Modeling Sea Level Rise and Wetland Migration Potential: Proactive Land-Use Planning for the Pamlico Sound

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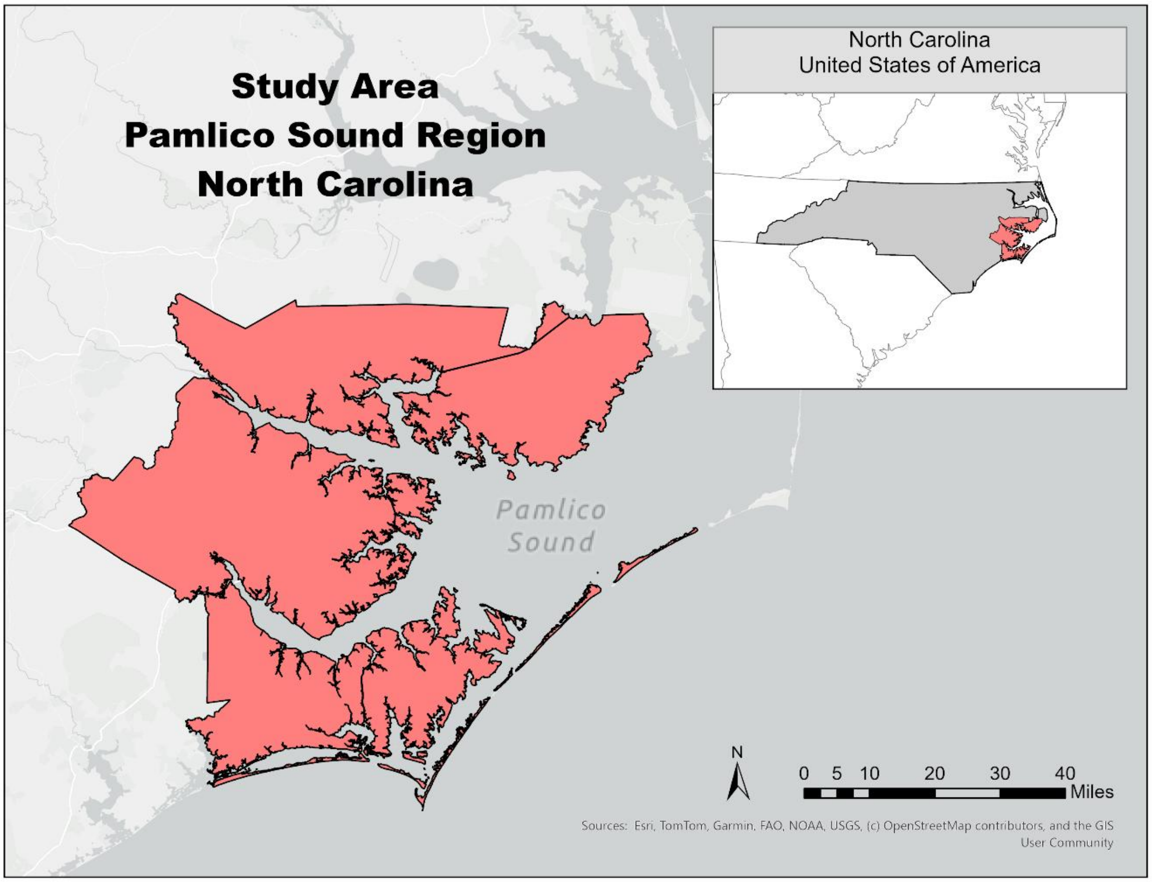
Abstract

Sea level rise (SLR) continues to threaten coastal wetlands in North Carolina's Pamlico Sound, harming critical ecosystem services and increasing the risk of wetland loss through inundation and coastal squeeze. This study employs GIS to quantify projected wetland loss under three sea level rise scenarios (2, 4, and 7 feet by 2100) and to identify adjacent areas most suitable for inland marsh migration. Results found substantial wetland loss across all scenarios, especially among estuarine systems, with approximately one-quarter, one-third, and one-half of all existing wetlands inundated under 2, 4, and 7 feet of SLR, respectively. The findings highlight the importance of proactive land-use planning, conservation, and nature-based adaptation strategies to help best facilitate long-term wetland resilience.

Keywords: Sea Level Rise, Wetlands, Marsh Migration, Coastal Squeeze, Wetland Loss, Adaptation Planning, Climate Change, Pamlico Sound, North Carolina.

Table of Contents **Pg. #**

List of Figures **Pg. #**



Introduction

North Carolina's Pamlico Sound is one of the nation's largest and most vital coastal regions, supporting wetlands, fisheries, and communities across the eastern plain (APNEP, n.d.). Wetlands act as vital habitats to support regional biodiversity, with research showing that over half of all commercially important fish and shellfish in the US depend on them to survive and reproduce (Johnson et al., 2019). They offer storm protection valued at over $25 billion dollars annually, provide nearly $300 million annually in carbon storage and sequestration alone, and support North Carolina's multi-billion-dollar fishing and tourism industries (NCDWR, 2025; APNEP, 2016). Yet, as climate change accelerates and sea levels continue to rise, coastal environments face increasing risk of degradation, with SLR of 0.9 meters projected to displace 4.3 million people in the US and just under 200,000 in North Carolina alone (Hauer et al., 2016). With SLR in the American Southeast projected to exceed one foot by 2050, immediate, informed action must be taken to sustain the natural systems and services that this region relies on so heavily (NCDEQ, 2024).

Existing research shows that SLR can produce a range of harmful impacts on both coastal ecosystems and communities. Tourism, an industry which added $37 billion to North Carolina's economy in 2024 alone according to the Department of Commerce, is threatened by accelerating beach erosion that damages properties and reduces recreational space (NC Commerce, 2025; Lopez, 2024). Rising seas also jeopardize coastal agriculture by washing away fertilizers and increasing groundwater salinity, which both reduce crop yields. In the Pamlico Sound, Tapas et al. (2024) found that fertilizer runoff contributes to elevated nitrate levels, driving harmful algal blooms that deplete oxygen and block sunlight needed for aquatic wildlife and vegetation (p.2). Beyond these impacts, SLR also facilitates saltwater intrusion (SWI), where saline water moves into freshwater aquifers and contaminates groundwater. This process not only decreases drinking water quality but also causes widespread tree mortality in forested coastal wetlands, creating "ghost forests" of standing and fallen dead trees along the coastal plain (Ury et al., 2021, p.1).

While many coastal ecosystems can be lost due to inundation or SWI, wetlands possess the natural ability to migrate inland when faced with sea level rise, a process known as marsh migration. Historically, marsh migration allowed wetlands to adapt sustainably to gradual shifts in sea level. This process has been studied in the greater Pamlico Sound region, with rising seas having already caused 19,000 hectares of coastal forests to transition to salt marsh and open water along the Alligator River (Ury et al., 2021, p.6). However, as SLR rates continue to accelerate, wetlands are running out of time and space to migrate inland. Hard infrastructure like seawalls, roads, and housing developments block many of these migration corridors, trapping wetlands between human development and a continuously rising sea (Johnson et al., 2019). This process, known as coastal squeeze, greatly limits the ability of wetlands to persist and adapt naturally, highlighting the need for proactive land-use planning towards migration corridors.

To address the challenges associated with SLR in the Pamlico Sound region, this study seeks to answer the following question: How will sea level rise influence wetland loss and migration potential in the Pamlico Sound, and how can local and state agencies prioritize land acquisition to facilitate future wetland migration? Following a review of existing literature, the paper will examine a study done by state of Delaware assessing statewide marsh migration potential using geospatial technology. Then, using a GIS analysis, this study estimates total wetland loss under three different sea level rise scenarios for the year 2100: low (2 feet), intermediate (4 feet), and high (7 feet), as defined by the North Carolina Department of Environmental Quality (2024, p.12). Then, building on the methodology developed by Delaware's Department of Natural Resources and Environmental Control, this paper will use GIS to identify the most suitable areas for marsh migration using datasets on wetlands, impervious surfaces, slope, land use, and sea level rise projections. Through analysis of existing literature and spatial analyses, this study aims to quantify potential wetland loss, identify potential migration corridors, and inform land-use and conservation planning to support long-term wetland resilience in the Pamlico Sound.

Literature Review

The Pamlico Sound is the largest embayed estuary in the world, defined as an enclosed coastal basin partially separated from the ocean by barrier islands (APNEP, n.d.). Sea level rise has dramatically impacted this estuary, with researchers focusing on issues like saltwater intrusion, coastal deforestation, wetland migration, and the human dimensions of coastal resilience. This literature review examines current research on topics related to SLR to identify key findings, existing gaps in the literature, and possible implications for adaptation in the Pamlico Sound region. By reviewing relevant literature, this section establishes a solid foundation for understanding how sea level rise affects local ecosystems and informs strategies to support wetland resilience.

Coastal Implications of Sea Level Rise

Climate change, once caused by mostly natural cycles, has accelerated greatly due to human activities like burning fossil fuels, manufacturing goods, and deforestation (NASA Science, 2022). These activities have increased greenhouse gas concentrations in the atmosphere, leading to warmer global temperatures, more frequent extreme weather events, and subsequent accelerated sea level rise due to the melting of glaciers and ice sheets (Lindsey, 2023). While Earth's coastlines have shifted naturally over time, the rate and magnitude of current change is much more intense. For example, North Carolina's shoreline has historically migrated as much as 100 miles depending on climate conditions. It has gone east around 40 miles past the Outer Banks during the last ice age, and has receded inland by approximately 75 miles during some of the earth's warmest periods (APNEP, n.d.). Today, however, the pace of sea level rise far exceeds historical natural rates, posing urgent challenges for both human communities and the ecosystems that wrap North Carolina's coast.

Sea level rise poses substantial economic risks for coastal communities, especially in regions dependent on tourism. Nichols (2014) found that approximately one-third of Caribbean resorts are within one meter of the water line, and that sea level rise of this magnitude could cause more than half of the region's tourist properties to be lost (p.6). Similar patterns are emerging in the US, including along North Carolina's low-lying coast, where shoreline erosion and flooding is a persistent challenge. In addition to physical land loss, rising seas and saltwater intrusion threaten the state's drinking water supply, degrading water quality in coastal areas, impacting both local public health and the tourism industry. A study by Whitehead et al. (2024) estimated that between \$200-\$232 million dollars in tourism revenue could be lost due to poor drinking water quality by 2040, and between \$336-\$402 million by 2080 in North Carolina alone (p.11). These statistics demonstrate the detrimental loss in tourism-driven revenue for coastal communities, directly influenced by sea level rise.

Wetland Ecosystem Services

Wetlands perform vital ecological functions, helping sustain both natural systems and human well-being. They filter sediments and pollutants from runoff, which helps provide cleaner water for both drinking and aquatic habitats (NCDWR, 2025). By holding rainfall and slowing runoff, wetlands also help control flooding, with one acre of wetland able of storing between 1-1.5 million gallons of floodwater (NCDWR, 2025). Subsequently, this flood reduction also influences shoreline erosion reduction, with wetland contributing an estimated \$25.6 billion in storm protection value annually (NCDWR, 2025). Beyond their hydrologic services, wetlands provide critical habitat that supports a wide variety of flora and fauna. According to North Carolina's Wetlands Program, "wetlands serve as homes for 31% of the United States' plant species," and "up to one-half of North American bird species nest or feed [there]" (NCDWR, 2025). The services that wetlands give to this variety of wildlife help maintain stability within these ecosystems, supporting species' resilience amongst uncertain environmental changes.

In addition to their ecological importance, wetlands provide substantial economic, cultural, and climate-related benefits that directly support human life. They sustain commercial and recreational fisheries, producing approximately $70 million in 2016 off shellfish and fish harvest alone (NCDWR, 2025). They also support a variety of recreational opportunities, from fishing and hunting to birdwatching, camping, and hiking. Wetlands also play a major part in carbon sequestration, as they act as natural carbon sinks, directly supporting human well-being and long-term climate resilience. According to a study by Shiau et al. (2019), coastal ecosystems can accumulate carbon "at a rate up to 100 times faster than terrestrial forest ecosystems" (p.579). Additionally, an inventory done by the North Carolina Natural Heritage Program presented that the state's coastal wetlands hold the equivalent of 71.7 MMT of coal burned (NCNHP, 2023, p.1). Studies like these reflect the true impact that wetlands can have environmentally, especially as carbon emissions continue to rise globally. Collectively, these services reflect the importance of wetlands in the services they provide both ecologically and for humans.

Saltwater Intrusion

While wetlands provide these immense ecological and economic benefits, they are threatened by saltwater intrusion, a process where sea level rise pushes saline water further inland, contaminating freshwater environments and altering ecosystem chemistry. This phenomenon has become one of the most defining challenges for southeastern US wetlands, as it threatens drinking-water quality, damages soils, and disrupts forest health. In North Carolina's coastal plain, this phenomenon has caused extensive mortality, producing "ghost forests" which are characterized by standing dead trees and fallen trunks (Ury et al., 2021, p.1). Ury et al. (2021) found that these forests are both "prevalent and transient", often transitioning to shrubland/ marshland within only a few years (p.6). This quick change reflects the rapid, drastic changes that saltwater intrusion can cause in coastal forests. In addition to the ecological issues of deforestation and biodiversity loss, coastal forests support a variety of human activities. As Tully et al. (2019) note, coastal forest loss reduces timber, habitat resources, aesthetic value, and recreational opportunities, all while facilitating the occupation of invasive species in these ecosystems (p.374). Despite this growing threat, a study done by Panthi et al. (2022) found that the USGS SWI network has seen little expansion since the early 2000s, leaving gaps in data across the US (p.7). This underscores the need for a larger, more connected monitoring system across the continental US to ensure comprehensive data across a variety of locations. Overall, these findings show how saltwater intrusion drives ecological and socioeconomic loss, reflecting the urgency of improved monitoring and proactive adaptation planning to protect the coastal ecosystems that remain.

On top of its ecological and socioeconomic impacts, saltwater intrusion can also threaten the structure and function of coastal wetlands, disrupting the ecological balance on which these systems depend. Romañach et al. (2019) found that human activities like residential, canal, and levee development can exacerbate the effects of sea level rise because it restricts freshwater flow, which causes these ecosystems to be unable to support freshwater flora and fauna (p.1601). As ecosystems increase in salinity, native species tend to struggle more, leading to biodiversity loss which allows invasive species to become more prominent. Increase in salinity can also significantly transform wetland soils and vegetation. Zhang et al. (2022) found that saltwater intrusion impacts marsh accretion, producing varying patterns of flooding and salinity. More specifically, they found that "a longer duration of inundation in [a] depression zone will increase the toxicity of the soil, which may result in the mortality of marsh vegetation" (p.12). Put simply, there is a stronger likelihood of marsh vegetation mortality due to marsh accretion caused by saltwater intrusion. The effects of saltwater intrusion can be devastating for coastal wetlands, making prevention and adaptation measures essential for their survival. However, wetlands possess a way to naturally adapt to sea level rise: **marsh migration**.

Marsh Migration and Coastal Squeeze

Marsh migration, the ability for coastal wetlands to move inland to higher ground when faced with sea level rise, is a natural response that allows these ecosystems to persist in changing coastal environments. For this process to occur most effectively, wetlands require low-lying, undeveloped areas with gentle slopes, which were ideally once occupied by forests or other coastal vegetation (Kottler, 2021). Through this migration, wetlands can maintain their natural functions, such as carbon sequestration, habitat provision, and inundation regulation, even as shorelines shift and sea levels rise. Historically, this movement inland served as a natural buffer against changing seas, allowing coastal ecosystems to sustain themselves long-term. However, the combination of increasing rates of sea level rise and continuous human development is proving to exceed wetlands' natural ability to adapt. Smith et al. (2021) found that total carbon stocks decreased by nearly 50 percent when transitioning from forest to marshland (p.4). This highlights that marsh migration can often bring with it periods of ecosystem instability. This study also found that marsh soils eventually accumulate enough carbon to partially offset these losses, but often marsh submergence and erosion occur before full carbon recovery (pp.7-8). These findings reflect how the pace of environmental change exceeds the pace at which ecosystems can naturally adapt. However, wetlands face an even greater challenge than reduced carbon storage: a phenomenon called coastal squeeze.

Coastal squeeze refers to the restriction of suitable land for marsh migration caused by human activities such as coastal residential development, levee and seawall installation, and other land development projects. As shorelines continue to rise, marshes are actively running out of space to migrate into, leaving them trapped between increasingly rising seas and immovable human infrastructure. Johnson et al. (2019) highlights the impacts of this phenomenon, finding that this loss will reduce the population of wetland-dependent animals and reduce the natural protection against flooding and severe storms that wetlands provide communities (pg.8). Smart et al. (2021) found that coastal squeeze also acts as a threat to the cultural ecosystem services, natural areas with values like beauty, community, and sense of place (p.6). Together, these findings show how mitigating the effects of coastal squeeze is important to both ecosystem and human well-being. Protecting these upland areas and identifying potential migration corridors is essential for facilitating natural wetland adaptation, ensuring the ecosystem services which coastal communities depend upon are still provided.

Addressing coastal squeeze requires proactive planning strategies, like upland conservation and living shorelines/breakwaters, that both protect current undeveloped lands and use nature-based solutions to ensure wetland resilience and function. Johnson et al. (2019) found that living shorelines, a natural alternative to hard shoreline infrastructure by using oyster shells, plants, sand, rocks, and wood, can both protect and restore coastal ecosystems while giving wetlands a natural buffer against sea level rise (para. 9). Tully et al. (2019) argued that management responses to the consequences of sea level rise would have beneficial outcomes for both public and private sectors (p.375). For example, nonaction when faced with freshwater wetland loss could lead to a decrease in both ecosystem health and recreational value, whereas better inflow and outflow management would sustain and even increase ecosystem and recreational benefits (p.375). In addition to these management efforts, Borchert et al. (2018) emphasizes the importance of conducting small-scale, localized analyses to identify the most suitable migration corridors for wetlands. Their research found that migration corridor models increase in accuracy as spatial scale is refined, since higher resolution provides more precise hydrologic and geographic datasets (p.2882). Such modeling helps identify areas where migration potential is greatest, informing local and regional planners and policymakers to make proactive land-use decisions to sustain coastal wetland resilience and guide future conservation efforts.

The existing literature clearly illustrates complex challenges that sea level rise poses on coastal areas like the Pamlico Sound. From decreasing carbon storage and biodiversity loss to the impact on local economies and cultural identity, it is clear that the rate of environmental change surpasses the natural ability of wetlands and the communities they support to adapt in a sustainable, resilient manner. Proactive, targeted planning that combines nature-based solutions with small-scale spatial modeling is essential to ensure wetland ecosystem health. Both independent and state-level studies have found that combining spatial modeling with coastal land conservation and planning can help facilitate marsh migration and long-term wetland health, as this informs where exactly to target conservation efforts (Borchert et al., 2018; Delaware DNREC, 2025). Building on these findings, this paper answers this question: How will sea level rise influence wetland loss and migration potential in the Pamlico Sound? First this paper will examine a study conducted by Delaware’s Department of Natural Resources and Environmental Control to understand marsh migration potential using geospatial analysis. Then, building off that study, this paper will quantify wetland loss under different sea level rise scenarios and identify potential migration corridors to inform future conservation and land-use planning in the Pamlico Sound region.

Policy Approaches

Given these threats, understanding how other coastal states have prepared for marsh migration is essential for shaping North Carolina's own adaptation strategies. While North Carolina has outlined broad goals for wetland resilience, states like Delaware and Virginia have already begun implementing targeted, data-driven approaches that directly inform environmental management decisions. This section first examines the *Delaware Marsh Migration Suitability Analysis* developed by the state DNREC to understand how other state agencies are implementing spatial analyses in wetland conservation planning. Building off this study, this paper employs two GIS analyses within the Pamlico Sound study area: One quantifying wetland loss under three SLR scenarios, and another assessing the suitability of inland areas for marsh migration. Finally, the results are evaluated in the context of existing state environmental goals for North Carolina wetlands, and policy recommendations are proposed to better protect and facilitate resilient marsh ecosystems when faced with continued sea level rise.

Delaware

Delaware provides one of the most direct policy examples of how spatial analyses can be implemented to proactively plan for marsh migration when faced with SLR. As is the case with many other state wetland program plans, the *Delaware Wetland Management Plan* (2021) follows the EPA's four core elements: Monitoring and Assessment, Voluntary Restoration and Protection, Education and Collaboration, and Regulation (Delaware DNREC, p.2). Within this framework, Delaware emphasizes the development of standardized mapping and monitoring of coastal wetlands in order to maintain accurate, up-to-date data that can be used in the long-term. It also prioritizes public engagement and education as well as collaboration between local governments, state agencies, and local organizations to strengthen support and conservation of coastal land. However, most relevant to this paper, the Monitoring and Assessment objective includes a Climate Adaptation component that focuses on the identification and protection of coastal areas suitable for wetland migration whilst promoting natural buffers, managing SWI, and analyzing habitat and ecosystem transitions (p.13).

Building on these policy goals, Delaware's Department of Natural Resources and Environmental Control released the *Delaware Marsh Migration Suitability Analysis* (2025) as a means of translating adaptation goals into actionable planning resources. This analysis integrates spatial data such as elevation, slope, soil type, land use, impervious surface coverage, proximity to wetlands, and sea level rise scenarios to locate areas most suitable for marsh migration (p.2). The results of this analysis sorted coastal land into five categories of suitability and can be used to identify total acreage of suitable land, total acreage of suitable land by county, and current land use types of suitable land. A key point of emphasis made in this analysis is the fact that marsh migration is a phenomenon dependent on a multitude of complex ecological functions, so this model doesn't provide definitive locations of where marshes will be in the future. Rather, the results of this analysis should be used to identify potential lands that may limit the ability of marshes to migrate inland, facilitating proactive conservation planning in the necessary areas. This approach to wetland resilience planning demonstrates how geospatial analyses can help inform state agencies on how to transform broad policy objectives to targeted action. This study builds upon Delaware's framework by using similar methods to identify migration potential within the Pamlico Sound, providing a localized spatial analysis that can inform future environmental policy and planning at a regional level.

Data Analysis

This study will now employ two spatial analyses, building on the guidelines outlined in North Carolina's wetland plans and the framework developed by the Delaware DNREC. The following analyses directly address *Monitoring and Assessment Activity B* from the NCDEQ Wetland Program Plan (2021): "Assess changes in the quantity and quality of coastal wetlands (e.g., sea level rise, wetland migration, general data, hotspots, landowners, and constitutional, financial, and legal implications)" (p.12). It also responds to one of the document's outlined Additional Stakeholder Interest, to "…establish priority areas for land conservation easements/buy-outs in coastal areas" (p.26). It first quantifies wetland loss within the study region to better understand how the current extent of wetlands may change depending on the SLR scenarios. It then identifies lands most suitable for marsh migration in order to inform future acquisition, conservation, and land-use planning decisions in the Pamlico Sound.

The following datasets were compiled to evaluate wetland loss and identify areas with high migration potential. Raster data representing 2021 land use across North Carolina's coast was obtained from the National Oceanic and Atmospheric Administration (NOAA, 2021). Soil data, including soil type and drainage capacity, were extracted from the Gridded Soil Survey Geographic Database (gSSURGO, 2020). County boundary data were extracted from the North Carolina Department of Transportation through the state's OneMap database (NCDOT, 2024). Elevation data at the county level was then downloaded from North Carolina's Emergency Management's GIS portal (NC Spatial Data Download, 2020). Lastly, shoreline boundaries were derived using Esri's U.S. Congressional Districts dataset from their Living Atlas, which was used to clip the county data to only included land area (Esri, 2025). The study area was defined by using the select by feature tool to select the five counties adjacent to the Pamlico Sound: Beaufort, Craven, Carteret, Hyde, and Pamlico. These five counties were exported as a new shapefile, which was then clipped by the Congressional Districts dataset to establish a shoreline. The dissolve tool was then used to merge the county polygons, ultimately producing a polygon depicting the extent of this study's analyses, as depicted in **Figure 1**.

Quantifying Wetland Loss

a. Methodology

To estimate potential wetland loss, raster layers of the three SLR projections for the year 2100 were created following the methodology outlined by NCDEQ (2024, p.12). First, the land use and elevation raster data were uploaded to a new ArcGIS Pro project. The elevation layers were by county, so the mosaic function was used to combine them, yielding a single elevation raster for the five study counties. These data were then projected to the NAD 1983 StatePlane North Carolina coordinate system using the project raster function, and subsequently masked by the study area shapefile, yielding elevation and land use data depicting only land in the study area. The processing environment was then standardized to match the land use raster, ensuring consistency across layers for the analyses. The following parameters were set: output coordinate system set to NAD 1983 StatePlane North Carolina, processing extent set to the land use raster, cell size set at 30 meters, cell alignment to match processing extent, and finally the land use layer as the snap raster.

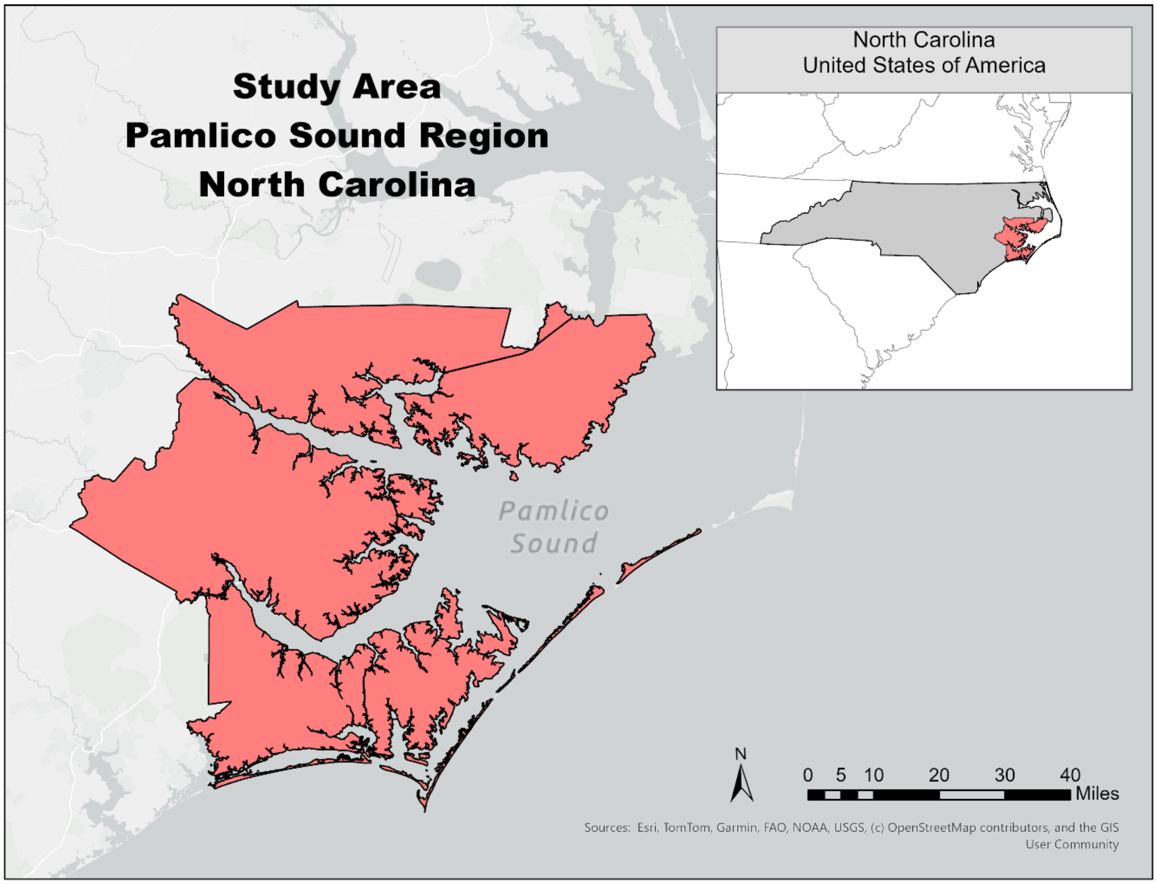


Figure 1. Depicts the study extent used for the following analyses.

Then, the elevation raster was reclassified three separate times using the reclassify tool, yielding layers corresponding with 2-, 4-, and 7-foot sea level rise scenarios. Each of these layers represent areas equal to or below the respective elevation threshold, with inundated cells assigned a value of 1 and all other cells assigned no data. The reclassify tool was then used on the land cover raster to isolate wetlands by classification, assigning all non-wetland land use as no data and keeping existing wetland classification. The reclassified wetland layer was then clipped to the study area extent defined in the previous section, yielding the layer shown in **Figure 2**. The tabulate area tool was then applied to the reclassified wetlands raster to calculate the total wetland area lost under each SLR scenario. This tool produced a table reporting land area lost in square feet, which was converted to acres using the calculate geometry tool and dividing each value by 43,560.

b. Results

Six wetland types exist in the study area: Palustrine Forested, Palustrine Scrub/ Shrub, Palustrine Emergent, Estuarine Forested, Estuarine Scrub/ Shrub, and Estuarine Emergent. The extent of inundation projected for 2100 under 2, 4, and 7 feet of sea level rise is depicted in **Figure 3,** with most of the land lost to inundation concentrated in Hyde, Carteret, and Pamlico counties. Results from the tabulate area analysis indicated substantial loss across all wetland types and SLR scenarios. Of the total 816,866.56 acres of wetland in this region, 254,274.13 were lost under 2 feet of SLR, 355,239.87 under 4 feet, and 418,425.77 under 7 feet. Percent loss

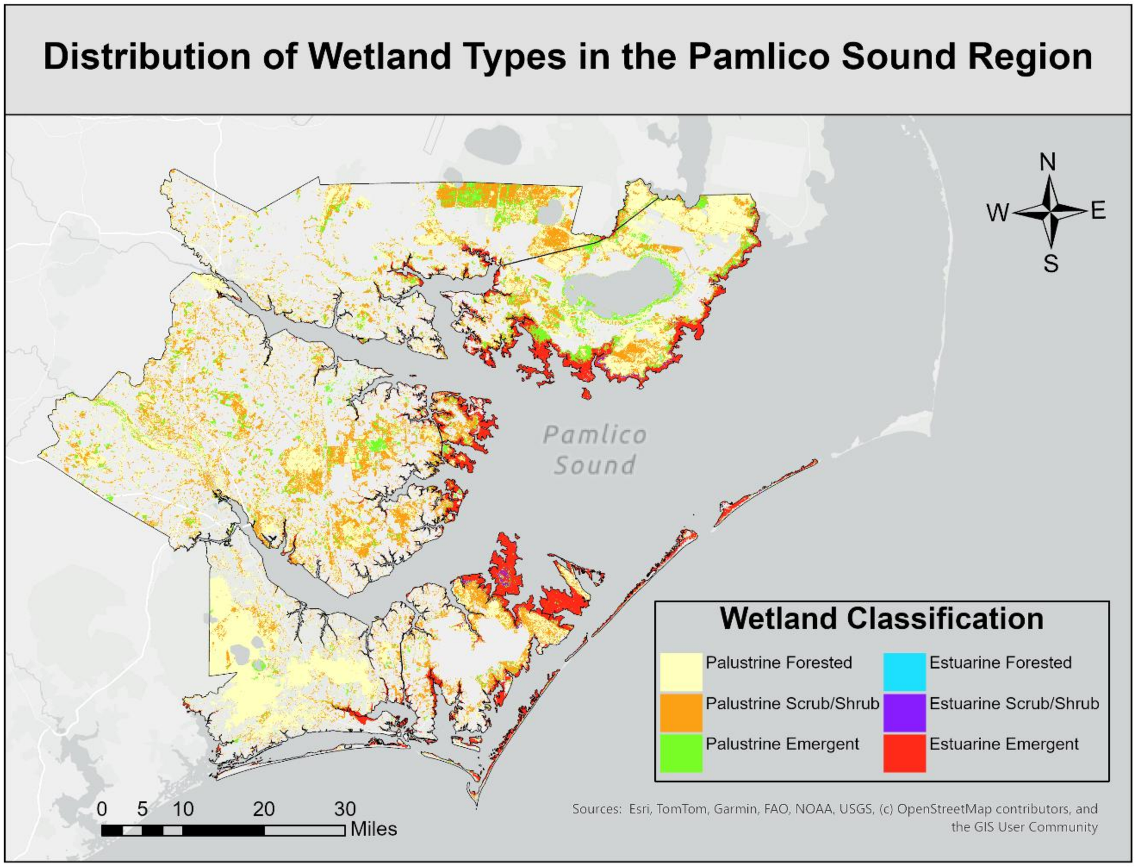


Figure 2. Depicts the distribution of wetlands in the Pamlico Sound region.

by wetland type per scenario was also calculated, which found all classes of estuarine wetlands to be at significantly more risk than the palustrine classes, as depicted in **Figure 4**. This difference makes sense, as estuarine wetlands are naturally closer to the ocean than palustrine wetlands are. Overall, these findings demonstrate a clear relationship between increasing rates of SLR and wetland degradation. While wetlands do possess the ability to migrate inland, these results reflect the extent to which these natural lands may shift in the coming decades, limiting ecosystem resilience.

To further develop these findings, a second analysis will be conducted to identify the most suitable lands for wetlands to potentially migrate as sea levels rise. This portion of the analysis will focus on determining the suitability of lands for marsh migration using factors like impervious surface, soil drainage, slope, and land use.

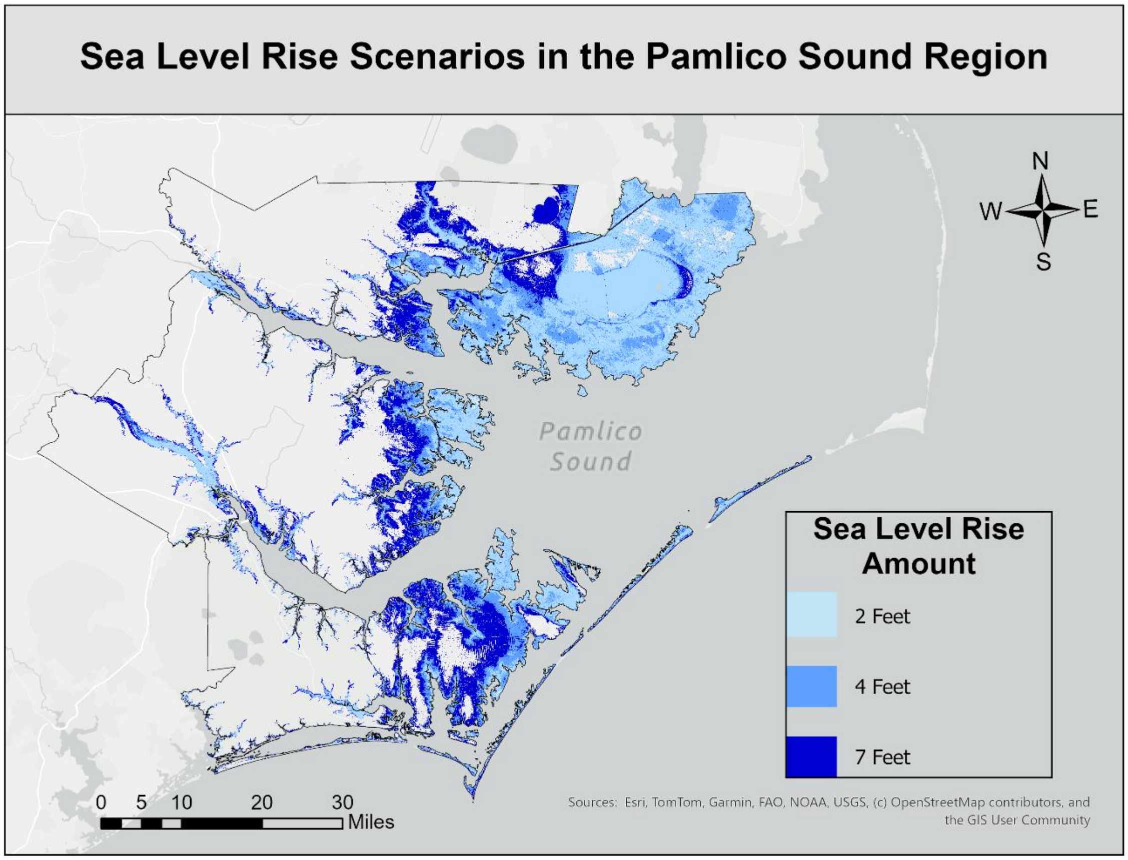


Figure 3. Depicts the three SLR scenarios in the Pamlico Sound, symbolized by amount of SLR.

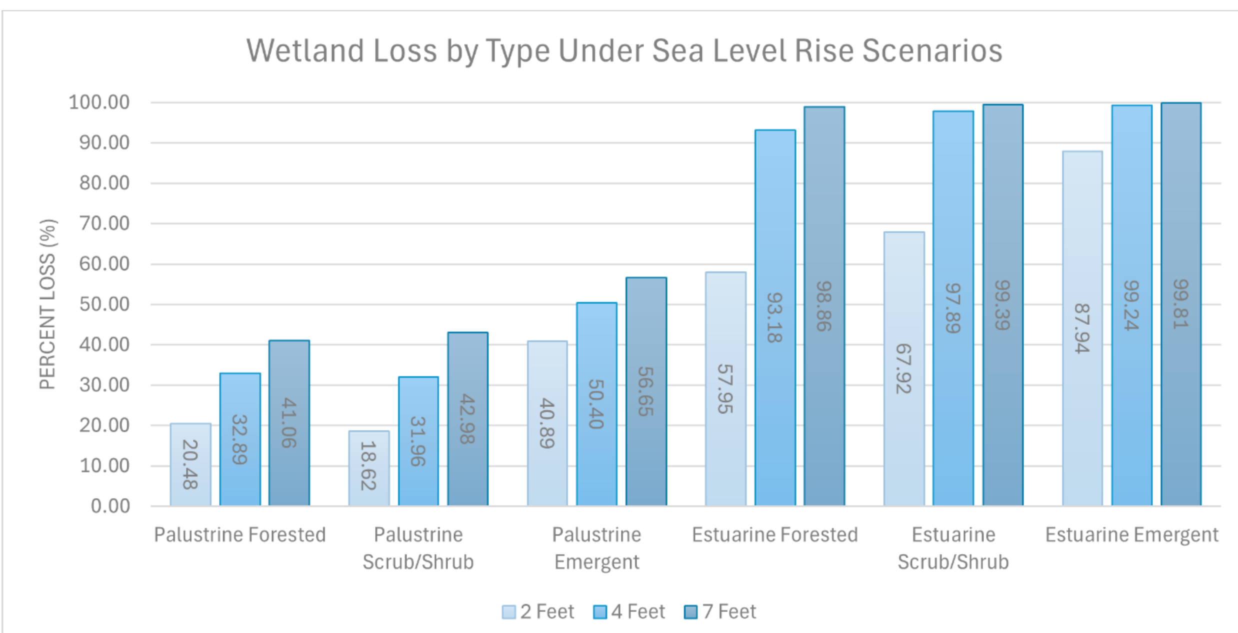


Figure 4. Depicts the percent loss of wetlands by type depending on SLR scenario.

Identifying Suitable Migration Corridors

a. Methodology

To identify wetland migration potential under projected sea level rise scenarios, a second geospatial analysis was conducted. Building off the previous analysis, the following datasets were uploaded to a new ArcGIS Pro project: land use raster, soil survey file geodatabase, elevation, wetlands layer created in previous analysis, and the SLR scenarios from the previous analysis. Each dataset was projected to the NAD 1983 StatePlane North Carolina coordinate system, using the project raster and project functions for raster layers and vector layers, respectively. The same processing environment was set as the previous analysis, using the following parameters: output coordinate system set to NAD 1983 StatePlane North Carolina, processing extent set to the land use raster, cell size of 30 meters, cell alignment matching processing extent, and the land use raster as the snap raster.

First, the land use raster was extracted by mask to the study area and reclassified using the reclassify tool to represent land suitability for marsh migration. All developed lands, palustrine wetland classes, and open water were reclassified as 0. Agricultural lands, all estuarine wetland classes, and consolidated shores were reclassified as 1. Developed open space were reclassified as 2, leaving all forest classes, grasslands, and shrublands to be reclassified as 3, as they are the most suitable lands. Separate layers for exclusion were also created for wetlands and impervious surfaces, as wetlands cannot exist on impervious surfaces or migrate to other wetlands. Using the reclassify tool, wetlands and impervious surface were valued at 0 with all other values reclassified as 1, yielding two separate exclusion layers.

The reclassify tool was again used to generate a raster of only estuarine wetlands, which was then run through a Euclidean distance function to generate a raster depicting distance from tidal wetlands. This raster was then reclassified so that cells proximate to wetlands were assigned 3 (0-700 ft.), moderate proximity to wetlands were assigned a 2 (700-1400), distant values were assigned a 1 (1400-14000), and all other values were assigned a 0 as they are too far to be migratable. The slope function was then used on the masked elevation raster from the previous analysis, which yielded a slope raster layer in degrees. This layer was then reclassified so that slopes between 0-1 degrees had a value of 3, slopes between 1-3 degrees a value of 2, slopes between 3-8 degrees a value of 1, and all greater slopes a value of 0 (unsuitable).

Soil drainage data was incorporated by importing the soil polygon dataset and the corresponding attribute table from the gSSURGO database. The polygon layer was first masked by the study area, yielding a polygon layer depicting only soils in the study area. The attribute table was then joined to the polygon layer using the *mukey* field. The polygon to raster tool was then used to create a soil raster layer using drainage class as the value field. The raster was then reclassified to assign well-drained soils a value of 1, moderately drained soils a 2, and poorly soils a 3, reflecting wetland preference in soil drainage.

Once all layers were prepared, the raster calculator was used to combine the land use, soil, slope, and distance raster layers to create an inclusionary layer. Wetland and impervious surface layers were then multiplied using the raster calculator to yield an exclusionary layer. The inclusionary and exclusionary layers were then multiplied together to yield the final suitability surface. This surface was reclassified into five categories: 0 (unsuitable, 1-3 (low suitability), 4-6 (moderate suitability), 7-9 (high suitability), and 10-12 (most suitable). Finally, the suitability surface was multiplied by each of the three sea level rise raster layers (2-, 4-, and 7-foot inundation), producing three scenario specific suitability maps representing land suitability for marsh migration under project SLR. Lastly, the tabulate area tool was used to calculate total acreage of the most suitable land classification by county.

b. Results

The final marsh migration suitability models for 2-, 4-, and 7-foot projections of sea level rise can be seen in **Figure 5**. Highest suitability across the three models was concentrated in the central peninsula of the study area. Counties with the largest area most suitable for migration include Beaufort, Pamlico, and Carteret, though every county has portions of this suitability classification. These regions were characterized as having low slopes, poorly drained soils, and primarily undeveloped land use while being close to existing tidal wetlands. Moderate zones of suitability were concentrated adjacent to these areas, often on agricultural or open lands that could feasibly support marshes in the future if managed properly.

To better inform future steps for coastal land managers, **Figure 6** depicts the three primary land use classifications of lands that were identified as most suitable for wetland migration by SLR scenario. The two most common land use classifications for most suitable migratory lands were consistent across all SLR scenarios: Evergreen Forest covered an average of 64.37% of the most suitable land across SLR scenarios, while Scrub/Shrub covered average of 16.34%. There was slight differentiation in the third most coverage across the most suitable migration areas. Under 4-foot and 7-foot projections, Grasslands covered 6.14% and 7.13% of most suitable lands, respectively. However, Cultivated Cropland covered 7.77% of the most suitable lands under the 2-foot projection.

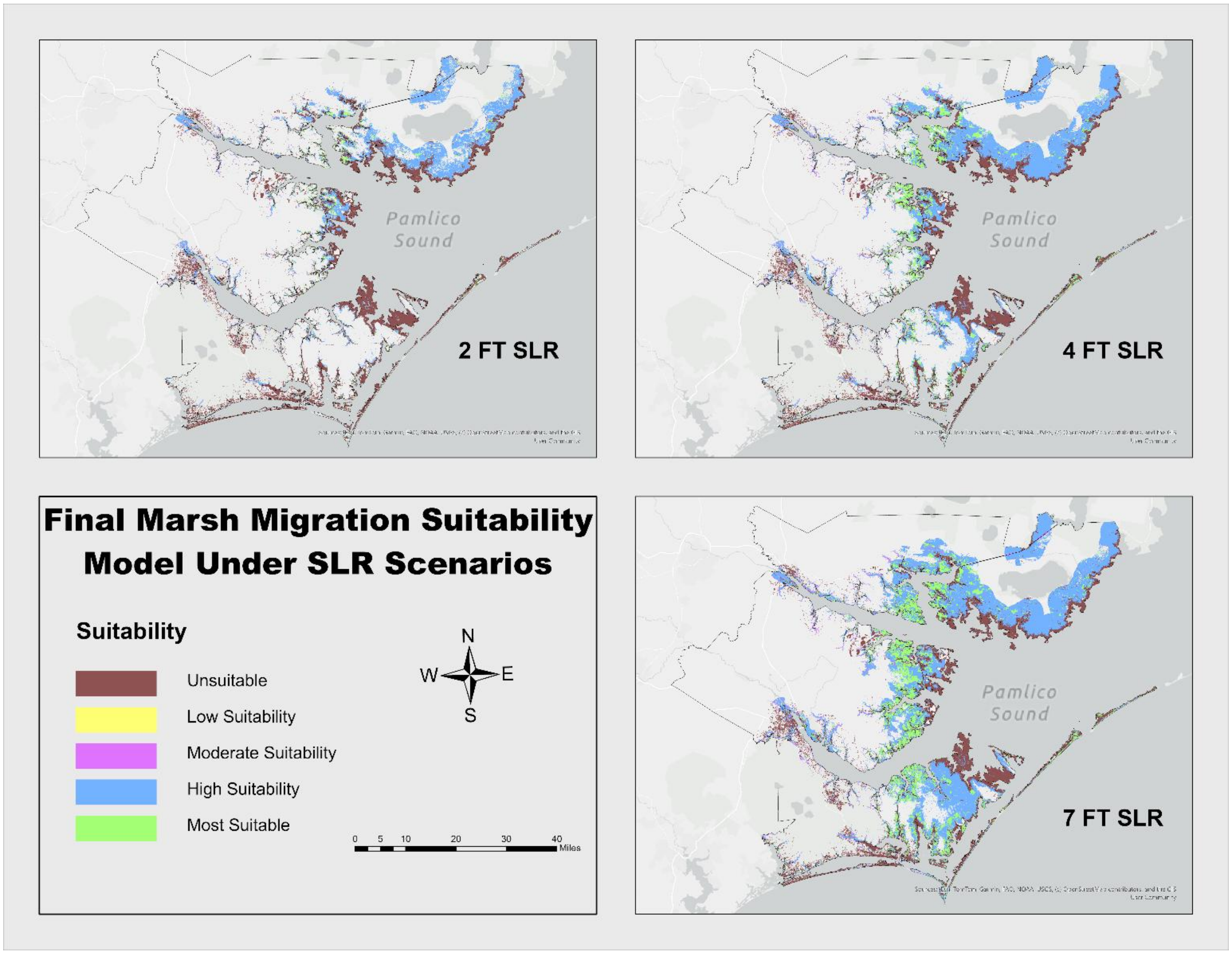


Figure 5. Depicts the final suitability models given 2-, 4-, and 7-feet of SLR.

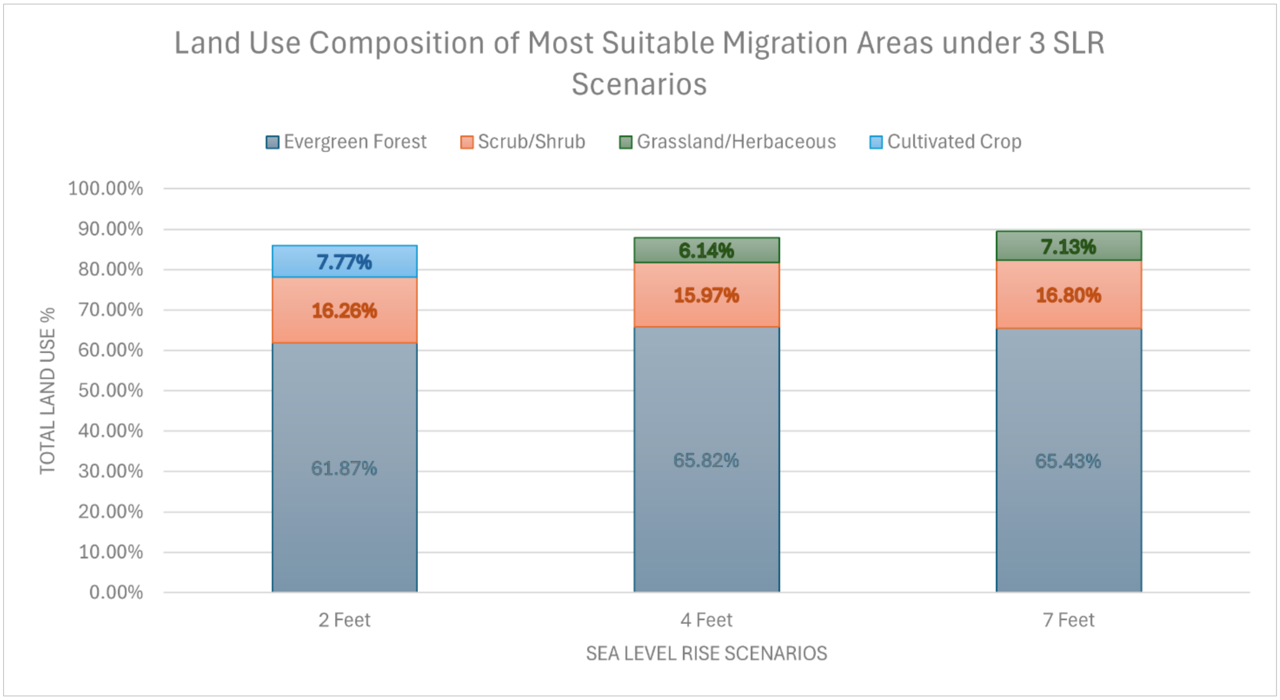


Figure 6. Depicts the top three land use types for the most suitable land under SLR scenarios.

Discussion of Findings

The results of this analysis highlight the significant future changes wetlands are projected to endure due to sea level rise. Of the total 816,866.56 acres of wetland in the Pamlico Sound region, 254,274.13 acres were lost under the 2-foot scenario, 355,239.87 acres under the 4-foot scenario, and 418,425.77 acres under the 7-foot scenario. Estuarine wetlands were found to be most vulnerable, which aligns with their tidal nature and proximity to the sound. The suitability analysis further revealed that Carteret, Pamlico, and Beaufort Counties contain the largest extent of most suitable lands, characterized by low slope, absence of development, and poor soil drainage (**Figure 7**). It is important to note that areas classified as "most suitable" in the final suitability model represent transition zones where wetlands could potentially exist in the future as sea levels rise, not definite areas where they will exist. To further develop these findings, state agencies and regional partnerships are recommended to confirm these findings via on-site assessments, as well as conduct studies to identify which of those parcels identified as most suitable for migration are privately or publicly owned. These results emphasize the need for proactive land acquisition and conservation at both the state and local level, ensuring wetlands have the best chance to retain their natural ecosystem functions.

These findings directly support the goals outlined in North Carolina's Wetland Program Plan (2021), particularly the Monitoring and Assessment objective to "assess changes in the quantity and quality of coastal wetlands (e.g., sea level rise, wetland migration, general data, hotspots, landowners, and constitutional, financial, and legal implications)" (NCDEQ, p.12). The spatial analyses conducted in this study contribute to improving predictive mapping and identifying priority lands for marsh migration, both of which being needs identified explicitly by state agencies. In addition to state agencies, regional partners like the North Carolina Coastal Federation (NCCF) offer additional guidelines for this region that directly align with this study's

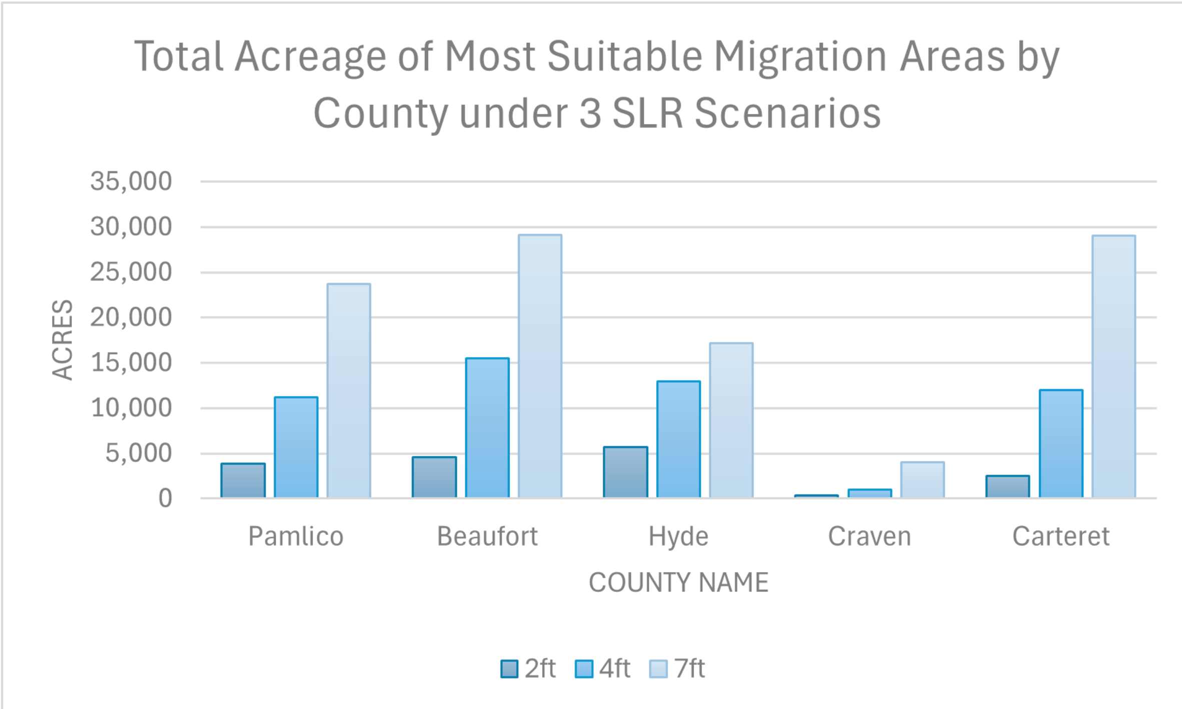


Figure 7. Depicts the total acreage for the most suitable land by county depending on SLR scenario.

findings. For example, a major objective of NCCF's Salt Marsh Action Plan (2024) is the "[advancement of] research and assessment of salt marsh migration areas" (p.28). With this analysis addressing key state goals for the monitoring and assessment of existing wetlands, implementing solutions grounded in these spatial findings is essential for conservation, restoration, and long-term ecosystem health.

Suggestions

To understand what other states have already implemented in sea level rise adaptation and coastal resilience planning, this study will look at what policies Virginia implemented in their *Virginia Coastal Resilience Master Plan* (2021). Virginia was selected as a comparative case due to its similar coastal geography and climate, proximity to North Carolina, and shared presence of a large estuarine system in the Chesapeake Bay. Their coastal resilience plan, released by the Virginia Department of Conservation and Recreation (VDCR), emphasizes the use of nature-based solutions to address wetland loss, marsh migration, and coastal flooding. Particularly relevant to this study, VDCR's plan includes a section devoted entirely to natural and nature-based projects that the state has already implemented (pp.170-179). One of these projects, the Eastern Shore Marsh Migration project, prioritized using conservation easements to help protect both inland migration corridors and upland buffers (p.174). Other projects, including the Saxis Living Breakwaters and the Wachapreague Reef Restoration, focus more on implementing nature-based solutions, like living breakwaters and reef restoration, to help reduce coastal erosion and buffer the impacts of Sea Level Rise (pp.172-173, p.175). Together, these efforts demonstrate how a state facing SLR impacts comparable to those in North Carolina has implemented targeted, nature-based strategies to support wetland resilience. Building on these examples, the following policy recommendations highlight actionable and realistic strategies that

North Carolina agencies can implement in buffering the impacts of sea level rise on wetlands in the Pamlico Sound region.

The first policy recommendation North Carolina should prioritize is the use of targeted conservation to protect upland areas that could serve as future marsh migration corridors as sea levels continue to rise. Results from this study's analysis identified extensive areas of low-slope, undeveloped, and poorly drained lands that are suitably positioned to support future wetlands. Protecting these lands through conservation easements, land acquisition buy-outs, or development restrictions would help preserve the existing natural ecosystem services and limit conflicts between human activity and wetland migration. Virginia's Eastern Shore Marsh Migration project provides a useful metric for cost, with estimations totaling around $1,000,000 for construction and implementation (VDCR, 2021, p.174). However, implementation in the Pamlico Sound could likely be expected to cost more due to this being a larger study area than in Virginia. This strategy directly supports North Carolina's Wetland Program Plan suggested activity to "… establish priority areas for land conservation easements/ buy-outs in coastal areas," as well the overall goal to develop public facing maps of wetland assets, including conservation easements (NCDEQ, 2021, p.26, p.12).

The second policy recommendation North Carolina should prioritize is the expansion of using nature-based shoreline protection measures like living shorelines and restored oyster reefs. Further implementing these measures helps stabilize shorelines, reduce wave impact on shorelines, and protect adjacent marshland, all while enhancing estuarine ecosystems by restoring native vegetation and wildlife. These approaches are well suited for the Pamlico Sound, given the extensive shoreline and shallow coastal waters which make traditional hard infrastructure suboptimal beyond their ecologically disruptive nature. Incorporating nature-based shoreline protection alongside marsh migration planning would help preserve existing wetlands while creating a stronger buffer between them and sea level rise, helping facilitate inland transition. Again, using Virginia as an example, the Wachapreague Reef Restoration and Saxis Living Breakwater projects combined to cost approximately $4,000,000 to construct and implement (VDCR, 2021, pp.172-173, p.175). This metric provides a practical benchmark for North Carolina agencies, as similar projects have already been implemented and funded in similar coastal areas like Virginia. To further encourage funding of similar projects, regional partnership APNEP also suggested facilitating economic incentives for landowners to convert hardened shoreline infrastructure to living shorelines (APNEP, 2025, p.71). This recommendation aligns with North Carolina's Wetland Program Plan suggested monitoring and assessment activity to "research successful shoreline stabilization alternatives, with an emphasis on living shorelines" (NCDEQ, 2021, p.12).

The third and final policy recommendation North Carolina should prioritize is the promotion of upland forest restoration using native, salt-tolerant, and climate-resilient tree species. Over 60% of the most suitable land for marsh migration across all sea level rise scenarios is classified as evergreen forest land use type, which underscores the importance of reforesting areas upland that won't be impacted to offset the forest cover lost. Restoring these upland forests can slow saltwater intrusion, help stabilize soils, and create future transition zones that continue to support the gradual ecosystem shifts caused by sea level rise. This approach complements the natural functions of marsh migration and how wetlands interact with upland forests, as it reduces abrupt habitat change. Unlike the previous recommendations, the costs associated with proactive upland forest restoration are more difficult to estimate, as funding is dependent on the desired extent of replanted forests, land ownership, species selection, site selection, and long-term forest health projections. Despite this variability, upland forest restoration helps offset the extent to which existing forests will be lost in the future due to SLR. This recommendation, along with the first recommendation of proactive land conservation, directly support's the current Governor's 2024 goal to "permanently conserve one million new acres of natural lands (with a focus on wetlands), [and] restore or reforest one million new acres of forests and wetlands…" (NCCF, 2024, p.2).

Conclusion

Sea level rise presents an escalating threat to coastal wetlands along North Carolina's coast, especially within the Pamlico Sound region. This study demonstrates how spatial analysis can be used to assess wetland extent, exposure under sea level rise, and wetland migration potential when faced with SLR. Results indicate that almost half of the existing wetlands in the Pamlico Sound are at risk of inundation, with just under a quarter of those areas (~100,000 acres) possessing land classified as most suitable for migration. Areas most suitable for marsh migration are unevenly distributed across counties and highly dependent on current land use and development patterns. These findings highlight the necessity of effective adaptation and conservation planning to ensure long-term wetland health and resilience as sea levels rise. This analysis, consistent with existing literature, reinforces the risks posed by sea level rise to coastal communities and ecosystems, and reflects how geospatial analyses can help inform targeted, data-driven wetland resilience planning.

Properly addressing the coastal impacts of sea level rise requires collaboration between state agencies, regional partnerships, researchers, policymakers, and local communities. The results of this study emphasize the need for proactive policy implementation alongside continued spatial assessment. While restoration and protection efforts are suggested in North Carolina's state and regional wetland management plans, this study provides actionable next steps to be taken. Comparisons with policy approaches in Delaware and Virginia both provide insights into what other states have already done and provide strong examples of states that have already implemented similar policies to those proposed here. Inland conservation for marsh migration, nature-based shoreline protection, and ecosystem buffering have all proven to be successful coastal management practices in other states, offering feasible pathways for action in North Carolina. As sea level rise continues to reshape coastal ecosystems, spatial analyses offer a foundational tool for coastal environmental planning, guiding conservation priorities, policy development, and resource allocation. Through continued research, spatial analysis, and coordinated policy implementation, North Carolina can strengthen the long-term resilience of its coastal wetlands and the communities that depend on them.

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