site the

year 2006 was used instead of 2005, as the image was either unavailable or was too blurry to get a proper tracing of the shoreline.

The shoreline was traced between the two pinned GPS points surveyed at each site previously in winter/spring 2020 (G. Spellmann pers comm). When possible, images in the summer months were chosen, as almost all years had a clear summer image to use and vegetation was more readily apparent than during the winter months. When doing the tracing, the point where the water meets the sediment was followed. In some cases, the vegetation line had to be followed as trees planted along the property obscured the actual shoreline. If there was no sediment or vegetation visible in front of the HS, the hard substrate was followed. This tracing process was done at all six sites, for all three shoreline types, for all four years (6 sites x 3 shoreline types at each site x 4 years studied = 72 tracings in total).

Next, baselines were created in Google Earth to provide a framework to follow when measuring the shoreline retreat over decades, following the general methods outlined in the United States Geological Survey (USGS) Digital Shoreline Analysis System (DSAS) – DSAS approach (Himmelstoss *et al.,* 2018). This was done to lessen measurement error and bias when choosing points to measure the distance between tracings. In some cases, alternate baselines had to be created to correct for misalignment issues in certain images. For more details about this process please refer to Appendix A.

Shoreline Erosion Rate Analysis

The distance between the back baseline and the decadal shoreline tracings was then measured along each of the four transects, for all four timepoints (72 shoreline tracing x 4 replicate transects = 288 length measurements). Subsequently, at each

individual transect the difference between the shoreline lengths was calculated for the three separate ‘decades’ and for the overall change over 27 years. The three decades were 1992-2005 (13yrs), 2005-2011 (6yrs), and 2011-2019 (8yrs). The difference between the years along each of the transects represents the erosion (positive value) or progression (negative value) of that shoreline. The average erosion rate per year was then calculated for each transect in the three ‘decades’ as well as over the entire 27 years. These erosion rate values per transect were imported into SPSS to perform one-way ANOVA tests to determine if there was any significant difference between factors. The factors considered were wave energy, decade, and treatment type.

Data were tested for assumptions of normality using Shapiro-Wilk’s statistic and Q-Q plots, and homoscedasticity using the Levene test. Most data met these assumptions, with the exception of the prograding shoreline at the Hancock County Marsh site, which formed a large outlier to the remaining data points and was excluded from subsequent analyses. Significant ANOVA results were accepted with an alpha value of <0.05. Post-hoc tests using Tukey’s HSD test were conducted after a significant finding to determine groups with similar means.

Shoreline Slope Determination

Elevation Data

At each of the 18 locations two transects were laid perpendicular to the shoreline to be assessed for elevation change. Two different GPS points along the shoreline were established as the mid-point of the transects, located at the current water level on the day of sampling. This mid-point became the reference (0 m) elevation for that transect. The GPS coordinates of the spot were recorded, and the tidal stage during sampling was

obtained from tide charts and NOAA water level gauges (e.g., https://tidesandcurrents.noaa.gov/stationhome.html?id=8741533) at the time of data collection.

In the field, the ends of the transect were marked by PVC posts with a 20m transect tape extending between the two end posts. Using a ruled H-frame and level, the elevation relative to the reference (set as 0m) midpoint was recorded every 1m along the transect line (Figure 5). The maximum distance recorded was 10 m inland (upslope) and 10 m offshore (downslope). However, this distance was subject to change depending on site conditions and water depth. If water depth exceeded 1.5 m the transect was stopped at that location. The H-frame used consisted of two vertical poles set 1m apart with a level attached to the horizontal pole connecting them (Figure 5). One leg of the H-frame was fixed while the other leg was marked at 1cm intervals with the ability to move up and down within the frame. The fixed leg was first placed on top of the sediment, at the reference mid-point. The ruled leg was then set on the ± 1 m point of the transect. Next, the connecter pole was adjusted until the level, attached to the horizontal pole, was level. The difference between the two legs' positions, indicated by the ruler on the sliding leg, was then recorded. The vegetation and sediment found at the spot were also recorded. The framework was then moved along the transect so the fixed leg was on the ± 1m spot and the ruled leg was on the ± 2m spot to be measured. This was repeated along the whole ± 10 m transect (site permitting) starting from the original mid-point and extending in either the upslope or downslope direction in order to obtain elevation data along the whole 20m transect. This process was done twice at all six sites, for all three shoreline

types (6 sites x 3 shoreline types at each site x 2 transects studied = 36 elevation transects in total).

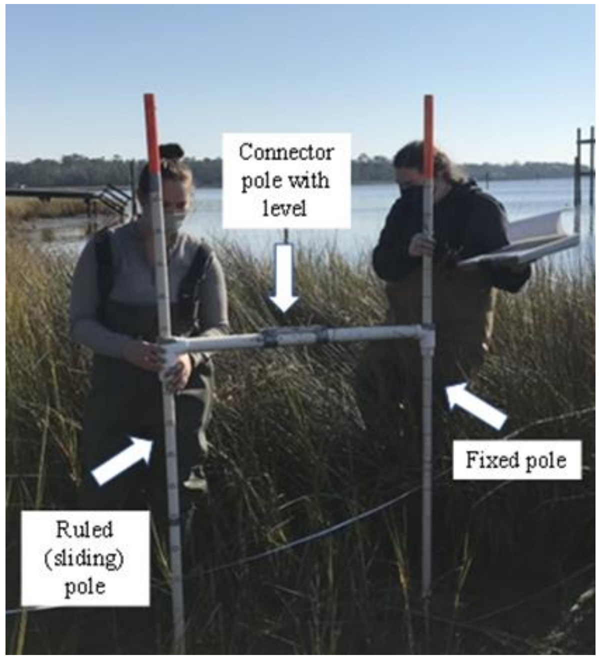

Figure 5. Image of the H-frame used to measure elevation change along transects. The labels on the image show the fixed pole, the ruled (sliding) pole, and the connector pole.

Elevation Data Analysis

The field transect data, which had previously displayed the differences between each 1m mark, was corrected relative to the 0m midpoint elevation measurement. This allowed the data to be plotted so the elevation profile could be seen for all transects with the mid-point set on the axis at 0cm. The slope was then calculated for each transect at different distances from the 0m origin. It was decided that the slope calculated from the +3 m point to the -3 m point was the most representative of the shoreline slope as this distance best accounted for the hardened and living shoreline elements right along the shore. This length also encompasses the expanse of the shoreline that is most affected by waves and tidal patterns, as AL and MS do not experience extreme tides (apart from

storm conditions). The slopes for each transect were then imported into SPSS so ANOVA tests could be performed to test for significance. The factors considered were wave exposure, and treatment type. Significant ANOVA results were accepted with an alpha value of <0.05. Post-hoc tests using Tukey's HSD test were conducted after a significant finding to determine groups with similar means.

Correlating Shoreline Slope and Erosion

Linear regression models were created to visualize the relationship between erosion rates determined from decade three (2011-2019) and slope measured in December 2020. The average erosion rate and average slope for each site were compared to each other for the three treatment types. The linear equation and the R^2 value were determined for each treatment type. The LS and HS regression lines were calculated with five sites instead of the original six. This is because all Hancock County shores either acted as NS or were considered outliers in the erosion data due to construction. In 2011, the Hancock LS was built up with vegetation ~130m offshore with a Geo-tube lining the edge of the shoreline, causing the site to be an outlier. The Hancock HS has a hard element that juts out ~45 degrees from the shore. This component was not added until recently, so erosion rates were measured on a NS parallel to where the hard structure was eventually placed.

CHAPTER III: RESULTS

Fetch Distances

Fetch distances were recorded at each shoreline to determine if they supported a priori groupings where two of the sites were classified as have long wave fetch, two represented medium wave fetch, and the remaining two represented short wave fetch distances (Table 1). While lengths do seem to lump together into low, medium, and high exposure categories, post-hoc groups suggest that instead of three categories there are two groupings (a low-medium and a high exposure group) as there was not enough of a difference between the a priori low and medium groupings. It should be noted that all other analyses performed were done with three fetch length categories.

Table 1.

The maximum fetch distances for the three shoreline types at each of the six sites. Max fetch average is the mean of all three shoreline types. Fetch avg is the mean of all 16 cardinal direction fetch vectors for that site. Tukey's subsets indicate significance among sites' fetch average.

Site	NS max fetch	LS max fetch	HS max fetch	Max fetch avg	Fetch avg
Ocean Springs	108.17 m	225.16 m	197.55 m	176.96 m	71.78 m^a
Grand Bay	45.06 m	189.51 m	86.47 m	107.01 m	46.05 m^a
Camp Wilkes	1252.10 m	318.05 m	1045.30 m	871.82 m	281.46 m^a
Alonzo Landing	245.54 m	43.19 m	260.41 m	183.05 m	107.22 m^a
Hancock County	34607 m	20710 m	27626 m	27647 m	11689 m^b
Swift Tract	34951 m	8186.80 m	28495 m	23878 m	9605.50^b

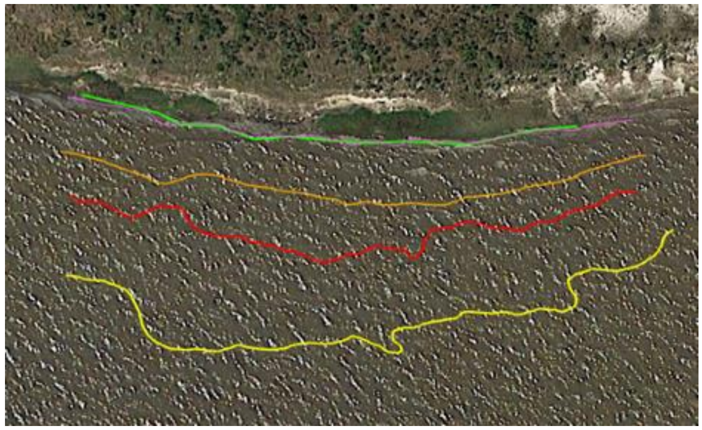

Figure 6. Tracings for the Hancock County NS for the three different decades sampled. The yellow tracing is the 1992 shoreline, the red is 2005, the orange is 2011, and the green/pink is the 2019 shoreline.

Shoreline Erosion Rates

Mean erosion rates were highest in the Natural Shoreline (NS) type in all three decades (Table 2), and lowest in the Hardened Shoreline (HS), with the Living Shoreline (LS) intermediate. Shoreline erosion rates were lower in decade 2 (2005-2011) compared to earlier and later time periods (Table 2). Mean erosion rates increased with fetch distance. When separated by shoreline type, erosion rates were most affected by fetch exposure at NS and least affected at HS, with LS intermediate. An example of how shoreline retreat looked in the program used with the tracings is shown in Figure 6.

ANOVAs were performed to test for significance for main factors (decade, shoreline treatment) and results tables are provided in Appendix B. Over all three decades, the erosion rates for the three shoreline treatment types were found to have a significant difference ($p < 0.000$) to one another (Table 2, Table B.1). The HS displayed the least amount of shoreline retreat with an average of 0.0290 meters lost per year, LS had an average erosion of 0.1824 m/yr, and NS showed the highest erosion rate at 0.7194 m/yr. Shoreline treatment effectiveness was then evaluated by comparing decadal

erosion rates to determine if the rates changed significantly after the living element was added. It is important to note that when looking at decadal change, decade 2 (2005-2011) was found to be an outlier in all tests. There was a significant difference ($p < 0.000$) in rates from decade 2 to both decade 1 and decade 3, which were not different from each other (Table B.2). Therefore, when making the comparisons to determine if element installation was effective over time only decade 1 and decade 3 were compared. This ANOVA showed that there was no significant difference between decade 1 and decade 3 erosion rates for the three shoreline types. The LS sites had a trend with higher erosion in decade 1 (0.3215 m/yr), than in decade 3 (0.3013 m/yr), but this was not significant ($p = 0.854$) (Table B.3). The opposite trend was found for NS, where decade 3 (0.8588 m/yr) had higher erosion than decade 1 (0.7447 m/yr). Assuming the NS represents a control for the average shoreline erosion at the LS sites, these results suggest that the addition of the LS element contributed to slowing erosion rates. When comparing specific sites, the LS at the Swift Tract location (site 6) had marginally lower erosion rates after the installation of a LS breakwater element (Figure 7). The rate decreased from 0.9455 m/yr in decade 1 to 0.416 m/yr in decade 3. No other site had as drastic a reduction from decade 1 to decade 3 (Figure 7).

ANOVA tests were performed to determine if different shoreline treatments influenced erosion rates within the three fetch exposure categories. The erosion rates in the three fetch categories were significantly different ($p < 0.000$) from each other when all shoreline treatments were combined, with low energy sites having the lowest erosion rates (0.0583 m/yr) and high energy sites having the highest rates (0.7552 m/yr) (Table.B.4). Hardened shorelines did not show a difference ($p = 0.765$) in erosion rates

as a function of fetch exposure, with a mean erosion rate of 0.0256 m/yr across all sites (Table B.5). In contrast, NS did show a significant difference ($p < 0.000$) with erosion rates of 0.1400 m/yr for low, 0.6895 m/yr for medium, and 1.0850 m/yr for high fetch exposure respectively, following the pattern of increasing erosion with increasing fetch mentioned previously (Table B.6). Living shorelines followed this same pattern, however, there was no significant difference between medium (0.2642 m/yr) and high energy sites (0.4020 m/yr), which were both higher than the lower energy sites (-0.0079 m/yr) ($p < 0.002$) (Table B.7). Tukey's subsets show that a majority of the low wave exposure sites, for all treatment types, were grouped together with lower erosion rates when rates were separated into the three decades (Table 3). In contrast, high fetch exposure sites were often grouped together with higher erosion rates, with the exception of HS that experienced minimal erosion (Table 3). In should be noted that the Camp Wilkes LS negative erosion rate in decade 2 was likely due to measurement error arising from image georectification problems (Table 3).

Table 2.

The mean ± S.D. erosion rate within each of the three decades for all shoreline types. All decadal HS rates do not include Hancock County. Decade 3 LS rates do not include Hancock County. Tukey's subsets are within each decade.

Decade Surveyed	NS rate	LS rate	HS rate
Decade 1 (1992-2005)	0.74 ± 0.603^{a}	0.32 ± 0.385^{b}	0.06 ± 0.099^{b}
Decade 2 (2005-2011)	0.55 ± 0.437^{a}	-0.07 ± 0.271^{b}	0.02 ± 0.159^{b}
Decade 3 (2011-2019)	0.86 ± 0.759^{a}	0.30 ± 0.299^{b}	0.01 ± 0.135^{b}

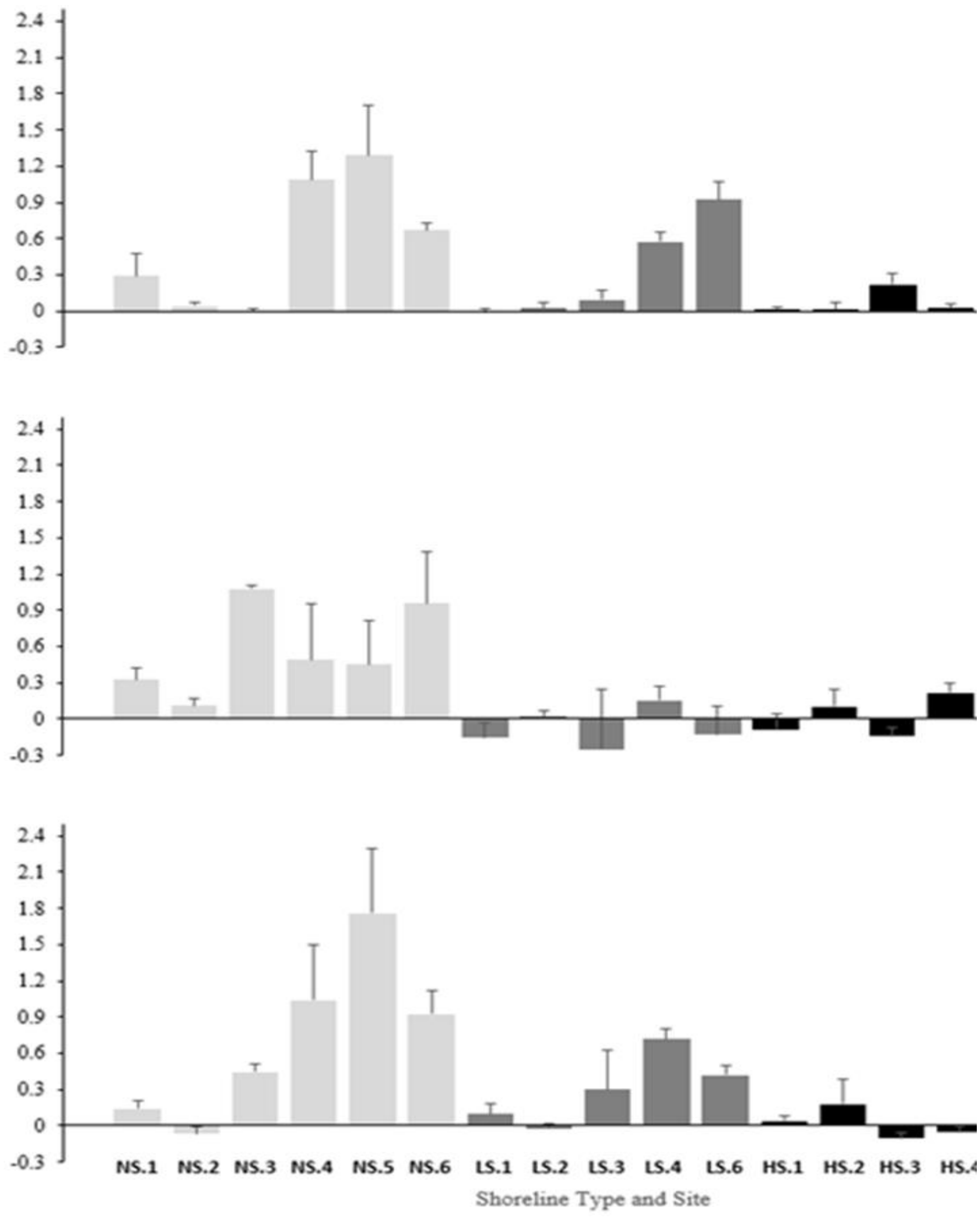

Figure 7. Mean erosion rate + S.D. by the shoreline type and site evaluated over three decades. Panel (a) is decade 1 (1992-2005), (b) is decade 2 (2005-2011), (c) is decade 3 (2011-2019). Shoreline types were natural (NS), living (LS), or hardened (HS) and site is numbered as Ocean Springs (1), Grand Bay (2), Camp Wilks (3), Alonzo Landing (4), Hancock County (5), and Swift Tract (6). Hancock County does not have an erosion rate for a living or hardened shoreline.

Table 3.

The average erosion rate (m/yr) ± S.D. for each of the three decades, six sites, and three shoreline types - natural (NS), living (LS), or hardened (HS) shoreline. Tukey's subsets are between all shoreline types by sites combined within each decade. N/A indicates sites where there is no data available.

Site	NS rate	LS rate	HS rate
Decade 1 (1992-2005)			
Ocean Springs	0.28 ± 0.185^{abc}	-0.01 ± 0.038^{a}	0.01 ± 0.022^{a}
Grand Bay	0.04 ± 0.033^{a}	0.02 ± 0.046^{a}	0.02 ± 0.060^{a}
Camp Wilkes	-0.01 ± 0.029^{a}	0.10 ± 0.079^{ab}	0.22 ± 0.087^{abc}
Alonzo Landing	1.09 ± 0.232^{ef}	0.57 ± 0.075^{bcd}	0.03 ± 0.034^{a}
Hancock County	1.29 ± 0.414^{f}	N A	N A
Swift Tract	0.67 ± 0.055^{cde}	0.92 ± 0.144^{def}	0.01 ± 0.060^{a}
Decade 2 (2005-2011)			
Ocean Springs	0.32 ± 0.095^{abcd}	-0.16 ± 0.123^{ab}	-0.08 ± 0.126^{abc}
Grand Bay	0.11 ± 0.055^{abc}	0.02 ± 0.051^{abc}	0.10 ± 0.150^{abc}
Camp Wilkes	1.07 ± 0.216^{e}	-0.25 ± 0.489^{a}	-0.14 ± 0.070^{abc}
Alonzo Landing	0.49 ± 0.465^{cde}	0.15 ± 0.113^{abc}	0.21 ± 0.0776^{abc}
Hancock County	0.45 ± 0.370^{bcde}	N A	N A
Swift Tract	0.96 ± 0.419^{de}	-0.13 ± 0.243^{abc}	0.02 ± 0.064^{abc}
Decade 3 (2011-2019)			
Ocean Springs	0.14 ± 0.062^{ab}	0.10 ± 0.089^{ab}	0.04 ± 0.041^{a}
Grand Bay	-0.07 ± 0.056^{a}	-0.02 ± 0.033^{a}	0.18 ± 0.208^{ab}
Camp Wilkes	0.44 ± 0.069^{abcd}	0.30 ± 0.327^{abc}	-0.11 ± 0.052^{a}
Alonzo Landing	1.04 ± 0.463^{cd}	0.71 ± 0.092^{bcd}	-0.06 ± 0.053^{a}
Hancock County	1.76 ± 0.528^{e}	N A	N A
Swift Tract	0.93 ± 0.193^{cd}	0.42 ± 0.077^{abcd}	-0.01 ± 0.031^{a}

Shoreline Elevation Change

Wave level information was recorded on the day elevation profiles were measured at each site (Table 4). Mean shoreline slope measured in winter of 2020 was highest at the HS sites, followed by NS and then LS sites with smallest elevation change within ± 3m of the water line (Figure 8, Table 5). The elevation profile of all three shoreline types at the six sites was created using the average of the two duplicate transects' elevation change at each shoreline (Figure 9). A drastic elevation difference is seen (Figure 8b)

due to the LS element at the site. This element was a large Geo-tube placed in front of the shoreline after the shore was built up ~130m offshore in 2011.

Table 4.

Water level information for the field day that the elevation transects were surveyed. Tidal data was retrieved using the MLLW datum from station 8741533 at the Pascagoula NOAA Lab, Pascagoula, MS.

Site	Date Surveyed	Time Range of Survey	Low Tide	High Tide
Ocean Springs	12/08/20	~9:00am -- 12:00pm	0.04 ft @ 2pm	0.73 ft @ 9am
Grand Bay	12/16/20	~10:00am – 12:30pm	-0.29 ft @ 2pm	2.46 ft @ 4am
Camp Wilkes	12/09/20	~10:00am -- 1:00pm	-0.10 ft @ 2pm	0.51 ft @ 4am
Alonzo Landing	12/15/20	~10:00am – 12:30pm	-0.85 ft @ 2pm	1.76 ft @ 5am
Hancock County	12/11/20	~10:30am – 3:00pm	0.14 ft @ 10am	1.73 ft @ 11pm
Swift Tract	12/17/20	~10:00am – 3:30pm	-0.49 ft @ 4pm	2.05 ft @ 5am

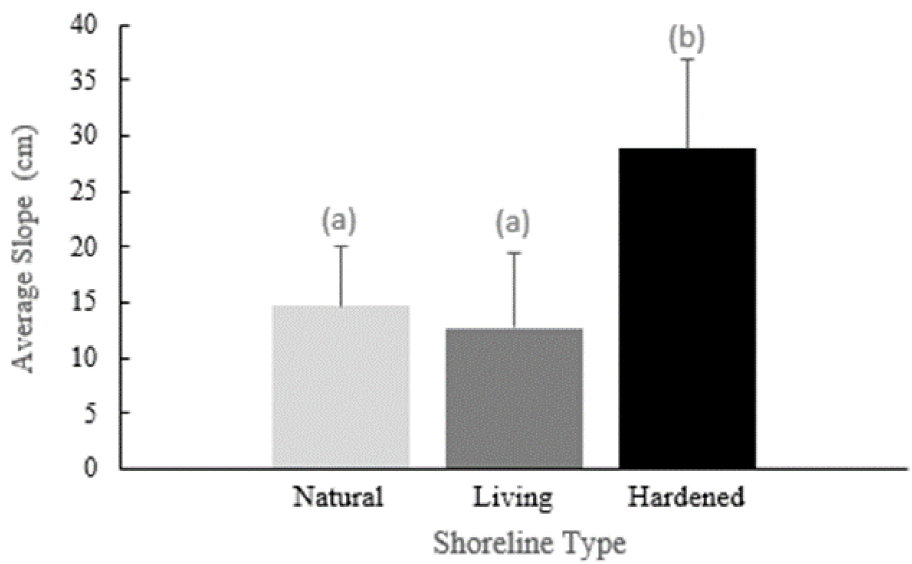

Figure 8. The average slope (cm/m) + S.D. of the three shoreline types evaluated for all six sites combined.

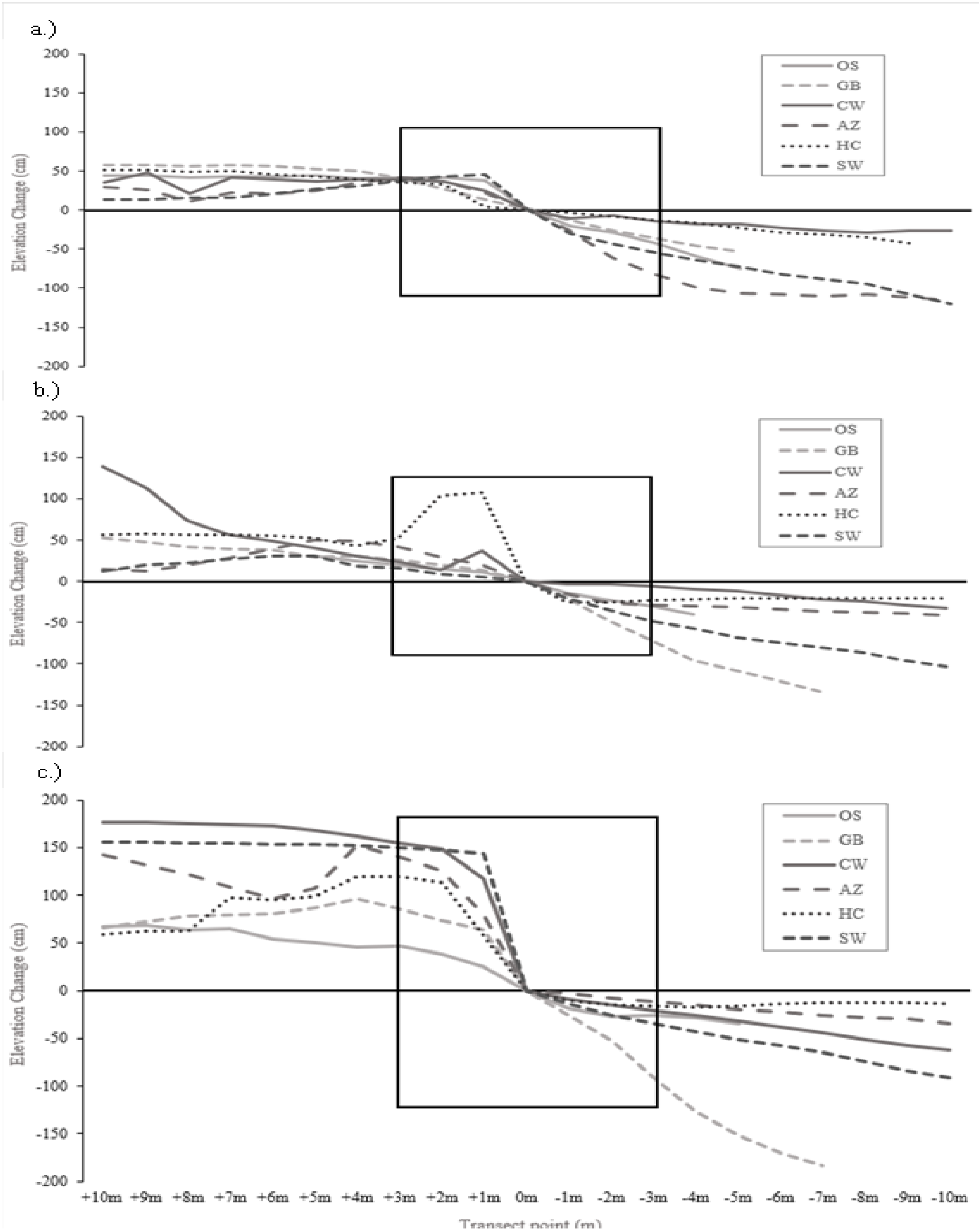

Figure 9. Elevation profiles along the 20m transects evaluated in the field. Panel a.) NS profiles, b.) LS profiles, c.) HS profiles surveyed at the six sites. A box was drawn around the sites' profiles from -3m to +3m to show the part of the transect that was used for subsequent analysis. The sites surveyed are Ocean Springs (OS), Grand Bay (GB), Camp Wilks (CW), Alonzo Landing (AL), Hancock County (HC), and Swift Tract (SW).

Mean slopes of the duplicate elevation transects (Figure 8) were compared using ANOVA tests to determine if elevations significantly differed between fetch exposure and shoreline treatment types. It was found that low, medium, and high fetch exposure did not have a significant impact on the slope of the transects surveyed ($p = 0.598$) (Table B.8). ANOVA showed that elevation was affected by treatment type ($p < 0.000$). The HS (28.869 cm) had a significantly steeper slope then the NS (14.619 cm) and LS (12.699 cm), which grouped together (Figure 8, Table B.9). While all LS were determined to not be significantly different to NS, post-hoc analysis showed that all LS grouped together and had the gentlest slopes when all shorelines were compared (Table 5, Table B.10).

Table 5.

The average slope (cm) ± S.D. for each of the six sites and three shoreline types - natural (NS), living (LS), or hardened (HS) shoreline. Tukey's subsets are between the six sites within each of the three treatment types.

Site	NS mean (cm)	LS mean (cm)	HS mean (cm)
Ocean Springs	16.05 ±0.681^{ab}	8.96 ±3.283^{a}	14.10 ±2.171^{a}
Grand Bay	11.98 ±0.076^{ab}	15.75 ±2.071^{a}	32.03 ±0.404^{bc}
Camp Wilkes	10 ±1.56^{a}	5.76 ±4.066^{a}	35.07 ±1.616^{bc}
Alonzo Landing	22.12 ±6.54^{b}	12.76 ±3.005^{a}	28.75 ±5.001^{bc}
Hancock County	8.85 ±0.91^{a}	21.98 ±12.399^{a}	26.14 ±-0.101^{b}
Swift Tract	18.69 ±0.43^{ab}	10.96 ±0.656^{a}	37.10 ±1.767^{c}

Slope vs. Erosion

The averaged slopes and decade 3 erosion rates for each site were plotted together in a linear regression model to illustrate the interaction between the two variables by shoreline treatment type. The regression model shows that as the HS' slopes decreased the erosion rates increased (Figure 10). However, the R^2 value was -0.0391, suggesting

that this negative relationship between the slope and erosion rate is not very strong (Table 6). The NS and LS' regression suggests there is no relationship between slope and erosion rate at these sites, as both have a R^2 value < 0.00.

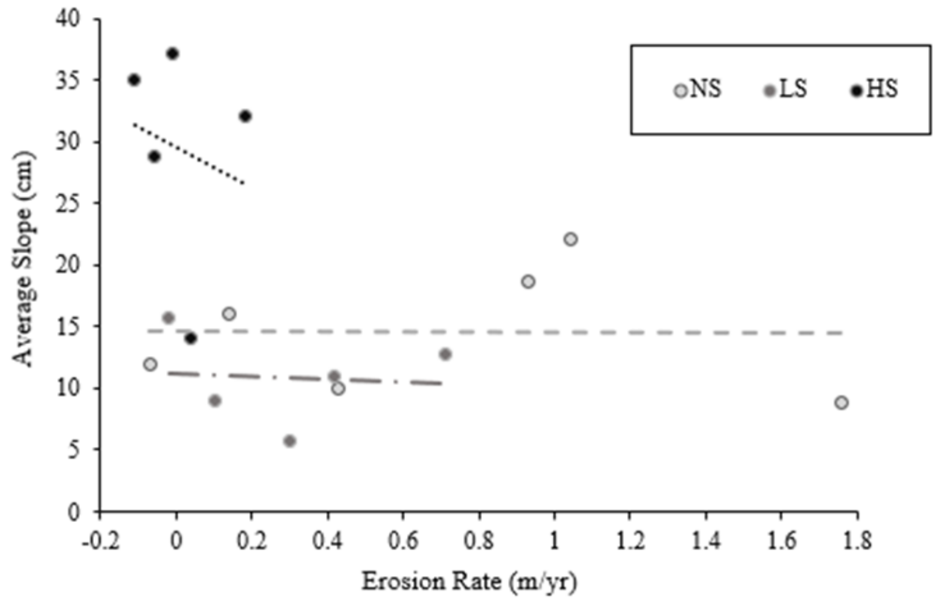

Figure 10. The regression between each shoreline's average erosion rate and slope with points separated into treatment categories. Shoreline types are natural = NS, living = LS, hardened = HS. Both the LS and HS' regression line was determined with five sites instead of the original six because all Hancock County shores either acted as natural shorelines or were considered outliers in the erosion data due to construction.

Table 6.

The linear regression equation and R^2 value calculated for the three shoreline types - natural (NS), living (LS), and hardened (HS) shoreline.

Treatment Type	Linear Equation	R^2
Natural (NS)	Y= -0.059x + 14.662	0.0001
Living (LS)	Y= -1.199x + 11.204	0.0082
Hardened (HS)	Y= -16.218x + 29.544	-0.0391

CHAPTER IV: DISCUSSION

Shoreline Geomorphology

Along the shores of the Gulf of Mexico erosion rates have begun to steadily increase in the past few decades (Davis, 1997). This has caused shorelines' shape and slope to change as environmental pressures have increased. For example, shoreline slopes can be seen increasing dramatically due to natural marsh edge erosion resulting in cut banks instead of a more natural gradual shoreline slope. This change can cause shoreline instability, with uprooting of marsh vegetation and thereby a further increase in erosion from this undercutting and the resulting lack of a natural vegetation buffer. This is a concern to not only natural systems, but also to human communities that live in coastal zones and which depend on the coast for income (Bilkovic & Mitchell, 2013; Bryars *et al.*, 2016).

Several hypotheses were tested throughout the study to provide information on how erosion rates and elevation change differ among these three shoreline types. The null hypothesis that there are no significant differences in erosion rates among sites or shoreline types was proven false as erosion rates increased at all sites through Hardened Shoreline (HS)-> Living Shoreline (LS) -> Natural Shoreline (NS). The null hypothesis that there are no significant differences in erosion rates among sites with different fetch distances was also proven false as erosion increased through low->medium->high fetch exposure sites. However, post-hoc tests suggest that the sites tested fall into two categories (low/medium or high fetch exposure) as opposed to three categories. As all prior tests were performed with three exposure categories instead of two, the conclusion that erosion increases with energy could be skewed due to uneven groupings. The null

hypothesis that there are no significant differences in shoreline slope among sites or shoreline types was proven false as HS were shown to have steeper slopes. The null hypothesis that there are no significant differences in shoreline slope among sites with different fetch distances was accepted. The null hypothesis that erosion rates and shoreline slope have no relationship to each other could not be rejected in the case of NS and LS, and the relationship between erosion rate and slope was not strong for HS.

Mean erosion rates were lowest in the HS in all three decades studied. Hardened structures are designed to be stationary and not change over time unless storm damage occurs and the HS element is damaged or destroyed (Bryars *et al.,* 2016). Even then, the structure frequently is rebuilt in the same location. Mean erosion rates were highest in the NS type, with the LS as the intermediate between the NS and HS rates. The purpose of installing a LS is to reduce the rate of erosion by either providing a buffer against waves or by facilitating the establishment of plant and root systems to trap sediment (Bryars *et al.,* 2016). In comparison, NS are fully exposed to waves and have no added protection which may explain why NS had the highest erosion rates in my study. The data for AL and MS indicates that LS could be an effective technique to mitigate erosion as opposed to leaving the NS as is, given the high erosion documented.

The decadal erosion rate data supports the idea that implementing LS techniques makes a quantitative difference in shoreline condition relative to unprotected NS. Decadal erosion rates were compared to test treatment effectiveness (NS -> LS) to determine if the rates changed significantly after the living shoreline element was added. In this comparison decade 2 (2005-2011) was excluded as it was found to be an outlier in all significance tests. This could potentially be because Hurricane Katrina (August 2005)

hit the northern Gulf Coast, which caused major changes to shoreline morphology throughout the study area. Therefore, when making the comparisons to determine if LS element installation was effective over time, only decade 1 and decade 3 were compared. The results showed that, while not significant, LS sites had higher erosion in decade 1 (before installation) than in decade 3 (after installation). The opposite trend was found for NS, where decade 3 had higher erosion rates than decade 1. Assuming NS acts as a control for the average erosion at the sites, these results suggest that the addition of LS elements contributed to slowing erosion rates. When comparing specific sites, the LS at the Swift Tract location (site 6) had lower erosion rates from decade 1 to decade 3 after the installation of a LS breakwater element. No other site had as drastic a reduction from decade 1 to decade 3. This could suggest that implementation of LS has a greater impact at high energy sites. However, the second high energy site (Hancock County) LS was excluded from analysis due to it being an outlier. It was found to be an outlier because the contractor built up the shore ~130m out from the prior eroded marsh in 2011. Because of this site exclusion there is not enough replication to say with certainty that LS function better at shores with higher fetch exposure. The results over all sites also showed that mean erosion rates increased with fetch distance. This aligns with prior research that indicates wave energy is one of the driving forces behind erosion rates (Davis, 1997). Within each treatment category (NS, LS, HS) erosion rates had varying dependency on wave energy. The HS did not show a difference in erosion rates as a function of fetch exposure. In contrast, both NS and LS erosion rates increased with fetch distance. However, LS erosion rates were not as dependent on fetch exposure in the medium and high fetch categories, as the rates were similar, compared to the low exposure category.

Mean shoreline slope within ± 3m of the water line was highest at the HS sites, followed by NS and then LS sites. The results showed that slope was not affected by fetch exposure as much as erosion rate, rather slope was strongly influenced by the height of the HS element. This could be because both AL and MS are known to have waves less than 0.75 m tall (Davis, 1997). This relatively small wave height could mean that a larger portion of the shore face is not in direct contact with the water at any given time point, causing slope differences to be minimal. However, slope was found to be dependent on shoreline type. The HS were found to have the steepest slope of the three shoreline types at all sites except for Ocean Springs. This difference was due to the type of structure implemented. At the Ocean Springs HS there were two bulkheads, the first was a failed bulkhead with a second one placed a meter behind it. Vegetation was present between the two bulkheads and in front of the failed bulkhead. The presence of the vegetation surrounding the failed bulkhead more than likely contributed to this site's low slope in comparison to other HS, as it caused the shoreline to act more like a hybrid structure. Regardless of Ocean Springs' smaller slope, overall HS had steeper slopes than both NS and LS. This finding aligns with the literature, as HS are designed to be a vertical structure that are often meant to stand above MHHW to stop water from reaching the shore behind the structure (Bryars *et al.,* 2016). Living Shorelines in contrast are designed to create gentle slopes as vegetation renourishment efforts have shown to be more successful on graded banks, which explains why this type has the smallest slope (Bryars *et al.,* 2016). Exceptions to this finding for LS designs are hybrid structures whose purpose is to fortify the shore by implementing natural barriers, like sandbags, to protect against high wave action (Bryars *et al.,* 2016).

The regression models of erosion rate to shoreline slope further demonstrate how HS are often built. The HS structure is designed to be a near vertical structure that stops or reflects waves from hitting the shoreline directly behind it (Bryars *et al.*, 2016). Their design is reflected in the negative relationship between slope and erosion rate, because the higher the HS structure the less likely waves (normal or storm related) are going to go over the structure (Bryars *et al.*, 2016). The regression models did not show any strong relationship between slope and erosion rates for both NS and LS. However, the scatterplot of data obtained provides a visual representation of the distribution for both slope and erosion observed. The LS site had a much narrower range of means for both variables compared to the NS, which suggests that LS are more stable.

It should be noted that some of the data or methods used for determining erosion rate and shoreline slope could be biased due to technology and resource constraints. For example, Google Earth historical imagery was used in this study as it was an open-source program that allowed for my data analysis. These images could have potentially been improperly georectified, which could have led to measuring errors. Steps were taken to limit these errors (selecting clearer dates and realigning the image), however, it is possible that spatial bias still occurred. Other errors could also be introduced from sampling errors in the field during the slope measurements, as some parts of the shoreline were inaccessible on foot. Results for slope data could also potentially be skewed due to only having two transects at each site. In the future, it could be beneficial to do similar analysis of shorelines with more transects or better historical data. Additionally, it could also be beneficial for researchers to incorporate wind and wave height/frequency data

into their analysis to obtain a clearer picture on the role of fetch distance directly on these shorelines.

Wider Implications

This study demonstrated that out of HS and LS, HS were the most effective of the two shoreline protection strategies at resisting erosion over the long-term. However, this study did not test for neighboring shoreline erosion, which is a known consequence of implementing HS, as it can strongly affect longshore sediment transfer (Bryars *et al.*, 2016). Employing HS could have detrimental effects on surrounding ecosystems by exacerbating local erosion and by destroying intertidal habitats with its construction (Bilkovic and Mitchell, 2013). These morphology changes to the shoreline have the potential to cause negative changes to natural abundances and diversity of flora and fauna in the area (Bilkovic and Mitchell, 2013). Additionally, while HS do protect the shore against wave action, they are often vulnerable to severe storm conditions that have the power to destroy the hardened structure (Gittman *et al*., 2014). The breaching of the HS structure is not only expensive to repair but can also cause major shifts to the surrounding sediment, furthering damage to the shoreline (Gittman *et al*., 2014). In comparison vegetated shores have the ability to recover naturally after a storm (Gittman *et al*., 2014). Considering these factors, while HS are effective at protecting the shoreline against erosion directly behind the structure, HS might not be the best choice when considering shoreline protection, as they can cause negative effects to surrounding areas. This study also demonstrates that alternative methods to armoring the shoreline are effective against erosion. The LS, while not able to reduce erosion as much as HS, were shown to be successful at resisting erosion when compared to NS. Combining the facts that LS can

increase natural functions and have the ability to adapt to changing sea levels, LS could be a better long-term investment when considering shoreline protection strategies.

Conclusions

With currents trends of intensifying global climate change and the threats, such as sea-level rise, it poses to aquatic ecosystems, research on shoreline morphology and its relationship to the environment is becoming more important. In this study I found that erosion rate was dependent on treatment type, with rates increasing from HS to LS, to NS. Erosion rates were found to increase with fetch exposure, with NS erosion rates being the most affected. In contrast, shoreline slope was found to not be significantly affected by fetch. However, the slope was dependent on treatment type, with slopes increasing from LS to NS, to HS.

This research is vital for the health of both natural environments and human communities as approximately 10% of the world's population resides in places that are considered threatened by loss of shorelines (Bilkovic & Mitchell, 2013). This study provides insight on the relationship between protection techniques and the shoreline's morphology by examining erosion rates and shoreline elevation. This type of information can be used by wildlife managers, planning committees, and homeowners to make more informed and sustainable decisions to better protect our coastlines.

APPENDIX A: IMAGE ANALYSIS AND GEORECTIFICATION

In order to determine how shoreline erosion rate varied among shoreline types and wave energies, historical imagery was used to measure shoreline retreat over a span of ~30 years. This imagery was obtained from Google Earth Pro, which allowed the maps to be manipulated to gain a better understanding of the shoreline retreat through time. To begin, the sites were geolocated and GPS coordinates of both ends of the surveyed shoreline were recorded. The distance of the surveyed shorelines varied from ~100m–110m to ~40m–60m depending on the site. This range was due to physical constraints when surveying the shoreline, and the varying lengths of the living and hardened components at each of the sites. Once the site was geolocated a tracing of the shoreline was drawn using the path tool for each of the four desired years.

The four years chosen in this study were 2019, 2011, 2005, and 1992. The year 2019 was chosen to represent the current shoreline as not all sites had viewable or clear images available in 2020. The year 1992 was chosen as the starting point in this study as it was the earliest year available in the Google Earth database. 2011 and 2005 were used as intermediate time point markers to determine if erosion rates differed depending on the 'decade'. There were some exceptions to the years used due to difficulties with the images provided. At certain sites, the image was too blurry to discern where the shoreline was, the image had cloud-cover obscuring the shoreline, or the year's image was not available in the database. For instance, at the Hancock County Marsh site the year 1989 was used because there was no 1992 image available. At the Swift Tract and Grand Bay site the year 2006 was used instead of 2005, as the image was either unavailable or was too blurry to get a proper tracing of the shoreline.

To draw the tracing along the shoreline segment, the desired year was first brought up using the history view function. In some cases, there were anywhere from 1-3 pictures available for the desired years. When possible, summer months were chosen as almost all years had a clear summer image to use. The line/path tool was then used to trace the edge of the shoreline along the length of land between the two pinned GPS points indicating the beginning and ending shoreline transect that was surveyed previously in winter/spring 2020 (G. Spellmann pers comm). The tracing was then colored and labeled for easy visibility. When doing the tracing, the point where the water meets the sediment was followed. In some cases, the vegetation line had to be followed as trees planted along the property obscured the actual shoreline. If there was no sediment or vegetation visible in front of the hardened shoreline then the hard substrate was followed. This tracing process was done at all 6 sites, for all 3 shoreline types, for all 4 years (6 sites x 3 shorelines types at each site x 4 year studied = 72 tracings in total).

Next, baselines were created in Google Earth to provide a framework to follow when measuring the shoreline (Figure A.1). This way each tracing could be compared to each other at the same point on the shore to determine how it changed throughout the years (Figures A.2 – A.4). This was done to lessen measurement error and bias when picking points to measure the distance from. To begin, a line connecting the previously pinned GPS Points was created for each shoreline using the ruler tool and saved as a path. The angle of the line was recorded and was labeled baseline.1 as it was the closest to the water. Exceptions were made in how baseline.1 was determined for the Hancock County living and hardened sites. At the Hancock living shoreline the baseline was moved about 130m inshore from where the shore is now in 2019. This is because when the living

element was installed in 2011 the contractor built up the shore further out from where the three other tracings were located. The baseline was shifted back to where the original shoreline was to accurately measure the other tracings. For the Hancock hardened shoreline, the hard element surveyed juts out ~45 degrees from the shore. This component was not added until recently, so the baseline was shifted to be parallel to the original shoreline to measure that change.

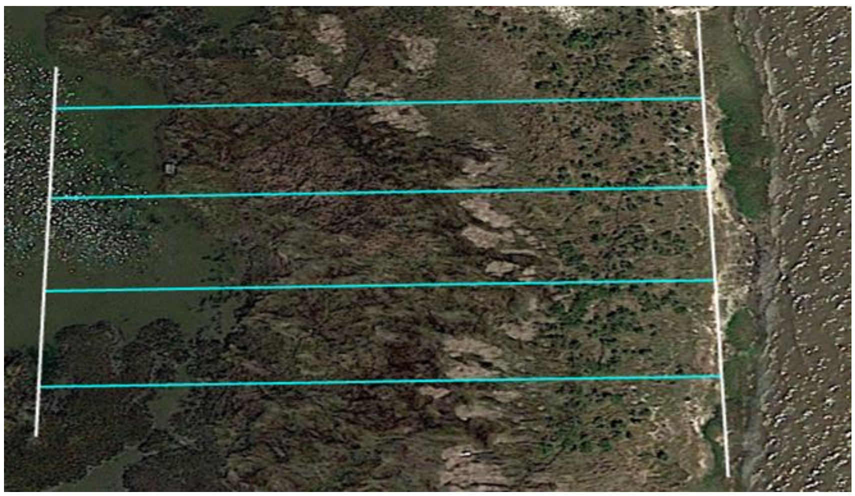

Figure A.1. Image depicting the baselines created in Google Earth Pro to measure the traced shorelines from thru the 4 time points. Baseline.1 is the white line closest to the water's edge on the right of the image, while baseline.2 is on the left. The blue lines are the transects, with transect.1 at the bottom of the image. This image was taken of the baseline for the natural shoreline at the Hancock County site.

Once baseline.1 was determined two perpendicular lines 100m in length were drawn going in the inshore direction. A second baseline was then created at this point with the same angle as baseline.1, creating a rectangular framework. If the area surveyed was larger than 80m than the inshore baseline (baseline.2) was drawn 80m long. If the shoreline surveyed was smaller than this, the back baseline was drawn at 40m. In all cases baseline.2 was drawn parallel to the center of the shoreline surveyed. Four

transects were then drawn connecting the two baselines. These transects were used as the points to measure the subsequent shoreline tracings from. The transects were decided based off of the fixed location of baseline.2. When drawing the transects and baselines all images were oriented to where the baseline.1 (the shoreline) was on the right, and baseline.2 (inshore) was on the left. If baseline.2 was 80m long then the placement of transect.1 on the baseline was determined by going 10m along baseline.2 from the bottom end of the line in the upward direction. This point 10m into the baseline.2 was called transect 1. For the following 3 transects they were measured in a similar fashion, going up baseline.2 when the image was oriented with the shoreline on the right. However instead of 10m the distance between all transects, the distance was now 20m. If the back baseline was 40m the same procedure was followed, except the first transect was found by only going 5m upward along baseline.2. The difference between the transects was changed to be only 10m. Once finished the baseline framework had a front and back baseline with 4 evenly spaced 100m long transects between them. This baseline procedure was repeated for each shoreline type, at each site. The distance between baseline.2 and the tracing for the year being evaluated was than measured along these 4 transects, for all year categories.

It should be noted that in some instances the baseline used had to be shifted for certain years at certain sites. This was due to alignment issues with the images at certain years, most likely due to georectification issues of the image on Google's end. If this was the case for one of the 4 images at a specific site, then the baseline was shifted to accommodate this misalignment issue. It was assumed that the most accurate image was from 2019 as it was the most recent. Therefore, the 'true' baseline was drawn in

accordance to where the 2019 image said the shoreline was. The other 3 years studied were than compared to this image to determine if there was an alignment issue. To do this, a hard structure that persisted through all images for the whole site or specific shoreline was identified to base the alignment issues off of. (When possible one structure was used as the anchor for the entire site at all 3 shorelines. However, some shorelines were too far away from each other to assume the alignment shift was true for all shorelines, so individual structures were determined). The structure was used if it had clean/easily identified lines and if it was unlikely to change or erode with time. When available, the structure used was within 100m of the shoreline measured. However, in some cases the structure had to be farther away as there was no other option. On average the outlier structures were 100-400m away. The farthest one was 4000m away from the living shoreline at Swift Tract. Once the anchor was identified, the structure in the 2019 image was outlined with the ruler function and then saved. These lines were used as the standard to compare the other image's structure edges too. To do this a clear distinguishable point on the 2019 structure was picked and a line was drawn to this same point on the other year's structure. The length and angle of the line drawn was then recorded. The line was drawn from the 2019 image to whatever year it was being compared to. This is because the line needs to show how the 2019 baseline changed in prior years in order to accurately apply the corrections to it later. This line was repeated at several other points along the structure to make sure the shift was accurate and represented the whole image. In the case where there was no clear point indicated the horizontal and vertical movement was recorded and the hypotenuse of the lines weas found. This line was then used to represent the shift of the shoreline. The finalized line's

length and angle was then drawn from the original baseline at each transects' end to show where the tracing should now be measured. A new baseline framework was then created to match the alignment shift for that year's image.

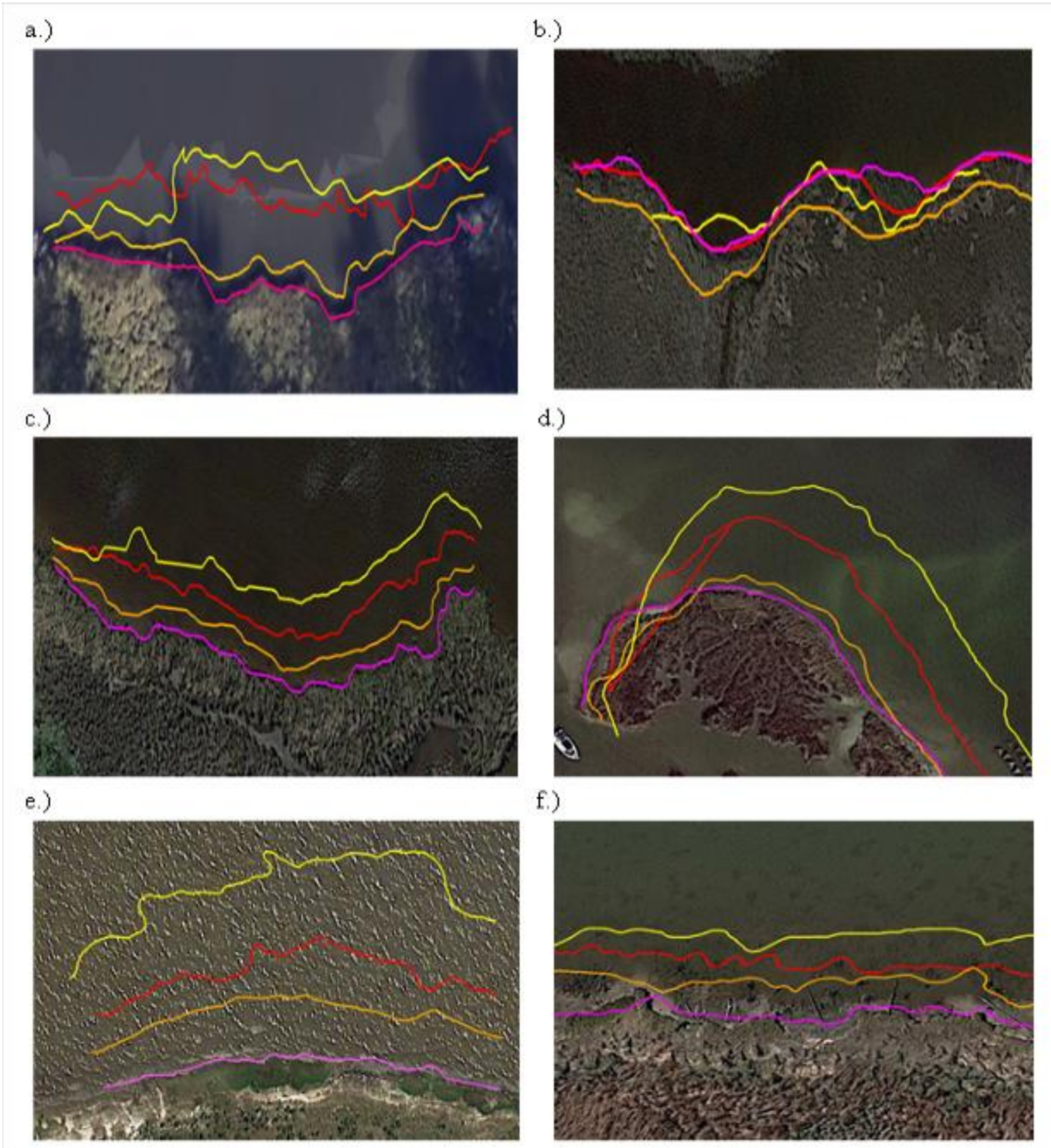

Figure A.2. Images of the Natural Shorelines (NS) tracings in Google Earth. It should be noted that some individual tracings are out of alignment Panels are a.) Ocean Springs, b.) Grand Bay, c.) Camp Wilkes, d.) Alonzo Landing, e.) Hancock County, f.) Swift Tract. Colors represent certain years: yellow (1992), red (2005), orange (2011), pink (2019).

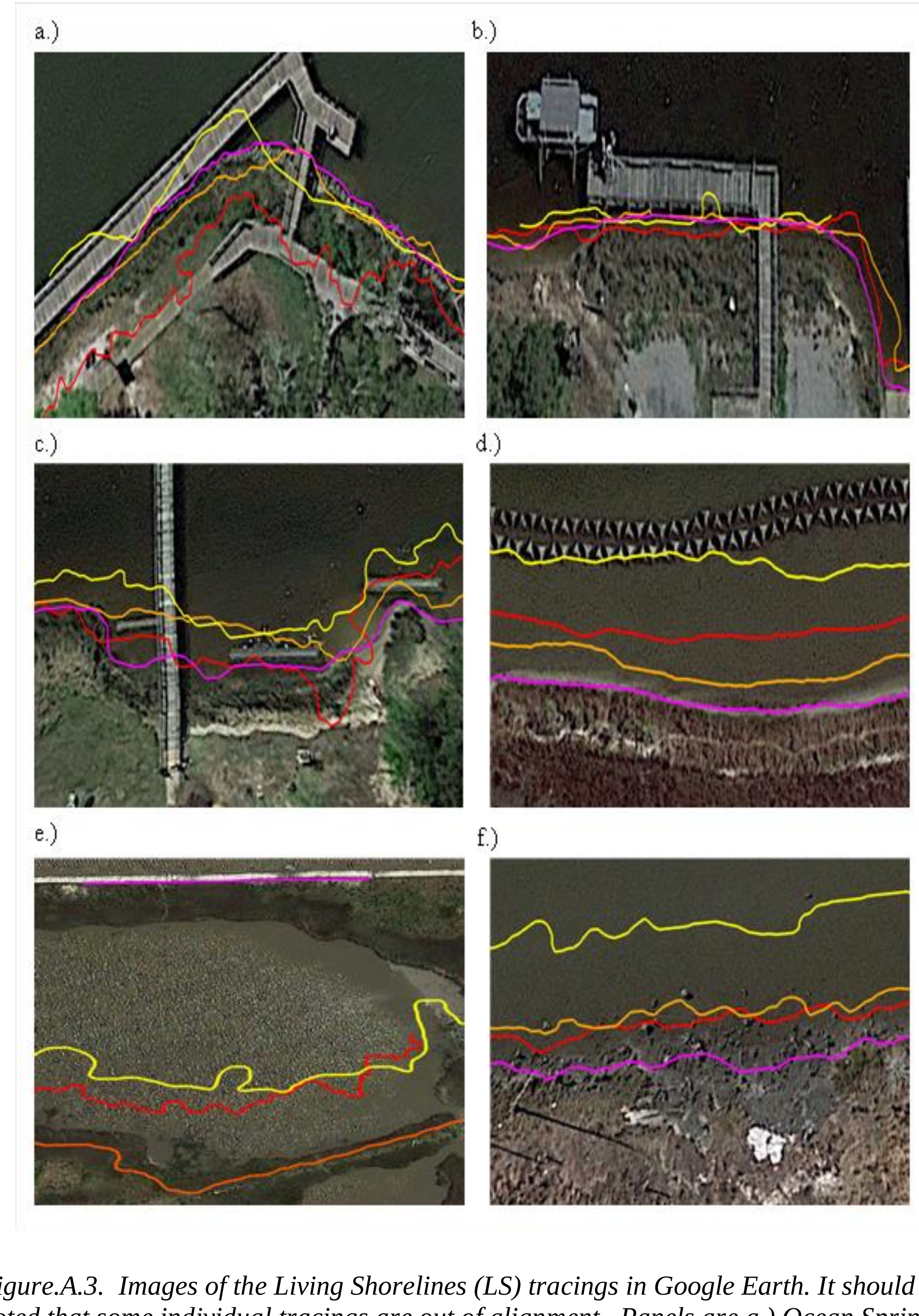

Figure.A.3. Images of the Living Shorelines (LS) tracings in Google Earth. It should be noted that some individual tracings are out of alignment. Panels are a.) Ocean Springs, b.) Grand Bay, c.) Camp Wilkes, d.) Alonzo Landing, e.) Hancock County, f.) Swift Tract. Colors represent certain years: yellow (1992), red (2005), orange (2011), pink (2019.)

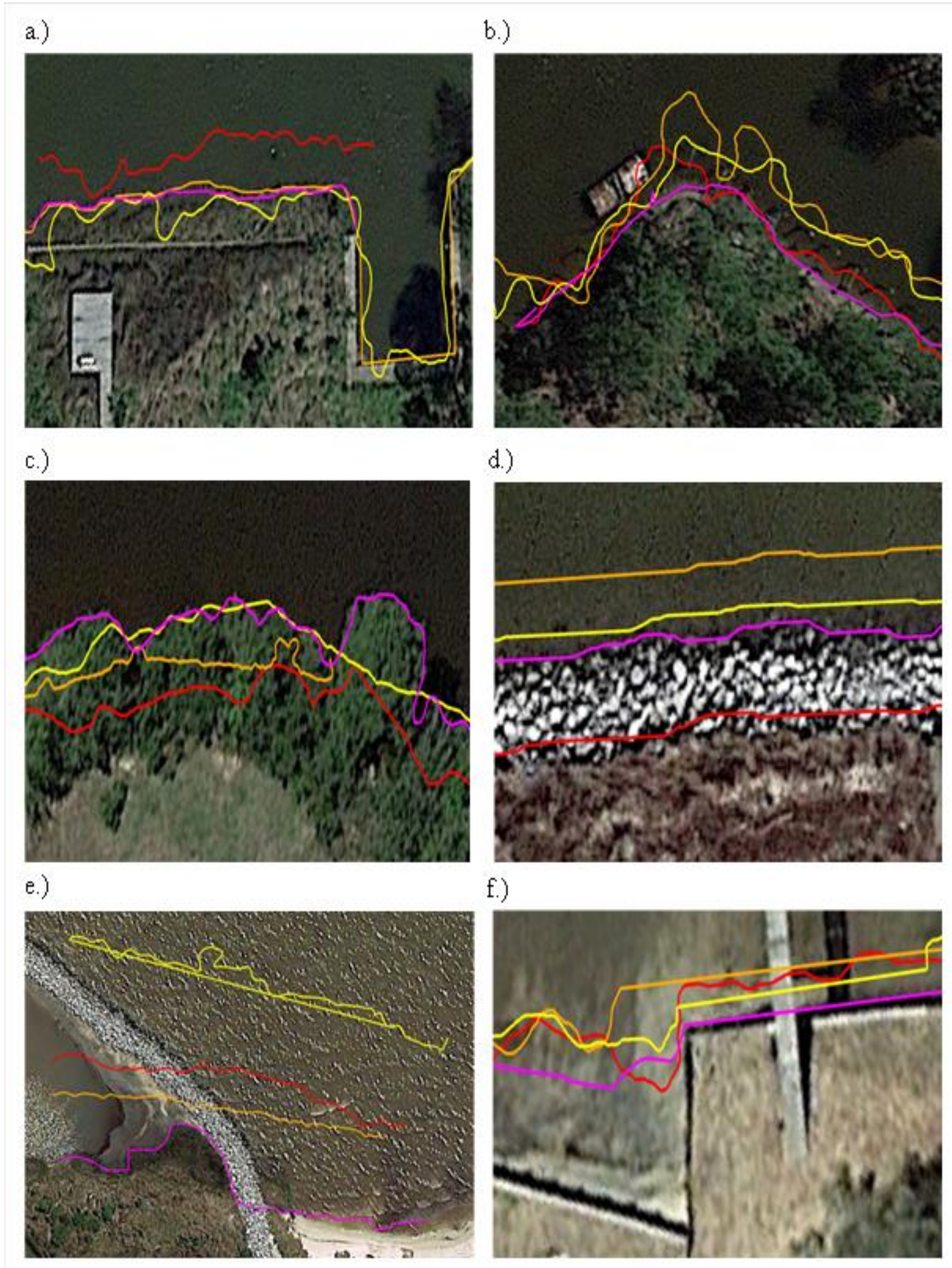

Figure.A.4. Images of the Hardened Shorelines (HS) tracings in Google Earth. It should be noted that some individual tracings are out of alignment. Panels are a.) Ocean Springs, b.) Grand Bay, c.) Camp Wilkes, d.) Alonzo Landing, e.) Hancock County, f.) Swift Tract. Colors represent certain years: yellow (1992), red (2005), orange (2011), pink (2019).

APPENDIX B: ANOVA SIGNIFICANCE TABLES FOR TESTS REPORTED

Table.B.1

Erosion rates of six sites analyzed by the factor shoreline treatment type (HS, LS, NS).

	df	SS	Mean Square	F	Sig.
Between Groups	2	19.818	9.909	48.022	0.000
Within Groups	205	42.300	0.206		
Total	207	62.118			

Table.B.2

Erosion rates of all three shoreline treatments analyzed by the factor decade (D1, D2, D3).

	df	SS	Mean Square	F	Sig.
Between Groups	2	2.402	1.201	4.123	0.018
Within Groups	205	59.716	0.291		
Total	207	62.118			

Table.B.3

Erosion rates of the LS sites analyzed by the factor decade (D1= pre-construction vs D3 = post-construction).

	df	SS	Mean Square	F	Sig.
Between Groups	1	0.004	0.004	0.034	0.854
Within Groups	38	4.520	0.119		
Total	39	4.524			

Table.B.4

Erosion rates off all the six sites analyzed by the factor fetch exposure (low, medium, high).

	df	SS	Mean Square	F	Sig.
Between Groups	2	16.623	0.311	37.451	0.000
Within Groups	205	45.496	0.222		
Total	207	62.118			

Table.B.5

Erosion rates of the six HS analyzed by the factor fetch exposure (low, medium, high).

	df	SS	Mean Square	F	Sig.
Between Groups	2	0.010	0.005	0.269	0.765
Within Groups	57	1.033	0.018		
Total	59	1.043			

Table.B.6

Erosion rates of the six NS analyzed by the factor fetch exposure (low, medium, high).

	df	SS	Mean Square	F	Sig.
Between Groups	2	13.425	6.713	28.617	0.000
Within Groups	85	19.938	0.235		
Total	87	33.363			

Table.B.7

Erosion rates of the six LS analyzed by the factor fetch exposure (low, medium, high).

	df	SS	Mean Square	F	Sig.
Between Groups	2	1.608	0.804	7.290	0.002
Within Groups	57	6.286	0.110		
Total	59	7.894			

Table.B.8

Slope of elevation transects at all six sites analyzed by the factor fetch exposure (low, medium, high).

	df	SS	Mean Square	F	Sig.
Between Groups	2	105.20	52.600	0.522	0.598
Within Groups	33	3322.2	100.67		
Total	35	3427.4			

Table.B.9

Slope of elevation transect at all six sites analyzed by the factor shoreline treatment type (NS,LS,HS).

	df	SS	Mean Square	F	Sig.
Between Groups	2	1872.8	936.41	19.877	0.000
Within Groups	33	1554.6	47.109		
Total	35	3427.4			

Table.B.10

Slope of elevation transects analyzed for all 18 shoreline types by sites combined using a dummy factor coding for treatment.

	df	SS	Mean Square	F	Sig.
Between Groups	17	3150.3	185.31	12.035	0.000
Within Groups	18	277.16	15.397		
Total	35	3427.4			

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