DETERMINING LIVING SHORELINE SUITABILITY AT THE WORMSLOE

STATE HISTORIC SITE

by

CHRISTOPHER WISENER

(Under the Direction of Jon Calabria)

## ABSTRACT

Sea level rise threatens cultural resources at the Wormsloe State Historic Site. Green infrastructure techniques known as living shorelines offer protection from coastal erosion, enhance environmental conditions and can adapt to sea level rise when located properly. This research developed a living shoreline suitability pilot model to determine the most suitable locations for living shoreline placement at the Wormsloe State Historic Site. Then, the model was compared to oyster recruitment data collected in the waterways tested in the suitability pilot model. The combination of recruitment data and suitability results determined that living shorelines could be implemented around the Wormsloe State Historic Site. The results display that living shorelines are suitable for the shorelines around Wormsloe and could be a successful climate adaptation strategy for the future.

INDEX WORDS: Living Shorelines Oyster Recruitment Climate Resiliency Wormsloe State Historic Site

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# DEDICATION

I would like to dedicate my work to my family who has always supported and encouraged me to be the best that I can. I would also like to dedicate this to my fiancé Hannah.

ACKNOWLEDGEMENTS

I would like to thank Jon Calabria who constantly helped me in my search to learn more about the Georgia coast and ecological restoration. I also want to thank Sarah Ross the Director of the Wormsloe Institute for Environmental History for selecting my research to be funded through a Wormsloe Fellowship. I want to thank Craig and Diana Barrow and the rest of the Wormsloe Institute board members for allowing me the opportunity to receive my education and conduct meaningful research on challenging and rewarding topic. I want to especially thank Alison Smith. I want to thank her for her months of work with me to get my GIS models to run. I want to thank Tom Bliss, Mark Risse, and especially Rob Hein of UGA MAREX for their support and collaboration on running the oyster recruitment study. I also would like to thank GA DNR staff Gretchen Greminger and CRD staff Jan Mackinnon, Deb Barreiro and others for their advice and cooperation for potential future projects. Thank you to all of my professors in the Master of Environmental Planning and Design program my courses and skills developed in the classroom prepared me to complete this thesis.

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# CHAPTER 1

## INTRODUCTION

Bank erosion and subsequent failure threaten cultural resources at the Wormsloe State Historic Site on the Isle of Hope. Currently, the erosion is due to a tidal creek meandering into a portion of the eastern bank of the Isle. The tidal creek known as Jones Narrows was significantly altered after the installation of the Diamond Causeway coastal highway in the 1971. As the waterway attempts to return to its original state it has destabilized the bank and upland area near the Wormsloe Tabby Fort Ruins. Sea level rise will likely exacerbate the destabilization of the shoreline. This scenario establishes the need for coastal protection and bank stabilization. A living shoreline in the form of an oyster reef can offer protection from erosion and provide ecological benefits that shoreline hardening such as a bulkhead cannot (Bilkovic et al. 2017).

Living shorelines are not suitable in all locations (Bilkovic et al. 2017). Living shoreline suitability can be modeled using ArcGIS software to produce maps depicting locations with the physical characteristics needed for living shoreline implementation. The goal is to develop a living shoreline suitability pilot model centered around the Wormsloe State Historic Site and to my knowledge is novel for the state of Georgia. A literature review was conducted and found no living shoreline suitability model for areas within the state of Georgia. Currently, living shoreline suitability models (LSSMs) exist for states on the eastern seaboard like Connecticut, Maryland, North Carolina and Florida. This pilot aims to be a tool used by Wormsloe State Historic Site staff and state decision makers for climate resiliency adaptation measures in the future.

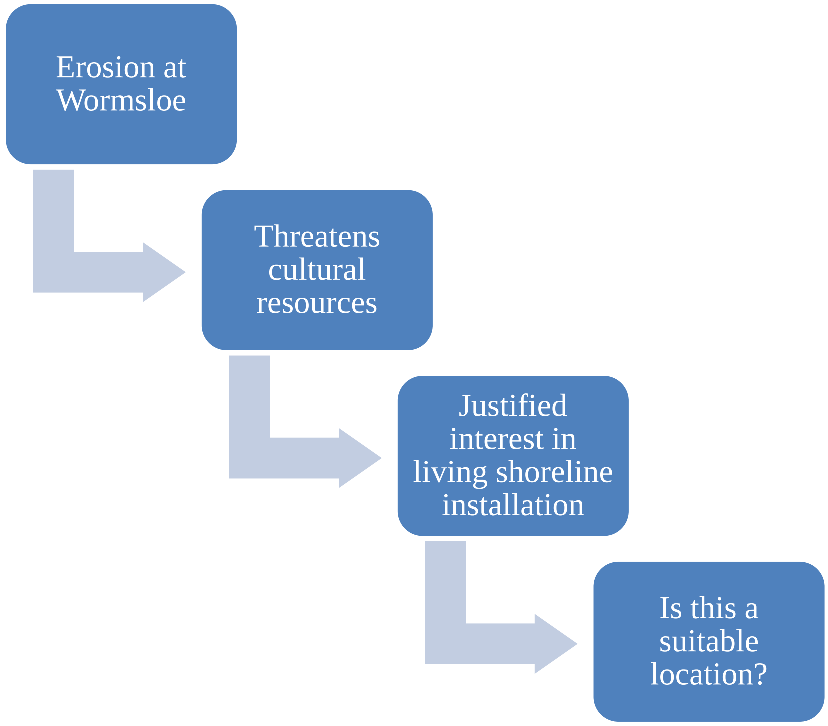



Figure 1: Process for establishing the interest in living shoreline research at the Wormsloe State Historic Site. The diagram depicts the thought process and justification for the research on living shoreline suitability at Wormsloe

The Wormsloe scale LSSM pilot study is twofold. The ArcGIS suitability model was also developed with the goal of cross referencing suitable locations with oyster recruitment data from an ecological observation study conducted during the summer of 2017. Recruitment is when larvae known as spat attach to a substrate (Seabrook 2012, 202). Areas that are suitable for living shorelines due to the physical site conditions could be analyzed in reference to locations where oyster recruitment occurred; yielding areas where hybrid living shorelines such as oyster reefs could be successfully implemented.

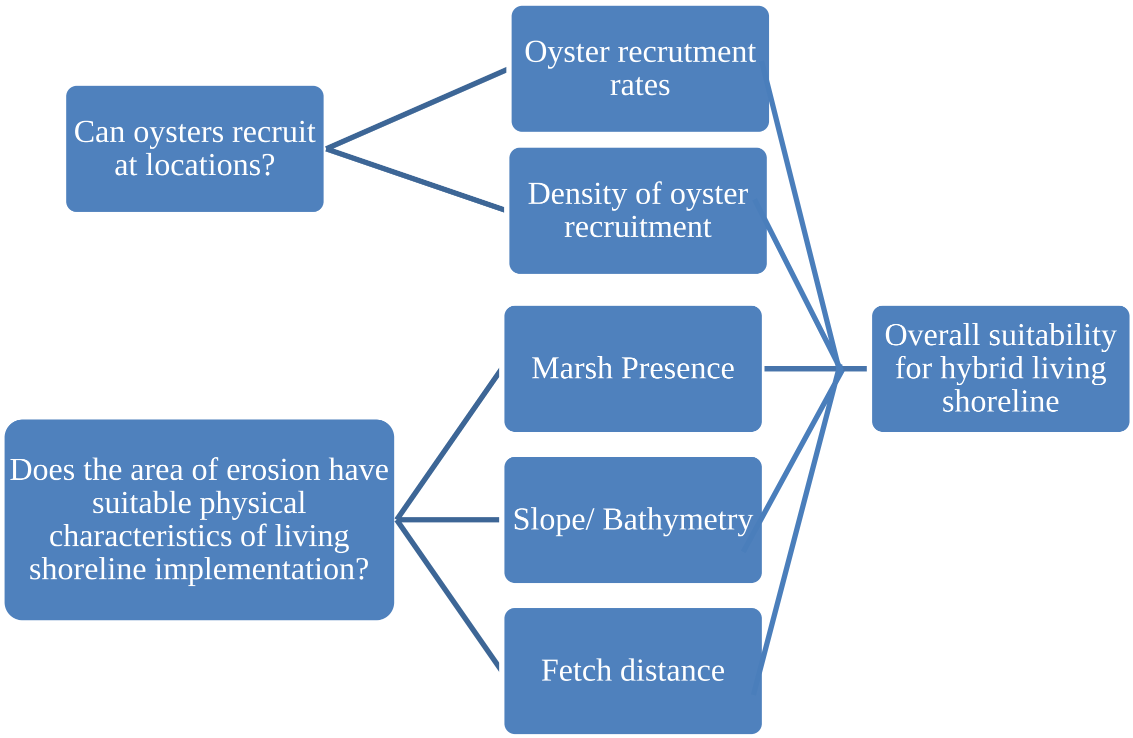



Figure 2: Diagram depicting the relationship between the geospatial analysis and the ecological observation study. The combination of the successful recruitment of oysters and areas deemed suitable by the model would be ideal for hybrid living shoreline installation.

The first chapter of this thesis establishes the historical importance of the Wormsloe State Historic Site detailing important events, historical individuals that have visited the site and provides justification for its protection from erosion. The introduction also provides background on living shorelines, global climate change and the limitations and delimitations of this research. Chapter Two, the literature review discusses oyster recruitment studies in Georgia and living shoreline suitability models. Chapter Three, the methods discusses the processes of creating and executing the ecological observation study on oyster recruitment and the development of the ArcGIS LSSM pilot for Wormsloe. Next, Chapter Four discusses the results of both the model and the study. Finally, Chapter Five is a conclusion discussing areas for future research and lessons learned after the completion of this research.

***Wormsloe State Historic Site: Historical and Archeological Resource***

The state of Georgia has the second largest amount of salt marshes in the United States and contains a third of all of the salt marsh habitat along the eastern seaboard (UGA Marine Extension 2018). "The one hundred miles of Georgia's coast has approximately one-half million acres of marshland, each marsh ranging from 4 to 8 miles wide" (UGA Marine Extension 2018). Georgia's coastal area an important ecological region is also rich in historically significant sites and cities. Savannah, Georgia's largest coastal city, is one of the earliest established cities in America and is rich in historic structures, buildings, and sites of Revolutionary War and Civil War skirmishes. Savannah has continued to grow outward and sprawl onto islands and former marshland habitats. The Isle of Hope just east of Savannah, Georgia is home to the Wormsloe State Historic Site. The northern half of the Isle contains suburban development, roadway infrastructure, and a local marina. The southern portion that includes Wormsloe is heavily forested, has little impervious cover and few only one private dwelling. Craig and Diana Barrow own the only private residence on the southern portion of the Isle of Hope. Craig Barrow and his family are the direct decedents of Noble Jones and have held continuous residence at Wormsloe since its settlement in 1736 until the present day (Swanson 2012).

The history of Wormsloe and the Isle of Hope dates back further than the British colonial period and establishment of the Georgia colony. Native American populations, specifically the Guale people inhabited the area at least until the 1600s (Cady and Goetcheus 2015). Guale people were semi-nomadic. The Guale lived in villages growing crops during warmer months while in the winter tribes relied on hunting, fishing and shellfish gathering for sustenance. (Cady and Goetcheus 2015) The Guale are believed to be the creators of the large oyster middens that line the eastern shorelines of the Isle of Hope at Wormsloe. (Swanson 2012; Cady Goetcheus 2015)

### *Colonial Period*

In 1736 Noble Jones, the founder of Wormsloe leased 500 acres of land from James Oglethorpe and in 1737 began settlement of the strategic peninsula that protected alternative river entry to Savannah (Coulter 1955). Archeological explorations of the Fort House Ruins found that one of the first homes was present at Wormsloe as early as 1737 (Kelso 1979). The war of Jenkin's Ear, a dispute between England and Spain broke out in 1739 and escalated as a result of Oglethorpe's failed attempt to capture St Augustine from the Spanish in 1740 (Averitt 1964). Archeological investigations of Wormsloe suggest that the original home of Noble Jones expanded into a fort complex between 1739 and 1744 complete with scout boats, a company of twelve marines and a cannon (Coulter 1995; Kelso 1979; Kimber 1974). Tabby was used to construct the Wormsloe fort; tabby is a building material made from oyster shells, lime, and sand typically found in the low country of Georgia (Kelso 1979).

John Bartram, one of the most prominent natural botanists in history, is thought to have visited Wormsloe. Bartram visited the nearby Bethesda Orphan House and described a nearby forested property containing "pomegranates, figs, oranges, peaches, apricots, grapes and nectarines" (Bartram 1942; Cady and Goetcheus 2015). Exotic plants were a staple of Wormsloe during the period as Noble Jones was an avid horticulturalist. Fruit trees were not the only staple of Wormsloe agriculture. George Jones, Noble Jones grandson hired John Rawls in 1810 to grow cotton at Wormsloe and manage slaves on the property (Cady and Goetcheus 2015; Historical De Renne Family Paper). Jones family tax records state that in 1819 125 acres on the Isle of Hope were planted in Sea Island cotton (Cady and Goetcheus 2015; Historical De Renne Family Paper).

### *The Civil War Era*

Approximately forty slaves worked on the property through the remainder of the 1850s and into the 1860s as Noble Jones descendant G. Wymberley Jones increased cotton production at Wormsloe (Bragg 1999). Production continued throughout the civil war as the Emancipation Proclamation was ineffective and slaves remained at Wormsloe. The Civil War Era saw a transformation of Wormsloe from a place of agriculture to key military infrastructure. In 1862 Confederates prepared for the inevitable confrontation with Union forces.

The Confederates constructed a sizeable earthen fortification on the southern tip of Wormsloe, known as Ft. Wimberley. (Bragg 1999) Construction on the fortifications began around March 1862, following the Confederate evacuation of Skidaway Island (Bragg 1999). An escape causeway was created, called 'New Exit' was built from Skidaway Island to a southern point on Wormsloe this is one of the earliest modifications of tidal flows in the area. (Bragg 1999) Ft. Wimberly housed six pieces of field artillery. A regiment of fifty men and two officers more than tripled to 176 men on the Isle of Hope by the summer of 1864 (Coulter 1995). Savannah surrendered to Union control in December of the same year. After seizing Savanah, General William Tecumseh Sherman sent forces out to occupy Confederate strongholds. (Bragg 1999) The Federal government occupied Wormsloe until March 29, 1865, (Letter from WB Hodgson to GW Smith, March 29, 1865, George Wymberley Jones De Renne Family Papers)

After the Civil War, Wormsloe and the descendants of Noble Jones returned to natural resource extraction and management as a way of life.  Oysters became a prominent source of food and income as Edward M. Nelson was granted an oyster lease for the western side of Wormsloe on January 8, 1870. (280) Wormsloe continued as a center for agricultural production, saw the expansion of the main home into a large main residence with formal gardens open to the public with admission. Change around Wormsloe further intensified after World War II.  The importance of oysters was again noted, as a study was conducted to determine the reason for their disappearance around the Isle of Hope. The study concluded a boring sponge (Cliona spp.) and waterway pollution had decimated the oyster population and had prevented the Nelson family from harvesting oysters in the tidal marshes around Wormsloe. (Linton 1968)

***Modern Wormsloe***

Tidal marsh and ecological dynamics around Wormsloe and the Isle of Hope continued to be altered by development as the construction of the Diamond Causeway began in 1969 (Bragg 1999). The Diamond Causeway was completed by 1971 and spurred the development of Skidaway Island. Surrounding development continued to increase the value of the Wormsloe estate leading to a significant tax burden on the family of Noble Jones decedents (Swanson 2012). This led to the creation of the Wormsloe Foundation to hold, monitor and attend to land holdings. The Wormsloe Foundation donated lands to the Nature Conservancy on December 31, 1972; the Nature

Conservancy then transferred the Wormsloe land holdings to the state of Georgia (Swanson 2012). Wormsloe was nominated to the National Register of Historic Places and accepted on April 26, 1973 (Swanson 2012). The official ceremony to pass the land to the State Georgia occurred on August 18, 1973.

The construction of the Diamond Causeway produced fill and debris that was left at Wormsloe to alter and block tidal flows. (Cady and Goetcheus 2015) In 1977 the Georgia Department of Natural Resources (GA DNR) agreed to remove the fill, a tidegate next to the bridge over the Moon River, a road from Wormsloe to the Diamond Causeway, and reopen the canal to the Isle of Hope River (Daniels 452). A 1979 aerial of the property displays siltation of the marshes between Wormsloe and Long Island resulting in the blocking of the Isle of Hope River. State development of infrastructure and control of the former one thousand acres Wormsloe estate had resulted in tidal estuarine dynamics much different from those when Noble Jones first settled the Isle of Hope.

Wormsloe remains a site highly valued for ecological and cultural importance and is a symbol of the environmental movement on the Georgia coast. In 1973, the acting Governor and future President of the United States Jimmy Carter declared that the establishment of the Wormsloe State Historic Site served as a victory against, "the bulldozer of misguided progress [that] is awaiting the signal to destroy your heritage and mine" (Swanson 2012). Former President Jimmy Carter has often stated his love for the Georgia coast. The former state governor and US President visited Wormsloe in 1972 he left the property certain that it was worth preserving (Swanson 2012). President Carter declared that Wormsloe was the intersection of natural resources and a landscape that reminds all that visit of the region's past human history and should be protected for future generations (Swanson 2012).

### *The Coastal Marshlands Protection Act*

President Carter's visit to Wormsloe and the protection of coastal resources exemplify the environmental movement to protect the Georgia Coast during the 1970's. Concern grew around the coast over the conversion and degradation of Georgia's coastal marshes (Kundell et al. 1988) The Coastal Marshlands Protection Act (CMPA) of 1970 allowed for the state of Georgia to regulate and permit activities that would degrade or convert coastal marshlands (Kundell et al. 1988). The CMPA jurisdiction under the law is any alteration of salt or brackish marsh which requires a permit from the Coastal Marshlands Protection Committee. Jurisdiction areas of the CMPA are defined as any marsh lying within the estuarine environment that is tidally influenced and within the tide elevation range (Kundell et al. 1988).

The actions of the Kerr-McGee Corporation of Oklahoma spurred the creation of the CMPA and much of the environmental movement to protect the Georgia coast (Seabrook 2012). The Kerr-McGee Corporation quietly and methodically purchased thousands of acres of marshlands and small islands on the Georgia coast. The corporation revealed their intentions to strip mine the marshes, river bottoms, and seabeds of an area encompassing 25,000 acres (Seabrook 2012). The news of massive landscape changes at the hands of an out of state mega-corporation for profit shocked residents and legislators throughout the state. This led to the advocacy for the protection of marshland habitat and the eventual signing of the CMPA by Governor Lester Maddox (Seabrook 2012).

Although the CMPA is an all-encompassing piece of legislation that regulates any attempt to alter marshland habitats in Georgia, there are several exemptions to the Act's permit requirements. First, any activity of the Department of Transportation related to constructing, maintaining or repairing the public road system in Georgia is exempt from permitting (Kundell et al. 1988). Second, public utilities regulated by the Public Service Commission activities related to construction, repair or maintenance of utility infrastructure are not subject to permits (Kundell et al. 1988). Activites associated with installation and repair of railroad lines are exempt from permitting. Finally, the construction of private docks on pilings, and walkways over marsh grass build by landowners are not subject to permitting requirements (Kundell et al. 1988).

Permits issued by the Coastal Marshlands Protection Committee must be in and consider the 'public interest' (Kundell et al. 1988). The CMPA defines areas of public interest as for whether or not "any unreasonably harmful obstruction to or alteration of the natural flow of navigational water with the affected area will arise as a result if the proposal" (Kundell et al. 1988). It also defines areas of public interest as "wheter of not unreasonably harmful or increased erosion, shoaling of channels or stagnant areas of water will be created to the contrary of public interest" (Kundell et al. 1988). Finally, the CMPA defines the last category of public concern to be "whether or not the granting of a permit will unreasonably interfere with the conservation of fish, shrimp, oysters, crabs, clams, or any of the marine life or wildlife". This also includes natural resources including water and oxygen supply (Kundell et al. 1988).

***Global Climate Change and its threats to the Planet, Georgia, and Wormsloe***

It is widely acknowledged that global climate change is causing drastic changes across the planet. Climate change is causing increases in temperature across the southeastern United States. Since 1970, average annual temperatures in the region have increased by about 2°F (EPA 2017; Carter et al. 2014). The most significant impact of temperature increases is in the summer where heat waves are intensifying and increasing in duration (EPA 2017; Carter et al. 2014). Temperatures in the region are expected to increase an additional 4°F to 8°F by the end of the century (EPA 2017). Rising temperatures result in more days of extreme heat and fewer freezing events on average during the colder winter months. Coastal regions compared to inland areas will be spared as heatwaves, and temperature fluctuations will be most significant in inland areas.

Rising global temperatures will also have implications that affect other weather and climatic cycles. El Niño Southern Oscillation, atmospheric pressure systems, and tropical weather systems are anticipated to be altered by rising temperatures while simultaneously driving short-term temperature fluctuations. Changes in temperatures and weather systems will also significantly alter rainfall totals. Storm events have already increased in the Southeastern United States (Carter et al 2014). There has also been a simultaneous escalation of intensity, frequency, duration, and strength of Atlantic Ocean hurricane activity since the 1980's. The 2017 hurricane season (the most recent on record) was one of the most active, deadly, and the most destructive (in USD) on record. The season produced three particularly devastating storms Harvey, Irma, and Maria. Research and media coverage often focuses on the intense storms and flooding, however, in addition to some wet periods, the southeast has also experienced periods of extreme drying (Carter et al. 2014).

### *Sea Level Rise*

Climate change will likely harm property, cultural resources, and coastal ecology. Sea level rise, intense hurricanes, and storm surge threaten coastal populations and ecosystems in the Southeast. Rising sea levels are results of both increased warming of oceans and ground subsidence (sinking). Many locations in the Southeast are vulnerable to the impacts of sea level rise. Southern cities, Miami and New Orleans are experiencing ongoing problems associated with rising seas, but all of the southeastern coasts will feel the impacts (EPA 2017). Scientists state with high confidence that global sea-levels in the year 2100 will be at least eight inches higher than the present, but could potentially rise by up to 6.6 feet (Parris et al. 2012). Future projections indicate that sea level will rise will accelerate "throughout the rest of this century and is expected to exacerbate existing threats in this region" (Carter et al. 2014). Sea level rise will also lead to shoreline erosion, decrease the number of wetlands and threaten coastal infrastructure (Carter et al. 2014).

Large areas of the US southeast are under threat from sea level rise and areas of coastal Georgia rank from moderate to very high risk on the *Coastal Vulnerability Index*. "The Coastal Vulnerability Index is based on tidal range, wave height, coastal slope, shoreline change, landform and processes, and historical rate of relative sea level rise" (Carter et al. 2014). Sandy shorelines and coastal marshes are under increased threat from sea level rise. Shoreline retreat is more dynamic than just inundation as a complex feedback loop occurs within the littoral zone impacting beach erosion and migration and loss of marshlands (Passeri et al. 2015). Long term gradual shoreline loss is thought to be mainly driven by sea level rise and alterations in sediment supplies this threatens barrier islands and other coastal shoreline gradients.

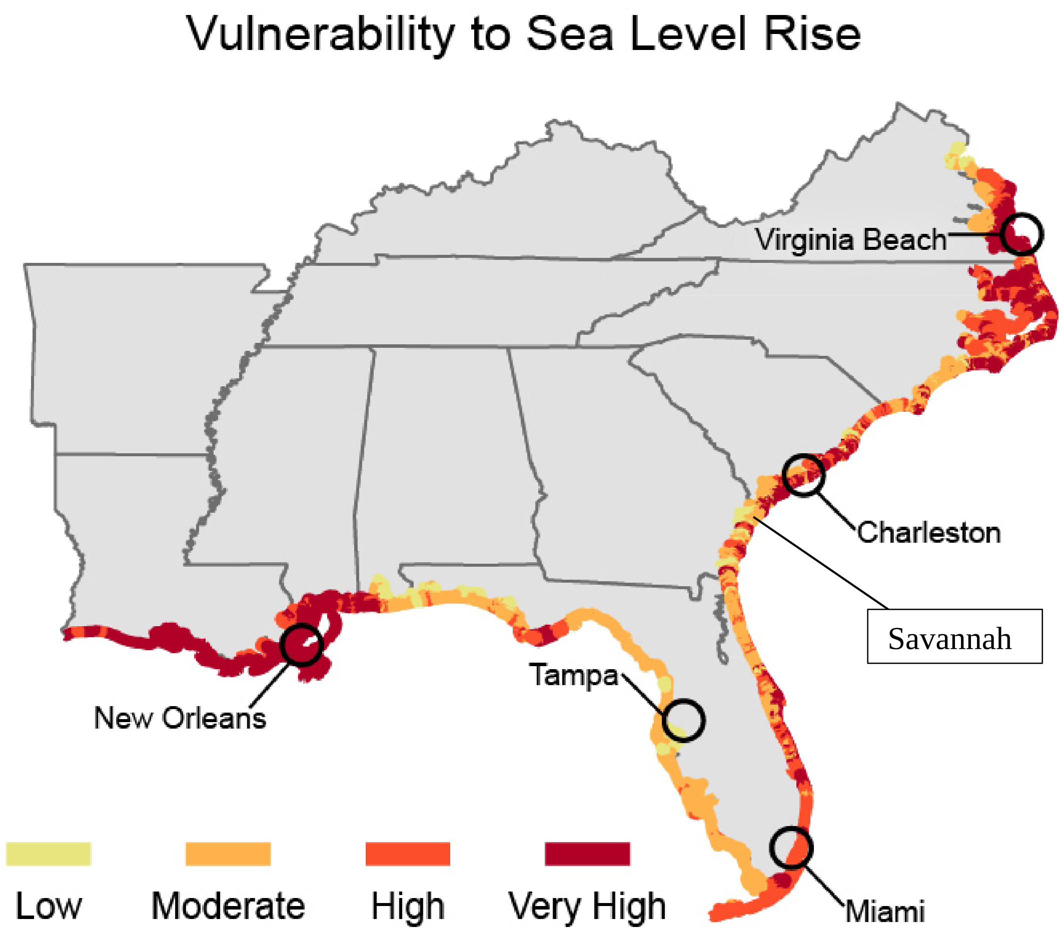



Figure 3: Displays shoreline vulnerability to sea level rise for the southeastern United States. Savannah and most of the Georgia coast is are listed from moderate to very high taken from (US EPA 2017)

### *Salt Marshes Under Threat*

Climate change not only threatens coastal shorelines the impacts from a destabilizing climate significantly impact the survival of salt marsh habitats. Salt marshes are under threat from a two-pronged attack from climate change. Inundation, as previously discussed will flood marshland habitats and force marsh migration inland. Climate change will likely increase the frequency and intensity of storm activity. Storm activity increases marsh vulnerability and erosion (Wigand et al. 2015). Barrier islands act as a buffer to the open ocean to marshland habitats and estuarine environments. Storms such as tropical cyclones and hurricanes drastically increase erosion rates and stability of barrier island shorelines (Nebel, Trembanis and Barber 2013). Barrier island and marshland habitat loss will likely increase in the future due to sea levels rising and storm frequency and intensity increasing.

Marshes also face threats from higher temperatures and drought. In 2002 coastal Georgia experienced high temperatures and prolonged drought. During the summer of 2002, nearly 1000 acres of marsh experienced what is known as sudden marsh dieback. The marsh dieback was due to the prolonged drought and high temperatures that altered the pH of the marsh soil (Seabrook 2012, 223-226). The change in pH led to the Spartina alterniflora up taking metals in the soil and reduced the ability of the marsh to take in freshwater from rivers and streams (Seabrook 2012, 223-226). The need for freshwater uptake is problematic as in the future freshwater supplies will be scarcer due to climate change.

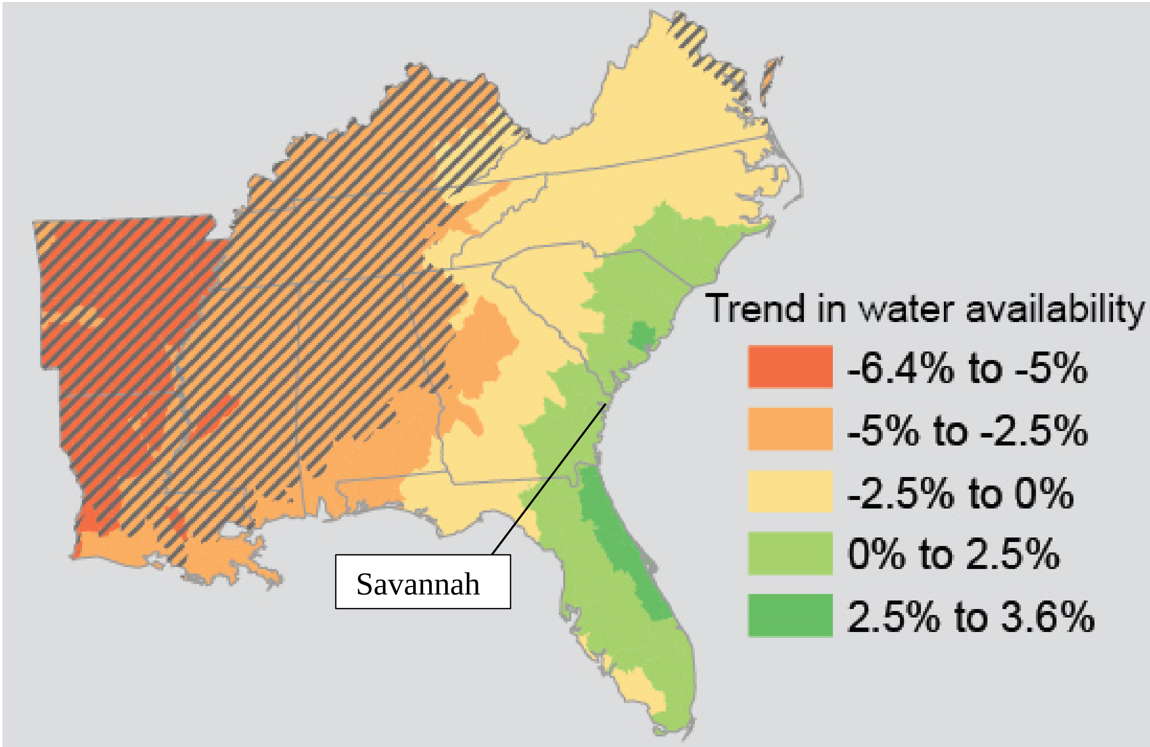



Figure 4: Displays future water scarcity in Georgia based of climate projections (hatched area displays area of extreme drying while areas in green are likely to gain freshwater availability, from (US EPA 2017)

Although, the Georgia coastal region's freshwater availability may increase in the future based on current predictions other areas of the state will not be as fortunate. Most of the state of Georgia will see a decrease in freshwater supplies up to 5% (Carter et al. 2014). The decrease in freshwater availability will place additional strain on rivers and tributaries leading to the Georgia coast. Freshwater availability is the leading factor in Spartina alterniflora production and growth (Wieski and Pennings 2014). River discharges that decrease salinity along with temperature were found to be the greatest factors that impact the most common marsh grass growth. Large-scale loss of marshes from lack of future growth or sudden marsh dieback could be catastrophic for the Georgia coast. Populations of bird, shrimp, crab, and fish would be without habitat (Seabrook

2012). Without the marsh grass, Spartina marshes would experience heavy erosion causing marsh soils to erode into tidal creeks further exposing upland shoreline to erosion (Seabrook 2012).

### *Georgia's Coastal Vulnerability*

The negative impacts that climate change will bring to the Georgia coast have not gone undocumented. Recent vulnerability assessments found that Chatham County is one of three counties of Georgia's 159 total to receive the highest vulnerability ranking possible (KC, Shepherd and Gaither 2015). The Georgia Coastal Management Program ranked coastal hazards such as flooding, shoreline erosion, and sea level rise as the highest priority for coastal planning (GADNR 2015). The program identified that 43% of the Georgia coastal shorelines are vulnerable to erosion. Also, the Coastal Management Program identifies that 77% of the Georgia coast is vulnerable to sea level rise (GADNR 2015). The threats of sea level rise, drought, heatwaves, marsh dieback, and increases in storm frequency and intensity will lead to increases in shoreline erosion in the future. This serves as a justification of the importance in finding future solutions to shoreline erosion.

### *The Eastern Oyster, Crassostrea virginica*

The Georgia coastal region has an unusually high tidal amplitude and high levels of water fluctuations daily (Byers et al. 2013). Georgia also has some of the highest levels of Eastern Oyster *Crassostrea virginica* recruitment in the country (Byers et al. 2013). The Eastern Oyster *Crassostrea virginica* dominates the marshland landscape in the area known as the South Atlantic Bight due to its larger intertidal area available from the six to nine-foot tidal range and flat topography (Seabrook 2012, 200; Stevens 1983, 4). In addition to a larger intertidal range, the Georgia coastal tides flush marshes and mix algae, detritus and organic matter into waterways that act as food sources for oyster populations (Seabrook 2012, 200). Oysters thrive in areas draining muddy waterways where organic matter is high (Stevens 1983, 8). Oyster reefs develop where chemical cues and physical conditions mix to create suitable locations. Adult oysters release a biochemical substance into the water that attracts new larvae (Stevens 1983, 39). Exact factors controlling the spatial distribution of oyster reefs are unknown, this is exemplified by oyster larvae being ubiquitous, yet reefs have a discontinuous distribution throughout Georgia (Stevens 1983, 6).

***Reef Locations***

Oyster reefs rarely colonize areas of high wave energy and can only withstand sedimentation rates of 2 to 5cm annually; oyster larvae require a substrate to attach to, water currents to import food and remove sediments (Seabrook 2012, 201; Stevens 1983, 9). Reefs are often in areas of high current velocity, low sediment deposition, and on soils with higher clay components as opposed to sandy soils (Stevens 1983, 58). Oyster reefs are also frequently within tidal creek systems. The location of reefs within tidal creek meanders is predictable; reefs occur at intervals of 5.1 times the width of the stream (Stevens 1983, 128). A study analyzing oyster reefs and feeding habits in a tidal creek of Sapelo Island found that oysters create dams within creek systems resulting in ponds formed at low tide (Stevens 1983, 129). The ponds serve as a new cyclical environment where microbes and diatoms on oyster reefs increase in production from nutrients such as phosphorus and ammonia added to the water from oyster feces (Stevens 1983, 129). Oysters then feed on the microbes and diatoms along with Spartina alterniflora detritus. Spartina alterniflora detritus (and its microbes) are the most abundant food supply for oyster populations on the Georgia coast (Stevens 1983, 130).

Although Eastern Oysters require suitable site conditions, once established they can endure fluctuations in temperature, high turbidity, changes in oxygen levels and for short durations, changes in salinity (Seabrook 2012, 201). Oysters become sessile once attached and remain in one location for the entirety of their lives. Oyster populations build on each other creating reef structures that grow as new oyster larvae attach to older ones and become new spat (Seabrook 2012, 201). Spat are attached oyster larvae (Seabrook 2012, 202).

Oyster reproduction occurs during warm weather months ranging from May to September. During this timeframe warm temperatures and light prompt male oysters to release sperm, followed by females releasing eggs into waterways (Seabrook 2012, 202). Tidal currents assist in dispersing the larvae, but after two to three weeks larvae develop the ability to move through the water column in search of hard surfaces to recruit on (Seabrook 2012, 202). The chemical cue of ammonia associated with oyster reefs can signal to larvae suitable locations to settle (Seabrook 2012, 202). Once attached larvae become known as spat and the process of recruitment has occurred. Soft-shelled until about two inches in size, oysters fall prey to a host of predator in marshland habitats. At two inches in size oysters have built up strong shells of calcium carbonate, reducing the threat of predation (Seabrook 2012, 202). Established oyster reefs act as ecosystem engineers continuing to spread interacting with nearby marshland species.

### *Historical importance of Oysters in Georgia*

Although oysters permeate the coastal marshlands of Georgia, populations are at historic lows (Seabrook 2012, 203). Oysters have historical significance to the Southeast and coastal Georgia. The first legislation in Georgia regulating oyster management passed in 1873. Due to good management practices and public support the largest record season catch for oysters was set in 1908 when over 8 million pounds of Georgian oysters were harvested. Georgia had since lost its first-place record in oyster production in 1979 the state industry brought in only 11,375 pounds of oyster meat (Stevens 1983). Oyster populations can recover if restoration efforts are taken to increase the total acreage of oyster reefs and subsequent reproducing populations (Stevens 1983). In the Apalachicola Bay, Florida, the oyster fishery suffered a collapse and is within a string of environmental stressors to this region that has included hurricanes, tropical storms, and intense drought (Camp et al. 2015). The oyster population decline is thought to be linked to a series of anthropogenic and environmental stressors that including storms, drought, increased predation, disease, and habitat loss (Camp et al. 2015). Global climate change will exacerbate many of these stressors to oyster populations in the future.

### *Oyster Restoration*

Reef restoration efforts have gained momentum in nearly every state on the eastern seaboard and the Gulf of Mexico. States have recognized the various beneficial ecosystem services that oyster reefs provide such as water filtration, erosion control, and providing habitat to other estuarine species. The restoration of the oyster reefs will depend on the execution of best management practices including a reduction in harvest amounts and extensive habitat restoration (Camp et al. 2015). Building a successful oyster reef requires various resources and a suitable location. The first step of reef restoration is the placement of new material to provide a settlement location of new oyster populations (Seabrook 2012, 205). Cultch, the hard substrate also needs to be placed in a suitable location. Locating cultch in a suitable location becomes difficult as salinity, water flow, temperature, and food sources must be adequate for oysters to colonize the new reef substrate (Seabrook 2012, 205).

Suitable substrate is at a premium as other organisms such as barnacles will outcompete oysters for suitable substrate (Stevens 1983, 39). Cultch material can range from cement coated bamboo stakes, PVC pipe, tree logs, or pieces of cement; recycled oyster shell is the most preferred substrate for reef restoration (Seabrook 2012, 205). Newly established reefs can be rapidly successful in restoring ecosystem services to suitable locations. In Florida, seven acres of oyster mats placed in the Mosquito River Lagoon within the Canaveral National Seashore took hold. One year later, the restoration efforts yielded healthy oyster reefs that were home to more than one hundred species utilizing the reefs. Within two years, restored reefs in South Carolina had colonies of oysters, crabs, mussels, and had Spartina alterniflora growing behind them signaling that the reefs were preventing erosion (Seabrook 2012, 206). The use of oyster reefs as an erosion control/ shoreline stabilization technique has become more popular and referred to as a living shoreline.

### *Living Shorelines*

Currently, 90 % of global coastlines are experiencing coastal erosion, and large portions of the United States are experiencing long-term erosion trends (Passeri et al. 2015). Traditionally, coastal armoring, also known as coastal hardening has been the solution to coastal erosion issues and implemented globally. There are five main types of shoreline hardening seawalls, bulkheads, riprap revetments, breakwaters, and sills (Gittman et al. 2016). "Shoreline hardening, defined as the installation of engineered-shore structures to (a) stabilize sediment and prevent erosion and/or (b) provide flood protection" (Gittman et al. 2015, 763). Currently, over 22,000 kilometers (roughly 14%) of shorelines within the United States are hardened (Gittman et al. 2015, 763). Shoreline hardening will increase in the future as estimates predict by 2100 33% of total US shoreline will be hardened (National Ocean Service 2017). Increases in shoreline hardening predict movements of populations to coastal areas, and rising sea levels increase the needs for coastal erosion control. Shoreline hardening negatively impacts local ecosystems and reduces coastline capacity to provide habitat, absorb and reduce floodwaters, and adapt to changes in water levels over time (Bilkovic and Mitchell 2017). Urban shorelines that are armored also trap marshes from migrating inland as a result of sea level rise.

***The Advantages of Living Shoreline Implementation***

Living shorelines are the ideal form of shoreline protection technique as they can reduce erosion rates, allow for biological processes to occur and can adapt to rising sea levels (Bilkovic et al. 2017). Living shorelines are a green infrastructure technique using native vegetation alone or in combination with offshore sills to stabilize the shoreline" (NOAA 2017). "Through the promotion of native species and habitats, living shorelines can preserve and enhance the ecological integrity of the coastal environment (GA DNR 2013).  Living shorelines utilizing oyster reefs have been found to be particularly successful in adapting to sea level rise when placed in the most suitable locations (Bilkovic et al. 2017). The suitable locations of living shoreline utilizing oyster reefs serve as the main interest for this thesis research.

The advantages of living shorelines are numerous. Living shorelines create a vegetated buffer that absorbs wave energy and reduces erosion rates (GA DNR CRD 2017). Living shorelines mimic natural shoreline dynamics and allow for connection between upland and aquatic habitats; preserving habitat for aquatic plants and animals can restore habitat for fish populations (GA DNR CRD 2017). In addition to being equal or less expensive to traditional shoreline hardening techniques such as bulkheads living shorelines can trap and retain upland runoff (GA DNR CRD 2017). This reduces nutrients and pollution entering waterways.

### *The Living Shoreline Spectrum*

The types of living shorelines are numerous and range on a spectrum from lower impact marsh grass plantings to gray materials such as breakwaters and oyster structures (Figure 5). The different types of living shoreline materials allow for customization of shoreline design for specific site needs. Marsh grass plantings are the least impactful treatment for sites in need of shoreline stabilization. Breakwater and sills increase disturbances in marshland habitats.

| | Material type | Description | Function |
|---|---|---|---|
| Green Materials | *Marsh grasses* | Native grasses planted within the intertidal or mid-intertidal area or at the mean high tide mark. Plantings may be more successful when performed in Spring in areas of existing marsh where there is < 3 miles of open water, and where the prevailing winds will not destroy the newly established vegetation. | Dissipate wave energy<br>Filter upland runoff<br>Improve habitat for fish and wildlife<br>Base of food web |
| | *Mangroves* | Mangroves are woody plant communities that are found in estuarine tropical and subtropical environments including central and southern Florida, and portions of south Louisiana. | Stabilize shoreline<br>Trap sediments and nutrients<br>Dissipate wave energy<br>Provide habitat for fish and wildlife |
| | *Tree and grass roots* | Vegetation colonized naturally or planted. Common riparian vegetation used at specific sites differ depending on the species native to that area, but typically includes a combination of native woody trees, shrubs, and grasses. | Stabilize the riparian zone above high tide<br>Minimize bank erosion<br>Filter upland runoff<br>Provide habitat |
| | *Submerged aquatic vegetation* | SAV is vegetation rooted in the substrate of a body of water (usually no deeper than 10 feet) that does not characteristically extend above the water surface and usually grows in beds. Creates a natural shoreline buffer when used with other living shoreline components such as marsh grasses, reduces coastal erosion via root growth. | Dissipate wave energy<br>Stabilize sediments,<br>Improve water quality<br>Provide habitat<br>Base of food web |
| | *Natural fiber logs (bio-logs)* | Made of biodegradable coconut fiber and netting. Logs are placed at the foot of bank slopes or in the water, molded to fit the bank line, and then anchored in place. | Stabilize slopes and minimize bank erosion<br>Trap and retain sediment<br>Retain moisture |
| | *Filter fabric* | A porous layer of geotextile material placed beneath rock sills and breakwaters, or under oyster bags to prevent sand movement into or through the rock, concrete structure, or oyster shell bags. | Trap sediments |
| | *Natural fiber matting* | Made of coir fiber, wood, straw, jute, or a combination of organic, biodegradable materials. | Prevent sediment loss<br>Trap sediment<br>Stabilize shoreline |
| | *Oyster reefs (natural)* | Oyster reefs can be enhanced or created at living shoreline sites as protective structures. Oyster shell bars use natural shell material (e.g., oyster shell bags, oyster encrusted mats), and appear and function similarly to a natural shoreline oyster reef when mature. | Dissipate wave energy<br>Decrease erosion<br>Provide fish habitat<br>Improve water quality |
| Gray Materials | *Low-crested segmented rock sills* | Freestanding rock structures placed in the water parallel to shore. Sills are generally segmented and stand no more than 6 to 12 inches above mean high water so that boats- and wind- induced waves can pass over the sill and wildlife has access to the water and the shoreline habitat. | Dissipate wave energy<br>Protect eroding marshes and shorelines |
| | *Breakwaters* | Structures constructed from rock, rubble, or recycled concrete that are placed parallel to the shore in medium- to high-energy open-water environments. Can be seeded with oyster spat to create a "living" breakwater where conditions are suitable for oyster growth. | Dissipate wave energy<br>Provide habitat<br>Stabilize shorelines<br>Improve water quality |
| | *Sediment-filled geotextile material tubes* | Placed parallel to shore in high-energy environments. The tubes serve as a hard surface on which oysters can construct reefs. | Dissipate wave energy<br>Provide habitat |
| | *Oyster (structures & fabricated)* | Oyster castles or reef balls are hollow concrete structures that provide a surface on which oysters colonize and form small living reefs. Gabions filled with limestone rubble or oyster shell and oyster encrusted crab pots can also create suitable oyster habitat. | Dissipate wave energy<br>Decrease erosion<br>Provide fish habitat<br>Improve water quality |

Adapted from NOAA (http://www.habitat.noaa.gov/restoration/techniques/lsimplementation.html)

Figure 5: This displays the spectrum of living shoreline techniques, from (Myszewski, Margaret A. and Merryl Alber, 2016)

Currently, there are gaps in the research on living shorelines. First, the ecological impacts of installing living shorelines in salt marsh habitats is not fully understood.

Second, the regional environmental consequences of converting subtidal to intertidal habitat and existing soft-bottom intertidal habitat into artificial rocky shore are unknown (Bilkovic et al. 2016; Myszewski and Alber 2016). The conversion of soft bottom intertidal habitat to hard surfaces such as oyster reefs could be less impactful as oyster reefs are at historic lows. In the past, the higher prevalence in oyster reefs would have resulted in more hard structures in soft-bottom marshlands. In the future, living shorelines exemplify promise as a mixed ecological/engineering solution to adapt to coastal stressors (Bilkovic and Mitchell 2017). Living shorelines offer a solution that can promote human and ecological coastal resilience. Due to the current gaps in living shoreline research and the relatively new field of living shoreline installation all shoreline implementation projects should imitate the surrounding environment wherever possible (Bilkovic and Mitchell 2017).

### *Living Shorelines in Georgia*

Living shorelines are still an uncommon form of shoreline stabilization in Georgia. Throughout the state of Georgia, there are only six completed living shorelines (GA DNR 2013). Living shoreline locations are within the three Georgia coastal counties (Glynn, McIntosh, and Chatham). The six locations are the Tybee Island Burton 4-H Center, Skidaway Island State Park, Sapelo Island Long Tabby, Sapelo Island Ashantilly, Little St. Simon's Island and the St Simon's Island Cannon's Point (GA DNR 2018). The Tybee Island Burton 4-H center living shoreline included the placement of oyster shell bags on an eroding tidal creek bank to substrate for a future oyster reef. Similarly, the Skidaway Island State Park living shoreline was located in a small tidal creek channel that was experiencing erosion threatening a bridge. These two projects appear to be the most similar to the potential site at Wormsloe for living shoreline installation due to their similar tidal creek habitat and low energy environments.

### *Delimitations and Limitations*

The delimitations of this thesis research narrow the scope of the studies. The scope of both the ecological observation study and the LSSM pilot study were confined to the Wormsloe area. The ecological study on oyster recruitment sites were limited to specific areas on the Wormsloe State Historic Site and private land owners Craig Barrow and Craig Bell. Private landowners expressed interest in having oyster recruitment analyzed on their property. The number of sites were also limited due to only one person being able to count oyster recruitment numbers each month. The LSSM pilot study was limited by the study extent of the Wormsloe area. The pilot study was also limited by the lack of LSSMs analyzing the Georgia coastal morphology and physical characteristics.

Limitations of this thesis research identify potential weaknesses of the studies. The type of analysis (weighted overlay) limited the LSSM pilot study. The weighted overlay analysis in ArcGIS is limited due to the cell size of raster inputs, meaning that the entire study is limited by the data that has the largest cell area. Large cell area can lead to data that can be less accurate on the ground due to the large block sizes of cells. Secondly, the model is limited based on the inputs. The model analyzed four inputs, had other inputs been utilized the LSSM pilot study likely would have been different. Finally, weighted overlay analysis requires that each of the input variables receive a weight that determines the importance of that feature to the model. The weight of each input is inherently subjective. Different weights can produce different results altering the model's suitable areas. Although, this research has its limitations and delimitations it is still a strong study analyzing multiple variables and addressing gaps in living shoreline research for the state of Georgia.

# CHAPTER 2

# LITERATURE REVIEW

Coastal erosion and bank failure threaten invaluable cultural resources at the Wormsloe State Historic Site. The Fort Tabby Ruins of Wormsloe are only 250 feet away from were a tidal creek meander is causing bank failure and subsequent vegetation loss. The vegetation on the shoreline at near the Fort Tabby Ruins is minimal in part due to the walking trail that is less than five feet from the shoreline. Historic oyster middens of past native American populations are directly adjacent to the erosion site. Climate change and sea level rise will likely exacerbate the failure of the bank and erosion at Wormsloe. Living shorelines offer an alternative to shoreline hardening and could alleviate bank failure if adequately installed at Wormsloe. The threat of losing cultural resources created the need for a living shoreline suitability model and ecological observation study of the area surrounding Wormsloe.

## *Oyster Recruitment Studies*

This thesis focused on two main topics, ecological observation studies on oyster recruitment and living shoreline suitability models. In Georgia, over the past thirty years, several ecological observation studies on oyster recruitment have been conducted. The production of oysters for aquaculture purposes was the primary focus for past research (Manley, Power, and Walker 2008; Manley, Power, and Walker 2008; Manley, Power, and Walker 2009; Moroney 1997; O'Beirn 1995). Oyster populations and recruitment at Wormsloe have not been studied since just after World War II when a study was conducted to determine the reason for their disappearance around the Isle of Hope. The study concluded a boring sponge (*Cliona spp*.) and waterway pollution had decimated the oyster population and had prevented the harvesting oysters in the tidal marshes around Wormsloe (Linton 1968). The lack of study on Wormsloe oyster populations is a gap in the research that this thesis aims to address.

Studies analyze oysters throughout their natural range in intertidal and subtidal zones. The intertidal area is where the land submerges under the ocean and is exposed from tidal fluctuations (National Park Service 2015). Subtidal areas remain submerged even during low tides. Intertidal oyster reefs are a characteristic of Georgia and South Carolina making them unique to other areas (Moroney 1997; O'Beirn 1995). Oyster recruitment is a complex biological process. During warm summer months oyster larvae are released into the water column (O'Beirn 1995; O'Beirn 1996). Once reproduction has occurred larvae move around the water column and settle on a substrate; this process is not to be confused with recruitment. Settlement is the reversible process where larva explores a substrate and can resuspend into the water column in search of other substrates. Recruitment is the attachment and subsequent survival of the oyster on the selected substrate (Moroney 1997). A study found that the first recruitment is observed in May and peaks in June (Moroney 1997). The majority of settlement occurred between 23.5$^{o}$ C and 29$^{o}$C and peaked at 27.5$^{o}$C (Moroney 1997). Warmer temperatures ranging from 29-31.5$^{o}$C have coincided with low recruitment rates (O'Beirn 1996).

Other studies found that peak recruitment was in August. Methods throughout recruitment studies remain similar as all utilized PVC pipe as recruitment substrate and successfully recruited oysters (Manley, Power, and Walker 2008; Manley, Power, and

Walker 2008; Manley, Power, and Walker 2009; Moroney 1997; O'Beirn 1995). Identical substrates yet varying recruitment months suggested variability in other factors affecting oyster populations. Recruitment levels can be very high in Georgia up to 35,000 oyster spat per square meter (O'Beirn 1996). Studies found that smaller sheltered tidal creeks throughout marshes were more reliable than open water bodies for increased recruitment. Due to difficulty and high variability observed in recruitment levels from the biweekly collection of spat sticks monthly collection of spat sticks were preferred (O'Beirn 1996). Spat sticks are objects often PVC pipe that are placed in the marsh to recruit oyster spat Figure 6: Image display spat sticks (PVC) located in marsh at Wormsloe (Figure 6).

Figure 6: Image display spat sticks (PVC) located in marsh at Wormsloe

Oysters mature quickly in coastal Georgia as young can recruit to a substrate and reproduce within the same year. Oysters were found to be productive in Georgia as seen in quick maturity rates. Though possessing high fecundity, Georgia oyster populations are affected by predation. Predation affects the intertidal distribution of oysters in coastal Georgia (O'Beirn 1996). Sex ratios of oyster populations also differed at tidal heights. In high intertidal areas proportionally, female oysters were more prevalent; males oyster levels were proportionally higher in the low intertidal areas (O'Beirn 1996).

### *Oyster Reefs as Living Shorelines*

Oyster reefs preserve marsh sediments from erosion and can colonize exposed marsh shorelines (Ridge, Rodriquez, and Fodrie 2016). The growth in knowledge of the ecosystem services that oyster reefs and salt marshes provide has led to the adoption of green infrastructure know as living shorelines. A living shoreline is a green infrastructure technique that implements natural features such as oyster reefs instead of propagating shoreline armaments such as a seawall or bulkhead. Projects are only considered living shorelines if there is a connection between terrestrial and aquatic habitats that are not solely dependent on a heavily engineered maintained structure (Bilkovic et al. 2017, 6). In a sense, an oyster reef restoration project is not a living shoreline if oysters do not colonize the new substrate and establish a new reef system (Bilkovic et al. 2017, 6). Oyster reefs can be implemented as a living shoreline in the form of breakwaters sills or revetments. Oyster reefs can reduce marsh edge erosion an average of a meter annually and sills colonized by oysters supported higher abundance in species of fish than natural marshes (La Peyre et al. 2015; Gittman et al. 2016). Living shorelines can enhance some ecosystem services provided by marshes, such as erosion control and provision of nursery habitat (Gittman et al. 2016). Living shorelines utilizing oyster reefs placed in suitable locations can protect shorelines and adapt to sea level rise (Bilkovic et al. 2017, 7). The determination of areas where living shorelines are suitable and oyster reefs can colonize is the primary justification for this thesis as it analyzes both oyster recruitment data and living shoreline suitability together for the Wormsloe State Historic Site.

### *Coastal Bioengineering*

Coastal bioengineering is a complex implementation of artificial structures in ecological habitats.  Two main environmental components affect structures, the first category being physical components the second biological (Hall et al. 2017). Physical components that structures must endure include wave energy, currents, water chemistry, and bathymetry. Biological components could include colonizing organisms such as oysters, barnacles and others like fish and plankton species (Hall et al. 2017). Living shorelines operate as both habitat and serve as protection. Living shorelines exemplify holistic solutions as oyster reef implementation can alter sediment flows, stop erosion and result in accretion (Hall et al. 2017). Bioengineered structures, like living shorelines that are intended to encourage connection between biological processes like plant and animal growth, can affect the physical environment around them. The reciprocal impacts of living shoreline installation require an analysis to determine appropriate, suitable areas and site-specific design for each project (Hall et al. 2017).

### *Living Shoreline Precedents*

Precedents exist for the protection of cultural resources with living shorelines. In Florida, Turtle Mound Historic Site is one of the largest and renowned archeological sites in the state; the site is listed on the National Register for Historic Places and is nominated as a National Historic Landmark (Walters et al. 2017). Bank erosion threatened the historic native American oyster midden at the historic site. Previous attempts at bank stabilization included the placement of stacked concrete bags forming a seawall. This measure failed to adequately protect the site (Walters et al. 2017). At Turtle Mound in May of 2011, a living shoreline was implemented. Two years later, in 2013 in front of the seawall, a hybrid shoreline design was also implemented. The site designs included alterations to the upper intertidal zone with the planting of native upland plant species, the mid-intertidal zone with Spartina alterniflora plugs, and lower intertidal zone with the placement of oyster shell mats (Walters et al. 2017). Not only did oysters colonize the new substrate, but plant cover also increased, and significant accretion has occurred at the site over the last two years.  Accretion rates are currently observed at an estimated five times faster than estimated sea level rise of the region (Walters et al. 2017). Also, in the Mosquito Lagoon region of Florida stands the Eldora State House. The 105-year-old structure abuts a rapidly eroding shoreline that has lost 14 percent of its shoreline from 2001 to 2013. At the Eldora State House, like Turtle Mound, the same living shoreline implementation technique was implemented. The implementation of native upland shrubs like mangroves, Spartina alterniflora plantings, and oyster reefs again proved to be successful in protecting another nationally registered historic site (Walters et al. 2017).

The protection of historic resources with living shorelines provides precedent for other coastal areas throughout the southeastern United States.

### *Living Shoreline Suitability and Implementation*

Living shoreline implementation is not a one size fits all approach to ecological restoration. Living shorelines attempt to provide equilibrium between natural forces and human-built structures (Priest III 2017, 188). It is always to the goal of living shorelines to be the least invasive as possible. Living shorelines such as marsh grass plantings are less impactful to the neighboring environment and preferred over revetment installation. All living shorelines have shared common physical parameters that are required of potential sites for shoreline restoration efforts to be successful (Priest III 2017, 188).

The Chesapeake Bay area of Virginia and Maryland has been the focus much of living shoreline research. This research resulted in detailed understandings of living shoreline suitability for the shorelines of the Chesapeake. Factors impacting living shoreline suitability in Maryland and Virginia are recognized as fetch, storm surge, bank height and condition, sediment type, riparian buffer condition and erosion rates (Priest III 2017, 188). Fetch, the distance that wind blows across waterways increasing wave energy determines the level of protection and material size of living shorelines. Living shorelines are considered suitable at locations of low fetch were the distance traveled is between 0 and 5 miles (Priest III 2017, 190). Fetch levels can be further divided into very low <0.5 miles; low .5 to 1 mile; and medium 1 to 5 miles. Very low to medium fetch values are desired when determining living shoreline suitability; high fetch levels often require harder shoreline techniques like breakwaters which are more expensive and impactful to surrounding environments (Priest III 2017, 190). Storm surge is also important; it dictates the level of protection needed at a particular site. Storm surge levels compounded with wave heights determine the levels of inundation and wave energy impacting shorelines during storm events Priest III 2017, 191).

The height and condition of shoreline banks are important in determining living shoreline suitability. The higher the bank, the more protection needed. Subsequently, bank condition refers to the quality of bank stability. Stable banks are banks that have gentle slopes, are vegetated, and have no signs of erosion (Priest III 2017, 191). Sparse vegetation, steep faces, and signs of undercutting at the base of the shoreline exemplify an eroding bank. Intermediate banks are noted to have partially stable portions but suffer from some undercutting and slumping of the bank face (Priest III 2017, 191). Sediment type is important to living shoreline implementation success as settlement can occur after project completion (Priest III 2017, 192). Sandy substrates or stiff clay sediments are the best types for living shoreline construction (Priest III 2017, 192).

Riparian buffer condition can also impact living shoreline design and suitability. Forested buffers adjacent to shorelines have their benefits but can create problems for living shoreline installation. Forested shorelines particularly northern facing shorelines, can block sunlight from reaching marsh grasses, preventing the growth of an essential tool for shoreline stabilization (Priest III 2017, 196). Finally, erosion rates determine the suitability of living shorelines and specific design choices. High erosion rates indicate the need for stronger "harder" structures, and minimal erosion rates are more suitable for minimalist applications like marsh plantings (Priest III 2017, 194). Determining living shoreline suitability and designing living shorelines are detailed, complex and site-specific, but as stated above there are commonalities that are desirable for project installation.

### *The Need for Living Shorelines in Georgia*

Coastal planners and government agencies utilize models and data to make the best decisions for adaptation strategies. After an extensive literature review, no living shoreline suitability model could be found for any coastal area of the state of Georgia. The lack of a living shoreline suitability model is problematic due to the threats of coastal shoreline erosion and the likely exacerbation of this problem due to global climate change. The State of Georgia Coastal Management Program displays a need for coastal planning and preparation for the impacts of climate change. The program compiled by the Georgia Department of Natural Resources Coastal Resources Division (GADNR CRD) and the National Oceanic and Atmospheric Administration highlights the largest threats to Georgia coast in the future. Coastal hazards were ranked the highest level of priority.

Shoreline erosion and sea level rise are two identified coastal hazards that justify the importance of this thesis research. The program states that 77% of the Georgia coast is moderately or highly vulnerable to sea level rise (GA DNR CRD 2015, 12). Subsequently, 53% of the Georgia coast is stated to be moderately highly or very highly vulnerable to shoreline erosion. An alarming 22% of the Georgia coastal shoreline is deemed as very highly vulnerable and could experience up to 2 meters annually of erosion (GA DNR CRD 2015, 12). Living shorelines utilizing oyster reefs can successfully address the threats of sea level rise and coastal shoreline destabilization (La Peyre et al. 2017, 378). A living shoreline suitability model can determine the most suitable locations for living shoreline implementation. Living shoreline suitability models exist for several states including Connecticut, Maryland, Florida and North Carolina. As previously stated there currently is no living shoreline suitability model for Georgia; this thesis aims to be the first living shoreline suitability model analyzing portions of Georgia. Chapter three of this thesis describes the process of creating the living shoreline suitability model for Wormsloe. Other living shoreline suitability models served as precedent studies for this thesis.

### *Maryland Living Shoreline Suitability Model*

Maryland's living shoreline suitability model was completed in 2008 by the Center for Coastal Recourses Management Virginia Institute of Marine Science (VIMS), and the College of William and Mary. VIMS's model was applied to Worcester County, Maryland with the stated goal to "expand the toolbox of resources available to local governments to assist with shoreline management issues" (Berman and Rudnicky 2008). The model classified shorelines into three categories: suitable for soft stabilization, suitable for hybrid options, and not suitable for living shoreline. Random field inspections of areas analyzed in the model validated the results (Berman and Rudnicky 2008). The Worcester County, Maryland model, analyzed various data inputs including fetch, bathymetry, marsh presence, beach presence, bank condition and tree canopy. All of the data was in ArcGIS format and specifically made for the area from the Center for Coastal Resource Management VIMS and the Maryland Department of Natural Resources.

Suitable areas for soft stabilization would be targeted for the use of fiber logs, marsh grass plantings and site enhancement (Berman and Rudnicky 2008). Areas suitable for hybrid options would be areas where soft stabilization techniques in combination with traditional structures would be effective. Hybrid techniques include treatments such as marsh toe rock revetments, construction of marsh sills, bank grading, and planting of upland vegetation and tree management (Berman and Rudnicky 2008). The model does not capture any site-specific anthropogenic conditions and is only as accurate as the GIS data available. The Worcester County, Maryland model was reasonably accurate in predicting areas that are generally suitable or unsuitable for living shoreline installation at 78% accurate (Berman and Rudnicky 2008). Accuracy was determined by industry experts conducting random site visits to locations that the model determined as suitable and visually checked site conditions. Unfortunately, the model was much less successful in determining accurate areas for the installation of hybrid option living shorelines at just 58% accurate (Berman and Rudnicky 2008). Conclusions of the model stated that in areas where no model exists at all broad scale need outweigh the limitations and that the product should be applied regionally, not used for determining site-specific decisions on living shoreline installations (Berman and Rudnicky 2008).

### *North Carolina Living Shoreline Suitability Model*

The second model analyzed was a model analyzing living shoreline suitability in the Albemarle-Pamlico Estuarine System of North Carolina. The study focused on an area in the center of the system with 145.68 kilometers of shoreline; the study included shorelines of the eastern Albemarle-Pamlico Peninsula and Roanoke Island (Carey 2013).

Carey 2013, is an adaption of the VIMS Maryland living shoreline suitability model. Data inputs analyzed in the North Carolina model include fetch, boat traffic and nearshore depth (bathymetry) which constitute wave energy. Marsh presence and the presence of semi-aquatic vegetation constitute the presence of vegetation. Wave energy and presence of vegetation are used to determine overall suitability (Carey 2013). All ArcGIS data was created by the University of North Carolina -Chapel Hill, North Carolina Wildlife Resources Commission, North Carolina Division of Coastal Management and the North Carolina Department of Transportation in and was specific to North Carolina (Carey 2013).  Suitability was determined by adding the scores that each shoreline segment received in relation to its attributes from the input data classified based on known criteria needed for living shoreline projects (Carey 2013). The weighted results ranging from 23-100 were 100 is the most suitable, determined that nearly 72% of the study area shorelines scored above a 57, meeting half the criteria for soft stabilization practices (Carey 2013). The model also determined that 94% of shorelines in the study area meet half of the criteria for hybrid stabilization techniques. Model results are not site-specific recommendations but are valuable information for decision-makers. Industry experts and government officials should verify model results by ground-truthing the suitable locations before creating site plans.

***Connecticut Living Shoreline Suitability Model***

Finally, the last living shoreline suitability model analyzed modeled the coastline of Connecticut. The study area was a 300-foot buffer both seaward and landward of the shoreline (Zylberman 2016). Zylberman 2016 analyzed five data inputs including fetch, bathymetry, marsh presence, beach presence, and erosion data. All data was created or preprocessed in ArcGIS format. Data sources included the Connecticut Department of Energy and Environmental Protection's GIS downloads and from the study titled Analysis of Shoreline Change in Connecticut (Zylberman 2016). The Connecticut suitability model followed the precedent set by Carey 2013 stating that living shoreline suitability is a function of wave energy and presence of vegetation (Zylberman 2016). All data used was specific to the Connecticut coastal area and was preprocessed except for beach presence data that was created for the study. The study revealed that 47% of Connecticut coastlines are suitable for living shorelines.

# CHAPTER 3

# METHODS

Coastal erosion and bank failure threaten invaluable cultural resources at the Wormsloe State Historic Site. The Fort Tabby Ruins of Wormsloe are only 250 feet away from were a tidal creek meander is causing bank failure and subsequent vegetation loss. Implementation of a hybrid living shoreline utilizing an oyster reef would require modeling to determine suitable locations for implementation and an ecological experiment that tests oyster recruitment in the waterways around Wormsloe. This chapter details the methods used for the creation of the Wormsloe LSSM pilot study and the oyster recruitment experiment.

## ***Ecological Observation Study***

The methods for this thesis contains two phases. Phase one was the design and execution of an ecological observation experiment to measure recruitment of the Eastern oyster *Crassostrea virginica* at ten locations around the Wormsloe State Historic Site east of Savannah, Georgia during May through August of 2017. The monthly sampling of the ten sites commenced on April 10th, 2017 and concluded on September 21st, 2017. Spat sticks are substrates often PVC pipe, bamboo coated in cement, shingle, or tile (Manley, Power, and Walker 2008; Manley, Power, and Walker 2008; Manley, Power, and Walker 2009). Spat sticks were placed at ten sites within three distinct waterways within an approximate 3 square mile area centered around the Wormsloe tabby fort ruins (Figure 6).

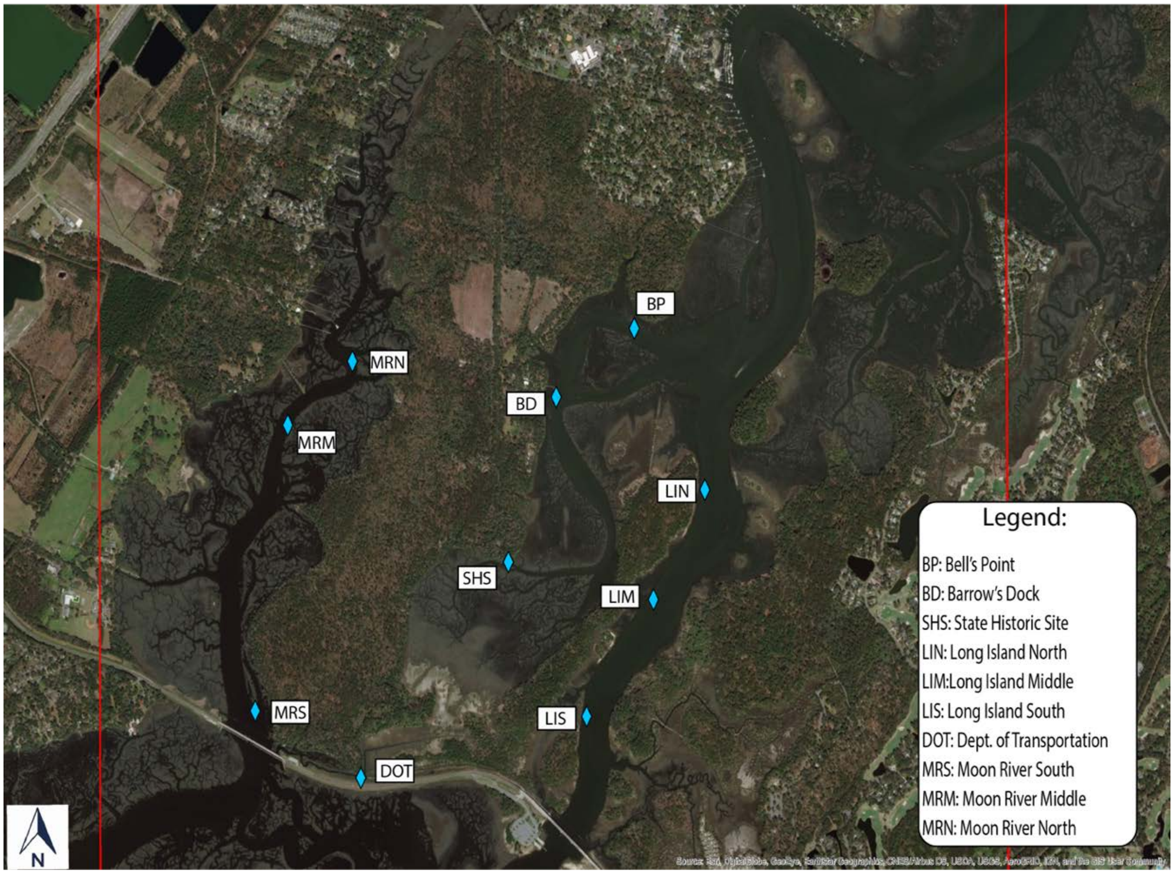



Figure 7: This map displays the ten spat stick locations and their corresponding name

Placement and collection of spat sticks occurred at low tide as the sticks were placed directly into the mud in the intertidal zone of the marshlands. Three waterways, each with differing hydrographic characteristics were selected surrounding Wormsloe

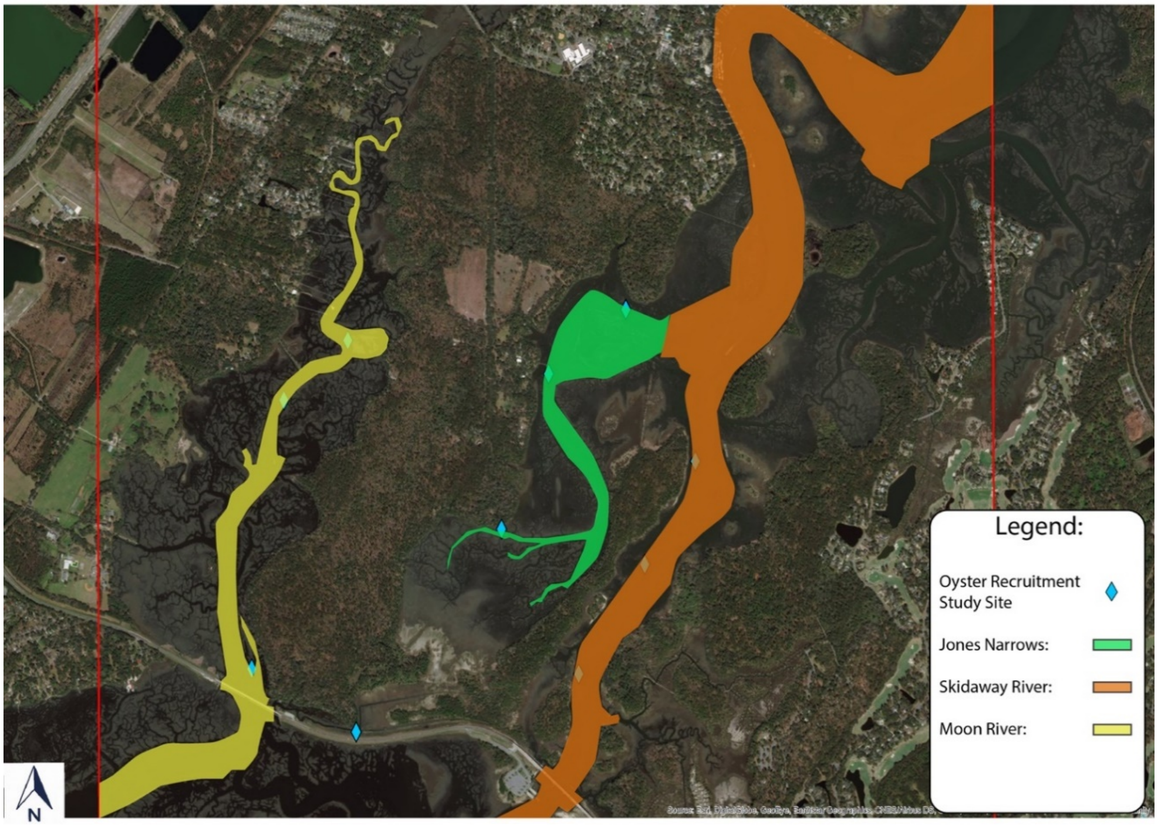



Figure 8: Map displaying the three rivers selected for site locations. Jones Narrows in green was the smallest of the three waterways containing high oyster populations and low erosion. Skidaway River in orange was the largest waterway analyzed. Skidaway River was characterized by the large distance between its banks, low oyster populations, and areas of erosion. Moon River was characterized by high sinuosity and high numbers of oyster reefs.

The first waterway selected to the east of Wormsloe and Long Island was the Skidaway River. The Skidaway River, characterized by marshlands of Spartina alterniflora and minimal oyster reefs and received heavier boat traffic from the access points the Rodney J Hall Boat Ramp to the south and the Isle of Hope Marina to the north. The Skidaway River was the largest of the three selected water bodies. Three sites on Wormsloe State Historic Site property were selected. The sites were approximately .40-mile increments apart from each other and ran linearly down the channel's western bank on Long Island. Site labels correspond to their location/ identifying features. All of the sites placed on Long Island contain LI for Long Island; site names were (LIN) for Long Island North, (LIM) Long Island Middle, (LIS) for Long Island South.

The second waterway analyzed was Jones Narrows. Jones Narrows, an offshoot of the Skidaway River was the least linear of the three selected waterways displaying high sinuosity. Sinuosity is the bend or curvature of a water way. Three sites were selected within meanders of the waterway and are nearby existing oyster populations. Jones Narrows contained the largest oyster beds observed in the study. The three sites on Jones Narrows varied. One site was selected and labeled (SHS) for State Historic Site labeled due to its proximity to the Wormsloe Tabby Fort Ruins and located at the site of bank failure. The site labeled (BD) for Barrow's Dock was set 100 ft from the Barrow family's private dock. The site labeled (BP) for Bell's Point was located 200 ft from the shoreline of Bells Point, a geographic marker for the area with extensive oyster reef structures.

The third waterway, Moon River was the only waterway on the western bank of the Isle of Hope analyzed in the study. Moon River acted as a medium between the other two waterways. Moon River experienced boat traffic from private docks along the river and a public boat access point to the south of the study area. Moon River also acted as a medium regarding hydrographic features; Moon River contained higher sinuosity than the Skidaway River but was also more linear than Jones Narrows. Site locations were on the eastern bank of Moon River along Wormsloe State Historic Site property. The site (MRN), Moon River North, was placed within a narrowing tidal creek within close proximity to private docks. (MRM) Moon River Middle approximately .30 miles south of

MRN was placed on an outward meander surrounded by large oyster reefs. (MRS) Moon River South was placed approximately .85 miles south of MRM close to the public boat access point and established oyster reefs. Finally, the tenth site selected was within a humanmade channel created with the construction of the Diamond Causeway. This site was called (DOT) for its proximity to the Diamond Causeway and Department of Transportation owned land. The DOT site spat sticks were placed on the southern tip of the Wormsloe State Historic Site. The site was unique as it is in a rigid and straight channel that meandered back towards the highway. Riprap revetments were placed to protect the highway from bank failure. There were very few oysters observed within the channel.

**Table of Sites and Selection Criteria**

Table 1: Displays the site locations, names, river, and waterway characteristics

| Sites | River | Waterway Size | Boat Traffic | Selection Criteria |
|---|---|---|---|---|
| SHS | Jones Narrows | Smallest | Lowest | Area of interest for living shoreline |
| BP | Jones Narrows | Smallest | Lowest | Interest from private property owner |
| BD | Jones Narrows | Smallest | Lowest | Interest from private property owner |
| LIN | Skidaway River | Largest | Highest | River contains erosion hotspots and low oyster populations |
| LIM | Skidaway River | Largest | Highest | River contains erosion hotspots and low oyster populations |
| LIS | Skidaway River | Largest | Highest | River contains erosion hotspots and low oyster populations |
| DOT | Humanmade channel | N/A | N/A | Bank failure and high erosion rates |
| MRS | Moon River | Intermediate | Intermediate | Area near fishing pier |
| MRM | Moon River | Intermediate | Intermediate | Area near large oyster reefs |
| MRN | Moon River | Intermediate | Intermediate | Area near large oyster reefs |

Four spat sticks were placed in the cardinal directions of north, east, south, and west at each of the ten sites. This was the designed experimental unit and used for replication purposes for later statistical analysis and in case a stick was lost during the month duration between collection. Spat sticks were collected each month by boat and on land. Eight of the sites were only accessible by boat. The University of Georgia Marine Extension (MAREX) provided boat travel. Rob Hein captained the boat during the six trips to place, tag and collect the spat sticks. Two sites were unable to be collected by boat due to shallow depths in tidal creeks near sites SHS and DOT. At the recommendation of industry experts spat sticks were created from PVC pipe. In an email conversation on April 5th, 2017 the Director of the University of Georgia Shellfish Lab Tom Bliss recommended the placement of four one-meter length PVC pipes at each site. Studies show that PVC pipe could be a successful oyster recruitment substrate (Manley, Power, and Walker 2008; Manley, Power, and Walker 2008; Manley, Power, and Walker 2009).

The PVC pipes were collected monthly and replaced with new PVC pipe. This was repeated to determine the amount of recruitment per month in the waterways surrounding Wormsloe. Finally, the substrate PVC was used due to its surface area and efficiency to recruit oysters in past ecological observation studies (Manley, Power, and Walker 2008). PVC spat sticks were not coated in cement but instead sanded with the 80-grain sandpaper by hand. Industry experts and Marine Extension employees Tom Bliss and Rob Hein stated that the cement was used for studies for commercial grow out of spat that would need to be removed from the stick. Ecological observation studies on oyster recruitment verified that cement was used on PVC sticks and minimized damage to spat near the shell attachment area during removal (Manley, Power, and Walker 2008).

Spat sticks were measured to one meter in length and marked with permanent marker at 40 cm up each stick. The line signified the portion of the stick that would be pushed into the marsh; 60 cm were left above the mud to recruit oysters. The first 40 spat sticks were placed on April 10th of 2017. May 10th of 2017 was the first date that spat sticks were both collected and replaced. The process of collection and replacement of spat stick continued through September. Hurricane evacuations, rainstorms, and boat failure disrupted the process of spat stick collection and placement. The experiment planned for spat sticks to be collected the second Monday of every month. The last 40 sticks were scheduled for collection on September 11th, 2017. Hurricane Maria a category five storm at the time forced evacuations of the Georgia coast during the final collection week. This included the evacuation of the UGA Marine Extension facility on Skidaway Island which pulled boats from the water and closed the facility. The collection of the last 40 spat sticks was rescheduled for September 20th, 2017. Unfortunately, that day only one site was able to be collected as the boat being used to collect spat sticks experienced mechanical breakdown and had to be towed back to shore at the UGA Marine Extension facility. This lead to the other nine locations being collected the next afternoon on September 21st, 2017.

The six-month ecological observation study could not have been completed without the assistance of UGA Marine Extension and Shellfish Lab staff. Tom Bliss, Justin Manley, and Rob Hein all offered advice and expertise on spat stick creation and placement. The collaboration between the UGA Marine Extension and the Wormsloe

Institute for Environmental History led to a beneficial partnership. The partnership allowed for the completion of the first oyster recruitment study in the waterways surrounding the Wormsloe State historic site. The new data on oyster recruitment in Moon River, Jones Narrows, and the Skidaway River also inform the second phase of this thesis. Oyster recruitment data was collected to inform the living shoreline suitability pilot model for Wormsloe the first living shoreline suitability pilot model to analyze areas within the state of Georgia.

***Wormsloe's Living Shoreline Suitability Model***

Living shorelines are a green infrastructure technique that implement natural features such as oyster reefs to connect terrestrial and aquatic habitats. Living shorelines are not solely dependent on a heavily engineered structure. In a sense, an oyster reef restoration project is not a living shoreline if oysters do not colonize the new substrate and establish a new reef system (Bilkovic et al. 2017, 6). This establishes a need not only for a living shoreline suitability model that can determine areas suitable for living shoreline installation but the subsequent combination of living shoreline suitability models with ecological observation experiments. This stated goal of this thesis was to create a living shoreline suitability pilot model for the shorelines of the Wormsloe State Historic Site; the pilot model results would be compared to oyster recruitment data, yielding areas that are potentially suitable and have displayed recruitment of oysters.

A living shoreline suitability pilot study was developed for a twelve square mile area surrounding the Wormsloe State Historic Site. The model analyzed the three main channels (Jones Narrows, portions of Moon River and the Skidaway River) previously discussed in the ecological observation phase of the methods (Figure 8). The living shoreline suitability pilot model created for Wormsloe followed the precedent of other living shoreline suitability models for other areas of the United States east coast like Connecticut, Maryland, and North Carolina (Zylberman 2016, Berman and Rudnicky 2008, and Carey 2013). The Wormsloe pilot model analyzed fetch, bathymetry, marsh presence, and erosion hotspot data to determine areas where living shorelines are more suitable. The four data inputs of the living shoreline suitability pilot for Wormsloe were determined due to all four inputs being present in the three precedent models. After the three precedent models were studied the data inputs that were present in all three models were determined as the data needed for the Wormsloe living shoreline suitability pilot model.

***Data Collection and Methods***

This thesis focuses on oyster recruitment and living shoreline suitability at Wormsloe the project boundary centered around the Wormsloe State Historic Site. The project extent also was drawn to include the three waterways sampled in the ecological observation experiment. After determining the project boundary, a shapefile containing a 12 square mile rectangle centering on Wormsloe was created using ArcGIS (ESRI 2018). The next data inputs (fetch, bathymetry, marsh presence and erosion hotspots) were collected or created.

### *Marsh Presence and Erosion Hotspots*

Marsh presence and erosion hotspots were gathered from (SAGIS) the Savannah Area Geographic Information System and G-WRAP the Georgia Wetlands Restoration Access Portal. Through Environmental Protection Agency (EPA) funding, the Georgia Tech Center for Geographic Information Systems created the Georgia Wetlands Restoration Access Portal for Georgia's Department of Natural Resources (GADNR). A majority of the data layers found on the portal were created by the University of Georgia's Skidaway Institute of Oceanography (SkIO). Within the G-WRAP metadata, the erosion hotspots shapefile is attributed to Dr. Chester Jackson of Georgia Southern University. The G-WRAP dataset was requested from Tony Giarrusso in the School of City and Regional Planning at Georgia Tech and Jan Mackinnon of Georgia Department of Natural Resources and was shared on an external drive.

After the marshland and erosion hotspot data files were collected, they were clipped to the study boundary. This resulted in shapefiles that only displayed marshlands and erosion hotspots within the twelve square mile study area. These were converted to raster files by utilizing the point to raster and polygon to raster tools. The erosion hotspot raster was further processed by utilizing the Euclidean distance spatial analyst tool to provide areas around the single cell in every direction that could be affected by erosion. This was completed as a precaution because not all sites of erosion hotspots could be verified or measured. Instead, Euclidean distance highlights cells within a prescribed area in every direction emanating from a source. This was utilized for the erosion hotspot data because areas in between hotspot points likely experienced erosion and the points reflect areas of erosion larger than the single cell size. The output distance was set at 100ft and the maximum distance of 500ft.

### *Bathymetry and Slope*

Bathymetric data was not available for the Wormsloe scale study area. Bathymetric data are contour data sets measured in meters developed from NOAA bathymetry and USGS topographic-bathymetric maps that display shoreline and underwater topography (NOAA 2017). The Connecticut model appended the NOAA Continually Update Shoreline Product (CUSP) file to the bathymetric contour dataset. The NOAA CUSP shapefile delineates the shoreline location. Contour lines were created from a coastal DEM (Digital Elevation Model) file from the G-WRAP data set. The DEM is cited in the G-WRAP metadata sheet originating from GADNR Wildlife Resources Division, where Jason Lee mosaicked various collected datasets. The DEM is for all six Georgia coastal counties. The DEM was masked out to the Wormsloe study area, effectively clipping the raster to the Wormsloe scale. Next, the spatial analyst contour tool was used to create contour lines from the masked DEM surface. The Connecticut model and the Maryland model both analyze contour data in relation to the CUSP line location (Zylberman 2016; Berman and Rudnicky 2008). The CUSP line was buffered by 30m for the Connecticut model and 10m for the Maryland model respectively (Zylberman 2016; Berman and Rudnicky 2008). The Connecticut model determined that areas, where the 1m contour is greater than 30m from the shoreline, are suitable for living shoreline installation (Zylberman 2016). The Maryland model states that areas in which the 1m contour is greater than 10m from the shoreline, are suitable for marsh planting living shorelines (Berman and Rudnicky 2008).

These distances were interpreted as describing slope. Areas, where the 1m contour line is 10m from the CUSP shoreline, have a higher slope than areas where the 1m contour is 30m from the shoreline. Using the rise over run technique slopes were calculated for the models. The Connecticut model stated that 3% slope was suitable, and the Maryland model determined 10% slope was suitable respectively. Therefore, since the goal of bathymetric data was to determine slope, a slope raster was created for Wormsloe. The slope spatial analyst tool created a slope raster that displayed vertical units in feet and horizontal units in meters. The tools input raster was the masked DEM. The output measurement selected was percent rise. The z factor was .3048 resulting in outputs in the same unit as 1 foot is equal to 0.3048 meters. All raster cell sizes produced for the living shoreline pilot study at Wormsloe are at 10ft cell sizes.

### *Fetch*

Fetch data was also not available and had to be created for the Wormsloe scale study area. Two of the three living shoreline suitability models Connecticut, and North Carolina used the same method for creating fetch data (Zylberman 2016; Carey 2013). Both studies utilized the United States Geological Survey (USGS) Wind Fetch Model for Habitat Rehabilitation and Enhancement Projects (WFMHREP) (Rohweder et al. 2012). A wind fetch model is an ArcGIS tool that requires titled *Waves 2012* and was downloaded from the USGS website. The wind fetch tool requires two inputs. First, "it requires a land cover raster where land is aggregated to one class and given a value greater than 0 while water is given a value equal to 0" (Zylberman 2016). Second, the wind fetch tool requires a "comma delimited text file that contains wind directions and percentages from that direction" (Zylberman 2016). Wind direction is measured in azimuthal degrees, where 0 degrees is due north. (Rohweder et al., 2012). Both the land raster and wind direction text files were created for the Wormsloe model. The land raster was created by utilizing a polygon the same shape as the project boundary and merging it to the NOAA CUSP line. The polygon to raster tool was used to give areas within the NOAA CUSP shoreline a value of 0 (representing water) and outside of the CUSP line a value of 2 (representing land).

After the land-water raster was created, a wind direction text file was created. Ten years of buoy climate data created an average wind direction and weights based on the percentage of time the wind blew in a particular direction (Zylberman 2016). Before the wind direction text file could be created wind data was downloaded from the NOAA National Data Buoy Center. The Ft. Pulaski buoy station (Station FPKG1) used for the Wormsloe pilot model. The Ft. Pulaski buoy station was selected due to its close proximity to Wormsloe at 12 miles, as the next closest buoy, located at Sapelo Island, was just over 40 miles from the study area. Buoy data was downloaded for the years 2007 through 2016 in the form of text files. The data was processed and missing or data with errors were deleted. The frequencies of each group of wind direction data were calculated for model input (Appendix 3). Finally, tables were left with the cardinal direction and the percentage that the wind was blowing in the direction known as the weight. The weights for each year were averaged over the 10-year period of 2007 to 2016. The end product was each of the directions and their weight for the 10-year period which was exported to a comma delimited text file. The text file and land water raster were placed into the USGS fetch model. The model produced fetch results for the three waterways around Wormsloe.

There were a few steps taken before the fetch data was incorporated into the suitability model (Figure 9). First, there were negative fetch values, which are a product of the fetch model created when water is not bound by land (Rohweder et al. 2012). Zylberman 2016 and Carey 2013 deleted the negative fetch values from the raster. The negative fetch values were not deleted from the Wormsloe fetch results as this could alter the overall suitability results. Negative fetch values were remedied instead by reclassifying the fetch raster. All of the negative values were listed as least suitable the same as a fetch value of 750ft or greater.

Secondly, fetch is a water-based layer where all of the other inputs are land-based. All layers in a weighted overlay analysis must be able to overlay with one another to successfully perform a site selection analysis (Zylberman 2016). This was remedied by shifting the fetch pixels over the land and was accomplished by interpolating fetch landward. The raster to point tool was used to interpolate the fetch landward. This converted the raster results from pixels to points. Once the points were created, the IDW Inverse Distance Weighted spatial analyst tool was used. The tool shifts data by predicting values for an area based on the known points nearby it, meaning that the tool created new points for the fetch landward based on the results in the water closet to it (ESRI 2017).

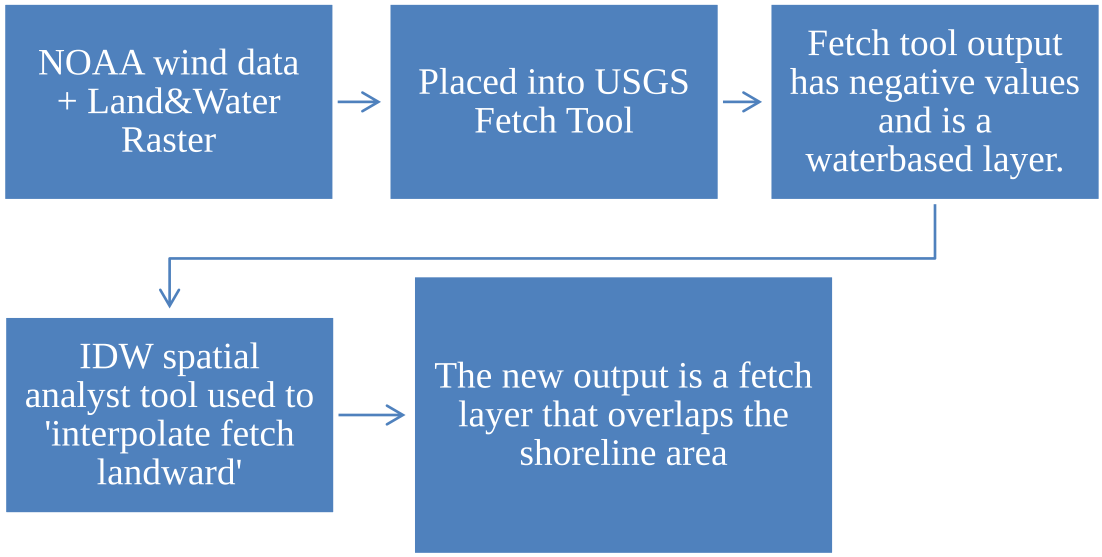



Figure 9: Displays the method used to create the fetch data for the waterways around Wormsloe. It included the use of other GIS tools and multiple data sets

***Reclassification and Weighted Overlay Analysis***

After the fetch values were shifted landward, all of the rasters for fetch, marsh presence, slope, and erosion were reclassified for the weighted overlay analysis. Each of the inputs was previously converted to rasters by using the point to raster and polygon to raster tools respectively. The fetch raster was reclassified to have three values of 3, 2, and 1 where 3 is the most suitable. In all four of the reclassified rasters, 1 is least suitable, and 3 is most suitable. Fetch values of 1 were all negative values and distances over 750ft. Reclassified fetch values of 2 were distances of 500ft to 750ft and fetch values of 3 were 0ft-500ft. The slope raster was reclassified as 0% -3.3% slopes were the most suitable and given a value of 3. Slopes of 3.3% to 10% were moderately suitable and given a value of 2. Slopes of 10% and greater were given a value of 1 for low suitability. Slope raster reclassification followed the precedent of the Connecticut model instead of the

Maryland model. This was due to the Connecticut model using lower slopes as more suitable which applied more to the Wormsloe study area as Georgia's main coastal feature of the South Atlantic Bight results in gradually sloping shores, expansive marshes and lower wave energy (Passeri, Hagen, and Irish 2014). Marsh presence was the only input that binary in the fact that marsh is either present or not. The presence of marsh was reclassified as a 3 for high suitability and areas without marsh were classified as a 1. Erosion hotspots were reclassified as 500ft and greater from an erosion hotspot being the most suitable. Areas within 500ft of an erosion hotspot as moderately suitable and areas within 100ft of an erosion hotspot as having low suitability (Figure 10).

| Living Shoreline Suitability | | | | | |
|---|---|---|---|---|---|
| Priority: | | High Suitablity (3) | Moderate Suitablity (2) | Low Suitability (1) | Scale Factor |
| Suitability Criteria | % Weight | Data Reclass: High to Low Suitability | | | Weighted ov |
| Weighted Fetch | 30 | Lowest Fetch (0-500 feet) | 500'-750' | 750' & greater | 3=10<br>2=5<br>1=1 |
| Slope | 30 | 0-3.3% | 3.3%-10% | 10% and greater | 3=10<br>2=5<br>1=1 |
| Marsh Presence | 20 | Marsh is present | NA | areas without marsh | 3=10<br>2=5<br>1=1 |
| Bank Erosion Hot Spots | 20 | 500' and greater from erosion hotspot | < 500' from erosion hotspot | < 100' from erosion hotspot | 3=10<br>2=5<br>1=1 |
| | | | | | |

Figure 10: This figure shows the suitability index for each of the four data inputs. It also displays The assigned weights, scale factor and criteria for the Wormsloe living shoreline suitability pilot study.

Following the reclassification of all the rasters, the newly reclassified rasters were placed into a weighted overlay analysis. The weighted overlay spatial analyst tool allows for the calculation of a multiple criteria analysis between several rasters (ESRI 2016). To allow for a gradient in suitability a 1 to 10 by 1 evaluation scale was selected. Evaluation scales analyze the cell values for each input raster based on their assigned values. The scale value column represented assigned values within the weighted overlay tool. The reclassified fetch raster was given scale values of 1 to 1; 2 to 5; 3 to 10 (Figure 10). The fetch raster that used to have the value of 1 for low suitability, 2 for moderate and 3 for high was converted to 1 for low suitability, 5 for moderate, and 10 for high suitability. This was repeated for all of the reclassified rasters. The reclassified erosion hotspot values were given a scale value where 1 remains 1, 2 becomes 5 and 3 becomes ten. The reclassified slope raster was also given scale values the same as fetch and the erosion hotspot rasters. The reclassified marsh presence raster remained binary as 1 retained a scale value of 1 and 3 became 10. The weighted overlay tool then analyses cells that have overlaid rasters and added up the score. For example, a cell with maximum suitability in every raster would have a value of 40 and a cell with the minimum suitability contain a value of 4.

The weighted overlay tool also required that each raster be given a percentage of influence. The percentage of influence acts as a weight determining how much each raster is valued compared to each other. Living shorelines are not suitable in areas of high erosion (Currin, Davis and Malhotra 2017). The two factors that most impact salt marsh erosion are fetch and bathymetry, understood as slope (Currin, Davis and Malhotra 2017). Due to these two inputs being the most important, fetch and slope were given percentages of influence of 30% while marsh presence and erosion hotspots were given each 20% (Figure 10). After the percentage of influences were established the tool was executed, and suitability results were produced for the Wormsloe study area. To get data specifically focused on the shoreline, the NOAA CUSP line was buffered by 50ft on either side creating a 100ft buffer polygon of the shorelines within the Wormsloe study area. The extract by mask tool was used to isolate the weighted overlay suitability analysis results of the shoreline areas (Figure 11).

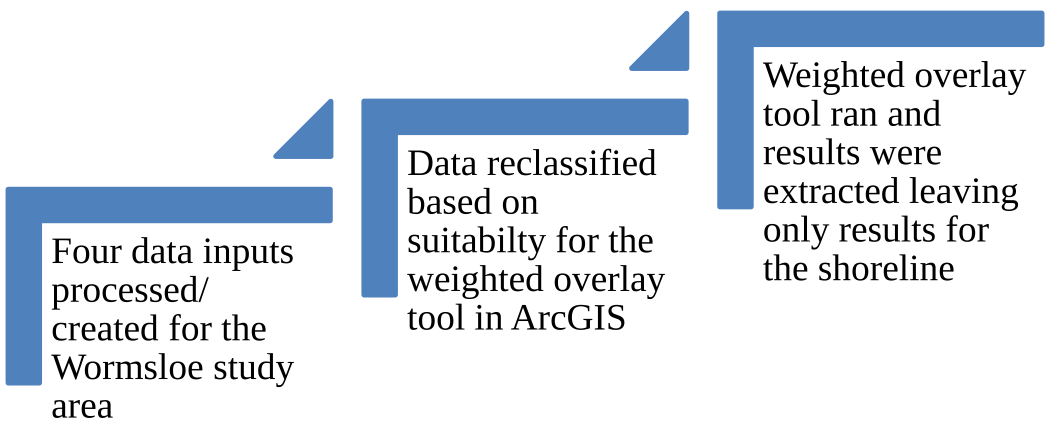



Figure 11: The diagram displays a summary of the methods utilized to create the weighted overlay analysis results. The weighted overlay tool was used to determine the most suitable locations for low impact living shoreline placement.

# CHAPTER 4

# RESULTS AND DISCUSSION

The goal of this thesis research is to produce a living shoreline suitability pilot study for the Wormsloe State Historic Site that is informed by oyster recruitment data from ten locations around Wormsloe. The research resulted in two sections of results the data from the ecological observation study on oyster spat recruitment and the living shoreline suitability pilot study. The results reveal important information and aim to provide clarity in the complex decision-making process for living shoreline installation.

## *Living shoreline suitability results*

The results of the Wormsloe living shoreline suitability pilot study were the second portion of results. The living shoreline suitability pilot study analyzed fetch, slope, marsh presence and erosion hotspots to categorize areas based on suitable characteristics for living shoreline installation. The pilot study model analyzed all shorelines around Wormsloe; there was an effort to analyze the model results in relation to each of the ten site locations selected in the recruitment study. Overall, suitability around Wormsloe was high (Figure 17). All of the areas around the oyster recruitment sites display varying degrees of suitability (Figure 18; Figure 19; Figure 20: Figure 21; Figure 22; Figure 23; Figure 24; Figure 25; Figure 26; Figure 27).

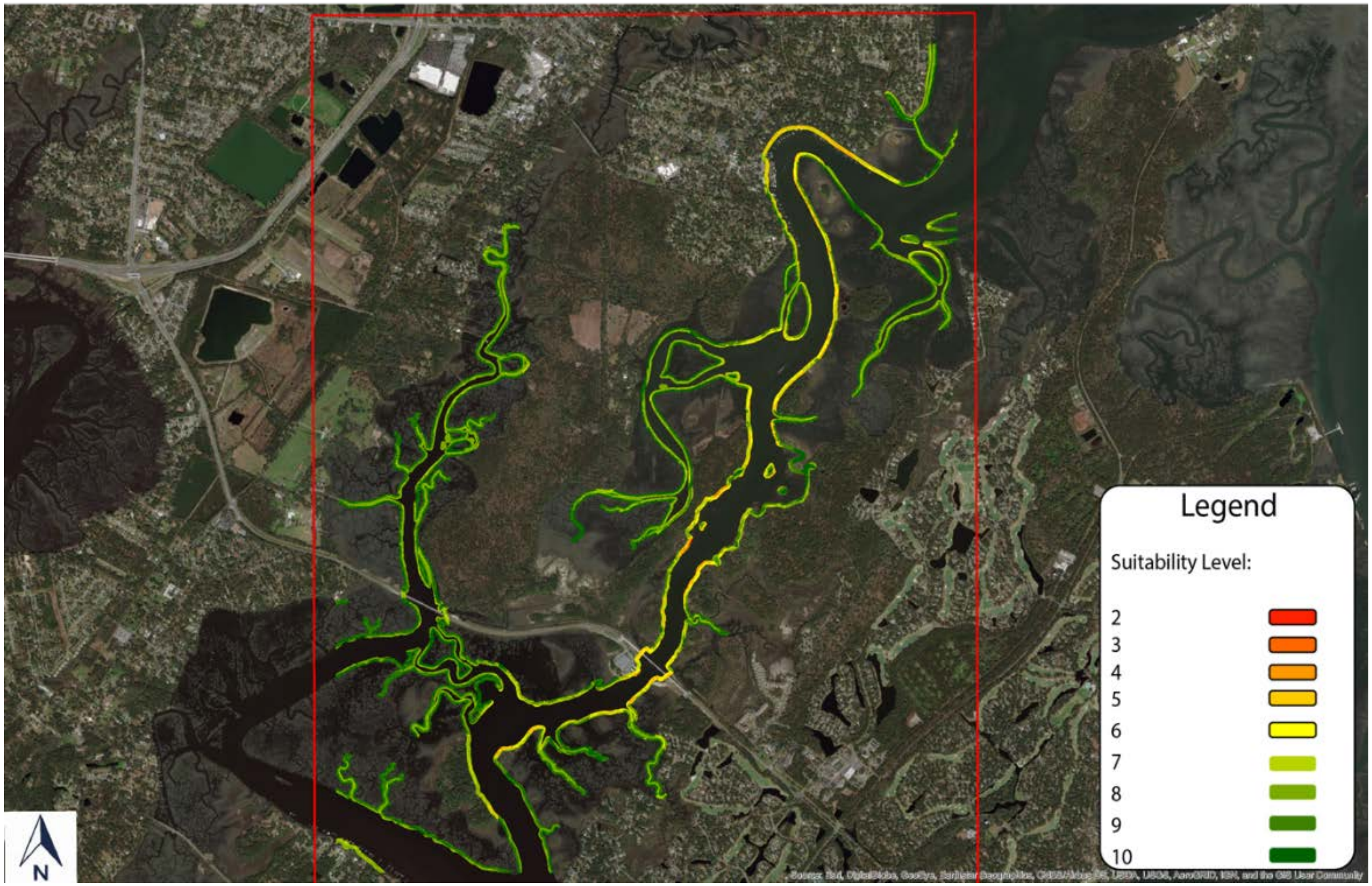



Figure 12: This map displays the overall suitability results from the living shoreline suitability pilot model that was created for the shorelines of the Wormsloe State Historic Site.

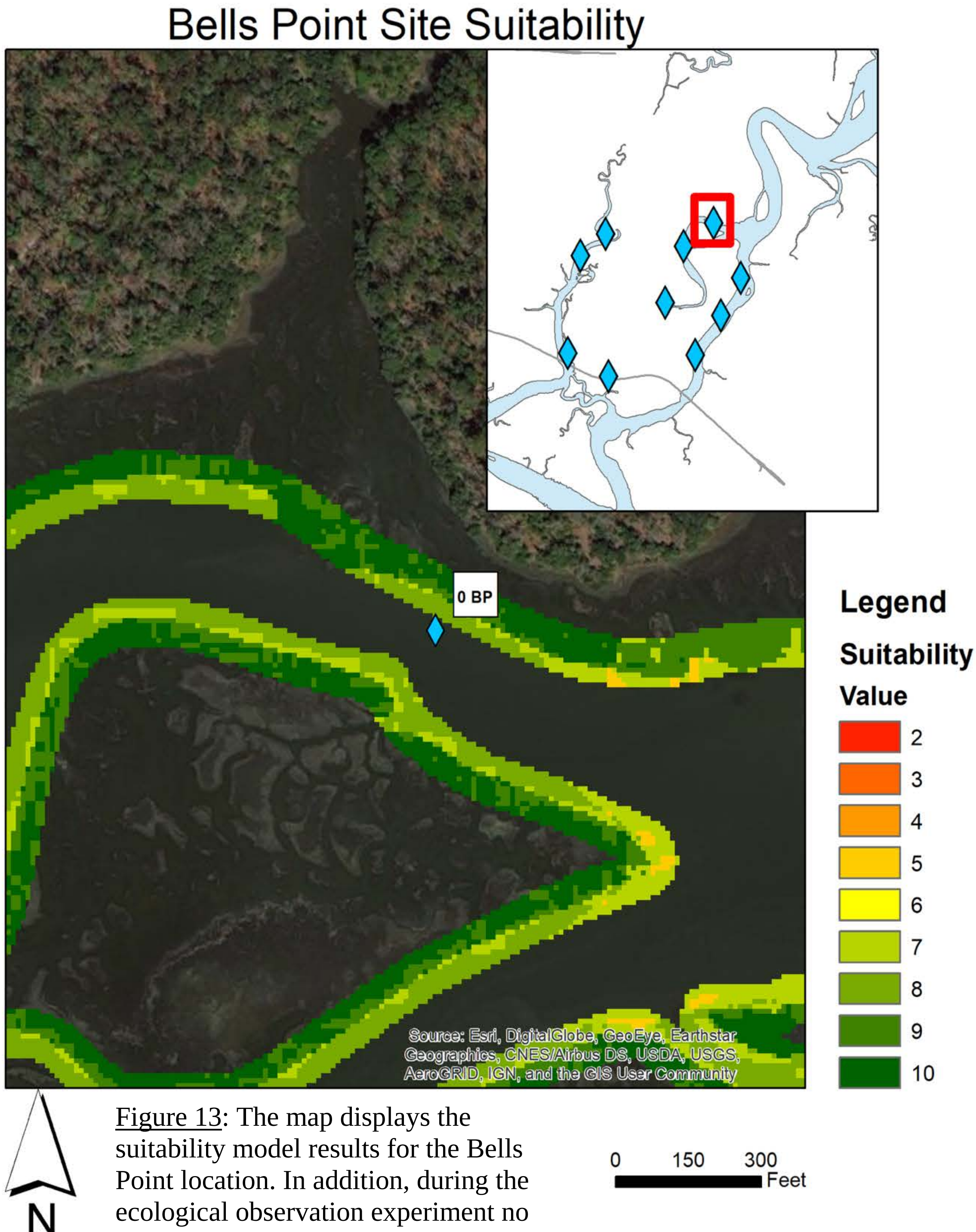



Figure 13: The map displays the suitability model results for the Bells Point location. In addition, during the ecological observation experiment no oyster spat recruited at this site.

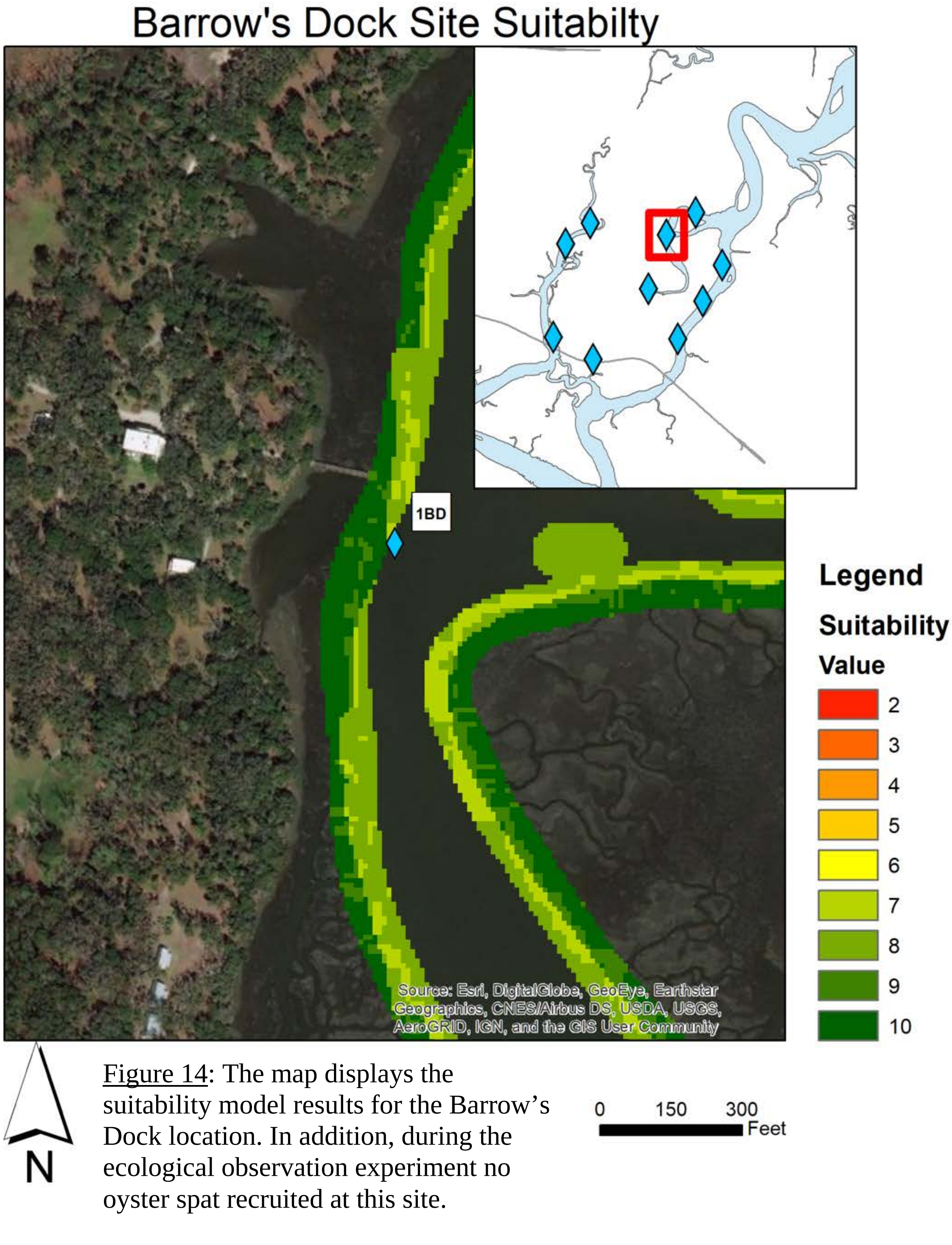



Figure 14: The map displays the suitability model results for the Barrow's Dock location. In addition, during the ecological observation experiment no oyster spat recruited at this site.

# Long Island North Site Suitability

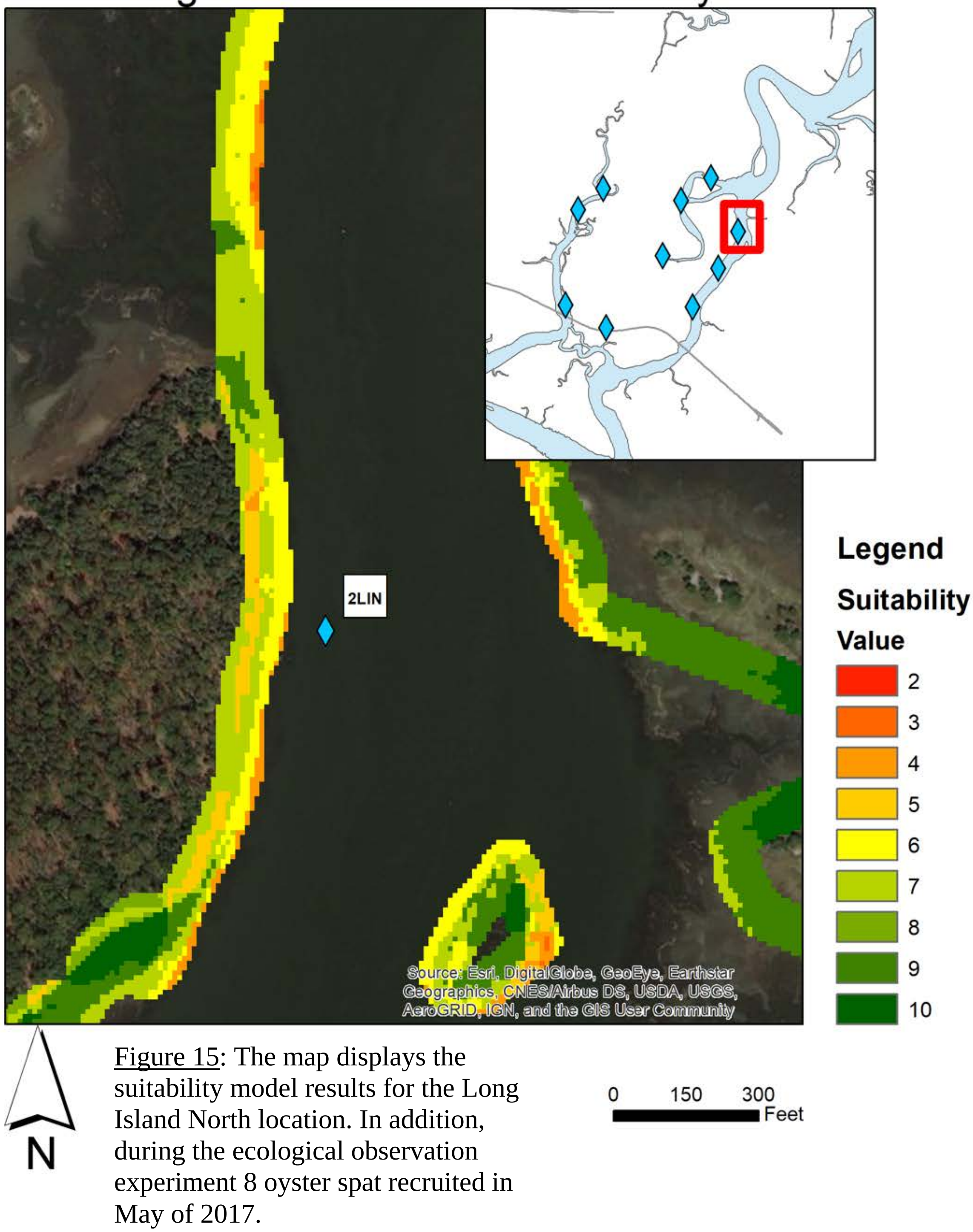



Figure 15: The map displays the suitability model results for the Long Island North location. In addition, during the ecological observation experiment 8 oyster spat recruited in May of 2017.

Long Island Middle Site Suitability

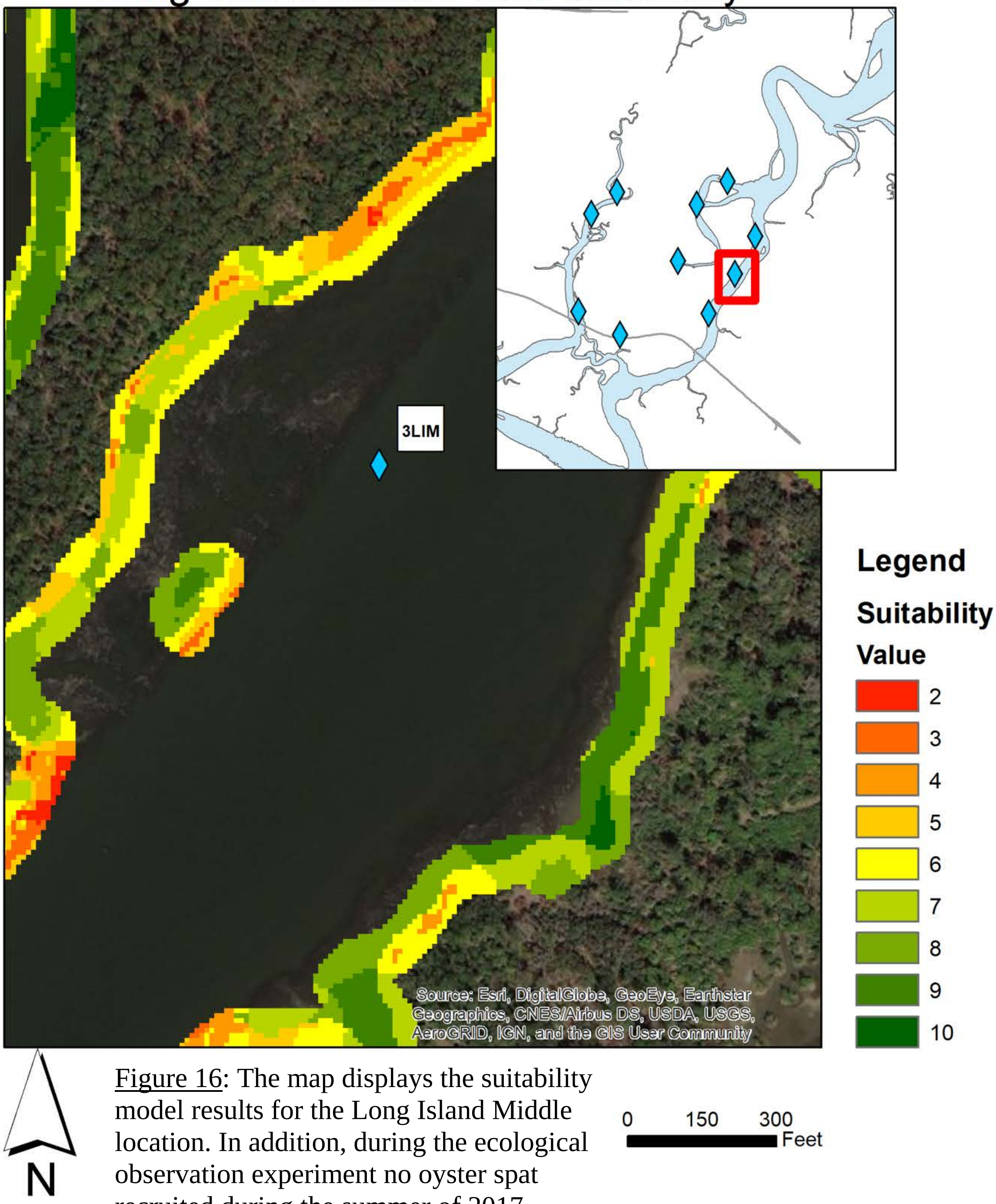



Figure 16: The map displays the suitability model results for the Long Island Middle location. In addition, during the ecological observation experiment no oyster spat recruited during the summer of 2017.

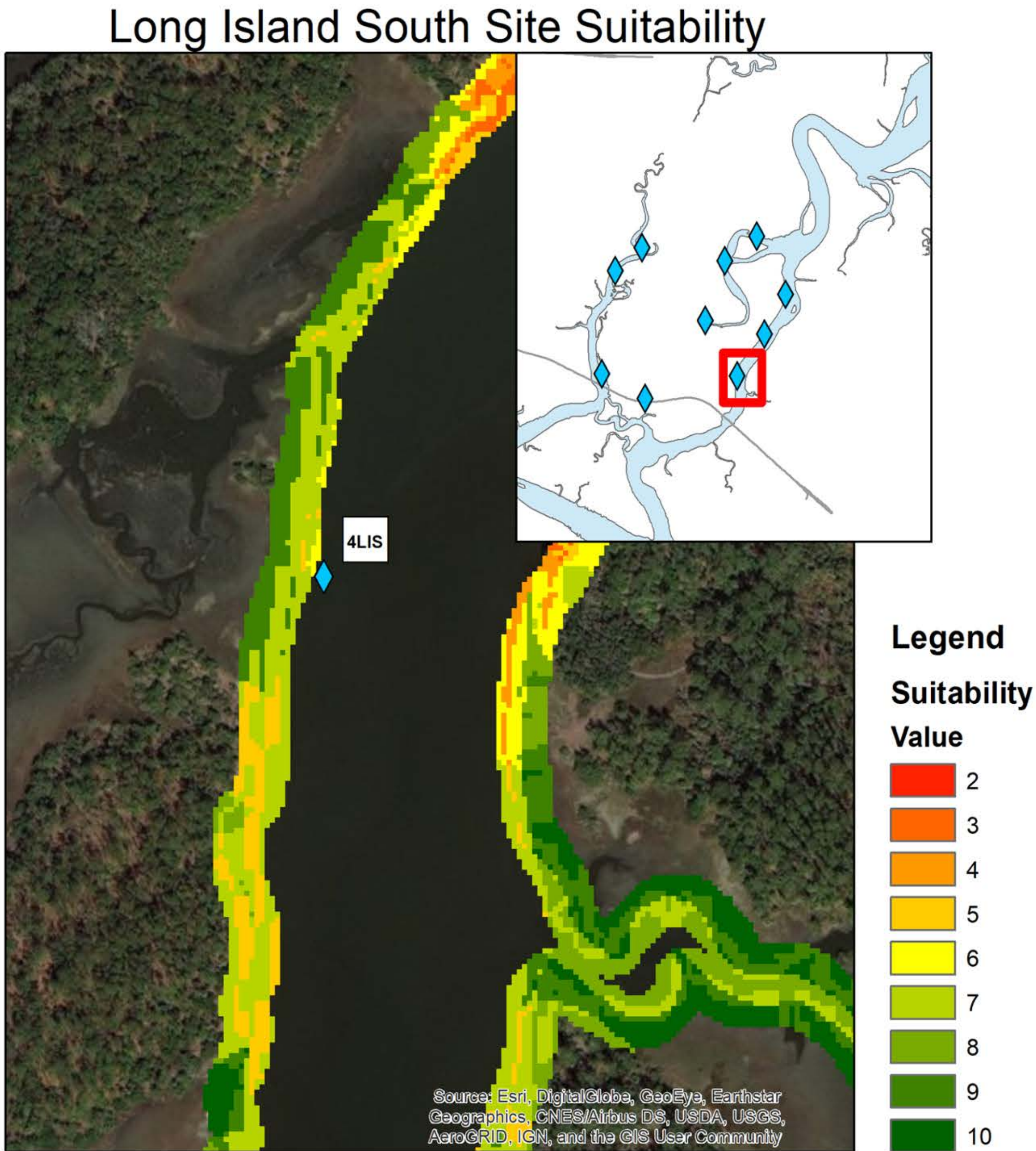



Figure 17: The map displays the suitability model results for the Long Island South location. In addition, during the ecological observation experiment 3 oyster spat recruited in April of 2017.

# Moon River South Site Suitability

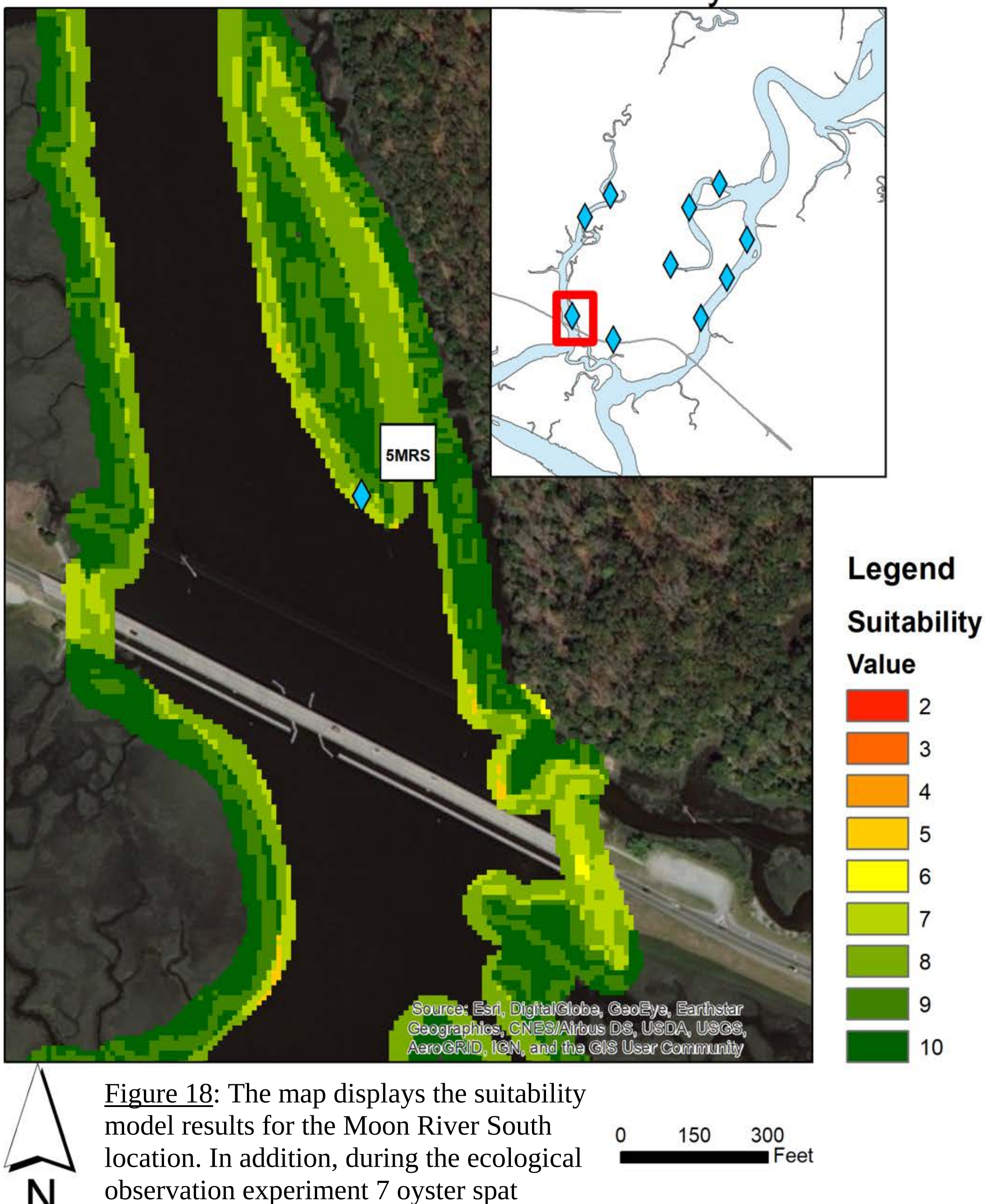



Figure 18: The map displays the suitability model results for the Moon River South location. In addition, during the ecological observation experiment 7 oyster spat recruited in May and 3 spat recruited in July. This was the only site with recruitment during multiple months.

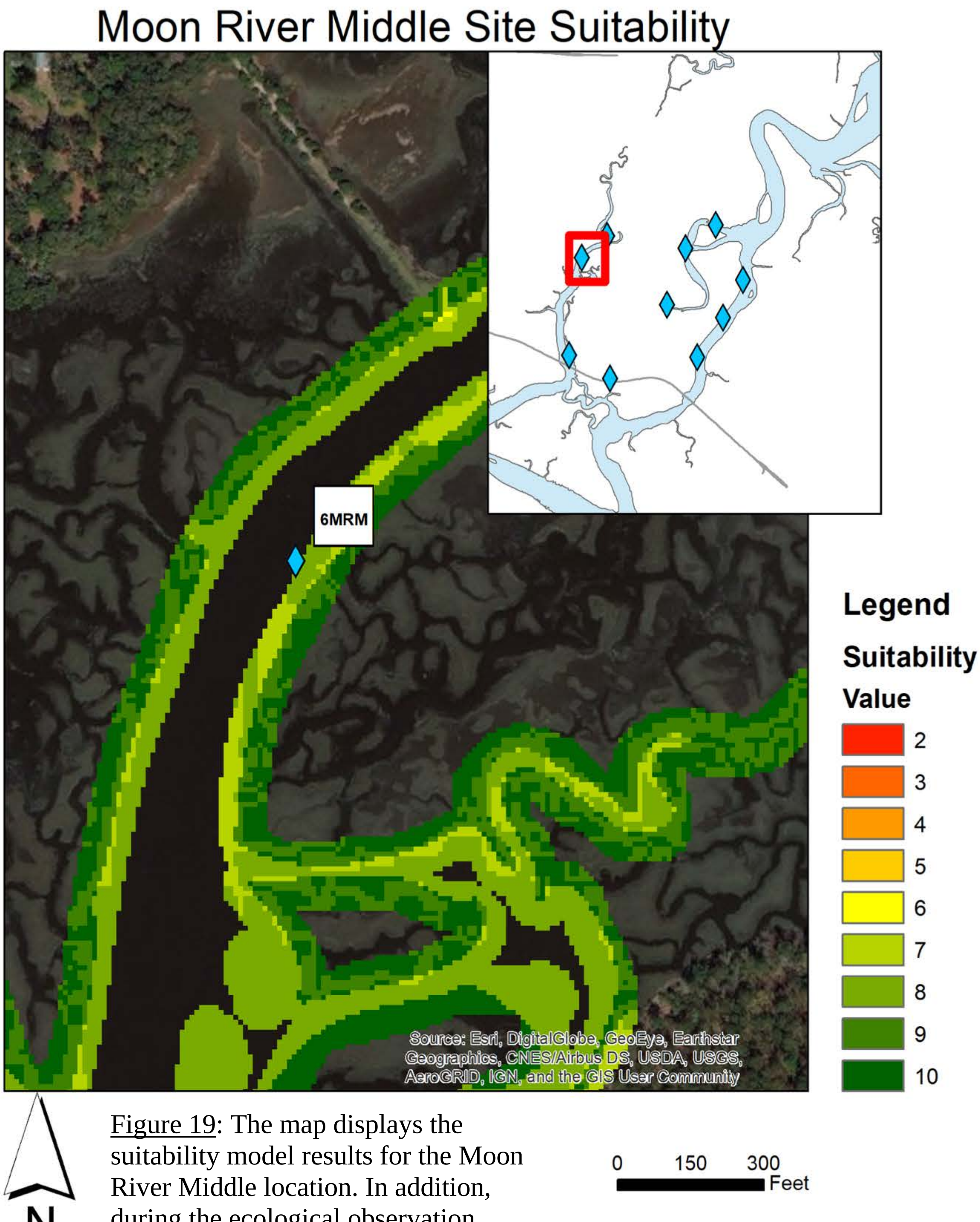



Figure 19: The map displays the suitability model results for the Moon River Middle location. In addition, during the ecological observation experiment 7 oyster spat recruited in May of 2017.

Moon River North Site Suitability

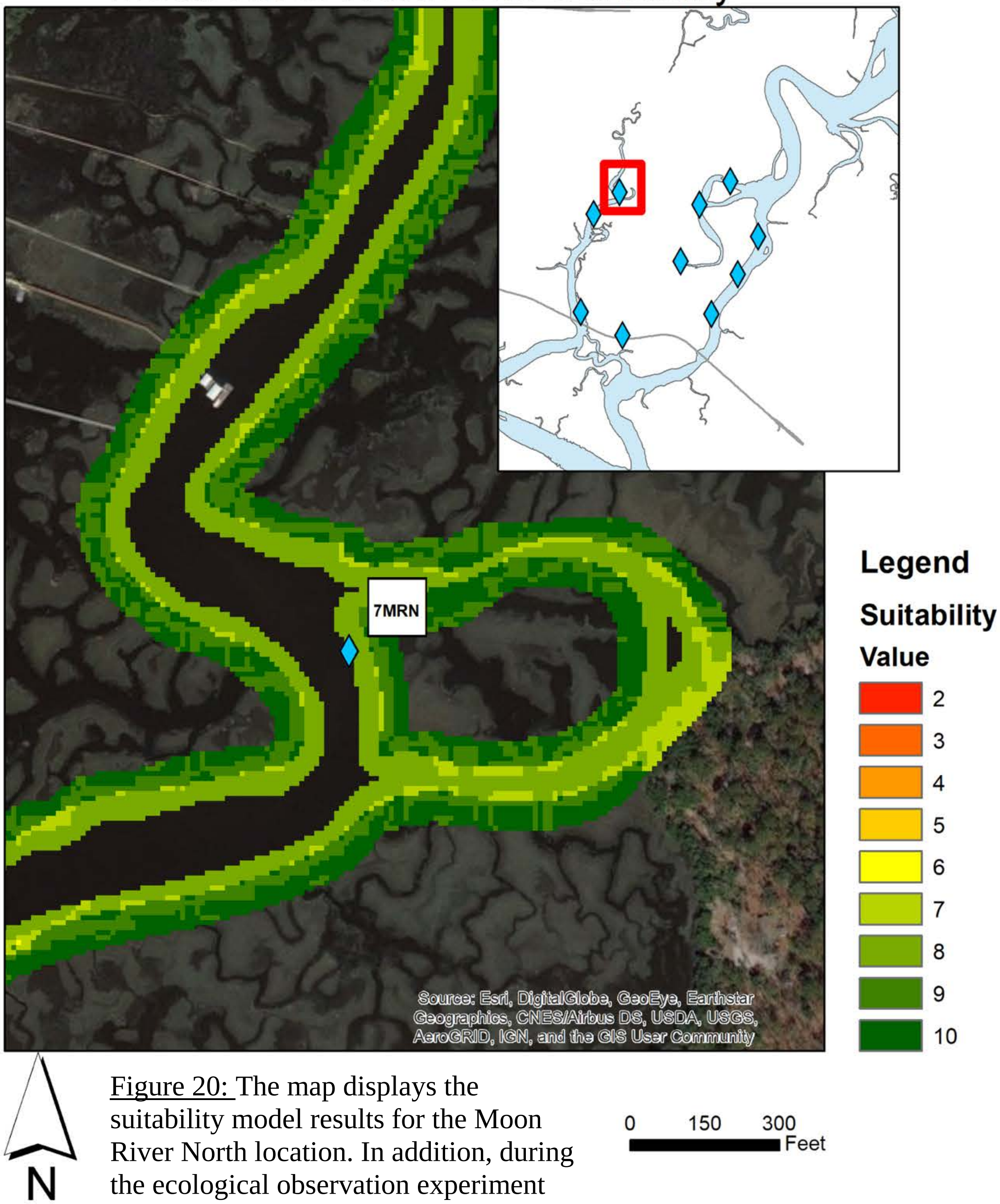
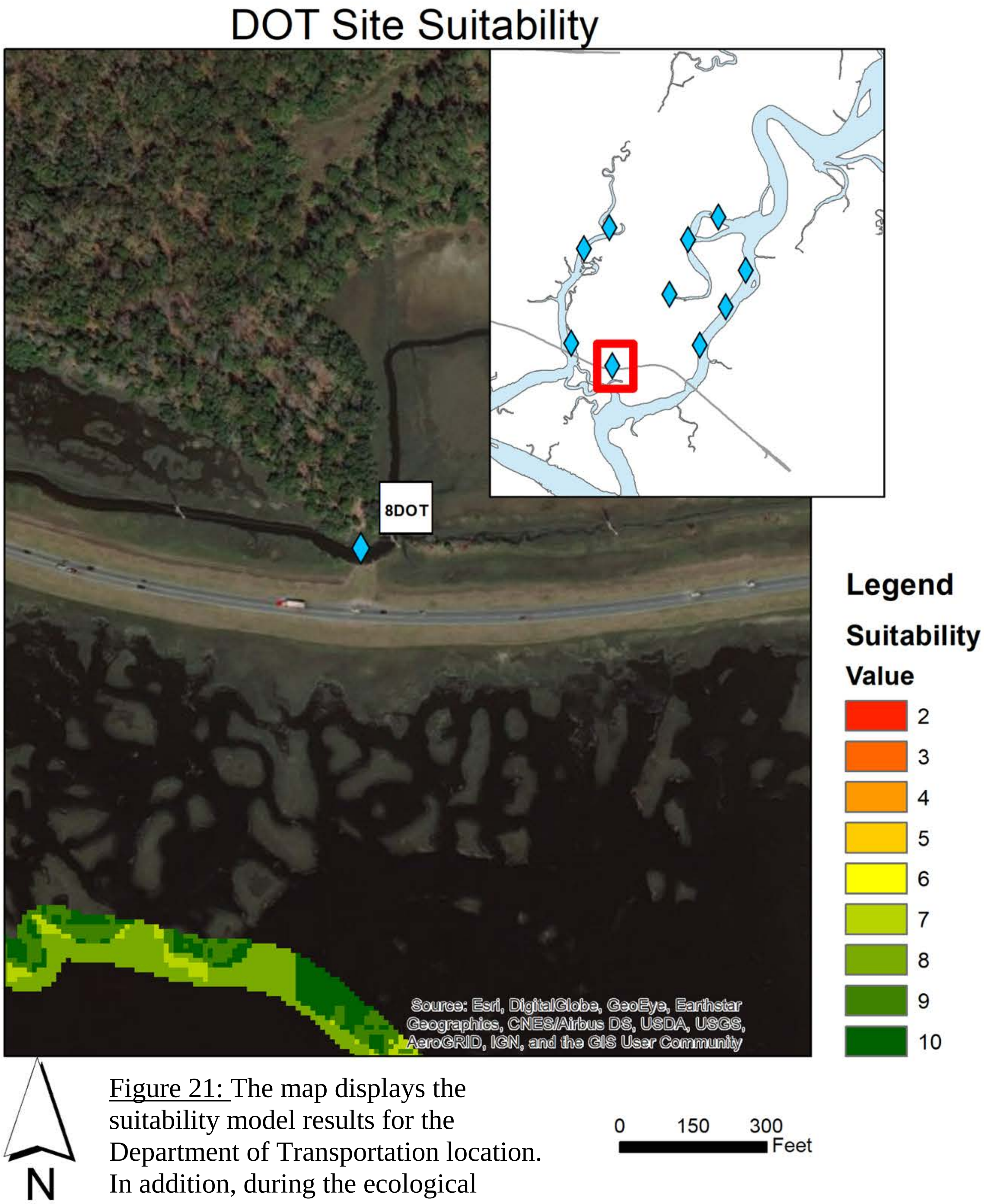



Figure 20: The map displays the suitability model results for the Moon River North location. In addition, during the ecological observation experiment no oyster spat recruited at this site.




<u>Figure 21:</u> The map displays the suitability model results for the Department of Transportation location. In addition, during the ecological observation experiment no oyster spat recruited at this site.

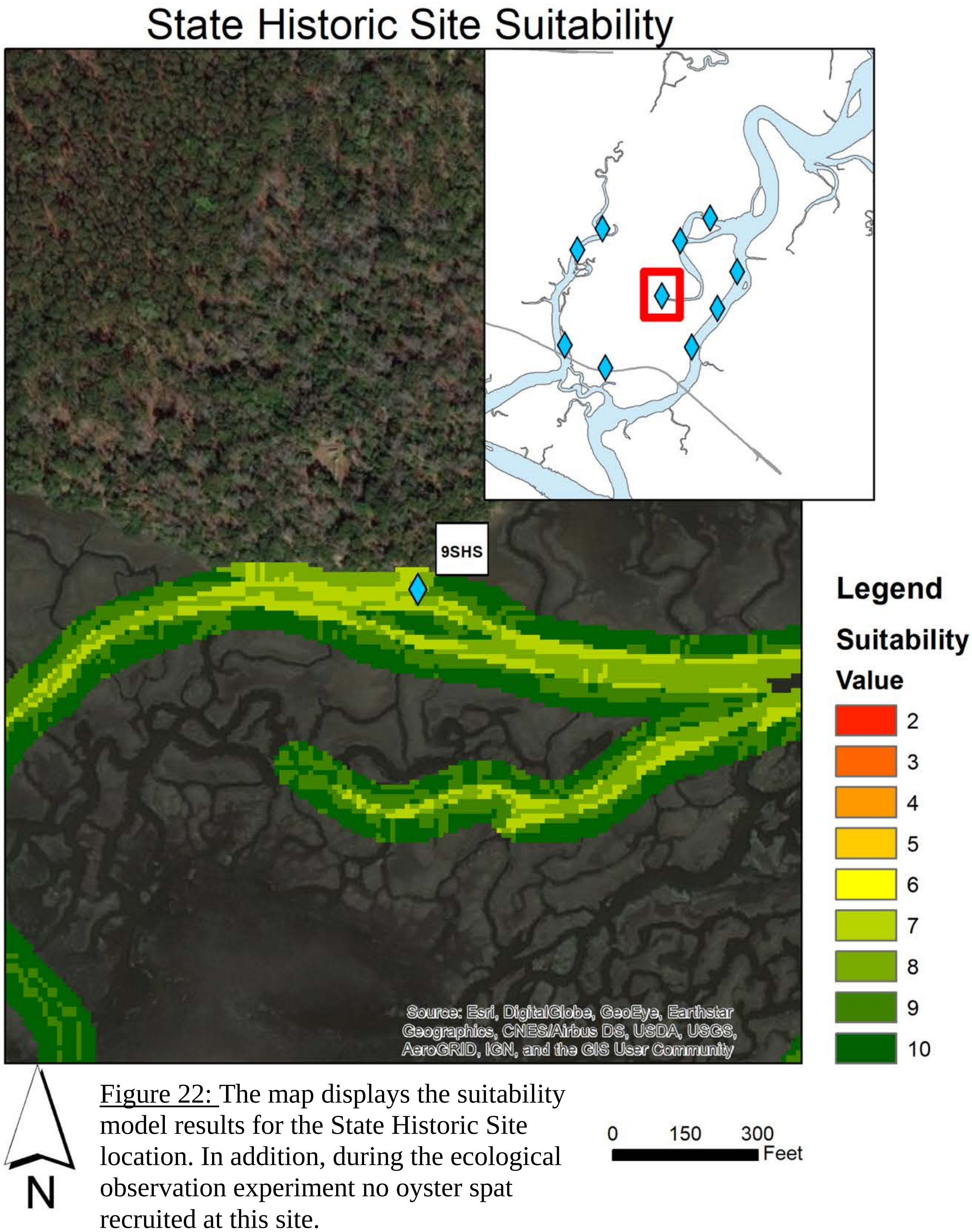



Figure 22: The map displays the suitability model results for the State Historic Site location. In addition, during the ecological observation experiment no oyster spat recruited at this site.

The 12 square mile study area is suitable for living shoreline installation based on the factors analyzed. 95% of the study area's shorelines received a score of 6 or more the weighted overlay analysis, meaning that they are moderately suitable to highly suitable for living shoreline installation (Table 2). 28% of the shoreline areas within the 12-mile study area received a 10 out of 10 scores meaning that they are most suitable areas analyzed by the model. This equates to nearly 30% of the shorelines around Wormsloe having the highest suitability regarding fetch, slope, the presence of marsh and distance from erosion hotspots. Particular areas of interest were the sites of the ecological observation study. Of the ecological observation study sites, SHS (state historic site) was the main point of interest. Although, oyster recruitment was not observed at the site the area is deemed suitable to moderately suitable for living shoreline installation by the living shoreline suitability model (Figure 20).

**Suitability Area and Score Breakdown**

Table 2: This table illustrates the breakdown of raster cells created by the living shoreline suitability pilot study. 76% of the study area rasters fall into the top three scores of 8, 9, and 10 corresponding to the highest level of suitability.

| Suitability Score | Suitability Level | Number of Cells | Percentage of Total |
|---|---|---|---|
| 2 | Low | 57 | < 1% |
| 3 | Low | 358 | < 1% |
| 4 | Low | 2,770 | 1.3% |
| 5 | Moderate | 6,151 | 2.9% |
| 6 | Moderate | 9,645 | 4.6% |
| 7 | Moderate | 30,111 | 14.4% |
| 8 | High | 51,853 | 24.9% |
| 9 | High | 47,712 | 22.9% |
| 10 | High | 59,567 | 28.6% |

Jones Narrows was not the most suitable waterway for living shoreline installation. An area of interest was the location of the SHS spat stick sampling site along Jones Narrows. The SHS location is of interest due to the erosion and upland bank failure at the Wormsloe State Historic Site. This erosion threatens cultural resources including one of the oldest European structures in Savannah and will likely be exacerbated by global sea level rise as a result of climate change.

Moon River had the highest concentration of highly suitable areas for living shorelines. Moon River has a boat access point similar to Skidaway River connected by the Diamond Causeway highway. Interestingly, the Moon River boat access area appears to be much more suitable based off of the four criteria analyzed. The Skidaway River had the highest concentration of areas that received a low suitability score. All three locations (LIN, LIM, and LIS) along the Skidaway River had cells that received scores of 3 and 4. The high fetch and erosion hotspots are thought to contribute to the low suitability for living shorelines along the Skidaway River. The low suitability scores indicate that implementing a living shoreline along the Skidaway River could be difficult and would likely require more intensive shoreline hardening and management.

### *Results and Discussion: Oyster Recruitment Study*

There was little to no oyster recruitment at the ten tested locations of the oyster recruitment study. In fact, there was only 28 oyster spat recruited total during the five-month study (Appendix C).

The goal of this thesis research was to establish a living shoreline suitability pilot model that is informed by oyster recruitment data. This was accomplished by comparing recruitment results to suitability model results. Prior to the oyster recruitment study certain waterways around Wormsloe were expected to produce high numbers of oyster spat. Due to the vast number of oyster reefs in the waterways of Jones Narrows and Moon River it was expected that hundreds even thousands of oyster spat would recruit during the summer of 2017. In the past, Georgia consistently had some of the highest oyster recruitment in the country. Past ecological observation studies in Georgia produced up to 35,000 oyster spat per $m^2$ (O'Beirn 1996). If these numbers were standardized to the Wormsloe ecological observation study, it would have resulted in 3,290 oysters spat recruiting per stick and the study would have produced 658,000 total oyster spat. The ecological observation study on oyster recruitment at Wormlsoe did not reach close to the previously recorded recruitment levels. The causes of the low recruitment are unknown.

There are several possible explanations for low recruitment totals during the summer of 2017. Past recruitment studies using the same PVC pipe substrate as this study found that peak recruitment occurred in either June or August (Moroney 1997; O'Beirn 1996).). Warmer temperatures ranging from 29-31.5$^{o}$C have coincided with low recruitment rates (O'Beirn 1996). Water temperatures at the Ft. Pulaski NOAA Buoy Station reached 29$^{o}$ as early as June 27th during the summer of 2017; water temperatures continued to climb during the study as the highest temperature recorded was 31$^{o}$ on August 20th, 2017. Exceedingly warmer water temperatures during the peak recruitment months of June and August could have contributed to low spat recruitment. This is also combined with the fact that oyster populations are under more stress as temperatures rise. Oyster populations exposed to high heat and lower salinity have difficulties reproducing and increased mortality. Salinity levels lower than two parts per thousand (ppt) combined with temperatures above 28$^{o}$C can result in critical levels of mortality in eastern ouster populations (Southword, Long and Mann 2017). Salinity levels around the ten Wormsloe test sites were not tested for temperature or salinity; however, temperatures above the thresholds of 29$^{o}$ and 28$^{o}$ likely harmed recruitment and caused higher mortality in oyster populations (O'Beirn 1996; Southword, Long and Mann 2017).

Evidence throughout the southeast supports the claim that low salinity and high temperatures negatively impact oyster populations. In the Breton Sound estuary part of the Plaquemines-St. Bernard delta complex, located approximately 20 km southeast of New Orleans, experiments demonstrated that high water temperatures (> 30o) and low salinities (< 5) negatively impact oyster growth and survival (Rybovich 2014). The study also found that high temperatures alone may negatively impact oysters. (Rybovich 2014). High temperatures place stress on oyster populations and cause low fecundity and recruitment rates. Research also suggests that oyster populations absorb toxins faster in higher temperature waters (Cherkasov, Taylor and Sokolova 2009). Cadmium levels were absorbed and accumulated faster in the tissues of oyster populations sampled in Texas and North Carolina (Cherkasov, Taylor and Sokolova 2009).

Another possible explanation for low recruitment was the result of high impact hurricanes entering the region during the study duration. Hurricane Irma and Maria, occurred during the scope of the ecological observation experiment. Recruitment rates and oyster survival rates are impacted by strong tropical storms (Parker et al. 2013). A study in Florida's St Lucie and Sebastian River estuarine areas found that oyster populations and recruitment levels were lowest during a two-year period after tropical storms impacted the region (Parker et al. 2013). Tropical storms were thought to have decreased the salinity rates in the area leading to declines in recruitment and high mortality rates in established oyster populations (Parker et al. 2013). Salinity is also related to the survival and growth of other organisms in the marshland environment.

Salinity levels particularly the production and availability of freshwater supplies greatly impact the growth of *Spartina alterniflora*. A study evaluating *Spartina alterniflora* growth in the Altamaha River estuary of the Georgia coast found that the river discharge of freshwater was the most important factor impacting the annual net primary production (ANPP) levels of *Spartina alterniflora* growth (Wieski and Pennings 2013). This was found throughout the different zones of the marsh and that higher temperatures also impacted *Spartina* growth levels (Wieski and Pennings 2013). A severe drought impacted Georgia in the months leading up to the launch of the oyster recruitment study. The drought was the most significant during February, March, and April of 2017 (Figure 26; Figure 27; Figure 28).  This is important in the context of the Wormsloe ecological observation study on oyster recruitment as *Spartina alterniflora* detritus (and its microbes) are by far the most abundant food supply for oyster populations on the Georgia coast (Stevens 1983, 130).

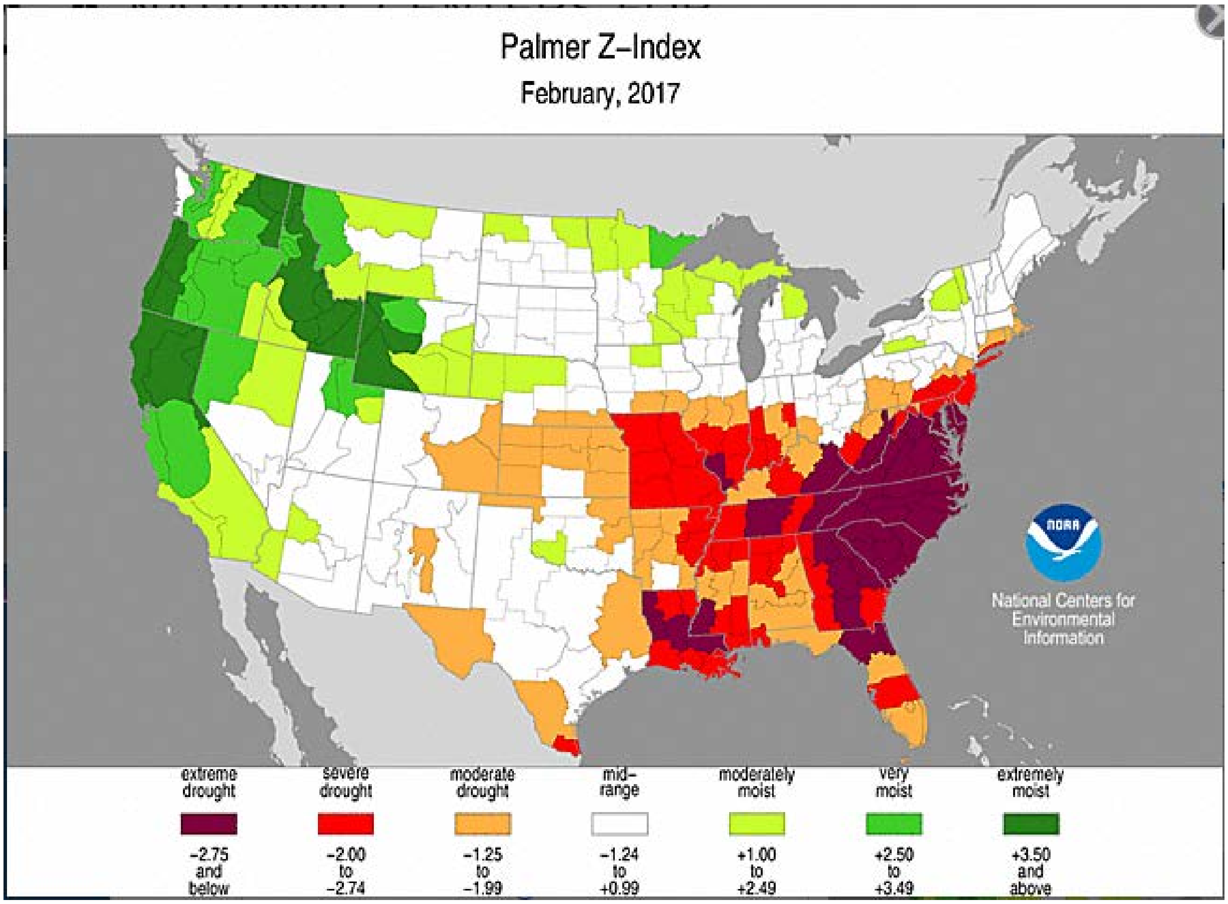



Figure 23: This image displays the widespread drought of 2017 that could have impacted oyster populations. Taken from (NOAA 2017)

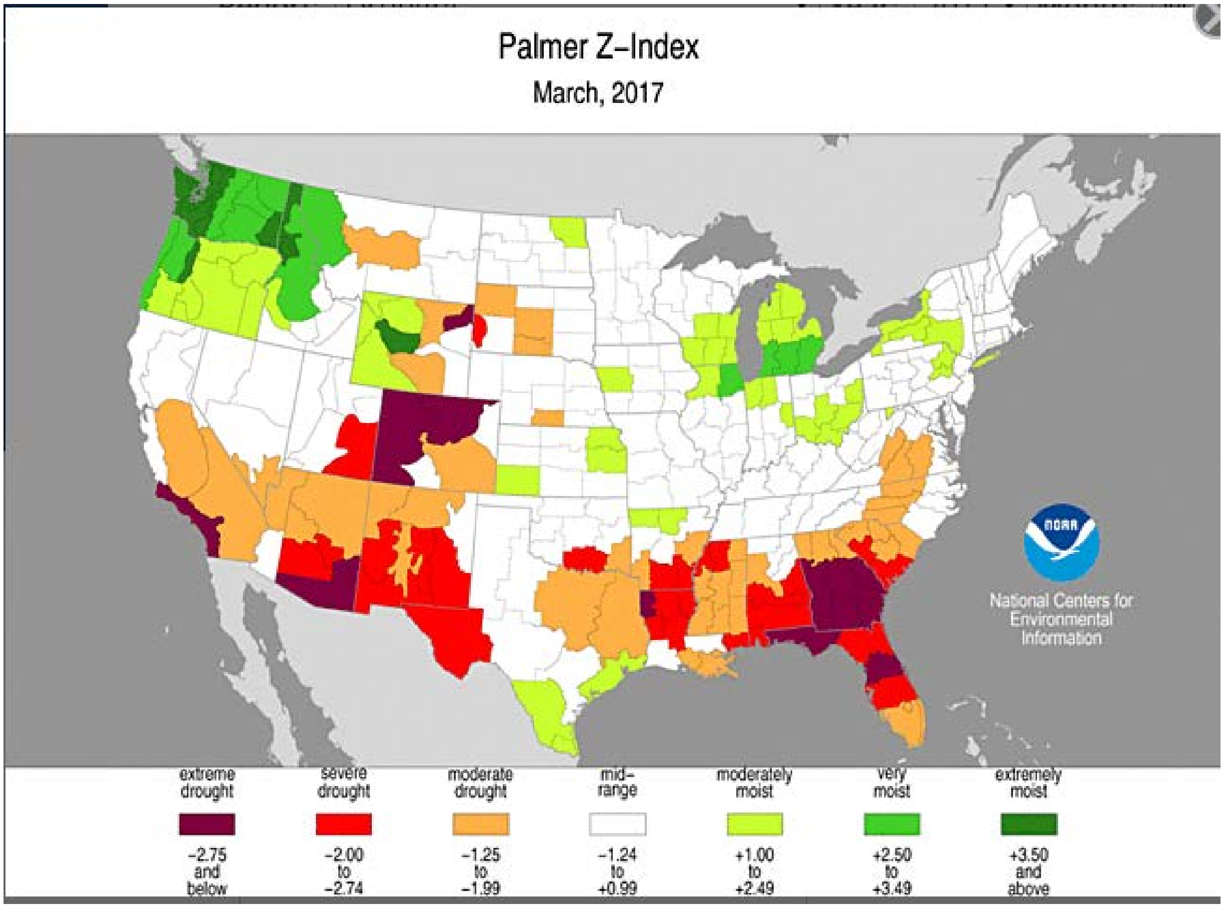



Figure 24: This image displays the widespread drought of 2017 that could have impacted oyster populations, taken from (NOAA 2017)

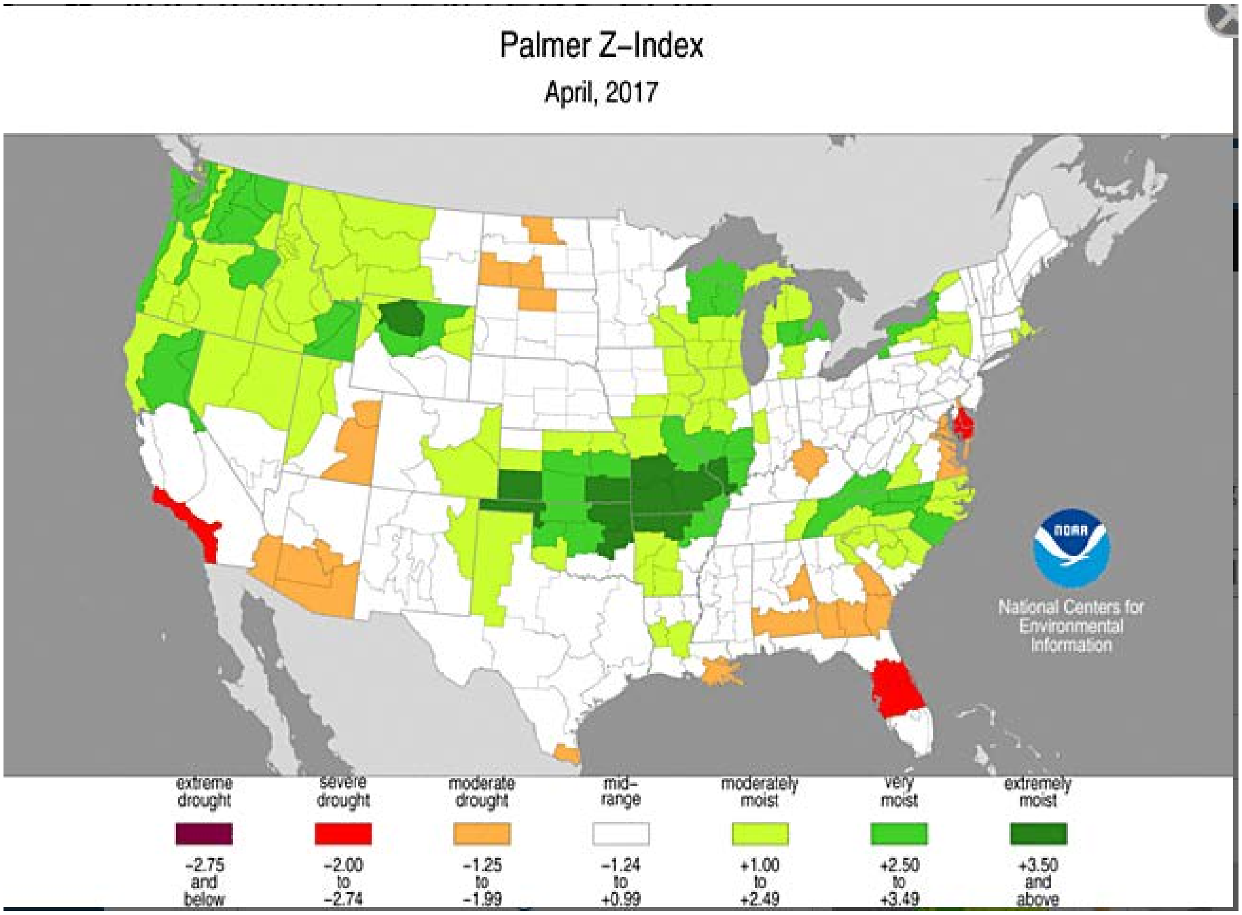



Figure 25: This image displays the widespread drought of 2017 that could have impacted oyster populations, taken from (NOAA 2017)

It is possible that the lack of freshwater impacted river levels and subsequent *Spartina alterniflora* production. Historically, studies debated the main driver of Spartina *alterniflora* growth as being top-down or bottom-up. Top-down refers to the predation and grazing of *Spartina* from organisms in the marsh; the bottom-up approach states that the basis of *Spartina* growth is from environmental factors like salinity, temperature, and sediment availability (Alberti et al. 2009; Elschot et al. 2017). Recent studies find that the holistic combination of both biotic organisms and environmental factors drive *Spartina* marsh growth rates (Alberti et al. 2009; Elschot et al. 2017).

The possible drop in *Spartina alterniflora* growth and subsequent lack of detritus could have lessened the available food supply for oysters in the area around Wormsloe. Possible lower food levels combined with higher water temperatures that can lead to higher rates of toxin uptake and low reproduction rates, compounded by two high impact hurricane disturbances offer clarity into the low recruitment totals of the 2017 season. In the future it is essential to realize the potential impacts of global climate change as heat waves, changes in weather patterns and drought will be some of the impacts in the future as Georgia continues to become warmer and more arid (KC, Shepherd, and Gaither 2015).

A single recruitment season may not be enough time to understand potential reasons for low recruitment. It is also not enough time to determine if oyster reef restoration is possible due to oyster recruitment levels; the single season length of this research was one of the main delimitations of this study. The time duration of a single season and the limited number of sample sites (10) were both main delimitations of this study. The study is still an important first step in understanding living shoreline suitability and oyster recruitment, and hopefully, another Wormsloe Fellow will continue the research on this topic at the Wormsloe State Historic Site.

***Areas for future research and consideration***

It is important to state that all living shoreline suitability models including the results of this thesis the pilot model created for Wormsloe are not site-specific measures. All areas for potential living shoreline installation should be ground-truthed by state permitting staff and restoration experts. The goal of this pilot model is to determine areas with physical characteristics that are more suitable for living shoreline implementation. Other inputs would have likely altered the results of the model created for Wormsloe. The model at Wormsloe was created on the best data available at the time and data that was deemed useful. For example, other living shoreline literature states that inputs such as storm surge are important to living shoreline suitability. Currently, the entire shoreline area analyzed for living shoreline suitability around Wormsloe is submerged at a Category 1 storm. This would result in all of the areas receiving the same score and would not alter the suitability of the shoreline segments analyzed.

The living shoreline suitability pilot model for Wormsloe yielded results that the shorelines around Wormsloe are highly suitable for living shoreline installation based off of fetch, slope, marsh presence, and erosion hotspots. 76.4 percent of the shorelines around the Wormsloe State Historic Site received a score of 8-10 corresponding to high levels of suitability. This model should be used as a tool for living shoreline installation. Not every area that receives a high score in the model should receive a living shoreline treatment. In many cases, it is best to let the marshland dynamics take their natural course. It is up to state officials, concerned citizens, and coastal planners to determine what areas are in need of protecting, what the treatment should be for those sites, and what the accepted best management practice for shoreline erosion remediation and prevention will be in the future. Local planners, state officials, and community members could work to create areas of priority or high value and weigh the cost-benefit analysis of living shoreline installation. Areas of critical infrastructure and cultural resources would be areas for prime living shoreline installation if deemed suitable by a LSSM.

In a meeting with DNR CRD wetland permitting staff at Wormsloe on Monday, April 2nd, 2018 state officials gave feedback on the living shoreline suitability pilot model for Wormsloe. The officials' recommendations included the collection of shear stress levels at different tidal creek locations, more long-term monitoring of spat recruitment, and conducting recruitment studies with other substrates instead of the sanded PVC used in this research. These suggestions could be utilized to bolster the living shoreline suitability pilot model for Wormsloe and create a model that could be replicated for the entire state of Georgia.

Currently, the state of Georgia has only permitted living shorelines with the use of oyster reefs. This is possibly due to Georgia having the reputation of being rich in oyster spat but lacks the appropriate substrate for recruitment of new reefs. The ecological observation experiment conducted at Wormsloe during the summer of 2017 did not support the notion that the area was rich in spat. Only 28 spat were recruited over the five month duration of the study. There is a need for the Living Shoreline Working Group, nonprofits and educational institutions like the UGA Marine Extension to collaborate to establish a protocol for monitoring oyster recruitment in high priority areas such as state parks, cultural resources and critical infrastructure. This would allow for the question of will oysters recruit at a high priority site experiencing erosion to be answered. The recruitment of oysters at high priority sites facing erosion is important as living shorelines utilizing oyster reefs can adapt to sea level rise in addition to preventing erosion (Bilkovic et al. 2017). Climate change will be placing new stress on oyster populations that are already historically low. Changes in water temperature, salinity, and sea level will alter existing oyster habitat increasing the need for new substrate for colonies to form.

The research and new information produced by this thesis is the first step in modeling living shoreline suitability on the Georgia coast. It can play an important role in guiding the conversation on living shoreline installation and suitability in Georgia. The model created by this research aims to serve as screening tool for environmental planners, homeowners, and state officials. Currently, this model has an opportunity to evolve into a policy tool and spur new research that can allow for a better understanding of living shoreline suitability and placement in Georgia. If a statewide model tailored to Georgia with tidal shear-stress and salinity inputs added, it could be utilized as a tool for citizens and policymakers. The benefits would include appropriately sited living shoreline projects, better use of state funding, and protection of valuable resources and infrastructure. The development of a statewide living shoreline suitability model would allow for DNR staff to advocate for easier permitting in areas that are deemed suitable by a more robust model, and citizens could make more informed decisions about private shoreline hardening practices. New research on oyster recruitment levels, salinity rates, and shear-stress in tidal creeks could allow for the modeling of living shoreline suitability at the regional scale and implementation of new living shorelines around the state.

# CHAPTER 5

# CONCLUSION

The Wormsloe State Historic Site is one the most important cultural sites on the Georgia coast. The founder of Wormsloe Noble Jones traveled to establish the colony of Georgia with James Oglethorpe. Noble Jones' direct decedents still live on the property today nearly 300 years later and have held continuous residence at the former plantation (Cady and Goetcheus 2015). Wormsloe has significant Native American, European colonization period, slavery and African American, and Civil War period historical importance (Cady and Goetcheus 2015; Coulter 1995; Kelso 1979; Kimber 1974; Bragg 1999; Swanson 2012). In addition to layers of history, important historical figures such as botanist John Bartram and former US President Jimmy Carter have visited Wormsloe (Swanson 2012). Cultural resources such as Native American oyster middens and Civil War defensive earth mounds still remain on the Island and are threatened by shoreline erosion. Department of Transportation infrastructure known as the Diamond Causeway, located south of the Wormsloe State Historic Site has also experienced erosion and bank failure.

The green infrastructure technique known as a living shoreline can successfully adapt to moderate sea level rise and maintain ecological processes while minimizing erosion (Bilkovic et al. 2017; Currin et al 2017; GA DNR 2013; GA DNR CRD 2017). Living shorelines replicate the natural coastal processes of unarmored shorelines while allowing for the connection between upland and lowland habitats (Bilkovic et al. 2017).

Living shorelines techniques fall on a spectrum of green to grey implementation strategies. The greenest or least invasive techniques include marsh grass plantings, bank grading and restoration of natural riparian buffers (Bilkovic et al. 2017). Gray or hybrid techniques are designed to provide more protection than non-structural shoreline stabilization techniques. Hybrid living shoreline techniques range from sills, breakwaters, to artificial reefs for oyster colony formation (La Peyre et al 2017; Bilkovic et al. 2017). Living shorelines have grown in popularity and have been widely adopted in states like Florida, North Carolina, Virginia, Maryland and Connecticut (Bilkovic et al. 2017).

A living shoreline suitability pilot model was created in ArcGIS utilizing the weighted overlay tool. Living shorelines utilizing marshland vegetation were determined to be moderately to highly suitable in this study and around most of the Wormsloe State Historic Site. In addition to the suitability pilot model an ecological observation study was conducted during the summer of 2017 to evaluate the potential for living shorelines utilizing oyster reefs. Ten sites were selected around within the Wormsloe State Historic and spat sticks were placed and collected monthly. The site closest to the Wormsloe tabby ruins, called (SHS) the justification for this research as Native American oyster middens are threatened by erosion. The oldest European structure in Savannah, the Wormsloe tabby ruins are approximately 250 feet away from the eroding shoreline at the SHS site and undiscovered archeology and popular walking trails will likely be threatened in the future. The issues of erosion and bank failure need solutions as sea level rise will likely continue to accelerate the degradation of the shoreline and threaten the cultural resources of Wormsloe.

In addition to the model predicting high and moderate suitability for most of the shorelines of Wormsloe a living shoreline project could be very successful at Wormsloe due to educational exposure opportunity from site visitors. Thousands of visitors visit the Wormsloe State Historic Site annually and could allow for greater exposure for living shoreline projects. Implementing a living shoreline at Wormsloe would also continue the practice of placing living shoreline projects on state owned land as all seven living shorelines in the state of Georgia are on state owned property. The implementation of a living shoreline with an oyster reef at Wormsloe would also have the potential to create area for future research analyzing the impacts of an oyster reef/revetment in a marshland environment. Wormsloe fellows could provide long-term monitoring of a living shoreline at Wormsloe. Long-term monitoring of living shorelines is rare due to lack of personnel and resources. The potential project would address one of the central areas of need for living shorelines in the southeast (Bilkovic et al. 2016; Myszewski and Alber 2016).

Further research on the topic of living shorelines could prove to be useful in the request for a state policy change or adoption of ordinances that allow for the faster and more widespread implementation of living shorelines in Georgia. In addition, this could lead to the use of living shorelines for the protection of historic and cultural resources in Georgia. A framework could be created that allows for expedited permitting or additional funding from state agencies such as GA DNR to be used to protect valuable cultural sites through living shoreline implementation. Turtle Mound State Historic Site and the Eldora House Historic Sites demonstrated the protection of historic coastal resources by using living shorelines in Florida. These projects can serve as a precedent for Wormsloe moving forward and act as a potential resource to understand how living shoreline implementation can affect coastal resources in the future.

This thesis created new knowledge and pointed to more areas for future research. The Wormsloe living shoreline suitability pilot study determined that the shorelines around Wormsloe are currently suitable for marsh grass and vegetation living shoreline installation. It is hoped that this research will continue at the Wormsloe Institute for Environmental History in partnership with UGA MAREX, the UGA Sea Grant, the UGA Shellfish Lab, and the GA DNR CRD. One possible area for future research and collaboration of regional partners could be a living shoreline installation project at Wormsloe. The project could include a constructed shoreline with differing treatments of oyster spat and substrates. This could lead to more information about recruitment rates long-term and further understanding of dynamics between oyster recruitment and shoreline stabilization.

Another area for future research is the need to understand the connection between oysters, marshland *Spartina alterniflora*, and freshwater availability. The top-down and bottom-up ecological theories of *Spartina* production requires further evaluation if governments, citizens and interest groups are able to accommodate changing coastlines. Sea level rise, drought, and heat will likely negatively affect *Spartina*, and subsequently place stress on oyster populations as rivers decrease from drought. As temperatures and sea levels rise and freshwater availably decreases marshland habitats of *Spartina alterniflora* and the eastern oyster could become less prevalent.

Living shoreline suitability and oyster recruitment are two different and complex processes that must overlap for a living shoreline to be permitted in Georgia. Oysters might not recruit where an oyster reef shoreline is suitable due to lack of substrate. There is a need for future research to address the delimitations of this study by analyzing oyster recruitment at more locations and over multiple seasons around Wormsloe. More sample locations for oyster spat recruitment and recruitment data over multiple seasons could address the questions that surround the correlation between oyster recruitment and living shoreline suitability. Successful modeling of living shoreline locations combined with oyster recruitment levels would allow for areas of interest in the future to be targeted by decision makers for living shoreline implementation and better address coastal resiliency needs.

In the future it is hoped that a living shoreline suitability model can be created for the entire state of Georgia and that it will be more robust with inputs such as shear stress and salinity. This could then be combined with recruitment levels from oyster populations around the coast to analyze if oysters recruit better at areas of higher suitability for shoreline installation. The next question that state officials, academics and communities will need to address is prioritizing protection areas, which will require a framework that identifies key cultural resources, critical infrastructure and valuable properties to the public that are worth protecting. Not all locations are suitable for living shorelines; in most cases marshland erosion cycles should be allowed to occur naturally. It is only in areas of prioritization that resources should be utilized to protect shorelines from erosion.

Living shorelines offer a solution to coastal erosion and can adapt to sea level rise if placed in the most suitable locations. Further research on living shorelines in Georgia is needed and a state wide living shoreline suitability model could be a valuable tool in coastal resiliency planning. It is critical for research to be conducted on living shoreline implementation in Georgia including topics like oyster recruitment, tidal movements, salinity changes and existing living shoreline monitoring. This living shoreline suitability pilot model aims to be a first step in furthering the knowledge on living shoreline suitability in Georgia and provide more information furthering the installation of living shorelines in Georgia.

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# APPENDICES

## *A: Process of Spat Stick Creation and Transportation*

Spat sticks were created from 10 ft long ¾ in diameter PVC pipe purchased from a local home improvement store. The sticks were cut using a hand held pipe cutter. Each 10 ft long pipe yielded three 1 meter spat sticks. After the spat sticks were measured and cut they were sanded by hand with 80-grain course sandpaper until rough.

An 18-gallon clear storage container was purchased for each month. The container was used to transport the spat sticks to and from collection sites, on and off of the boat and storage for counting recruitment of oyster spat. Towels were layered in between stacked spat sticks after their collection from each site, to prevent any oyster spat from breaking off before recording data. Data was recorded by counting all oyster spat on the sticks from the 60 cm above the sharpie line and was entered into Excel spreadsheets.

### *B: Process of Wind Data Creation*

First, excess data like water temperature, air temperature, pressure and others were deleted leaving only the date, time, wind direction and speed. Next, all of the data that appeared to be the result of errors were deleted; several hundred rows of data in each year's data sheet were errors that displayed wind direction and speeds as 999. The NOAA buoy data proved to be tedious as the buoy recorded the wind direction and speed multiple times daily. Each of the ten years of buoy data had an average of 83,352 data columns per excel file. Next, Excel was used to organize the percentage of entries blowing in each direction based on each degree's portion of the total. Meaning if the data recorded the wind direction blowing north 298 times of the 83,352 it would make up .36% of the wind from that year. After the data was synthesized as a portion of the total, it was organized by each of the 16 cardinal directions. Each direction 0o through 359o were divided into groups of either 22 or 23, alternating each time. This was completed to sort the wind directions based on the cardinal direction that it was closest to. For example, 0o north received all the wind directions from 348o to 11o. This was replicated around the entire compass until all of the 83,352 entries were grouped into 16 directions instead of 360. Next, pivot tables were created for each of the newly sorted annual wind data Excel files. The pivot tables summed all of the data points from each of the directions now represented by 16 cardinal directions instead of 360, into percentages of the total for that year.

***C: Recruitment Data and Densities***

Recruitment Data

| Site | 04/17 -Spat | 04/17 - Barnacle | 05/17 -Spat | 05/17 - Barnacle | 06/17 -Spat | 06/17 - Barnacle | 07/17 -Spat | 07/17 - Barnacle | 08/17 -Spat | 08/17 - Barnacle |
|---|---|---|---|---|---|---|---|---|---|---|
| DOT 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| DOT 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| DOT 3 | 0 | 0 | Stick Lost | Stick Lost | 0 | 0 | 0 | 0 | 0 | 0 |
| DOT 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| SHS1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | Stick Lost | Stick Lost |
| SHS2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | Stick Lost | Stick Lost |
| SHS3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | Stick Lost | Stick Lost |
| SHS4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Stick Lost | Stick Lost |
| BP1 | 0 | 4 | 0 | 0 | 0 | 3 | 0 | 22 | 0 | 25 |
| BP2 | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 41 | 0 | 23 |
| BP3 | 0 | 7 | 0 | 0 | 0 | 2 | 0 | 67 | 0 | 66 |
| BP4 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 51 | 0 | 27 |
| BD1 | 0 | 3 | 0 | 0 | 0 | 1 | 0 | 59 | 0 | 42 |
| BD2 | 0 | 1 | 0 | 3 | 0 | 2 | 0 | 192 | 0 | 72 |
| BD3 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 102 | 0 | 32 |
| BD4 | 0 | 8 | 0 | 0 | 0 | 2 | 0 | 57 | 0 | 50 |
| LIN1 | 0 | 1 | 3 | 0 | 0 | 3 | 0 | 47 | 0 | 27 |
| LIN2 | 0 | 1 | 2 | 0 | 0 | 1 | 0 | 23 | 0 | 14 |
| LIN3 | 0 | 0 | 1 | 0 | 0 | 2 | 0 | 36 | 0 | 17 |
| LIN4 | 0 | 2 | 2 | 1 | 0 | 2 | 0 | 56 | 0 | 11 |
| LIM1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 58 | 0 | 7 |
| LIM2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 64 | 0 | 6 |
| LIM3 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 51 | 0 | 1 |
| LIM4 | 0 | 3 | 0 | 0 | 0 | 1 | 0 | 65 | 0 | 4 |
| LIS1 | 3 | 0 | 0 | 0 | 0 | 1 | 0 | 32 | 0 | 12 |
| LIS2 | 0 | 3 | 0 | 1 | 0 | 2 | 0 | 55 | 0 | 41 |
| LIS3 | 0 | 7 | 0 | 2 | 0 | 4 | 0 | 46 | 0 | 33 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| LIS4 | 0 | 9 | 0 | 0 | 0 | 1 | 0 | 49 | 0 | 29 |
| MRS 1 | 0 | 0 | 2 | 3 | 0 | 1 | 1 | 17 | 0 | 12 |
| MRS 2 | 0 | 0 | 2 | 1 | 0 | 2 | 2 | 25 | 0 | 22 |
| MRS 3 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 15 | 0 | 17 |
| MRS 4 | 0 | 0 | 3 | 0 | 0 | 4 | 0 | 16 | 0 | 38 |
| MR M1 | 0 | 1 | 1 | 0 | 0 | 2 | 0 | 12 | 0 | 10 |
| MR M2 | 0 | 1 | 2 | 0 | 0 | 0 | 0 | 26 | 0 | 1 |
| MR M3 | 0 | 1 | 4 | 0 | 0 | 2 | 0 | 17 | 0 | 7 |
| MR M4 | 0 | 2 | 0 | 1 | 0 | 0 | 0 | 3 | 0 | 8 |
| MRN 1 | 0 | 2 | 0 | 102 | 0 | 0 | 0 | 20 | 0 | 17 |
| MRN 2 | 0 | 0 | 0 | 93 | 0 | 0 | 0 | 13 | 0 | 11 |
| MRN 3 | 0 | 0 | 0 | 47 | 0 | 0 | 0 | 9 | 0 | 21 |
| MRN 4 | 0 | 0 | 0 | 62 | 0 | 0 | 0 | 48 | 0 | 32 |

Recruitment Density Data

| Site | April-Spat-Densities | April-Barnacle-Densities | May-Spat-Densities | May-Barnacle-Densities | June-Spat-Densities | June-Barnacle-Densities | July-Spat-Densities | July-Barnacle-Densities | August-Spat-Densities | August-Barnacle-Densities |
|---|---|---|---|---|---|---|---|---|---|---|
| DOT 1 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| DOT 2 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| DOT 3 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| DOT 4 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| SHS1 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.004 | 0.000 | 0.000 |
| SHS2 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.003 | 0.000 | 0.000 |
| SHS3 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 |
| SHS4 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| BP1 | 0.000 | 0.004 | 0.000 | 0.000 | 0.000 | 0.003 | 0.000 | 0.023 | 0.000 | 0.027 |
| BP2 | 0.000 | 0.006 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.044 | 0.000 | 0.024 |
| BP3 | 0.000 | 0.007 | 0.000 | 0.000 | 0.000 | 0.002 | 0.000 | 0.071 | 0.000 | 0.070 |
| BP4 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.054 | 0.000 | 0.029 |
| BD1 | 0.000 | 0.003 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.063 | 0.000 | 0.045 |
| BD2 | 0.000 | 0.001 | 0.000 | 0.003 | 0.000 | 0.002 | 0.000 | 0.204 | 0.000 | 0.076 |
| BD3 | 0.000 | 0.008 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.108 | 0.000 | 0.034 |
| BD4 | 0.000 | 0.008 | 0.000 | 0.000 | 0.000 | 0.002 | 0.000 | 0.060 | 0.000 | 0.053 |
| LIN1 | 0.000 | 0.001 | 0.003 | 0.000 | 0.000 | 0.003 | 0.000 | 0.050 | 0.000 | 0.029 |
| LIN2 | 0.000 | 0.001 | 0.002 | 0.000 | 0.000 | 0.001 | 0.000 | 0.024 | 0.000 | 0.015 |
| LIN3 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.002 | 0.000 | 0.038 | 0.000 | 0.018 |
| LIN4 | 0.000 | 0.002 | 0.002 | 0.001 | 0.000 | 0.002 | 0.000 | 0.059 | 0.000 | 0.012 |
| LIM1 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.062 | 0.000 | 0.007 |
| LIM2 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.068 | 0.000 | 0.006 |
| LIM3 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.054 | 0.000 | 0.001 |
| LIM4 | 0.000 | 0.003 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.069 | 0.000 | 0.004 |
| LIS1 | 0.003 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.034 | 0.000 | 0.013 |
| LIS2 | 0.000 | 0.003 | 0.000 | 0.001 | 0.000 | 0.002 | 0.000 | 0.058 | 0.000 | 0.044 |
| LIS3 | 0.000 | 0.007 | 0.000 | 0.002 | 0.000 | 0.004 | 0.000 | 0.049 | 0.000 | 0.035 |
| LIS4 | 0.000 | 0.010 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.052 | 0.000 | 0.031 |
| MRS 1 | 0.000 | 0.000 | 0.002 | 0.003 | 0.000 | 0.001 | 0.001 | 0.018 | 0.000 | 0.013 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| MRS 2 | 0.000 | 0.000 | 0.002 | 0.001 | 0.000 | 0.002 | 0.002 | 0.027 | 0.000 | 0.023 |
| MRS 3 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.016 | 0.000 | 0.018 |
| MRS 4 | 0.000 | 0.000 | 0.003 | 0.000 | 0.000 | 0.004 | 0.000 | 0.017 | 0.000 | 0.040 |
| MR M1 | 0.000 | 0.001 | 0.001 | 0.000 | 0.000 | 0.002 | 0.000 | 0.013 | 0.000 | 0.011 |
| MR M2 | 0.000 | 0.001 | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | 0.028 | 0.000 | 0.001 |
| MR M3 | 0.000 | 0.001 | 0.004 | 0.000 | 0.000 | 0.002 | 0.000 | 0.018 | 0.000 | 0.007 |
| MR M4 | 0.000 | 0.002 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.003 | 0.000 | 0.008 |
| MRN 1 | 0.000 | 0.002 | 0.000 | 0.108 | 0.000 | 0.000 | 0.000 | 0.021 | 0.000 | 0.018 |
| MRN 2 | 0.000 | 0.000 | 0.000 | 0.099 | 0.000 | 0.000 | 0.000 | 0.014 | 0.000 | 0.012 |
| MRN 3 | 0.000 | 0.000 | 0.000 | 0.050 | 0.000 | 0.000 | 0.000 | 0.010 | 0.000 | 0.022 |
| MRN 4 | 0.000 | 0.000 | 0.000 | 0.066 | 0.000 | 0.000 | 0.000 | 0.051 | 0.000 | 0.034 |