ABSTRACT

MODELING WETLAND RESPONSE TO FUTURE SEA-LEVEL RISE IN THE PAMLICO AND CROATAN SOUNDS, NORTH CAROLINA

by

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Coastal habitats are among the world's most vulnerable environments to climate change and are highly sensitive to the impacts of future SLR. During the course of this century sea-level rise (SLR) enhanced by global climate change will become a major issue affecting coastal wetlands. Predicted SLR in the future could have major impacts on estuarine systems and will likely force changes in wetland spatial extent, geographic location, and type. Coastal wetlands located along the Pamlico and Croatan Sounds in eastern North Carolina will undoubtedly be greatly affected by future SLR due to their large spatial extent and high vulnerability, and will need to be closely monitored and mapped to determine their future locations and rates of change, including erosion, accretion, and loss. Research assessing the impacts of future SLR on coastal wetlands is vital for determining ways to conserve and protect these natural resources. The use of GIS-based, ecological SLR modeling is essential in order to analyze and explore the potential habitat changes of coastal wetlands during long-term SLR.

The purpose of this study is to determine the relative accuracy of the Sea-Level Affecting Marshes Model (SLAMM) in predicting wetland response to future SLR in the Pamlico and Croatan Sounds, North Carolina. SLAMM accuracy was determined by performing a model hindcast and outputs were compared to current wetland maps utilizing point and cell-based accuracy assessments, as well as various descriptive statistics. Accuracy results from model hindcasting were deemed acceptable to run model forecasts through 2100 using varying SLR scenarios. Future wetland change in both spatial extent and type were assessed using both quantitative and visual analysis. Model forecast results predict major changes within the study area, even devastating ones ecologically to wetlands and all interlinked habitats and ecological systems. Additional studies should be conducted using SLAMM utilizing hindcasting for calibration of model parameters and implementing higher-quality input data to yield better model outputs and accuracy.

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DEDICATION

This thesis is dedicated to Jeanette and Cadence.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS/ABBREVIATIONS

APES	Albemarle-Pamlico Estuarine System
APNEP	Albemarle-Pamlico National Estuary Partnership
DEM	Digital Elevation Model
GHG	Greenhouse Gas
GIS	Geographic Information Systems
HGM	Hydrogeomorphic
IPCC	Intergovernmental Panel on Climate Change
LIDAR	Light Detection and Ranging
MTL	Mean Tide Level
NAVD88	North American Vertical Datum of 1988
NCDCM	North Carolina Division of Coastal Management
NED	National Elevation Dataset
NOAA	National Oceanic and Atmospheric Administration
NWI	National Wetland Inventory
SLAMM	Sea-Level Affecting Marshes Model
SLR	Sea-Level Rise
USGS	U.S. Geological Survey

1 INTRODUCTION

During the course of this century sea-level rise (SLR) enhanced by global climate change will become a major issue affecting coastal wetlands. Short-term data and long-term geological records reveal that coastal wetlands are highly vulnerable to disturbances within the coastal environment (McFadden et al., 2007). Predicted SLR in the future could have major impacts on estuarine systems and will likely force changes in wetland spatial extent, geographic location, and type (McFadden et al., 2007; Pethick, 2001).

Coastal wetlands located along the Pamlico and Croatan Sounds in eastern North Carolina will undoubtedly be greatly affected by future SLR due to their large spatial extent and high vulnerability. Due to the low topographic elevation and slope gradient present throughout the region, the majority of coastal wetlands are within only a few feet of current sea level (Corbett, Walsh, Cowart, Riggs, Ames, & Culver, 2008; Phillips, 1986). These extensive wetland communities comprised of low-lying swamp forests and fringing marshes, support a multitude of ecological functions that are critical to the health of the regional ecosystem (APNEP, 2011).

Research assessing the impacts of future SLR on coastal wetlands is vital for determining ways to conserve and protect these natural resources. Coastal wetlands in eastern North Carolina will need to be closely monitored and mapped to determine their future locations and rates of change, including erosion, accretion, and loss. The Sea level Affecting Marshes Model (SLAMM) is a relatively high resolution model that utilizes the dominant processes associated with wetland conversion to predict regional-scale marsh response to future rises in sea-level (McLeod et al., 2010; Clough, 2010). The use of GIS-based, ecological SLR modeling is essential in order to analyze and explore potential habitat change of coastal wetlands during long-term SLR.

Future Sea-Level Rise and the Coast

Coastal habitats are among the world's most vulnerable environments to climate change and are highly sensitive to the impacts of future SLR (Poulter, et al., 2009; Neumann, Hudgens, Herter, & Martinich, 2010). Current research suggests that climate change will increase the rate of SLR along a majority of the U.S. coastline causing flood damages, erosion, wetland inundation, and other ecological damage (Neumann, Hudgens, Herter, & Martinich, 2010). Even without an expected increased rate of SLR resulting from climate change, sea levels in many coastal regions around the world would rise due to geological processes such as land subsidence. Future SLR impacts will also combine with other coastal problems (e.g., pollution and urbanization) to degrade the overall quality of coastal systems.

One of the most critical scientific issues regarding coastal environments is predicting how coastlines will respond to future SLR (Gesch, 2009). Similar to other natural hazards, awareness and communicating the threats and risks associated with SLR remains an obstacle. Difficulty in communicating SLR risks may be related to the fact the SLR is a long-term process in which its effects are not always immediately felt, leading to controversy and denial in some instances.

Many forecasted climate changes and their associated effects will have important consequences for coastal environments. Potential acceleration of future SLR rates could worsen the already high amount of vulnerability of coastal areas to natural hazards. Despite vast uncertainties associated with the specific impacts climate change will have on certain areas, experts agree that SLR is a definite consequence of global climate change (Wu et al., 2002).

Global climate change is a vital threat that challenges the global community today and in the future. One of the potential consequences of global climate change is a rise in global sea levels due to a warming of the atmosphere triggering increased warming and thermal expansion in the oceans, and the melting of snow and ice pack from the world's temperate glaciers and Greenland and Antarctic ice sheets (Kostelnick, McDermott, & Rowley, 2009). Currently, global sea-level is rising at a rate of 1-2mm/yr, and can be mainly attributed to the two prior causes as well as land subsidence (Poulter, et al., 2009). Looking forward, Kostelnick, et al. (2009) estimate that global sea level could rise almost 80m if the Greenland and Antarctic ice sheets were to completely melt.

Some of the direct impacts associated with global SLR include inundation and increased vulnerability to changes in hurricane frequency and intensity. Worldwide, there is an estimated 2 million km of coastline that are vulnerable to SLR and other climate change effects, with around 60% of the world's population at risk (Poulter, et al., 2009). Results from recent climate change studies suggest that rates of SLR will continue to increase over the next century (Poulter, et al., 2009).

Studies addressing projections of global SLR as a result of human-induced climate change have risen in recent years, mainly due to an increased awareness of its potentially severe impacts (Weiss et al., 2011). These studies have revealed new SLR projections that surpass the most recent high–end SLR projection released by the Intergovernmental Panel on Climate Change (IPCC) of 0.26-0.59m and a low-end projection of 0.18-0.38m of global SLR by 2100 based on the A1FI and B1 emissions scenarios respectively (Weiss, Overpeck, & Strauss, 2011; (Kostelnick, McDermott, & Rowley, 2009; Climate Change 2007: Synthesis Report, 2007). The IPCC A1FI emissions scenario assumes a world of high economic growth, a global population that peaks in mid-century, and rapid development of new and more efficient technologies; as well as still highly fossil fuel dependent (Climate Change 2007: Synthesis Report, 2007). The B1 emissions scenario describes a highly-interconnected world, with a similar global population as

A1, but with more rapid changes in economic frameworks toward a service and information-based global economy (Climate Change 2007: Synthesis Report, 2007). The IPCC SLR projections are conservative as compared to other potential SLR projections and they do not consider local and regional SLR variability. They also exclude natural subsidence and future changes in sea and land-based ice melt.

Several other independent studies estimate future SLR could reach 1m or more along the NC coast by 2100, even if moderate reductions of greenhouse gas (GHG) emissions are implemented over the rest of this century (Weiss, Overpeck, & Strauss, 2011). The North Carolina Resources Commission's Science Panel on Coastal Hazards has recommended that a single set of sea level projections be adopted for planning purposes (NCCRC, 2010). The science panel's low-end sea level projection of roughly 0.40m of relative SLR by 2100 represents a linear projection with no expected acceleration; a relative SLR of 1m represents increasingly warm ocean temperatures based on an increase in ocean temperatures over the last century; and a high-end relative SLR of 1.4m includes the rises in sea level due to rapidly melting glaciers and ice sheets (NCRC, 2010). A 2m rise is possible, but would only happen with rapidly accelerating SLR stemming from very high rates of warming and ice sheet melting (NCRC, 2010).
Global GHG emissions will not only affect SLR over the rest of the 21st century, but will also continue to affect global SLR into the future (Weiss, Overpeck, & Strauss, 2011). By the end of the 21st century the planet may warm to the point of potentially ensuring 4-6m of global SLR over following centuries. Results from many recent climate change studies have shown global SLR accelerating over time, which is why assessing and planning for potential SLR impacts to coastal environments has recently increased in importance.

Wetlands and Sea-Level Rise

It is generally acknowledged throughout the scientific community that wetlands will attempt to respond to future SLR by both horizontal migration and vertical accretion (McFadden, Spencer, & Nicholls, 2007; Pethick, 2001). There are three likely responses of tidal salt marshes to rising sea levels: *marsh inundation* if sediment supply and growth is less than the rate of coastal submergence; *marsh expansion* if sedimentation surpasses coastal submergence; and *marsh maintenance* if sedimentation is in equilibrium with coastal submergence (Phillips, 1986). In addition to sediment supply, the ability of wetlands to react and adapt to future rises in sea level will depend on additional factors such as tidal range, sediment supply and accommodation space (McFadden, Spencer, & Nicholls, 2007).

According to McFadden et al. (2007), an area's tidal range is an important factor when determining vulnerability to future SLR. More often than not, wetlands are usually subject to slow rates of relative SLR caused by eustatic factors and geomorphologic subsidence. An impact of a slow increase in sea level would be an adjustment in the variability of tidal flooding. Wetlands that are subject to SLR without equal increases in ecosystem elevation will most likely change to a wetland type typical of a lower position in the tidal frame; mainly due to an increase of duration and depth of tidal flooding (McFadden, Spencer, & Nicholls, 2007). Many researchers argue that wetlands maintaining equilibrium under a large tidal range may have greater resilience towards the potential impacts of future SLR than wetlands in an area subject to lower tidal ranges (McFadden, Spencer, & Nicholls, 2007). Nevertheless, a rapid rate of SLR does not correlate well with wetland adaptation and development, however a lower rate tends to better facilitate wetland development (Phillips, 1986).

The long-term stability and adaptability to future SLR is dependent on the ability of wetlands to maintain their relative position (elevation) in the tidal zone via sufficient sediment supply so that they are able to keep pace with the rate of future SLR (McFadden, Spencer, & Nicholls, 2007; Pethick, 2001). McFadden et al. (2007) reported that regional and local characteristics in sediment supply are difficult to determine and parameterize due to their highly variable temporal and spatial behavior, and given a sufficient sediment supply, available accommodation space is a critical factor influencing the horizontal migration responses of wetland ecosystems. Coastal geomorphology and coastal defense structures play large roles in wetland migration. Coastal areas with steeper slopes inhibit the capacity for wetland landward movement and coastal areas where coastal defense structures have been implemented effectively diminish the accommodation space available for wetland landward migration (McFadden, Spencer, & Nicholls, 2007; Pethick, 2001).

The Albemarle-Pamlico Estuarine System

The Albemarle-Pamlico peninsula region is located in eastern North Carolina and is one of the most vulnerable estuarine systems in the U.S. to future SLR (Figure 1). Much of the region has less than 2 ft. of elevation (Figure 2), which makes it extremely susceptible to coastal storms and SLR (Corbett et al., 2008). The various coastal ecosystems that comprise the Albemarle-Pamlico region make it the second largest estuary in the United States (Corbett et al., 2008). The Albemarle-Pamlico Peninsula is bordered to the north, east, and south by the Albemarle, Croatan, and Pamlico Sounds respectively, as well as by the Suffolk Scarp (Figure 1) to the west (Moorhead and Brinson, 1995). The peninsula is home to Tyrrell, Hyde, Washington, and portions of Dare and Beaufort Counties, and also has a unique combination of geomorphic features and lagoon-like ecosystems (Moorhead and Brinson, 1995). In addition to being extremely low-lying, much of the peninsula includes low-gradient streams and poorly-drained soils (Moorhead and Brinson, 1995).

The total land area in the Albemarle-Pamlico Peninsula is roughly 502,621 ha (1940.6 square miles), with palustrine forest accounting for nearly 66 percent of all wetlands and estuarine wetlands totaling almost 10 percent (mainly located in central and east of peninsula) (Moorhead and Brinson, 1995). Based on 2001 US National land Cover data, woody and emergent herbaceous wetlands are the two dominant land cover types (Wang and Allen, 2008). In both wetland types, the soil is periodically inundated and saturated with fresh or salt water, or a mix of both (Wang and Allen, 2008). Roughly 77 percent of all wetlands in the peninsula are located at elevations less than 1.5m and almost all estuarine wetlands are located below 1.5m (Figure 2) close to the shoreline (Moorhead and Brinson, 1995). Elevations in the peninsula are lowest in the eastern portion (roughly <1.5m) and highest in the western portions (Moorhead and Brinson, 1995).

Figure 1. Overview map of the Albemarle-Pamlico Peninsula and Outer Banks areas.

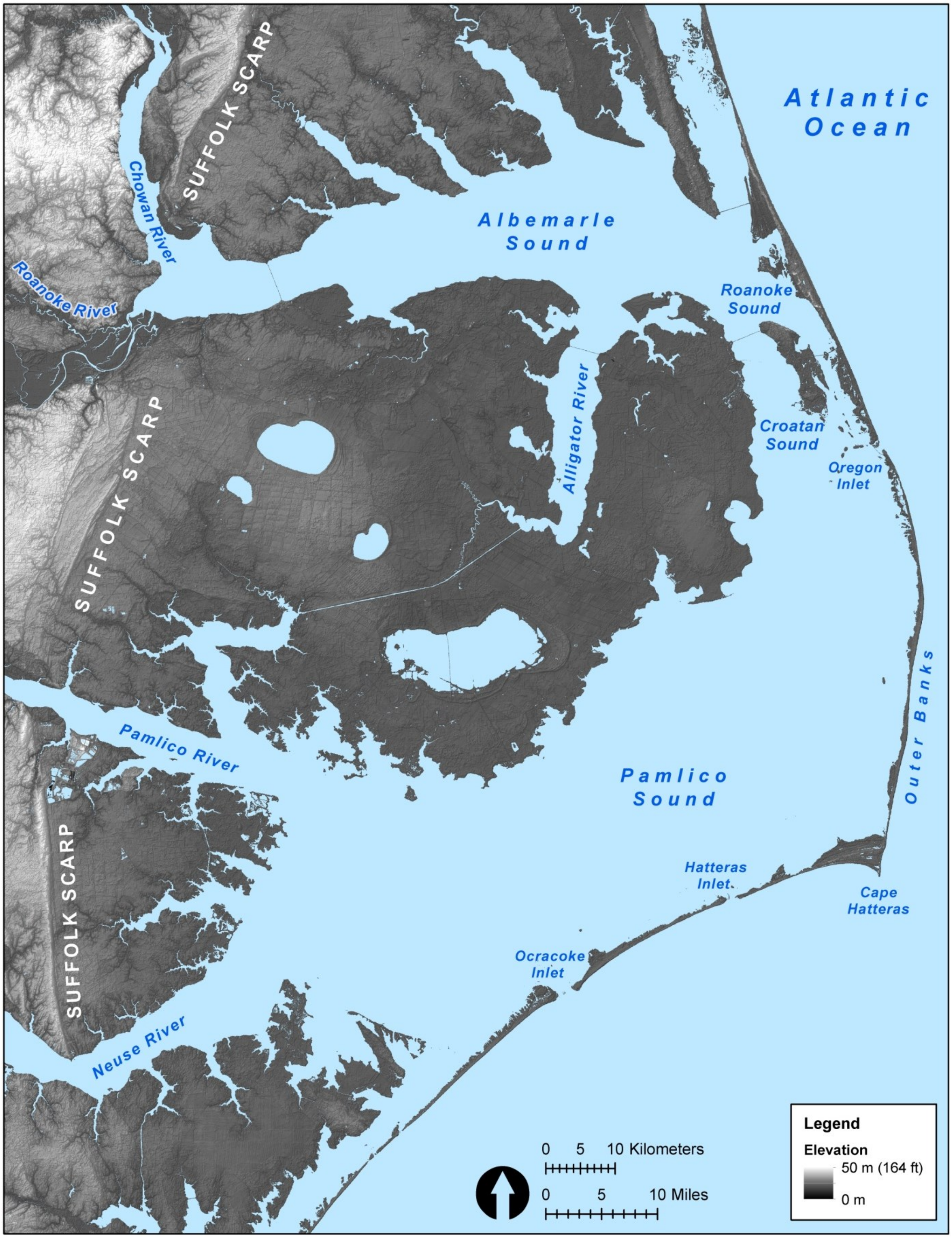

Figure 2. Elevation of the Albemarle-Pamlico Peninsula and Outer Banks areas.

The Pamlico Sound is located in eastern North Carolina (Figure 1) and is one of the largest sounds on the east coast of the U.S., comprising roughly 5340 square kilometers (Abbene et al., 2006). It stretches SW to NE extending roughly 80 miles long and 30 miles at the widest point (The Pamlico Sound, 2011; Pamlico Sound, Encyclopedia Britannica Online). The Pamlico is fairly shallow with maximum depths reaching 8 meters (26 feet) and a low astronomical tidal range of 10-100 centimeters that varies heavily by location (Abbene et al., 2006; Pamlico Sound, Encyclopedia Britannica Online). Since the Pamlico Sound has such a low tidal range, it is arguably less resilient to the impacts of future SLR landwards (McFadden et al., 2007). Wind tides are dominant in the Pamlico with strong winds causing water buildup along windward-facing shorelines (Abbene et al., 2006). The Pamlico is protected by the Outer Banks (a series of barrier islands) and Cape Hatteras (Figure 2), and has connections to the Atlantic Ocean through inlets which produces such a minor astronomical tidal range (Phillips, 1986). Fresh water is released into the sound by the Neuse and Pamlico Rivers (Figure 2) and brackish water is released into the Pamlico from the Albemarle River to the north (Abbene et al., 2006).

The geologic history of the Pamlico Sound indicates that Holocene SLR has slowly moved the majority of fluvial sediment deposits in upstream rivers (Phillips, 1986). It is assumed that the rate of sediment supply to the Pamlico Sound marshes has been diminishing as sediment accumulation is deposited upstream, thus limiting the ability of marshes to maintain equilibrium in response to SLR (Phillips, 1986). As lack of sufficient sediment supply is coupled with increased shoreline erosion, it is expected that a net loss of Pamlico Sound wetlands will occur with the onset of future SLR majority of estuarine wetlands below. Slopes of uplands in the Pamlico Sound region are fairly low and range from close to zero to roughly 2 degrees (Phillips, 1986, Corbett et al., 2008). The low slope gradient along the coast in the Pamlico Sound region is acceptable enough to suggest that wetlands would be able to migrate landward, given that all successful wetland adaptation requirements are in equilibrium. Since slopes of uplands in the Pamlico Sound region range from close to zero to roughly 2 degrees, there is highly variable accommodation space for wetland transgression (Phillips, 1986).

The Pamlico Sound also includes numerous critical nurseries for marine species, with shoreline marshes playing a major role (Phillips, 1986). Other animals that inhabit the Pamlico region include numerous species of birds and reptiles, as well as black bears and deer. There are many wildlife refuges located along the shorelines of the Pamlico such as the Swanquarter National Wildlife Refuge in southern Hyde County, NC and Cedar Island National Wildlife Refuge located in northern-most Carteret County, NC. These refuges seek to protect many coastal ecosystems and are monitored by the U.S. Fish and Wildlife Service (Figure 1).

The Croatan Sound is a small body of water located in northeastern North Carolina bordered to the north and south by two large sounds, the Albemarle and Pamlico, respectively (Figure 1). It experiences connectivity to the ocean through small inlets and has a wind-dominated tidal regime. The Croatan Sound represents a drowned lateral tributary that, with the Roanoke Sound to the east, once flowed northwards to the paleo-Roanoke River (presently the Albemarle Sound) and formed Roanoke Island which is a product of the interstream divide which separated the two drainages (Parham et al., 2007). The Croatan Sound stretches from northwest to southeast, and ranges in width from 4.2-8 km and in depth from 5-7.5 m (Parham et al., 2007). The primary pathway to the Pamlico Sound and the Atlantic Ocean for the Roanoke/Albemarle drainage system is through the Croatan Sound (Parham et al., 2007). Salt water is supplied into the Croatan Sound from the Atlantic Ocean through Oregon Inlet to the east. Given the close proximity of Croatan Sound to Oregon Inlet, its waters tend be more salty than waters found in the Albemarle to the north (Xie and Pietrafesa, 1999). The large salinity gradient found in the Albemarle-Pamlico Estuarine System (APES) and close to the mouths of rivers and inlets are known to produce baroclinic, density-driven circulation (Xie and Pietrafesa, 1999).

The vast majority of North Carolina's Coastal Plain is occupied by wetlands, which in many areas account for nearly 50 percent or more of the landscape (NCDCM, 2003). Wetland ecosystems are of high ecological importance because they account for such a large spatial extent and are a vital component of almost all coastal habitats (NCDCM, 2003). Coastal wetlands also play a large role in water quality, estuarine productivity, wildlife habitats, and the overall aesthetic of the coastal zone, however, past land use practices in coastal North Carolina have drained or converted almost 50 percent of original wetlands (NCDCM, 2003).

Wetland ecosystems are such a dominant part of the coastal North Carolina landscape and are so important to many aspects of the region's ecology, that their management and protection is a major priority for the North Carolina Division of Coastal Management (NCDCM) (NCDCM, 2003). The NCDCM developed a strategy for improving wetland ecosystem protection and management by implementing a Wetland Conservation Plan for coastal North Carolina (NCDCM, 2003). The main objective of the plan is to improve the management and protection of wetlands in North Carolina (NCDCM, 2003). The NCDCM uses hydrogeomorphic (HGM) classifications to describe wetlands in the North Carolina Coastal Plain; four classes include riverine, headwater, estuarine, and non-riverine/flat (NCDCM, 2003). All wetlands that are located next to streams or rivers are considered to be riverine and include all bottomland hardwood forests and some swamp forests (NCDCM, 2003). Wetlands that are considered in the headwater category are defined as areas next to riverine areas that do not have a stream located on the hydrography data layer (data required for NCDCM wetland mapping) (NCDCM, 2003). Wetlands designated as estuarine are found along the coast and include estuarine shrub, estuarine forest, and salt/brackish marsh (NCDCM, 2003). Lastly, wetlands that reside on interstream divides are termed non-riverine/flat wetlands (NCDCM, 2003). The main wetland types found in 37 North Carolina Coastal Plain counties (by acreage) according to the NCDCM include (in descending order): Managed Pineland, Riverine Swamp Forest, Pocosin, Pine Flat, Depressional Swamp Forest, Hardwood Flat, Bottomland Hardwood, and Salt/Brackish Marsh (NCDCM, 2003).

Sea-Level Rise Modeling

Broad-scale modeling of future wetland response to SLR is an important scientific tool for many reasons. Models increase our understanding of the components that control the behavior of the wetland system, locate hotspots of wetland loss, and determine the levels of wetland vulnerability which enables coastal managers and environmental agencies to make decisions on how to most-effectively manage wetland change due to SLR (McFadden, Spencer, & Nicholls, 2007). Broad-scale modeling of wetlands is also important to our understanding of long-term characteristics of future wetland behavior.

For the present and future, government and private agencies alike will need reliable scientific tools to determine the vulnerability of coastal areas threatened by future SLR (McLeod, Poulter, Hinkel, Reyes, & Salm, 2010). Coastal impact models such as SLAMM and hydrologically-connected single-value surface inundation models (“bathtub models”) are useful tools for first-order estimates to forecast environmental responses to future sea-level rise, as well as assessing the impacts that alternative management plans have on natural ecosystems (McLeod et al., 2010).

SLAMM

SLAMM is a GIS-based model that simulates the dominant processes influencing wetland and shoreline change from long-term sea-level rise (Craft, et al., 2009; McLeod, Poulter, Hinkel, Reyes, & Salm, 2010). It has the ability to forecast marsh migration at local and regional scales with an appropriate scale range from greater than 1 to 100,000 km^2, and can produce realistic output maps displaying changes in various marsh types at a high resolution (McLeod, Poulter, Hinkel, Reyes, & Salm, 2010). SLAMM uses a complex decision tree featuring various geometric and qualitative relationships that represent changes among coastal land types (Clough, 2010). Study sites used in SLAMM are divided into cells of equal area, with each cell containing attributes that include elevation, slope, aspect and land type (Clough, 2010).

The model is composed of five primary processes that determine wetland response to different scenarios of SLR (Clough, 2010). These primary processes include inundation, erosion, overwash, saturation (soil), and accretion (McLeod, Poulter, Hinkel, Reyes, & Salm, 2010; Clough, 2010). SLAMM also has the ability to create different scenarios of SLR by giving the user the option to accelerate SLR. The model determines relative SLR for each study site and time increment by calculating the sum of the historic eustatic trend, the rate of elevation change due to subsidence and isostatic adjustment for each specific site, and the rate of accelerated SLR depending on the specific scenario selected (Clough, 2010). The standard time increment recommended for SLAMM is 5-25 years, although longer time increments can be utilized (McLeod, Poulter, Hinkel, Reyes, & Salm, 2010).

SLAMM requires diverse types of data and process parameters in order to be implemented effectively and efficiently. The model was originally created to be compatible with 30m cell size digital elevation models (DEM’s), specifically the U.S. Geological Survey (USGS)

National Elevation Dataset (NED), although it can accommodate varying DEM cell sizes (Craft, et al., 2009; McLeod, Poulter, Hinkel, Reyes, & Salm, 2010; Clough, 2010). SLAMM also uses National Oceanic and Atmospheric Administration (NOAA) tidal data, LIDAR (Light Detection and Ranging) elevation data, global sea-level rise data (different SLR projections) and wetland data derived from U.S. Fish and Wildlife Service National Wetland Inventory (NWI) maps (McLeod, Poulter, Hinkel, Reyes, & Salm, 2010; Clough, 2010). If it is available, high-quality LIDAR-based elevation data should be used in order to reduce model uncertainty and improve model output resolution (Clough, 2010).

The current version of the model, SLAMM6, is a newly improved cell-based model of the original (Craft, et al., 2009; Clough, 2010). SLAMM6 is the first open-source version of the model and it has now been fitted with advanced tools that produce more realistic model outputs (Craft, et al., 2009; McLeod, Poulter, Hinkel, Reyes, & Salm, 2010; Clough, 2010). These new tools include an accretion refinement component, salinity model, integrated elevation analysis, flexible elevation ranges for land categories, user import of uplift and subsidence maps, significant graphical user interface upgrades, and sensitivity assessment tools (Clough, 2010).

SLAMM6 also allows for the use of hindcast simulations for model calibration. Model hindcast analysis is achieved by starting a simulation at the date of the oldest wetland data from the NWI, projecting sea-level rise through to the present day, and then determining model predictive power by comparing the hindcast simulation output to current NWI data (Warren Pinnacle Consulting, SLAMM Analysis of Grand Bay NERR and Environs, 2011; Clough, 2010). Calibration is used to improve model predictions by adjusting values for parameters which have the most influence on model outputs. Warren Pinnacle Consulting, Inc. (Analysis of Grand Bay NERR and Environs, 2011) used a hindcast analysis in the Grand Bay region of the

Alabama and Mississippi and found that the SLAMM model consistently underpredicted the amount of loss of key land cover types compared to observed changes. Although analysis of the hindcast yielded differences between the predicted and observed amounts of change, the associated underpredictions were relatively small and the hindcast output was deemed acceptable in the Grand Bay analysis to be used in model forecasting.

Recent studies have used SLAMM5 and SLAMM6 along the U.S. East and Gulf Coasts. Glick, et al. (2008) used SLAMM5 in the Chesapeake Bay region of Virginia and Maryland, and portions of Delaware Bay located in New Jersey and Delaware. They found that SLR had the most significant impacts on coastal wetlands and other habitats along the eastern and southern regions of the Chesapeake Bay, the majority of Delaware Bay, along the shorelines of barrier islands. Areas in the northern portion of the Chesapeake Bay were able to keep pace with lower to moderate rates of SLR through sediment accretion provided by the Susquehanna River and its tributaries. Nieves (2009) applied SLAMM5 in the Lower Delmarva Peninsula and found that the most compelling changes were associated with coastal marsh and beach habitats on barrier islands located along the eastern shores. Warren Pinnacle Consulting, Inc. (Analysis of Grand Bay NERR and Environs, 2011) applied SLAMM6 to the Grand Bay region of the Alabama and Mississippi, and concluded that the area is particularly vulnerable to higher rates of SLR, especially when SLR rates exceed accretion rates for irregularly-flooded marsh. SLAMM6 was applied to extensive areas of dry land both developed and undeveloped, along Saint Andrew and Choctawatchee Bays located on the Florida Gulf Coast (Warren Pinnacle Consulting, Application of the SLAMM 6) to Saint Andrew and Choctawhatchee Bays, 2011). SLAMM predicted that the majority of dry land in the area would not be severely impacted by higher rates of SLR by 2100. Even though they composed a smaller percentage of total land cover, coastal marsh and beach habitats were predicted to incur heavy losses.

Like all models, SLAMM model outputs are subject to uncertainty (Clough, 2010), and SLAMM results are particularly sensitive to uncertainty and errors associated with input data, inadequate knowledge about factors that control the behavior of the system being modeled, and generalizations made of the system (Craft, et al., 2009; McLeod, Poulter, Hinkel, Reyes, & Salm, 2010; Clough, 2010). SLAMM also possesses various model limitations. The model lacks the ability to analyze and report many potentially important and complex relationships between hydrodynamic and ecological systems that may be affected by future changes in SLR (McLeod, Poulter, Hinkel, Reyes, & Salm, 2010). Few validation studies have been conducted on SLAMM output. SLAMM requires that changes in SLR be predetermined, which does not take into account changes in wave regime from erosion or sub-surface vegetation characteristics. It does not integrate a detailed bathymetric model, so tidal effects of an estuary's geometry are not predicted. There is also a lack of an integrated modeling of sea grasses or other marine flora (Clough, 2010). The overwash model component in SLAMM is subject to issues of uncertainty because the frequency and magnitude of storms and their effects are difficult to validate. Limitations exist with SLAMM input data, particularly USGS NED elevation data because of its large spatial coverage and moderate resolution (Craft, et al., 2009; Clough, 2010). LIDAR-derived elevation data reduces uncertainty because of its higher resolution. SLAMM also does not have a socioeconomic dynamic component with the ability to assess the approximate costs (monetary and population) in response to changes in future SLR (McLeod, Poulter, Hinkel, Reyes, & Salm, 2010). It is recommended by SLAMM developers that persons with GIS expertise be utilized in order to effectively produce raster inputs and interpret model outputs (Clough, 2010). While SLAMM may have certain limitations, it serves as a useful, high-resolution model that provides feedback on how future SLR may impact coastal environments.

Inundation Modeling

In contrast to the landscape and wetland habitat focus of SLAMM, inundation models are a common method that can be used primarily to predict areas vulnerable to flooding from SLR (McLeod, Poulter, Hinkel, Reyes, & Salm, 2010; Mapping Inundation Uncertainty, 2010). Mapping SLR inundation using elevation data and tidal surfaces as the primary variables are usually referred to as *single-value surface models* or *bathtub models* (Mapping Inundation Uncertainty, 2010). A bathtub inundation model is typically composed of only two variables, the inundation level and the land elevation, and has the capacity to be applied at local, regional, or global scales (McLeod, Poulter, Hinkel, Reyes, & Salm, 2010; Mapping Inundation Uncertainty, 2010). There are also advanced inundation models which incorporate more complex hydraulic and geomorphic algorithms that include additional variables to more accurately portray projected SLR (Mapping Inundation Uncertainty, 2010). Elevation data used in bathtub inundation models are usually referenced to the North American Vertical Datum of 1988 (NAVD88). NAVD88 is the vertical datum created for vertical control surveying in the U.S., but it is not a tidal datum so a value of “0” does not equate to any particular local tidal value. Elevation data can be modified from NAVD88 to a tidal datum in order to link coastal inundation that is linked to a specific local tidal regime.

Inundation models use various SLR scenarios which highlight coastal areas vulnerable to future SLR. Coastal areas that could potentially be inundated can be calculated based on elevation and proximity to a water source, the ocean for example (McLeod, Poulter, Hinkel, Reyes, & Salm, 2010). Specific algorithms can be used in a GIS to determine how many raster cells in a DEM lie next to the water source, and cells that have an elevation less than or equal to a specific SLR height and lie next to the water source are reclassified as inundated cells (McLeod, Poulter, Hinkel, Reyes, & Salm, 2010). Complete hydro-connectivity can be achieved when all cells connected to the water source are classified as inundated. Additional statistical analysis can be implemented to inundation model results calculate the estimated area of land inundated and population affected in each SLR scenario.

Inundation models have many advantages and limitations. Inundation models are fairly inexpensive to run and are effective in communicating potential vulnerability to SLR. Some inundation models only require Internet access, while others have more advanced requirements such as GIS expertise and software, elevation datasets, SLR projections (scenarios), and hydro-connectivity algorithms (McLeod, Poulter, Hinkel, Reyes, & Salm, 2010). SLR vulnerability maps can be produced fairly quickly and cheaply using inundation models and free elevation data via the Internet. Inundation modeling can yield quick model outputs regarding coastal areas that are most susceptible to SLR at almost all spatial scales, and can also be used as a potential communication tool for coastal managers and decision makers.

The limitations of these models and their results must be evaluated as having inherent accuracy and uncertainty limitations (McLeod, Poulter, Hinkel, Reyes, & Salm, 2010). Simple inundation models usually ignore important feedbacks such as wetland accretion and erosion and, hence, the geomorphic role wetlands play in landscape evolution and change. Inundation models are also subject to uncertainties in underlying global SLR projections (e.g., scenarios), elevation data, sediment dynamics, and lack of feedbacks relating to biological, ecological, and socioeconomic systems. Mapping and modeling the landscape distribution and potential change in estuarine ecotopes, unique ecologically distinct and mappable features, is a key component to the research and management of landscape structure, function, and change (Forman, 1986; Zonneveld, 1989).

While simple inundation models can be a useful communication tool for relaying information on regional vulnerability to SLR, they are less suited for mitigation, adaptation, and policy-making (McLeod, Poulter, Hinkel, Reyes, & Salm, 2010). Therefore, investigation of the SLAMM model for coastal marshes in light of uncertainty and coastal management would be a valuable contribution to coastal research and management communities.

Research Questions

1. SLR Effects: What effects will future sea-level rise have on wetlands in the Pamlico and Croatan Sounds, North Carolina?
2. Model Hindcasting: Do recent observed wetland changes support model-based historical simulations using SLAMM (e.g., 1983-2010)? How does the short-term decadal change during this historical period inform and potentially improve future SLR simulation modeling?

Objectives

1. Determine how future sea-level rise will affect wetlands in the Pamlico and Croatan Sounds, North Carolina, including the loss, transgression, and lateral migration of estuarine marsh classes.
2. Address temporal uncertainty associated with future SLR by implementing different rise heights at varying temporal scales in order achieve optimal representation of the full range of possible SLR in the future.
3. Analyze and determine if recent observed historical wetland changes accredit SLAMM hindcast model runs.

4. Determine the level of agreement between model calibration outputs utilizing historical simulation and derived current condition wetland maps.
5. Determine the relative accuracy and analyze potential error sources for SLAMM model calibration results.

2 STUDY AREA

SLAMM Study Sites

The selected SLAMM "Global" study area for this research includes extensive coastal marshes located along the eastern shoreline of the Pamlico Peninsula, shorelines of Roanoke Island, and the Nags Head and Pea Island area of the Outer Banks in eastern North Carolina (Figure 3). SLAMM sub-sites (grey areas on Figure 3) within the study area are located around Pt. Peter Rd. on the eastern portion of the Pamlico Peninsula and on the southern end of Pea Island barrier island on the Outer Banks. These areas are bordered by the Pamlico, Albemarle, Croatan, and Roanoke Sounds, and include swamp forests, shrub-scrub, emergent brackish and salt marsh, and scattered patches of *Phragmites australis* (common reed, an invasive marsh species). The region is characterized by a wind-dominated tidal regime and is comprised of mainly low-lying coastal plain swamp and marshland making it highly susceptible to shoreline erosion and inundation associated with coastal storms, variable tide heights, and SLR. The eastern shore of the Pamlico Peninsula is a remote area which exhibits few vehicular passable roads and includes vast coastal marshes located within the U.S. Fish and Wildlife Service Alligator River National Wildlife Refuge. The shorelines of Roanoke Island include the remote fishing village of Wanchese to the south, the larger town of Manteo to the north, as well as extensive, low-lying fringe marshes that inhabit the shoreline. The barrier island areas of the Outer Banks include areas around Nags Head and Pea Island, which includes a portion of the U.S. Fish and Wildlife Service, Pea Island National Wildlife Refuge north of Rodanthe.

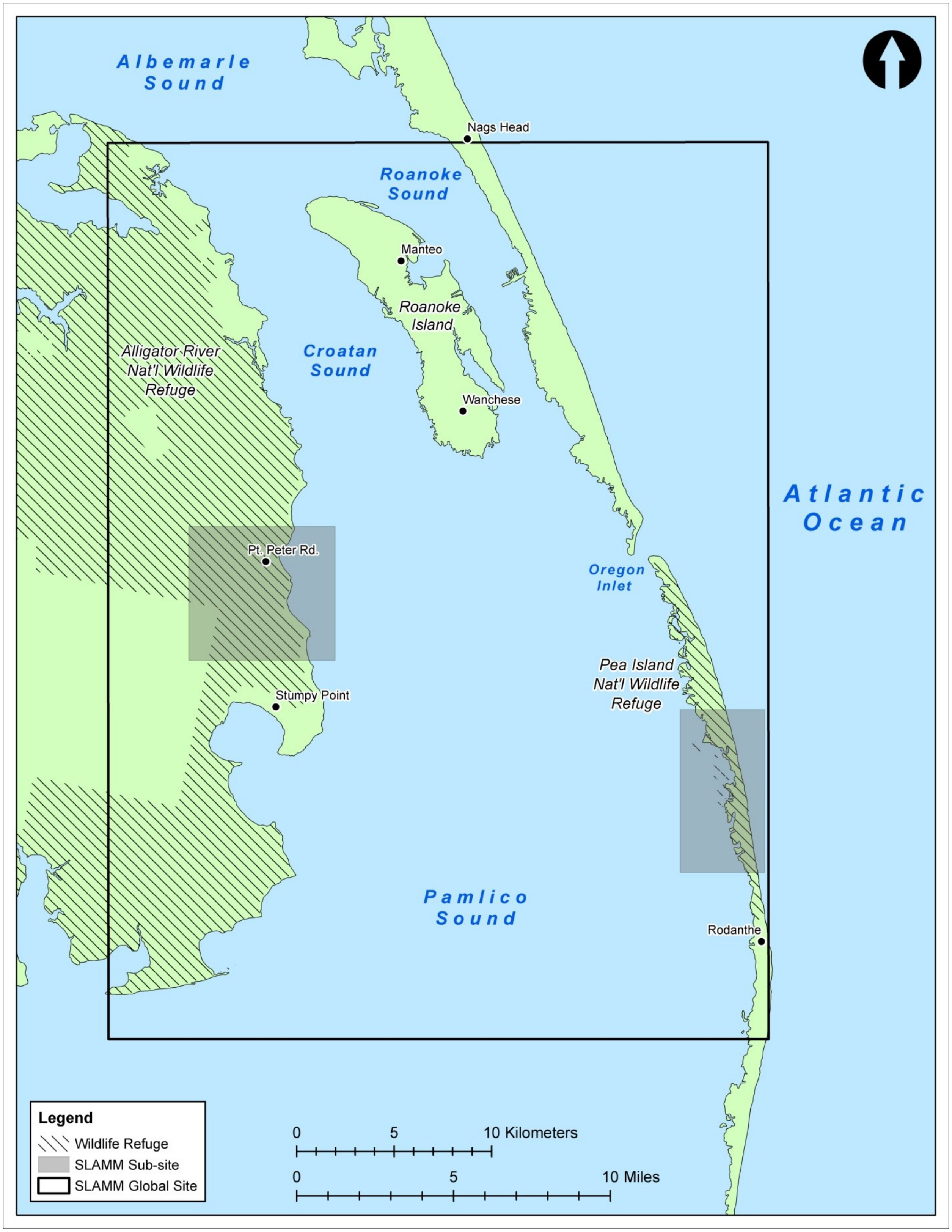

Figure 3. SLAMM study area.

3 DATA AND METHODS

Data Preprocessing

SLAMM requires various input data to effectively run the model. The basic data needed to run the model includes elevation data, NWI wetland data, and slope data for a specific focus area. The use of LIDAR elevation data for hydrological modeling has become the standard in recent years due to its higher accuracy and resolution. Although LIDAR elevation data can achieve higher accuracy than older elevation data such as USGS National Elevation Dataset (NED) elevation data, LIDAR data still exhibits various limitations. Some of these limitations include errors introduced when the elevation data are collected by a sensor. Data collected by satellite sensors are usually subject to errors relating directly to distortion caused by atmospheric conditions. Data from aerial LIDAR sensors, while still vulnerable to errors inherent with atmospheric distortion, tend to have less error due to LIDAR flight time selectivity and flight altitude usually below levels where weather can interfere. For this study, error introduced into the LIDAR elevation data by atmospheric distortion was minimal.

Due to budget and time constraints, the best available LIDAR elevation data was used for implementation into SLAMM. The elevation data used in this study consisted of a seamless 50 ft. (15 m) 2002 LIDAR DEM obtained from the NC Floodplain Mapping Program and was within the accepted resolution for use in hydrological modeling at regional scales. The LIDAR DEM was previously preprocessed to ensure that it was of the highest possible quality for use in hydrological and geohazard modeling (Allen, 2011). A low pass minimal elevation threshold filtering algorithm was applied to the LIDAR DEM in order to smooth elevation values and improve overall quality. This method reassigns a mean elevation value for a specified pixel window around a group of cells, removing erroneous values above a specified minimum elevation threshold (Poulter and Halpin, 2008; Allen, 2011). Additional preprocessing with the DEM included major hydrological-correction of features, accuracy verifications, and vertical datum adjustments. Areal features such as bridges, rivers, canals, and dikes were either removed or mitigated to achieve the best hydro-connectivity for floodplain delineation. DEM accuracy was analyzed using GPS point data and NOAA tidal benchmarks. SLAMM requires that input elevation data be standardized from NAVD88 to local mean tide level (MTL) vertical datum in order to optimize hydrological-modeling. NOAA VDATUM software was used for vertical datum correction following standard protocols. Slope data was obtained from geoprocessing of the DEM (U.S. Fish and Wildlife Service, 2013).

The vertical datum of the 2002 LIDAR DEM, as well as in all other input data, was adjusted for each year used in the modeling, 1983 and 2010. These adjustments were necessary in order to represent the changes in relative sea-level rise during the two dates. The datum shift to reflect conditions in 1983 assumes a fairly stable geomorphology but is reasonable given that LIDAR-accuracy DEM's weren't available in 1983.

Another important input requirement for SLAMM is NWI wetland data produced by the U.S. Fish and Wildlife Service. Although currently considered in the process of map updating, the most current and complete NWI wetland data available for the study area was from 1983 and was interpreted from 1982 aerial imagery (U.S. Fish and Wildlife Service, 2013; Allen, 2011). For implementation into SLAMM, the NWI data needs to be recoded into SLAMM categories (Table 1). In this study, not all SLAMM categories were used because not all of the wetland types occur in Eastern North Carolina. Mangrove was not used in the study and is not found further north than South Carolina along the East Coast of the U.S. For model hindcasting, previously recorded preliminary 2010 NWI to SLAMM wetland data was used as a baseline to check for accuracy of model forecasting.

SLAMM Categories	
SLAMM Code	**SLAMM Name**
1	Developed Dry Land
2	Undeveloped Dry Land
3	Swamp
4	Cypress Swamp
5	Inland-Fresh Marsh
6	Tidal-Fresh Marsh
7	Trans. Salt Marsh
8	Regularly-Flooded Marsh
9	Mangrove
10	Estuarine Beach
11	Tidal Flat
12	Ocean Beach
13	Ocean Flat
14	Rocky Intertidal
15	Inland Open Water
16	Riverine Tidal
17	Estuarine Open Water
18	Tidal Creek
19	Open Ocean
20	Irreg.-Flooded Marsh
21	Not Used
22	Inland Shore
23	Tidal Swamp
24	Blank
25	Vegetated Tidal Flat
26	Backshore

Table 1. SLAMM categories.

Model Parameters

Input values for numerous SLAMM parameters (Table 2) were obtained and corroborated from multiple thesis and dissertations supervised by ECU faculty, pilot studies by ECU faculty, and recent studies using SLAMM. Some of sources include a NOAA-funded project assessing the ecological effects of SLR in North Carolina, an APNEP sponsored study for high-resolution and seasonal versus interannual assessment of estuarine shoreline erosion using GPS ground-truthing and balloon aerial photography, and an ECU doctoral dissertation providing recent data on estuarine shoreline erosion rates in a portion of the study area (Allen, 2011). Historical observations were also implemented into the parameters by utilizing Riggs and Ames' (2007) North Carolina Sea Grant report entitled *Drowning the North Carolina Coast: Sea-Level Rise and Estuarine Dynamics* (Allen, 2011). Table 3 shows the several studies and reports that were used select values for numerous SLAMM parameters.

Parameter	Global	SubSite 1	SubSite 2
		Pt. Peter Rd.	Pea Island
NWI Photo Date (YYYY)	1983	1983	1983
DEM Date (YYYY)	2002	2002	2002
Direction Offshore [n,s,e,w]	East	East	West
Historic Trend (mm/yr)	3	3	3
MTL-NAVD88 (m)	0.0439	0.0439	0.0439
GT Great Diurnal Tide Range (m)	1.2	0.1	0.2
Salt Elev. (m above MTL)	0.15	0.15	0.15
Marsh Erosion (horz. m /yr)	0.7	1.2	0.43
Swamp Erosion (horz. m /yr)	0.7	0.7	0.7
T.Flat Erosion (horz. m /yr)	6	6	6
Reg. Flood Marsh Accr (mm/yr)	2	2	2
Irreg. Flood Marsh Accr (mm/yr)	2	2	2
Tidal Fresh Marsh Accr (mm/yr)	0.5	0.5	0.5
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5
Freq. Overwash (years)	10	10	10
Use Elev Pre-processor [True,False]	FALSE	FALSE	FALSE

Table 2. SLAMM parameters.

Parameters	Study
Estuarine erosion and accretion rates cross-sectional history across hydrogeomorphic settings	Riggs and Ames (2006)
Estuarine marsh erosion rates (2010-present high-resolution aerial mapping) for Pamlico and Albemarle Sounds, Pamlico R. estuary	Eulie, Walsh, Corbett (APNEP study)
Estuarine erosion hotspots from ALOS Palsar satellite	Wang and Allen (2008)
Sediment storage and delivery by coastal plain rivers	Phillips et al. (2006)
Overwash extent, beach accretion, and backbarrier response	Allen et al. (ongoing)
Spatial dynamics of ecological zones across estuarine geomorphology	Kunz (2009) dissertation (Brinson and Christian)
Variation in marsh accretion across tidal regimes	Voss (2010) dissertation (Christian)
Estuarine sediment dynamics	Eulie (2011) thesis
Variations in microtidal marsh sedimentation	Lagomasino (2009) thesis
Salinity and swamp forest hydrology in Alligator River	Giuliano (2012) thesis
Floodplain sedimentation in Pamlico-Tar	Quafisi (2010) thesis
SLAMM Studies	
Chesapeake Bay Region of VA, MD, DE	Glick et al. (2008)
Lower Delmarva Peninsula	Nieves (2009)
Grand Bay Region of AL and MS	Clough (2011)
FL Gulf Coast	Clough (2011)

Table 3. Sources consulted for SLAMM parameter development.

Accuracy Assessment Preprocessing

Following SLAMM hindcast simulation, the 2010 hindcast raster output and 2010 SLAMM raster layer coded from preliminary 2010 NWI were analyzed to determine the accuracy of the SLAMM hindcast simulation. Before an accuracy assessment could be generated, some preprocessing (Figure 4) had to take place to ensure that both raster layers had the same spatial reference and horizontal resolution. This preprocessing step is important because analyzing data layers on the cellular level with different spatial references and horizontal resolutions can lead to results with more uncertainty, adding higher levels of error that were already present within the source data to begin with.

After the SLAMM hindcast simulation was executed, the resulting output ASCII file was converted into an ERDAS Imagine raster format so that it could be imported into ArcGIS 10 for future analysis (Figure 4). Following ASCII to raster conversion, the raster layer projection needed to be defined because of a missing spatial reference. The spatial reference for the raster layer was defined to WGS 1984 UTM Zone 18 North. Following ASCII to raster conversion, the preliminary 2010 NWI SLAMM raster layer was resampled from a cell size of 50m to 15m to match the horizontal resolution of the 2010 hindcast raster. This technique was chosen because it is appropriate to handling discrete thematic data (i.e., land-use classification) since it will not change the values of the cells.

Extraneous land from the 2010 NWI SLAMM raster layer was masked out using the 2002 DEM as a mask layer (Figure 4). It was necessary to clip out lands in the preliminary 2010 NWI SLAMM raster layer that extended beyond the extent of land in the 2010 hindcast raster layer for future spatial analysis. The DEM used in the hindcast simulation did not include all land that was present in the preliminary 2010 NWI SLAMM raster layer. SLAMM does not track cells without elevation and essentially masks out land in the NWI raster input layer that is outside of the extent of land in the DEM. In order to get an accurate depiction of model performance and avoid skewed analysis results, both the 2010 hindcast raster output layer and 2010 NWI SLAMM raster layer had to have the same land cover extent to be used for future analysis.

When the extraneous land was masked from the 2010 NWI SLAMM raster Layer using the DEM, it also removed all of the water classes as well. The same water classes need to be added back into the 2010 NWI SLAMM raster minus the extraneous land that was already taken out. All open water classes from both the 2010 hindcast raster output layer and the preliminary

2010 NWI SLAMM raster layer were extracted (Figure 4). Next, both raster layer water classes were then converted from raster format to vector polygon format in ArcGIS 10. Once both water raster layers were converted to vector polygon format, both layers were clipped to the same extent. The resulting two water polygon clip layers were then merged into a single poygon layer. This merge was necessary in order to fill any spatial water gaps between the 2010 hindcast and preliminary 2010 NWI SLAMM polygon layers. The resulting merged water polygon layer was then edited in order to redefine the boundaries of the water classes present in the original preliminary 2010 NWI SLAMM raster layer.

Once the original water boundaries were redefined in the merged water polygon layer, a new field ("VALUE") was added to the attribute table of the merged water polygon layer and water class SLAMM code values were populated into the correct cells. This step was necessary so that once the merged water polygon layer is converted into raster format it can merge correctly with the land-masked preliminary 2010 NWI SLAMM raster layer. The new water raster layer was then merged with the land-masked preliminary 2010 NWI SLAMM raster layer. The resulting output was a new preliminary 2010 NWI SLAMM raster layer that contained the same land cover classifications as the original layer, but also matches the extent of land contained within the 2010 hindcast raster layer.

In order for future accuracy assessment and spatial analysis processing to function properly and effectively, developed and undeveloped dry land classes were removed from the 2010 hindcast raster layer. Since the preliminary 2010 NWI SLAMM layer did not contain developed and undeveloped dry land classes, they were extracted out of the 2010 hindcast raster layer to avoid confusing in future processing steps.

Due to inconsistencies and errors associated with NWI-to-SLAMM recode methods and NWI maps themselves, it was necessary to aggregate the SLAMM classes from both raster layers into fewer classes representing the major estuarine/coastal zones dominant throughout the North Carolina coastal region. The aggregation of classes was achieved by reclassifying SLAMM classes into four new classes: Forested Wetland, Estuarine Emergent Wetlands, Shore, and Water. For the reclassification NWI maps, satellite imagery and spatial distribution were used in order to qualitatively determine which SLAMM classes fall into what new recode class. SLAMM classes that contained majority tree cover and shrub-scrub vegetation, and were located further from the shoreline, were classified as *forested wetlands*. SLAMM classes with that contained majority emergent wetland vegetation and few areas of shrub-scrub vegetation, and were located in the nearshore zone, were classified as *estuarine emergent wetlands*. SLAMM classes that contained majority unconsolidated shore were classified as *shore*. SLAMM classes that contained majority open water or open ocean were classified as *water*. Following completion of the reclassification of the two raster layers into aggregated classes, an accuracy assessment and further spatial analysis was ready to be conducted.

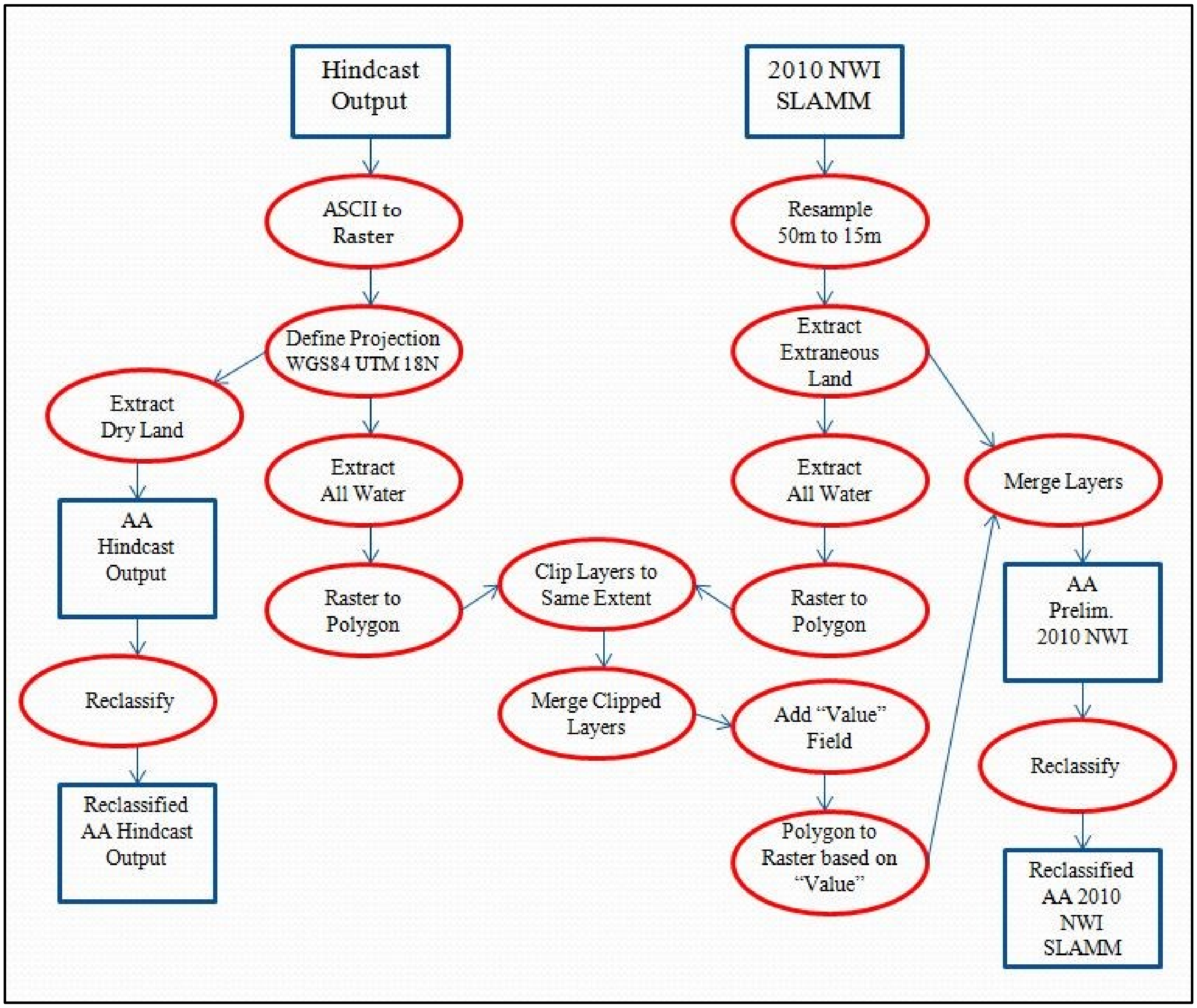

Figure 4. Accuracy assessment preprocessing steps flow chart.

Accuracy Assessment Geoprocessing

ERDAS Imagine 2011 software was used to perform an accuracy assessment to determine model performance based on the results of the SLAMM hindcast simulation. In order for the two raster layers to be used properly in the *Accuracy Assessment* tool with ERDAS Imagine, they had to be converted from signed 8-bit continuous raster layers into unsigned 8-bit thematic raster layers for the tool to be as effective and accurate as possible. This data geoprocessing step (Figure 5) helps to define discrete boundaries between the different land classes, as well as the possible value range within each cell. Converting the two raster layer data types from signed 8-bit to unsigned 8-bit ensured exclusion of any negative values, changing the range of possible values in each cell from -128 – 127 (signed 8-bit), to 0 – 255 (unsigned 8-bit). A cell in continuous raster data contains a floating point value that represents continuous data, such as the elevation of a certain place. A cell in discrete raster data contain integer values and represent a finite number of possible values, such as a specific land cover class number.

Once the two raster data layers were converted from signed 8-bit continuous raster layers into unsigned 8-bit thematic raster layers the *Accuracy Assessment* tool within ERDAS Imagine was run (Figure 5). A value of 3 used for window size represents the size of the window used for determining the class value and in this case, a 3 x 3 cell window was utilized. A majority threshold value of 7 was used in order to set the minimum number of class values needed to create a majority of class values in the 3 x 3 cell window. This means that in order for the window to assign a group of 9 pixels a class value, roughly 77% (7 out of 9) of the pixels or greater have to contain the same class value.

The equalized random distribution parameter was used in order to generate the same number of randomly placed points in each class for a normal distribution throughout the entire amount of generated points. The sampling protocol generated 180 sites (approximately 45 points for each class), an acceptable sample size given the relatively confined extent and limited areal coverage of non-water classes encountered with the search windows exhausting the search count quickly and the creation of points that contained a "0" class value which is not associated with a specific land class in this analysis.

Once all of the accuracy assessment parameters were inserted, the random points were created for each class and added on top of the 2010 SLAMM hindcast raster layer. With the accuracy assessment points displayed on top of the reference file, each point class value was entered into the "Reference" column in the accuracy assessment table. Once both the "Class" and "Reference" columns were completely filled out, an accuracy report was generated that included an error matrix, accuracy totals, and kappa statistics.

Following the accuracy assessment which allows for the evaluation of a classified thematic raster image by generated random points representing specific land class values by comparing the classification to reference data layer, further spatial analysis was conducted to determine model performance on the cellular level. Since the *Matrix Union* tool only produces an image output showing areas of both class agreement and disagreement, it was necessary to use the *Summary Report of Matrix* tool to get statistics that compare the value areas between the two thematic raster files.

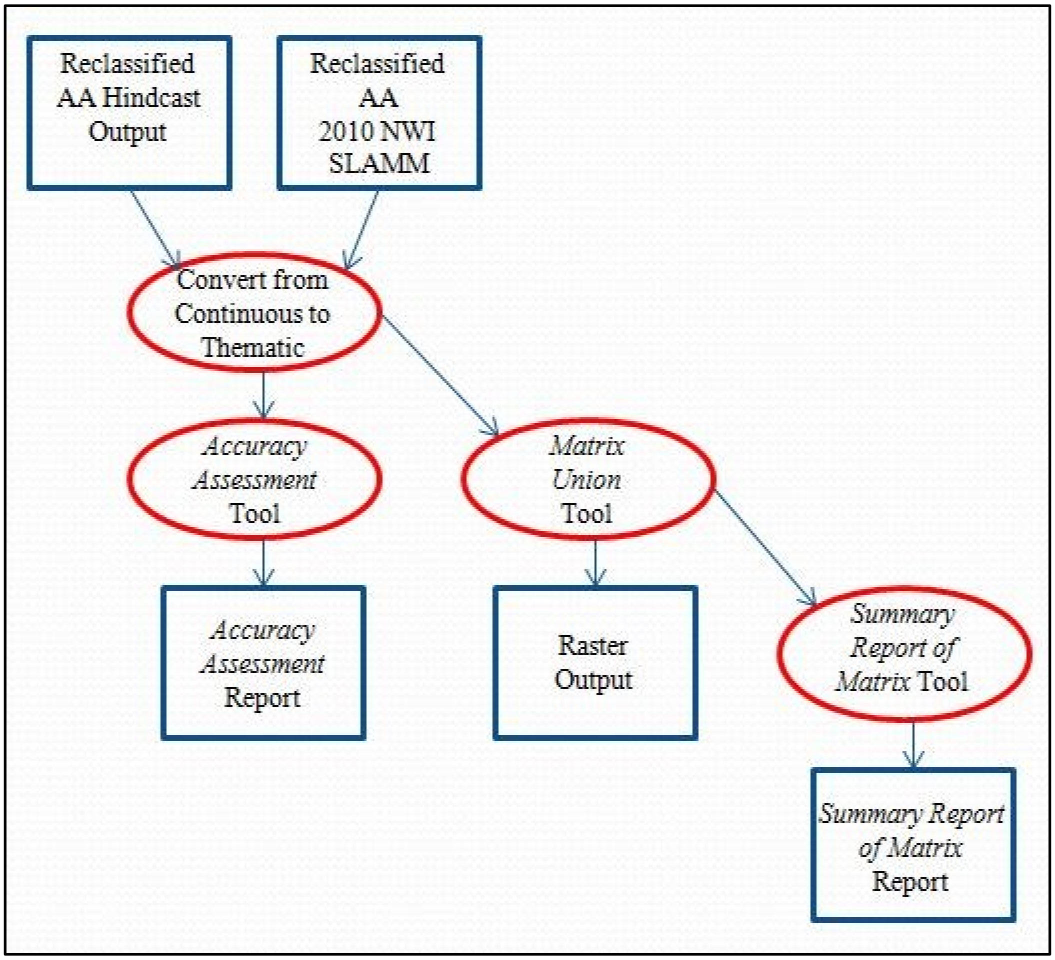

Figure 5. Accuracy assessment geoprocessing steps flow chart.

4 RESULTS

Hindcast Results - 1983 to 2010

Visual analyses of SLAMM hindcast results indicate a relatively small amount of change from initial condition (1983) to 2010 (current). SLAMM hindcast results from intial condition to 2010 show relatively small amounts of change. The change that is seen from a visual analysis of Figures 6 and 7 occurs along the immediate shoreline and nearshore zone of the eastern portion of the Pamlico Peninsula, with noticeable change also occurring along Roanoke Island and lands adjacent to the Roanoke Sound along the backside of Nags Head, NC. Few changes are seen in the proximity of the Pea Island barrier island on the Outer Banks. Regularly flooded marsh and tidal flat display slight increases in both areal coverage and migration inland, replacing areas previously inhabited by transitional salt marsh, irregularly flooded marsh, and swamp. Patches of increased estuarine open water can also be seen in areal distribution and slight movement inland, inundating areas of regularly flooded marsh, irregularly flooded marsh, and transitional salt marsh. Table 4 shows that regularly flooded marsh and tidal flat exhibit relatively small increases in area of 0.16% (253.9 hectares) and 0.26% (408 hectares), respectively, as well as estuarine open water with a minor increase of 0.04% (58.2 hectares) and open ocean with a small increase of 0.18% (286.6 hectares). The largest losses were exhibited by swamp, irregularly flooded marsh, and transitional salt marsh of 0.32% (503.9 hectares), 0.16% (242.2 hectares), and 0.07% (112.5 hectares), respectively. Ocean-facing shoreline within the study area exhibited ocean beach loss of 0.01% (15.5 hectares), while undeveloped dry land lost 0.04% (67.9 hectares) in land area.

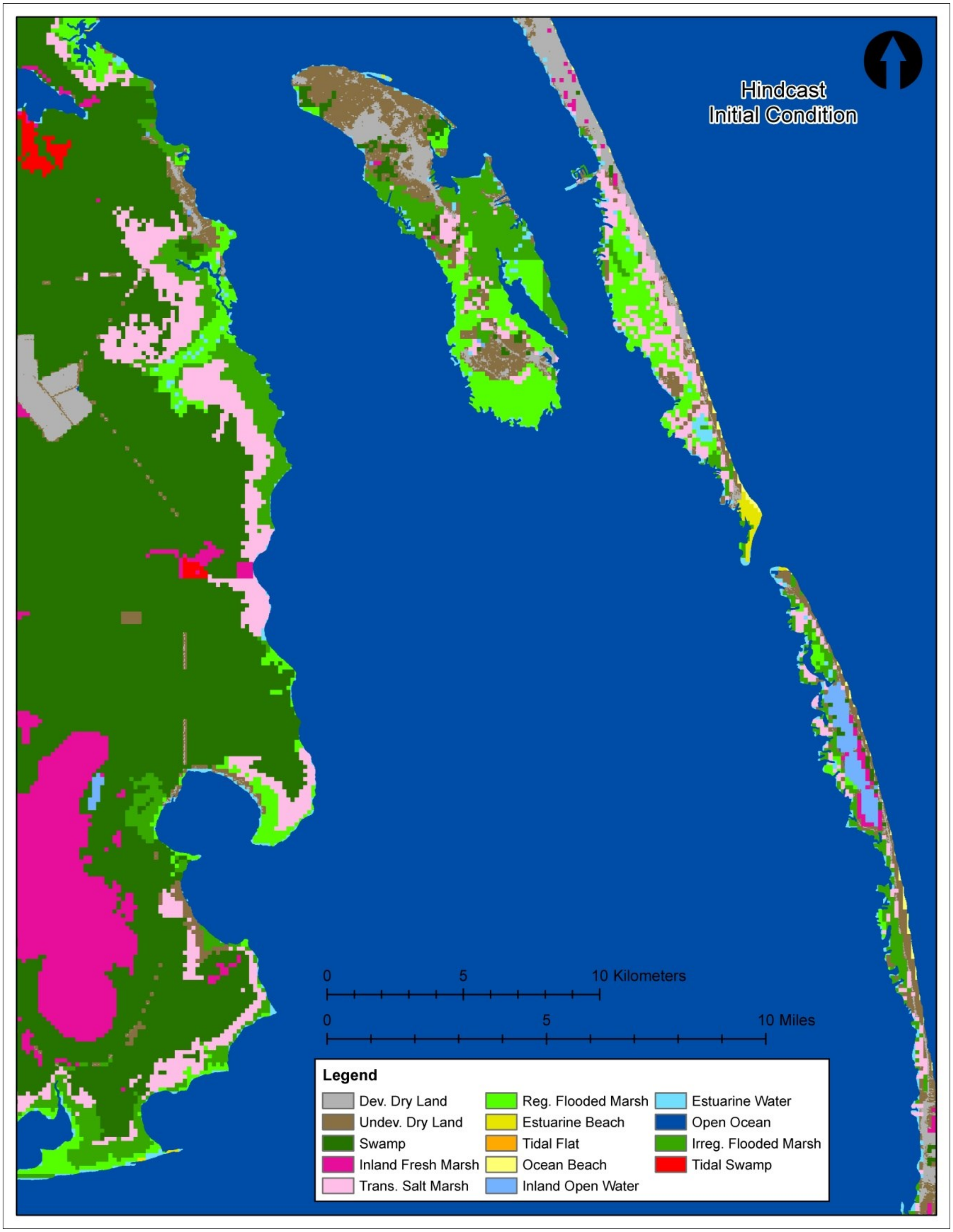

Figure 6. SLAMM hindcast results showing initial condition.

2010 SLAMM Hindcast Results								
SLAMM Code	SLAMM Name	Site	Initial Cond. (IC)		2010		Total Change: IC-2010	
			Ha	%	Ha	%	Ha	%
1	Developed Dry Land	Global	1964.386	1.261	1935.063	1.242	-29.323	-0.019
2	Undeveloped Dry Land		2763.199	1.774	2695.259	1.730	-67.940	-0.044
3	Swamp		20673.442	13.272	20169.563	12.948	-503.879	-0.323
5	Inland Fresh Marsh		3795.822	2.437	3775.148	2.424	-20.674	-0.013
7	Trans. Salt Marsh		2033.810	1.306	1921.356	1.233	-112.455	-0.072
8	Regularly Flooded Marsh		6905.696	4.433	7159.578	4.596	253.882	0.163
10	Estuarine Beach		93.732	0.060	83.997	0.054	-9.735	-0.006
11	Tidal Flat		236.093	0.152	644.134	0.414	408.041	0.262
12	Ocean Beach		158.703	0.102	143.199	0.092	-15.505	-0.010
15	Inland Open Water		356.625	0.229	355.793	0.228	-0.832	-0.001
17	Estuarine Open Water		812.275	0.521	870.444	0.559	58.168	0.037
19	Open Ocean		113427.086	72.818	113713.680	73.002	286.594	0.184
20	Irreg. Flooded Marsh		2313.392	1.485	2071.150	1.330	-242.243	-0.156
23	Tidal Swamp		233.869	0.150	229.769	0.148	-4.100	-0.003

Table 4. Table showing the results of the hindcast simulation from initial condition to 2010 in percent and hectares.

Hindcast Accuracy Assessment

Due to inconsistencies between the 1983 NWI to SLAMM class recode for the 2010 SLAMM hindcast and the preliminary 2009 NWI to SLAMM recode for the reference 2010 SLAMM map (Figure 8), both the 2010 SLAMM hindcast output map and 2010 SLAMM reference map were reclassified into four classes (forested wetland, estuarine marsh, shore, and water) to achieve a level of consistency in order to perform an accuracy assessment to gauge model performance (Figure 9 and Table 5). A visual analysis of Figure 9 shows that the reclassified 2010 SLAMM hindcast output map did manage to capture the general spatial distribution and trends/patterns of land classes found in the reclassified 2010 SLAMM reference map. The areal distribution of estuarine marsh is larger in the reclassified 2010 SLAMM hindcast output map than displayed in the reclassified 2010 SLAMM reference map, although along the immediate shoreline and nearshore zone, the areal distribution and spatial patterns of estuarine marsh between the two maps is relatively similar. Conversely, the areal distribution of forested wetland is larger in the reclassified 2010 SLAMM reference map than displayed in the reclassified 2010 SLAMM hindcast output map. While there are obvious differences in land area between the two maps, the general spatial distribution and spatial patterns in forested wetland are quite similar. Similarities of estuarine marsh and forested wetland between the two maps start to decrease with movement further inland. There are discrepancies of shore spatial distribution between the two maps, with the reclassified 2010 SLAMM hindcast output map predicting more land area in different locations than in the reclassified 2010 SLAMM reference map. There are also few discrepancies on the spatial distribution of water between the two maps, with the reclassified 2010 SLAMM reference map showing a little more inland water and estuarine/ocean water than in the reclassified 2010 SLAMM hindcast output map. But overall, the spatial distribution of water in both maps matches fairly well.

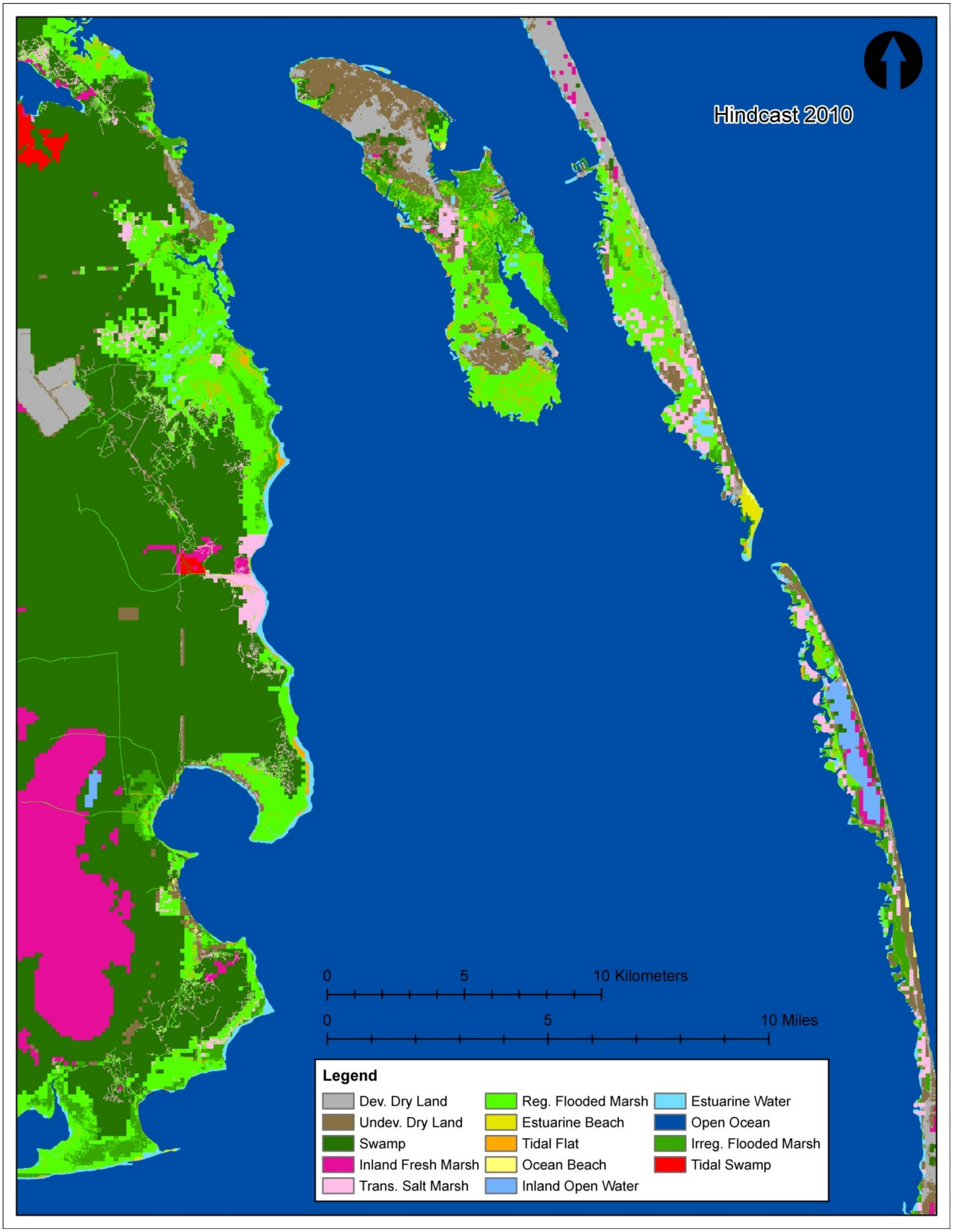

Figure 7. SLAMM hindcast results showing the 2010 (current condition) output map.

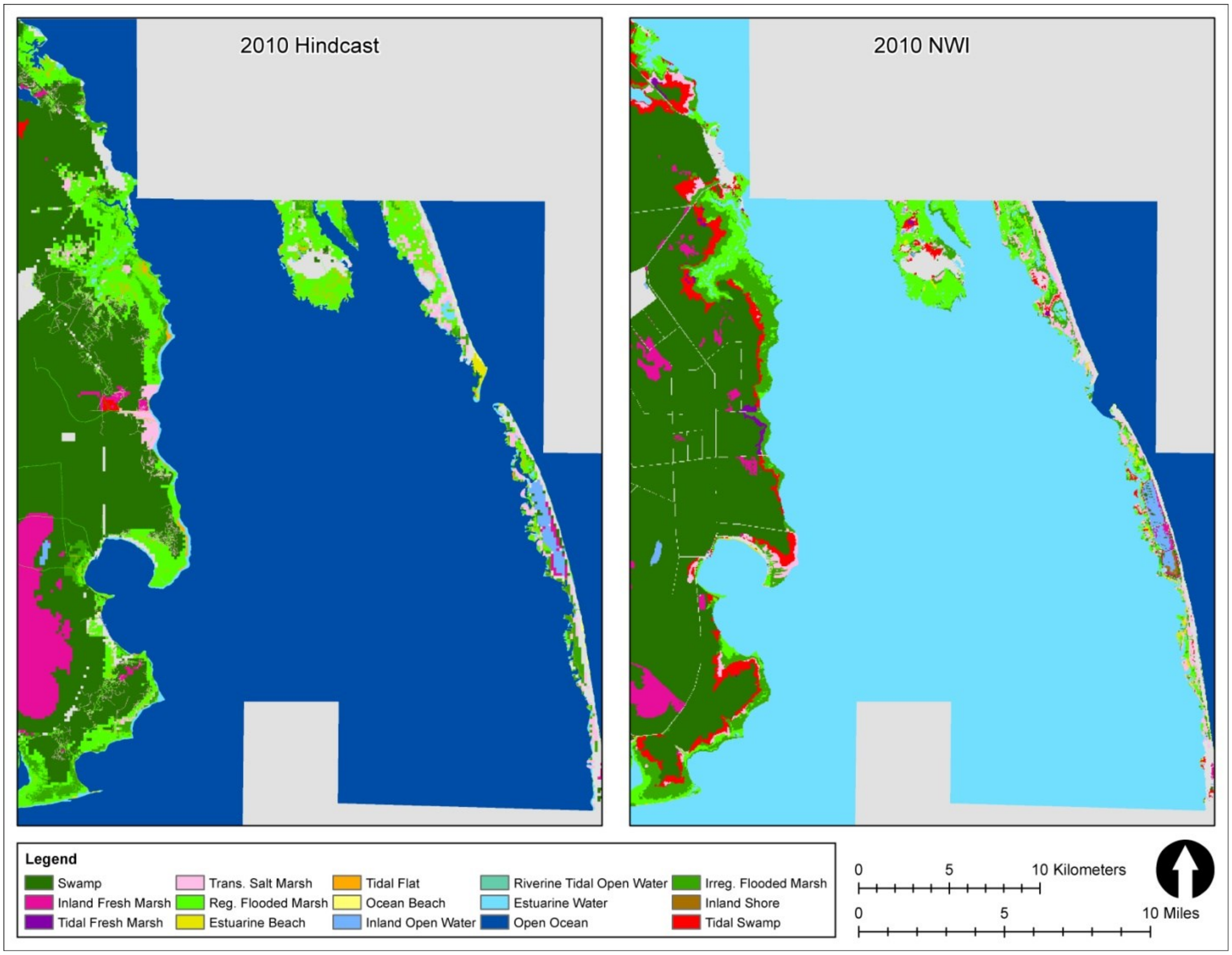

Figure 8. 2010 hindcast and preliminary NWI 2010 SLAMM maps.

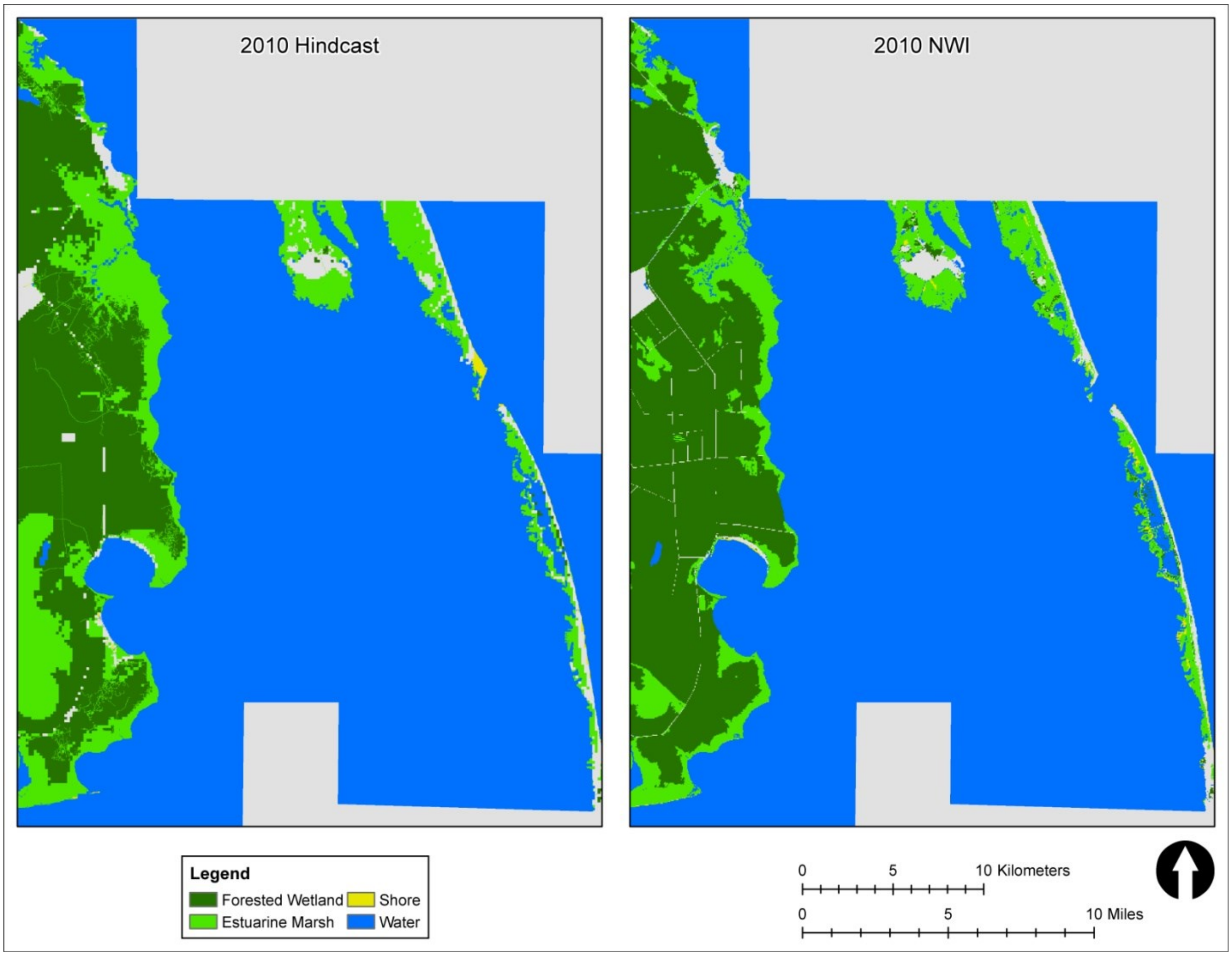

Figure 9. Reclassified 2010 hindcast and preliminary NWI 2010 SLAMM maps.

2010 SLAMM Hindcast				2010 NWI SLAMM			
SLAMM Code	**SLAMM Name**	**New Code**	**New Name**	**SLAMM Code**	**SLAMM Name**	**New Code**	**New Name**
3	Swamp	1	Forested Wetland	3	Swamp	1	Forested Wetland
5	Inland Fresh Marsh	2	Estuarine Marsh	5	Inland Fresh Marsh	2	Estuarine Marsh
7	Transitional Salt Marsh	2	Estuarine Marsh	6	Tidal Fresh Marsh	2	Estuarine Marsh
8	Regularly Flooded Marsh	2	Estuarine Marsh	7	Transitional Salt Marsh	2	Estuarine Marsh
10	Estuarine Beach	3	Shore	8	Regularly Flooded Marsh	2	Estuarine Marsh
11	Tidal Flat	2	Estuarine Marsh	10	Estuarine Beach	3	Shore
12	Ocean Beach	3	Shore	12	Ocean Beach	3	Shore
15	Inland Open Water	4	Water	15	Inland Open Water	4	Water
17	Estuarine Water	4	Water	16	Riverine Tidal Open Water	4	Water
19	Open Ocean	4	Water	17	Estuarine Water	4	Water
20	Irregularly Flooded Marsh	2	Estuarine Marsh	19	Open Ocean	4	Water
23	Tidal Swamp	1	Forested Wetland	20	Irregularly Flooded Marsh	2	Estuarine Marsh
No Data	N/A	0	N/A	22	Inland Shore	3	Shore
				23	Tidal Swamp	1	Forested Wetland
				No Data	N/A	0	N/A

Table 5. Table showing the reclassification of the 2010 SLAMM hindcast output map and 2010 SLAMM reference map to four classes.

A total of 180 accuracy assessment points were generated for use by the *Accuracy Assessment* tool in ERDAS Imagine software in order to assess the predictive power and relative accuracy of SLAMM. Table 7 indicates an overall map accuracy of 81.1%. This simple descriptive statistic is computed by dividing the total correct accuracy assessment points by the total number of points Congalton, 1991). Although this overall accuracy value can be considered fair-good, it is necessary to utilize other descriptive and analytical statistical analyses in order to get a better overall picture of model performance. In order to get a better sense of model performance, analysis on the accuracies of individual land classes was calculated. Both producer's and user's accuracy were calculated for each land class. Producer's accuracy essentially indicates the probability of a reference class being classified correctly and the user's accuracy can be thought of as "reliability", essentially indicating the probability that a land class classified on the classified image actually represents ground truth (Congalton, 1991).

The producer's accuracy of forested wetland was 77.97% and was calculated by dividing the number correct, 46, by the total column number of 59 (Table 6). Estuarine marsh had a producer's accuracy of 76.09% (35/46), shore had a producer's accuracy of 94.74% (18/19), and water had a producer's accuracy of 83.93% (47/56) (Table 6). The user's accuracy of forested wetland was 92% and was calculated by dividing the number correct, 46, by the total row number of 50 (Table 6). Estuarine marsh had a user's accuracy of 70% (35/50), shore had a producer's accuracy of 60% (18/30), and water had a producer's accuracy of 94% (47/50) (Table 6).

The forested wetland column on Table 6 shows that of the 180 total points, 59 were actually forested wetland on the reference image. Of the 59 forested wetland points on the reference image, 46 were classified as forested wetland and 13 were classified as estuarine marsh on the classified image. The forested wetland row shows that of the 180 total points, 50 were forested wetland, generated on the classified image. Of the 50 forested wetland points on the classified image, 46 were actually forested wetland, 3 were actually estuarine marsh, and 1 was actually water on the reference image. A look at the error matrix (Table 6) will show slight confusion in discerning forested wetland from estuarine marsh. Even though only 77.97% of forested wetland areas have been correctly identified as forested wetland, 92% percent of the land classes classified as forested wetland are actually forested wetland (Table 7).

Hindcast Accuracy Assessment Error Matrix					
	Reference Data				
Classified Data	Forest Wetland	Estuarine Marsh	Shore	Water	**Row Total**
Forest Wetland	46	3	0	1	50
Estuarine Marsh	13	35	0	2	50
Shore	0	6	18	6	30
Water	0	2	1	47	50
Column Total	59	46	19	56	180

Table 6. Accuracy Assessment tool error matrix.

Hindcast Accuracy Totals						
Class	**Number Correct**	**Reference Totals**	**Classified Totals**	**Producers Accuracy**	**Users Accuracy**	**Overall Accuracy**
Forest Wetland	46	59	50	77.97%	92.00%	
Estuarine Marsh	35	46	50	76.09%	70.00%	
Shore	18	19	30	94.74%	60.00%	
Water	47	56	50	83.93%	94.00%	
Totals	146	180	180			81.11%

Table 7. Accuracy Assessment tool output table showing accuracy totals.

The estuarine marsh column on Table 6 shows that of the 180 total points, 46 were actually estuarine marsh on the reference image. Of those 46 points, 35 were classified as estuarine marsh, 3 as forested wetland, 6 as shore, and 2 as water on the classified image. The estuarine marsh row shows that of the 180 total points, 50 were estuarine marsh, generated on the classified image. Of those 50 estuarine marsh points, 35 were actually estuarine marsh, 13 were actually forested wetland, and 2 were actually water on the reference image. The error matrix shows that there was moderate to large confusion in distinguishing estuarine marsh from forested wetland. Although 76.09% of estuarine marsh areas have been correctly identified as estuarine marsh, only 70% of the land classes classified as estuarine marsh are actually estuarine marsh.

The shore column on Table 6 shows that of the 180 total points, 19 were actually shore on the reference image. Of those 19 points, 18 were classified as shore and 1 was classified as water on the classified image. The shore row shows that of the 180 total points, 30 were shore, generated on the classified image. Of those 30 shore points, 18 were actually shore, 6 were actually estuarine marsh, and 6 were actually water on the reference image. The error matrix shows that there was moderate confusion in distinguishing shore from estuarine marsh and water. Although 94.74% of shore areas have been correctly identified as shore, only 60% of the land classes classified as shore are actually shore.

The water column on the error matrix shows that of the 180 total points, 56 were actually water on the reference image. Of those 56 points, 47 were classified as water, 6 were classified as shore, 2 were classified as estuarine marsh, and 1 was classified as forested wetland on the classified image. The water row on the error matrix shows that of the 180 total points, 50 were water, generated on the classified image. Of those 50 water points, 47 were actually water, 2 were actually estuarine marsh, and 1 was actually water on the reference image. The error matrix shows that there was moderate confusion in distinguishing water from estuarine marsh and shore. Although 83.93% of water areas have been correctly identified as water, 94% of the land classes classified as water are actually water.

Along with an error matrix, the accuracy assessment tool in ERDAS imagine also provides a KHAT statistic as a result of performing a KAPPA analysis. KAPPA is essentially a measure of agreement or accuracy which determines whether results exhibited in the error matrix are significantly better than a chance (random) result (Jensen, 2007; Campbell, 2002, Congalton, 1991). A simplified version of KHAT is as follows:

KHAT = Observed Correct - Expected Correct/ 1 - Expected Correct

Table 8 shows an overall KHAT of 0.743, which indicates an above-average accuracy regarding model performance. A value closer to -1 means poor accuracy and a value closer 1 mean great accuracy. So, a KHAT of 0.743 can be explained as the classification attained an above-average level of accuracy that is 74.3% better than would be expected from random chance (Congalton, 1991, Jensen, 2007; Campbell, 2002, Congalton, 1991). A look at the individual KAPPA of each class in Table 8 corroborates the user's accuracy of each class from Table 7. The user's accuracy for forested wetland was 92% with a KHAT coefficient of fairly high agreement of 0.881. The user's accuracy of estuarine marsh was 70% with a KHAT coefficient of average agreement of 0.597. The user's accuracy of shore was 60% with a KHAT coefficient of average agreement of 0.553. Lastly, the user's accuracy of water was 94% with a KHAT coefficient of high agreement of 0.913.

Hindcast Kappa Statistics	
Class	**Kappa**
Forest Wetland	0.881
Estuarine Marsh	0.597
Shore	0.553
Water	0.913
Overall Kappa	0.743

Table 8. Accuracy Assessment tool output table showing class-specific and overall Kappa values.

Hindcast Matrix Union Summary

Following the accuracy assessment to gauge model accuracy, a cell-based analysis was performed on both the reclassified 2010 SLAMM hindcast output map reclassified 2010 SLAMM reference map using the *Matrix Union* tool in ERDAS Imagine. The *Matrix Union* tool in indicates how the classes from two thematic images overlap by providing an output image showing areas of agreement and non-agreement. The *Matrix Summary* tool was used to output cross-tabulation statistics that compare class value areas between the two thematic images. The *Matrix Summary* tool is similar to the *Matrix Union* tool, except it does not provide an output image but rather descriptive statistics in tabular format.

The results of the *Matrix Summary* tool comparing both the reclassified 2010 SLAMM hindcast output map reclassified 2010 SLAMM reference map at the pixel level support results from the point-based accuracy assessment. Table 10 shows a 95.49% of agreement of total pixels for forested wetland between the reclassified 2010 SLAMM hindcast output map reclassified 2010 SLAMM reference map. This percentage equates to an agreement of 19,035.6 hectares (Table 9) and 846,028 pixels (Table 11) for forested wetland. Estuarine marsh exhibited a 55.23% agreement at the pixel level (Table 10), comprising 7,544.8 hectares (Table 9) and 335,326 pixels (Table 11). Table 10 shows that shore had the worst percentage of agreement of 20.6%, which equates to 19.9 hectares (Table 9) and 883 pixels (Table 11). Water exhibited the highest percentage of agreement of 99.6% (Table 10), totaling 78,612.3 hectares (Table 9) and 3,493,881 pixels (Table 11).

Hindcast Matrix Tool Summary (Hectares)				
Class	Forest Wetland	Estuarine Marsh	Shore	Water
Forest Wetland	19,035.60	5,284.22	5.22	45.18
Estuarine Marsh	844.43	7,544.84	34.02	247.28
Shore	0.00	111.49	19.87	32.51
Water	55.06	72.61	37.35	78,612.30

Table 9. Matrix Summary tool output table showing the amount of class agreement and disagreement between the reclassified 2010 hindcast and preliminary NWI 2010 SLAMM maps in hectares.

Hindcast Matrix Tool Summary (%)				
Class	Forest Wetland	Estuarine Marsh	Shore	Water
Forest Wetland	95.49	38.68	5.41	0.06
Estuarine Marsh	4.24	55.23	35.27	0.31
Shore	0.00	0.82	20.60	0.04
Water	0.28	5.27	38.72	99.59

Table 10. Matrix Summary tool output table showing percent class agreement and disagreement between the reclassified 2010 hindcast and preliminary NWI 2010 SLAMM maps.

Hindcast Matrix Tool Summary (Pixels)				
Class	Forest Wetland	Estuarine Marsh	Shore	Water
Forest Wetland	846,028	234,854	323	2,008
Estuarine Marsh	37,530	335,326	1,512	10,990
Shore	0	4,955	883	1,445
Water	2,447	32,027	1,660	3,493,881

Table 11. Matrix Summary tool output table showing the amount of class agreement and disagreement between the reclassified 2010 hindcast and preliminary NWI 2010 SLAMM maps in number of pixels.

The results from the *Matrix Summary* tool output tables are corroborated by the *Matrix Union* output map (Figure 10). The majority of agreement between the reclassified 2010 SLAMM hindcast output map reclassified 2010 NWI SLAMM reference map is exhibited on Map 1 by forested wetland and water (Figure 10). Much of the forested wetland agreement occurs on the eastern portion of the Pamlico Peninsula inland from the nearshore zone. Estuarine marsh agreement (Map 1) occurs mainly in the nearshore zone along the eastern portion of the Pamlico Peninsula, Roanoke Island, back-side of Nags Head, NC, and the back-barrier portion of Pea Island (Figure 10). Occurrences of agreement of shore are shown on Map 1, with small patches located along the eastern portion of the Pamlico Peninsula near Stumpy Point and larger patches on the north end of Oregon Inlet, south of Nags Head, NC (Figure 10). The majority of forested wetland disagreement or confusion occurs in Map 2 along the nearshore zone of eastern portion of the Pamlico Peninsula, where it was most likely confused with estuarine marsh or patches of shore (Figure 10). Water exhibited the majority of disagreement along the immediate shoreline of Roanoke Island, the backside of Nags Head, NC, and the Pea Island portion of the Outer Banks (Map 2, Figure 10). There was also some confusion with water along the north-eastern portion of the Pamlico Peninsula from the nearshore zone extending slightly inland. Estuarine marsh exhibited the most widespread and extensive disagreement mainly in the nearshore zone along the eastern portion of the Pamlico Peninsula (Map 2), with smaller areas also occurring along Roanoke Island, the backside of Nags Head, NC, and the Pea Island portion of the Outer Banks (Figure 10). Map 2 also shows a fairly large area of estuarine marsh disagreement located inland on the south-eastern portion of the Pamlico Peninsula. The majority of shore disagreement occurs in roughly the same areas of shore agreement, mainly appearing as smaller patches along the north-eastern and south-eastern portions of the Pamlico Peninsula, as well as and larger patches on the north end of Oregon Inlet, south of Nags Head, NC.

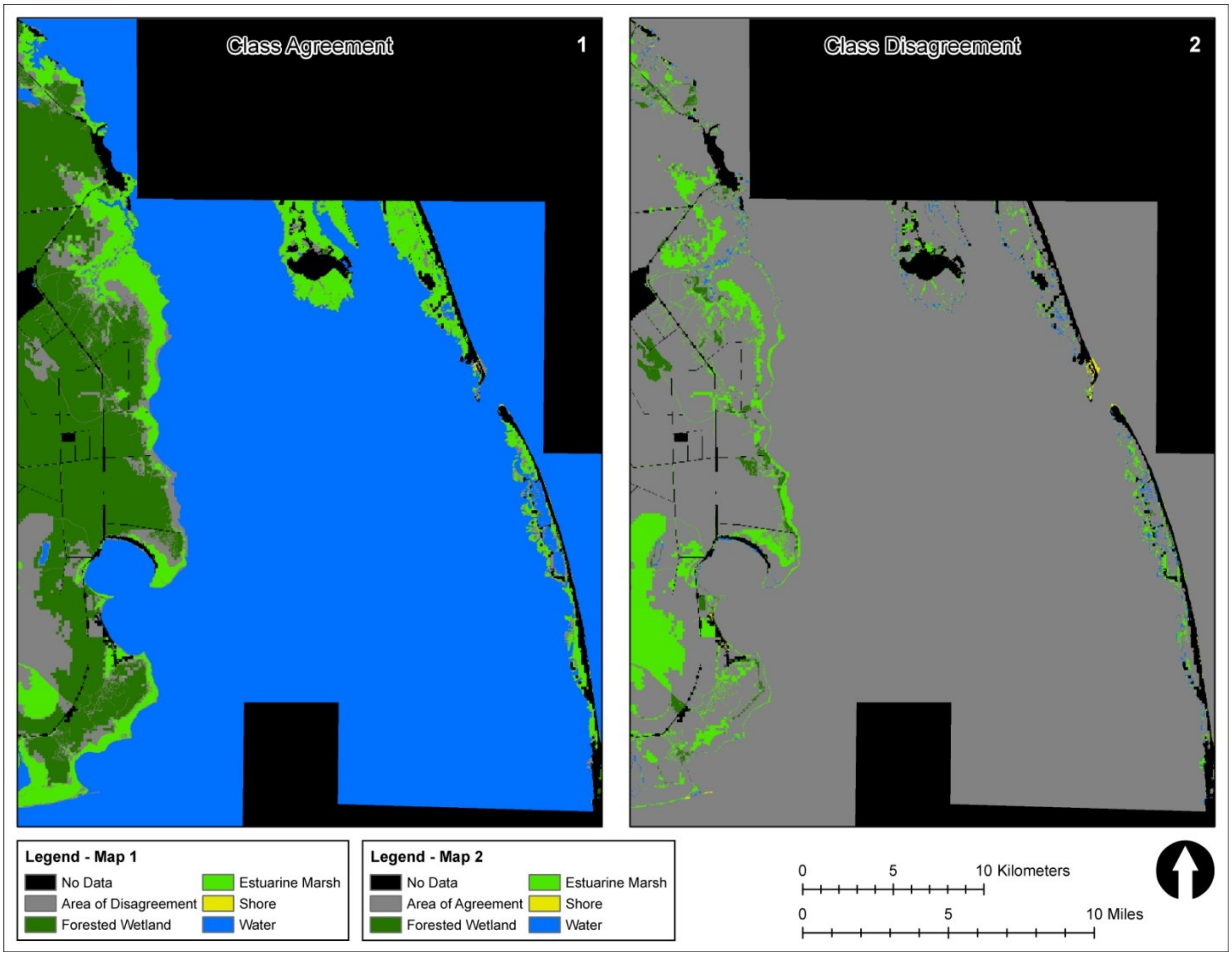

Figure 10. Matrix Union tool output maps showing areas of class agreement and disagreement between the reclassified 2010 hindcast and preliminary NWI 2010 SLAMM maps.

Forecast Results - 0.4m SLR

Visually, the amount of change from 2025 to 2100 with 0.4 m rise in sea-level by visually analyzing Figures 11 and 12, is fairly minimal. In 2025, the greatest amount of change occurs along the eastern portion of the Pamlico Peninsula, with noticeable change also occurring along Roanoke Island and lands to east along the backside of Nags Head, NC. From initial condition to 2025 in these areas (Figures 11 and 12), transitional salt marsh and irregularly flooded marsh are replaced and dominated by regularly flooded marsh. Transitional salt marsh and irregularly flooded marsh start to migrate inland from the shore during this rate of rise. Table 12 indicates a loss of transitional salt marsh and irregularly flooded marsh with 0.65% (1,008 hectares) and

1.08% (1,683 hectares) from initial condition, respectively. Regularly flooded marsh had the greatest amount charge with a gain of 2.59% (4,031 hectares) from initial condition. While transitional salt marsh and irregularly flooded marsh exhibited relatively little change quantitatively, they did change quite substantially spatially by their movement inland. Regularly flooded marsh took over locations inhabited previously by transitional salt marsh and irregularly flooded marsh, hence the relatively high amount of total area percent and hectare gain.

Forecast 0.4m - Global													
SLAMM Code	**SLAMM Name**	**Initial Cond.**		**Change**		**2025**		**Change**		**2050**			
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%		
1	Developed Dry Land	2051.06	1.32	131.18	0.08	1919.88	1.23	179.52	0.12	1740.36	1.12		
2	Undeveloped Dry Land	2893.05	1.86	244.77	0.16	2648.28	1.70	188.83	0.12	2459.45	1.58		
3	Swamp	21156.48	13.58	1508.72	0.97	19647.76	12.61	2447.50	1.57	17200.26	11.04		
5	Inland Fresh Marsh	3816.52	2.45	59.60	0.04	3756.92	2.41	76.69	0.05	3680.23	2.36		
7	Trans. Salt Marsh	4103.37	2.63	1008.28	0.65	3095.09	1.99	-917.35	-0.59	4012.44	2.58		
8	Regularly Flooded Marsh	3146.04	2.02	-4031.05	-2.59	7177.09	4.61	-1416.91	-0.91	8594.00	5.52		
10	Estuarine Beach	94.68	0.06	10.47	0.01	84.21	0.05	6.82	0.00	77.39	0.05		
11	Tidal Flat	0.00	0.00	-393.52	-0.25	393.52	0.25	-753.89	-0.48	1147.41	0.74		
12	Ocean Beach	90.59	0.06	-80.24	-0.05	170.83	0.11	-16.73	-0.01	187.56	0.12		
15	Inland Open Water	358.92	0.23	3.02	0.00	355.91	0.23	1.37	0.00	354.53	0.23		
17	Estuarine Open Water	789.50	0.51	126.76	0.08	662.74	0.43	-191.35	-0.12	854.09	0.55		
19	Open Ocean	113416.85	72.81	-283.92	-0.18	113700.77	72.99	-129.17	-0.08	113829.95	73.08		
20	Irreg. Flooded Marsh	3613.86	2.32	1683.10	1.08	1930.76	1.24	484.78	0.31	1445.97	0.93		
23	Tidal Swamp	237.22	0.15	12.83	0.01	224.39	0.14	39.89	0.03	184.49	0.12		
SLAMM Code	**SLAMM Name**	**2050**		**Change**		**2075**		**Change**		**2100**		**Total Change**	
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
1	Developed Dry Land	1740.36	1.12	270.51	0.17	1469.84	0.94	82.15	0.05	1387.69	0.89	-663.36	-0.426
2	Undeveloped Dry Land	2459.45	1.58	214.28	0.14	2245.17	1.44	198.92	0.13	2046.25	1.31	-846.80	-0.544
3	Swamp	17200.26	11.04	3873.35	2.49	13326.91	8.56	3520.16	2.26	9806.75	6.30	-11349.73	-7.286
5	Inland Fresh Marsh	3680.23	2.36	71.13	0.05	3609.10	2.32	62.44	0.04	3546.66	2.28	-269.86	-0.173
7	Trans. Salt Marsh	4012.44	2.58	-1332.72	-0.86	5345.16	3.43	758.15	0.49	4587.00	2.94	483.63	0.310
8	Regularly Flooded Marsh	8594.00	5.52	-720.39	-0.46	9314.39	5.98	-109.38	-0.07	9423.78	6.05	6277.74	4.030
10	Estuarine Beach	77.39	0.05	2.43	0.00	74.97	0.05	-1.10	0.00	76.07	0.05	-18.61	-0.012
11	Tidal Flat	1147.41	0.74	-2677.81	-1.72	3825.22	2.46	-4151.07	-2.66	7976.29	5.12	7976.29	5.121
12	Ocean Beach	187.56	0.12	-42.84	-0.03	230.40	0.15	-42.43	-0.03	272.83	0.18	182.25	0.117
15	Inland Open Water	354.53	0.23	1.22	0.00	353.32	0.23	1.10	0.00	352.22	0.23	-6.71	-0.004
17	Estuarine Open Water	854.09	0.55	-55.21	-0.04	909.30	0.58	-523.87	-0.34	1433.18	0.92	643.67	0.413
19	Open Ocean	113829.95	73.08	-241.48	-0.16	114071.43	73.23	-185.72	-0.12	114257.15	73.35	840.29	0.539
20	Irreg. Flooded Marsh	1445.97	0.93	575.94	0.37	870.03	0.56	358.40	0.23	511.63	0.33	-3102.23	-1.992
23	Tidal Swamp	184.49	0.12	61.60	0.04	122.89	0.08	32.25	0.02	90.64	0.06	-146.58	-0.094

Table 12. SLAMM global forecast results showing hectares and percentage of class change with a SLR rate of 0.4m by 2100.

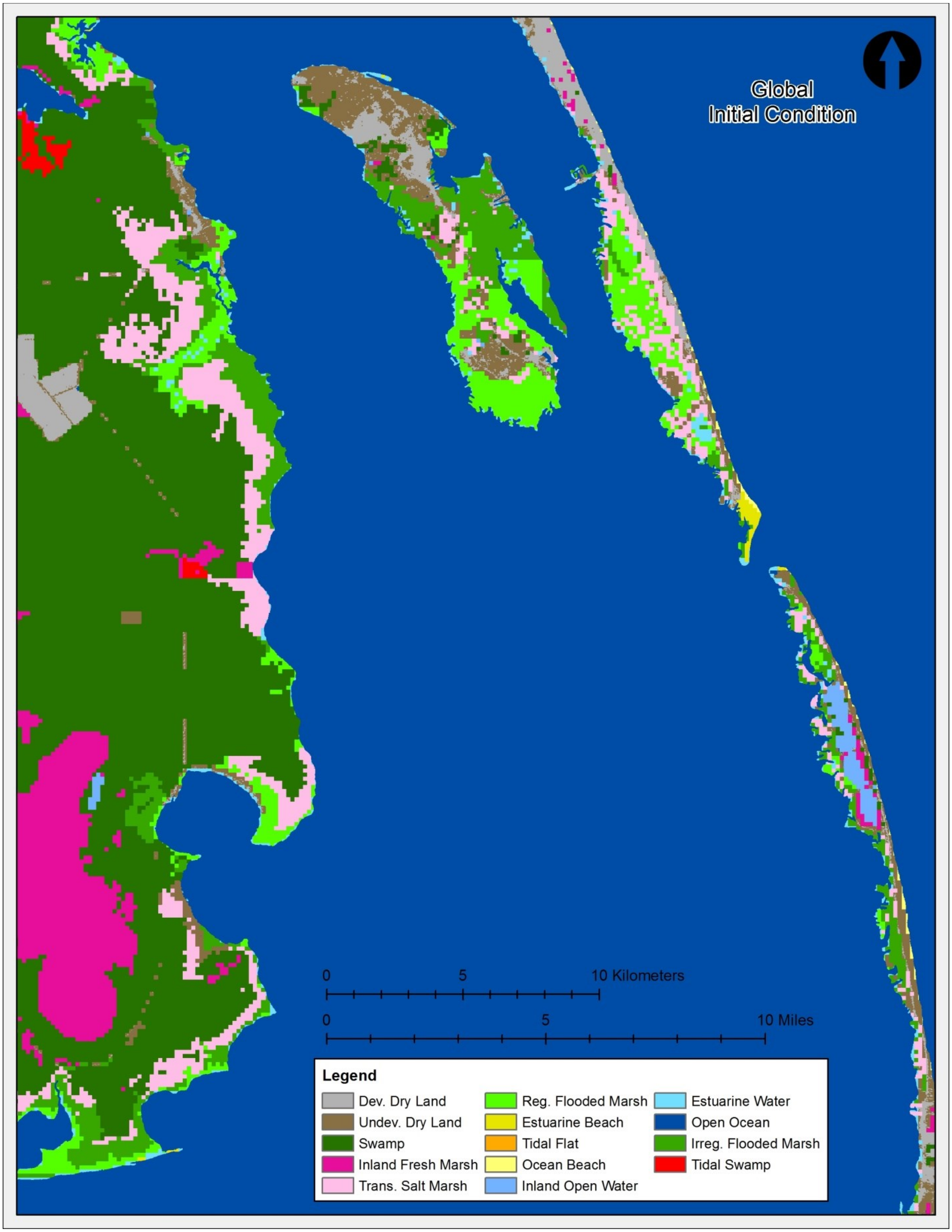

Figure 11. SLAMM global forecast maps showing initial condition.

From 2025 to 2050 with a 0.4m rise in sea-level, the greatest amount of change visually occurs along the eastern portion of the Pamlico Peninsula, with noticeable change also occurring along Roanoke Island and lands to east along the backside of Nags Head, NC (Figure 12). Transitional salt marsh and irregularly flooded marsh continue to be replaced by regularly flooded marsh, while Transitional salt marsh and irregularly flooded marsh continue to migrate inland. Tidal flats start to appear along or near the immediate shoreline, especially north of Pt. Peter Rd. on the eastern portion of the Pamlico Peninsula and on southern Roanoke Island. Table 12 corroborates this observation with an increase of regularly flooded marsh and tidal flat of 3.5% (5,448 hectares) and 0.75% (1,147 hectares) from initial condition, and 0.91% (1,417 hectares) and 0.48% (754 hectares) over the 25 year period, respectively. Over the 25 year period, a 0.59% (917 hectares) increase in transitional salt marsh is observed at the expense of swamp with a loss of 1.57% (2,448 hectares). As a result, transitional salt marsh is lost near the shore migrates inland and takes over areas previously dominated by swamp.

From 2050 to 2075 with a 0.4m rise in sea-level, the greatest amount of change visually occurs along the eastern portion of the Pamlico Peninsula, with noticeable change also occurring along Roanoke Island and lands to east along the backside of Nags Head, NC adjacent to the Roanoke Sound (Figure 12). Transitional salt marsh and regularly flooded marsh continue to dominate the nearshore zone, migrating slowly inland and replacing swamp in many areas. Tidal flats continue to increase throughout the higher impacted areas such as southern Roanoke Island and eastern Pamlico peninsula around Pt. Peter Rd. and the amount of change is reflected in Table 12, with a 0.46% (720 hectares) increase in regularly flooded marsh, a 0.86% (1,333 hectares) increase in transitional salt marsh, and a 1.72% (2,678 hectares) increase in tidal flats over the 25 year period. Swamp and Irregularly flooded marsh continue to decline and migrate inland as they are taken over by regularly flooded marsh and transitional salt marsh.

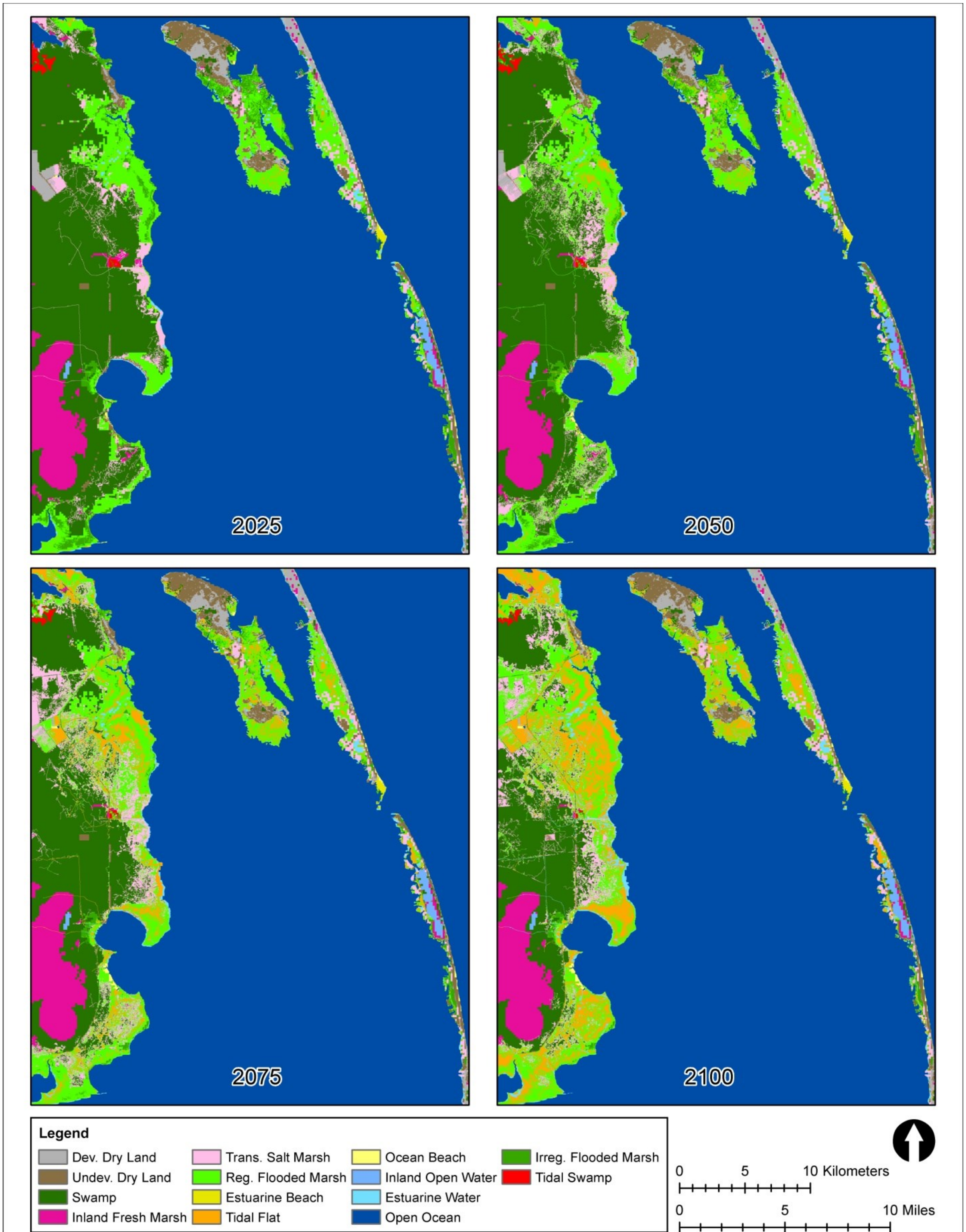

Figure 12. SLAMM global forecast map showing years 2025 - 2100 with a SLR rate of 0.4m by 2100.

The 25-year period from 2075 to 2100 with a 0.4m rise in sea-level shows the greatest amount of change. This change continues to occur along the eastern portion of the Pamlico Peninsula, with noticeable change also occurring along Roanoke Island and lands to east along the backside of Nags Head, NC adjacent to the Roanoke Sound (Figure 12). The emergence of fairly vast tidal flats and continuing spread of regularly flooded marsh and transitional salt marsh inland, mark the key changes over this 25 year period. Tidal flats have started to dominate the nearshore zone alongside regularly flooded marsh with an increase of 2.66% (4,151 hectares). A decrease in transitional salt marsh of 0.49% (758 hectares) and irregularly flooded marsh of 0.23% (358 hectares) can be attributed to the emergence and growth of regularly flooded marsh, and particularly tidal flats (Table 12).

A visual analysis of the Pea Island sub-site over the four time periods (2025, 2050, 2075, and 2100) with a 0.4m rise in sea-level corroborates the majority of trends found in the global forecast. From initial condition to 2025, not much change occurs although Figures 13 and 14 show an increase of regularly flooded marsh supplanting previous areas of irregularly flooded marsh. There is also the occurrence of tidal flats along the immediate back-barrier shoreline. Table 13 shows an increase of regularly flooded marsh and tidal flat of 0.35% (13 hectares) and 0.44% (16 hectares), respectively. Open ocean exhibited an increase of 0.89% (32 hectares) replacing areas of estuarine open water. From 2025 to 2050, the majority of changes can be seen in the immediate back-barrier nearshore zone with a slight increase in tidal flat and horizontal movement of both tidal flat and regularly flooded marsh (Figure 14). An increase in both open ocean and estuarine open water can also be seen from areas of land lost to water. These observations are supported by Table 13 which shows an increase in tidal flat, open ocean and estuarine open water of 0.08% (3 hectares), 0.12% (4 hectares), and 0.42% (15 hectares), respectively. Regularly flooded marsh did not change in areal amount but did migrate towards the middle of the barrier island from the sound-sound. From 2050 to 2075, the back-barrier side of Pea Island exhibits the most change (although relatively minor) with areas irregularly flooded marsh being replaced by regularly flooded marsh, tidal flat, estuarine open water, and open ocean (Figure 14). Figure 14 confirms these observations with an increase of regularly flooded marsh, tidal flat, estuarine open water, and open ocean of 0.25% (9 hectares), 0.21% (7.6 hectares), 0.16% (5.7 hectares), and 0.52% (18.6 hectares). Irregularly flooded marsh decreased in land area by 0.99% (35.7 hectares). From 2075 to 2100, relatively little change continues to occur on the back-barrier side of Pea Island. Tidal flat, estuarine open water, and open ocean exhibit small increases, while irregularly flooded marsh and undeveloped dry land decreased in area (Figure 14). This is validated by Table 13 which shows increases in tidal flat, estuarine open water, and open ocean of 0.20% (7.3 hectares), 0.62% (22.4 hectares), and 0.4% (14.6 hectares), respectively. Irregularly flooded marsh decreased by 0.97% (35.2 hectares) and undeveloped dry land decreased by 0.37% (13.4 hectares).

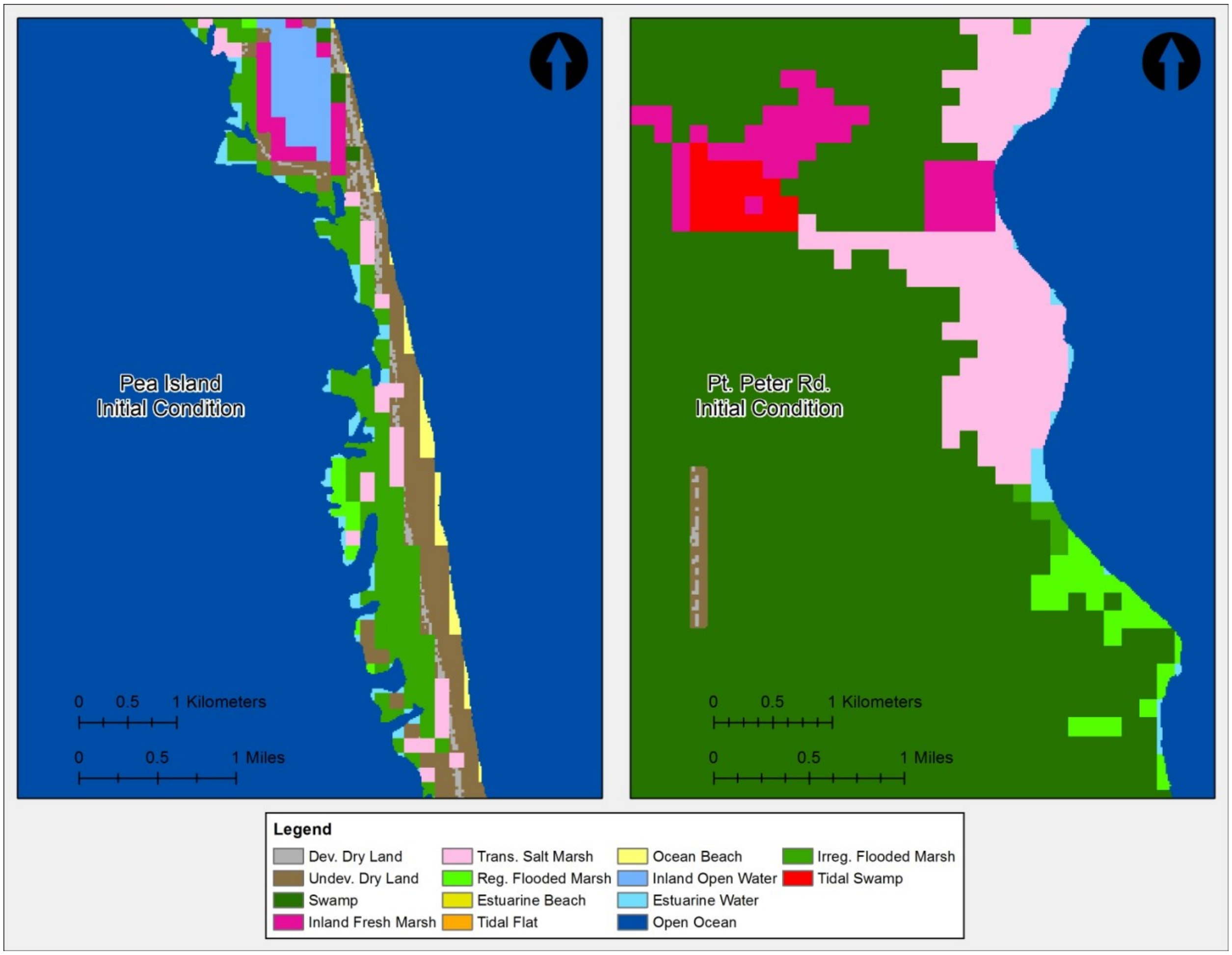

Figure 13. SLAMM Pea Island sub-site forecast map (on left) showing initial condition.

Forecast 0.4m - Pea Island													
SLAMM Code	**SLAMM Name**	**Initial Cond.**		**Change**		**2025**		**Change**		**2050**			
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%		
1	Developed Dry Land	33.08	0.91	0.83	0.02	32.24	0.89	0.18	0.00	32.06	0.89		
2	Undeveloped Dry Land	199.46	5.52	9.14	0.25	190.33	5.26	2.74	0.08	187.59	5.19		
3	Swamp	10.78	0.30	0.30	0.01	10.47	0.29	0.02	0.00	10.45	0.29		
5	Inland Fresh Marsh	43.34	1.20	0.17	0.00	43.16	1.19	0.53	0.01	42.63	1.18		
7	Trans. Salt Marsh	62.39	1.73	-4.74	-0.13	67.13	1.86	4.82	0.13	62.31	1.72		
8	Regularly Flooded Marsh	22.07	0.61	-12.62	-0.35	34.69	0.96	0.03	0.00	34.66	0.96		
10	Estuarine Beach	0.00	0.00	-0.02	0.00	0.02	0.00	0.02	0.00	0.00	0.00		
11	Tidal Flat	0.00	0.00	-15.95	-0.44	15.95	0.44	-3.04	-0.08	18.99	0.53		
12	Ocean Beach	23.87	0.66	-2.84	-0.08	26.72	0.74	0.62	0.02	26.09	0.72		
15	Inland Open Water	82.46	2.28	0.32	0.01	82.15	2.27	0.00	0.00	82.15	2.27		
17	Estuarine Open Water	33.12	0.92	29.36	0.81	3.76	0.10	-15.23	-0.42	18.99	0.53		
19	Open Ocean	2877.32	79.59	-32.32	-0.89	2909.64	80.48	-4.19	-0.12	2913.83	80.60		
20	Irreg. Flooded Marsh	227.50	6.29	28.37	0.78	199.13	5.51	13.50	0.37	185.64	5.13		
SLAMM Code	**SLAMM Name**	**2050**		**Change**		**2075**		**Change**		**2100**		**Total Change**	
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
1	Developed Dry Land	32.06	0.89	0.73	0.02	31.34	0.87	1.99	0.06	29.35	0.81	-3.73	-0.103
2	Undeveloped Dry Land	187.59	5.19	4.50	0.12	183.09	5.06	13.39	0.37	169.70	4.69	-29.76	-0.823
3	Swamp	10.45	0.29	0.12	0.00	10.33	0.29	0.20	0.01	10.12	0.28	-0.65	-0.018
5	Inland Fresh Marsh	42.63	1.18	0.26	0.01	42.37	1.17	0.50	0.01	41.87	1.16	-1.47	-0.041
7	Trans. Salt Marsh	62.31	1.72	0.75	0.02	61.56	1.70	-0.70	-0.02	62.27	1.72	-0.13	-0.003
8	Regularly Flooded Marsh	34.66	0.96	-8.87	-0.25	43.53	1.20	1.17	0.03	42.36	1.17	20.28	0.561
10	Estuarine Beach	0.00	0.00	-0.04	0.00	0.04	0.00	-0.28	-0.01	0.32	0.01	0.32	0.009
11	Tidal Flat	18.99	0.53	-7.58	-0.21	26.57	0.73	-7.31	-0.20	33.88	0.94	33.88	0.937
12	Ocean Beach	26.09	0.72	-1.19	-0.03	27.28	0.75	-7.12	-0.20	34.40	0.95	10.52	0.291
15	Inland Open Water	82.15	2.27	0.00	0.00	82.15	2.27	0.00	0.00	82.15	2.27	-0.32	-0.009
17	Estuarine Open Water	18.99	0.53	-5.72	-0.16	24.71	0.68	-22.44	-0.62	47.15	1.30	14.03	0.388
19	Open Ocean	2913.83	80.60	-18.64	-0.52	2932.47	81.11	-14.57	-0.40	2947.04	81.51	69.72	1.928
20	Irreg. Flooded Marsh	185.64	5.13	35.69	0.99	149.95	4.15	35.17	0.97	114.78	3.17	-112.72	-3.118

Table 13. SLAMM Pea Island sub-site forecast results showing hectares and percentage of class change with a SLR rate of 0.4m by 2100.

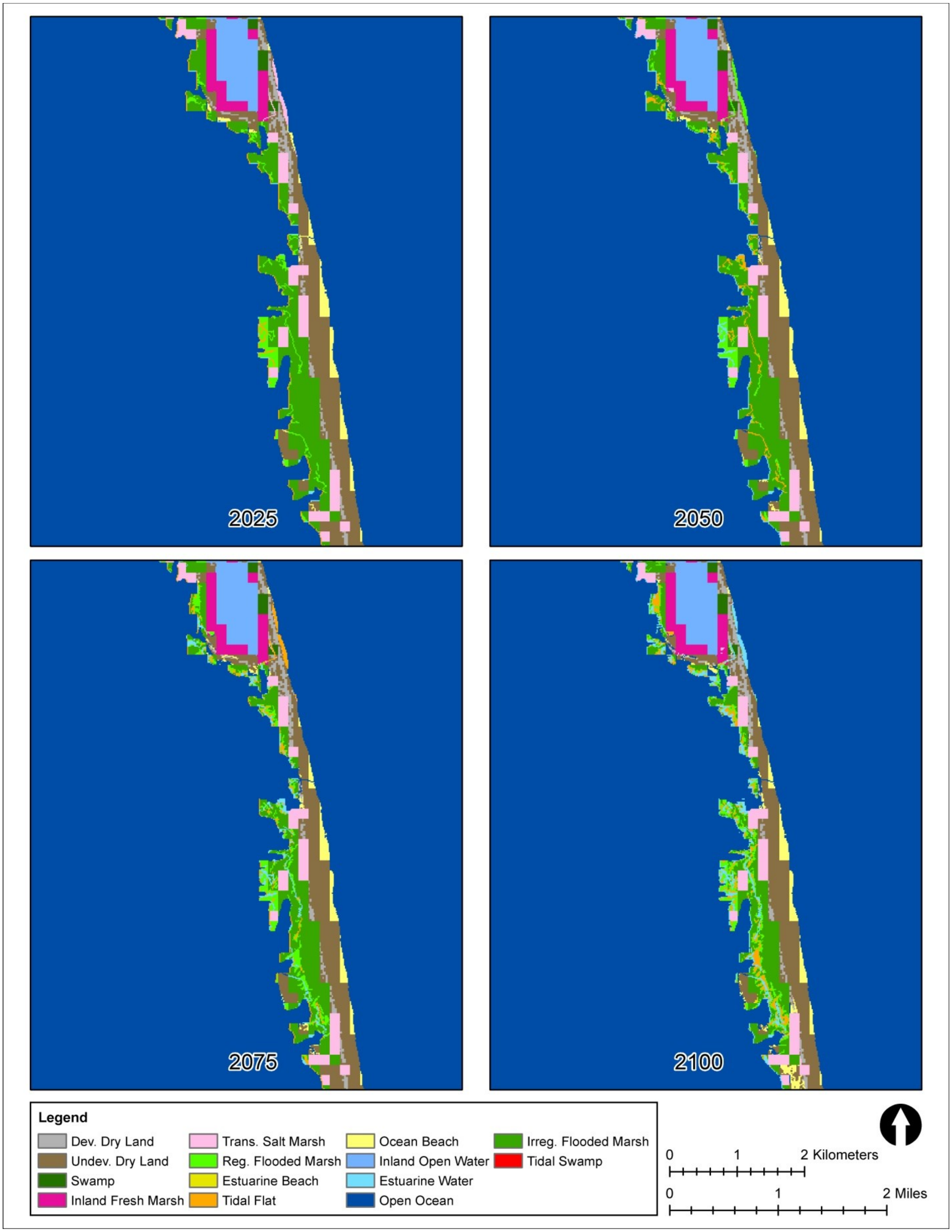

Figure 14. SLAMM Pea Island sub-site forecast map showing years 2025 - 2100 with a SLR rate of 0.4m by 2100.

A visual analysis of the Pt. Peter Rd. sub-site over the four time periods (2025, 2050, 2075, and 2100) with a 0.4m rise in sea-level corroborates the majority of trends found in the global forecast. From initial condition to 2025, small amounts of change are seen in the immediate nearshore zone with areas of swamp and inland fresh marsh being taken over by inland migrating transitional salt marsh and regularly flooded marsh. Small patches of tidal flat start to appear along the immediate shoreline (Figures 15 and 16). These observations are supported by Table 14 with an increase in transitional salt marsh, regularly flooded marsh, and tidal flat of 3.01% (155.4 hectares), 0.34% (17.6 hectares), and 0.26% (13.4 hectares), respectively. Both swamp and inland fresh marsh exhibited decreases of 3.38% (174.3 hectares) and 0.58% (29.7 hectares), respectively (Table 14). From 2025 to 2050, the trends seen previously continue to increase with transitional salt marsh and regularly flooded marsh increasing in areal extent and migrating further inland (Figure 16). An increase tidal flat can also be seen in Figure 16. This movement results in further loss of swamp, inland fresh marsh and tidal swamp. Table 14 supports these observations with an increase of transitional salt marsh, regularly flooded marsh, and tidal flat of 2.68% (138.1 hectares), 2.75% (141.7 hectares), and 0.53% (27.3 hectares), respectively. Open ocean (open water) also experienced an increase of 0.5% (25.7 hectares). Loss in land area of swamp, inland fresh marsh and tidal swamp is shown in Table 14 of 5.31 (273.9 hectares), 0.89% (46.1 hectares), and 0.16% (8.2 hectares), respectively. From 2050 to 2075, Figure 16 shows a fairly sharp increase in transitional salt marsh, regularly flooded marsh, and tidal flat, mainly supplanting areas of swamp and smaller patches of inland marsh. Estuarine open water also starts to increase along the immediate shoreline taking over areas previously occupied by tidal flat. These observations are corroborated by Table 14 with an increase in transitional salt marsh, regularly flooded marsh, and tidal flat of

2.86% (147.7 hectares), 4.48% (231 hectares), and 2.68% (138.6 hectares), respectively. Estuarine open water exhibited an increase of 0.72% (36.9 hectares). Swamp exhibited a fairly large decrease of 10.47% (540.3 hectares), while both inland fresh marsh and tidal swamp decreased 0.4% (20.8 hectares) and 0.22% (11.5 hectares), respectively (Table 14). From 2075 to 2100, substantial change can be seen in Figure 16 with regards to increasing regularly fresh marsh, tidal flat and estuarine open water. While transitional salt marsh does not appear to be increasing in land area, it is exhibiting movement further inland (Figure 16). Table 14 supports these observations with a sharp increase in regularly fresh marsh, tidal flat and estuarine open water of 5% (257.9 hectares), 4.65% (239.8 hectares), and 3.25% (167.8 hectares), respectively. Swamp exhibited a large decrease of 11.19% (577.7 hectares), while transitional salt marsh lost 1.33% (68.5 hectares) of land even though showing migration inland.

Forecast 0.4m - Pt. Peter Rd.													
SLAMM Code	SLAMM Name	Initial Cond.		Change		2025		Change		2050			
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%		
1	Developed Dry Land	3.60	0.07	0.00	0.00	3.60	0.07	0.05	0.00	3.55	0.07		
2	Undeveloped Dry Land	41.20	0.80	0.00	0.00	41.20	0.80	0.59	0.01	40.60	0.79		
3	Swamp	3067.16	59.42	174.32	3.38	2892.83	56.04	273.93	5.31	2618.90	50.74		
5	Inland Fresh Marsh	129.13	2.50	29.70	0.58	99.42	1.93	46.10	0.89	53.33	1.03		
7	Trans. Salt Marsh	302.11	5.85	-155.41	-3.01	457.51	8.86	-138.15	-2.68	595.67	11.54		
8	Regularly Flooded Marsh	57.85	1.12	-17.55	-0.34	75.40	1.46	-141.71	-2.75	217.11	4.21		
11	Tidal Flat	0.00	0.00	-13.43	-0.26	13.43	0.26	-27.29	-0.53	40.72	0.79		
17	Estuarine Open Water	12.94	0.25	-13.41	-0.26	26.35	0.51	6.49	0.13	19.86	0.38		
19	Open Ocean	1485.79	28.78	-12.94	-0.25	1498.73	29.03	-25.66	-0.50	1524.38	29.53		
20	Irreg. Flooded Marsh	13.91	0.27	2.12	0.04	11.78	0.23	-2.55	-0.05	14.33	0.28		
23	Tidal Swamp	48.15	0.93	6.58	0.13	41.57	0.81	8.20	0.16	33.36	0.65		
SLAMM Code	SLAMM Name	2050		Change		2075		Change		2100		Total Change	
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
1	Developed Dry Land	3.55	0.07	0.05	0.00	3.50	0.07	0.72	0.01	2.78	0.05	-0.82	-0.016
2	Undeveloped Dry Land	40.60	0.79	0.70	0.01	39.90	0.77	19.42	0.38	20.48	0.40	-20.72	-0.401
3	Swamp	2618.90	50.74	540.32	10.47	2078.58	40.27	577.69	11.19	1500.89	29.08	-1566.26	-30.343
5	Inland Fresh Marsh	53.33	1.03	20.75	0.40	32.58	0.63	10.20	0.20	22.38	0.43	-106.75	-2.068
7	Trans. Salt Marsh	595.67	11.54	-147.67	-2.86	743.34	14.40	68.53	1.33	674.81	13.07	372.70	7.220
8	Regularly Flooded Marsh	217.11	4.21	-231.02	-4.48	448.13	8.68	-257.91	-5.00	706.04	13.68	648.20	12.558
11	Tidal Flat	40.72	0.79	-138.58	-2.68	179.30	3.47	-239.84	-4.65	419.15	8.12	419.15	8.120
17	Estuarine Open Water	19.86	0.38	-36.98	-0.72	56.84	1.10	-167.76	-3.25	224.60	4.35	211.66	4.101
19	Open Ocean	1524.38	29.53	-14.79	-0.29	1539.17	29.82	-25.17	-0.49	1564.35	30.31	78.56	1.522
20	Irreg. Flooded Marsh	14.33	0.28	-4.29	-0.08	18.62	0.36	4.32	0.08	14.30	0.28	0.40	0.008
23	Tidal Swamp	33.36	0.65	11.52	0.22	21.85	0.42	9.80	0.19	12.05	0.23	-36.10	-0.699

Table 14. SLAMM Pt. Peter Rd. sub-site forecast results showing hectares and percentage of class change with a SLR rate of 0.4m by 2100.

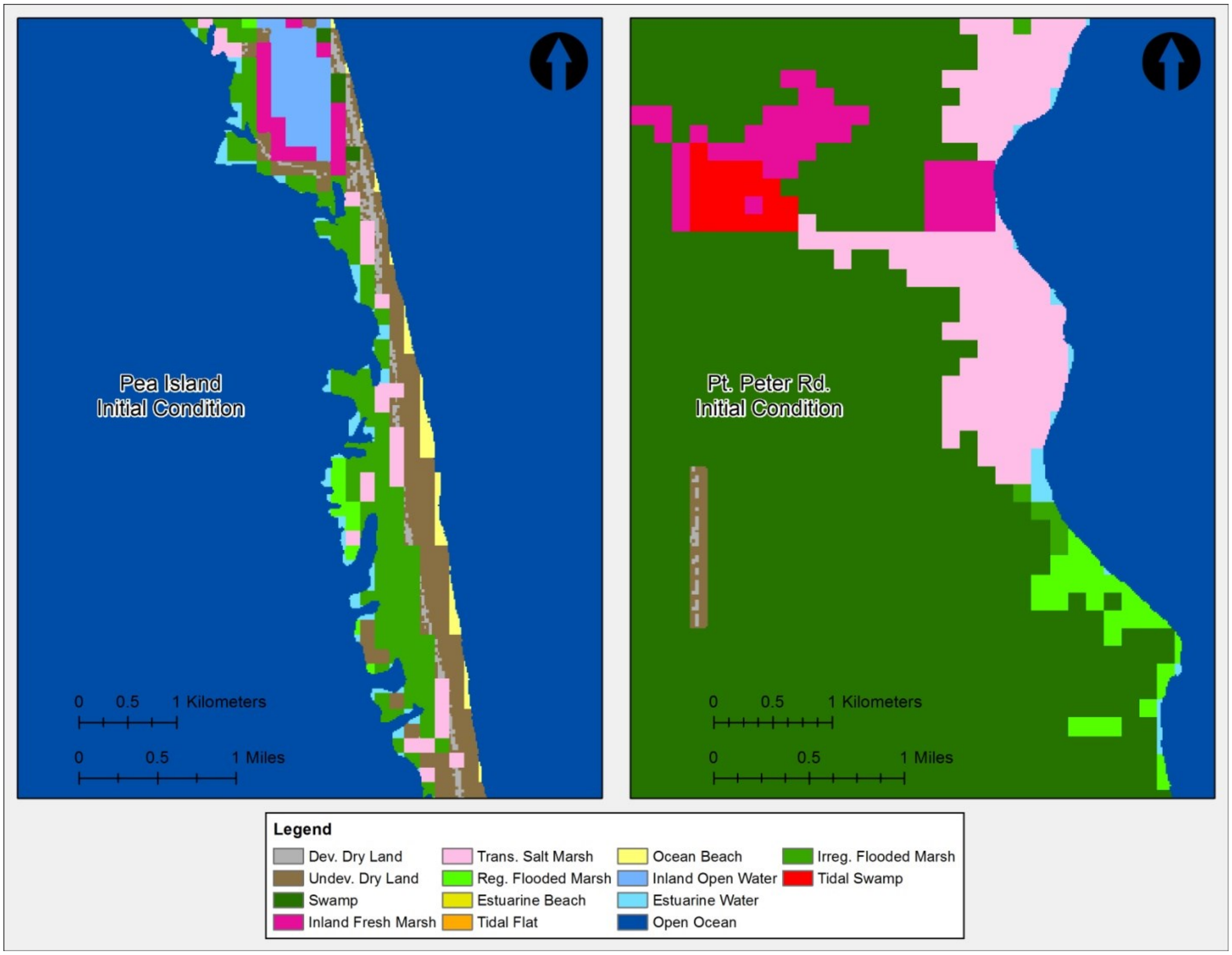

Figure 15. SLAMM Pt. Peter Rd. sub-site forecast map (on right) showing initial condition.

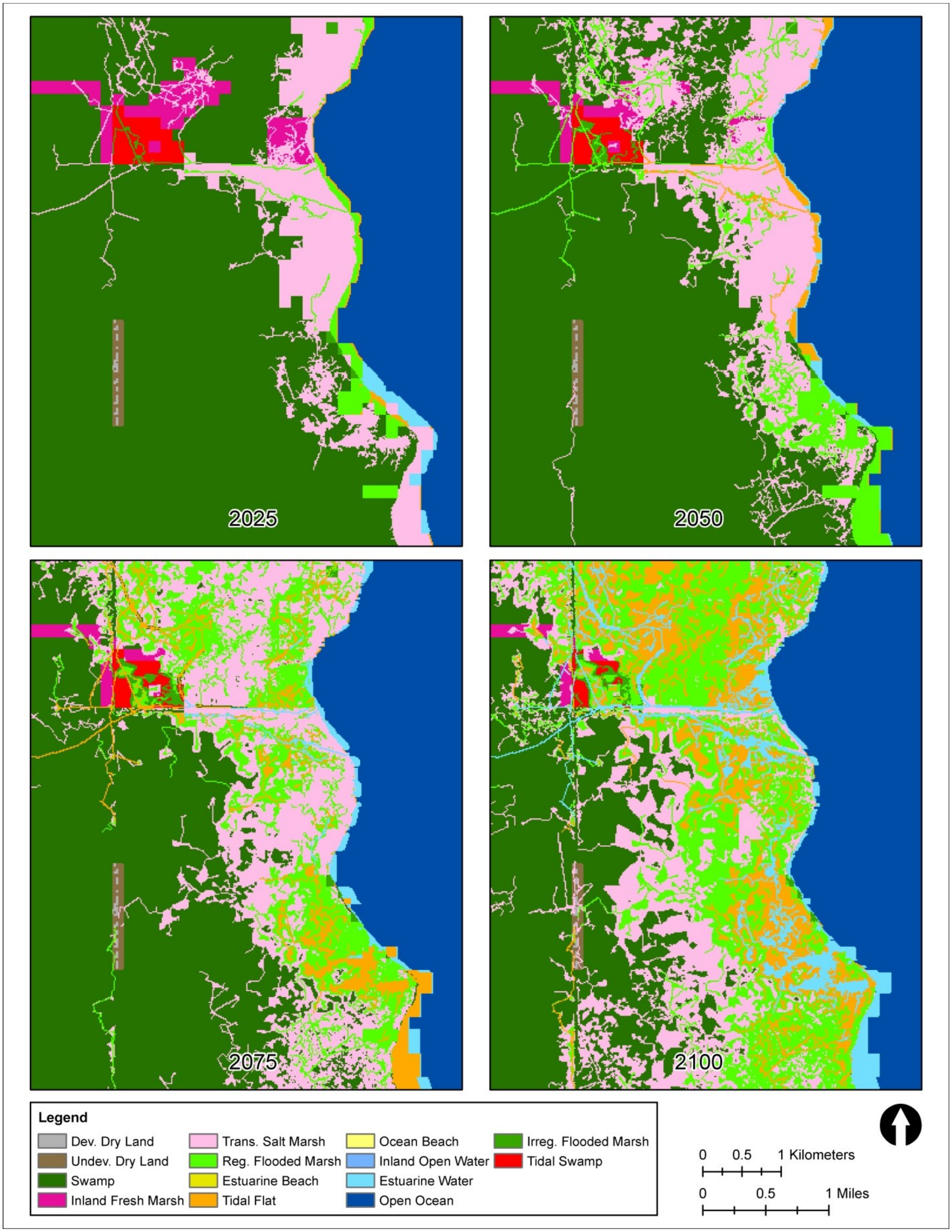

Figure 16. SLAMM Pt. Peter Rd. forecast map showing years 2025 - 2100 with a SLR rate of 0.4m by 2100.

Forecast Results - 0.7m SLR

Visually, there is a fair amount of change from 2025 to 2100 with 0.7m rise in sea-level by visually analyzing Figures 17. The most significant change with this rate of rise occurs during the 50 year period between 2050 and 2100. This trend in changes will continue to get more significant with higher rates of SLR.

In 2025, like with a 0.4m rise, the greatest amount of change occurs along the eastern portion of the Pamlico Peninsula, with noticeable change also occurring along Roanoke Island and lands to east along the backside of Nags Head, NC. From initial condition to 2025 in these areas, irregularly flooded marsh and transitional salt marsh start to be overtaken by regularly flooded marsh along the immediate shore. Irregularly flooded marsh and transitional salt marsh start to migrate inland and replace areas of swamp. This is validated by Table 15, which shows regularly flooded marsh with an increase of 2.82% (4,392 hectares) and both irregularly flooded marsh and swamp exhibiting losses of 1.32% (2,056 hectares) and 1.64% (2,551 hectares), respectively.

From 2025 to 2050 with a 0.7m rise in sea-level, by visually analyzing Figure 17, regularly flooded marsh continues to increase throughout the nearshore zone. Both transitional salt marsh and tidal flats start to increase, with transitional salt marsh migrating further inland and tidal flats taking over areas previously occupied by regularly flooded marsh. Swamp and irregularly flooded marsh continue to decrease being taken over by transitional salt marsh. Table 15 confirms these observations with regularly flooded marsh, transitional salt marsh and tidal flat increasing 1.14% (1,718 hectares), 1.38% (2,149 hectares), and 1.3% (2,032 hectares) respectively. Both swamp and irregularly suffered losses of 3.1% (4,825 hectares) and 0.49% (757 hectares,) respectively.

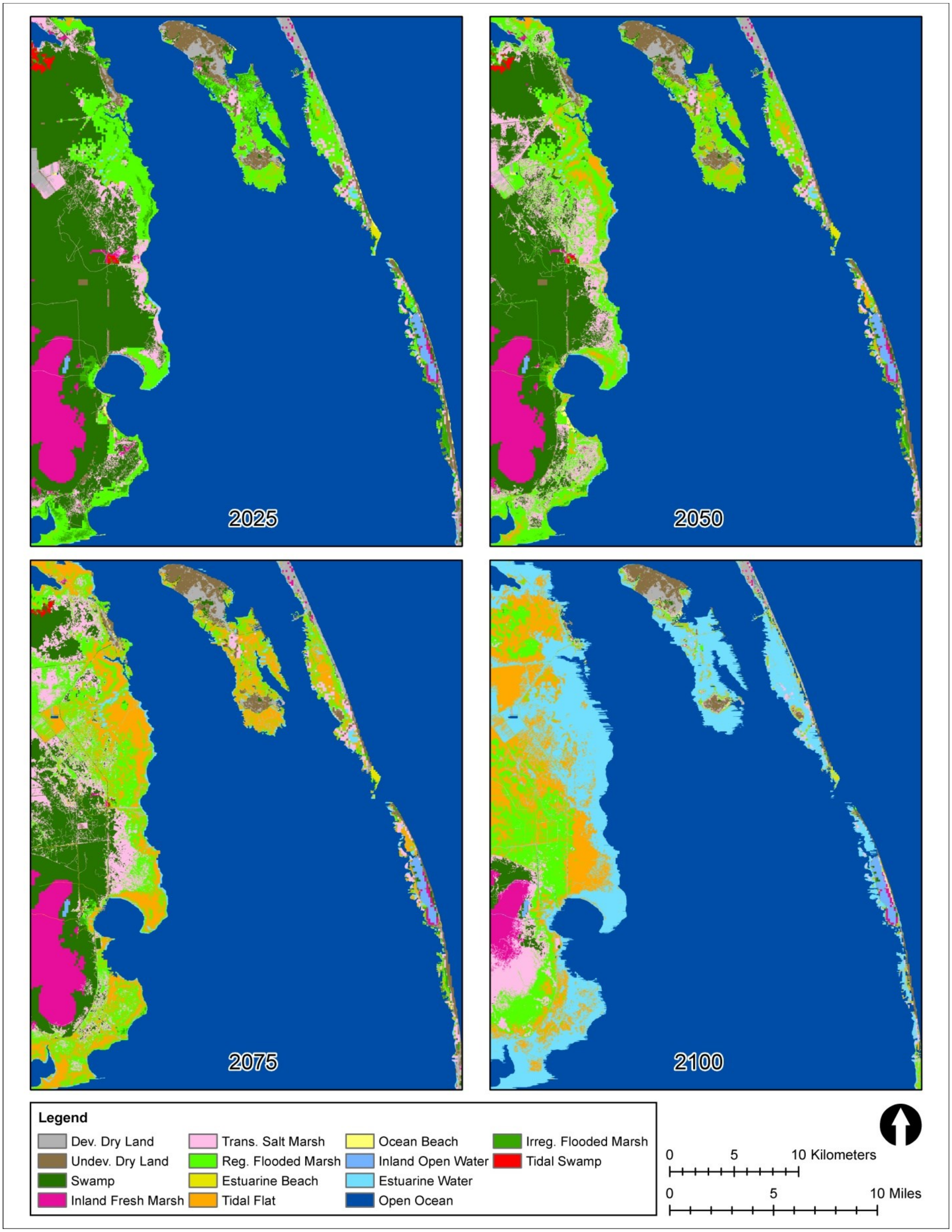

Figure 17. SLAMM global forecast map showing years 2025 - 2100 with a SLR rate of 0.7m by 2100.

Forecast 0.7m - Global													
SLAMM Code	SLAMM Name	Initial Cond.		Change		2025		Change		2050			
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%		
1	Developed Dry Land	2051.06	1.32	244.09	0.16	1806.96	1.16	320.71	0.21	1486.25	0.95		
2	Undeveloped Dry Land	2893.05	1.86	327.38	0.21	2565.67	1.65	291.52	0.19	2274.15	1.46		
3	Swamp	21156.48	13.58	2551.02	1.64	18605.46	11.94	4825.24	3.10	13780.22	8.85		
5	Inland Fresh Marsh	3816.52	2.45	95.43	0.06	3721.08	2.39	106.01	0.07	3615.07	2.32		
7	Trans. Salt Marsh	4103.37	2.63	-133.98	-0.09	4237.35	2.72	-2148.59	-1.38	6385.94	4.10		
8	Regularly Flooded Marsh	3146.04	2.02	-4392.32	-2.82	7538.36	4.84	-1781.28	-1.14	9319.64	5.98		
10	Estuarine Beach	94.68	0.06	10.28	0.01	84.40	0.05	2.87	0.00	81.53	0.05		
11	Tidal Flat	0.00	0.00	-520.11	-0.33	520.11	0.33	-2032.33	-1.30	2552.44	1.64		
12	Ocean Beach	90.59	0.06	-67.38	-0.04	157.97	0.10	35.19	0.02	122.78	0.08		
15	Inland Open Water	358.92	0.23	3.29	0.00	355.64	0.23	2.25	0.00	353.39	0.23		
17	Estuarine Open Water	789.50	0.51	112.90	0.07	676.60	0.43	-243.02	-0.16	919.62	0.59		
19	Open Ocean	113416.85	72.81	-318.33	-0.20	113735.18	73.02	-219.35	-0.14	113954.53	73.16		
20	Irreg. Flooded Marsh	3613.86	2.32	2056.37	1.32	1557.49	1.00	757.08	0.49	800.41	0.51		
23	Tidal Swamp	237.22	0.15	31.35	0.02	205.87	0.13	83.70	0.05	122.17	0.08		
SLAMM Code	SLAMM Name	2050		Change		2075		Change		2100		Total Change	
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
1	Developed Dry Land	1486.25	0.95	127.24	0.08	1359.01	0.87	140.95	0.09	1218.06	0.78	-832.99	-0.535
2	Undeveloped Dry Land	2274.15	1.46	296.73	0.19	1977.42	1.27	273.93	0.18	1703.49	1.09	-1189.56	-0.764
3	Swamp	13780.22	8.85	5477.67	3.52	8302.55	5.33	4120.01	2.64	4182.55	2.69	-16973.93	-10.897
5	Inland Fresh Marsh	3615.07	2.32	92.04	0.06	3523.03	2.26	189.33	0.12	3333.70	2.14	-482.82	-0.310
7	Trans. Salt Marsh	6385.94	4.10	-206.93	-0.13	6592.86	4.23	1369.93	0.88	5222.93	3.35	1119.56	0.719
8	Regularly Flooded Marsh	9319.64	5.98	695.37	0.45	8624.26	5.54	1850.37	1.19	6773.90	4.35	3627.86	2.329
10	Estuarine Beach	81.53	0.05	-4.81	0.00	86.34	0.06	-6.41	0.00	92.75	0.06	-1.93	-0.001
11	Tidal Flat	2552.44	1.64	-6160.74	-3.96	8713.18	5.59	-5220.93	-3.35	13934.11	8.95	13934.11	8.945
12	Ocean Beach	122.78	0.08	21.05	0.01	101.72	0.07	-11.42	-0.01	113.14	0.07	22.56	0.014
15	Inland Open Water	353.39	0.23	1.42	0.00	351.97	0.23	1.42	0.00	350.55	0.23	-8.37	-0.005
17	Estuarine Open Water	919.62	0.59	-443.68	-0.28	1363.30	0.88	-2505.16	-1.61	3868.45	2.48	3078.95	1.977
19	Open Ocean	113954.53	73.16	-395.48	-0.25	114350.01	73.41	-422.77	-0.27	114772.77	73.68	1355.92	0.870
20	Irreg. Flooded Marsh	800.41	0.51	450.59	0.29	349.82	0.22	172.59	0.11	177.23	0.11	-3436.63	-2.206
23	Tidal Swamp	122.17	0.08	49.51	0.03	72.66	0.05	48.17	0.03	24.49	0.02	-212.73	-0.137

Table 15. SLAMM global forecast results showing hectares and percentage of class change with a SLR rate of 0.7m by 2100.

From 2050 to 2075 with a 0.7m rise in sea-level, a visual analysis of Figure 17 shows a substantial increase in the amount of tidal flat and both regularly flooded marsh and transitional salt marsh have started to migrate further inland. Larger areas of swamp and irregularly flooded have declined due to being taken over by other land types. Much of the major change over this 25 year period occurs over large areas of the eastern portion of the Pamlico Peninsula, with noticeable change also occurring along Roanoke Island and lands to east along the backside of Nags Head, NC. Estuarine open water starts to increase more and infiltrate inland, as well as areas of transitional salt marsh. These observations from Figure 17 are corroborated by Table 15.

Tidal flat increased by 3.96% (6,161 hectares) and swamp and regularly flooded marsh decreased by 3.52% (5,478 hectares) and 0.45% (695 hectares).

From 2075 to 2100 with a 0.7m rise in sea-level, Figure 17 shows a large increase in estuarine open water and tidal flat over vast areas, replacing areas of regularly flooded marsh and transitional salt marsh. Large areas of swamp have been lost, as well as moderate-sized areas of undeveloped dry land and inland fresh marsh. Most of the major changes occur over a majority of the study area, specifically along the eastern portion of the Pamlico Peninsula, Roanoke Island, the backside of Nags Head, NC, and over the Pea Island portion of the Outer Banks. These changes are corroborated by Table 15 which shows an increase of both estuarine open water and tidal flat of 1.61% (2,505 hectares) and 3.35% (5,221 hectares), respectively

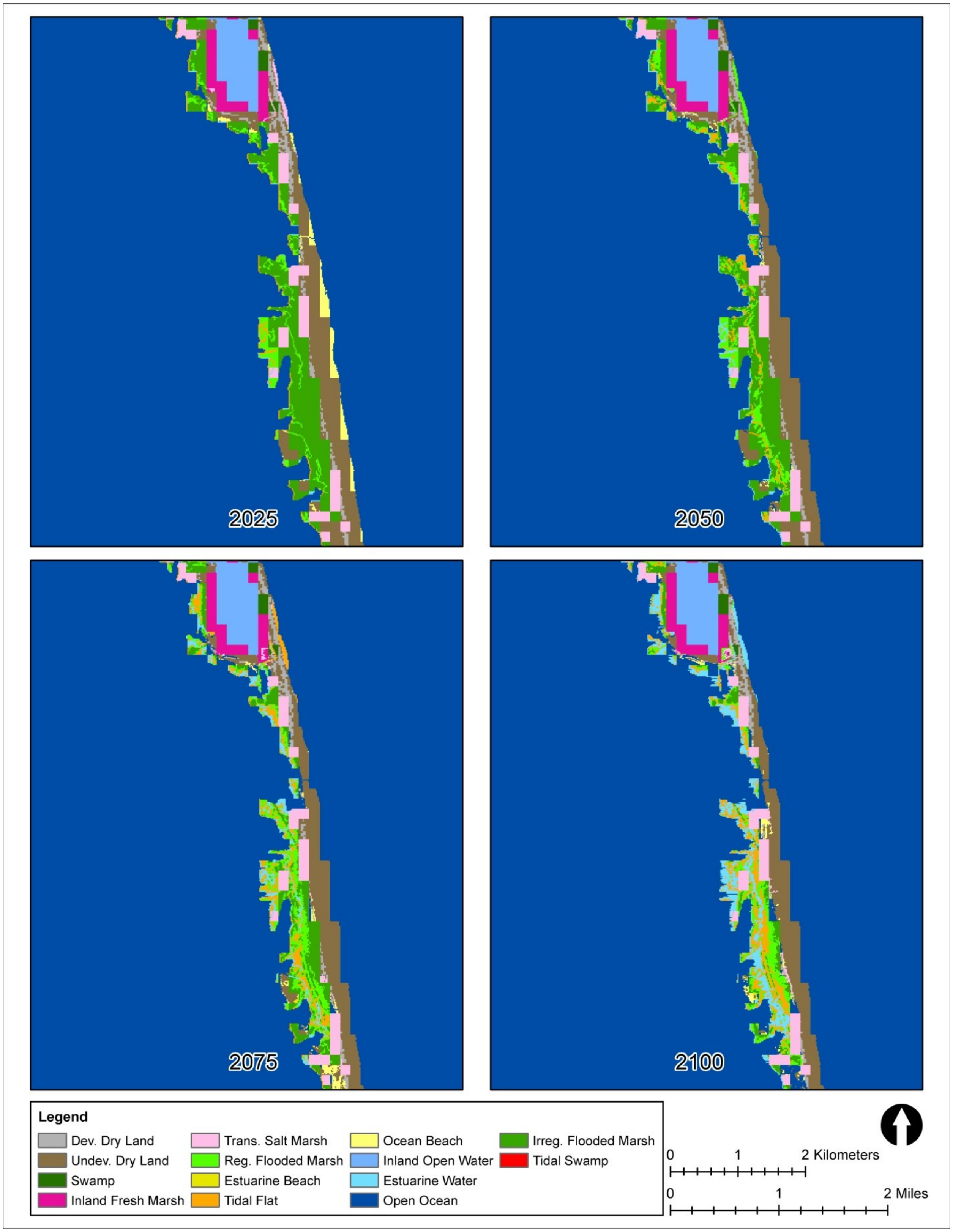

Figure 18. SLAMM Pea Island sub-site forecast map showing years 2025 - 2100 with a SLR rate of 0.7m by 2100.

A visual analysis of the Pea Island sub-site over the four time periods (2025, 2050, 2075 and 2100) with a 0.7m rise in sea-level corroborates the majority of trends found in the global forecast. From current condition to 2025, not much change occurs although Figure 18 shows an increase of regularly flooded marsh supplanting previous areas of irregularly flooded marsh. There is also the occurrence of tidal flats along the immediate back-barrier shoreline. Table 16 shows an increase of regularly flooded marsh and tidal flat of 0.59% (21.3 hectares) and 0.46% (16.6 hectares), respectively. Open ocean exhibited an increase of 1.1% (39.7 hectares) replacing areas of estuarine open water. From 2025 to 2050, the majority of changes can be seen in the immediate back-barrier nearshore zone with an increase in tidal flat and horizontal movement of both tidal flat and regularly flooded marsh (Figure 18). An increase in both open ocean and estuarine open water can also be seen from areas of land lost to water. These observations are supported by Table 16 which shows an increase in tidal flat, regularly flooded marsh, open ocean and estuarine open water of 0.39% (14.2 hectares), 0.54% (19.4 hectares), 0.57% (20.7 hectares), and 0.44% (16 hectares), respectively. The most amount of land loss was exhibited by irregularly flooded marsh of 1.23% (44.3 hectares). From 2050 to 2075, the back-barrier side of Pea Island exhibits the most change with areas of irregularly flooded marsh being replaced by regularly flooded marsh, tidal flat, estuarine open water, and open ocean (Figure 18). Table 16 confirms these observations with an increase of regularly flooded marsh, tidal flat, estuarine open water, and open ocean of 0.19% (6.7 hectares), 0.74% (26.8 hectares), 0.54% (19.7 hectares), and 0.83% (30 hectares). Irregularly flooded marsh decreased in land area by 1.86% (67.3 hectares). From 2075 to 2100, small change continues to occur on the back-barrier side of Pea Island. Estuarine open water and open ocean exhibit moderate increases, while irregularly flooded marsh and undeveloped dry land decreased in area (Figure 18). This is validated by Table 16 which shows a small increase in tidal flat and moderate increases of estuarine open water and open ocean of 0.14% (5.2 hectares), 1.39% (50.4 hectares), and 1.07% (38.5 hectares), respectively. Irregularly flooded marsh decreased by 1.28% (46.1 hectares) and undeveloped dry land decreased by 0.58% (21.1 hectares).

Forecast 0.7m - Pea Island													
SLAMM Code	SLAMM Name	Initial Cond.		Change		2025		Change		2050			
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%		
1	Developed Dry Land	33.08	0.91	0.86	0.02	32.21	0.89	0.83	0.02	31.38	0.87		
2	Undeveloped Dry Land	199.46	5.52	10.19	0.28	189.27	5.24	5.69	0.16	183.58	5.08		
3	Swamp	10.78	0.30	0.31	0.01	10.46	0.29	0.11	0.00	10.36	0.29		
5	Inland Fresh Marsh	43.34	1.20	0.58	0.02	42.76	1.18	0.35	0.01	42.41	1.17		
7	Trans. Salt Marsh	62.39	1.73	-5.14	-0.14	67.53	1.87	5.28	0.15	62.25	1.72		
8	Regularly Flooded Marsh	22.07	0.61	-21.25	-0.59	43.32	1.20	-19.39	-0.54	62.72	1.73		
10	Estuarine Beach	0.00	0.00	-0.02	0.00	0.02	0.00	0.02	0.00	0.00	0.00		
11	Tidal Flat	0.00	0.00	-16.62	-0.46	16.62	0.46	-14.17	-0.39	30.79	0.85		
12	Ocean Beach	23.87	0.66	3.59	0.10	20.28	0.56	13.73	0.38	6.55	0.18		
15	Inland Open Water	82.46	2.28	0.32	0.01	82.15	2.27	0.00	0.00	82.15	2.27		
17	Estuarine Open Water	33.12	0.92	29.12	0.81	4.00	0.11	-16.03	-0.44	20.03	0.55		
19	Open Ocean	2877.32	79.59	-39.70	-1.10	2917.03	80.68	-20.74	-0.57	2937.76	81.26		
20	Irreg. Flooded Marsh	227.50	6.29	37.76	1.04	189.74	5.25	44.32	1.23	145.42	4.02		
SLAMM Code	SLAMM Name	2050		Change		2075		Change		2100		Total Change	
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
1	Developed Dry Land	31.38	0.87	4.09	0.11	27.28	0.75	5.90	0.16	21.38	0.59	-11.69	-0.323
2	Undeveloped Dry Land	183.58	5.08	19.45	0.54	164.13	4.54	21.07	0.58	143.07	3.96	-56.40	-1.560
3	Swamp	10.36	0.29	0.31	0.01	10.05	0.28	0.40	0.01	9.65	0.27	-1.13	-0.031
5	Inland Fresh Marsh	42.41	1.17	1.27	0.04	41.14	1.14	1.10	0.03	40.04	1.11	-3.30	-0.091
7	Trans. Salt Marsh	62.25	1.72	-2.50	-0.07	64.75	1.79	-1.36	-0.04	66.11	1.83	3.71	0.103
8	Regularly Flooded Marsh	62.72	1.73	-6.74	-0.19	69.45	1.92	17.51	0.48	51.94	1.44	29.87	0.826
10	Estuarine Beach	0.00	0.00	-0.30	-0.01	0.30	0.01	-0.15	0.00	0.45	0.01	0.45	0.013
11	Tidal Flat	30.79	0.85	-26.78	-0.74	57.57	1.59	-5.24	-0.14	62.81	1.74	62.81	1.737
12	Ocean Beach	6.55	0.18	-6.40	-0.18	12.95	0.36	3.58	0.10	9.37	0.26	-14.51	-0.401
15	Inland Open Water	82.15	2.27	0.00	0.00	82.15	2.27	0.00	0.00	82.15	2.27	-0.32	-0.009
17	Estuarine Open Water	20.03	0.55	-19.65	-0.54	39.67	1.10	-50.40	-1.39	90.07	2.49	56.95	1.575
19	Open Ocean	2937.76	81.26	-30.03	-0.83	2967.79	82.09	-38.54	-1.07	3006.34	83.15	129.01	3.568
20	Irreg. Flooded Marsh	145.42	4.02	67.27	1.86	78.15	2.16	46.12	1.28	32.03	0.89	-195.47	-5.407

Table 16. SLAMM Pea Island sub-site forecast results showing hectares and percentage of class change with a SLR rate of 0.7m by 2100.

A visual analysis of the Pt. Peter Rd. sub-site over the four time periods (2025, 2050, 2075, and 2100) with a 0.7m rise in sea-level corroborates the majority of trends found in the global forecast. From initial condition to 2025, moderate amounts of change are seen in the immediate nearshore zone with areas of swamp and inland fresh marsh being taken over by inland migrating transitional salt marsh and regularly flooded marsh. Tidal flat also starts to appear along the immediate shoreline. These observations are supported by Table 17 with an increase in transitional salt marsh, regularly flooded marsh, and tidal flat of 5.18% (267.4 hectares), 0.57% (29.5 hectares), and 0.26% (13.6 hectares), respectively. Both swamp and inland fresh marsh exhibited decreases of 5.36% (276.8 hectares) and 0.99% (51.2 hectares), respectively. From 2025 to 2050, transitional salt marsh and regularly flooded marsh continue to increase in areal extent and migration further inland (Figure 19). An increase in tidal flat can also be seen in Figure 19. This movement results in further loss of swamp, inland fresh marsh and tidal swamp. Table 17 supports these observations with an increase of transitional salt marsh, regularly flooded marsh, and tidal flat of 5.3% (273.7 hectares), 7.1% (366.4 hectares), and 0.83% (43 hectares), respectively. Open ocean (open water) also experienced an increase of 0.5% (25.7 hectares). Loss in land area of swamp, inland fresh marsh and tidal swamp is shown in Table 17 of 12.51 (645.9 hectares), 0.86% (44.4 hectares), and 0.31% (16.12 hectares), respectively. From 2050 to 2075, Figure 19 shows an increase in transitional salt marsh, regularly flooded marsh, and tidal flat, mainly supplanting areas of swamp and smaller patches of inland marsh. Estuarine open water also starts to increase along the immediate shoreline taking over areas previously occupied by tidal flat. These observations are corroborated by Table 17 with an increase in transitional salt marsh, regularly flooded marsh, and tidal flat of 2.33% (120.3 hectares), 7.59% (391.8 hectares), and 7.31% (377.6 hectares), respectively. Estuarine open water exhibited an increase of 1.13% (58.2 hectares). Swamp exhibited a fairly large decrease of 17.52% (904.5 hectares). From 2075 to 2100, substantial change can be seen in Figure 19 with regards to increasing regularly fresh marsh, tidal flat and estuarine open water. Transitional salt marsh experiences a decrease in land area but exhibits movement further inland,

and at this stage swamp is nearly non-existent (Figure 19). Table 17 supports these observations with an increase in regularly fresh marsh, tidal flat and estuarine open water of 2.47% (127.4 hectares), 7.26% (374.9 hectares), and 8.67% (447.6 hectares), respectively. Swamp exhibited a large decrease of 12.76% (658.5 hectares), while transitional salt marsh lost 5.3% (273.5 hectares) of land even though showing migration inland.

Forecast 0.7m - Pt. Peter Rd.													
SLAMM Code	**SLAMM Name**	**Initial Cond.**		**Change**		**2025**		**Change**		**2050**			
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%		
1	Developed Dry Land	3.60	0.07	0.00	0.00	3.60	0.07	0.09	0.00	3.51	0.07		
2	Undeveloped Dry Land	41.20	0.80	0.00	0.00	41.20	0.80	1.06	0.02	40.14	0.78		
3	Swamp	3067.16	59.42	276.76	5.36	2790.39	54.06	645.94	12.51	2144.45	41.54		
5	Inland Fresh Marsh	129.13	2.50	51.19	0.99	77.94	1.51	44.36	0.86	33.58	0.65		
7	Trans. Salt Marsh	302.11	5.85	-267.42	-5.18	569.53	11.03	-273.67	-5.30	843.20	16.34		
8	Regularly Flooded Marsh	57.85	1.12	-29.51	-0.57	87.36	1.69	-366.43	-7.10	453.78	8.79		
11	Tidal Flat	0.00	0.00	-13.66	-0.26	13.66	0.26	-43.02	-0.83	56.68	1.10		
17	Estuarine Open Water	12.94	0.25	-13.41	-0.26	26.35	0.51	6.18	0.12	20.17	0.39		
19	Open Ocean	1485.79	28.78	-12.94	-0.25	1498.73	29.03	-25.66	-0.50	1524.39	29.53		
20	Irreg. Flooded Marsh	13.91	0.27	-1.38	-0.03	15.28	0.30	-4.97	-0.10	20.25	0.39		
23	Tidal Swamp	48.15	0.93	10.36	0.20	37.79	0.73	16.12	0.31	21.66	0.42		
SLAMM Code	**SLAMM Name**	**2050**		**Change**		**2075**		**Change**		**2100**		**Total Change**	
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
1	Developed Dry Land	3.51	0.07	0.96	0.02	2.55	0.05	0.90	0.02	1.65	0.03	-1.95	-0.038
2	Undeveloped Dry Land	40.14	0.78	23.32	0.45	16.82	0.33	12.01	0.23	4.81	0.09	-36.39	-0.705
3	Swamp	2144.45	41.54	904.49	17.52	1239.96	24.02	658.45	12.76	581.51	11.27	-2485.65	-48.155
5	Inland Fresh Marsh	33.58	0.65	14.79	0.29	18.78	0.36	14.54	0.28	4.25	0.08	-124.88	-2.419
7	Trans. Salt Marsh	843.20	16.34	-120.26	-2.33	963.46	18.67	273.48	5.30	689.97	13.37	387.87	7.514
8	Regularly Flooded Marsh	453.78	8.79	-391.76	-7.59	845.54	16.38	-127.38	-2.47	972.92	18.85	915.08	17.728
11	Tidal Flat	56.68	1.10	-377.56	-7.31	434.23	8.41	-374.87	-7.26	809.11	15.67	809.11	15.675
17	Estuarine Open Water	20.17	0.39	-58.15	-1.13	78.33	1.52	-447.61	-8.67	525.93	10.19	513.00	9.938
19	Open Ocean	1524.39	29.53	-14.81	-0.29	1539.20	29.82	-25.28	-0.49	1564.48	30.31	78.70	1.525
20	Irreg. Flooded Marsh	20.25	0.39	4.17	0.08	16.08	0.31	10.50	0.20	5.58	0.11	-8.33	-0.161
23	Tidal Swamp	21.66	0.42	14.80	0.29	6.87	0.13	5.26	0.10	1.61	0.03	-46.54	-0.902

Table 17. SLAMM Pt. Peter Rd. sub-site forecast results showing hectares and percentage of class change with a SLR rate of 0.7m by 2100.

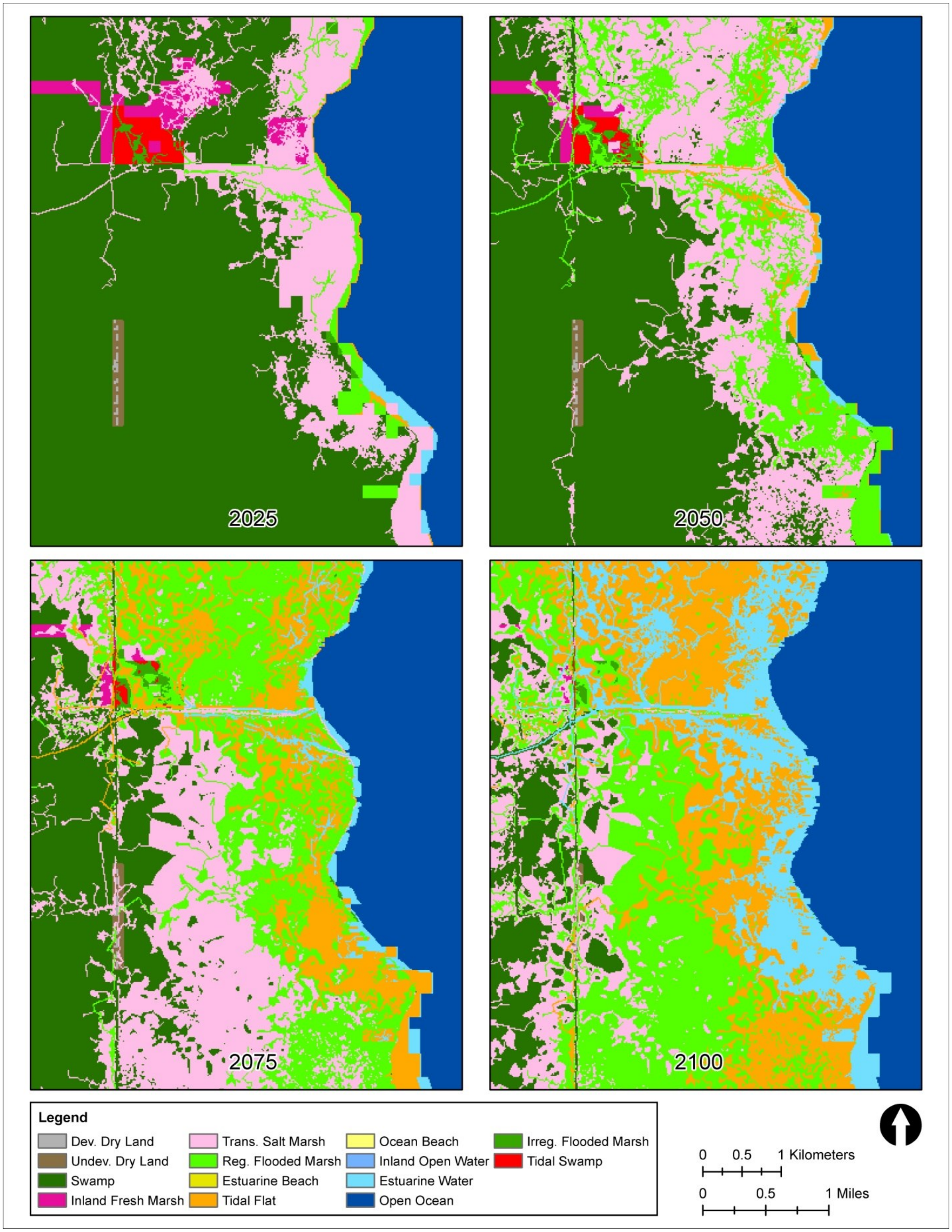

Figure 19. SLAMM Pt. Peter Rd. forecast map showing years 2025 - 2100 with a SLR rate of 0.7m by 2100.

Forecast Results - 1m SLR

From initial condition to 2025 with a 1m rise in sea-level, the majority of change occurs in the nearshore zone along the eastern portion of the Pamlico Peninsula, with noticeable change also occurring along Roanoke Island and lands to east along the backside of Nags Head, NC. A visual analysis of Figure 20 shows an increase in regularly flooded marsh and transitional salt marsh in both area and movement inland. A decrease in swamp and irregularly flooded marsh is seen in Figure 20, being overtaken by regularly flooded marsh and transitional salt marsh. Table 18 shows an increase in both regularly flooded marsh and transitional salt marsh of 3% (4,675 hectares) and 0.97% (1,512 hectares), respectively. Swamp had the largest decrease of 2.48% (3,869 hectares) and irregularly flooded marsh had a moderate decrease of 1.54% (2,405 hectares).

From 2025 to 2050 with a 1m rise in sea-level, the majority of change continues to occur along the eastern portion of the Pamlico Peninsula, with noticeable change also occurring along Roanoke Island and lands to east along the backside of Nags Head, NC. The Pea Island portion of the Outer Banks is starting to show some change on the sound side of the barrier island. A visual analysis of Figure 20 shows a substantial increase in tidal flat in the nearshore zone and an increase in transitional salt marsh especially in migration inland. Swamp experienced a large decrease in area being replaced by transitional salt marsh and regularly flooded marsh. These observations are corroborated by Table 18 which quantitatively shows an increase in tidal flat and transitional salt marsh of 2.62% (4,087 hectares) and 1.55% (2,418 hectares), respectively. Regularly flooded marsh and estuarine open water increased moderately as well with gains of 0.7% (1,094 hectares) and 0.24% (379 hectares), respectively. Swamp experienced a large decrease in area of 4.22% (6,574 hectares). Moderate declines in area were experienced by irregularly flooded marsh and undeveloped dry land of 0.46% (717 hectares) and 0.24% (367 hectares).

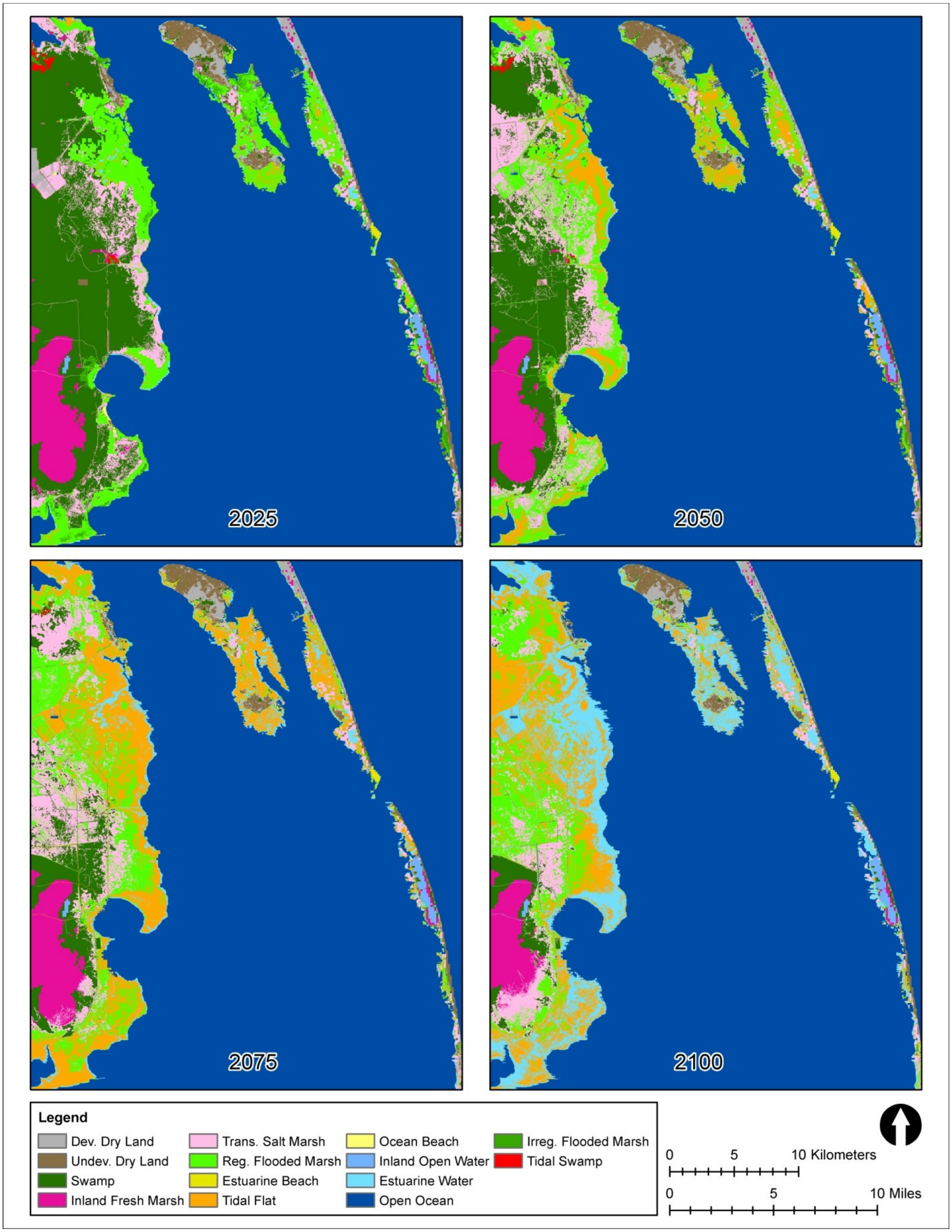

Figure 20. SLAMM global forecast map showing years 2025 - 2100 with a SLR rate of 1m by 2100.

Forecast 1m - Global													
SLAMM Code	SLAMM Name	Initial Cond.		Change		2025		Change		2050			
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%		
1	Developed Dry Land	2051.06	1.32	296.96	0.19	1754.09	1.13	343.38	0.22	1410.71	0.91		
2	Undeveloped Dry Land	2893.05	1.86	419.60	0.27	2473.45	1.59	366.45	0.24	2107.00	1.35		
3	Swamp	21156.48	13.58	3868.71	2.48	17287.77	11.10	6574.22	4.22	10713.55	6.88		
5	Inland Fresh Marsh	3816.52	2.45	133.45	0.09	3683.07	2.36	125.03	0.08	3558.04	2.28		
7	Trans. Salt Marsh	4103.37	2.63	-1512.32	-0.97	5615.69	3.61	-2417.66	-1.55	8033.35	5.16		
8	Regularly Flooded Marsh	3146.04	2.02	-4674.76	-3.00	7820.80	5.02	-1093.79	-0.70	8914.59	5.72		
10	Estuarine Beach	94.68	0.06	9.15	0.01	85.53	0.05	-2.05	0.00	87.58	0.06		
11	Tidal Flat	0.00	0.00	-695.46	-0.45	695.46	0.45	-4087.16	-2.62	4782.62	3.07		
12	Ocean Beach	90.59	0.06	-54.69	-0.04	145.27	0.09	41.16	0.03	104.11	0.07		
15	Inland Open Water	358.92	0.23	3.51	0.00	355.41	0.23	2.68	0.00	352.73	0.23		
17	Estuarine Open Water	789.50	0.51	95.29	0.06	694.22	0.45	-378.54	-0.24	1072.76	0.69		
19	Open Ocean	113416.85	72.81	-356.73	-0.23	113773.58	73.04	-274.94	-0.18	114048.52	73.22		
20	Irreg. Flooded Marsh	3613.86	2.32	2404.86	1.54	1209.00	0.78	717.37	0.46	491.63	0.32		
23	Tidal Swamp	237.22	0.15	62.43	0.04	174.79	0.11	83.84	0.05	90.95	0.06		

SLAMM Code	SLAMM Name	2050		Change		2075		Change		2100		Total Change	
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
1	Developed Dry Land	1410.71	0.91	168.29	0.11	1242.42	0.80	226.05	0.15	1016.37	0.65	-1034.69	-0.664
2	Undeveloped Dry Land	2107.00	1.35	370.22	0.24	1736.78	1.11	290.02	0.19	1446.76	0.93	-1446.29	-0.928
3	Swamp	10713.55	6.88	6170.07	3.96	4543.48	2.92	2740.51	1.76	1802.97	1.16	-19353.51	-12.425
5	Inland Fresh Marsh	3558.04	2.28	186.98	0.12	3371.07	2.16	733.31	0.47	2637.76	1.69	-1178.76	-0.757
7	Trans. Salt Marsh	8033.35	5.16	694.31	0.45	7339.04	4.71	3043.66	1.95	4295.38	2.76	192.01	0.123
8	Regularly Flooded Marsh	8914.59	5.72	723.38	0.46	8191.21	5.26	1262.74	0.81	6928.47	4.45	3782.43	2.428
10	Estuarine Beach	87.58	0.06	-11.25	-0.01	98.82	0.06	-22.12	-0.01	120.95	0.08	26.27	0.017
11	Tidal Flat	4782.62	3.07	-6788.05	-4.36	11570.66	7.43	1127.36	0.72	10443.31	6.70	10443.31	6.704
12	Ocean Beach	104.11	0.07	4.37	0.00	99.74	0.06	2.30	0.00	97.44	0.06	6.85	0.004
15	Inland Open Water	352.73	0.23	2.05	0.00	350.69	0.23	2.61	0.00	348.08	0.22	-10.85	-0.007
17	Estuarine Open Water	1072.76	0.69	-1394.24	-0.90	2467.00	1.58	-8752.88	-5.62	11219.88	7.20	10430.38	6.696
19	Open Ocean	114048.52	73.22	-495.34	-0.32	114543.86	73.53	-789.59	-0.51	115333.45	74.04	1916.60	1.230
20	Irreg. Flooded Marsh	491.63	0.32	303.82	0.20	187.80	0.12	113.15	0.07	74.66	0.05	-3539.20	-2.272
23	Tidal Swamp	90.95	0.06	65.38	0.04	25.56	0.02	22.90	0.01	2.67	0.00	-234.55	-0.151

Table 18. SLAMM global forecast results showing hectares and percentage of class change with a SLR rate of 1m by 2100.

From 2050 to 2075 with a 1m rise in sea-level, tidal flat and regularly flooded marsh continue to increase in both the nearshore zone and in expansion inland. Figure 20 displays this change occurs throughout the entire study area along the eastern portion of the Pamlico Peninsula, with noticeable change also occurring along Roanoke Island, the backside of Nags Head, NC, and the Pea Island portion of the Outer Banks. Estuarine open water is starting migrate further inland and transitional salt marsh is decreasing as a result of being taken over by other land classes. These observations are supported by Table 18 which shows a large increase in tidal flat and a moderate increase in open estuarine water of 4.36% (6,788 hectares) and 0.9%

(1,394 hectares), respectively. Regularly flooded marsh decreased by 0.46% (723 hectares), while open ocean increased 0.32% (495 hectares). The largest decrease was exhibited by swamp with a decrease of 3.96% (6,170 hectares) and transitional salt marsh also experienced a decrease in area of 0.45% (694 hectares).

From 2075 to 2100 with a 1m rise in sea-level there are major changes that occur within both the nearshore and inland zones throughout the entire study area. A visual analysis of Figure 20 displays a large increase in estuarine open water and vast migration of tidal flat, regularly flooded marsh, and transitional salt marsh inland. Swamp continues to decrease due to being replaced by other land classes and inland fresh marsh starts to experience moderate decreases in land area due to the inland migration of other land classes as well. These visual changes are confirmed by Table 18 which shows a large increase in estuarine open water of 5.62% (8,753 hectares). Table 18 also shows that regularly flooded marsh, transitional salt marsh, and tidal flat experienced declines of 0.81% (1,263 hectares), 1.95% (3,044 hectares), and 0.72% (1,127 hectares,) respectively. Although these land classes exhibited decline, they migration inland increased substantially. Swamp experienced losses of 1.76% (2,741 hectares) due to being supplanted by other inland migrated land classes.

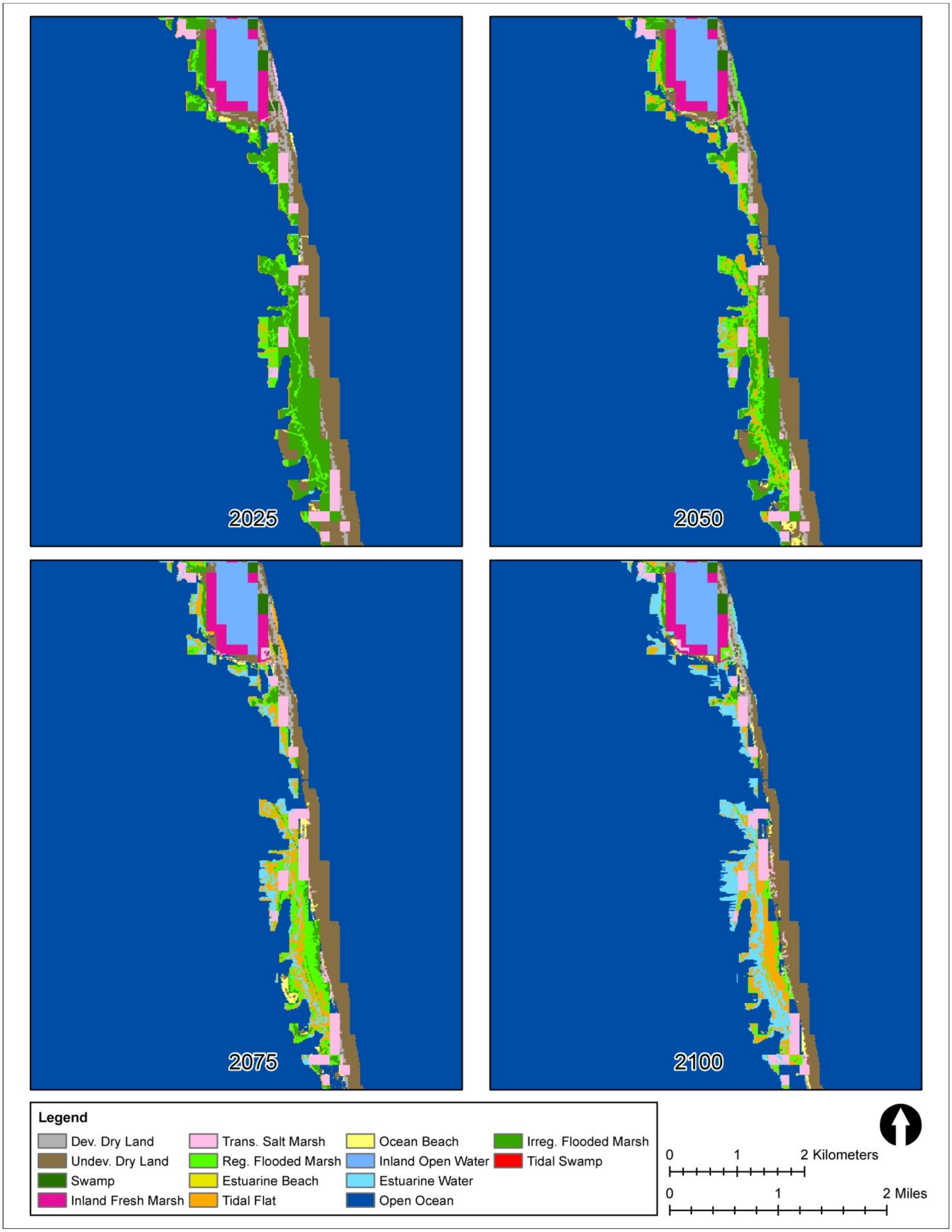

Figure 21. SLAMM Pea Island sub-site forecast map showing years 2025 - 2100 with a SLR rate of 1m by 2100.

A visual analysis of the Pea Island sub-site over the four time periods (2025, 2050, 2075, and 2100) with a 1m rise in sea-level corroborates the majority of trends found in the global forecast. From current condition to 2025, not much change occurs although Figure 21 shows an increase of regularly flooded marsh supplanting previous areas of irregularly flooded marsh. There is also the occurrence of tidal flats along the immediate back-barrier shoreline. Table 19 shows an increase of regularly flooded marsh and tidal flat of 0.99% (35.7 hectares) and 0.5% (17.9 hectares), respectively. Open ocean exhibited an increase of 1.35% (48.6 hectares) replacing areas of estuarine open water. From 2025 to 2050, the majority of changes can be seen in the immediate back-barrier nearshore zone with an increase in tidal flat and horizontal movement of both tidal flat and regularly flooded marsh (Figure 21). An increase in both open ocean and estuarine open water can also be seen from areas of land lost to water. These observations are supported by Table 19 which shows an increase in tidal flat, regularly flooded marsh, open ocean and estuarine open water of 0.88% (32 hectares), 0.76% (27.5 hectares), 0.55% (19.8 hectares), and 0.49% (17.7 hectares), respectively. The most amount of land loss was exhibited by irregularly flooded marsh of 1.97% (71.3 hectares). From 2050 to 2075, the back-barrier side of Pea Island exhibits the most change with areas of irregularly flooded marsh being replaced by transitional salt marsh, tidal flat, estuarine open water, and open ocean (Figure 21). Table 19 confirms these observations with an increase of transitional salt marsh, tidal flat, estuarine open water, and open ocean of 0.12% (4.2 hectares), 0.84% (30.4 hectares), 1.12% (40.4 hectares), and 1.2% (43.3 hectares). Irregularly flooded marsh decreased in land area by 2.02% (73 hectares). From 2075 to 2100, moderate change continues to occur on the back-barrier side of Pea Island. Estuarine open water and open ocean exhibit moderate increases, while irregularly flooded marsh and undeveloped dry land decreased in area (Figure 21). This is validated by Table 19 which shows a small increase in tidal flat and moderate increases of estuarine open water and open ocean of 0.26% (9.34 hectares), 1.84% (66.5 hectares), and 1.4% (50.8 hectares), respectively. Irregularly flooded marsh decreased by 0.59% (21.5 hectares) and undeveloped dry land decreased by 0.71% (25.7 hectares).

Forecast 1m - Pea Island													
SLAMM Code	SLAMM Name	Initial Cond.		Change		2025		Change		2050			
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%		
1	Developed Dry Land	33.08	0.91	0.96	0.03	32.12	0.89	2.40	0.07	29.72	0.82		
2	Undeveloped Dry Land	199.46	5.52	11.63	0.32	187.83	5.20	15.44	0.43	172.39	4.77		
3	Swamp	10.78	0.30	0.33	0.01	10.45	0.29	0.29	0.01	10.16	0.28		
5	Inland Fresh Marsh	43.34	1.20	0.68	0.02	42.66	1.18	0.44	0.01	42.22	1.17		
7	Trans. Salt Marsh	62.39	1.73	-5.39	-0.15	67.78	1.87	4.70	0.13	63.09	1.75		
8	Regularly Flooded Marsh	22.07	0.61	-35.71	-0.99	57.79	1.60	-27.49	-0.76	85.28	2.36		
10	Estuarine Beach	0.00	0.00	-0.02	0.00	0.02	0.00	0.02	0.00	0.00	0.00		
11	Tidal Flat	0.00	0.00	-17.91	-0.50	17.91	0.50	-31.97	-0.88	49.88	1.38		
12	Ocean Beach	23.87	0.66	11.26	0.31	12.61	0.35	2.39	0.07	10.22	0.28		
15	Inland Open Water	82.46	2.28	0.32	0.01	82.15	2.27	0.00	0.00	82.15	2.27		
17	Estuarine Open Water	33.12	0.92	28.90	0.80	4.22	0.12	-17.71	-0.49	21.93	0.61		
19	Open Ocean	2877.32	79.59	-48.64	-1.35	2925.96	80.93	-19.80	-0.55	2945.75	81.48		
20	Irreg. Flooded Marsh	227.50	6.29	53.61	1.48	173.89	4.81	71.29	1.97	102.60	2.84		
SLAMM Code	SLAMM Name	2050		Change		2075		Change		2100		Total Change	
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
1	Developed Dry Land	29.72	0.82	7.70	0.21	22.02	0.61	7.35	0.20	14.66	0.41	-18.41	-0.509
2	Undeveloped Dry Land	172.39	4.77	26.99	0.75	145.40	4.02	25.68	0.71	119.72	3.31	-79.74	-2.206
3	Swamp	10.16	0.28	0.45	0.01	9.71	0.27	0.53	0.01	9.18	0.25	-1.60	-0.044
5	Inland Fresh Marsh	42.22	1.17	2.08	0.06	40.14	1.11	2.19	0.06	37.95	1.05	-5.39	-0.149
7	Trans. Salt Marsh	63.09	1.75	-4.24	-0.12	67.33	1.86	3.27	0.09	64.05	1.77	1.66	0.046
8	Regularly Flooded Marsh	85.28	2.36	10.10	0.28	75.17	2.08	44.38	1.23	30.79	0.85	8.72	0.241
10	Estuarine Beach	0.00	0.00	-0.19	-0.01	0.19	0.01	0.09	0.00	0.10	0.00	0.10	0.003
11	Tidal Flat	49.88	1.38	-30.44	-0.84	80.32	2.22	9.34	0.26	70.98	1.96	70.98	1.963
12	Ocean Beach	10.22	0.28	-1.75	-0.05	11.97	0.33	2.92	0.08	9.05	0.25	-14.82	-0.410
15	Inland Open Water	82.15	2.27	0.00	0.00	82.15	2.27	0.00	0.00	82.15	2.27	-0.32	-0.009
17	Estuarine Open Water	21.93	0.61	-40.42	-1.12	62.35	1.72	-66.49	-1.84	128.84	3.56	95.72	2.648
19	Open Ocean	2945.75	81.48	-43.29	-1.20	2989.05	82.68	-50.76	-1.40	3039.81	84.08	162.49	4.494
20	Irreg. Flooded Marsh	102.60	2.84	73.00	2.02	29.60	0.82	21.48	0.59	8.11	0.22	-219.38	-6.068

Table 19. SLAMM Pea Island sub-site forecast results showing hectares and percentage of class change with a SLR rate of 1m by 2100.

A visual analysis of the Pt. Peter Rd. sub-site over the four time periods (2025, 2050, 2075, and 2100) with a 1m rise in sea-level corroborates the majority of trends found in the global forecast. From initial condition to 2025, moderate amounts of change are seen in the immediate nearshore zone with areas of swamp and inland fresh marsh being taken over by inland migrating transitional salt marsh and regularly flooded marsh. Tidal flat also starts to appear along the immediate shoreline (Figure 22). These observations are supported by Table 20 with an increase in transitional salt marsh, regularly flooded marsh, and tidal flat of 8.27% (426.8 hectares), 0.98% (50.8 hectares), and 0.27% (14 hectares), respectively. Both swamp and inland fresh marsh exhibited decreases of 8.42% (434.5 hectares) and 1.42% (73.5 hectares), respectively. From 2025 to 2050, transitional salt marsh and regularly flooded marsh continue to increase in areal extent and migration further inland (Figure 22). An increase in tidal flat can also be seen in Figure 22. This movement results in further loss of swamp, inland fresh marsh and tidal swamp. Table 20 supports these observations with an increase of transitional salt marsh, regularly flooded marsh, and tidal flat of 5.96% (307.9 hectares), 11.77% (607.8 hectares), and 1.53% (78.8 hectares), respectively. Open ocean (open water) also experienced an increase of 0.5% (25.7 hectares). Loss in land area of swamp, inland fresh marsh and tidal swamp is shown in Table 19 of 18.41% (950.1 hectares), 0.61% (31.2 hectares), and 0.37% (19.3 hectares), respectively. From 2050 to 2075, Figure 22 shows an increase in transitional salt marsh, regularly flooded marsh, and tidal flat, mainly supplanting areas of swamp and smaller patches of inland fresh marsh. Estuarine open water also starts to increase along the immediate shoreline taking over areas previously occupied by tidal flat. These observations are corroborated by Table 20 with an increase in transitional salt marsh, regularly flooded marsh, and tidal flat of 0.79% (40.9 hectares), 6.46% (333.3 hectares), and 11.78% (608.1 hectares), respectively. Estuarine open water exhibited an increase of 1.81% (93.5 hectares). Swamp exhibited a fairly large decrease of 19.93% (1028.8 hectares). From 2075 to 2100, substantial change can be seen in Figure 22 with regards to increasing regularly fresh marsh, tidal flat and estuarine open water. Transitional salt marsh experiences a decrease in land area but exhibits movement further inland,

and at this stage swamp is almost non-existent and inland fresh marsh is gone (Figure 22). Table 20 supports these observations with an increase in regularly fresh marsh, tidal flat and estuarine open water of 0.68% (35.2 hectares), 6.58% (339.8 hectares), and 13.29% (685.9 hectares), respectively. Swamp exhibited a large decrease of 11.9% (614.5 hectares), while transitional salt marsh lost 8.72% (450.4 hectares) of land even though showing migration inland.

Forecast 1m - Pt. Peter Rd.													
SLAMM Code	SLAMM Name	Initial Cond.		Change		2025		Change		2050			
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%		
1	Developed Dry Land	3.60	0.07	0.05	0.00	3.55	0.07	0.17	0.00	3.38	0.07		
2	Undeveloped Dry Land	41.20	0.80	0.57	0.01	40.62	0.79	14.81	0.29	25.81	0.50		
3	Swamp	3067.16	59.42	434.54	8.42	2632.61	51.00	950.12	18.41	1682.49	32.60		
5	Inland Fresh Marsh	129.13	2.50	73.50	1.42	55.62	1.08	31.23	0.61	24.39	0.47		
7	Trans. Salt Marsh	302.11	5.85	-426.84	-8.27	728.95	14.12	-307.87	-5.96	1036.82	20.09		
8	Regularly Flooded Marsh	57.85	1.12	-50.77	-0.98	108.61	2.10	-607.74	-11.77	716.35	13.88		
11	Tidal Flat	0.00	0.00	-14.03	-0.27	14.03	0.27	-78.75	-1.53	92.78	1.80		
17	Estuarine Open Water	12.94	0.25	-13.42	-0.26	26.35	0.51	4.95	0.10	21.40	0.41		
19	Open Ocean	1485.79	28.78	-12.94	-0.25	1498.73	29.03	-25.66	-0.50	1524.39	29.53		
20	Irreg. Flooded Marsh	13.91	0.27	-7.27	-0.14	21.18	0.41	-0.55	-0.01	21.73	0.42		
23	Tidal Swamp	48.15	0.93	16.59	0.32	31.56	0.61	19.30	0.37	12.26	0.24		
SLAMM Code	SLAMM Name	2050		Change		2075		Change		2100		Total Change	
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
1	Developed Dry Land	3.38	0.07	1.62	0.03	1.76	0.03	1.13	0.02	0.63	0.01	-2.97	-0.057
2	Undeveloped Dry Land	25.81	0.50	20.07	0.39	5.75	0.11	4.82	0.09	0.93	0.02	-40.27	-0.780
3	Swamp	1682.49	32.60	1028.81	19.93	653.68	12.66	614.49	11.90	39.19	0.76	-3027.97	-58.661
5	Inland Fresh Marsh	24.39	0.47	19.09	0.37	5.30	0.10	5.19	0.10	0.11	0.00	-129.02	-2.500
7	Trans. Salt Marsh	1036.82	20.09	-40.86	-0.79	1077.69	20.88	450.37	8.72	627.32	12.15	325.21	6.300
8	Regularly Flooded Marsh	716.35	13.88	-333.24	-6.46	1049.59	20.33	-35.24	-0.68	1084.83	21.02	1026.98	19.896
11	Tidal Flat	92.78	1.80	-608.06	-11.78	700.84	13.58	-339.75	-6.58	1040.59	20.16	1040.59	20.159
17	Estuarine Open Water	21.40	0.41	-93.50	-1.81	114.90	2.23	-685.89	-13.29	800.79	15.51	787.86	15.263
19	Open Ocean	1524.39	29.53	-14.76	-0.29	1539.15	29.82	-26.28	-0.51	1565.43	30.33	79.65	1.543
20	Irreg. Flooded Marsh	21.73	0.42	10.22	0.20	11.51	0.22	10.03	0.19	1.48	0.03	-12.42	-0.241
23	Tidal Swamp	12.26	0.24	10.61	0.21	1.65	0.03	1.13	0.02	0.52	0.01	-47.63	-0.923

Table 20. SLAMM Pt. Peter Rd. sub-site forecast results showing hectares and percentage of class change with a SLR rate of 1m by 2100.

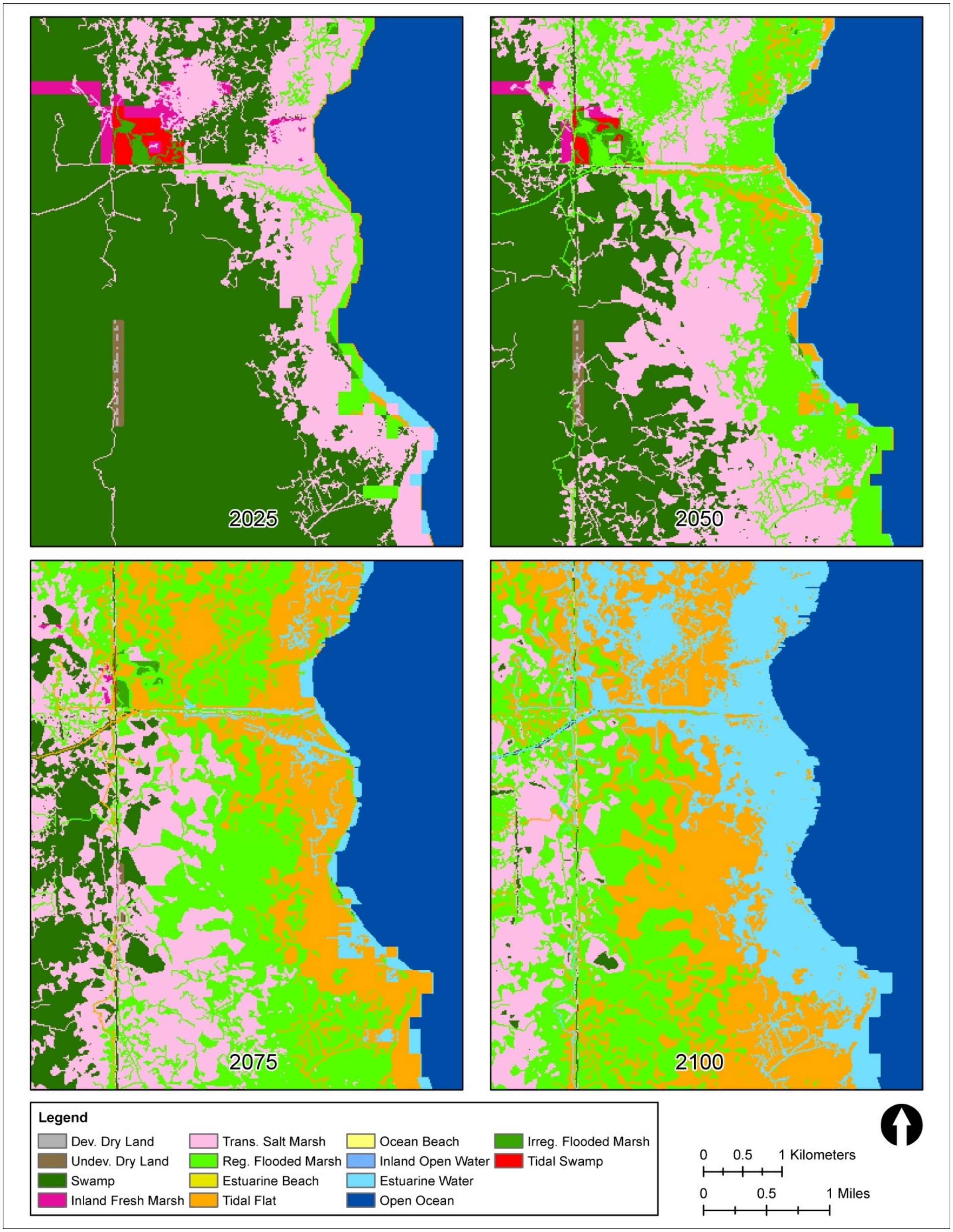

Figure 22. SLAMM Pt. Peter Rd. forecast map showing years 2025 - 2100 with a SLR rate of 1m by 2100.

Forecast Results - 1.4m SLR

From initial condition to 2025 with a 1.4m rise in sea-level, the majority of change continues to occur in the nearshore zone along the eastern portion of the Pamlico Peninsula, with noticeable change also occurring along Roanoke Island and lands to east along the backside of Nags Head, NC. A visual analysis of Figure 23 shows an increase in regularly flooded marsh and transitional salt marsh in both area and movement inland. A decrease in swamp and irregularly flooded marsh is seen in Figure 23, with these land classes being overtaken by regularly flooded marsh and transitional salt marsh. Table 21 shows an increase in both regularly flooded marsh and transitional salt marsh of 3.11% (4,851 hectares) and 2.39% (3,719 hectares), respectively. Swamp had the largest decrease of 3.77% (5,873 hectares) and irregularly flooded marsh had a moderate decrease of 1.77% (2,753 hectares).

From 2025 to 2050 with a 1.4m rise in sea-level, the majority of change continues to occur along the eastern portion of the Pamlico Peninsula, with noticeable change also occurring along Roanoke Island and lands to east along the backside of Nags Head, NC. The Pea Island portion of the Outer Banks is starting to show some change, during this time period, on the sound side of the barrier island. A visual analysis of Figure 23 shows a substantial increase in tidal flat in the nearshore zone and an increase in transitional salt marsh especially in migration inland. Swamp experienced a large decrease in area being replaced by transitional salt marsh and regularly flooded marsh. These observations are corroborated by Table 21 which quantitatively shows an increase in tidal flat and transitional salt marsh of 4% (6,227 hectares) and 1.16% (1,800 hectares), respectively. Regularly flooded marsh and estuarine open water increased moderately as well with gains of 0.46% (720 hectares) and 0.49% (770 hectares), respectively. Swamp experienced a large decrease in area of 5.36% (8,355 hectares). Moderate declines in area were experienced by irregularly flooded marsh and undeveloped dry land of 0.37% (577 hectares) and 0.29% (447 hectares).

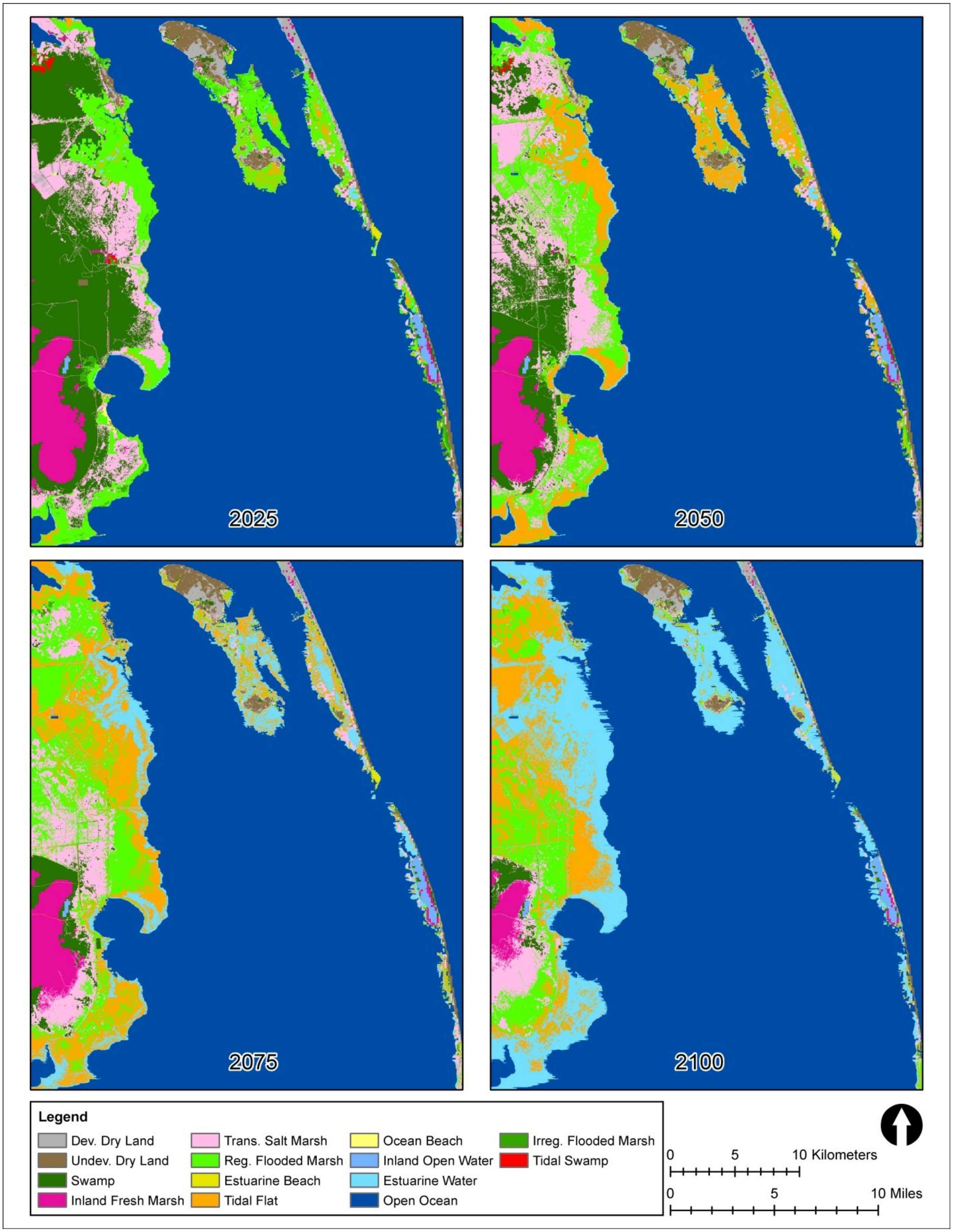

Figure 23. SLAMM global forecast map showing years 2025 - 2100 with a SLR rate of 1.4m by 2100.

Forecast 1.4m - Global

SLAMM Code	SLAMM Name	Initial Cond.		Change		2025		Change		2050			
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%		
1	Developed Dry Land	2051.06	1.32	511.04	0.33	1540.02	0.99	206.52	0.13	1333.50	0.86		
2	Undeveloped Dry Land	2893.05	1.86	534.01	0.34	2359.04	1.51	446.63	0.29	1912.41	1.23		
3	Swamp	21156.48	13.58	5872.86	3.77	15283.62	9.81	8355.30	5.36	6928.32	4.45		
5	Inland Fresh Marsh	3816.52	2.45	171.20	0.11	3645.31	2.34	150.54	0.10	3494.77	2.24		
7	Trans. Salt Marsh	4103.37	2.63	-3719.26	-2.39	7822.63	5.02	-1800.42	-1.16	9623.05	6.18		
8	Regularly Flooded Marsh	3146.04	2.02	-4850.88	-3.11	7996.92	5.13	-719.50	-0.46	8716.42	5.60		
10	Estuarine Beach	94.68	0.06	6.75	0.00	87.93	0.06	-3.02	0.00	90.96	0.06		
11	Tidal Flat	0.00	0.00	-1005.75	-0.65	1005.75	0.65	-6226.46	-4.00	7232.21	4.64		
12	Ocean Beach	90.59	0.06	-47.37	-0.03	137.96	0.09	30.10	0.02	107.85	0.07		
15	Inland Open Water	358.92	0.23	3.60	0.00	355.32	0.23	3.67	0.00	351.65	0.23		
17	Estuarine Open Water	789.50	0.51	64.19	0.04	725.31	0.47	-769.47	-0.49	1494.78	0.96		
19	Open Ocean	113416.85	72.81	-394.39	-0.25	113811.25	73.06	-333.86	-0.21	114145.11	73.28		
20	Irreg. Flooded Marsh	3613.86	2.32	2752.60	1.77	861.26	0.55	577.35	0.37	283.91	0.18		
23	Tidal Swamp	237.22	0.15	101.41	0.07	135.81	0.09	82.63	0.05	53.18	0.03		
SLAMM Code	SLAMM Name	2050		Change		2075		Change		2100		Total Change	
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
1	Developed Dry Land	1333.50	0.86	283.98	0.18	1049.52	0.67	258.39	0.17	791.12	0.51	-1259.93	-0.809
2	Undeveloped Dry Land	1912.41	1.23	430.18	0.28	1482.24	0.95	305.15	0.20	1177.09	0.76	-1715.96	-1.102
3	Swamp	6928.32	4.45	4942.10	3.17	1986.23	1.28	1142.52	0.73	843.71	0.54	-20312.77	-13.040
5	Inland Fresh Marsh	3494.77	2.24	734.97	0.47	2759.80	1.77	1371.44	0.88	1388.36	0.89	-2428.16	-1.559
7	Trans. Salt Marsh	9623.05	6.18	3066.71	1.97	6556.34	4.21	3544.77	2.28	3011.57	1.93	-1091.80	-0.701
8	Regularly Flooded Marsh	8716.42	5.60	-569.48	-0.37	9285.90	5.96	3101.93	1.99	6183.97	3.97	3037.93	1.950
10	Estuarine Beach	90.96	0.06	-32.84	-0.02	123.80	0.08	-11.38	-0.01	135.18	0.09	40.50	0.026
11	Tidal Flat	7232.21	4.64	-3726.32	-2.39	10958.53	7.04	1625.08	1.04	9333.45	5.99	9333.45	5.992
12	Ocean Beach	107.85	0.07	-20.70	-0.01	128.55	0.08	21.44	0.01	107.12	0.07	16.53	0.011
15	Inland Open Water	351.65	0.23	2.29	0.00	349.36	0.22	14.65	0.01	334.71	0.21	-24.21	-0.016
17	Estuarine Open Water	1494.78	0.96	-4619.81	-2.97	6114.60	3.93	-10372.46	-6.66	16487.06	10.58	15697.56	10.078
19	Open Ocean	114145.11	73.28	-721.29	-0.46	114866.39	73.74	-1075.70	-0.69	115942.09	74.43	2525.24	1.621
20	Irreg. Flooded Marsh	283.91	0.18	180.29	0.12	103.62	0.07	71.05	0.05	32.57	0.02	-3581.29	-2.299
23	Tidal Swamp	53.18	0.03	49.92	0.03	3.26	0.00	3.12	0.00	0.13	0.00	-237.09	-0.152

Table 21. SLAMM global forecast results showing hectares and percentage of class change with a SLR rate of 1.4m by 2100.

From 2050 to 2075 with a 1.4m rise in sea-level, Figure 23 exhibits a continuing increase of tidal flat and regularly flooded marsh in both the nearshore zone and in expansion inland. This change is displayed throughout the entire study area along the eastern portion of the Pamlico Peninsula, with noticeable change also occurring along Roanoke Island, the backside of Nags Head, NC, and the Pea Island portion of the Outer Banks. Estuarine open water is starting to expand and move further inland, and transitional salt marsh is decreasing as a result of being taken over by other land classes. These observations are supported by Table 21 which shows fairly large increases in tidal flat and open estuarine water of 2.39% (3,726 hectares) and 2.97% (4,620 hectares), respectively. Regularly flooded increased by 0.37% (570 hectares) and open ocean increased 0.46% (721 hectares). The largest decrease was exhibited by swamp with a decrease of 3.17% (4,942 hectares) and transitional salt marsh also experienced a decrease in area of 1.97% (3,067 hectares).

Over the 25 year period from 2075 to 2100, with a 1.4m rise in sea-level, significant (considerable) changes throughout the entire study area are observed from a visual analysis of Figure 23. The largest and most noticeable changes include a sizeable increase in the amount of estuarine open water, and the inland migration of tidal flat, regularly flooded marsh, and transitional salt marsh. Swamp and inland fresh marsh also start to experience moderate decreases in land loss. This visual analysis of Figure 23 is validated by Table 21 which shows a huge increase of estuarine open water of 6.66% (10,373 hectares). Moderate decreases in land area were exhibited by transitional salt marsh, regularly flooded marsh, and tidal flat of 2.28% (3,545 hectares), 1.99% (3,102 hectares), and 1.04% (1,625 hectares), respectively. This could be attributed to these land classes being supplanted by vast areas of estuarine open water and left with few other options but to migrate further inland. Swamp and inland fresh marsh also experienced losses of 0.73% (1,143 hectares) and 0.88% (1,371 hectares), respectively. This is due primarily to other land classes occupying their previous locations because of inland migration.

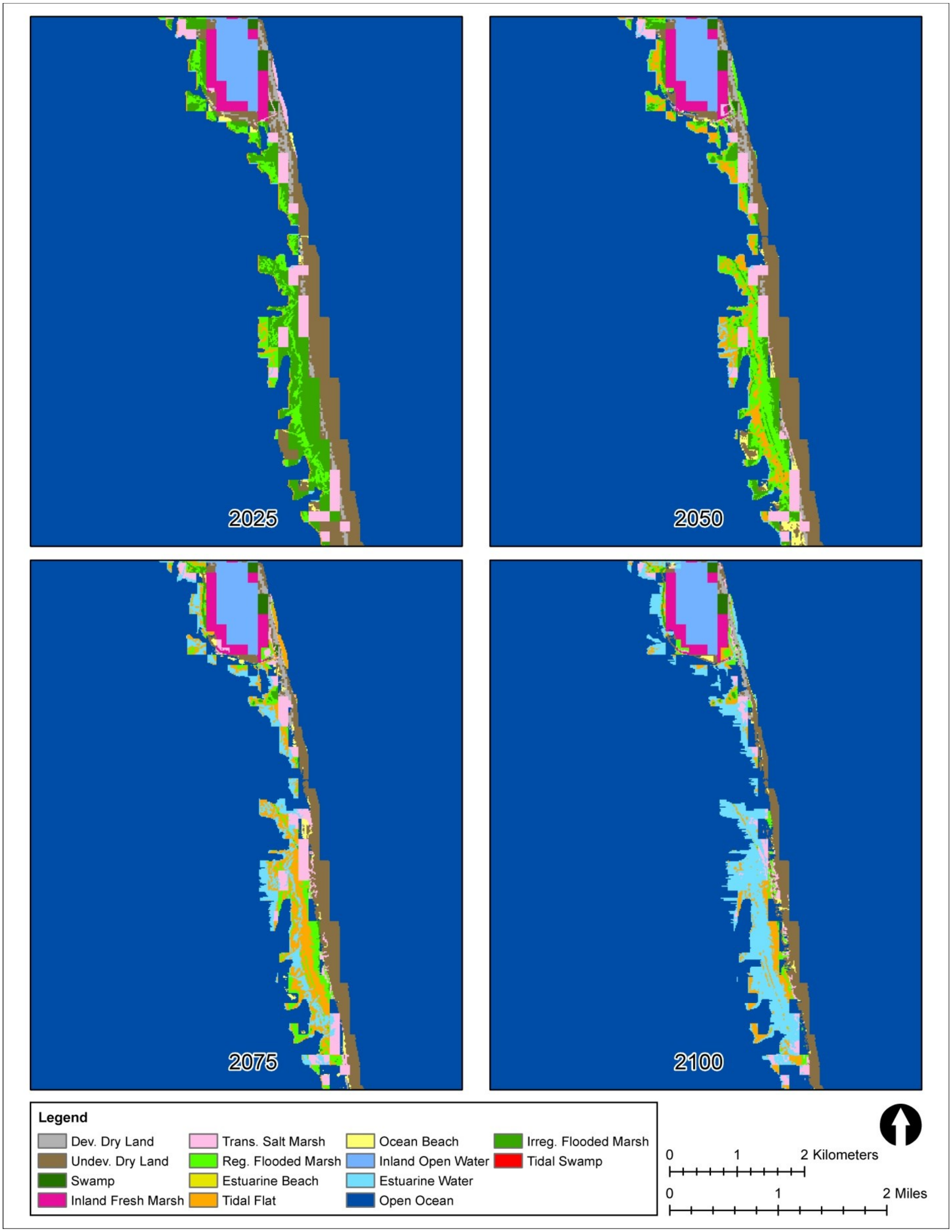

Figure 24. SLAMM Pea Island sub-site forecast map showing years 2025 - 2100 with a SLR rate of 1.4m by 2100.

A visual analysis of the Pea Island sub-site over the four time periods (2025, 2050, 2075, and 2100) with a 1.4m rise in sea-level corroborates the majority of trends found in the global forecast. From current condition to 2025, small to moderate change occurs and Figure 24 shows an increase of regularly flooded marsh supplanting previous areas of irregularly flooded marsh. There is also the occurrence of tidal flats along the immediate back-barrier shoreline. Table 22 shows an increase of regularly flooded marsh, transitional salt marsh, and tidal flat of 1.62% (58.4 hectares), 0.16% (5.6 hectares), and 0.54% (19.7 hectares), respectively. Open ocean exhibited an increase of 1.57% (56.9 hectares) replacing areas of estuarine open water. From 2025 to 2050, the majority of changes can be seen in the immediate back-barrier nearshore zone with an increase in tidal flat and horizontal movement of both tidal flat and regularly flooded marsh (Figure 24). An increase in both open ocean and estuarine open water can also be seen from areas of land lost to water. These observations are supported by Table 22 which shows an increase in tidal flat, regularly flooded marsh, open ocean and estuarine open water of 1.57% (56.9 hectares), 0.75% (27 hectares), 0.57% (20.7 hectares), and 0.56% (20.2 hectares), respectively. The most amount of land loss was exhibited by irregularly flooded marsh of 2.69% (97.4 hectares). From 2050 to 2075, the back-barrier side of Pea Island exhibits the most change with areas of irregularly flooded marsh being replaced by tidal flat, estuarine open water, and open ocean (Figure 24). Table 22 confirms these observations with an increase of tidal flat, estuarine open water, and open ocean of 0.71% (25.8 hectares), 2.08% (40.4 hectares), and 1.59% (57.3 hectares). Irregularly flooded marsh decreased in land area by 1.2% (43.5 hectares). From 2075 to 2100, moderate to high amounts of change occur on the back-barrier side of Pea Island. Estuarine open water and open ocean exhibit moderate to large increases, while irregularly flooded marsh and undeveloped dry land decreased in area (Figure 24). At this point irregularly flooded marsh is almost non-existent and moderate areas of tidal flat have been taken over by water. This is validated by Table 22 which shows large increases of estuarine open water and open ocean of 2.53% (91.4 hectares) and 1.93% (69.9 hectares), respectively. Irregularly flooded marsh decreased by 0.14% (4.9 hectares), tidal flat decreased by 1.51% (54.7 hectares), and undeveloped dry land decreased by 0.86% (31.1 hectares).

Forecast 1.4m - Pea Island													
SLAMM Code	SLAMM Name	Initial Cond.		Change		2025		Change		2050			
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%		
1	Developed Dry Land	33.08	0.91	1.32	0.04	31.76	0.88	5.93	0.16	25.83	0.71		
2	Undeveloped Dry Land	199.46	5.52	13.91	0.38	185.55	5.13	26.64	0.74	158.91	4.40		
3	Swamp	10.78	0.30	0.36	0.01	10.41	0.29	0.44	0.01	9.97	0.28		
5	Inland Fresh Marsh	43.34	1.20	0.81	0.02	42.52	1.18	1.71	0.05	40.81	1.13		
7	Trans. Salt Marsh	62.39	1.73	-5.63	-0.16	68.03	1.88	2.01	0.06	66.01	1.83		
8	Regularly Flooded Marsh	22.07	0.61	-58.42	-1.62	80.49	2.23	-27.01	-0.75	107.50	2.97		
10	Estuarine Beach	0.00	0.00	-0.02	0.00	0.02	0.00	0.02	0.00	0.00	0.00		
11	Tidal Flat	0.00	0.00	-19.68	-0.54	19.68	0.54	-56.90	-1.57	76.58	2.12		
12	Ocean Beach	23.87	0.66	17.33	0.48	6.55	0.18	-9.36	-0.26	15.90	0.44		
15	Inland Open Water	82.46	2.28	0.32	0.01	82.15	2.27	0.00	0.00	82.15	2.27		
17	Estuarine Open Water	33.12	0.92	28.27	0.78	4.85	0.13	-20.69	-0.57	25.54	0.71		
19	Open Ocean	2877.32	79.59	-56.92	-1.57	2934.25	81.16	-20.22	-0.56	2954.47	81.72		
20	Irreg. Flooded Marsh	227.50	6.29	78.36	2.17	149.14	4.13	97.42	2.69	51.72	1.43		
SLAMM Code	SLAMM Name	2050		Change		2075		Change		2100		Total Change	
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
1	Developed Dry Land	25.83	0.71	11.02	0.30	14.81	0.41	4.20	0.12	10.61	0.29	-22.47	-0.621
2	Undeveloped Dry Land	158.91	4.40	35.48	0.98	123.43	3.41	31.13	0.86	92.29	2.55	-107.17	-2.964
3	Swamp	9.97	0.28	0.71	0.02	9.26	0.26	1.27	0.04	7.99	0.22	-2.78	-0.077
5	Inland Fresh Marsh	40.81	1.13	2.76	0.08	38.05	1.05	0.93	0.03	37.11	1.03	-6.22	-0.172
7	Trans. Salt Marsh	66.01	1.83	3.34	0.09	62.67	1.73	26.87	0.74	35.80	0.99	-26.59	-0.735
8	Regularly Flooded Marsh	107.50	2.97	56.87	1.57	50.63	1.40	30.20	0.84	20.43	0.56	-1.65	-0.046
10	Estuarine Beach	0.00	0.00	-0.04	0.00	0.04	0.00	-0.07	0.00	0.11	0.00	0.11	0.003
11	Tidal Flat	76.58	2.12	-25.80	-0.71	102.38	2.83	54.66	1.51	47.72	1.32	47.72	1.320
12	Ocean Beach	15.90	0.44	4.75	0.13	11.15	0.31	5.91	0.16	5.24	0.14	-18.63	-0.515
15	Inland Open Water	82.15	2.27	0.00	0.00	82.15	2.27	1.24	0.03	80.91	2.24	-1.55	-0.043
17	Estuarine Open Water	25.54	0.71	-75.23	-2.08	100.76	2.79	-91.42	-2.53	192.18	5.32	159.06	4.400
19	Open Ocean	2954.47	81.72	-57.33	-1.59	3011.80	83.31	-69.85	-1.93	3081.66	85.24	204.33	5.652
20	Irreg. Flooded Marsh	51.72	1.43	43.46	1.20	8.26	0.23	4.92	0.14	3.34	0.09	-224.16	-6.200

Table 22. SLAMM Pea Island sub-site forecast results showing hectares and percentage of class change with a SLR rate of 1.4m by 2100.

A visual analysis of the Pt. Peter Rd. sub-site over the four time periods (2025, 2050, 2075, and 2100) with a 1.4m rise in sea-level corroborates the majority of trends found in the global forecast. From initial condition to 2025, moderate to high amounts of change are seen in the immediate nearshore zone with areas of swamp and inland fresh marsh being taken over by inland migrating transitional salt marsh and regularly flooded marsh. Tidal flat also starts to appear along the immediate shoreline (Figure 25). These observations are supported by Table 23 with an increase in transitional salt marsh, regularly flooded marsh, and tidal flat of 12.81% (661.2 hectares), 2.08% (107.2 hectares), and 0.32% (16.3 hectares), respectively. Both swamp and inland fresh marsh exhibited decreases of 13.79% (711.9 hectares) and 1.72% (88.6 hectares), respectively. From 2025 to 2050, transitional salt marsh and regularly flooded marsh continue to increase in areal extent and migration further inland (Figure 25). A moderate increase in tidal flat can also be seen in Figure 25. This movement results in further loss of swamp, inland fresh marsh and tidal swamp. Table 23 supports these observations with an increase of transitional salt marsh, regularly flooded marsh, and tidal flat of 7.77% (400.9 hectares), 15.77% (814 hectares), and 2.74% (141.6 hectares), respectively. Open ocean (open water) also experienced an increase of 0.5% (25.7 hectares). Large loss in land area of swamp and decrease in inland fresh marsh and tidal swamp is shown in Table 23 of 25.18% (1299.7 hectares), 0.5% (26 hectares), and 0.40% (20.8 hectares), respectively. From 2050 to 2075, Figure 25 shows a large increase in transitional salt marsh, regularly flooded marsh, and tidal flat, mainly supplanting areas of swamp and eliminating smaller patches of inland fresh marsh. Estuarine open water also starts to increase along the immediate shoreline and migrate inland taking over areas previously occupied by tidal flat. These observations are corroborated by Table 23 with an increase in regularly flooded marsh and tidal flat of 7.76% (400.4 hectares) and 15.5% (800.3 hectares), respectively. Estuarine open water exhibited an increase of 3.18% (163.9 hectares). Swamp exhibited a fairly large decrease of 19.1% (986.1 hectares). From 2075 to 2100, substantial change can be seen in Figure 25 with regards to increasing tidal flat and estuarine open water with regularly flooded moving further inland. Transitional salt marsh also experiences a decrease in land area but exhibits movement further inland, and at this stage swamp is nearly non-existent with inland fresh marsh and tidal swamp gone (Figure 25). Table 23 supports these observations with an increase in tidal flat and estuarine open water of 8.11% (418.5 hectares) and 18.1% (934.2 hectares), respectively. Swamp exhibited a decrease of 1.27% (65.5 hectares), while transitional salt marsh and regularly flooded marsh lost 18.42% (951 hectares) and 6.95% (358.7 hectares) of land even though showing migration inland.

Forecast 1.4m - Pt. Peter Rd.													
SLAMM Code	SLAMM Name	Initial Cond.		Change		2025		Change		2050			
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%		
1	Developed Dry Land	3.60	0.07	0.07	0.00	3.53	0.07	1.19	0.02	2.35	0.05		
2	Undeveloped Dry Land	41.20	0.80	0.70	0.01	40.49	0.78	26.97	0.52	13.52	0.26		
3	Swamp	3067.16	59.42	711.91	13.79	2355.25	45.63	1299.69	25.18	1055.56	20.45		
5	Inland Fresh Marsh	129.13	2.50	88.62	1.72	40.51	0.78	25.95	0.50	14.56	0.28		
7	Trans. Salt Marsh	302.11	5.85	-661.16	-12.81	963.27	18.66	-400.90	-7.77	1364.17	26.43		
8	Regularly Flooded Marsh	57.85	1.12	-107.19	-2.08	165.03	3.20	-814.04	-15.77	979.07	18.97		
11	Tidal Flat	0.00	0.00	-16.31	-0.32	16.31	0.32	-141.60	-2.74	157.91	3.06		
17	Estuarine Open Water	12.94	0.25	-13.42	-0.26	26.36	0.51	1.68	0.03	24.67	0.48		
19	Open Ocean	1485.79	28.78	-12.94	-0.25	1498.73	29.03	-25.67	-0.50	1524.40	29.53		
20	Irreg. Flooded Marsh	13.91	0.27	-13.84	-0.27	27.75	0.54	5.95	0.12	21.79	0.42		
23	Tidal Swamp	48.15	0.93	23.56	0.46	24.59	0.48	20.77	0.40	3.82	0.07		
SLAMM Code	SLAMM Name	2050		Change		2075		Change		2100		Total Change	
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
1	Developed Dry Land	2.35	0.05	1.54	0.03	0.81	0.02	0.81	0.02	0.00	0.00	-3.60	-0.070
2	Undeveloped Dry Land	13.52	0.26	12.20	0.24	1.32	0.03	1.30	0.03	0.02	0.00	-41.18	-0.798
3	Swamp	1055.56	20.45	986.14	19.10	69.41	1.34	65.51	1.27	3.90	0.08	-3063.26	-59.345
5	Inland Fresh Marsh	14.56	0.28	14.41	0.28	0.16	0.00	0.16	0.00	0.00	0.00	-129.13	-2.502
7	Trans. Salt Marsh	1364.17	26.43	344.17	6.67	1020.00	19.76	951.04	18.42	68.96	1.34	-233.15	-4.517
8	Regularly Flooded Marsh	979.07	18.97	-400.44	-7.76	1379.51	26.73	358.67	6.95	1020.84	19.78	962.99	18.656
11	Tidal Flat	157.91	3.06	-800.26	-15.50	958.16	18.56	-418.47	-8.11	1376.63	26.67	1376.63	26.669
17	Estuarine Open Water	24.67	0.48	-163.92	-3.18	188.60	3.65	-934.20	-18.10	1122.79	21.75	1109.85	21.501
19	Open Ocean	1524.40	29.53	-14.80	-0.29	1539.19	29.82	-28.61	-0.55	1567.81	30.37	82.02	1.589
20	Irreg. Flooded Marsh	21.79	0.42	17.64	0.34	4.15	0.08	3.28	0.06	0.87	0.02	-13.03	-0.252
23	Tidal Swamp	3.82	0.07	3.31	0.06	0.51	0.01	0.51	0.01	0.00	0.00	-48.15	-0.933

Table 23. SLAMM Pt. Peter Rd. sub-site forecast results showing hectares and percentage of class change with a SLR rate of 1.4m by 2100.

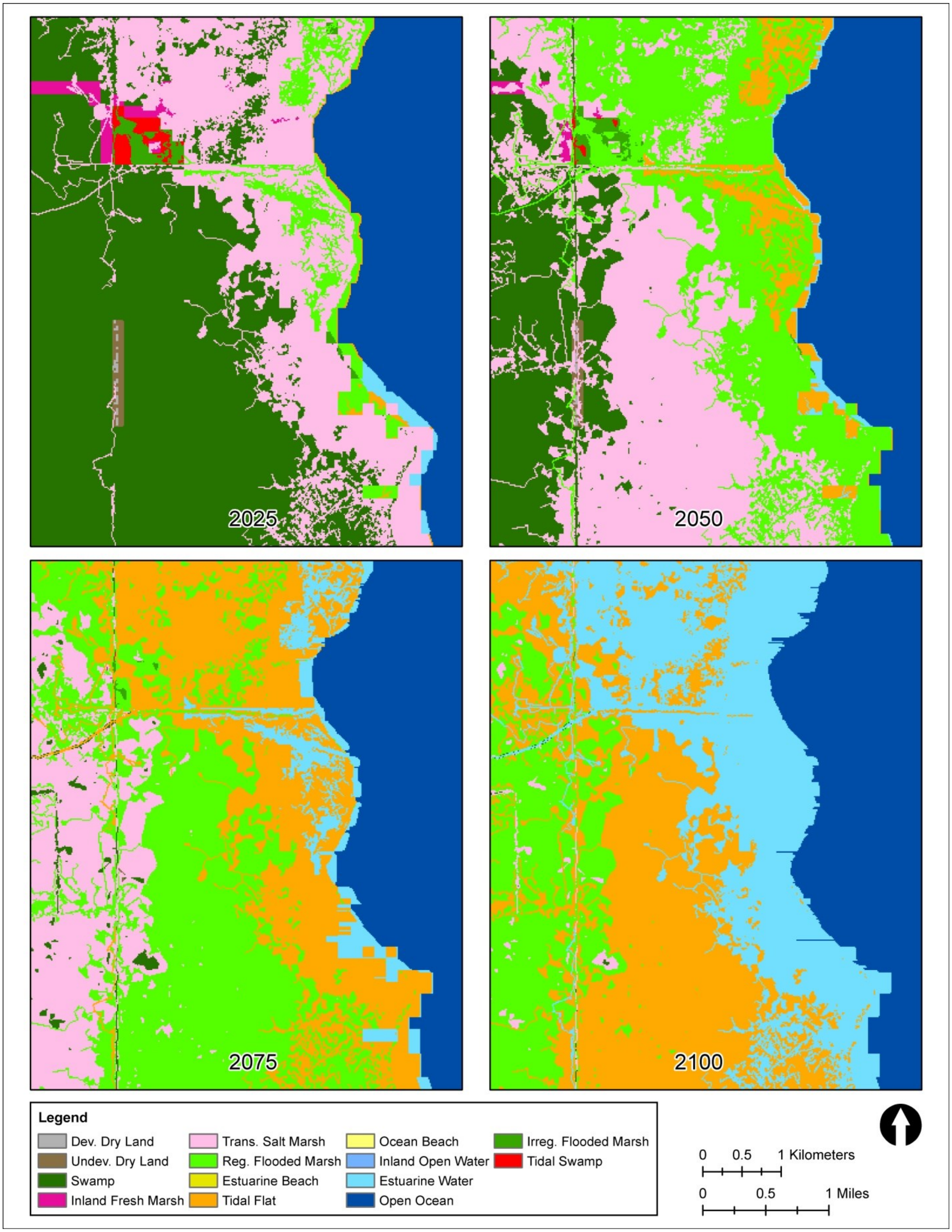

Figure 25. SLAMM Pt. Peter Rd. forecast map showing years 2025 - 2100 with a SLR rate of 1.4m by 2100.

Forecast Results - 2m SLR

From initial condition to 2025 with a 2m rise in sea-level, a visual analysis of Figure 26 shows there is much more change associated with an increase in transitional salt marsh and tidal flat than with the other four lower scenarios of rise. The major changes can be immediately seen throughout a majority of the study area, especially along the eastern portion of the Pamlico Peninsula, with noticeable change also occurring along Roanoke Island and lands to east along the backside of Nags Head, NC. Also Figure 26 shows that both swamp and irregularly flooded marsh experience large losses of land area. These visual observations are supported by Table 24 which shows large increases of transitional salt marsh, regularly flooded marsh, and tidal flat of 4.33% (6,751 hectares), 3% (4,676 hectares), and 1.03% (1,601 hectares), respectively. Swamp and irregularly flooded marsh exhibited large decreases in land area of 5.67% (8,840 hectares) and 1.94% (3,027 hectares), respectively. Moderate loss of land was also exhibited by both developed and undeveloped dry land of 0.39% (602 hectares) and 0.44% (683 hectares), respectively.

From 2025 to 2050 with a 2m rise in sea-level, the majority of change occurs throughout the entire study area (Figure 26) with tidal flat increasing vastly and both regularly flooded marsh and transitional salt marsh migrating further inland taking over area once inhabited by swamp and inland fresh marsh. Estuarine open starts to infiltrate moderate-sized areas in the nearshore zone and significant changes are beginning to occur along the Pea Island portion of the Outer Banks. These changes are supported by Table 24 which shows major increases in tidal flat and regularly flooded marsh of 3.98% (6,202 hectares) and 1.95% (3,031 hectares), as well as a major decrease in swamp of 5.74% (8,941 hectares). Estuarine open water exhibited a moderate increase of 0.97% (1,507 hectares), and undeveloped dry land, inland fresh marsh, transitional salt marsh, and irregularly flooded marsh all experienced moderate decreases of 0.36% (567 hectares), 0.25% (396 hectares), 0.32% (504 hectares), and 0.27% (416 hectares), respectively.

Over the 25 year period from 2050 to 2075, significant changes throughout the entire study area can be seen by visually analyzing Figure 26. Estuarine open water increased in both area and inland migration tremendously, and tidal flat also exhibited a fairly substantial increase in land area. Vast areas of transitional salt marsh have been taken over by regularly flooded marsh and tidal flat and medium-sized areas of undeveloped dry land have started in decrease. Large areas of inland fresh marsh have been supplanted by transitional salt marsh and regularly flooded marsh, and moderate-sized areas of developed and undeveloped dry land are starting to decline especially around Pea Island, Roanoke Island, and south of Nags Head, NC. These visual observations are validated by Table 24 which shows a large increase in both estuarine open water and tidal flat of 5.02% (7,819 hectares) and 1.82% (2,836 hectares), respectively. The largest decline in land area was incurred on swamp, inland fresh marsh, and transitional salt marsh of 1.59% (2,475 hectares), 1.09% (1,705 hectares), and 3.6% (5,607 hectares), respectively. Areas of moderate land loss include regularly flooded marsh, developed and undeveloped dry land with 0.54% (834 hectares), 0.24% (370 hectares), and 0.29% (445 hectares) decline, respectively.

Forecast 2m - Global

SLAMM Code	SLAMM Name	Initial Cond.		Change		2025		Change		2050			
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%		
1	Developed Dry Land	2051.06	1.32	602.16	0.39	1448.89	0.93	268.14	0.17	1180.75	0.76		
2	Undeveloped Dry Land	2893.05	1.86	683.07	0.44	2209.98	1.42	566.76	0.36	1643.22	1.05		
3	Swamp	21156.48	13.58	8839.53	5.67	12316.95	7.91	8941.16	5.74	3375.79	2.17		
5	Inland Fresh Marsh	3816.52	2.45	227.99	0.15	3588.52	2.30	396.25	0.25	3192.27	2.05		
7	Trans. Salt Marsh	4103.37	2.63	-6751.33	-4.33	10854.70	6.97	503.51	0.32	10351.19	6.65		
8	Regularly Flooded Marsh	3146.04	2.02	-4675.52	-3.00	7821.56	5.02	-3031.35	-1.95	10852.91	6.97		
10	Estuarine Beach	94.68	0.06	2.03	0.00	92.65	0.06	-19.39	-0.01	112.05	0.07		
11	Tidal Flat	0.00	0.00	-1601.31	-1.03	1601.31	1.03	-6201.63	-3.98	7802.94	5.01		
12	Ocean Beach	90.59	0.06	-73.67	-0.05	164.25	0.11	9.62	0.01	154.63	0.10		
15	Inland Open Water	358.92	0.23	3.92	0.00	355.01	0.23	4.34	0.00	350.66	0.23		
17	Estuarine Open Water	789.50	0.51	-6.41	0.00	795.92	0.51	-1506.79	-0.97	2302.71	1.48		
19	Open Ocean	113416.85	72.81	-414.95	-0.27	113831.80	73.08	-434.43	-0.28	114266.23	73.36		
20	Irreg. Flooded Marsh	3613.86	2.32	3027.40	1.94	586.46	0.38	416.00	0.27	170.46	0.11		
23	Tidal Swamp	237.22	0.15	137.09	0.09	100.13	0.06	87.79	0.06	12.34	0.01		

SLAMM Code	SLAMM Name	2050		Change		2075		Change		2100		Total Change	
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
1	Developed Dry Land	1180.75	0.76	369.49	0.24	811.26	0.52	298.52	0.19	512.74	0.33	-1538.31	-0.988
2	Undeveloped Dry Land	1643.22	1.05	445.39	0.29	1197.83	0.77	316.24	0.20	881.59	0.57	-2011.46	-1.291
3	Swamp	3375.79	2.17	2474.96	1.59	900.83	0.58	839.07	0.54	61.76	0.04	-21094.72	-13.542
5	Inland Fresh Marsh	3192.27	2.05	1704.63	1.09	1487.64	0.96	1414.94	0.91	72.71	0.05	-3743.81	-2.403
7	Trans. Salt Marsh	10351.19	6.65	5607.44	3.60	4743.75	3.05	2149.07	1.38	2594.68	1.67	-1508.69	-0.969
8	Regularly Flooded Marsh	10852.91	6.97	833.50	0.54	10019.41	6.43	5386.48	3.46	4632.93	2.97	1486.89	0.955
10	Estuarine Beach	112.05	0.07	-32.32	-0.02	144.37	0.09	43.37	0.03	101.00	0.06	6.32	0.004
11	Tidal Flat	7802.94	5.01	-2836.37	-1.82	10639.30	6.83	793.94	0.51	9845.37	6.32	9845.37	6.321
12	Ocean Beach	154.63	0.10	15.03	0.01	139.60	0.09	63.81	0.04	75.78	0.05	-14.80	-0.010
15	Inland Open Water	350.66	0.23	14.49	0.01	336.17	0.22	7.02	0.00	329.15	0.21	-29.77	-0.019
17	Estuarine Open Water	2302.71	1.48	-7819.08	-5.02	10121.79	6.50	-9262.99	-5.95	19384.78	12.44	18595.28	11.938
19	Open Ocean	114266.23	73.36	-914.56	-0.59	115180.79	73.94	-2076.62	-1.33	117257.41	75.28	3840.56	2.466
20	Irreg. Flooded Marsh	170.46	0.11	125.22	0.08	45.23	0.03	27.02	0.02	18.22	0.01	-3595.64	-2.308
23	Tidal Swamp	12.34	0.01	12.18	0.01	0.15	0.00	0.14	0.00	0.01	0.00	-237.21	-0.152

Table 24. SLAMM global forecast results showing hectares and percentage of class change with a SLR rate of 2m by 2100.

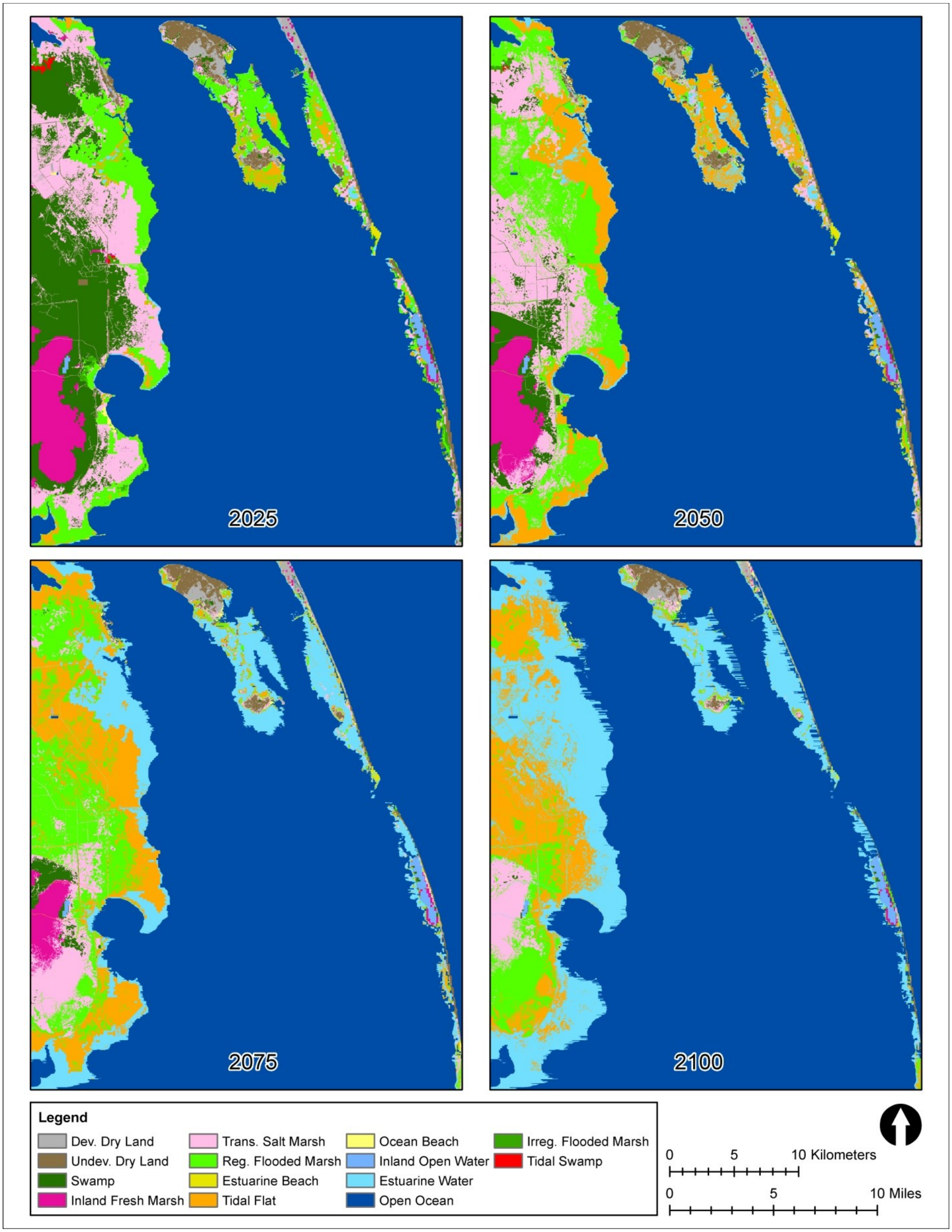

Figure 26. SLAMM global forecast map showing years 2025 - 2100 with a SLR rate of 2m by 2100.

As expected, the 25-year period from 2075 to 2100 with a 2m rise in sea-level exhibited the most drastic changes throughout the entire study area. In the year 2100, estuarine open water and open ocean (really just "open water") account for roughly 88% of the total study area (Table 24). A visual analysis of Figure 26 shows an extremely large increase in estuarine open water and open ocean. These classes have taken over vast areas of tidal flat, regularly flooded marsh, and transitional salt marsh. Much of the eastern Pamlico Peninsula, southern portion of Roanoke Island, majority of Pea Island barrier region, and large areas south of Nags Head, NC are inundated with open water (either estuarine or ocean). Tidal flat, regularly flooded marsh and transitional salt marsh land classes have all migrated inland substantially, and have almost completely taken over areas once inhabited by inland fresh marsh. Large areas of developed and undeveloped dry land are also either completely inundated or have transformed into another land class. These observations are validated by Table 24 which shows a large increase in estuarine open water and open ocean of 5.95% (9,263 hectares) and 1.33% (2,077 hectares), respectively. Despite large migration inland, tidal flat, regularly flooded marsh and transitional salt marsh experienced relatively large declines in land area of 0.51% (794 hectares), 3.46% (5,387 hectares), and 1.38% (2,149 hectares). Inland fresh marsh and swamp are almost completely gone throughout the entire study area and experienced relatively large decreases in land area of 0.91% (1.415 hectares) and 0.54% (839 hectares). Other land classes experienced decreases in land area such as undeveloped dry land with 0.2% (316 hectares) loss and developed dry land with 0.19% (299 hectares) loss.

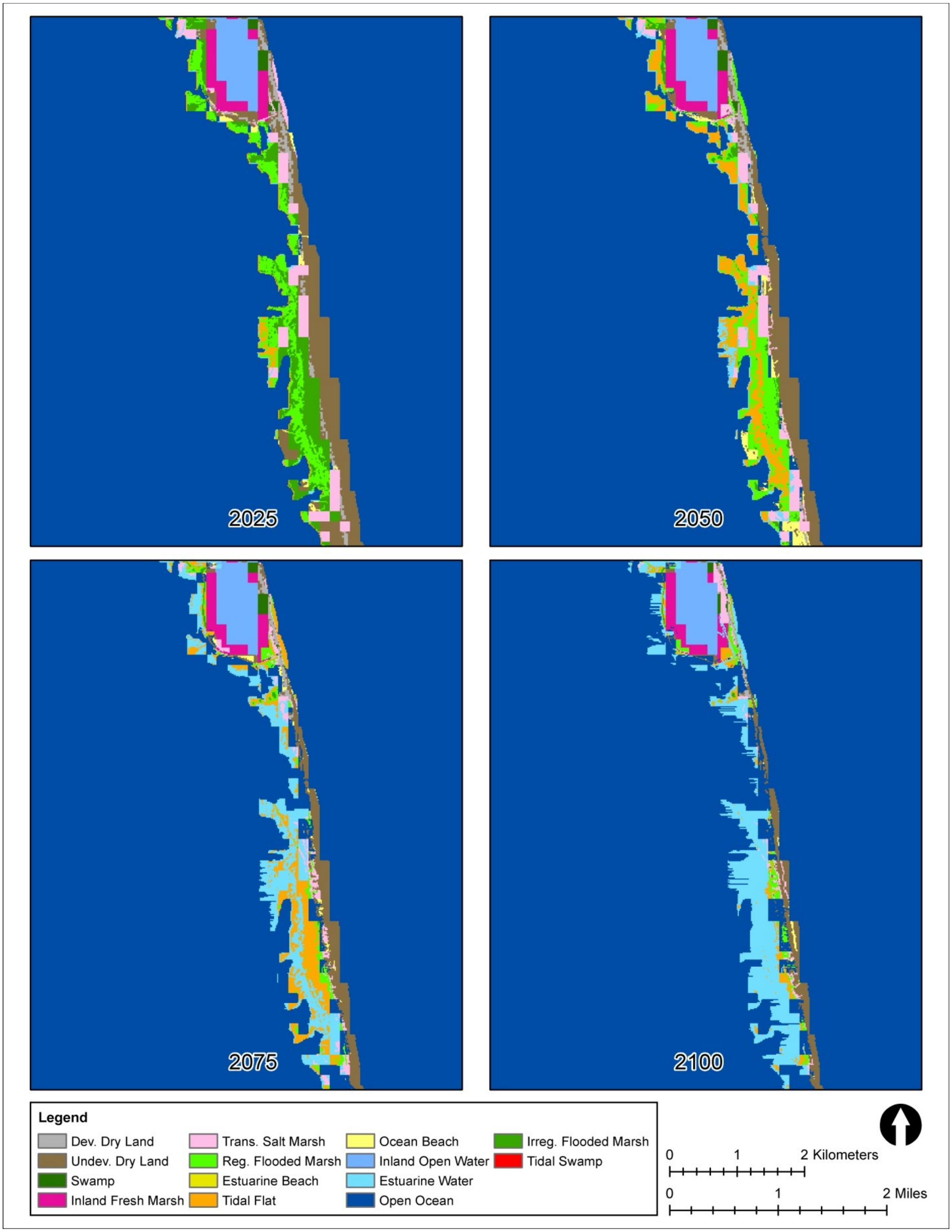

Figure 27. SLAMM Pea Island sub-site forecast map showing years 2025 - 2100 with a SLR rate of 2m by 2100.

A visual analysis of the Pea Island sub-site over the four time periods (2025, 2050, 2075, and 2100) with a 2m rise in sea-level corroborates the majority of trends found in the global forecast. From current condition to 2025, moderate to large change occurs and Figure 27 shows an increase of regularly flooded marsh supplanting previous areas of irregularly flooded marsh. There is also a moderate occurrence of tidal flats along the immediate back-barrier shoreline. Table 25 shows an increase of regularly flooded marsh, transitional salt marsh, and tidal flat of 2.56% (92.7 hectares), 0.16% (5.8 hectares), and 0.64% (23.3 hectares), respectively. Open ocean exhibited an increase of 1.63% (58.9 hectares) replacing areas of estuarine open water, and irregularly flooded marsh lost 3.23% (116.8 hectares) of land. From 2025 to 2050, the majority of changes can be seen in the immediate back-barrier nearshore zone with a large increase in tidal flat and horizontal movement of both tidal flat and regularly flooded marsh (Figure 27). An increase in both open ocean and estuarine open water can also be seen from areas of land lost to water. These observations are supported by Table 25 which shows an increase in tidal flat, open ocean and estuarine open water of 2.46% (89 hectares), 0.94% (33.8 hectares), and 0.9% (32.5 hectares), respectively. The most amount of land loss was exhibited by irregularly flooded marsh of 2.64% (95.6 hectares). From 2050 to 2075, the back-barrier side of Pea Island exhibits the most significant change with large areas of irregularly flooded marsh being replaced by tidal flat, estuarine open water, and open ocean (Figure 27). Table 25 confirms these observations with an increase of estuarine open water and open ocean of 3.67% (132.6 hectares) and 1.97% (71.1 hectares). Irregularly flooded marsh decreased in land area by 0.33% (11.9 hectares). From 2075 to 2100, extremely high amounts of change occur on the back-barrier and ocean sides of Pea Island. Estuarine open water and open ocean exhibit additionally large increases, while tidal flat, irregularly flooded marsh and undeveloped dry land decreased in area (Figure 27). At this point irregularly flooded marsh and ocean beach are almost non-existent and moderate to large areas of tidal flat have been taken over by water. This is validated by Table 25 which shows large increases of estuarine open water and open ocean of 1.17% (42.3 hectares) and 2.71% (98 hectares), respectively. Irregularly flooded marsh decreased by 0.05% (1.8 hectares), tidal flat decreased by 2.1% (76 hectares), and undeveloped dry land decreased by 0.82% (29.5 hectares).

Forecast 2m - Pea Island													
SLAMM Code	SLAMM Name	Initial Cond.		Change		2025		Change		2050			
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%		
1	Developed Dry Land	33.08	0.91	2.18	0.06	30.89	0.85	11.68	0.32	19.22	0.53		
2	Undeveloped Dry Land	199.46	5.52	17.70	0.49	181.77	5.03	45.41	1.26	136.35	3.77		
3	Swamp	10.78	0.30	0.52	0.01	10.26	0.28	0.68	0.02	9.57	0.26		
5	Inland Fresh Marsh	43.34	1.20	1.00	0.03	42.34	1.17	2.52	0.07	39.82	1.10		
7	Trans. Salt Marsh	62.39	1.73	-5.84	-0.16	68.23	1.89	4.41	0.12	63.82	1.77		
8	Regularly Flooded Marsh	22.07	0.61	-92.73	-2.56	114.80	3.18	9.82	0.27	104.98	2.90		
10	Estuarine Beach	0.00	0.00	-0.02	0.00	0.02	0.00	0.02	0.00	0.00	0.00		
11	Tidal Flat	0.00	0.00	-23.25	-0.64	23.25	0.64	-89.04	-2.46	112.29	3.11		
12	Ocean Beach	23.87	0.66	15.32	0.42	8.55	0.24	-14.75	-0.41	23.30	0.64		
15	Inland Open Water	82.46	2.28	0.32	0.01	82.15	2.27	0.00	0.00	82.15	2.27		
17	Estuarine Open Water	33.12	0.92	26.90	0.74	6.22	0.17	-32.53	-0.90	38.75	1.07		
19	Open Ocean	2877.32	79.59	-58.86	-1.63	2936.18	81.21	-33.83	-0.94	2970.01	82.15		
20	Irreg. Flooded Marsh	227.50	6.29	116.76	3.23	110.74	3.06	95.61	2.64	15.13	0.42		
SLAMM Code	SLAMM Name	2050		Change		2075		Change		2100		Total Change	
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
1	Developed Dry Land	19.22	0.53	8.39	0.23	10.83	0.30	4.14	0.11	6.70	0.19	-26.38	-0.730
2	Undeveloped Dry Land	136.35	3.77	41.88	1.16	94.47	2.61	29.47	0.82	65.00	1.80	-134.46	-3.719
3	Swamp	9.57	0.26	1.54	0.04	8.04	0.22	4.05	0.11	3.98	0.11	-6.79	-0.188
5	Inland Fresh Marsh	39.82	1.10	2.65	0.07	37.17	1.03	4.37	0.12	32.80	0.91	-10.53	-0.291
7	Trans. Salt Marsh	63.82	1.77	29.63	0.82	34.19	0.95	12.08	0.33	22.11	0.61	-40.28	-1.114
8	Regularly Flooded Marsh	104.98	2.90	77.82	2.15	27.16	0.75	4.18	0.12	22.98	0.64	0.91	0.025
10	Estuarine Beach	0.00	0.00	-0.04	0.00	0.04	0.00	-0.27	-0.01	0.31	0.01	0.31	0.009
11	Tidal Flat	112.29	3.11	11.64	0.32	100.66	2.78	75.99	2.10	24.67	0.68	24.67	0.682
12	Ocean Beach	23.30	0.64	17.05	0.47	6.25	0.17	3.98	0.11	2.27	0.06	-21.61	-0.598
15	Inland Open Water	82.15	2.27	1.19	0.03	80.96	2.24	0.50	0.01	80.46	2.23	-2.00	-0.055
17	Estuarine Open Water	38.75	1.07	-132.55	-3.67	171.30	4.74	-42.29	-1.17	213.59	5.91	180.47	4.992
19	Open Ocean	2970.01	82.15	-71.08	-1.97	3041.09	84.12	-97.97	-2.71	3139.06	86.83	261.74	7.240
20	Irreg. Flooded Marsh	15.13	0.42	11.88	0.33	3.25	0.09	1.79	0.05	1.46	0.04	-226.04	-6.252

Table 25. SLAMM Pea Island sub-site forecast results showing hectares and percentage of class change with a SLR rate of 2m by 2100.

A visual analysis of the Pt. Peter Rd. sub-site over the four time periods (2025, 2050, 2075, and 2100) with a 2m rise in sea-level corroborates the majority of trends found in the global forecast. From initial condition to 2025, large amounts of change are seen in the immediate nearshore zone to inland areas, with large areas of swamp and moderate areas of inland fresh marsh and tidal swamp being taken over by inland migrating transitional salt marsh and regularly flooded marsh. Tidal flat also starts to appear in moderate coverage along the immediate shoreline and some areas inland. These observations are supported by Table 26 with a large increase in transitional salt marsh, regularly flooded marsh, and tidal flat of 18.78% (969.4 hectares), 4.03% (208.1 hectares), and 0.53% (27.6 hectares), respectively. Swamp, inland fresh marsh, and tidal swamp exhibited decreases of 21.71% (1120.8 hectares), 1.9% (98.1) and 0.64% (32.8 hectares), respectively. From 2025 to 2050, transitional salt marsh and regularly flooded marsh continue to increase substantially in areal extent and migration further inland (Figure 28). A moderate increase in tidal flat can also be seen in Figure 28. This movement results in large loss of swamp, inland fresh marsh and tidal swamp. Table 26 supports these observations with an increase of transitional salt marsh, regularly flooded marsh, and tidal flat of 6.59% (340.3 hectares), 20.02% (1033.4 hectares), and 4.48% (231.3 hectares), respectively. Open ocean (open water) also experienced an increase of 0.5% (25.7 hectares). Large loss in land area of swamp and decrease in inland fresh marsh and tidal swamp is shown in Table 26 of 29.81% (1538.7 hectares), 0.57% (29.2 hectares), and 0.27% (14.2 hectares), respectively. From 2050 to 2075, Figure 28 shows a large increase in regularly flooded marsh and tidal flat, mainly supplanting areas of swamp and eliminating smaller patches of inland fresh marsh and tidal swamp. Estuarine open water also starts to increase heavily along the immediate shoreline and migrate inland taking over areas previously occupied by tidal flat and regularly flooded marsh. These observations are corroborated by Table 26 with an increase in regularly flooded marsh and tidal flat of 6.27% (323.7 hectares) and 19.64% (1013.9 hectares), respectively. Estuarine open water exhibited a moderate increase of 5.25% (271.2 hectares). Swamp exhibited a fairly large decrease of 7.82% (403.5 hectares). From 2075 to 2100, substantially large change can be seen in Figure 28 with regards to increasing tidal flat and estuarine open water with regularly flooded decreasing but moving further inland. Transitional salt marsh also experiences a decrease in land area but also exhibits movement further inland, and at this stage swamp is nearly non-existent with inland fresh marsh and tidal swamp eliminated (Figure 28). Table 26 supports these observations with an increase in tidal flat and estuarine open water of 6.74% (347.8 hectares) and 24% (1239.6 hectares), respectively. Swamp exhibited a decrease of 0.06% (2.87 hectares), while transitional salt marsh and regularly flooded marsh lost 7.95% (410.2 hectares) and 23.44% (1210 hectares) of land even though showing migration inland.

Forecast 2m - Pt. Peter Rd.

SLAMM Code	SLAMM Name	Initial Cond.		Change		2025		Change		2050			
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%		
1	Developed Dry Land	3.60	0.07	0.12	0.00	3.48	0.07	2.02	0.04	1.47	0.03		
2	Undeveloped Dry Land	41.20	0.80	1.48	0.03	39.72	0.77	36.02	0.70	3.70	0.07		
3	Swamp	3067.16	59.42	1120.75	21.71	1946.40	37.71	1538.65	29.81	407.76	7.90		
5	Inland Fresh Marsh	129.13	2.50	98.14	1.90	30.99	0.60	29.19	0.57	1.80	0.03		
7	Trans. Salt Marsh	302.11	5.85	-969.38	-18.78	1271.49	24.63	-340.30	-6.59	1611.79	31.23		
8	Regularly Flooded Marsh	57.85	1.12	-208.14	-4.03	265.98	5.15	-1033.43	-20.02	1299.41	25.17		
11	Tidal Flat	0.00	0.00	-27.57	-0.53	27.57	0.53	-231.28	-4.48	258.85	5.01		
17	Estuarine Open Water	12.94	0.25	-13.49	-0.26	26.43	0.51	-9.91	-0.19	36.34	0.70		
19	Open Ocean	1485.79	28.78	-12.94	-0.25	1498.73	29.03	-25.68	-0.50	1524.40	29.53		
20	Irreg. Flooded Marsh	13.91	0.27	-21.77	-0.42	35.67	0.69	20.58	0.40	15.10	0.29		
23	Tidal Swamp	48.15	0.93	32.80	0.64	15.35	0.30	14.16	0.27	1.20	0.02		

SLAMM Code	SLAMM Name	2050		Change		2075		Change		2100		Total Change	
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
1	Developed Dry Land	1.47	0.03	1.47	0.03	0.00	0.00	0.00	0.00	0.00	0.00	-3.60	-0.070
2	Undeveloped Dry Land	3.70	0.07	3.67	0.07	0.03	0.00	0.03	0.00	0.00	0.00	-41.20	-0.798
3	Swamp	407.76	7.90	403.50	7.82	4.26	0.08	2.87	0.06	1.39	0.03	-3065.76	-59.393
5	Inland Fresh Marsh	1.80	0.03	1.80	0.03	0.00	0.00	0.00	0.00	0.00	0.00	-129.13	-2.502
7	Trans. Salt Marsh	1611.79	31.23	1198.35	23.22	413.44	8.01	410.15	7.95	3.29	0.06	-298.82	-5.789
8	Regularly Flooded Marsh	1299.41	25.17	-323.68	-6.27	1623.09	31.44	1209.99	23.44	413.10	8.00	355.25	6.882
11	Tidal Flat	258.85	5.01	-1013.89	-19.64	1272.74	24.66	-347.77	-6.74	1620.51	31.39	1620.51	31.394
17	Estuarine Open Water	36.34	0.70	-271.24	-5.25	307.58	5.96	-1239.63	-24.02	1547.21	29.97	1534.27	29.724
19	Open Ocean	1524.40	29.53	-14.48	-0.28	1538.88	29.81	-37.14	-0.72	1576.03	30.53	90.24	1.748
20	Irreg. Flooded Marsh	15.10	0.29	13.30	0.26	1.79	0.03	1.51	0.03	0.28	0.01	-13.62	-0.264
23	Tidal Swamp	1.20	0.02	1.20	0.02	0.00	0.00	0.00	0.00	0.00	0.00	-48.15	-0.933

Table 26. SLAMM Pt. Peter Rd. sub-site forecast results showing hectares and percentage of class change with a SLR rate of 2m by 2100.

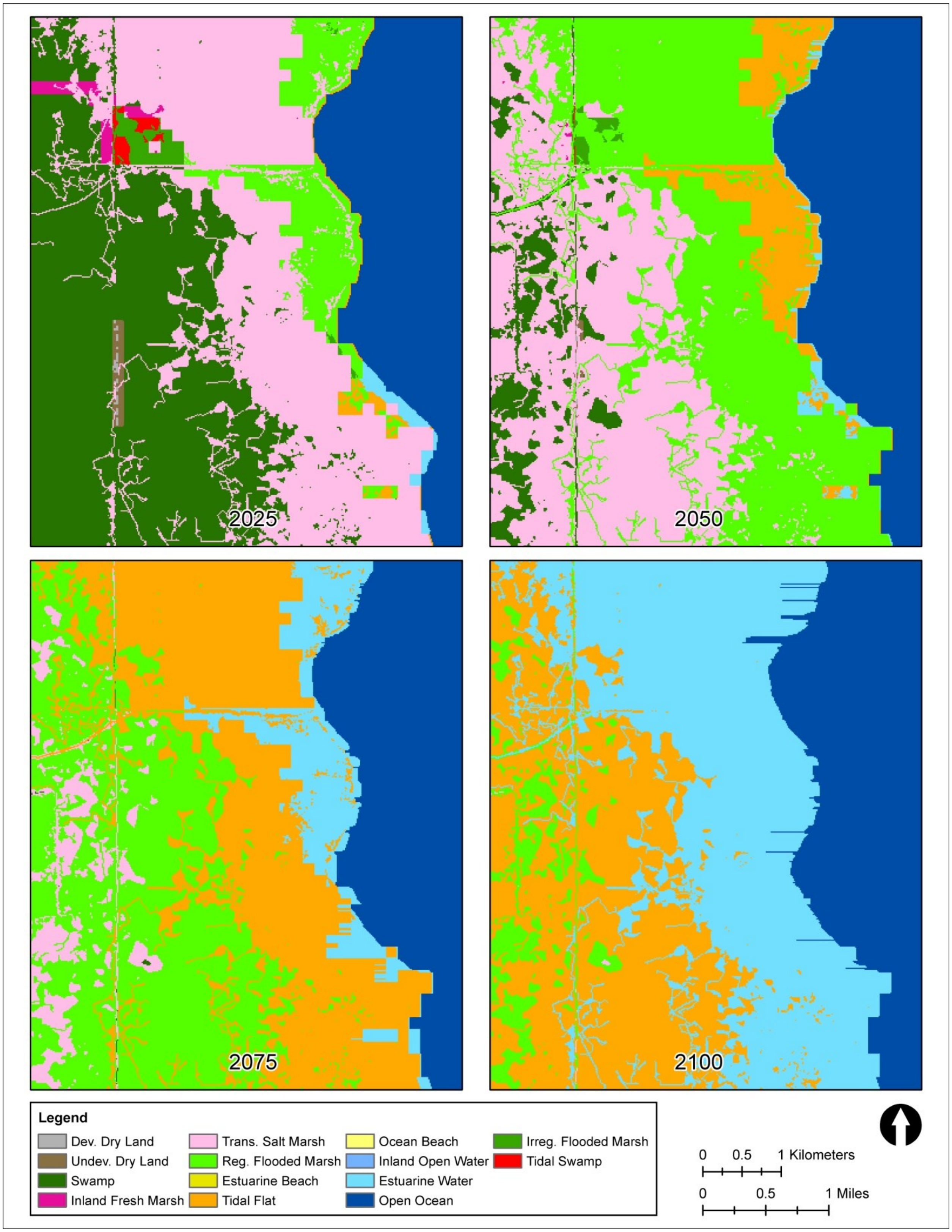

Figure 28. SLAMM Pt. Peter Rd. forecast map showing years 2025 - 2100 with a SLR rate of 2m by 2100.

5 DISCUSSION AND CONCLUSIONS

Issues of Uncertainty

Issues of uncertainty were addressed in this study in various ways. The main issues of uncertainty discussed in this section relate to the accuracy of SLAMM input data and reference data, SLAMM input parameters, model limitations and criticisms, and temporal uncertainty of SLR.

The uncertainty dealing with the accuracy of SLAMM input data and reference data were acknowledged or addressed for this study in multiple ways. While a high-resolution Lidar DEM (sub-meter resolution) would have been the preference for use in this study, a seamless 50 ft. (~15m) Lidar DEM was obtained due to time and budget constraints. Due to vertical error associated with the DEM, SLR rates for SLAMM forecast simulations were specifically chosen to be above the confidence interval of the DEM (< 25 cm or 0.25 m) (Allen, 2011, Gesch, 2009). That is why 40 cm (0.4 m) of SLR by 2100 was chosen as the baseline or lowest rate of rise. For the model hindcast, it is acknowledged that the amount of SLR between the date of the NWI map (1983) and DEM (2002) is below the confidence interval of the DEM (~6 cm or 0.06 m). This obviously raises concerns about the validity of the model hindcast results, but Lidar DEM accuracy tends to be better in areas of shore or low estuarine vegetation and degrades in areas of taller vegetation such as forested wetlands, which have a canopy that can interfere with Lidar signals reaching the ground. Nonetheless, it was determined that in order to assess model performance, the best method was to perform a hindcast analysis and compare that output mainly qualitatively with preliminary 2010 NWI data acting as reference data. It was also concluded that although there is a ~25 cm confidence interval associated with the DEM, there is also a chance, although unlikely, that the DEM could be spot-on with regards to elevation accuracy and exhibit little to no error within the coverage area. This would ease some concerns relating to DEM accuracy having negative impacts on the validity of hindcast results.

NWI maps contain a certain amount of error owing to the methodologies in which they were produced. The NWI data used as the SLAMM input data in this study was primarily from 1982-83, created by both manual and automated classification techniques, including aerial photointerpretation and limited field verification (Allen, 2011). Error is inherent in all of those classification and quality assurance techniques. A preliminary 2010 NWI map was acquired which exhibited areas of spatial incompleteness and differences in land-class codes and spatial location when compared with the 1983 NWI map. These differences made it necessary to standardize both maps for the hindcast accuracy assessment by reclassifying both sets of data into the same types of classes. Also, due to acknowledged error issues with NWI data, protection scenarios were not chosen because that would imply levels of high confidence with the spatial locations and boundaries of NWI land classes.

Limitations and issues of uncertainty exist with the SLAMM input parameters used in this study. Although historical shoreline change and marsh accretion and erosion data are available for areas of coastal North Carolina, data for the estuarine environment specific to the study area are few (Allen, 2011). Change analyses for the estuarine environment are spatially variable and exhibit inconsistent time frames, context, and methodologies (Allen, 2011). Many of the input parameters were determined from using various types of sources consisting of recent and ongoing theses supervised by ECU faculty primarily in the Departments of Geology, Biology, and Geography, studies sponsored by private and government agencies, and previous SLAMM studies conducted in estuarine environments similar to those found in eastern North Carolina. Some parameter values were stand-alone rates and others were produced by using a combination of sources and averages of certain parameters. To avoid using questionable parameter values consisting of little or no data, SLAMM default parameters were used instead. The rational was that SLAMM can be run with default parameter values and that these default parameter values were instituted by developers of the model and represent values concluded from previous SLAMM studies, as well as various other sources.

Temporal uncertainty of SLR was addressed within the study by applying multiple rates of rise over varying periods of time in order to assess the full-range of possible scenarios. Given the sensitivity of the subject of SLR and its impact on coastal environments, a relatively conservative range of possible rise heights was used. Using potential SLR rates by 2100 specific to North Carolina supported by The North Carolina Resources Commission's Science Panel on Coastal Hazards, SLR rates of 0.4 m, 0.7 m, 1 m, 1.4 m, and 2 m were chosen. A SLR rate of 0.4 m was used as a low-end baseline projection representing no expected SLR acceleration. A 2 m rise in SLR was deemed as high-end possibility and would only occur with rapidly accelerating SLR stemming from high rates of warming and ice sheet melting. SLAMM also assumes a linear relationship between time and SLR, essentially using a uniform acceleration of SLR and does not take into account a non-linear relationship where there could be accelerated SLR at different time increments.

There are some criticisms and limitations of SLAMM, mainly how it generalizes complex processes and feedback mechanisms that affect coastal marsh response to SLR. SLAMM simplifies and ignores certain processes and factors that affect estuarine ecosystem response to SLR (Allen, 2011, Craft, et al., 2009; McLeod, Poulter, Hinkel, Reyes, & Salm, 2010; Clough, 2010). The affects of variable storm and flood events that influence marsh development and change are also not accounted for. SLAMM is unique in that it represents a balance between one-dimensional mass-balance and complex landscape modeling techniques (Allen, 2011). Although biological feedback mechanisms such as accretion are simplified in SLAMM, the model is essentially a rational way to represent the MEMII (Marsh Equilibrium Model) model which estimates biomass as a function of depth below mean high tide, forecasting changes in the relative elevation of the marsh surface and response to SLR (Allen, 2011).

SLAMM Studies

While there have been other recent studies utilizing SLAMM along the U.S East Coast, there are many differences between this research and other SLAMM studies. Many recent SLAMM studies have used SLR scenarios recommended by the IPCC and have not used SLR rates and parameters specific to the areas where the studies were conducted (South Atlantic Landscape Conservation Cooperative; Wu, Yarnal, & Fisher, 2002; Warren Pinnacle Consulting, Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Saint Andrew and Choctawhatchee Bays, 2011; Warren Pinnacle Consulting, SLAMM Analysis of Grand Bay NERR and Environs, 2011.). The IPCC SLR rates are based upon global scenarios of change, and do not take into variable characteristics at the local to regional levels. The SLAMM study conducted by the South Atlantic Landscape Conservation Cooperative (SALCC) uses the IPCC A1FI emissions scenario which assumes a world of high economic growth, a global population that peaks in mid-century, and rapid development of new and more efficient technologies; as well as still highly fossil fuel dependent (Climate Change 2007: Synthesis Report, 2007; South Atlantic Landscape Conservation Cooperative). The SLR rates in the SALCC were fairly aggressive and not specific to the study area which was the southeastern coast of the U.S. The implementation of strictly global parameters caused multitude of artifacts to occur on the

SLAMM outputs represented by shorelines and wetlands moving in a uniform direction which does not reflect the way these systems change in reality.

As in this study other recent SLAMM studies have utilized hindcasting, however, they were utilized in different ways. Hindcasting using SLAMM was performed near Grand Bay, TX by Warren Pinnacle Consulting in order to calibrate SLAMM to reflect current conditions. Their hindcast output was utilized as a guide to calibrate their parameter values and determine the validity of those values (Warren Pinnacle Consulting, SLAMM Analysis of Grand Bay NERR and Environs, 2011.). This study utilized the hindcasting in order to run an accuracy assessment against current conditions in order to assess model performance.

Conclusions and Future Work

The purpose main of this study was to assess the response of wetlands to future SLR on the regional scale using SLAMM. The main analysis component was focused on the model hindcast simulation to determine model performance by comparing hindcast simulation output against current wetland data. Even though certain levels of error and uncertainty were acknowledged to be inherent within the input data, hindcast results qualitatively showed that SLAMM did a fair job in predicting current wetland conditions relating to spatial patterns and trends. The hindcast simulation output reflecting current condition was deemed acceptable to use for SLAMM forecasting with results corroborated in the hindcast accuracy assessment. Although quantitative results were provided as an output feature and were analyzed, the exact amount of estuarine marsh area that may be lost with SLR was not the main point of this study. The main emphasis is placed on how well SLAMM qualitatively captures the general trends and spatial movement patterns of wetlands when exposed to future rises in sea-level on the regional level. When analyzing the results of the model hindcast in this way, SLAMM did do a fairly good job at predicting those trends. With higher-quality input data and more time, it is the author's opinion that results yielded in this study would have been better.

While sub-sites were analyzed in this study at a local scale, its purpose was to show SLAMM capabilities and how different parameters could be applied at specific areas within the study that exhibit different conditions than those of the regional study area as a whole. All models have inherent limitations and sources of error. From the findings in this study, it is the author's recommendation that SLAMM not be utilized as a stand-alone tool for planning purposes. However, used in conjunction with other models and tools that can bridge the gap in the complex processes and feedback mechanisms that affect coastal marsh response to SLR that the model lacks, SLAMM could be a useful tool in mitigating the effects of future SLR.

With more time and better resources, I would have liked to concentrate on developing more fine-tuned input parameters, obtain a higher resolution LiDAR DEM, preferably sub-meter resolution, and obtain more complete and recent NWI wetland map for my study site. I feel that replicating my methodology with these three improvements would lead to more accurate results. The next student or researcher following me this area should concentrate on getting higher resolution LiDAR DEMs, researching and fine-tuning input parameters, and obtaining updated wetland maps. A future assessment on how DEMs of different resolutions affect SLAMM forecasting accuracy could be really interesting and could also help inform and potentially improve future SLR simulation modeling.

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Appendix A: ACCUARCY ASSESSMENT

Preprocessing Steps

Following SLAMM hindcast simulation, the 2010 hindcast raster output and 2010 SLAMM raster layer coded from preliminary 2010 NWI were analyzed to determine the accuracy of the SLAMM hindcast simulation. Before an accuracy assessment could be generated, some preprocessing had to take place to ensure that both raster layers had the same spatial reference and horizontal resolution. This preprocessing step is important because analyzing data layers on the cellular level with different spatial references and horizontal resolutions can lead to results with more uncertainty, adding higher levels of error that were already present within the source data to begin with.

After the SLAMM hindcast simulation was executed, the resulting output ASCII file was converted into an ERDAS Imagine raster format so that it could be imported into ArcGIS 10 for future analysis. This conversion was achieved by using the following method in ArcGIS 10: ArcToolbox → Conversion Tools →To Raster → ACSII to Raster. Following ASCII to raster conversion, the raster layer projection needed to be defined because of a missing spatial reference. The spatial reference for the raster layer was defined to WGS 1984 UTM Zone 18 North with ArcGIS 10 using the following method: ArcToolbox → Data Management Tools → Projections and Transformations → Define Projection. Following ASCII to raster conversion, the preliminary 2010 NWI SLAMM raster layer was resampled from a cell size of 50m to 15m to match the horizontal resolution of the 2010 hindcast raster using the following method: ArcToolbox → Data Management Tools → Raster → Raster Processing → Resample. For the resampling, a nearest neighbor resampling technique was used. This technique was chosen because it appropriate to handling discrete thematic data (i.e., land-use classification) since it will not change the values of the cells.

Extraneous land from the 2010 NWI SLAMM raster layer was masked out using the 2002 DEM as a mask layer. This step was achieved in ArcGIS 10 using the following method: ArcToolbox → Spatial Analyst Tools→ Extraction → Extract by Mask. It was necessary to clip out lands in the preliminary 2010 NWI SLAMM raster layer that extended beyond the extent of land in the 2010 hindcast raster layer for future spatial analysis. The DEM used in the hindcast simulation did not include all land that was present in the preliminary 2010 NWI SLAMM raster layer. SLAMM does not track cells without elevation and essentially masks out land in the NWI raster input layer that is outside of the extent of land in the DEM. In order to get an accurate depiction of model performance and avoid skewed analysis results, both the 2010 hindcast raster output layer and 2010 NWI SLAMM raster layer had to have the same land cover extent to be used for future analysis.

When the extraneous land was masked from the 2010 NWI SLAMM raster Layer using the DEM, it also removed all of the water classes as well. The same water classes need to be added back into the 2010 NWI SLAMM raster minus the extraneous land that was already taken out. This was achieved in ArcGIS10 using the following method: ArcToolbox → Spatial Analyst Tools→ Extraction → Extract by Attributes. All open water classes from both the 2010 hindcast raster output layer and the preliminary 2010 NWI SLAMM raster layer were extracted. Next, both raster layer water classes were then converted from raster format to vector polygon format in ArcGIS 10 using the following method: ArcToolbox → Conversion Tools → From Raster → Raster to polygon. Once both water raster layers were converted to vector polygon format, both layers were clipped to the same extent using the following method in ArcGIS 10: ArcToolbox →

Analysis Tools → Extract → Clip. The resulting two water polygon clip layers were then merged into a single poygon layer in ArcGIS 10 using the following method: Data Management Tools→ General → Merge. This merge was necessary in order to fill any spatial water gaps between the 2010 hindcast and preliminary 2010 NWI SLAMM polygon layers. The resulting merged water polygon layer was then edited using the Editor Toolbar in ArcGIS 10 in order to redefine the boundaries of the water classes present in the original preliminary 2010 NWI SLAMM raster layer.

Once the original water boundaries were redefined in the merged water polygon layer, a new field ("VALUE") was added to the attribute table of the merged water polygon layer and water class SLAMM code values were populated into the correct cells. This step was necessary so that once the merged water polygon layer is converted into raster format it can merge correctly with the land-masked preliminary 2010 NWI SLAMM raster layer. ArcGIS 10 was then used to convert the merged water polygon layer to raster format based on the newly created "VALUE" field with the following method: ArcToolbox → Conversion Tools → To Raster → Feature to Raster. The new water raster layer was then merged with the land-masked preliminary 2010 NWI SLAMM raster layer in ArcGIS 10 using the following method: Data Management Tools → Raster → Raster Dataset → Mosaic to New Raster. The resulting output was a new preliminary 2010 NWI SLAMM raster layer that contained the same land cover classifications as the original layer, but also matches the extent of land contained within the 2010 hindcast raster layer.

In order for future accuracy assessment and spatial analysis processing to function properly and effectively, developed and undeveloped dry land classes were removed from the 2010 hindcast raster layer. Since the preliminary 2010 NWI SLAMM layer did not contain developed and undeveloped dry land classes, they were extracted out of the 2010 hindcast raster layer to avoid confusing in future processing steps. The extraction of developed and undeveloped dry land classes (SLAMM classes 1 and 2) from the 2010 hindcast raster layer was achieved using the following method in ArcGIS 10: ArcToolbox → Spatial Analyst Tools → Extraction → Extract by Attributes.

Due to inconsistencies and errors associated with NWI-to-SLAMM recode methods and NWI maps themselves, it was necessary to aggregate the SLAMM classes from both raster layers into fewer classes representing the major estuarine/coastal zones dominant throughout the North Carolina coastal region. The aggregation of classes was achieved by reclassifying SLAMM classes into four new classes: Forested Wetland, Estuarine Emergent Wetlands, Shore, and Water. The following method using ArcGIS 10 was utilized for the reclassification: ArcToolbox → Spatial Analyst Tools → Reclass → Reclassify. For the reclassification NWI maps, satellite imagery and spatial distribution were used in order to qualitatively determine which SLAMM classes fall into what new recode class. SLAMM classes that contained majority tree cover and shrub-scrub vegetation, and were located further from the shoreline, were classified as *forested wetlands*. SLAMM classes with that contained majority emergent wetland vegetation and few areas of shrub-scrub vegetation, and were located in the nearshore zone, were classified as *estuarine emergent wetlands*. SLAMM classes that contained majority unconsolidated shore were classified as *shore*. SLAMM classes that contained majority open water or open ocean were classified as *water*. Following completion of the reclassification of the two raster layers into aggregated classes, an accuracy assessment and further spatial analysis was ready to be conducted.

Geoprocessing Steps

ERDAS Imagine 2011 software was used to perform an accuracy assessment to determine model performance based on the results of the SLAMM hindcast simulation. In order for the two raster layers to be used properly in the *Accuracy Assessment* tool with ERDAS Imagine, they had to be converted from signed 8-bit continuous raster layers into unsigned 8-bit thematic raster layers for the tool to be as effective and accurate as possible. This data processing step helps to define discrete boundaries between the different land classes, as well as the possible value range within each cell. Converting the two raster layer data types from signed 8-bit to unsigned 8-bit ensured exclusion of any negative values, changing the range of possible values in each cell from -128 – 127 (signed 8-bit), to 0 – 255 (unsigned 8-bit) (ESRI Help). A cell in continuous raster data contains a floating point value that represents continuous data, such as the elevation of a certain place. A cell in discrete raster data contain integer values and represent a finite number of possible values, such as a specific land cover class number. The following method using ERDAS Imagine 2011 was utilized for the data type conversion of both raster layers: Raster → Subset & Chip → Create Subset Image.

Once the two raster data layers were converted from signed 8-bit continuous raster layers into unsigned 8-bit thematic raster layers, the *Accuracy Assessment* tool within ERDAS Imagine was ready to be run using the following method: Raster → Supervised → Accuracy Assessment. Once the *Accuracy Assessment* tool was opened up, the following parameters were used:

Inputs:

Classified File: 2010 SLAMM hindcast raster layer

Reference File: Preliminary 2010 NWI SLAMM raster layer

1. *Class Value Assignment Options Dialogue Box*

Window Size: 3

Majority Threshold: 7

A value of 3 used for window size represents the size of the window used for determining the class value and in this case, a 3 x 3 cell window was utilized. A majority threshold value of 7 was used in order to set the minimum number of class values needed to create a majority of class values in the 3 x 3 cell window (ERDAS Help). This means that in order for the window to assign a group of 9 pixels a class value, roughly 77% (7 out of 9) of the pixels or greater have to contain the same class value.

2. *Create/Add Random Points*

   Search Count: 3000

   Number of Points: 300

   Distribution Parameters: Equalized Random; Selected classes 1 through 4

The equalized random distribution parameter was used in order to generate the same number of randomly placed points in each class for a normal distribution throughout the entire amount of generated points. The sampling protocol generated 180 sites (approximately 45 points for each class), an acceptable sample size given the relatively confined extent and limited areal coverage of non-water classes encountered with the search windows exhausting the search count quickly and the creation of points that contained a "0" class value which is not associated with a specific land class in this analysis (Figure 29).

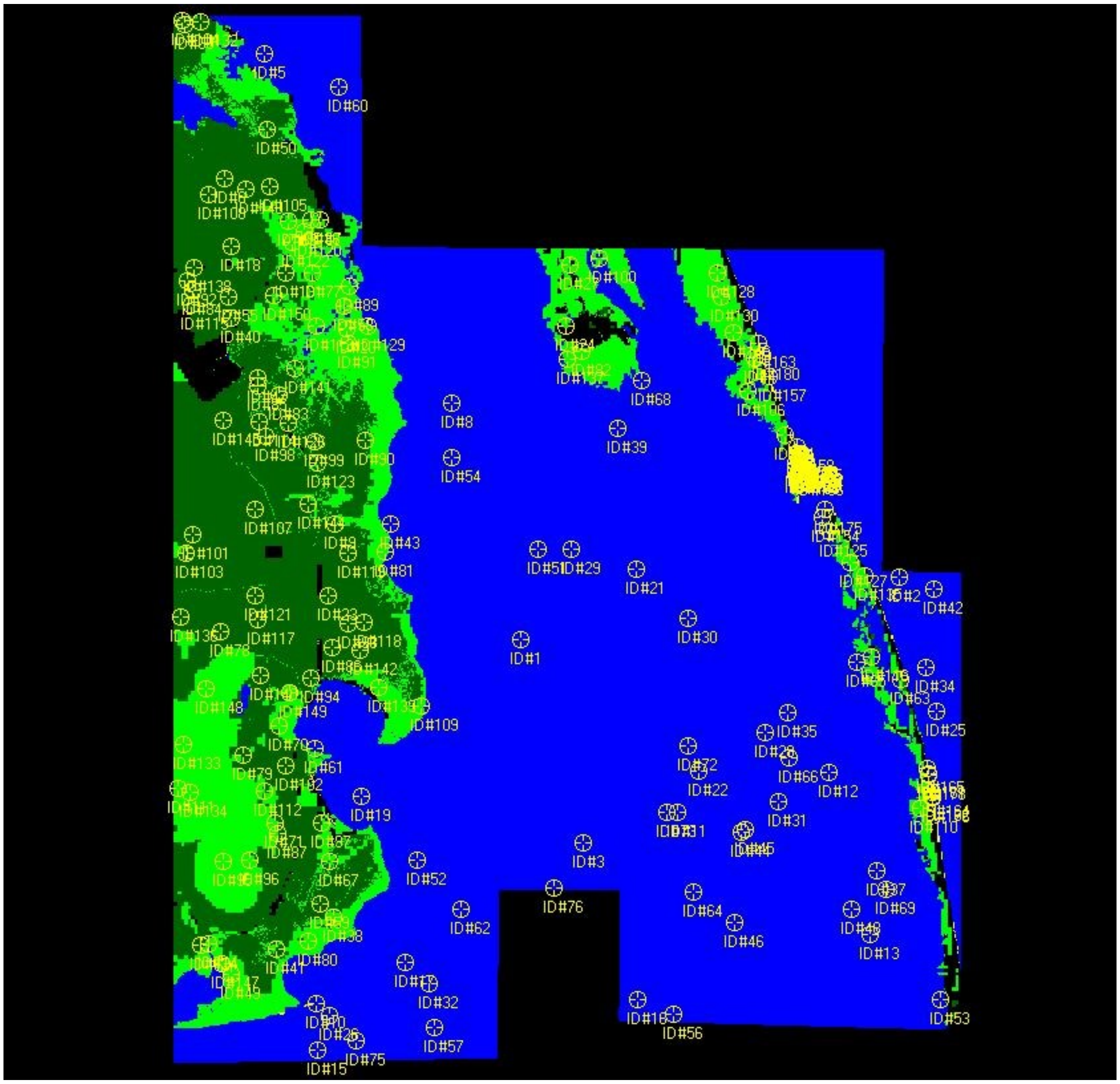

Figure 29. Map showing an example and the location of accuracy assessment points.

Once all of the accuracy assessment parameters were inserted, the random points were created for each class and added on top of the 2010 SLAMM hindcast raster layer using the “Show All” option. The “Select Viewer” icon was chosen and the cursor was moved into the current window displaying the 2010 SLAMM hindcast raster layer in order to select the window for viewing the accuracy assessment points. The “Show Class Values” option was chosen in order to momentarily show class values represented by the accuracy assessment points, class values were sorted in ascending order within the “Class” column, and then the “0” class points were deleted. The “Hide Class Values” option was then chosen in order to mask class values in the “Class” column for the accuracy assessment. The reference file (preliminary 2010 NWI SLAMM raster layer) was then added to the viewer window on top of the classified file. With the accuracy assessment points displayed on top of the reference file, each point class value was entered into the “Reference” column in the accuracy assessment table. Once both the “Class” and “Reference” columns were completely filled out, an accuracy report was generated that included an error matrix, accuracy totals, and kappa statistics.

Post Accuracy Assessment Geoprocessing/Spatial Analysis

Following the accuracy assessment which allows for the evaluation of a classified thematic raster image by generated random points representing specific land class values by comparing the classification to reference data layer, further spatial analysis was conducted to determine model performance on the cellular level. A cell by cell change analysis was performed using ERDAS Imagine utilizing the following method: Raster → Thematic → Matrix Union. The *Matrix Union* tool produces an output raster file that contains classes that indicate how the class values from two input thematic raster layers overlap (ERDAS Help). The following parameters were selected for use in the *Matrix Union* tool:

Inputs:

Thematic Image 1: 2010 SLAMM hindcast raster layer

Thematic Image 2: Preliminary 2010 NWI SLAMM raster layer

Ignore Zero in Stats

Output Data Type: Unsigned 8-bit

Area: Intersection (only uses image area that both input thematic raster files have in common)

Since the *Matrix Union* tool only produces an image output showing areas of both class agreement and disagreement, it was necessary to use the *Summary Report of Matrix* tool to get statistics that compare the value areas between the two thematic raster files. The *Summary Report of Matrix* tool is similar to the *Matrix Union* tool except that instead of producing an output image, it produces cross-tabulation statistics that include number of points or cells in common, number of acres (or hectares or square miles) in common, and percentages. The *Summary Report of Matrix* tool was performed using ERDAS Imagine utilizing the following method: Raster → Thematic → Summary Report of Matrix. The parameters chosen include:

Inputs:

Zone File: 2010 SLAMM hindcast raster layer

Class File: Preliminary 2010 NWI SLAMM raster layer

Output: Output Report Only (.txt)

Options: Ignore Zeros; Omit Empty Classes; Omit Empty Zones

The input "zone" file within the *Summary Report of Matrix* tool is essentially used as a classified layer where each class in the layer becomes an analysis category. The tool then calculates statistics for each land class based on the occurrences of land classes from the "class" file. The output report consists of zonal statistics that include majority, mean, median, minimum, range, diversity, standard deviation, majority count, and majority percent. These zonal statistics are calculated for all combinations of class comparisons between the "zone" file and "class" file.

Appendix B: SLAMM

Model Preparation

SLAMM6 has been upgraded from previous versions to create a user-friendly, graphical interface that is visually appealing and easy to navigate. This new interface may appear more complex than older versions because many features that were once hidden within the source code have been rendered as graphical options that enhance usability when running the model.

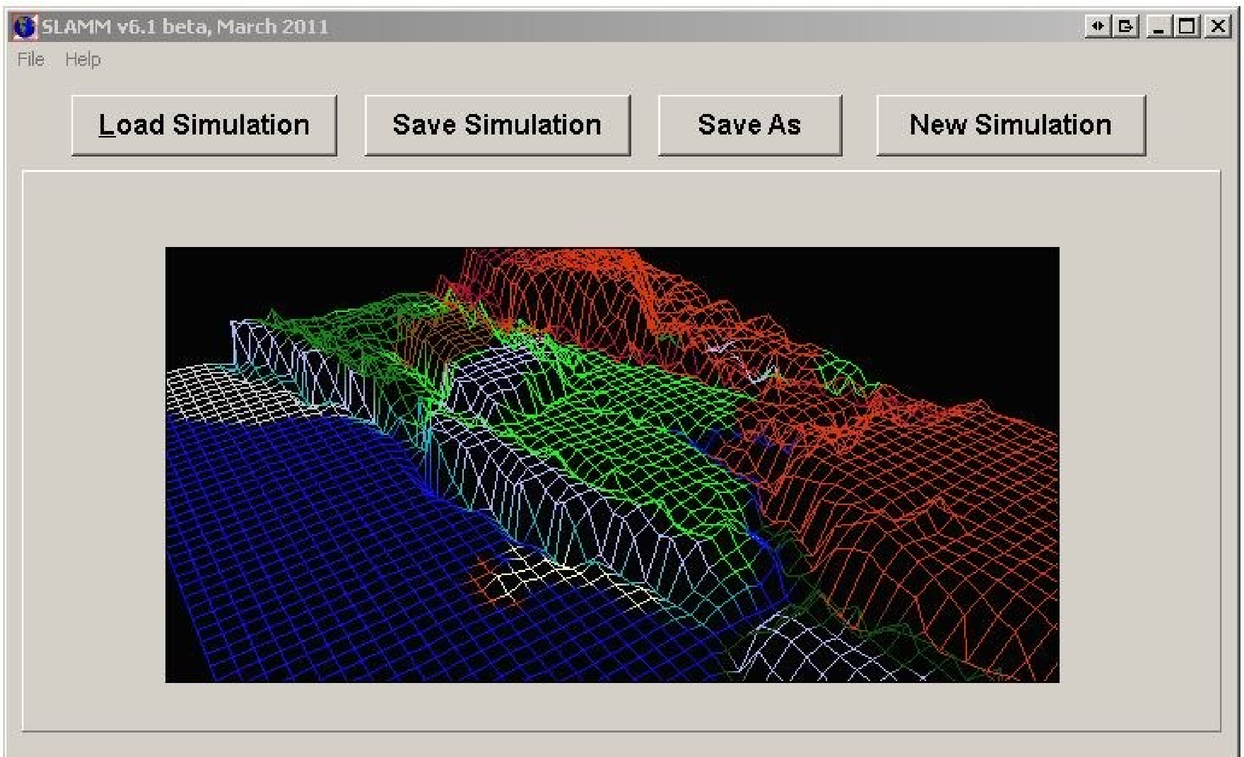

Figure 30. SLAMM opening screen.

Preparing to operate SLAMM6 can be laborious and time-consuming. Specific input data and parameter values must be imported into the model in order for it to run correctly. The SLAMM6 graphical interface contains multiple options for data input. Each of these options has their own specific data requirements and formats. SLAMM6 is activated by an executable file that opens the SLAMM6 opening screen presenting the user with several options (Figure 30):

1. *Load Simulation* – Loads an existing SLAMM6 project.

2. *Save Simulation* – Saves a current project in SLAMM6 binary or text formats.
3. *Save As* – Saves a project under a different name or file type.
4. *New Simulation* – Starts a new SLAMM6 project.

When starting a new project, make sure to set up the correct input data using the *File Setup, Site Parameters* and *Elevation Statistics* options before executing the model. These options are part of the expanded opening screen (Figure 31). If loading an existing SLAMM6 project, navigate to the folder containing the file .SLAMM6 extension and open it. The existing project will be loaded and all parameters will be the same and when they were last saved.

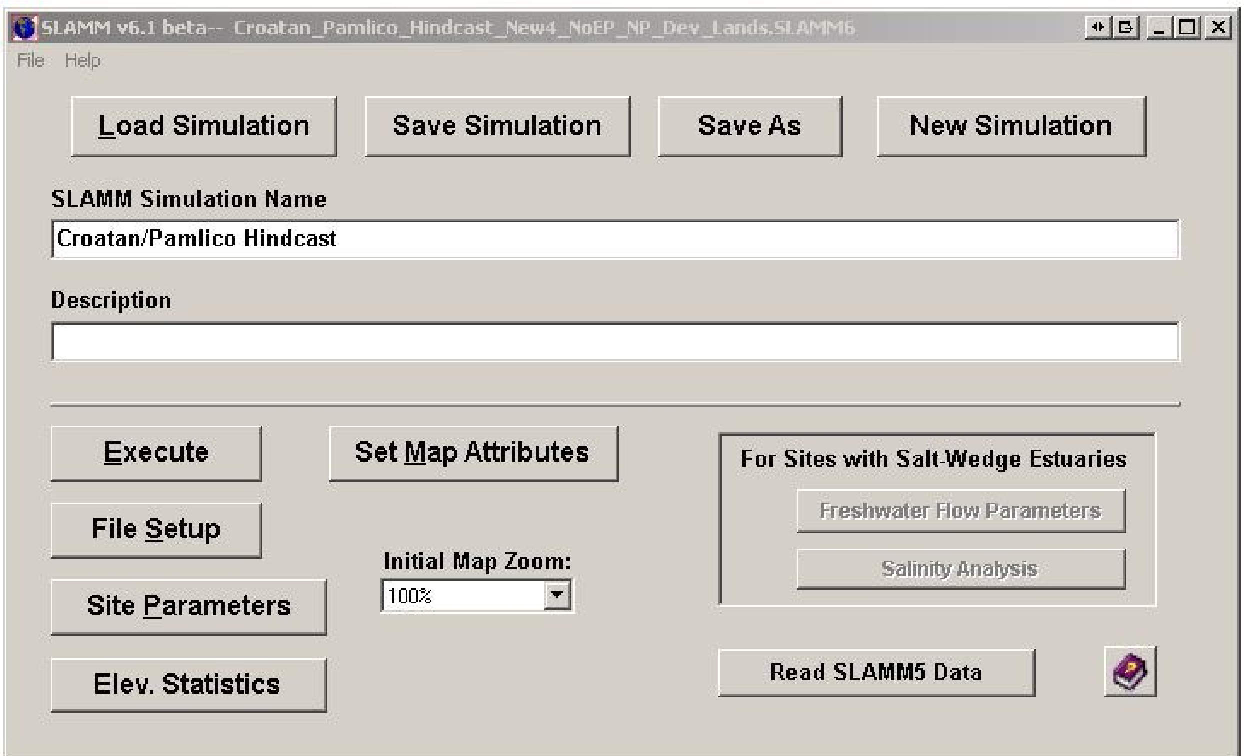

Figure 31. SLAMM expanded opening screen.

The *File Setup* option opens the file setup screen (Figure 32) and allows the user to specify the locations of input data files and choose amongst a variety of memory management options. The file setup screen allows the user to input various ASCII raster GIS files into a project. All input raster data must have the same dimensions, projections, and locations for the model to produce acceptable outputs. The various options utilized for this research within the file setup screen include:

1. *DEM File (elevation)* – Links the location of the DEM data layer to the project. This data is required to run a simulation and elevation units are meters above the vertical datum (normally NAVD88).
2. *SLAMM Categories (NWI)* – Links the location of the converted NWI wetland data layer to the project. This data is required to run a simulation and numeric values within the data layer correspond to SLAMM categories.
3. *SLOPE File* – Links the location of the slope data layer to the project. This data is required to run a simulation and units are in angular degrees.

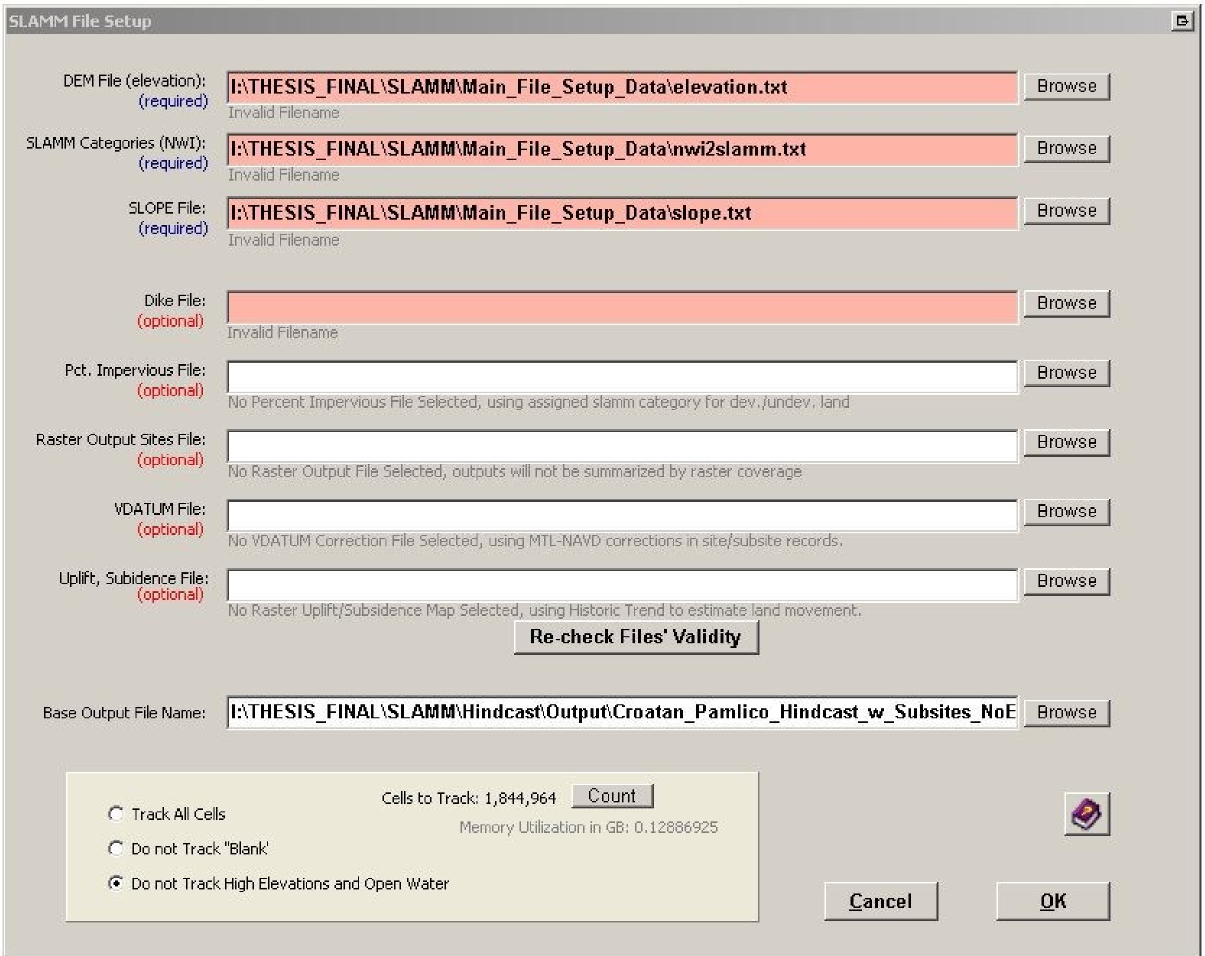

Figure 32. SLAMM file setup screen.

The *Site Parameters* option opens the site parameter screen and allows the user to specify dates of main input data, accretion and erosion rates, historic SLR trend, etc., for a global site and sub-sites. These parameters can be applied to an entire raster map, as well as sub-sites within the main raster map that may contain unique parameters. The sub-sites can be defined by delineating their boundaries with a polygonal GIS data layer. The various parameters utilized for this research within the site parameters screen include:

1. Description – The name of main site or sub-site.
2. NWI Photo Date – The year that the U.S. Fish and Wildlife National Wetland Inventory aerial photography was taken for wetland mapping.

3. DEM Date – The year the elevation data layer was created.
4. Direction Offshore – The direction of open water from the shoreline of the main site or sub-sites. Only a single value is permitted per global site and sub-site.
5. Historic Trend – The historic rate of SLR in mm/year. This parameter is used to estimate land subsidence or uplift unless a raster data file of land movement is specified (e.g., the option to use an *Uplift, Subsidence File* located within the file setup screen and was not used in this research.)
6. MTL minus NAVD88 – The elevation correction based on the mean tide level. Values of this correction can be varied across the main site and designated with sub-sites.

Hindcast Simulation

Historical simulations using SLAMM were conducted in order to determine the predictive power of the model. This was achieved by starting the simulation at the photo date of the oldest NWI wetland data and projecting SLR through to the present date. For this project, the NWI wetland data is from 1983 and the present date used is 2010. Project-specific methodology using SLAMM6 for historical simulations is as follows:

1. *New Simulation* located on the SLAMM6 opening screen was chosen and an appropriate name was given, in this case 'Croatan/Pamlico Hindcast'.
2. *File Setup* located on the expanded opening screen was used to import the main data files required to run the model. The imported data consisted of elevation, NWI, and slope ASCII raster files.
    a. The option "Do not Track High Elevations and Open Water" was turned on because it was unnecessary to track cells of open water and those that are 8 meters and above in relation to MTL.

3. *Site Parameters* located on the expanded opening screen was used to input specific site and sub-site parameter values used for the hindcast simulations.
4. *Elevation Statistics* located on the expanded opening screen was used to input specific elevation thresholds/ranges and units of measure for each SLAMM land category for model conversion during hindcast simulation.
5. The *SLAMM Execution* screen was then used to setup different parameters before the hindcast simulation was executed.
    a. A customized SLR scenario of 0.4 meters of rise by 2100 was selected as the linear SLR projection for the hindcast based on historical SLR trend of roughly 3mm/year within the study area.
    b. The protection scenario "Don't Protect" was chosen in order to examine the full extent of potential change between classes.
    c. The option to "Run Model for NWI Photo Date (T0)" was chosen and is required for hindcast simulations. The specified year of 2010 was chosen for the "Run Model for Specific Years" option.
    d. The various options, "No-Data Elevs Loaded as Blanks" and "Use Connectivity Algorithm", were chosen before hindcast simulation execution.
    e. The option to "Save Output for GIS" was chosen for future data management and analysis purposes. Word documents consisting of hindcast output maps and ASCII raster files were created after each simulation run.
6. The SLAMM hindcast simulation setup was then validated for completeness and then executed.

Forecast Simulation

Based on the results from the accuracy assessment and cellular comparison analysis, it was determined that SLAMM accuracy from the hindcast simulation was acceptable in determining predictive power of the model for future SLR projections beyond 2010 (see “Results” section). The SLAMM hindcast simulation output had some spatial accuracy issues when compared to the preliminary 2010 NWI SLAMM layer, due largely to errors inherent with input data and parameters (i.e., accretion and erosion rates), but the 2010 SLAMM hindcast simulation output did manage to qualitatively capture the general trends inherent in the preliminary 2010 NWI SLAMM layer. Project-specific methodology using SLAMM6 for the forecast simulation is as follows:

7. *New Simulation* located on the SLAMM6 opening screen was chosen and an appropriate name was given, in this case ‘Croatan/Pamlico Forecast’.
8. *File Setup* located on the expanded opening screen was used to import the main data files required to run the model. The imported data consisted of elevation, NWI, and slope ASCII raster files.
    a. The option “Do not Track High Elevations and Open Water” was turned on because it was unnecessary to cells of open water and those that are 8 m and above in relation to MTL.
9. *Site Parameters* located on the expanded opening screen was used to input specific site and sub-site parameter values used for the forecast simulations.
10. *Elevation Statistics* located on the expanded opening screen was used to input specific elevation thresholds/ranges and units of measure for each SLAMM land category for model conversion during forecast simulation.

11. *Set Map Attributes* located on the expanded opening screen was used to create sub-sites for the forecast simulation. The two sub-site locations consisted of an area around Pt. Peter Rd. on the Albemarle-Pamlico Peninsula and an area around Pea Island on the Outer Banks.
12. The *SLAMM Execution* screen was then used to setup different parameters before the hindcast simulation was executed.
    a. Customized SLR scenarios of 0.4, 0.7, 1, 1.4, and 2 meters of rise by 2100 were selected as the linear SLR projections for the two different forecast runs based on potential SLR projections from the North Carolina Resources Commission's Science Panel on Coastal Hazards.
    b. The protection scenario, "Don't Protect", was chosen for this model run in order to examine the full extent of potential change between classes.
    c. The option to "Run Model for Specific Years" was chosen for both model runs and the years 2025, 2050, 2075, and 2100 were selected.
    d. For both model runs the various options, "No-Data Elevs Loaded as Blanks" and "Use Connectivity Algorithm", were chosen before forecast simulations were executed.
    e. For both model runs the option to "Save Output for GIS" was chosen for future data management and analysis purposes. Word documents consisting of forecast output maps were created after each SLR scenario.
13. The SLAMM forecast simulation setup was then validated for completeness and then executed for the model run.