A Shore Thing? An Environmental Assessment of Living Shorelines

UNC Institute for the Environment

Morehead City Field Site Capstone

Fall 2017

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UNC INSTITUTE OF MARINE SCIENCES

Overview of Capstone

North Carolina's coast attracts millions of visitors from around the world every year. Home to a wide diversity of species, rich marine habitats, and scenic views, North Carolina's coast is a hotspot for vacationers and marine scientists alike. Coastal recreation and tourism contributed an estimated $1.1 billion to the state economy in 2013, with over $225 million from Outer Banks tourism alone. Fisheries and seafood industries also contributed a sizable $188 million to North Carolina's economy, excluding any profits made from recreational fishing (Hallac, 2016; Harrison et al., 2017). With so much of the state relying on the ocean economy, North Carolina's coast is especially important to protect.

Coastal shorelines have long been stabilized with hardened structures, such as seawalls and bulkheads, in order to provide protection from coastal erosion and hazards. However, these engineered structures often decrease the ecological integrity of natural shorelines. In an attempt to mitigate human impacts on shorelines across the globe, coastal managers have recently emphasized "living shorelines," a term used to describe structures that incorporate natural components, such as oysters and marsh, to provide both shoreline protection and valuable habitat. Other hybrid approaches include granite sills, which serve as a hard substrate for the recruitment of other living components, like oysters and fish. While living shorelines are becoming a popular concept, there is relatively little information that quantifies the ecological value and ecosystem services that they offer. Considering projected sea-level rise and increasing frequency of tropical storms, there is an urgent need for understanding how coastal communities can maximize their shoreline stabilization efforts while maintaining ecological integrity.

In this capstone, the University of North Carolina at Chapel Hill Institute for the Environment (UNC-IE) Morehead City Field Site undergraduate students plan to address the differences between four living shorelines. The four studied sites include the following: [1] the Maritime Museum discontinuous granite sill (DGS) in Beaufort, [2] the Duke University Marine Lab continuous granite sill (CGS) on the west side of Pivers Island, [3] the NOAA continuous oyster sill (COS) on the east side of Pivers Island, and [4] the UNC Institute of Marine Sciences (UNC-IMS) discontinuous oyster sill (DOS) in Morehead City (Figure 1).

Wave attenuation was mapped and measured at each shoreline in order to contribute to our understanding of the physical differences between each living shoreline type. Nutrients, water quality, and biota around each site was also measured to better quantify the environmental impacts and quality of each shoreline in terms of habitat. The data collected on these factors will provide insight into the environmental implications that different types of living shorelines may have.

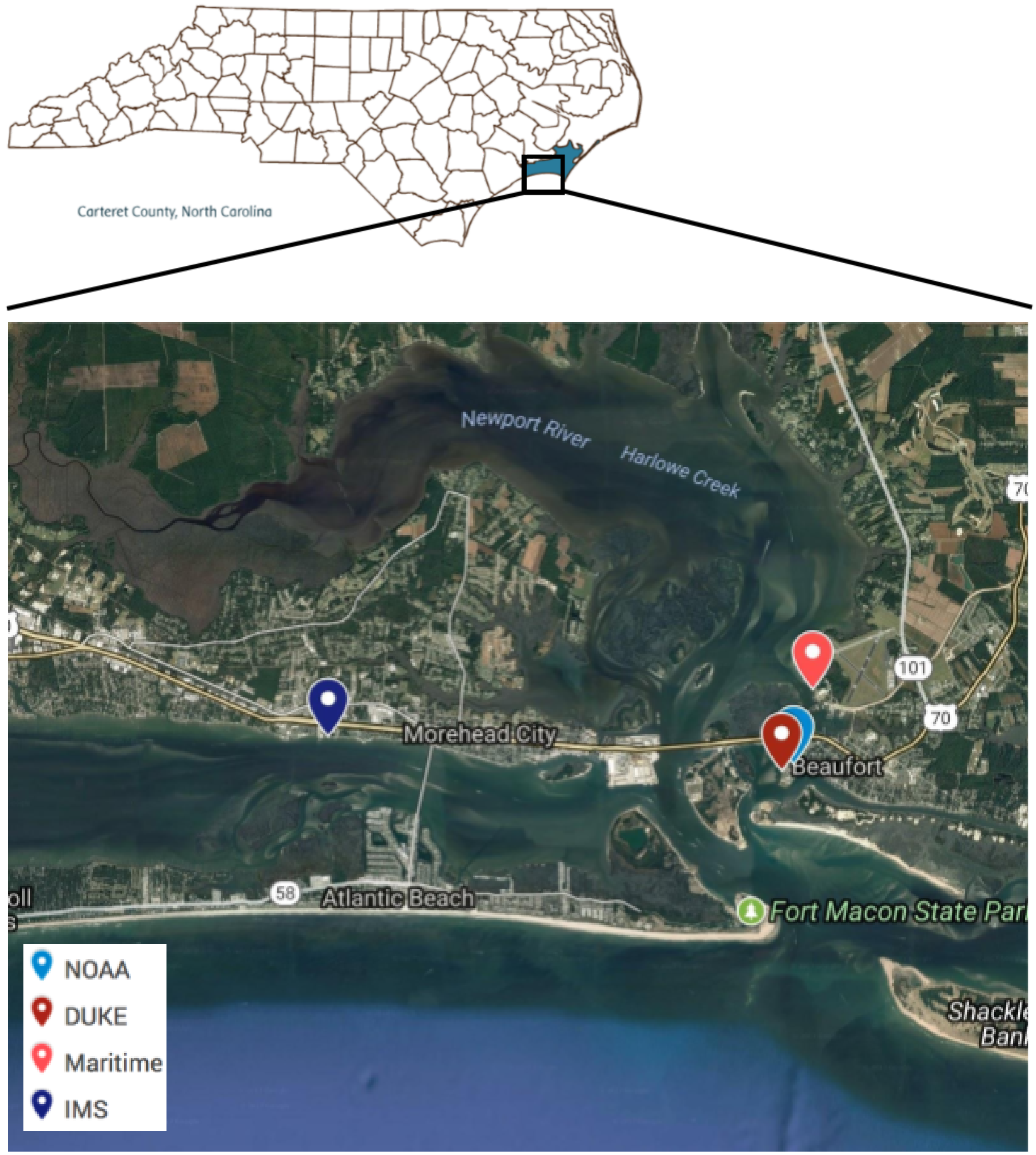

Figure 1. *Study sites of living shoreline locations of the 2017 Fall UNC-IE capstone project. All are within Carteret County, North Carolina. The sites include: [1] the Maritime Museum discontinuous granite sill (DGS) in Beaufort, [2] Duke's continuous granite sill (CGS) on the west side of Pivers Island, [3] NOAA's continuous oyster sill (COS) on the east side of Pivers Island, and [4] the UNC Institute of Marine Sciences (UNC-IMS) discontinuous oyster sill (DOS)*

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Living Shorelines Background

Shoreline stabilization is an increasingly important measure to protect coastal property against various hazards like coastal erosion and storms. Over a third of the world's population now lives within 100 kilometers of a coastline, and this proportion is expected to increase in the future (Small & Nicholls, 2003). With so much development and urbanization near the ocean, coastlines are vital to protect from erosion. Despite the over $150 million spent on erosion control measures each year in the US alone, an estimated $500 million of coastal property is still damaged or destroyed. Erosion is only expected to worsen with sea level rise and more frequent, intense storms (NOAA, 2013).

In response, many coastal areas have worked to stabilize shorelines, often with hard, man-made structures such as seawalls or bulkheads. Many coastal cities have over 50% of their shorelines hardened, with the US having a total of 14% of all shorelines armored (Bilkovic et al., 2017). Although hard shorelines have been used for decades, there has been speculation about whether these structures are actually more harmful than they are helpful. Some studies have shown that hard shorelines may actually increase erosion by effectively cutting off the ability of sand and wind to naturally deliver or redistribute sand (Sexton & Moslow, 1981; Pilkey & Wright, 1988; NOAA Living Shorelines Work Group, 2015). Aside from the uncertainty over the effectiveness of hard shorelines against erosion, environmental effects have not been well studied. From the studies that have been published, it appears as though hardened shorelines have a significantly adverse effect on the benthic organismal community and greatly reduce the amount of dry beach available for recreation (Gittman et al., 2016; Pilkey & Wright, 1988). This information, coupled with an increased awareness of the services of natural coastal habitats, has led to managers and property owners looking for alternative methods.

Living shorelines are an alternative to shoreline armoring that utilize natural materials and techniques. This method conserves and often restores the natural shoreline while still providing protective benefits typically sought through hard structures. This method of shoreline protection is being increasingly considered and implemented along coastlines. Living shorelines were first utilized in the 1970s along the Chesapeake Bay (Garbish & Garbish, 1994). Since, several governmental entities in the U.S. and Europe have employed incentives for using living shorelines as a primary shoreline protection method (Bilkovic et al., 2017). A few places have decided to opt out of hard shorelines almost entirely. For example, the North Carolina General Assembly unanimously voted in 2003 to ban hard structures along ocean property, with few exceptions, as part of the Coastal Management Act (NC Division of Coastal Management, 2016).

Whereas many shoreline protection methods prioritize erosion control over ecological goals, living shorelines have great potential to integrate both shoreline stabilization and habitat restoration. Hardened shorelines often degrade the surrounding habitat by lowering complexity, but living shorelines have the capacity to provide valuable space for feeding, larval settlement, and shelter from predators by increasing complexity. Because of these characteristics, several studies have found much higher abundances of commercially important fish and crabs around living shorelines, meaning living shorelines could be beneficial for both recreational and commercial fishing (Bilkovic et al., 2017). In addition, living shorelines have been shown to maintain water quality through increased N removal (Piehler & Smyth, 2011).

Living shorelines, when executed properly, tend to become more stable over time as plants, roots, and oyster reefs grow. For example, intertidal oyster reefs have shown potential for outpacing sea level rise (Rodriguez et al., 2014). Living shorelines have also been shown to increase shoreline resilience, with marshes with and without sills recovering much faster than bulkheads after storm events (Gittman et al., 2014). This is due to living shorelines' ability to maintain a dynamic interaction with both terrestrial and aquatic processes. For example, living shorelines can serve as depositional environments for sediment. These environments then allow for natural sediment redistribution after high energy events such as storms or intense waves. The ability to naturally respond to environmental disturbances is a key benefit of living shorelines.

As sea level rise continues, it is crucial for coastal areas to consider long-lasting shoreline protection methods that can keep up with changing climates while maintaining ecosystem services of marsh and wetland areas. Living shorelines may be the solution that threatened coasts need.

Chapter 1: Site Mapping

1. INTRODUCTION

As mentioned in the background, living shorelines have been proven to be more resilient than traditional hardened shorelines, and they can reduce erosion by accumulating sediment. These benefits, however, can be largely influenced by the height of the reef. In a study published in 2011, it was shown that shorter reefs often degrade quicker than high-relief reefs. Since oyster reefs do accumulate sediment, lower reefs were suffocated; higher reefs would persist through the high sediment accumulation, allowing for more oyster growth (Jordan-Cooley et al. 2011).

In order get a better understanding of what each sill looks like, their key habitat components (oyster and marsh) and elevations were observed, quantified, and mapped. The four sills included a discontinuous granite sill (NC Maritime Museum) in Beaufort, a continuous granite sill (Duke Marine Lab) on the west side of Pivers Island, a continuous oyster sill (NOAA) on the east side of Pivers Island, and a discontinuous oyster sill (UNC-IMS) in Morehead City (Figure 1).

***Figure 1**. The four sites used by all groups for data collection. Top left: Continuous oyster sill at NOAA; Top right: Discontinuous oyster sill at UNC-IMS; Bottom left: Continuous granite sill at Duke University Marine Lab; Bottom right: Discontinuous granite sill at NC Maritime Museum*

NOAA originally created the continuous oyster sill living shoreline in March 2000. Oysters were added in the summers of 2000, 2006, and 2007 and *Spartina alterniflora* was planted in 2000 (NOAA). The continuous granite sill at the Duke University Marine Lab was constructed in 2002 with help from the North Carolina Coastal Federation (NC Coastal Federation). The Coastal Federation also constructed the discontinuous granite sill at the NC

Maritime Museum site in 2000 and planted *S. alterniflora* in 2001. The UNC-IMS shoreline was completed in the summer of 2014, making it a much younger sill than the other three in the study (NC Coastal Federation Living Shorelines Database).

For the purpose of this study, oyster sills are characterized as sills where oyster shells were purposely placed parallel to the shore as a substrate for live oysters to grow on. These oysters theoretically grow vertically to create the height needed to protect the shoreline and the marsh grass behind the sill. Granite sills are characterized as granite rocks purposely placed parallel to the shore that provide the height needed to protect the shoreline and the marsh grass directly behind the sill. This granite sill can then serve as a hard substrate, onto which the intertidal fouling community, including oysters, can settle. In both granite sills studied, oysters were growing on and around the granite. The sites were also characterized as continuous or discontinuous sills. For the discontinuous sills, there was a large gap in between where the granite or oyster shells were placed. For the continuous sills, the granite or oyster shells were placed without any large gaps.

2. METHODS

2.1 Habitat Surveying and Mapping

To understand the spatial extent and characteristics of habitat types within our living shoreline sites, we focused on two key habitats: salt marsh and oyster sill. These habitat types were surveyed and spatially mapped using field techniques outlined below.

Oyster habitat surveys were completed using photo-quadrat surveys, which were determined to be the best non-destructive method to understand relative differences in live oyster cover between sites. Percentages of live oyster cover were determined by analyzing approximately 15 photos of randomly placed $0.0625m^2$ quadrats (Figure 2) placed along the sill at each site. Photos were taken at low tide when the oysters were exposed and were later analyzed for approximate percent live oyster cover. Group members reviewed the photos and estimated the percent live oyster cover for each quadrat. After estimating percent live oyster cover for all quadrat photos, the average percentage of live oyster cover was calculated for each of the four sites. These averages were later incorporated into the habitat maps for each study site.

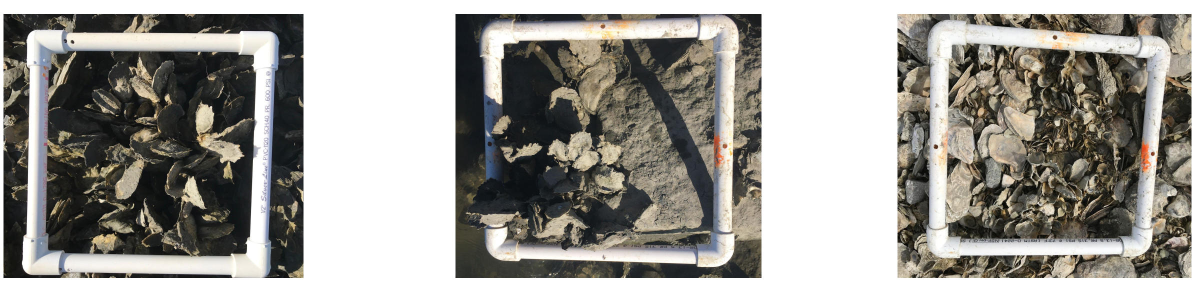

Figure 2. *Quadrats used for determining percent live oyster cover. Left: A quadrat placed at the COS (NOAA) site with an estimated 70% live oyster cover. Center: A quadrat placed at the CGS (Duke) site with an estimated 30% live oyster cover. Right: A quadrat placed at the DOS (IMS) site with an estimated 0% live oyster cover.*

Salt marsh habitat surveys focused on characteristics of marsh vegetation, specifically *Spartina alterniflora*. To collect this data, three transects perpendicular to shore, spread equally throughout the marsh area, were surveyed. Along each transect, a quarter meter quadrat (0.0635 m^2) was randomly thrown into the marsh, half to the right and half to the left of the transect line. There were six-ten evenly spaced replicates per transect. The discontinuous oyster sill had a smaller marsh area so six replicates was more appropriate; all of the other sites had ten replicates(as depicted in Figure 3). Within each quadrat, several data points were collected: the three tallest *S. alterniflora* shoot heights, the estimated percent cover, the number of shoots alive, and the number of shoots dead. The average density was calculated by comparing the number of alive shoots per quadrat, averaged over a site. This average shoot density was used to represent the relative marsh densities in the habitat maps.

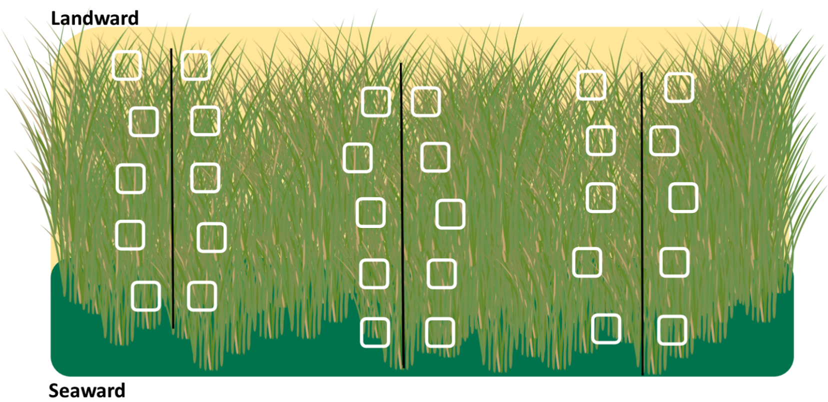

***Figure 3**. Left: Experimental design for salt marsh habitat survey. Black lines represent the three transects equally spread throughout the marsh; white boxes represent the randomly placed quarter meter quadrats. Right: Photo of two team members completing the salt marsh habitat surveys.*

To map the spatial boundaries of both target habitats a Trimble GPS unit was used, which records a latitude and longitude position. Points were taken approximately a meter apart while walking around the habitat boundary. Data was later mapped using ArcMap (version 10.3). To make the habitat maps, the *Draw Polygon* tool was used to create a graphic, from which the approximate area of both the marsh grass and oyster habitats could be determined. These graphics were then created to a feature class shapefile and colored according to relative values of shoots per quadrat and percent cover of live oyster per quadrat.

2.2 Elevation Data Collection and Mapping

In order to collect elevation data for the four living shorelines in this study, an EMLID RTK unit was used to take the latitude, longitude, and elevation of points. Points were taken at approximately every half meter along nine transects perpendicular to the shoreline and one along-sill transect parallel to the shoreline (Figure 4). Data for each site was exported into a feature class shapefile projects onto the datum WGS 1984. Using ArcMap (version 10.5) the data was exported from ArcMap, processed in Microsoft Excel, and re-imported into ArcMap.

Figure 4. *(Left) Continuous oyster sill transects and points, at which latitude, longitude, and elevation data taken using the EMLID. (Right) Photo of team members performing elevation surveys.*

In ArcMap, the 3D analyst tool *Raster Interpolation* was used to produce an inverse distance weighted (IDW) raster map of the four sites based on the input latitude, longitude, and elevation data. The resulting IDW is displayed in the final product maps as stretched values. The raster map was then cropped to an arbitrarily chosen depth into the water and the resulting map was produced using raster calculator. The map was also cropped to follow the morphology above the salt marsh using a manually drawn polygon, the habitat maps previously discussed, and the extract by mask tool to produce the final IDW map. The final maps were overlaid onto the World Imagery basemap from ArcMap 10.5.

3. RESULTS AND PRODUCTS

3.1 Habitat Map Products

Table 1. *Mean live oyster percent cover based off of photo-quadrat surveys for each sill*

Sill	DOS	CGS	COS	DGS
Average live oyster percent cover	2.92	14.29	45.71	9.58

Table 2. S. alterniflora shoots per quadrat for each sill

Sill	DOS	CGS	COS	DGS
Average *S. alterniflora* shoots per quadrat	13.94	10.00	8.23	15.05

This data was used in the creation of our habitat maps (Figure 5). Each site is shown below, with polygons representing the boundaries of respective habitat type and colors representing relative values of *S. alterniflora* shoots per quadrat and estimated percent cover of live oyster per quadrat.

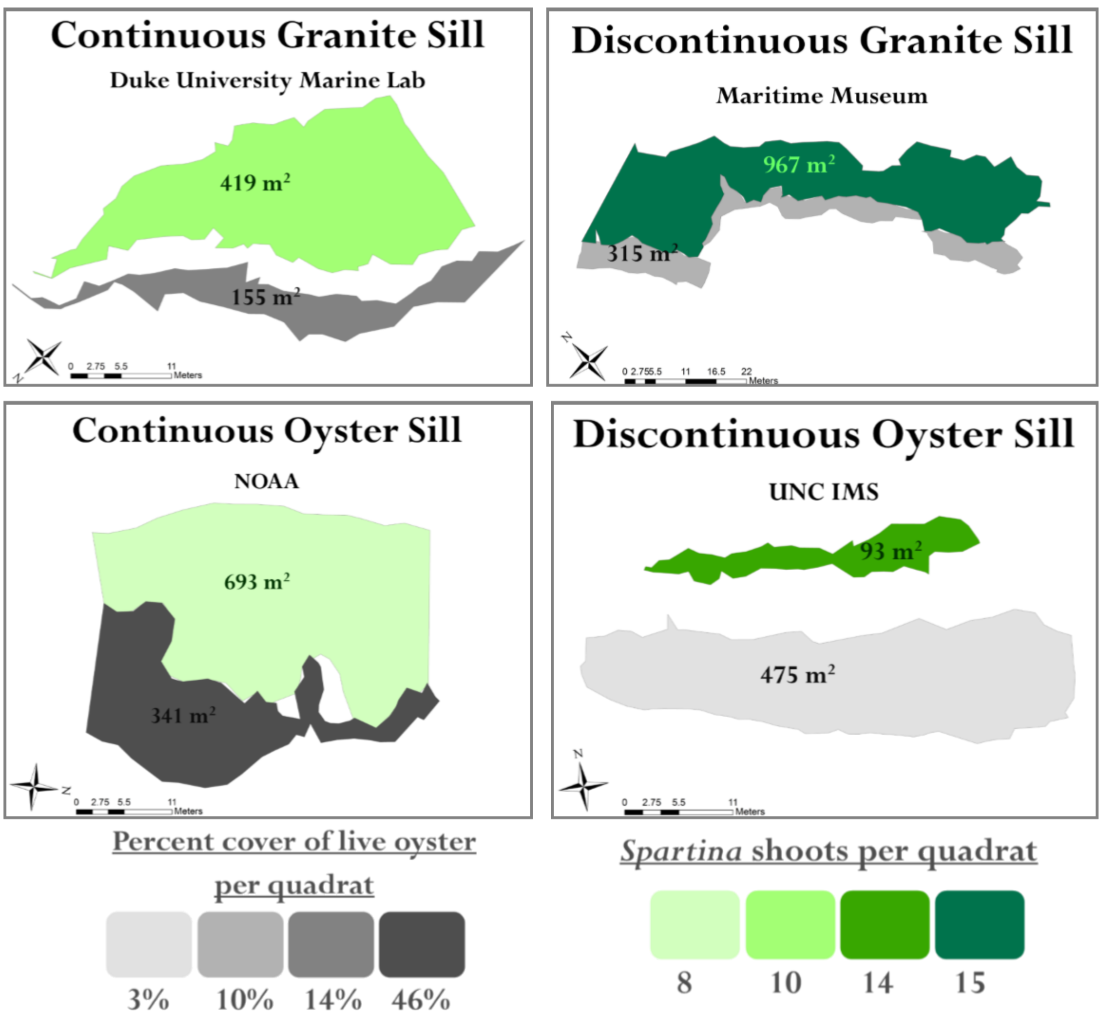

Figure 5. *Habitat maps of each site, showing polygons of both marsh grass and oyster habitats. Total habitat area is shown as m^2. Sites are oriented so that the sill, parallel to shore, is along the bottom.*

3.2 Elevation Map Products

Field surveys conducted with an EMLID RTK unit resulted in final map products of the elevation changes for the four living shorelines studied in this paper. Figure 6 below shows the final products of these maps oriented similarly to the habitat surveys, seaward at the bottom and landward at the top.

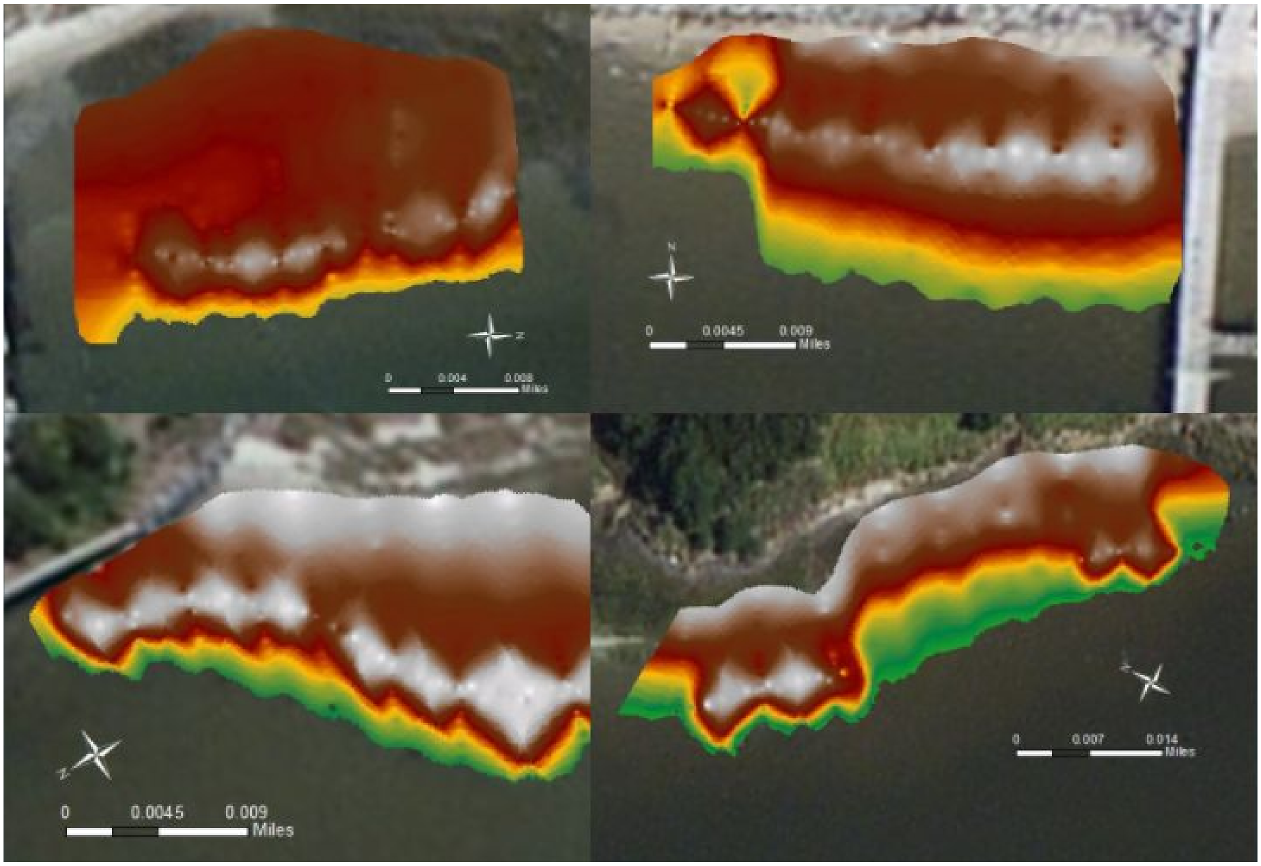

Figure 6*. IDW elevation maps of the four study sites: continuous oyster sill (top left), discontinuous oyster sill (top right), continuous granite sill (bottom left), and discontinuous granite sill (bottom right)*

The final maps were used to extract information about the shorelines studied such as the average and maximum heights of the sills and specific information used by other groups of this research papers. The sill with the highest maximum height was the discontinuous granite sill, following by the continuous granite sill, and finally the two oyster sills. The heights and width of of the sill (perpendicular to shore) were extracted from these elevation maps (Table 3) to be used in the study of wave attenuation by these sills later discussed in chapter two. These were taken from approximate locations on the sill that pressure sensors were placed during this study, discussed in chapter two.

Table 3. *Relative sill heights and sill widths behind pressure sensors used in Chapter 2 of this report to study wave attenuation.*

	COS	DOS	CGS	DGS
Sill height behind sensors	.460326 m	.425511 m	1.067215 m	.83388 m
Sill width behind sensors	9.688211 m	8.011717 m	3.880127 m	4.458925 m

4. DISCUSSION

To assess the utility of different types of living shorelines, it is important to understand how each type interacts with the surrounding ecosystems. This understanding begins with gathering contextual data that helps to define the unique characteristics of each site. For the four living shorelines that were investigated in this project, habitat area, habitat type, and elevation, were evaluated to create maps that highlight the differences between the sites.

The habitat surveys that were conducted focused on quantifying the extent of oyster and spartina at each site. The amount of space occupied by each of these habitat types varied between sills. As expected, both oyster sills had greater areas of oyster cover than the granite sills, though the granite sills did have some oyster cover (Figure 5). However, the percent cover of living oysters did not follow the same trend because the discontinuous oyster sill was almost entirely comprised of dead oyster shell (Table 1). Since this sill had next to no living oysters, its classification as an oyster sill limited our ability to find statistically significant differences between oyster and granite sills with respect to percent live oyster cover.

The data collected for *S. alterniflora* area differed from that of oyster area in that there was no pattern relating to area of cover and sill type. The discontinuous oyster sill had the largest area of *S. alterniflora* cover and the discontinuous oyster sill had the least amount of cover (Figure 5). This pattern meant that no significant differences could be found between marsh grass areas in oyster sills and granite sills, or between discontinuous and continuous sills. Similarly, no statistically significant difference was found between *S. alterniflora* densities for different sill types (Table 2). It is also important to note that no meaningful relationship was found between the areas and densities of *S. alterniflora*, nor between percent live oyster cover and *S. alterniflora* density.

The elevation data collected for each site revealed some promising trends among sill types. Both of the granite sills had higher maximum heights and steeper seaward slopes than either of the oyster sills (Table 3, Figure 6). This pattern could have interesting implications for how well oyster sills can protect a shoreline when compared to granite sills. For example, since shorter sills typically degrade faster, it is important to consider processes like sedimentation that affect oyster sill growth rates and may reduce their ability to protect shorelines (Jordan-Cooley et al. 2011).

In order to investigate how sill heights and habitat structure could impact the ability of a living shoreline to provide important ecosystem services (i.e. shoreline protection, nutrient cycling, feeding habitat, refuge), the data collected by this subgroup was distributed to the other subgroups (Coen et al., 2007). By coupling elevation and habitat data with data relating to other physical and biological processes, we hope to develop a more complete assessment of the impacts that each of these shorelines types can have on an ecosystem.

Chapter 2: Wave Attenuation and Erosion Implications

1. INTRODUCTION

The Atlantic coast of the United States experiences average annual erosion rates between two and three feet per year (H. John Heinz III Center for Science, 2000). The Outer Banks, a group of barrier islands off of North Carolina's coast, is especially susceptible to sea level rise and storms. Unlike some barrier islands, the Outer Banks are not anchored to offshore coral reefs, and consequently suffer significant beach erosion during severe storms. Storms frequently carve new inlets into the 200 mile stretch of barrier islands, redistributing or washing away sediment into entirely new areas. The area near Hatteras Island has receded around 2,500 feet in the past 150 years, narrowing it to just a quarter of its original width (Roach, 2003). By conservative estimates, sea levels are predicted to rise anywhere from 0.25 m to 1 m in North Carolina by 2100 (NC Division of Coastal Management, 2010). Along with more frequent, intense storms, erosion will become an even greater problem in coastal areas.

Rapid urbanization along coasts has caused increased necessity for shoreline protection, but erosion and sediment redistribution are powerful and natural processes that are difficult to prevent. Waves and wind often take sand from beaches and dunes, redistributing them along coasts through a constant give and take of sediments. Commonly implemented hardened shorelines, which may work well short-term, have been proven to consistently reduce the amount of dry sand available for recreational purposes by effectively cutting off the ability of wind and waves to deliver new sand (Pilkey & Wright, 1988). The disruption of natural sediment distribution can increase the amount of sediment accretion observed behind hardened sills as opposed to natural shorelines. Such an increase in elevation of the marsh can transform low marshes to high marshes and reduce values of fishery habitats (Currin et al., 2010). Hardened structures have also been shown to recover slower from storms compared to natural systems, as beaches are unable to move sand about to flatten the surf zone or form offshore bars to dissipate wave energy (Sexton & Moslow, 1981). Especially in high energy ocean locations, permanent, hardened shorelines have generally been shown to accelerate erosion, resulting in long-term losses (Defeo et al., 2009).

Realizing the importance of beach tourism and a healthy ecological system, North Carolina banned permanent hard shorelines in 2003 and has increasingly looked towards beach nourishment and living shorelines as primary shore stabilization methods (NC Division of Coastal Management, 2016). Despite many studies describing the potential benefits of living shorelines, very few have been done that actually quantify the ecological and physical impacts in a field setting. More surprisingly, there have only been a handful of studies that discuss the wave attenuation impacts of living shorelines. One experiment examined the effects of *Spartina alterniflora*, the most common marsh grass in North Carolina, on wave attenuation. It was found that *S. alterniflora* attenuated waves at a magnitude 1 to 2 times greater than adjacent mudflats, with wave height decreasing directly with plant height (Yang et al., 2011). Another study compared the effects of newly-deployed versus one-year old oyster shell and cordgrass in water tanks to examine wave attenuation effects from boat wakes. All one-year old treatments performed better than newly-deployed treatments, with the most significant damping effect of 67% using a combination of both one-year old oysters with one-year old *Spartina* compared to bare sediment (Manis et al., 2015). The most common form of living shoreline is simply the planting of native plants along the coast. The presence of living shorelines can aid in this creation or restoration of marsh vegetation by allowing these plantings to become established (Swann, 2008). Additionally, living shorelines can further help vital marsh plants by protecting them from stem breakage or weakening due to wave action (Vuik et al., 2017).

Living shorelines may effectively attenuate waves in two ways. First, the rugosity of shorelines increases friction with water, reducing the strength of waves. Secondly, shorelines can help to break waves before they reach the shore, resulting in less forceful waves on the coast. By decreasing the intensity or amount of waves reaching the coast, living shorelines may be able to reduce erosion.

To better understand how living shorelines mitigate erosion and compare which shorelines are most effective, a continuous granite sill (CGS), discontinuous granite sill (DGS), continuous oyster sill (COS), and discontinuous oyster sill (DOS) were examined for wave attenuation. Effectiveness of each shoreline was quantified by measuring parameters such as wave height and water level.

2. METHODS

2.1 Pressure Sensor Deployment and Retrieval

Four 6 Hz RBR pressure sensors were deployed at each site between September and October. Sensors were deployed and retrieved during low tide for ease of access. The sensors were covered in waterproof tape and attached to earth anchors and driven into the sediment to ensure stability. Each set of sensors was left to record data for approximately three days. On the third day after deployment, the sensors were retrieved from the site, recharged, and the data was downloaded before the sensors were deployed at the next site.

In order to compare the damping effects among different types of shorelines, sensors were placed in a similar pattern at each site (Figure 1). The first three sensors, placed in a straight line, were used to examine wave attenuation over the shoreline. The third and fourth sensors were used to compare the wave heights between a “protected” (behind shoreline) and “unprotected” (not behind shoreline) coast. For simplicity and continuity, the figures in the results section will label the sensors described above as “In front of sill,” “Directly behind sill,” “Behind sill, close to shore,” “No sill, close to shore,” respectively.

Figure 1. *Maps showing locations of pressure sensors at each of the four living shorelines. Each site has one sensor in front of the sill, one directly behind the sill, one along the shore in line with the two previously mentioned sensors, and one sensor along the shore that is not behind the sill.*

2.2 Data Analysis

A pre-configured program designed specifically for analyzing water data was used for calculations and creating figures in MATLAB (version R2017a). To determine hydrostatic pressure, atmospheric pressure data recorded by the National Oceanic and Atmospheric Administration (NOAA) Station BFTN7 on Pivers Island, NC, corresponding to the dates through which the sensors were deployed, was subtracted from raw sensor pressure data. The MATLAB program then calculated mean hydrostatic pressure over 5-minute intervals, creating a spectrum of fluctuating pressure. The pressure spectrum was converted to wave amplitudes, and high frequency areas were replaced with an f^{-4} tail. Mean wave heights and periods were then computed by integrating the wave amplitude spectra.

To determine damping effects of the sills, water data from directly behind each sill (inshore) was compared to its respective offshore sensor that measured initial wave conditions. Effects were viewed at various water depths to account for tidal influence. Regression lines, whose slopes indicated the fraction of the original wave, were added for the two lowest water depth bins. Only water depths for which inshore wave heights were considerably lower than offshore waves heights were deemed to have significant damping effects. The proportion of time each water depth occured was then calculated using five minute intervals and plotted on a histogram. Effectiveness was then determined by summing the proportion of time water depths with significant damping effects occurred, allowing one to approximate the amount of time the sill effectively attenuated waves.

3. RESULTS

3.1 Wave Attenuation

Discontinuous sills were compared for wave attenuation and effectiveness according to time (Figure 2). In general, significant damping was considered to be close to or greater than a 50% reduction in height from the initial, offshore wave. For a water depth of 0.5 m, the DOS attenuated the waves by 92%. For a higher water depth of 0.6 m, the sill was still attenuating waves by 74%. For the other water depths, the waves were only attenuated between 17-27%. Therefore, it was concluded that the DOS was effective approximately 36% of the time, for water depths at or below 0.65 m, which was the upper limit of the effective water depth bins.

The blue regression line in the DGS plot showed that the sensor directly behind the sill experienced waves that were damped by 47% from the original wave height at a water depth of 0.4 m (Figure 2). The gray regression line showed that the wave was damped by 57% at a depth of 0.6 m. For the other water depths, the waves were only attenuated between 7-39%. Therefore, it was concluded that the DGS was effective for water depths at or below 0.7 m, which was the upper limit of the effective water depth bins. The sill was effective approximately 27% of the time.

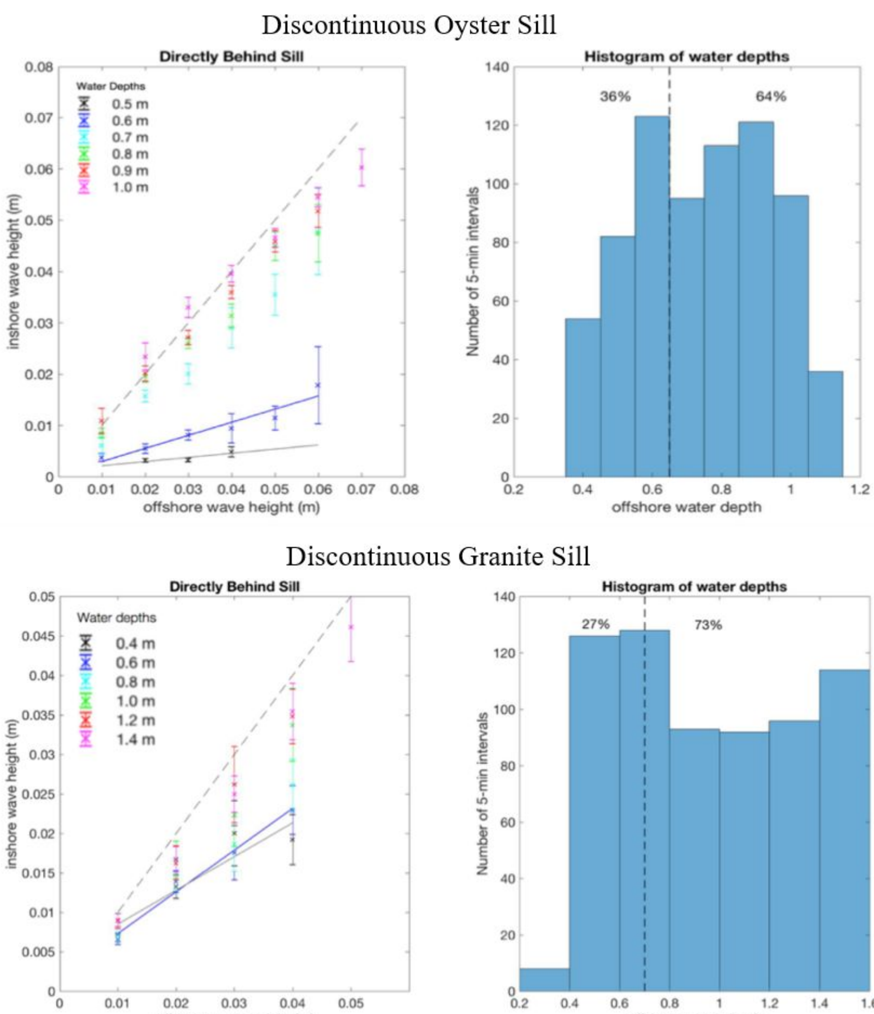

Figure 2. *The plots on the left side show offshore and inshore wave height comparisons for discontinuous sills at varying water depths. The dotted line represents where offshore and inshore wave heights are equal, or where no wave attenuation occurred. Points below the dotted line show some degree of wave attenuation, with inshore waves being smaller than initial offshore waves. Solid regression lines were used for water depths at which significant wave attenuation was determined to have taken place.*

The histograms show the percent of time the sill is effective at attenuating waves based on water depths, with the area and percent on the left side of the histogram representing percent of time the sill effectively attenuated waves.

Continuous sills were also compared for wave attenuation and effectiveness according to time (Figure 3). There are no regression lines for the two lowest water depth bins at the COS, 0.45 m and 0.65 m, because there were not enough data points at those depths. The water depths between 0.85 and 1.45 m only showed wave damping of between 20-26%. Therefore, it was concluded that the COS was not effective at wave attenuation for the time period it was tested.

The blue regression line on the CGS plot showed that the sensor directly behind the sill experienced waves that were damped by 60% from the original wave height at a water depth of 0.9 m (Figure 3). There was not enough data at the lowest water depth of 0.7 m. For the other water depths, the waves were only attenuated by roughly -6-50%. However, the standard error bars are fairly large and overlap between the various water depths, so it is more difficult to draw conclusions for these depths. Therefore, it was concluded that the CGS was effective for water depths at or below 1 m, which was the upper limit of the effective water depth bins. The sill was effective approximately 46% of the time.

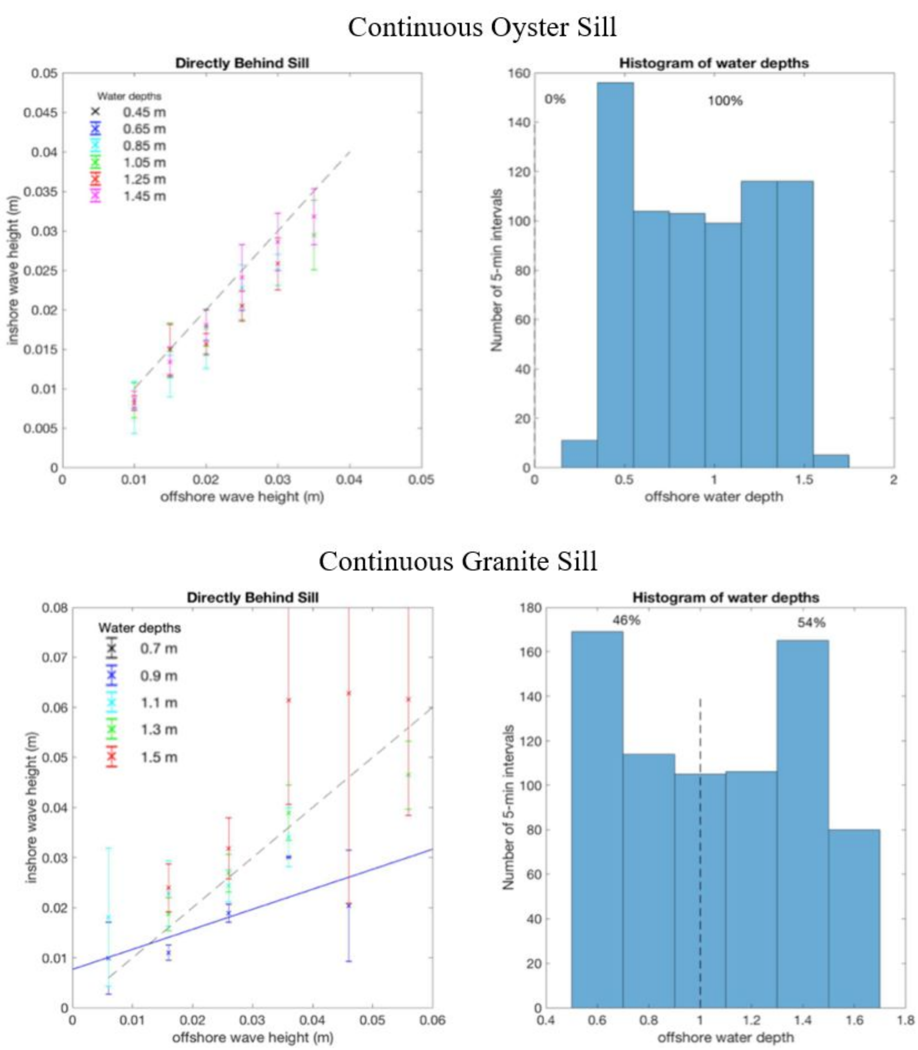

Figure 3. *The plots on the left side show offshore and inshore wave height comparisons for continuous sills at varying water depths. The dotted line represents where offshore and inshore wave heights are equal, or where no wave attenuation occurred. Points below the dotted line show some degree of wave attenuation, with inshore waves being smaller than initial offshore waves. Solid regression lines, whose colors correspond to water depths shown in the legend, were used for water depths at which significant wave attenuation was determined to have taken place.*

The histograms show the percent of time the sill is effective at attenuating waves based on water depths, with the area and percent on the left side of the histogram representing percent of time the sill effectively attenuated waves.

Overall, it appeared that the DOS had the greatest immediate damping effects at the low water depths, damping waves by 83% at low water depths. The DOS also effectively attenuated waves 36% of the time, being surpassed by the CGS with effective attenuation 46% of the time. The CGS was effective for the greatest proportion of time and damped waves by an average of 60% at low water depths. The DGS performed moderately well, attenuating waves by an average of 52% at low water depths 27% of the time. The COS performed poorly and showed no significant damping effects.

3.2 Topography Impacts on Sill Effectiveness

Water depth was plotted against fraction of original wave height to better understand how water depth affects wave attenuation (Figure 4). Increasing water depths seemed to decrease the ability of shorelines to damp waves. Certain sills, such the DOS, showed very significant damping effects at low water depths. This may be due to the considerable width of the sill, allowing for greater wave attenuation through frictional effects.

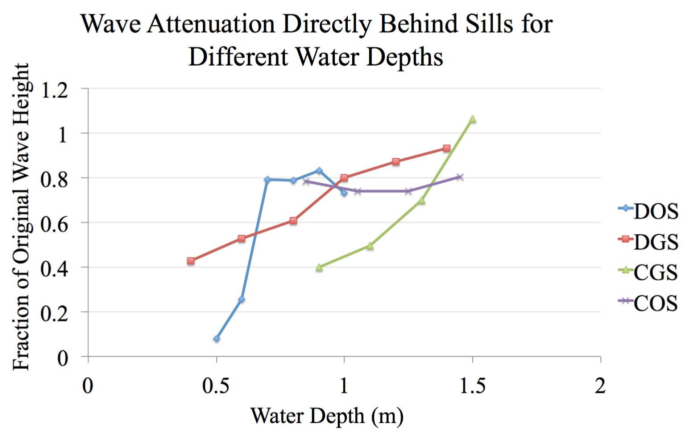

Figure 4. *Plot showing the variation in wave attenuation effectiveness directly behind the sill, as a fraction of the original wave, with water depth (m) for all four study sites.*

Sill heights relative to water height were calculated using the sill height data collected by the mapping group in *Chapter 1* and water depth data collected by the pressure sensors. The percent of time each sill was effective at damping waves was compared against sill heights relative to both average and maximum water depths at each site (Figure 5). A strong correlation was found between relative sill height and both maximum and average water depths, indicating that the effectiveness of shorelines depends heavily on the difference between sill height and water depth. Sill heights that are more similar or taller than average and maximum water depths tend to be more effective at attenuating waves.

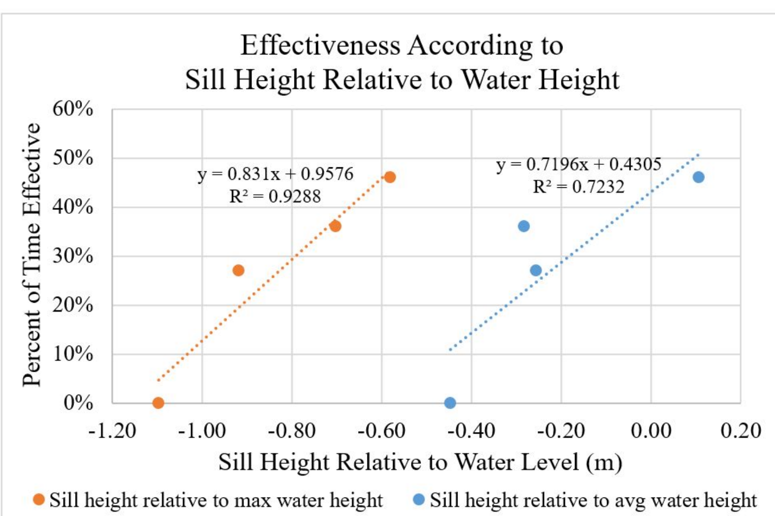

Figure 5. *Effectiveness of sills at damping waves according to recorded sill height relative to maximum recorded water height (orange) and average recorded water height (blue) for all sites. Included are the equations and R-squared values for each regression line.*

3.3 Erosion Implications from Coastal Sensors

In order to compare the potential effects that living shorelines may have on coastal erosion, the two "coastal" sensors near the shore were compared to ensure that the observed wave attenuation behind sills were not caused by a separate factor. The same process from *Chapter 2, Results 3.1* was used to compare wave heights between offshore sensors and coastal sensors (Figure 6). The coastal sensor behind the sill was classified as "protected" whereas the nearby sensor without a sill was classified as "unprotected."

Some degree of damping was found to occur at the locations of the unprotected sensors, likely due to frictional effects from the bottom or the presence of vegetation, however for the most part, no significant wave attenuation occurred. The protected sensors collected data that appeared to show a considerable wave damping effect by all shoreline types with the exception of the COS, which was also not found to have any immediate damping effects directly behind the sill, as mentioned previously.

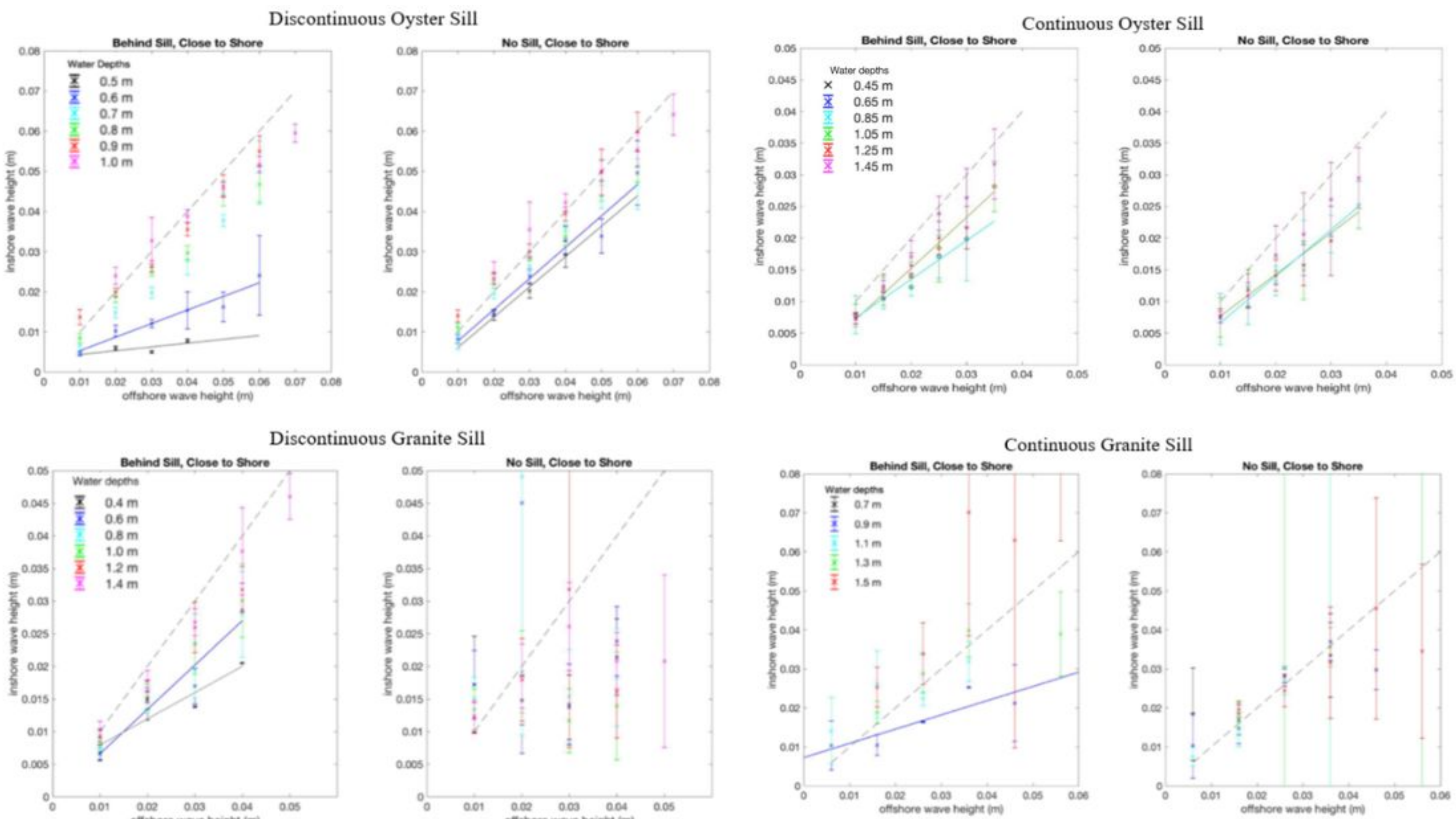

Figure 6. *Wave attenuation comparisons between protected (behind sill) and unprotected (no sill) sensors near the coast at each site. The dashed line represents where inshore and offshore wave heights were equal, or no damping occurred. Points below the dotted line, where inshore wave height is less than offshore wave height, indicate some degree of damping. The colored lines are regression lines that correspond to the water depths at individual sites (see legends). Only water depths with points consistently and considerably below the dashed line were assumed to have significant damping effects.*

Average wave attenuation was calculated for water depths that were found to have been significantly attenuated by sills (Table 1). For certain sites, such as the COS, the lowest water depths were unusable due to lack of data points, likely from not being submerged enough to get accurate or sufficient readings. To account for this issue, the lowest water depths with adequate data points were used. To determine average damping due to the sill alone, percent damping recorded at the unprotected sensor was subtracted from percent damping at the protected sensor. This difference theoretically corrected for site topography that may have contributed to wave attenuation regardless of sill presence, such as sediment type, bottom slope and shear, or vegetation.

Table 1. *Average percent damping (of original waves), measured by coastal sensors comparing protected versus unprotected coasts. Wave attenuation at unprotected sensors reveals damping that would have occurred regardless of sill presence due to site topography. These can be subtracted from protected sensor data to determine damping due to sill presence.*

Sill Type	Percent Damped: Protected Sensor	Percent Damped: Unprotected Sensor	Implied Damping due to Sill
DOS	79%	23%	56%
DGS	46%	0%	46%
COS	33%	34%	0%
CGS	64%	39%	25%

The sill types cannot be reasonably compared due to the different water depths that were used for calculating percent damping, however it can be stated that sills appear to have a significant damping effect overall. Reduced wave height typically implies decreased energy of a wave, which could imply reduced impacts from erosion on coasts protected by living shorelines.

4. DISCUSSION

Living shorelines appear to have great potential for reducing wave energy along coasts, which has great implications for abating uncontrolled erosion of shorelines. This being said, sill height makes a considerable difference in the effectiveness of each type. Sill heights that are too low relative to water depth may not cause any significant wave attenuation, as seen in the COS at NOAA. Although living shorelines tend to be implemented for erosion control, it is necessary to consider the ecological impacts and long-term effects. Sills that are too high relative to water depth could potentially limit biological interaction with the site, becoming more similar in structure to a vertical seawall or bulkhead than a living shoreline. Therefore, an intermediate sill height that is closer to average water depth or mid-tide water depth may sufficiently aid in reducing erosional effects while maintaining environment function and ecological services.

Although this study provided valuable insight into how shorelines may effectively attenuate waves, it is difficult to confidently conclude which shoreline type or substrate works best in reducing wave energy. The data suggests that site and sill topography may have greater effects than the material of sill itself. Wider and taller sills may be able to better attenuate waves through frictional effects and wave breaking. Areas with higher densities of vegetation or greater bottom slope may also naturally reduce wave energy, as seen from the unprotected coastal sensor data (Table 1).

This study was especially limited in analysis, as the MATLAB program used does not calculate means and standard deviations of bins containing fewer than three wave heights, resulting in a lack of data for lower water depths in the COS and CGS sites (Figure 3). Collecting long-term pressure data throughout the year could mitigate these errors while providing more understanding on how wave patterns vary seasonally and with extreme weather events. The sites studied in this capstone also had relatively different environmental and sill topographies. Incoming wave direction likely also affected results, with waves coming in perpendicular to sills at some sites and at an angle to sills at other sites. To correct for this difference, pressure sensors should be placed along a transect in line with dominant wave approach. Future studies aimed at examining wave attenuation among living shorelines should collect long-term data and further analyze the effects that topography play in reducing wave energy. Studying sills with similar heights and widths and in similar wave energy environments would provide a much better comparison between sill types and structures. Sediment accretion analysis could also provide valuable insight into how living shorelines affect sediment distribution and retention.

Chapter 3: Water Quality and Nutrient Cycling

1. INTRODUCTION

Water quality affects pelagic and benthic organisms in the water bodies in various ways; hypoxia promoted by increasing algal blooms could lead to sharp declines in water column dissolved oxygen availability and fish smothering. Biogeochemical cycling in water bodies is crucial in terms of nutrient availability to organisms and maintenance of ecosystem function. The nitrogen cycle, composed of denitrification (removal of nitrogen by releasing N2 into the atmosphere) and nitrogen fixation (fixing atmospheric N2 into inorganic nitrogen that is bioavailable to organisms) is especially crucial to organisms as it plays an important role in production of amino acids and proteins, which are the building blocks of life.

The conventional paradigm about living shorelines, especially oyster reef structures, is that they are to be able to improve water quality in different ways such as reducing water column chlorophyll-a, enhancing denitrification rates, reducing bacterial biomass, and reducing water turbidity. Filter-feeding bivalves are able to capture phytoplankton particles in the water column along with the associated nutrients (macronutrients like nitrogen and phosphorus) for their own metabolism, as well as shell and tissue construction (Newell & Mann, 2012). In this way, oyster reefs could enhance long-term sequestration of nutrients. By filter feeding the organic matter in the water column, oysters can also improve water clarity in the water column which increases light availability for benthic macroalgae (Newell et al., 2002). Oysters can enhance nitrogen cycling by depositing and concentrating nutrients in aerobic environments in subtidal zones, which is ideal for microbial denitrification process (Kellogg et al., 2013). Additionally, as outlined in Chapter 2, the wave attenuation caused by the sills can create a depositional environment due to the slowing of the water.

It is widely accepted that living shorelines improve water quality, but the objective of this section of the project was to determine how water quality and nutrient cycling varied between different types of living shorelines. The effects of the types of living shorelines on water quality and nutrient cycling were evaluated by testing chlorophyll-a, total suspended solids, total dissolved nitrogen, sediment organic matter, and nitrogen cycling.

2. METHODS

2.1 Water quality Measurements

Total suspended solids, Chlorophyll-a and nutrient concentration were measured as water quality parameters at each site. Water samples were collected at each site during high tide, when water was available from both inside and outside of the sill. For total suspended solids (TSS), 47 mm GF/F filter were dried in the oven for 2 hours, pre weighed, and then cooled to room temperature. 950 ml to 1 liter of each water sample were filtered through 47 mm GF/F filter, which were then placed onto labeled aluminum weighing dish. All aluminum pans containing filters were then dried in a 60 degree drying oven for 24 hours to remove any water in the samples. The filters were then set to cool to room temperature, dried, and weighed. TSS can be calculated by 1000 ml/vol. filtered x sed. wt. (gms) = gm/L x 1000 = mg/L. For chlorophyll a, each water sample was filtered through 25mm Whatman GF/F glass fiber filters, which were also pre-combusted. The filters were then wrapped with aluminum foil and stored in freezer overnight in order to prevent pigment degradation. The frozen filters were later extracted with addition of 90% acetone. Extracted filter pulp were then let settled in order to separate the pulp and liquid. The samples were then analyzed using the fluorometer for chlorophyll concentration by comparing to blank standards.

2.2 Sediment Characteristics

Sediment cores (6.4 cm x 17 cm) were taken at two of the four sites (Figure 1) with site specific water samples for continuous flow incubations. Three replicates were taken inside and three were taken outside of the sill for both sites; three core sample were also taken inside the marsh at both sites. The cores were capped with water-tight seals and incubated under in situ temperature (24 degrees Celsius) in an environmental chamber (Piehler et al., 2011). For the purpose of continuous water flow, two Tygon tubes were connected to each core, one for inflow and one for outflow with flow rate of 0.06 liters per hour. Cores were then pre-incubated for 19 hours before sampling in order for the system to reach equilibrium. A spike of 15 uM of nitrate was added after 29 hours of initial incubation to simulate the increase in nutrient-filled runoff following a rainfall event. Samples were taken 24, 29, 48 and 53 hours after initial setup.

MIMS (membrane inlet mass spectrometry) was used to analyze the dissolved nitrogen concentration by measuring a dissolved N^2 to argon ratio and deionized water was used as a standard. The 24 and 29 hour time points were pooled together for the ambient, “clear day” condition nitrogen flux, and the 48 and 53 hour time points were pooled together for the “stormy day” nitrogen flux. The nitrogen flux concentration is calculated using the following formula: (Concentration outflow - concentration inflow) x pump flow rate/ core surface area (Miller-Way & Twiley, 1996).

Sediment organic matter was measured by percent of mass loss by combustion. Sediment samples were taken at each site with three replicates inside of the sill and three outside of the sill. The sediment samples were dried in the furnace and weighed then ignited under 300 degrees Celsius. The samples were then weighed and the sediment organic matter is calculated by the difference in weight before and after ignition.

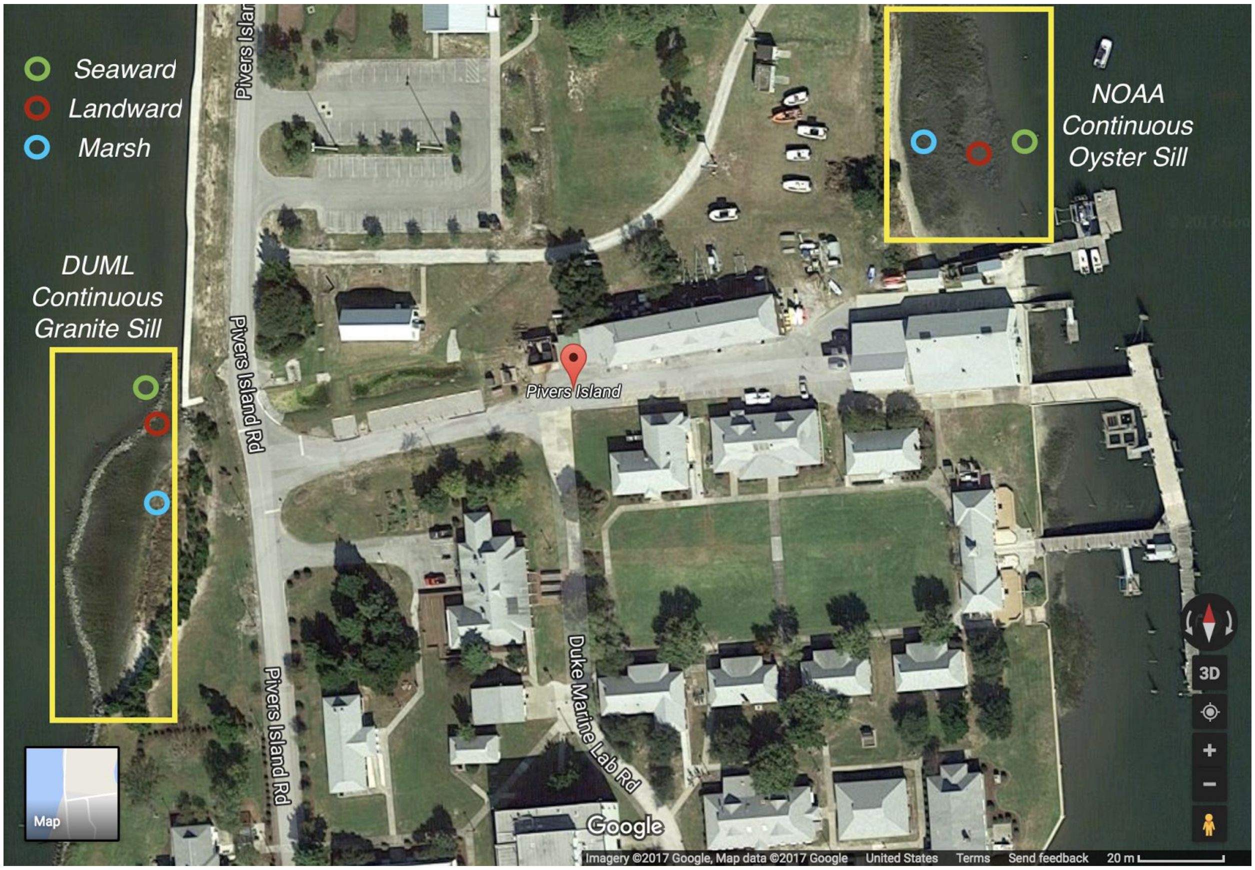

Figure 1. *The sampling site and locations of sediment core for the Nitrogen flux experiment*

3. RESULTS

3.1 Water Quality Results

The seaward and landward portions of the continuous and discontinuous oyster and granite sills displayed more suspended solids in the landward portion of each continuous sill relative to the seaward portion. The TSS concentrations are shown in µg of TSS per L of water (Figure 2). The maximum TSS values are associated with the continuous oyster sill, with a seaward value of 27.29 µg/L and a landward value of 41.64 µg/L. There was only one replicate completed, so the standard error of these measurements could not be calculated.

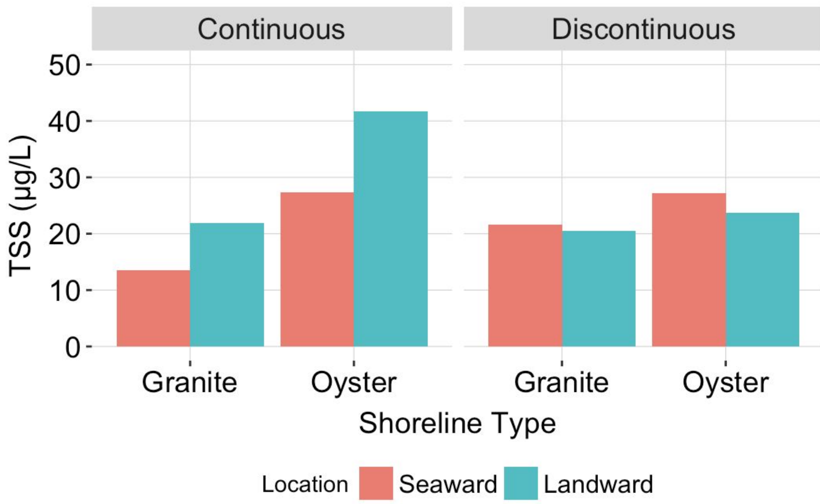

Figure 2. *Total Suspended Solids (TSS) for within the seaward and landward portions of each living shoreline are displayed above.*

Chlorophyll a concentrations were highest in the seaward side of the discontinuous granite sill, with a value of 265.77 Relative Fluorescence Units (RFU). All of the discontinuous sills had higher chlorophyll a concentrations than the continuous sills (Figure 3).

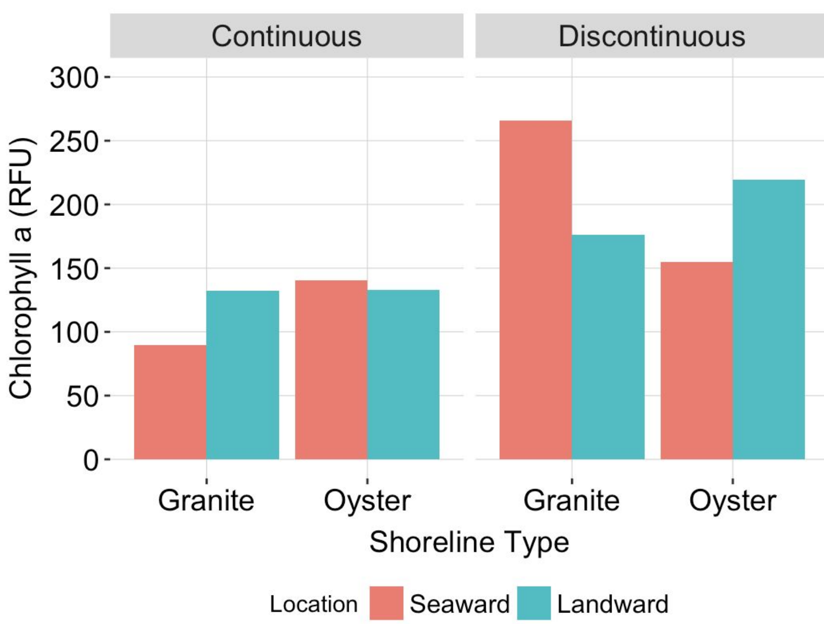

Figure 3. *Chlorophyll a concentrations within the seaward and landward portions of each living shoreline are displayed above. The Chlorophyll a measurements are displayed in Relative Fluorescence Units (RFU). There was only one replicate completed, so the standard error of these measurements could not be calculated.*

The discontinuous oyster sill had the maximum total dissolved nitrogen (TDN) concentrations in both the landward and seaward sides (Figure 4). For all sites except for the discontinuous oyster sill, the landward TDN concentrations are notably larger. The discontinuous oyster sill has more similar concentrations between the seaward and landward portions of the site.

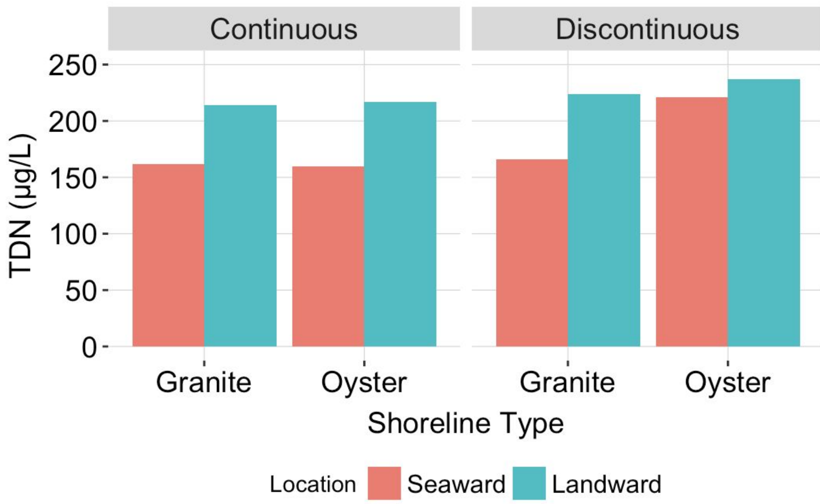

Figure 4. *Total dissolved nitrogen (TDN) in the water column in the seaward and landward portions of each type of living shoreline is displayed above. The TDN concentration is in µg of TDN per L of water. The maximum TDN concentrations occurred in both the seaward and landward sides of the discontinuous oyster sills. Only one replicate was completed, so standard errors of these values could not be calculated.*

3.2 Sediment Characterizations

The percent sediment organic matter (SOM) was higher in all portions of the sites in the continuous oyster sill than in the continuous granite sill (Figure 5). The SOM at the continuous oyster site was significantly larger than at the continuous granite sill (P=0.02041). At the continuous oyster sill, the marsh had significantly higher SOM percentages than in the seaward portion (P=0.03782). The continuous granite sill had significantly larger SOM percentages in the landward portion than in the seaward (P=0.01221) and the marsh (P=0.01063) portions of the site. The seaward portion of the continuous granite sill also had significantly higher SOM than the marsh portion (0.01063).

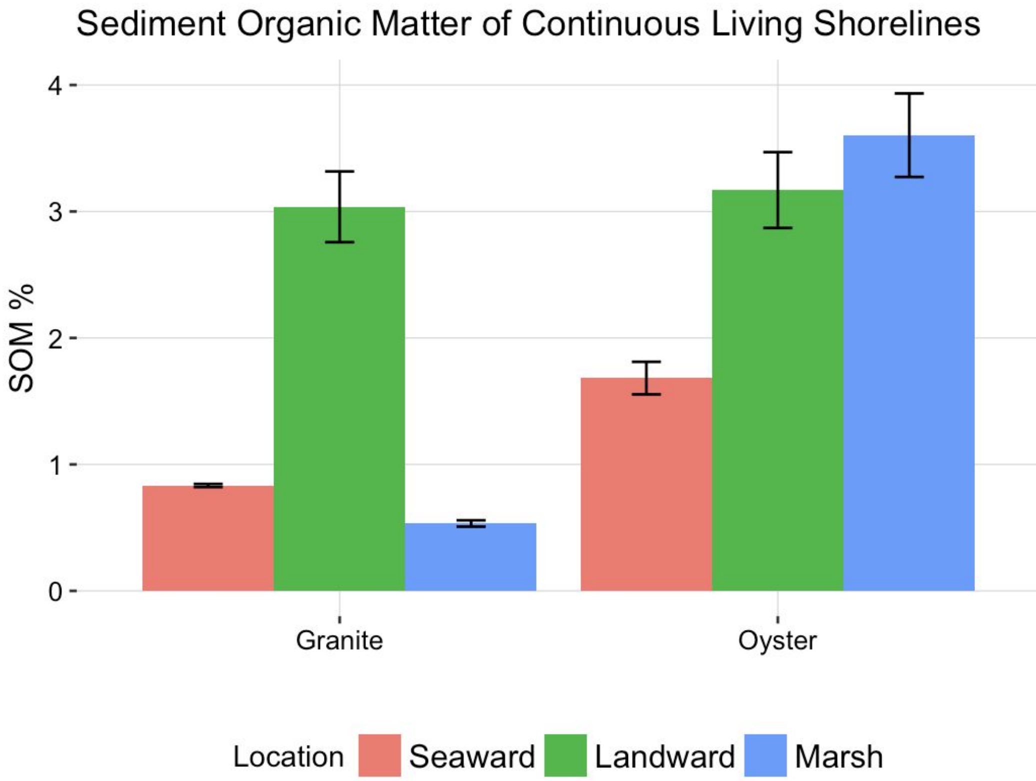

Figure 5. *Percent of sediment organic matter (SOM) for each location within the continuous oyster and granite sills. The continuous oyster sill had higher percentages of SOM than in the continuous oyster sill in the seaward, landward, and marsh portions of the sites. The error bars represent the standard error.*

To determine how the benthic community at the sediment-water interface affected biogeochemical cycling during "normal" conditions, we measured the nitrogen flux before adding nitrate (Figure 6). Anything above the red zero line signifies that denitrification is occurring, and points below the red line are nitrogen fixation. Only the seaward core from the continuous granite sill was significantly different from zero, and the other cores were slightly below zero, but still intersected the zero line.

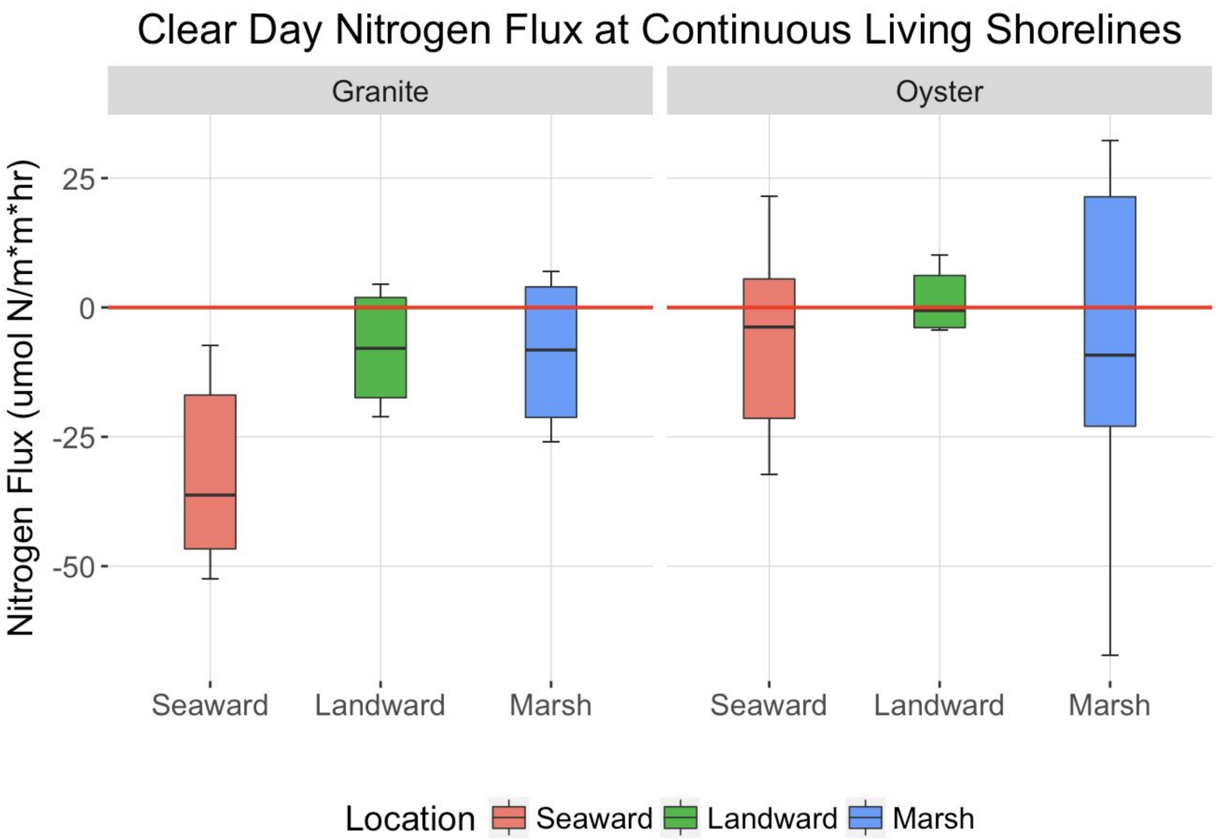

Figure 6. *Nitrogen Fluxes from the cores taken within the seaward, marsh, and landward portions of the continuous oyster and granite sills without additional nitrate (clear day conditions).*

To gauge how a rainfall event could affect nitrogen cycling within the sediment-water interface, we compared the clear day conditions presented above with a simulated stormy day (Figure 7). The nitrate addition was meant to stimulate microbial activity due to the influx of chemically-accessible nitrate. The seaward core from the granite sill changed from nitrogen fixation to denitrification after the addition of nitrate. All of the cores from the oyster sill had an increase in nitrogen fixation after the addition of nitrate.

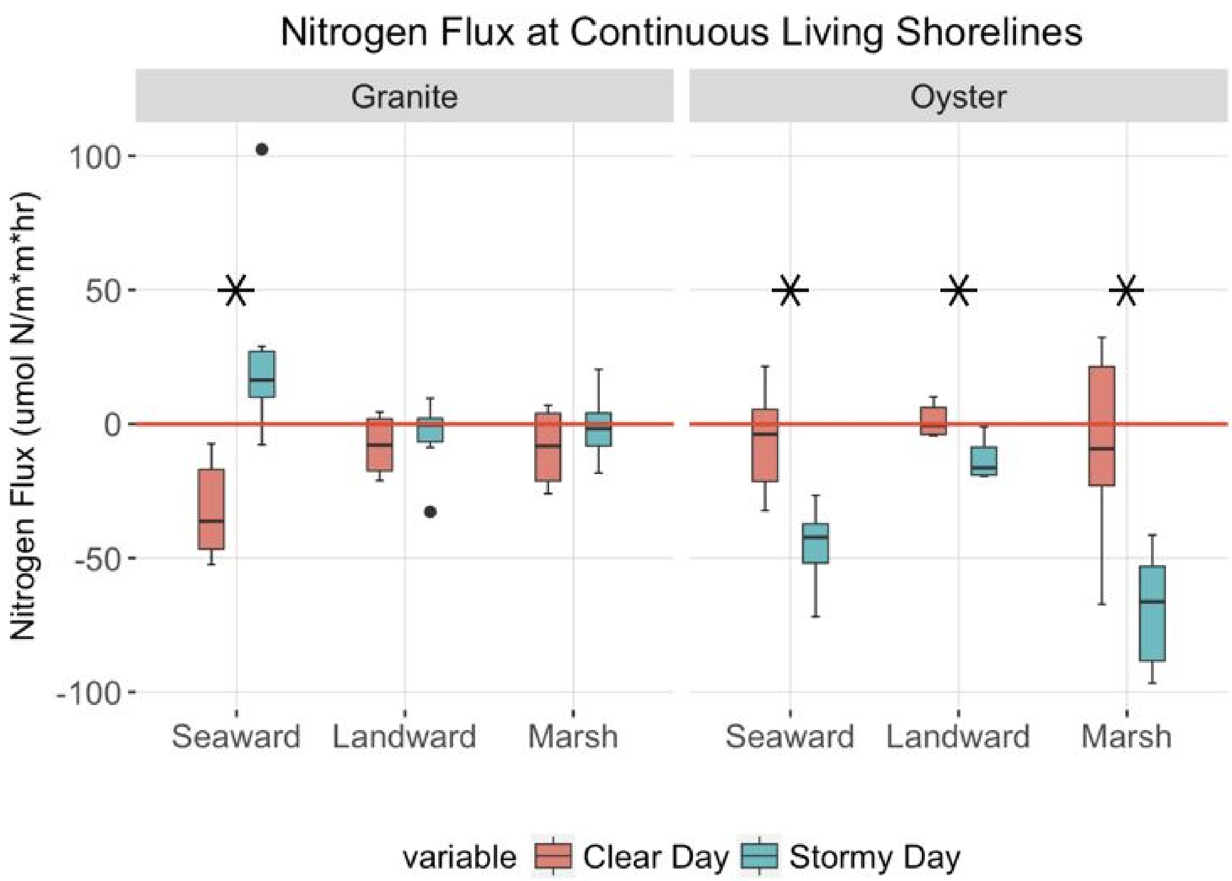

Figure 7. *Nitrogen Fluxes from the cores taken within the seaward, marsh, and landward portions of the continuous oyster and granite sills with (stormy conditions) and without additional nitrate (clear day conditions). The asterisks (*) denote significant differences (p-value < 0.05) between the clear and stormy day conditions.*

4. DISCUSSION

The results revealed that in the landward portion of the continuous sills, regardless of material, there is an increase in suspended solids inside the sill. This data includes any suspended benthic microalgae found in the samples. This trend is likely connected to the fact that water is trapped behind the sill during low tides, encouraging sediment build-up over time. One of the primary benefits of living shorelines is that they create habitats, improve ecosystem functioning, and contribute to biodiversity. However, this finding suggests that continuous sills may present some negative impacts for the organisms in the system as increased turbidity has been connected to decreased larval survival and decreased predator fitness (Fiksen, 2002). As one organism's ability to feed and survive is impacted, this effect is propagated down the food web, ultimately impacting more connected organisms. It is also important to consider the impact of wind, river input, and tidal cycle on total suspended solids in the water column which may have impacted the results (Doxaran et al., 2009).

Chlorophyll a is a proxy for standing stock of phytoplankton, which is an indicator of nutrient availability in the system. The discontinuous sills all had higher water column chlorophyll a concentrations than the continuous sills. This indicates that the continuous sills might have improved water quality and that material (granite or oyster) of the sill had less of an impact on the water column chlorophyll a concentrations. The discontinuous granite sill had the highest chlorophyll a concentration of all the sites, which might support the hypothesis that oysters are able to improve water quality by decreasing chlorophyll a concentrations in the water column. However, this conclusion cannot be drawn due to the conflicting chlorophyll a results and the lack of statistical analyses, due to only one replicate being taken at high tide.

The total dissolved nitrogen (TDN) concentrations within the water column displayed noticeably higher concentrations in the landward portions of the sites, except for that of the discontinuous oyster sill. The highest TDN occurred in the discontinuous oyster sill in both the seaward and landward portions of the site. The previous paradigm of living shorelines included the thought that water quality would be improved, specifically with decreased TSS and chlorophyll a concentrations. It was also thought that oysters, as filter feeders should improve water quality and so the oyster sills should theoretically have the lowest TSS and chlorophyll a concentrations. Our results do not conclusively support this evidence, with no definitive improvements in water quality from the granite to the oyster sills. The definition of granite and oyster sills are loose, with the granite sills having some oysters growing upon them and with the oyster sills not having very many live oysters. Conclusions are hard to determine due to the small number of replicates and sample sites.

The percent of sediment organic matter did not vary significantly in the landward portion of the sill between the continuous granite and oyster sills. However, the seaward and marsh portions of the oyster sill site had far higher SOM than in the granite sill site. This could indicate that the oyster sill sites might be far more productive systems, which would concur with the high chlorophyll a and TSS found within the oyster sill environments. Another possibility is that the oysters did proportionally decrease the SOM within the landward portion of the sites. The continuous granite sill had notably lower SOM in the seaward and marsh sections than that of the continuous oyster sill. If the similarity of the landward portion of both sills is considered, there is a possibility that the oysters relatively decreased the SOM in the landward portion of the continuous oyster sill. Oysters, in theory, are supposed to supply nutrients into the sediment to promote productivity in the sediment. This might contribute to differences in texture, with the marsh of the granite sills being sandy and that of the oyster sill being silty.

The nutrient flux experiment suggests that living shorelines are not as efficient at denitrification as previously thought. Compared to literature values for this experiment, the nitrogen flux rates that were calculated are relatively low, signifying that there may less microbial activity occurring at the sediment-water interface than expected (Piehler and Smyth, 2011). Only one core (seaward from the continuous granite sill) resulted in an increase in N^2 (denitrification) over the course of the experiment. All of the cores from the continuous oyster sill fixed more N^2 after the addition of nitrogen, which is the opposite of the previously accepted paradigm. It is unclear whether there were more nitrogen-fixing microbes at the sediment-water interface of the oyster sill cores, or if they are simply more active that the denitrifying microbes. These data suggest that living shorelines may act as a small source of nitrogen rather than as a nitrogen sink to sequester excess nutrients. More research is needed in this area to fully understand the biogeochemical cycles that occur in the sediment around living shorelines.

Chapter 4: Habitat and Biological Implications

1. INTRODUCTION

A full assessment of living shorelines would be incomplete without considering the impacts that habitat structures and functions may have on various marine organisms. In order to assess the impacts of living shorelines, biota was surveyed and analyzed at various trophic levels. Analysis was divided into three sub-groups: benthic microalgae, meiofauna and macrofauna, and fish.

At the lowest studied trophic level, benthic microalgae are photosynthetic organisms including diatoms, cyanobacteria and chlorophytes that comprise a major component of the estuarine ecosystem. Benthic microalgae live in the upper sediments and are consumed by benthic deposit and suspension feeders (during re-suspension) comprising a significant portion of the fundamental food supply for the estuarine and coastal ecosystems (Cahoon, 1999). In addition, benthic microalgae play a large role in the regulation of nutrient fluxes and gas exchange through sediment stabilization, by producing an extrapolymetric mucus that can hold together sediment particles and prevent re-suspension. This modification to the sediment composition can also alter activities of other benthic organisms (Tyler, 2003; Cahoon, 1999).

Infauna, which are any organisms living within the sediment, were studied for mid-trophic levels. They are typically dominated by two different size classifications, with meiofauna classified as organisms ranging between 63 microns and 500 microns, and macrofauna classified as anything larger than 500 microns. These organisms have been used as indicators of environmental quality, as they have been proven to enhance water quality through filtration, degrade pollutants through bioturbation, aid in nutrient cycling through digestion, and act as a food source for organisms like larval fish (Gerlach, 1971; Wakbara, Y., 1993; Newell, 1988; Rhoads, 1974).

The highest trophic level of the study surveyed fish, which are important to coastal ecosystems as ecological food web supporters for higher level predators both on and offshore, such as anglerfish and sharks. Fish are also important for the recreational and economic value of coastal communities which rely on fishing activities. In North Carolina alone, recreational fishing was estimated to provide an estimated $1.6 billion in sales and 16,150 jobs annually, signifying the importance of fish populations to economic development through direct profit and touristic value (NC Sea Grant, 2017).

Because of the aforementioned ecological benefits and ecosystem services that these organisms can provide, it is important to understand how living shorelines may affect the abundance and species richness of the organisms which live in these environments. These studies may also provide a greater implication for the effects of living shorelines on entire community structures, as we know that cascading effects of organismal abundances can be seen throughout the food web due to predator-prey interactions and trophic cascades. The organisms targeted for this capstone were studied due to their clear trophic level structure: juvenile fish eat infauna which eat benthic microalgae. This provides the study with a 3-tiered linkage between trophic levels. As living shorelines are considered for shoreline stabilization efforts, it is imperative to understand how living shorelines may affect all trophic levels and different groups of organisms.

2. METHODS

2.1 Sampling Benthic Microalgae

At each of the 4 sample sites, two replicates of a 1cc sediment core were extracted from the landward and seaward directions of each sill, using separate sawed-off 5-mL (5cc) syringes. The samples were then placed into test tubes, which were kept in a cooler containing ice packs, in order to preserve the samples until analysis.

In order to quantify the abundance of microalgae in the sediment samples, chlorophyll-a (chl-a) concentrations were measured using spectrophotometry, which is a standard method used to measure the extent to which a chemical substance absorbs light using transmittance values. First, 10 mL of a 45:45:10 dilution of methanol:acetone:DI water were pipetted into each test tube containing sediment samples. These test tubes were then inverted to mix the sediment with the methanol solution, and sonicated for 30 seconds each. Samples were then wrapped in tin foil and placed in a dark freezer. After 12-24 hours, the samples were removed from the freezer and allowed to return to room temperature. The samples were then inverted and passed through a fiberglass filter and poured into a 10-mm path length cuvette. Each cuvette was placed into a spectrophotometer and measured for optical density at 750 nm and 664 nm. 100 microliters of hydrochloric acid were then added to the cuvette, which was inverted and allowed to sit for 90 seconds. The cuvette was then placed in the spectrophotometer and optical density was measured for 750nm and 665nm. This absorbance data was used to calculate mg of chl-a per m^2 of sediment behind and in front of the sill at each site.

2.2 Sampling Meiofauna and Macrofauna

In a field survey, each of the 4 living shoreline sites was cored for meiofauna and macrofauna- once seaward and once landward for each type of infauna (n=1). Samples taken on the landward side of the sill were cored at the vegetation edge, where *Spartina alterniflora* culms met the exposed mudflat. Cores on the seaward side of the sill were taken just as the sill ended. Sampling began and was completed on September 19, 2017 at low tide when sediment was fully exposed, taking sediment cores 1cm wide by 3cm deep (total surface area: 2.36 cm^3) for meiofauna and 5 cm wide by 10 cm deep for macrofauna (total volume: 196 cm^3). One random sample was taken for each of the two treatments (seaward and landward) at all 4 living shoreline sites, resulting in 8 samples for meiofaunal analysis and 8 samples for macrofaunal analysis. This is further broken down into 4 samples for analysis of oyster sills (n=2) and 4 samples for analysis of granite sills (n=2). Meiofauna samples were sorted first through a 500 micron sieve, then through a 63 micron sieve to achieve the correct size classification for meiofauna. Macrofauna samples were sorted through a 500 micron sieve, as macrofauna are classified as any organism larger than this size. Samples were stored in formalin for 2 days, and then switched to 70%

ethanol for preservation. Rose bengal was added to each sample, which stains any protein on the organisms with a pink tint for easy identification. After preservation and staining, macrofaunal samples were sorted through to extract visually-observable organisms. These organisms were identified at the taxa level and counted under a dissecting microscope. A compound microscope was used for meiofaunal samples to identify organisms at the taxa level and to count for abundance. All p-values were calculated through a one-way analysis of variance (ANOVA) testing, using variables such as sampling site, location respective to the sill (seaward or landward), and type of sill (oyster or granite).

2.3 Sampling Fish

Each shoreline was fished within a two hour window of low or high tide for 15 minutes starting from the moment the first line was in the water. Each cast was made within five yards of the living shoreline. The same number of replicates were used for both high and low tides. Rods were rigged with a ⅛ oz jighead in either red or white and also rigged with a soft bodied plastic swimbait in green or white. Live bait was also tested. At each site, one rod was deployed with a 1 oz. pyramid sinker and two hooks using cut mullet as bait, allowing bottom dwelling fish to be caught. In total, three lines were in the water at a given time. Two rods, with artificial bait, were worked manually by two anglers and an additional live bait line was left sitting on the bottom and retrieved at any sign of being attacked by a fish. Upon catching a fish, the species was recorded, counted, and thrown back to sea. Minnow trap deployments included a single minnow trap roughly 5 meters away from the shore at each location. Traps were retrieved after twelve hours of time in the water. The number of minnows in each trap were recorded.

3. RESULTS

3.1 Benthic Microalgae

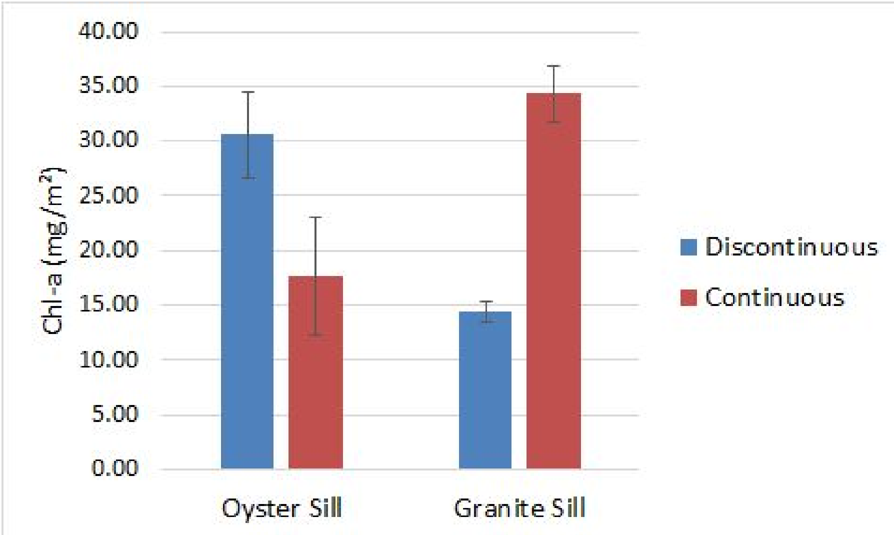

Figure 1. Chlorophyll-a Concentrations per Sill Type. *Mean chl-a abundances are displayed for all sill types (discontinuous oyster, continuous oyster, discontinuous granite, and continuous granite). The continuous granite sill contained the highest mean concentration of chl-a and the discontinuous granite sill contained the lowest concentration of chl-a. Mean chl-a concentration are significantly higher in the discontinuous oyster sill in comparison to the continuous oyster sill, and an opposite pattern is demonstrated in the granite sills, where there is a significantly lower concentration of chl-a in the discontinuous sill as opposed to the continuous sill.*

3.2 Infaunal Taxa Abundance and Diversity

Macrofaunal abundance per 196 cm^3 core volume was compared at granite sills to oyster sills, and landward compared to seaward cores within sites. Results were then tested for significance using a one-way ANOVA (Figure 2). ANOVA returned no significant results between individual sites, or oyster to granite groups ($p = .751$); however, granite sills were seen to have the highest organismal abundance, with the majority of macrofaunal organisms found at the discontinuous granite sill. Landward cores were seen to have a higher abundance than seaward sites, although not significantly ($p = .075$).

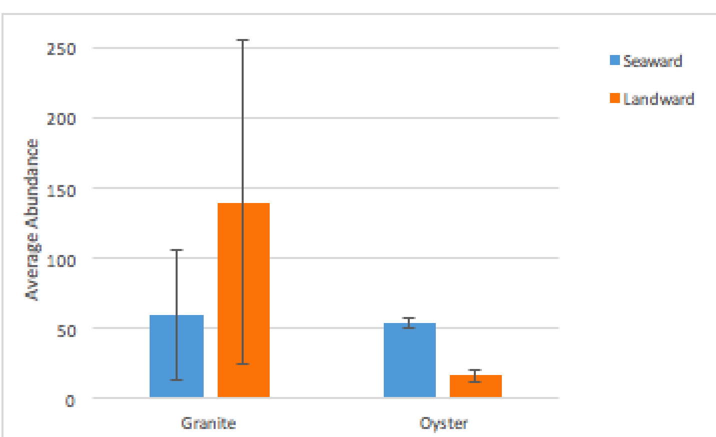

Figure 2. Meiofaunal Abundances. *Meiofaunal abundances are displayed above based on shoreline type (granite or oyster) and location respective to the sill (seaward or landward). ANOVA testing showed no statistically significant difference of meiofaunal abundance between site (0.514), sill type (p = 0.297), or location respective to the sill (p = 0.514).*

Meiofauna abundance per 2.35 cm^3 core volume was compared in in the same fashion as macrofauna abundance, and similar insignificant results were returned. Abundance was clearly higher at oyster sites, and with landward cores as opposed to seaward cores within groupings. However, when as a whole, meiofauna and macrofauna were compared as landward cores to seaward cores, a significant decline was seen in meiofauna abundance at seaward core sites (p = .05) (Figure 3). Macrofauna as a whole did not change at all in terms of abundance according to placement on sills. Therefore, it was concluded that size and nutrient input for consumption were primary drivers for abundance within sill sites. Meiofauna, due to small sizes, are more dependent on benefits created from wave attention properties of the sill, and so are more concentrated on the vegetative side where *Spartina alterniflora* further dampens waves while providing main nutrient sources for consumption. SOM concentration is much higher on the landward side of sills, which acts as a main food source for many taxa of meiofauna. This is highly compatible with nematodes, the most abundant taxa across all samples. On the contrary, macrofauna are less affected by wave properties, and de to their wide variety of subspecies within taxa groups, most of which include calcified protective shells, are dependent on nutrient availability.

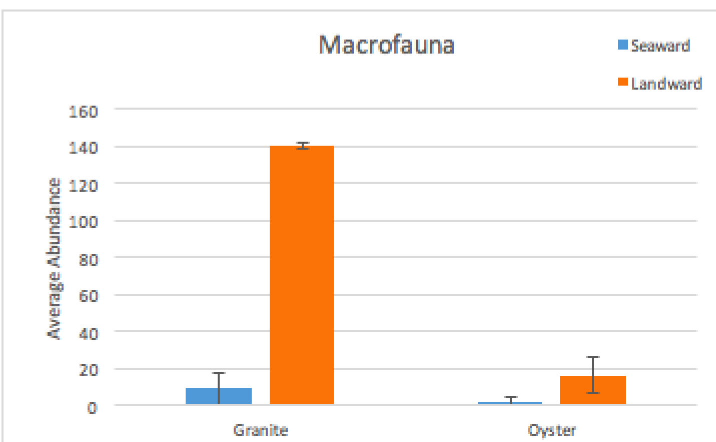

Figure 3. Macrofaunal abundances. *Macrofaunal abundances are displayed above based on shoreline type (granite or oyster) and location respective to the sill (seaward or landward). ANOVA testing showed no statistically significant difference of abundance between site (0.528) or sill type (p = 0.751). The location respective to the sill did not statistically determine abundance (p = 0.075), but a clear trend of higher landward abundance is observed, specifically at the granite sites.*

Species richness was calculated between sites for both meiofauna and macrofauna (Figure 4, 5). The highest species richness for both categories of infauna was the discontinuous granite site at the marina in Beaufort, NC, with 5 taxa identified for meiofauna, and 3 taxa identified for macrofauna. Nematodes accounted for approximately 85% of all meiofauna, with harpacticoids contributing another 8.3% on average of total composition. These taxa are competitive for nutrients, and typically show an inverse pattern of abundance over time. Gastropods were the most abundant taxa in macrofauna samples (72%), with variations of species identified depending on sediment type, as well as whether cores were taken landward or seaward.

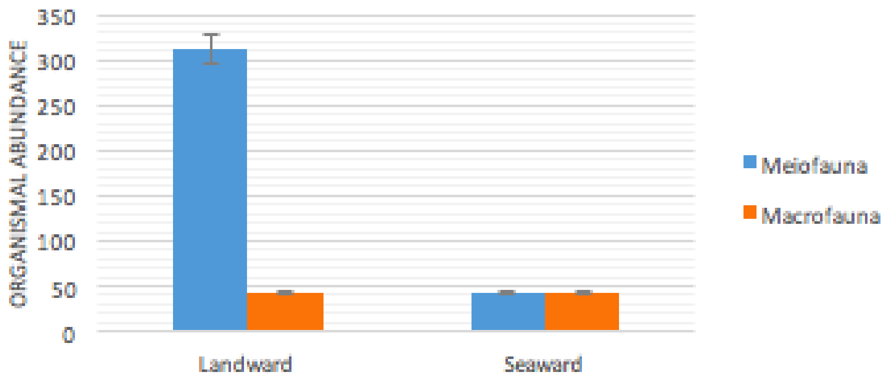

Figure 4. Abundance based on location within living shoreline. *Meiofaunal and macrofaunal abundances are categorized based on where the sample was collected respective to the sill: either landward or seaward. Landward abundance was significantly higher than seaward (p= 0.05), with meiofauna significantly contributing to this trend.*

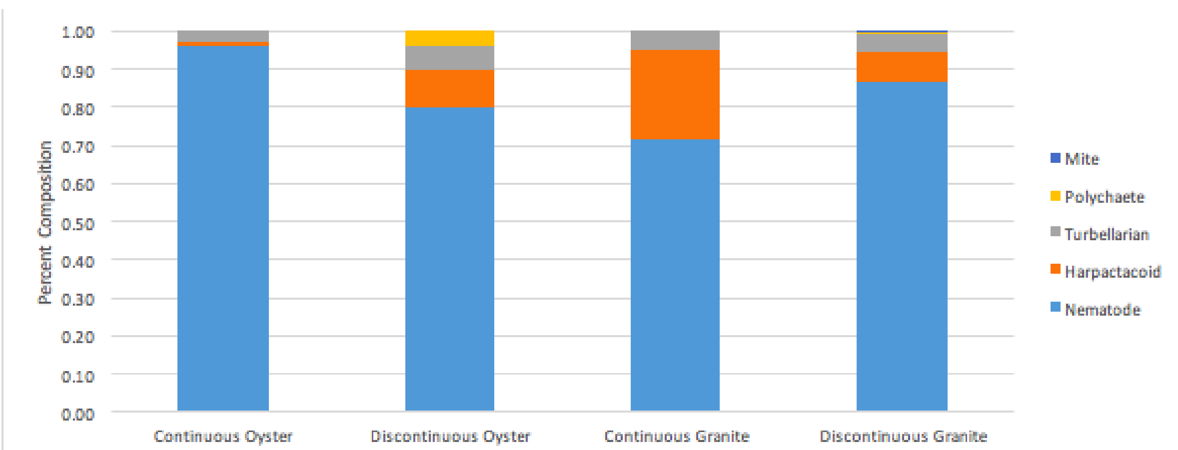

Figure 5. Meiofaunal Taxa Diversity. *The meiofaunal taxa composition is indicated by different colors that correspond to 5 different groups of taxa observed in samples: mites, polychaetes, turbellarians, harpactacoids, and nematodes. From left to right, taxa richness is 4, 4, 3, and 5.*

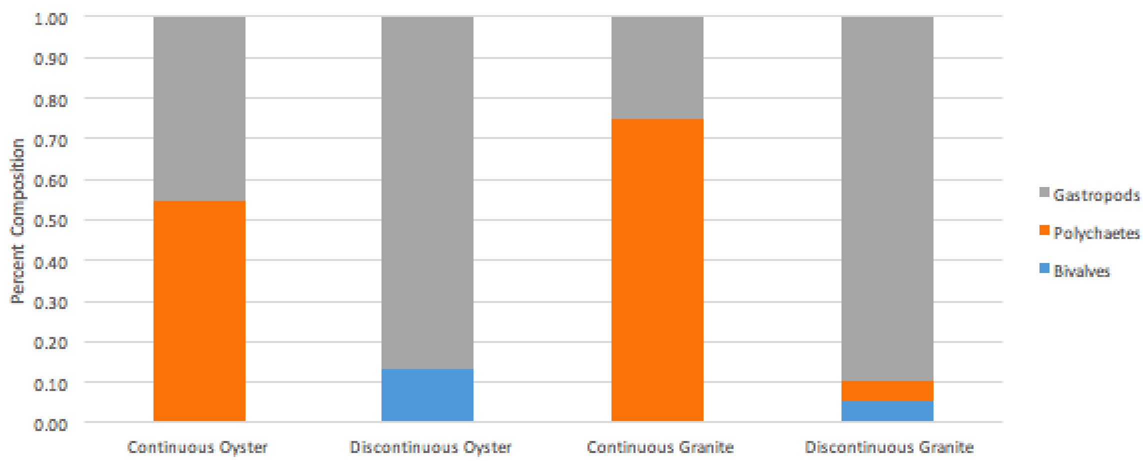

Figure 6. Macrofaunal Taxa Diversity *The macrofaunal taxa composition is indicated by different colors that correspond to three different groups of taxa observed in samples: gastropods, polychaetes, and bivalves. From left to right, taxa richness is 2, 2, 2, and 3.*

The effect *Spartina* stem density on meiofauna abundance was compared to determine direct impacts of vegetation on benthic invertebrate presence (Figure 7). A positive trend as notices, with a 0.45 correlation coefficient value. A highly significant correlation ($p = 0.07$) between the two variables, was not returned from ANOVA, but it was concluded this is lack of significance is attributed to sampling error and lack of replicates over sampling sites. Spartina alterniflora has been seen to establish an oxidized rhizosphere where nitrification can occur, enabling denitrifying bacteria go compete efficiently in the anaerobic soil community (Sherr & Payne, 1979). This facilitation of an efficient nutrient cycle within the soil surrounding vegetation increases overall usable forms of nitrogen and other nutrients, enabling the growth of meiofauna which feed on organic matter, bacteria, and diatoms.

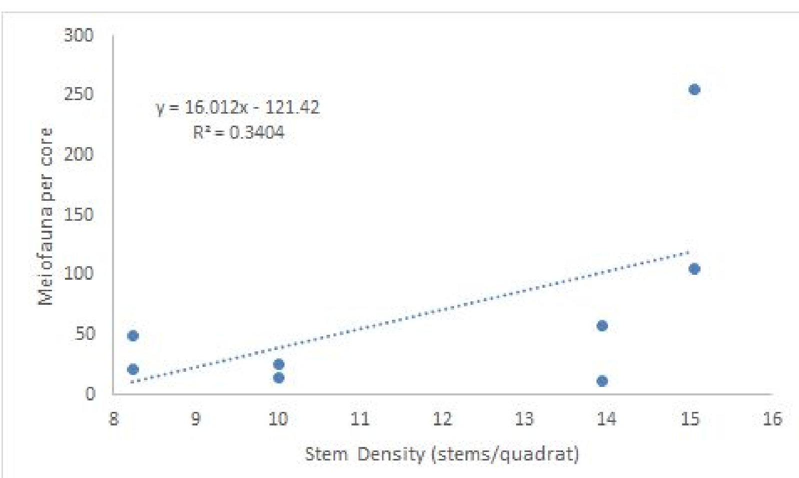

Figure 7. Meiofauna Abundance vs. S. alterniflora Stem Density. *In a comparison of fauna to flora, meiofauna abundance per core as compared to stem density at a given site is represented. A positive trend, where abundance increases with density, has a correlation coefficient of .34, although the trend is not significant (p = .07).*

Meiofauna abundance was then plotted against microalgae concentration (chl-a), to determine if direct interactions occurred between the two variables (Figure 8). An inverse relationship between meiofauna and Chlorophyll-a was shown, where an increase in benthic microalgae was seen to correspond to a decrease in overall meiofauna concentration per unit area. It was concluded that the relationship between *S. alterniflora* and chl-a is the driving factors of abundance. Decreased UV penetration to the soil surface and increased grazing induced by higher *Spartina* and meiofauna densities per unit area exponentially decrease chlorophyll-a, with a correlation coefficient of .45. ANOVA tests for significance revealed an insignificant difference between meiofauna and chlorophyll-a, but once again, this is likely due to sampling error and lack of replicates at various sites.

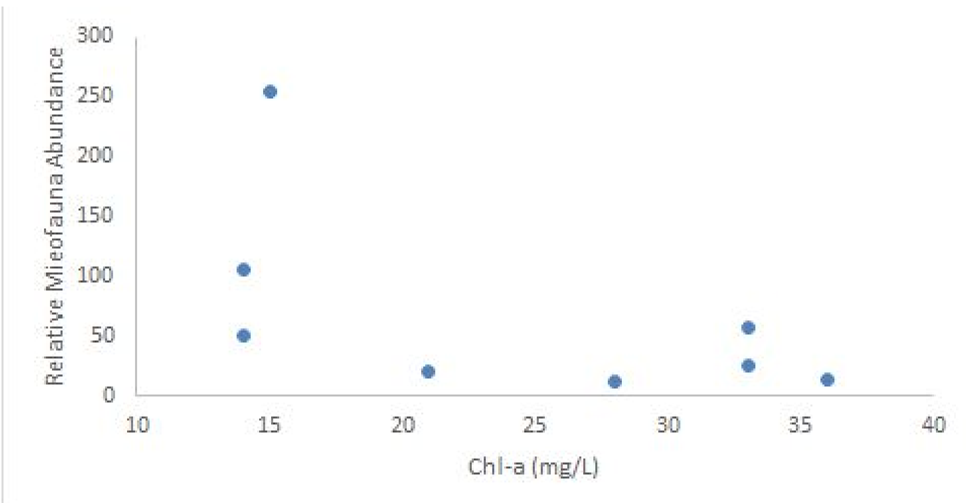

Figure 8. Effect of Chlorophyll-A on meiofauna abundance. *The sedimentary chlorophyll-a concentration plotted against meiofauna abundance. A negative linear regression, where the correlation coefficient is .45, shows that increased sedimentary chl-a concentration may have a negative but indirect impact on meiofauna abundance (p = .16).*

Macrofauna abundance was then compared to chl-a concentration, and a positive relationship was shown (Figure 9). Contrary to the interaction of meiofauna to chl-a, the most abundant species of gastropods found at the various sites are known to consume benthic microalgae for nutrition. While come species of gastropods, such as the marsh periwinkle, consume *Spartina alterniflora*, the most densely populated species included augers, lettered olives, and whelks, which sustain themselves primarily off of these topsoil plant species. Increases of microalgae in the soil due to lower densities of tall, light limiting vegetation such as *Spartina* can better support higher macrofauna densities.

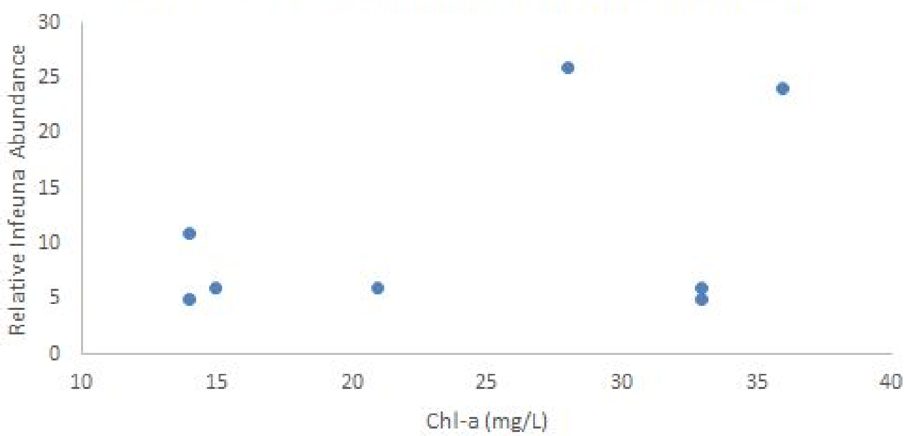

Figure 9. Effect of Chlorophyll-A on macrofauna abundance. *The macrofauna abundance was plotted against sedimentary chlorophyll-a concentration. A positive linear regression shows that chlorophyll-a significantly increases macrofauna abundance with higher chl-a concentrations (p = .012).*

3.3 Fish

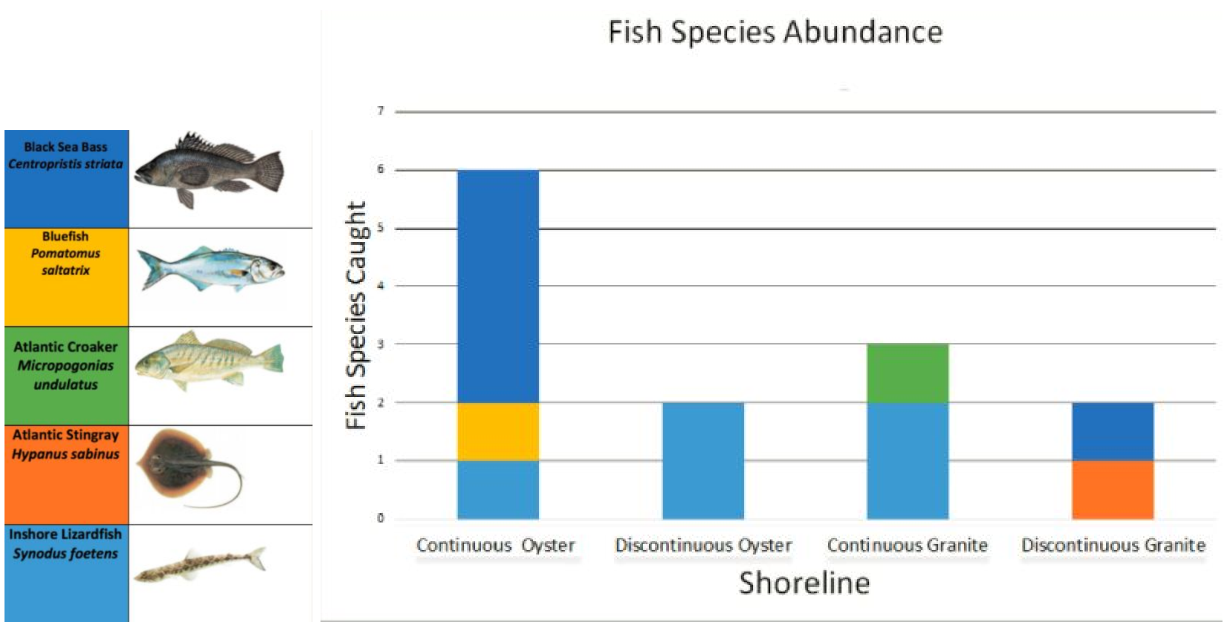

Figure 10. Abundance of fish caught at each shoreline type. *The total number of fish that were caught at each shoreline type. Additionally the diversity at each site can be observed by looking at the various colored bars. The species that each color represents is shown at the left.*

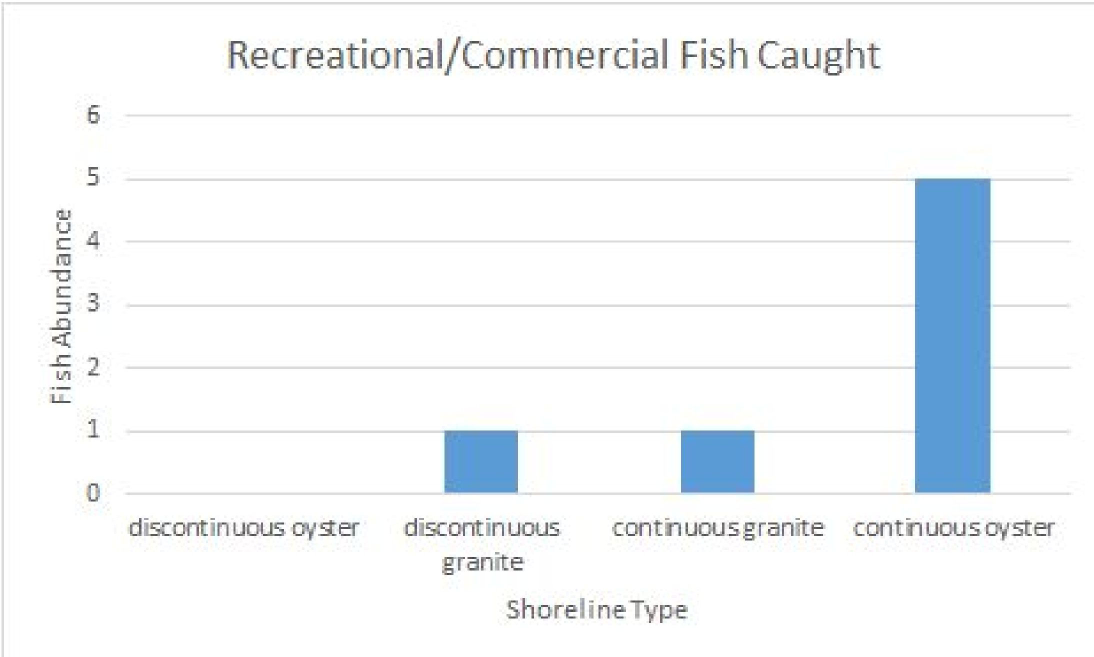

Figure 11. Recreational and Commercial Fish Caught at each Shoreline. *Recreational/Commercial Fish were defined as any fish species that would be commonly pursued by fishermen. The Sea Bass, Croaker, and Bluefish (Pomatomus saltatrix) were deemed a recreational/commercial fish species*

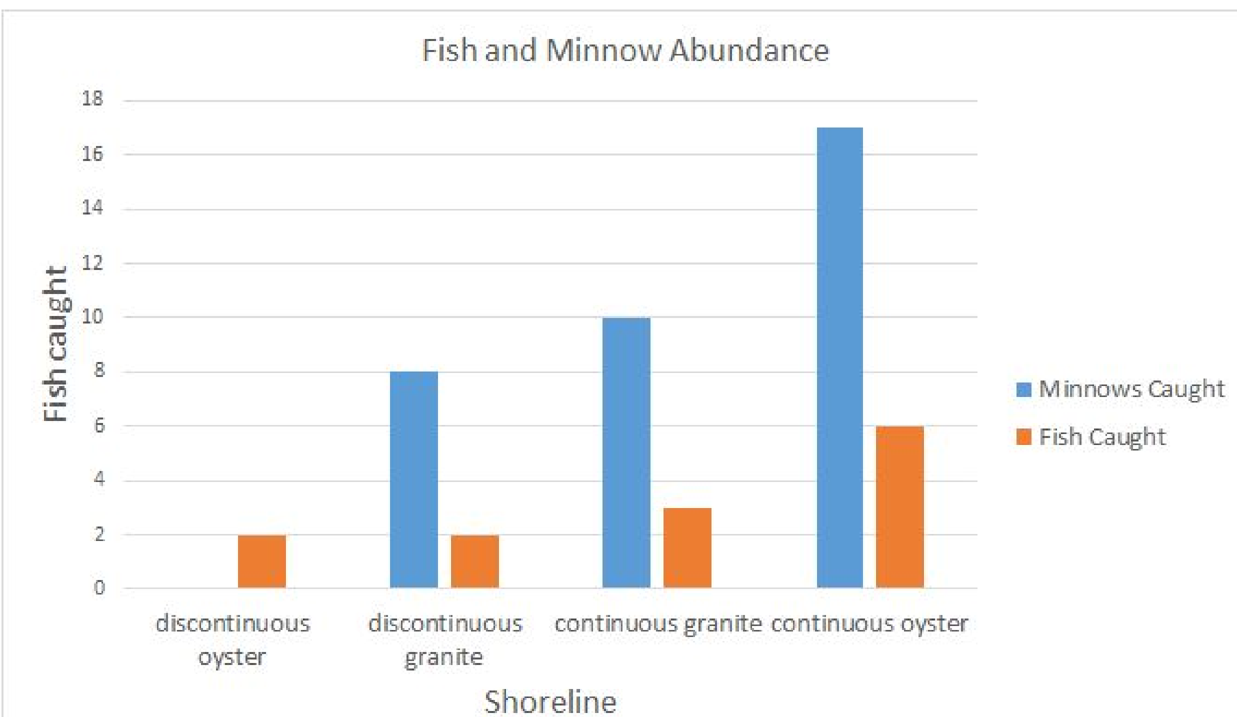

Figure 12. Abundance of fish and minnows caught at each shoreline type. *The overall trend of minnow abundance directly corresponded with the trend of fish abundance at all shorelines. The abundance of minnows was greatest at continuous shorelines and decreased at discontinuous shorelines. Specifically, the continuous oyster sill had the greatest abundance of minnows. No trend in minnow abundance was present between granite versus oyster sills.*

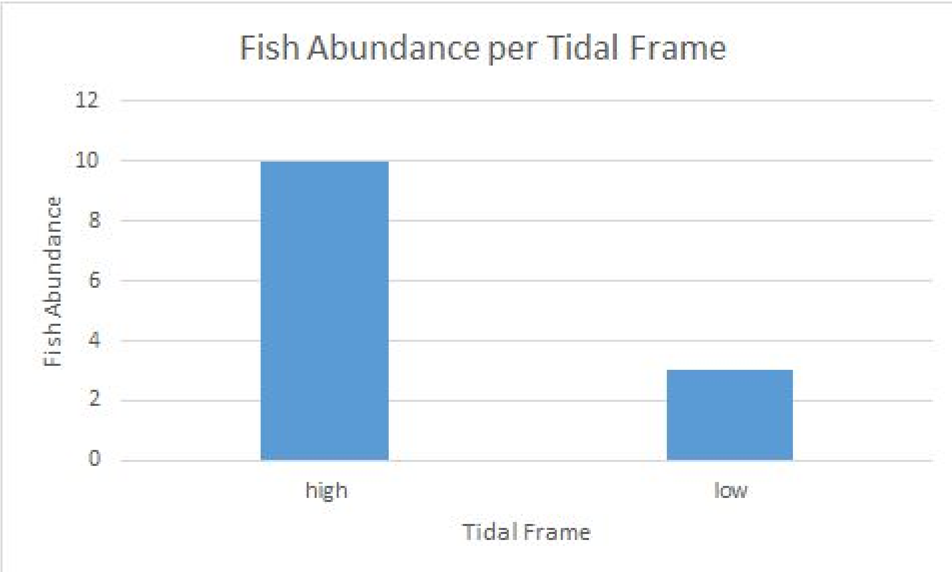

Figure 13. Fish abundance at each tidal frame. *The number of fish caught at all shorelines was influenced by the tides, presented in figure x. All shorelines are only effectively fished at high tide.*

4. DISCUSSION

4.1 Benthic Microalgae

There was no significant difference between granite and oyster sills or discontinuous and continuous sills. However, benthic microalgae concentrations were highest at the discontinuous oyster and continuous granite sill (Figure 1). The patterns found among benthic microalgae presence at the different sills could be dependent on a myriad of environmental and biotic relationships, through factors such as temperature, sunlight intensity, and predation. Benthic microalgae are preyed on by small benthic deposit and suspension feeders, and can be outcompeted for sunlight by other autotrophs such as *S. alterniflora*. Given this relationship, higher concentrations of chl-a were expected to be seen at sites with low infauna and *S. alterniflora*. The discontinuous granite sill had the highest density of *S. alterniflora* and the lowest concentration of chl-a. Moreover, the discontinuous granite and oyster sills had intermediate levels of *S. alterniflora* and the highest concentrations of chl-a, indicating that benthic microalgae might thrive with intermediate densities of *S. alterniflora*. Figure 9 showed that infauna abundances were weakly positively correlated with chl-a, indicating that infaunal species may depend on benthic microalgae as a food resource, and are therefore found in higher abundances where chl-a concentrations are higher, however infaunal abundance may not have an effect on the presence of benthic microalgae, representing a bottom-up control on the shoreline ecosystem. On the contrary, Figure 8 showed a negative correlation between meiofauna abundance and chl-a concentration, which may be an implication that meiofauna are feeding on benthic microalgae, controlling the concentrations of benthic microalgae in the sediment.

4.2 *Meiofauna and Macrofauna: Abundance and Diversity*

While there is no corresponding literature on the effects of granite sills as opposed to oyster sills for meiofauna and macrofauna abundance, it can be speculated that sill type is not a defining factor on organismal abundance. Rather, there are a number of other defining factors such as wave attenuation and current action, that may be a better indicator, as discussed in *Chapter 2*. Sills characteristics, such as width and height relative to water level, were shown to play a strong role in attenuating waves. The differences in these characteristics potentially could impact biota abundance and diversity. Sediment composition also could have played a major role. Some sites had a more sandy or silty sediment, possibly due to age differences between sills. A recent study unveiled that macrofauna abundances may be severely diminished by the implementation of a new shoreline type for anywhere from 2 to 8 years (Bilkovic, 2017). Altering macrofauna abundance and species richness, wave attenuation, and vegetation from shoreline implementation will also alter meiofauna abundance and species richness.

Increasing wave attenuation behind the sill could have allowed for diminished sorting of sediments, thereby increasing porosity and vegetation growth.. Both granite sills had a higher percent coverage and density of Spartina alterniflora, which supports nutrient cycling, supports higher diversity and trophic complexity, and attributes to enhanced soil and water quality through filtration. Wave attenuation effects and higher SOM concentration on the landward side of the sill, as discussed in *Chapter 3*, may contribute to meiofauna abundance and species richness.

4.3 Fish

A total of thirteen fish were caught during the study. Overall catch rates were higher at continuous shorelines. The continuous oyster sill had the greatest abundance of fish. Abundance of fish at the continuous oyster sill is double or triple the abundance of all other shorelines. No trend of fish species abundance was present between granite versus oyster sills. It is believed that the data was confounded somewhat for the discontinuous oyster sill because all of the oysters at this location were dead, thus providing little bottom up support for recreational fish species. The fish caught at each shoreline were composed of five different species. The most common species caught were Black Sea Bass (*Centropristis striata)* and Lizardfish (*Synodus foetens*). The greatest diversity of fish species was caught at the continuous oyster sill, which also had the most fish caught out of all of the different sills.

Conjointly, the greatest composition of recreationally-prized fish species was caught at the continuous oyster sill. The recreationally-prized species caught at the continuous oyster sill were four Black Sea Bass and one Bluefish (*Pomatomus saltatrix)*. Recreationally-prized fish were caught at low rates at the two granite sills and none were caught at the discontinuous oyster sill, which again is most likely attributable to the lack of live oysters on the sill.

Minnow counts were made in order to test if there was the possibility that by using baited fishing tackle that fish from off of the reef were being drawn in towards the reef. If they were being drawn in by fishing activity that would indicate that the reef was not supporting the fish and that bait alone was the reason fish were caught at the reef. Minnow counts were used as a means of determining if there were prey sources available for the fish that were being targeted. In Figure 12 it is evident that minnow catches were correlated with fish catches. At the discontinuous oyster reef no minnows were caught, likewise at this location few fish were caught, none of which of economical nor recreational value. Part of this, as mentioned earlier, is attributable to the lack of live oysters on the reef. The reef does not provide resources for baitfish which in turn does not provide support for the larger recreational fish that were being targeted. At the other reefs it was observed that as minnow counts increased the fish that were caught also increased. The combination of highest minnow counts

Additionally, fish catches were broken down by the tidal cycle that they occurred. In Figure 13 it can be seen that ten fish were caught during the window of high tide while only three fish were caught during the low tide window. Furthermore the three fish caught during low tide were all lizard fish, which reside on the seafloor and are not as affected by changes in tide, and are not typically desired for commercial purposes. Therefore, fishing at high tide is likely more successful than during low tide. Transitional periods between tides may also be good times to fish as well but these periods were not tested.

The continuous oyster sill had the most fish abundance in terms of minnows and fish species when compared to the other sills. Also, as seen in Figure 11 the commercial value of the fish caught at the continuous oyster sill far exceeded that of the granite sills. There could possibly be an advantage for fishing at oyster sills when compared to granite sills but the poor oyster health at the discontinuous oyster sill made this comparison impossible to make. In Figure 13 it can be seen that the tidal frame is a good indicator of when both granite or oyster sills should be fished, especially for recreational and commercial fish. Fishing at high tide provides an immense advantage when compared to fishing at low tide. By virtue of the lack of fish caught at the discontinuous oyster sill it can also be inferred that the health of the sill may play a role in the quantity and diversity of fish present at a sill.

Chapter 5: Synthesis

Conventional science deems that living shorelines provide significant wave attenuation, nutrient cycling, and enhanced habitat suitability. However, there are a limited number of scientific studies aimed at quantifying these benefits in a holistic, integrated ecosystem analysis. If coastal managers and cities are interested in implementing living shorelines, verification of these prior assumptions is necessary. Our research was designed to address this gap in existing scientific literature by assessing components of living shoreline composition, structure, wave attenuation, water quality, nutrient cycling, and organismal abundance. These components were analyzed throughout each of the previous chapters and provide insight for scientists, managers, and community members interested in living shorelines as an alternative to shoreline hardening.

Chapter 1 highlights the fact that living shorelines have many different arrangements and characteristics, consisting of various sill heights, configurations (continuous and discontinuous), and amounts of oyster and marsh grass densities. Each living shoreline is different in these respects, and with that comes a high variance in their functions. Mapping is an important way to understand each living shoreline on an individual basis to better understand how design may be altering overall function. This may be especially helpful in trying to maximize function for construction of the most cost-effective living shoreline possible.

Chapter 2 reveals that wave attenuation is heavily determined by sill topography, including sill width and height relative to water depth. Sills reduce wave energy by increasing frictional forces that can damp the waves before they break along the shore. The results suggest the importance of considering local wave energy and tidal influence when it comes to designing living shorelines. Living shorelines that were significantly below average and maximum water depths did not show significant wave attenuation effects. Sill heights and widths must be carefully considered when implementing living shorelines in order to effectively attenuate waves while still allowing for natural ecological functions and biological interactions to take place. Sea level rise and storm event frequency should also be considered when constructing living shorelines.

Chapter 3 finds that although living shorelines have been known to act as nitrogen sinks, they might not always function this way. Experimentation revealed some living shoreline sites to be a source of nitrogen rather than a sink. Contrary to the broad assumption that living shorelines with oysters will improve localized water quality, oyster sills did not significantly reduce the concentrations of water column chlorophyll-a, total suspended solids, or total dissolved nitrogen. Living shoreline composition and structure appear to be more impactful regarding water quality differences and nutrient cycling, circling back to the wave attenuation that create depositional environments mentioned in *Chapter 2*.

Chapter 4 shows that various trophic levels are affected differently by living shoreline type. Effects on organisms are likely to be indirect effects of living shoreline type, such as the impacts that wave attenuation or the trapping of nutrients and organic matter may have on organisms. When implementing a living shoreline, it is important to consider all trophic levels and multiple organisms within each trophic level to gain a holistic understanding of food web structure.

Though this environmental assessment reveals just a snapshot of the local state of living shorelines, our studies of various components of living shorelines located in Morehead City and Beaufort demonstrate the high variability that can occur even on a relatively small geographic scale. Because our studies occur in a dynamic environment, it is hard to conclude that some of our results are direct effects of living shorelines. Increased numbers of replicates including different seasons and spatial scales would be necessary to enhance our understanding of the role of living shorelines in coastal communities.

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