Resilient Coastal Sites for Conservation

in the South Atlantic US

The Nature Conservancy

Eastern Conservation Science

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Our approach and results were greatly improved by the attention and engagement of our steering committee. Committee members attended regular calls, constructively argued the concepts, checked details of the data sets, and thoroughly reviewed the draft results. Their review and feedback ensured that the results of this project are as scientifically sound and spatially robust as possible.

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INTRODUCTION

Objective

We assessed the coastal region of four Southeast states on the South Atlantic seaboard and estimated the relative resilience or vulnerability of 1,232 sites containing tidal marsh and other tidal habitats. We identified the sites most likely to continue to support biological diversity and ecological functions under rising sea levels up to 6.5 feet due to their ability to migrate and adapt. The results are summarized in this report and available via the accompanying data package, web site, and mapping tool.

Abstract

Coastal wetlands are critical to the productivity and diversity of marine ecosystems and to the human economies they support. The South Atlantic region of the US includes thousands of coastal wetlands. The varied shoreline is characterized by salt marshes, tidal flats, beaches, dunes, and a wide variety of river deltas, sounds, inlets, and estuaries. Many coastal counties are experiencing significant population growth, and with revised estimates of sea level rise in the range of six and a half feet to almost nine feet by 2100 (Sweet et al. 2017), it is likely that many of these wetland habitats and their ecosystem services will be lost.

The characteristics of some coastal wetlands make them more likely to adapt to sea level rise and remain diverse and productive even as they adjust to climate-induced changes. In this project, we comprehensively mapped these characteristics and estimated the relative resilience of coastal sites from North Carolina to the Florida Keys.

Technical methods for mapping and estimating coastal site resilience were developed in concert with a steering committee of coastal experts that included representatives from the U.S. Fish and Wildlife Service (USFWS), National Oceanic and Atmospheric Association (NOAA), and U.S. Geological Survey (USGS), as well as agency and academic staff from all four states. The committee met bimonthly to discuss data, concepts and methods, and to review results. Our methods are described fully in this report.

In brief, we divided the coast into 1,232 sites each centered around a natural complex of tidal habitats. For each site, we estimated the amount of migration space available under four sea-level rise scenarios. We quantified the physical properties and condition characteristics of each site using newly developed analyses as well as previously published and peer-reviewed datasets. Physical factors assessed included the size and tidal class diversity of the migration space, the size of the existing tidal complex, and the amount of shared upland edge between the tidal complex and its migration space. Condition factors assessed included the percent of the existing marsh's upland edge that is developed, estimated sediment balance of the current marsh relative to sea level rise, and measures of water quality and flow alteration for the marsh's migration space.

We also identified and mapped the buffer area surrounding the tidal complex and its migration space. We evaluated the buffer area with respect to three physical attributes: size of the buffer, variety of coastally compatible landforms, and acreage of maritime highlands. We also assessed the condition of the buffer area by calculating the percent natural cover and connectivity of wetlands within it.

We synthesized the above attributes by estimating a resilience score for each site. To calculate a resilience score, we combined the physical and condition scores for each site in to a single value and did the same for each site's buffer area. We then combined the site and buffer scores into a single integrated metric giving 90% of the weight to the site score. This resulted in a single resilience score for each site based on all the characteristics we assessed.

Given strong evidence in the literature for the importance of migration space in sustaining the resilience of coastal systems, we applied size thresholds to ensure that each site had adequate migration space. This ensured that high-condition sites with little to no migration space did not receive inflated resilience scores.

Resilience scores were calculated for each of four sea-level rise scenarios (1.5, 3.0, 4.0, and 6.5 feet). Our final maps are based on the 6.5-foot scenario because this scenario reveals the sites with the greatest long-term potential for adaptive response, and this scenario is plausible by the end of the century. We made the results even more robust by slightly boosting the resilience score if the size of a site's migration space showed a statistically significant increase from the 1.5 scenario to the 6.5 scenario, suggesting that the size will continue to increase after 6.5 feet.

The scores are presented relative to other sites within one of four coastal shoreline regions (CSRs). Coastal shoreline regions are geographic areas where the coasts and estuaries are dominated by a common set of processes and geomorphology. In the South Atlantic these include a lagoonal type, two river-dominated types (Coastal Plain basin or Piedmont basin), and one island archipelago type (the Florida Keys). Scores are presented in standardized normalized values (z-scores), which are units of standard deviations (SD) above or below the mean score of all sites in the coastal shoreline region (see Appendix II for more details). For example, a z-score of "3" for a site in the lagoonal region indicates that the site scores three standard deviations higher than the average score across all lagoonal sites.

Study Area

The study area included the entire South Atlantic coastline from North Carolina to the Florida Keys, and encompassed the areas from the intertidal region landward to the 6.5-foot elevation zone. States included were: North Carolina, South Carolina, Georgia, and the Florida coast along the Atlantic Ocean.

This study focuses on the ecological resilience of coasts and estuaries in this region to sea level rise (SLR). The region's coastline is well known for its productive estuaries that provide juvenile nursery and spawning grounds for fish, mollusks, seabirds, and crabs. The coastline is a critical ecological transition area, and although it forms a sharp natural boundary, it is very dynamic over geologic time. Over millennia, it has advanced and retreated thousands of kilometers inland and seaward in cycles, and it is now once again retreating as the sea level is rising at an unprecedented rate.

The focal area of this study is the zone of intertidal habitats and low elevation landforms sculpted by waves and tides and by the continuous flow of sediments carried by freshwater in coastal watersheds. This shallow, well-lit, and productive area gives rise to salt marshes, tidal flats, oyster reefs, and seagrasses that directly and indirectly support an abundance of species uniquely adapted to the intertidal zone.

Coasts and estuaries are also of great importance to humans. Tremendous material and aesthetic resources associated with shorelines have attracted and sustained humans for thousands of years. Coastal ecosystems help support the economy by providing beautiful places to live, opportunities for tourism, commercial fishing, seafood processing, shipping harbors, and transportation routes. The malfunctioning of coastal ecosystems due to sea level rise, pollution, habitat destruction, hypoxia, harmful algal blooms, fishery collapses, and/or increased coastal erosion can have devastating social and financial impacts for coastal communities.

Coastal counties in the US continue to experience greater population growth than inland counties, and this region had some of the fastest growing coastal areas in the nation. From 2010 to 2016, coastal Florida and South Carolina had the second and third greatest percent population growth of all coastal states, with Georgia coming in at seventh (U.S. Census Bureau, 2017a). These states are also prone to devastating hurricanes and storms. Since 2000, this region has been struck by six hurricanes that each caused $10 billion or more in damages (U.S. Census Bureau, 2019). Many coastal areas in this region are also experiencing increased “sunny day” or high tide flooding due to rising relative sea levels (Sweet et al. 2018).

Approach

In this two-year project, we quantified the resilience of 1,232 coastal sites by compiling and analyzing region-wide data on factors that influence a site’s vulnerability or resilience to SLR and other climate-driven changes. Physical and condition attributes were assessed and integrated into a spatially-explicit dataset. Using these attributes, we evaluated each site’s tidal habitats and estimated their ability to migrate landward in concert with rising seas based on the size, shape, condition, and context of their available migration space. The relative resilience of each site was determined by comparing it to other sites within the same coastal shoreline region. We hope the resulting maps and web tools will provide local communities, policy makers, resource managers, and conservationists with clear and objective information for understanding the vulnerable and resilient areas of their coasts.

Steering Committee

We convened a steering committee of 35 coastal experts representing state and federal agencies, conservation organizations, regional coalitions, and academic institutions within the study region. Committee members joined bimonthly web-meetings to discuss approaches, methods, and datasets, and to review interim products and results. The full list of steering committee members appears in the Acknowledgments.

CHAPTER
2

BACKGROUND

As sea levels rise and intense storms become more frequent, the impacts are being felt by coastal communities and there is an urgent and growing interest in building community and ecological resilience. Cities and towns are being forced to reconsider how and where to invest in their coastal resources. These decisions affect millions of people because SLR can alter coastal-based economies, disrupt livelihoods, or overwhelm existing infrastructure. Since 2007, TNC has led the development of an online decision support tool, "*Coastal Resilience*" (http://coastalresilience.org/), to help communities address the effects of climate change and natural disasters. The aim of the web site is to help coastal communities increase their resilience to climate change by identifying nature-based or green infrastructure solutions that will enable them to effectively protect, restore, and sustainably manage their natural resources while also strengthening local capacity for climate adaptation.

The challenge of identifying the places where conservation is likely to succeed in sustaining diverse and productive ecosystems is the topic of this study. The tools and products arising from this study can be used in conjunction with the *Coastal Resilience* tool or independently, depending on the needs of the user. Although *coastalresilience.org* is focused on facilitating decisions about human communities and green infrastructure, it is predicated on the need for diverse and productive coastal habitats. The question of how we sustain diverse and productive habitats while facilitating their inevitable migration and adaptation, is the topic of this study.

The future of coastal ecosystems in the South Atlantic region is uncertain and has given rise to many studies both in and outside this region. We compiled 45 studies and/or tools, and reviewed their methods and results to ensure that we were using the most recent information and not repeating studies that had already been completed. The studies included 13 national studies, six in the South Atlantic, ten in the Gulf of Mexico, and 17 state-based studies (Appendix I).

NOAA has sponsored a website, Digital Coast (https://coast.noaa.gov/digitalcoast/) that is focused on helping communities across the US address coastal issues, and it has become one of the most-used resources in the coastal management community. The web mapping tool allows users to visualize community-level impacts from coastal flooding or sea level rise and maintains data related to water depth, connectivity, flood frequency, socio-economic vulnerability, wetland loss and migration, and mapping confidence. We adapted the latest marsh migration data in NOAA's Sea Level Rise Viewer tool (Marcy et al. 2011) as the basis of our migration space models.

Our approach to mapping site resilience focuses on the characteristics of the underlying geophysical stage rather than on the dynamics of the biotic systems. We assume that the biotic systems will change in concert with the changing climate, but that sites with certain enduring physical characteristics will have a larger capacity to support diversity, productivity, and ecological function into the future (Anderson et al. 2014). This approach has been called "conserving nature's stage," and is supported by current and historical evidence (Lawler et al. 2015; Beier et al. 2015; Gill et al. 2015; Anderson & Ferree, 2010). In the case of coastal sites, the elevation, landforms, and parent material that underlie a site and its surrounding lands can determine whether the site has space and options for adaptation.

We use the term "site resilience" to distinguish this approach from "ecosystem resilience" as the latter implies that an ecosystem is rebounding back to a previous state. Site resilience, in contrast, refers to the capacity of a physical site to maintain species diversity and ecological function even as the composition and proportion of habitats change in response to climate change. A resilient site is characterized as an area with enough options to sustain species and ecosystems in the face of stress and uncertainty. Such options, or characteristics that foster resilience, may include topographic and elevation diversity that provide a range of habitat types and microclimates, and space for adaptive movements with minimal barriers that restrict the movement of species or ecosystems. A site without such options would be considered vulnerable in the face of climate change.

Prior to this study, we developed methods for estimating the resilience of terrestrial sites (Anderson et al. 2014) by evaluating a site's landscape diversity (microclimates created by a site's topography, elevation gradients, and wetlands) and local connectedness (the degree to which the land cover is conducive to the movement of organisms and the flow of ecological processes). We mapped areas with higher microclimate diversity and local connectedness across a range of geophysical sites within large geographic regions (e.g., Eastern US, Great Plains, Great Lakes) to identify resilient sites across the US (http://maps.tnc.org/resilientland/). We excluded the coastal region of these geographies so we could undertake a separate assessment that considered sea level rise and focused on the potential for coastal marsh migration. The terrestrial study has been used successfully to inform conservation decisions and we hope that this counterpart study addressing the coastal region will be equally useful.

Our approach has similarities to other models that estimate the vulnerability of coastal regions to SLR, erosion, and inundation. In particular, the USGS Coastal Vulnerabilities Index (Thieler & Hammar-Klose, 1999), InVEST Coastal Vulnerability Model (Sharp et al. 2016), and the National Estuarine Research Reserve multi-metric approach (Raposa et al. 2016). Ecosystem vulnerability, in these studies is defined in the terminology of the Intergovernmental Panel on Climate Change (IPCC) as a combination of sensitivity and exposure. A primary difference between these vulnerability studies and this study is that other than SLR, we do not use factors that are dependent on climate (e.g. exposure, surge potential, community composition). Instead, we assume all sites have high exposure, high surge potential, and a changing composition, and we then identify the sites with characteristics that allow them to persist and support diversity even under the extreme scenarios. By running multiple SLR scenarios and scaling our results to the extreme 6.5-foot SLR scenario, we can identify the sites with more options for adaptation. In our model, a site is not considered more vulnerable if it *has more exposure to risk*, rather it is considered more vulnerable if it *has no options for adapting to, or accommodating, risk*.

CHAPTER 3

DEFINING & MAPPING COASTAL SITES

A coastal site was defined as an area of land regularly flooded by saline tidal waters and that contained tidal and estuarine habitats. Our site definition encompassed the landforms, soils, and tidal inundation zones that define the boundary and regulate local processes. These physical features set the stage for a mix of biotic and abiotic habitats such as salt marsh and tidal flats that may move or expand with changes in climate. We mapped each site individually, and our analysis centered on measuring the characteristics and processes that influence its ability to accommodate sea level rise (SLR) by migrating inland and adapting to new conditions. To evaluate this, we divided each site into three components: the tidal complex, its migration space, and surrounding buffer area. Below we discuss the methods we used to map each component.

Tidal Complex

We used the term "tidal complex" to refer to a set of interconnected tidal and estuarine habitats that were spatially grouped into a contiguous area. The habitats included:

Tidal marsh: Intertidal wetlands of low energy environments that form expansive meadows or narrow shoreline fringes dominated by *Spartina patens* or *S. alterniflora* (i.e., salt marsh). Tidal marshes are one of the most productive ecosystems in the world, producing up to 20 tons of biomass per acre and providing shoreline stabilization, nutrient cycling and critical wildlife habitat for many species of plants, invertebrates, mammals and birds. Salt marshes also provide breeding, refuge, nursery, and forage habitats for marine fauna.

Brackish marsh: Brackish marshes are transitional between freshwater and salt marsh, and form along the upland edge of salt marshes where freshwater runoff or groundwater dilutes the salinity of the marsh surface. Dominated by bulrushes and sedges, the species vary depending on local hydrology and salinity levels.

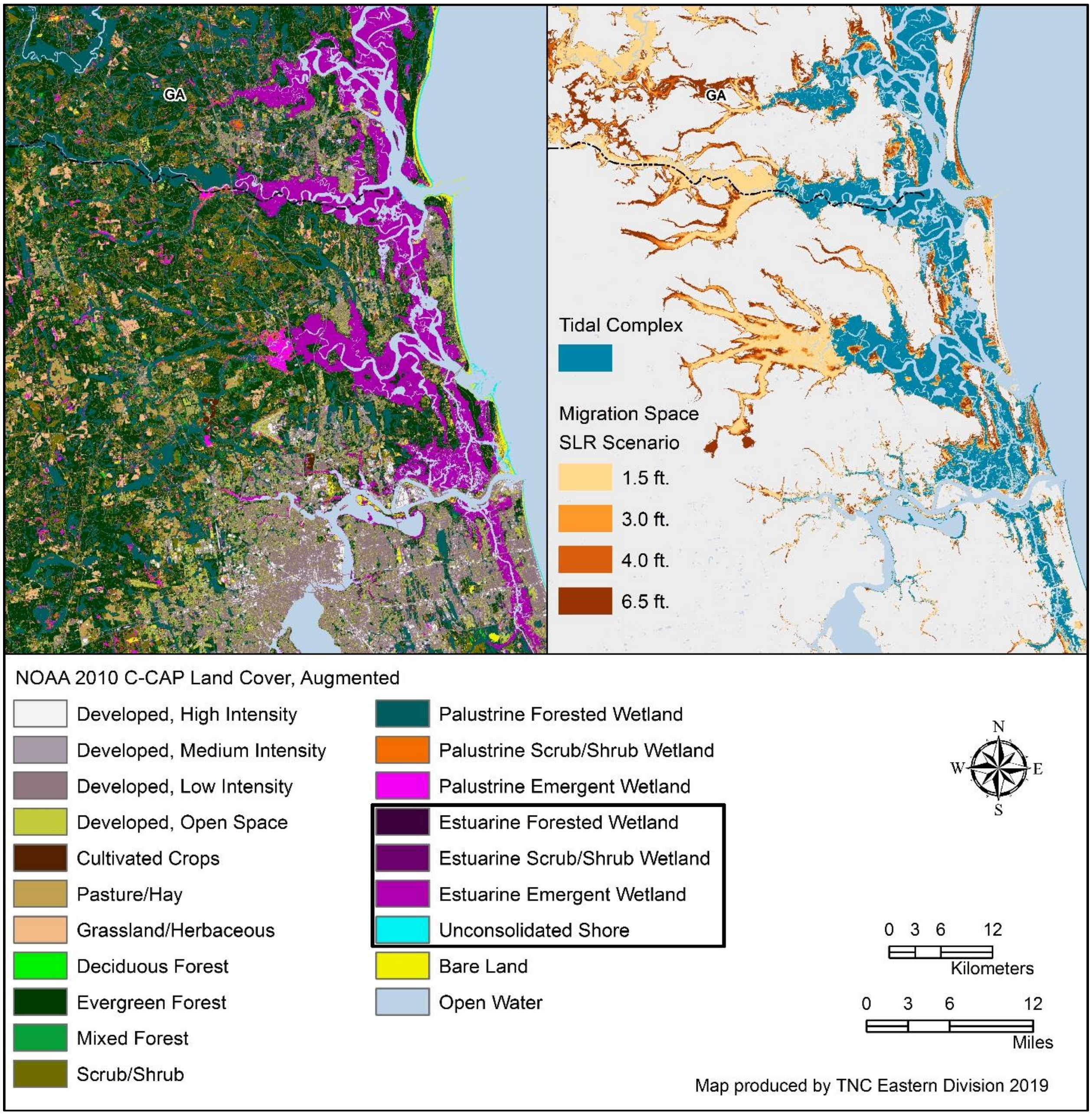
Tidal flat: Non-vegetated sand and mud flats are the central habitat for blue mussel, eastern oyster, hard clam, soft shell clam, horseshoe crab, marine annelids and many other invertebrates. At high tide, they are productive foraging grounds for fish, eels, crabs, and snails. At low tide, many shorebird species depend on them for grazing and foraging. Tidal flats have historically been undervalued by coastal managers and are poorly mapped for this region.

Mapping Tidal Complexes

To identify and map tidal complexes, we used NOAA's 2010 C-CAP 30-m land cover data (NOAA, 2017), which was also used in NOAA's Sea Level Rise Viewer (Marcy et al. 2011). We augmented the C-CAP land cover dataset by adding TIGER roads (major, minor, and residential) and TIGER railroads (US Census Bureau, 2017b) to ensure continuous road and railroad networks were included. We selected all pixels coded as unconsolidated shore or one of three estuarine wetland types: forested, scrub/shrub, or emergent (Figure 3.1).

We experimented with several different ways to aggregate cells into discrete units based on adjacencies and distances. No single approach worked perfectly as some distances resulted in units that seemed too big while others seemed too small, and the literature is sparse on distance thresholds for what constitutes an ecologically functioning tidal wetland complex. Based on previous studies (Faber-Langendoen et al. 2012; Mitchell et al. 2013; King County, WA, 2017), and on input from the steering committee, we chose 150 meters as the maximum distance between cells. We grouped pixels of estuarine habitat or unconsolidated shore that were less than or equal to 150 meters apart. This had the effect of aggregating adjacent cells of various tidal habitats into a single unit that we called a "tidal complex" (Figure 3.1). The units were then converted to discrete polygons, assigned unique IDs, and the acreage and perimeter of each tidal complex polygon was calculated.

Figure 3.1. Tidal complexes. The map shows the augmented NOAA 2010 C-CAP map of Nassau Sound, FL on the left, and the mapped tidal complex on the right. The tidal complex is in dark blue. Migration space (defined below) is in orange.

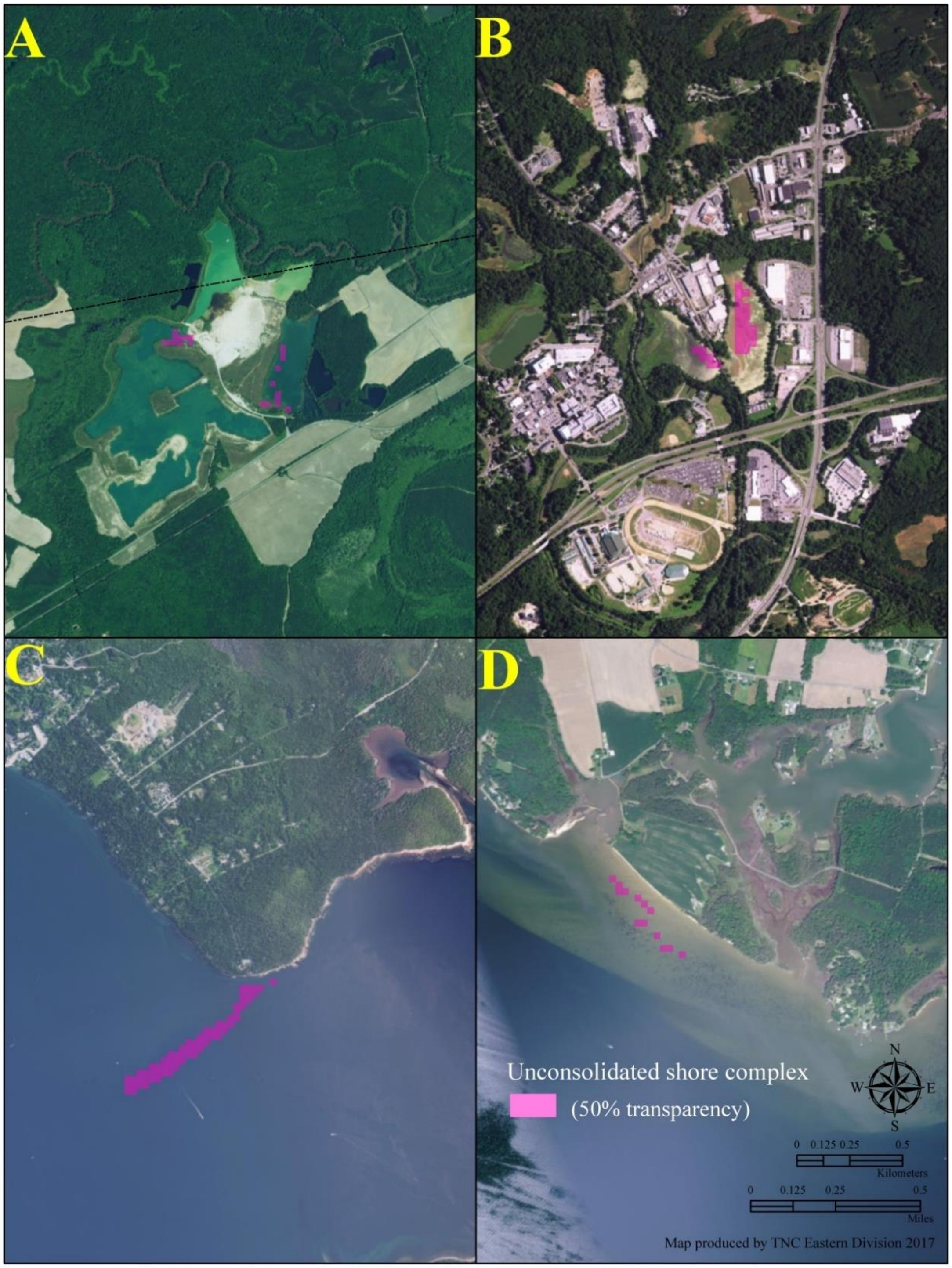


The mapping method resulted in thousands of polygons of which most were single pixel sites. To reduce noise in the dataset and focus on sites that were likely to be ecologically meaningful, we identified a subset of the tidal complex units that had at least two acres of estuarine wetland (salt marsh). Initially, we had included tidal complexes composed solely of unconsolidated substrate (i.e., beach and tidal flats).

However, after internal review, we excluded these sites as they were often erroneously and inconsistently mapped (Figure 3.2). We tried different approaches to identify real unconsolidated shore complexes, but we were unable to develop a successful technique due to variations in tide levels when the underlying imagery was taken.

The two-acre salt marsh threshold reduced the number of tidal complex units by almost 90 percent. After further review, we discovered that some of the remaining complexes seemed unlikely to be tidal wetlands based on their location. To review the complexes systematically, we intersected the National Wetlands Inventory (NWI) wetlands data (USFWS, 2015), classified into eight general types by USFWS, with the tidal complexes to calculate the amount of each wetland type in the unit. Using satellite imagery and improved land cover and ecological systems data, we manually reviewed the tidal complex units that had very little NWI estuarine or marine wetland to ensure the complexes were actually tidal marshes. This review resulted in the removal of almost fifty percent of the complexes, most of which were quite small. The results after applying our criteria and implementing some quality control was a final set of 1,232 tidal complex units assessed in this study.

Figure 3.2. Unconsolidated shore complexes. These four examples illustrate the problems with including complexes comprised solely of unconsolidated shore. In panels A and B, the unconsolidated shore complex is actually part of an industrial site. In B and C, the unconsolidated substrate is not visible in satellite imagery, likely due to when the imagery was captured.



Tidal Complex Delineation Challenges

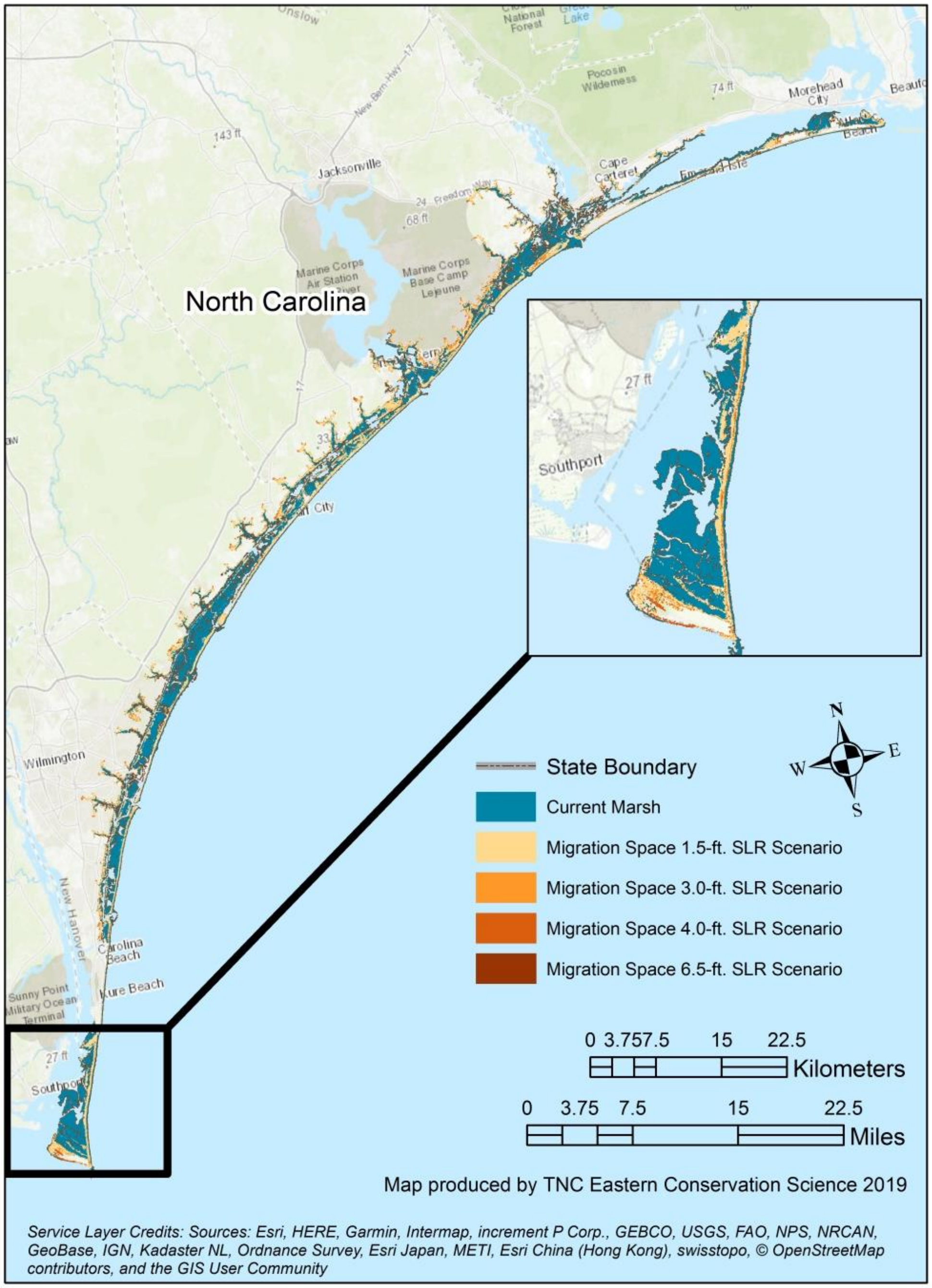
Large Complexes

The aggregation rule we used to create tidal complexes sometimes resulted in very large tidal complexes that may not actually function as one ecological unit or that are impractical from a management standpoint (Figure 3.3). To help address concerns with some of these large tidal complexes, we separated the tidal complexes into smaller units that allow a user to see individual marsh components of the larger wetland, and to evaluate how close some of these are to a particular migration space. This dataset, disaggregated tidal complexes, is included in the study’s downloadable data package.

Tidal Wetland Mapping Accuracy

Distinguishing tidal versus non-tidal wetlands is challenging, particularly when tidal influence extends far inland and is changing in response to SLR. We identified tidal wetlands by extracting the estuarine classes from NOAA’s 2010 C-CAP land cover dataset. However, the palustrine category can include some tidally-influenced wetlands, but there is no clear distinction, nor was there a reasonable approach we could use to make this distinction at a regional scale. As such, some wetlands that are actually tidally-influenced may not be represented in the tidal complex, and instead, are included in a site’s migration space. For example, study reviewers noted that Winyah Bay, near Georgetown, South Carolina, is missing existing tidal wetlands in the upper bay and riverine systems. These upstream areas were identified as migration space rather than existing tidal complexes. This case illustrates the importance of supplementing the study results with local site knowledge to interpret and appropriately use the findings to inform conservation and management actions.

Figure 3.3. Large tidal complex. This map shows a single tidal complex (site) in dark blue along the southern North Carolina coast. This complex is very long and connected, and we treated it as one site. At 1.5 feet of SLR (light orange), the current marsh has over 2,000 small migration space units that collectively total 8,219 acres, with the largest unit encompassing 557 acres at the marsh's southern end (see inset). If the marsh successfully migrates into that space, a large portion of the new marsh will be in a different place than the current marsh. By 6.5-feet of sea level rise, the largest migration space is 684 acres at the northern end of the marsh, near Camp Lejeune.



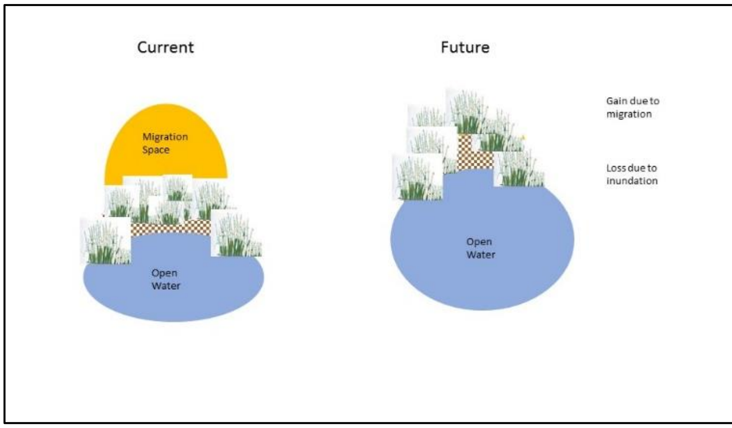
Migration Space

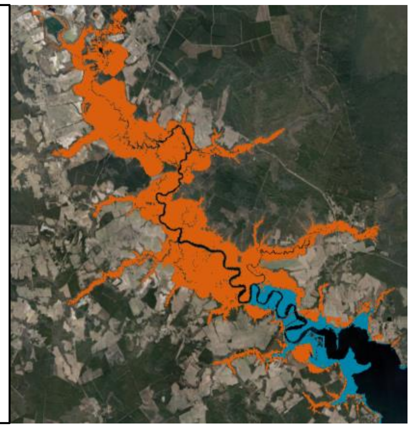
Migration space is defined as the area of low-lying land adjacent to the tidal complex that is potentially suitable for supporting tidal habitats in the future and into which the current habitats could migrate in response to rising sea levels. For example, as sea levels rose over the last century, Maryland's Blackwater National Wildlife Refuge gained 2,949 acres of new salt marsh at the existing marsh's upland edge (i.e., the migration space, Lerner et al. 2013). The concept of migration space appears in many coastal resilience studies where it has been variously called "accommodation space," "future marsh," "marsh migration opportunity areas," "migration pathways," "potential marsh zone," or "marsh migration opportunity areas" (Schuerch et al. 2018; C. Chaffee, pers. comm. 2017; K. Lucey, pers. comm. 2017; Maine Natural Areas Program, 2016). The transition process works like this: tidal marshes exist in a narrow zone between the mean high tide and the mean high-water line. As the tide rises, existing marshes become increasingly inundated, creating unsuitable conditions for vegetation growth and converting the marsh to unconsolidated substrate or open water. Meanwhile, new land suitable for habitat development may become available in the immediately adjacent lowlands as they start receiving regular tidal inundation. If conditions are right, the marsh may be able to migrate onto this land (Figure 3.4).

Sites vary widely in the amount and suitability of migration space they provide. This is determined by the physical structure of the site and the intactness of processes that facilitate migration. A marsh hemmed in by rocky cliffs will eventually convert to open water, whereas a marsh bordered by low lying wetlands with ample migration space and a sufficient sediment supply will have the option of moving inland.

As existing tidal marshes degrade or disappear, the amount of available high-quality migration space becomes an indicator of a site's potential to support estuarine habitats in the future. The physical size and shape of a site's migration space is dependent on the elevation, slope, and substrate of the adjacent land. The condition of the migration space also varies substantially among sites depending on the anthropogenic context. For some tidal complexes, the migration space contains roads, houses, and other forms of hardened structures that resist conversion to tidal habitats, while the migration space of other complexes consists of intact and connected freshwater wetlands that could convert to tidal habitats.

Figure 3.4. Migration space. Diagram illustrating how current tidal marsh is expected to move into its migration space, while the existing marsh is mostly lost to inundation. The image on the right shows the current marsh and migration space (orange) for the White Oak River tidal marshes in southern North Carolina.





Our aim was to characterize each site's migration space and estimate its capacity to support a diverse tidal complex in the future. Towards this end, we measured its size, shape, location, and condition, and we evaluated its tidal zones and shared adjacencies with the current tidal complex. We assumed that most migration space will support some combination of salt marsh, brackish marsh and tidal flat in the future, but we did not predict the future composition. Accurate predictions concerning the abundance and spatial arrangement of future tidal habitats are notoriously difficult to make because habitat transitions are often non-linear and facilitated by pulses of disturbance and internal competition among species. For instance, in response to a small 1.4 mm increase in the rate of SLR, the landward migration of low marsh cordgrass in some New York marshes appears to be displacing high marsh much more quickly than expected (Donnelly & Bertness, 2001). Our assumption was simply that a tidal complex with a large amount of high quality and heterogeneous migration space will have more options for adaptation, and will be more resilient, than a tidal complex with a small amount of degraded and homogenous migration space.

Mapping Migration Space

Given the importance of migration space in our analysis, we evaluated several potential ways to delineate it by reviewing existing work. In a previous project for the Northeast and Mid-Atlantic US (Anderson & Barnett, 2017), we opted to use data from NOAA's SLR Viewer which covers the entire US coast and uses a modified bathtub approach that considers local and regional tidal variability for multiple SLR scenarios. Our approach here was to start with the latest NOAA SLR model marsh migration data, convert it into a model of migration space, and then compare the results with other SLR studies done in the South Atlantic and neighboring regions.

The NOAA data does not map migration space per se, but instead predicts the distribution of future habitat types based on SLR scenarios and tidal class thresholds. To convert the results to migration space, we combined the area of three predicted habitat classes: brackish marsh, tidal marsh, and tidal flat into a single spatial extent. This simplified the individual habitat models into a single area of delineated migration space and eliminated error in habitat class predictions by focusing only on their combined spatial extent.

To delineate migration space for the full project area, we obtained the latest SLR Viewer marsh migration data from NOAA (N. Herold, pers. comm., 2018), with no accretion rate, for the four states in the project area, plus Virginia to address any edge of project boundary issues. We chose not to use any of the three SLR Viewer accretion rates because they were constants applied across each geographic region while actual accretion is very location specific. For each geography, we combined the four SLR scenarios (1.5′, 3′, 4′, and 6.5′) with the baseline scenario to identify pixels that changed from current baseline. We only selected cells that transitioned to tidal habitats (unconsolidated shoreline, salt marsh, and transitional/brackish marsh) and not to open water or upland habitat. We combined the results from each of the geographies and projected them to NAD83 Albers. The resultant migration space was then resampled to a 30-m grid and snapped to the NOAA 2010 C-CAP land cover grid.

The tidal complex grid and the migration space grid were combined to ensure that there were no overlapping pixels. Although developed areas were not allowed to be future marsh in the NOAA habitat models, we still removed development from the migration space using the original 30-m NOAA 2010 C-CAP land cover grid. This was necessary because differences in spatial resolution between the underlying elevation and land cover datasets could occasionally result in small amounts of roads or development in our resampled migration space. The remaining migration space was then spatially grouped into contiguous regions using an eight-neighbor rule that defined connected cells as those immediately to the right, left, above, or diagonal to each other. The region-grouped grid was converted to a polygon, and the SLR scenario represented by each migration space footprint was assigned to each polygon. Finally, the migration space scenario polygons that intersected any of the tidal complexes were selected for use in this study.

A single migration space polygon could be adjacent to and accessible to more than one tidal complex unit, so each migration space polygon was linked to its respective tidal complex unit(s) with a unique ID by restructuring and aggregating the output from a one-to-many spatial join in ArcGIS. This linkage enabled the calculation of attributes for each tidal complex and each migration space such as total acreage, total number of units, and the percent of the tidal complex perimeter that was immediately adjacent to migration space.

To ensure that the migration space derived from the NOAA SLR Viewer data was accurate and usable we compared it with migration space derived from three other regional studies completed for the Southeastern US, one in the South Atlantic and two in the Gulf of Mexico. We had done a similar comparison in the Northeast where the results had compared favorably with fine-scale local models in Virginia, Massachusetts, and Maine. The Southeast studies included:

(1) South Atlantic LCC: **Sea Level Rise Modeling for the South Atlantic Migratory Bird Initiative Designing Sustainable Landscapes Project** (Rubino, 2009) http://www.basic.ncsu.edu/dsl/slr.html

The objective of this project was to model landscape-scale changes to habitat based on various climate change scenarios within the South Atlantic Migratory Bird Initiative region. The author used a Sea Level Affecting Marshes Model (SLAMM v 5.0.1) applied to the National Elevation Dataset 30-m Digital Elevation Model (NED DEM) combined with North Carolina lidar resampled to 30 m, National Wetlands Inventory data, and NOAA NOS/CO-OPS tidal measurement stations. The study estimated the relative amount of sea level rise under four climate scenarios.

(2) USGS: **Incorporating future change into current conservation planning—Evaluating tidal saline wetland migration along the U.S. Gulf of Mexico coast under alternative sea-level rise and urbanization scenarios** (Enwright et al. 2015) http://dx.doi.org/10.3133/ds969.

The objective of this project was to identify future tidal saline wetlands under different SLR and urbanization scenarios. They used a modified bathtub model applied to lidar-based DEMs, National Wetlands Inventory Data, and NOAA's Vertical Data Transformation (VDATUM 3.1). They predicted the future distribution of three types of saline wetlands (mangrove forests, salt marshes, and salt flats) under five SLR scenarios (0.5, 1, 1.5, 2 meters).

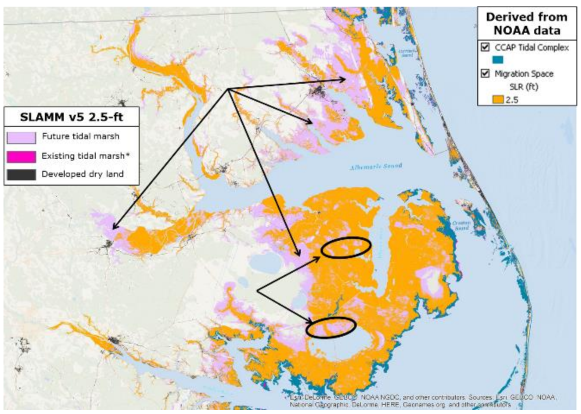
(3) Gulf Coast Prairie LCC: **Sea-Level Affecting Marshes Model Gap Analysis Project** (Warren Pinnacle Consulting, Inc., 2015)
http://warrenpinnacle.com/prof/SLAMM/GCPLCC/

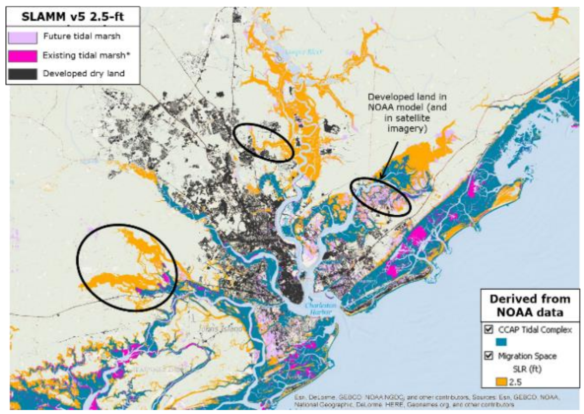
The objective of this project was to predict where marshes may migrate upland in response to changes in water levels, and to conduct focal species analysis using the new land cover projections. They used a Sea Level Affecting Marshes Model (SLAMM v 6.5) applied to data from multiple lidar sources (10 to 3-m resolution), National Wetlands Inventory data, and NOAA's Vertical Data Transformation (VDATUM 3.2 and 3.3). They predicted migration areas under five SLR scenarios for 2100: (0.5, 1, 1.2, 1.5, 2 meters).

Comparisons of the NOAA migration space model with migration space derived from the other regional data sets showed substantial agreement and overlap (Figure 3.5). Areas of disagreement were mostly the result of spatial resolution differences between input datasets (e.g., the SALCC study used coarser elevation models than the NOAA model) or differences in the base land cover. After an in-depth comparison and review with the steering committee, the team unanimously agreed to the use of the NOAA SLR Viewer data for this project due to its high consistency and relative accuracy across the study area.

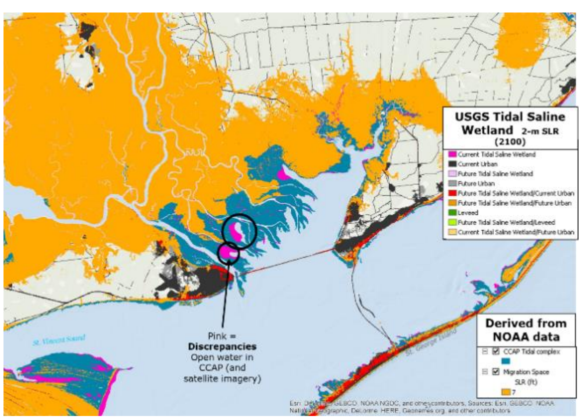
Figure 3.5. Migration space model comparisons. Comparisons of the migration space derived from the NOAA SLR Viewer marsh migration data with migration space derived from other regional datasets.

(A) The South Atlantic LCC. The left figure shows high congruence between the two models, but the SA LCC shows higher levels of inundation at 2.5 feet than the NOAA model. At 3-6 feet of inundation, the NOAA model shows the same areas. The right map shows the opposite, two areas of migration space (circled) that are not yet inundated at 2.5 feet in the SA LCC model. The rightmost circle shows an area classified as developed in the NOAA model and in satellite imagery, but was classified as available in the SA LCC model.





(B) USGS. The left figure shows high congruence between the two models, with the only difference being the pink areas classified by USGS as tidal marsh, and by NOAA and satellite imagery as open water. The figure on the right shows areas predicted to convert to open water in the NOAA data at 0.5 ft. of SLR, but classified as future tidal marsh in the USGS model.



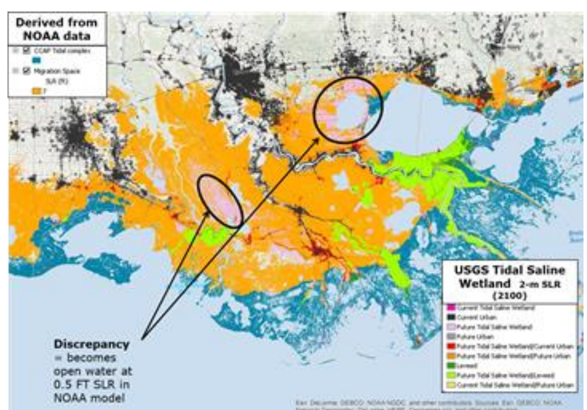
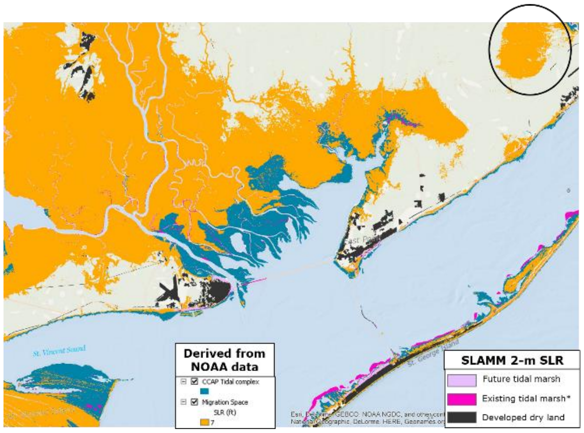
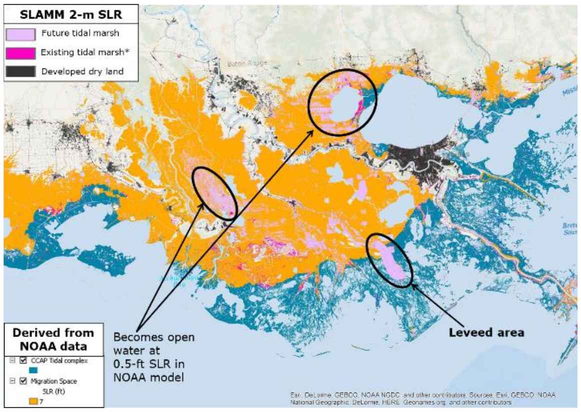


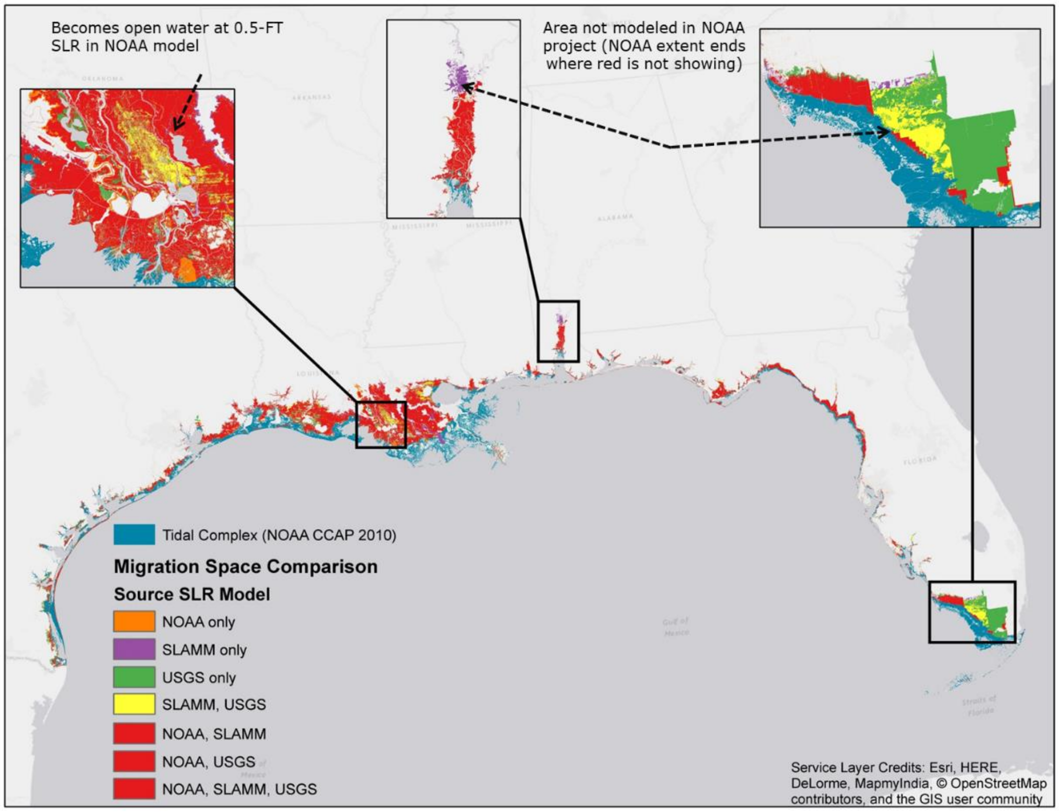
Figure 3.5. continued.

(C) Gulf Coast LCC. The left figure shows high congruence between the two models, but there are small discrepancies in the mapping of current tidal marshes, and the upper left circle shows migration space in both NOAA and USGS that is missing in the GC LCC model. The right figure shows some areas (light pink) of future marsh in the GC LCC that are inundated in the NOAA model.





(D) Integrated Model: We used the unmodified NOAA model in the South Atlantic, but we added the migration space shown by USGS and the GC LCC in the Gulf of Mexico.



Accessible Migration Space

As noted in the previous section, we removed development pixels from the resampled migration space using the original NOAA 2010 C-CAP land cover grid. Major roads are mapped as developed land in national land cover datasets such as NOAA's C-CAP and the National Land Cover Dataset (NLCD). However, due to pixilation, roads are not always mapped as continuous networks in these regional land cover datasets. In addition, smaller state roads and residential roads are often not included. If a road is not mapped as a continuous network, it's potential to fragment a migration space unit may not be fully realized. We wanted to examine the potential impact on migration space contiguity and size if we included all roads and railroads in the delineation of the migration space. To do this, we delineated "accessible" migration space, using the same approach as previously described, but using the augmented NOAA 2010 C-CAP land cover grid, which included a continuous representation of TIGER roads and railroads. We then calculated the total accessible migration space area for each site under the four SLR scenarios.

We recognize that whether a road will fragment the migration space of a marsh depends on a variety of physical and societal factors that cannot easily be measured and mapped at a regional scale. Thus, unless otherwise noted, the migration space analyses and attributes described in this study rely on the migration space previously described, in which development and major roads were removed.

We did not want to lose the information on the potential accessibility of migration space, so we developed an approach to impose a modest penalty for sites whose migration space was more fragmented (i.e., less accessible) than other sites within the same shoreline region. We adjusted a site's final physical score based on the percent of its migration space that was accessible ((accessible migration space size / migration space) * 100). The approach we used is described in detail in the "Integration of Physical and Condition Characteristics" section of Chapter 5. The adjustment most strongly impacted sites with migration space in more urban and developed settings.

Migration Space Scenarios

The amount of migration space available to a tidal complex is a function of the surrounding elevation and topography, combined with the amount of expected sea level rise. Initial estimates of global sea level rise over the next century suggested a range from 1.6 to 4.6 feet (Rahmstorf et al. 2007; IPCC, 2013) and have recently increased by up to three additional feet based on the volatility of the Antarctic ice sheet (DeConto & Pollard, 2016). In the US, an interagency team led by NOAA recently revised the lower and upper bounds of their global and regional sea level rise scenarios for 2100 based on the latest peer-reviewed research on global mean sea level rise that considers the possibility of rapid ice melt in Greenland and Antarctica (Sweet et al. 2017). The estimates have been increased from 0.65– 6.5 ft. up to 1.0 to 8.2 ft. (0.2 - 2.0 m up to 0.3 - 2.5 m). The report also found that along all US coasts except Alaska, relative sea level is expected to be greater than the global average under several of the scenarios.

To map a range of possible migration space amounts we estimated its extent with respect to four SLR scenarios: 1.5′, 3.0′, 4.0′, and 6.5′ (Figure 3.6). These matched the scenarios used in the existing regional studies, and results for all scenarios are available to users of this project (see accompanying spatial datasets). However, after studying the patterns across all scenarios, we scaled our results to the 6.5-foot scenario because we wanted to identify sites that were robust to the most extreme events. Except for the Island Archipelago region, the average migration space size of sites increased from the 1.5-foot SLR scenario to the 6.5-ft. scenario.

In the results presented here, sites with increasing migration space over all scenarios scored higher than sites whose migration space declined with increasing inundation. We examined the trend of the migration space size from the 1.5 to 6.5-foot scenario to identify sites where the migration space was continuing to increase in size (Figure 3.7). This was done by fitting a regression line to the size of the new migration space across all four scenarios (1.5, 3.0, 4.0, and 6.5 -foot). Sites where the regression showed a significant trend ($p \leq 0.05$) were scored as increasing or decreasing depending on the trend sign (positive or negative). Sites that had a significant positive trend in migration space size received a small bonus of 0.5 SD to their final resilience score.

Figure 3.6. Migration space scenarios. This map shows the migration space under four SLR scenarios for the White Oak River tidal complex in southern North Carolina. The amount of migration space accumulates for each scenario, but at this site, most migration space is gained at the lowest sea level rise scenario (1.5 ft.).

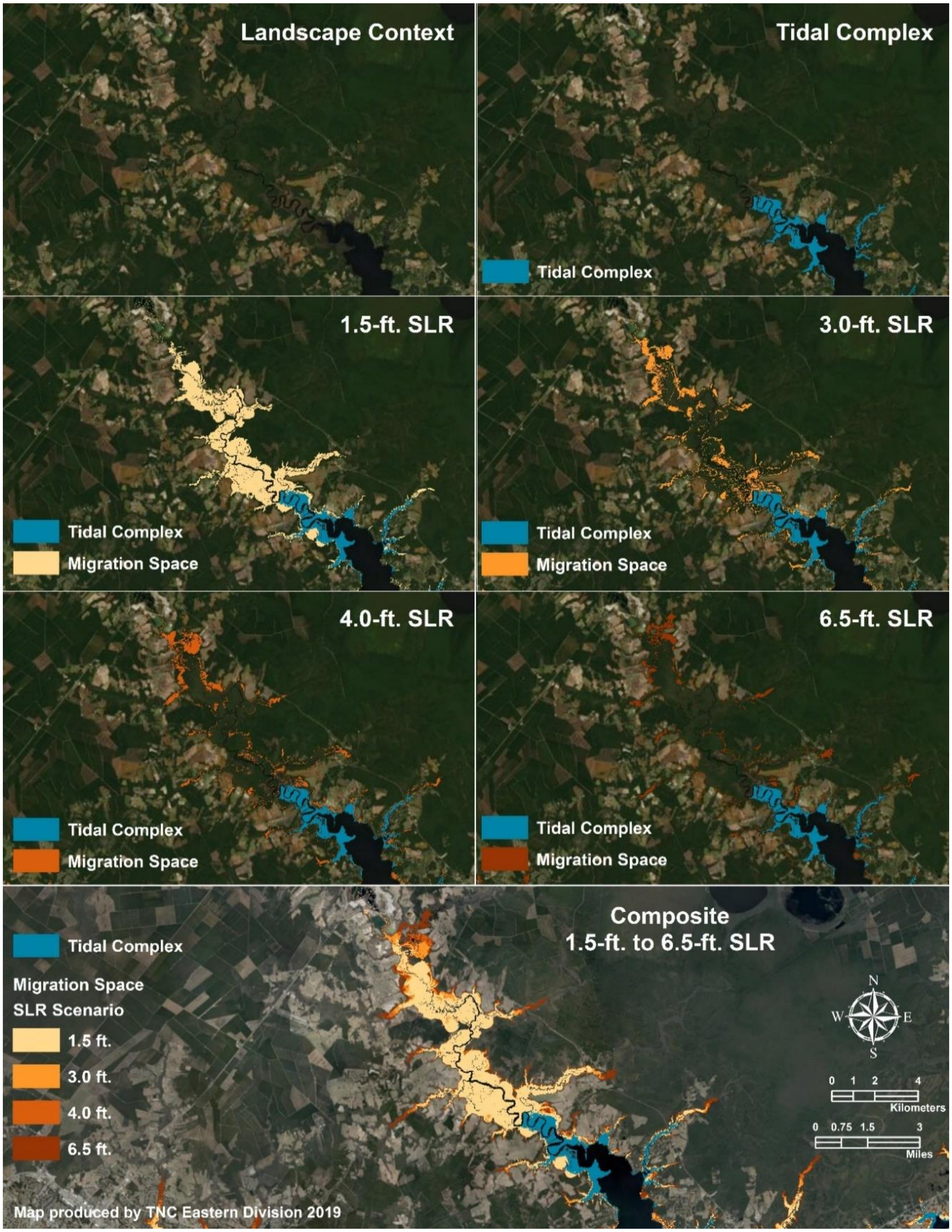
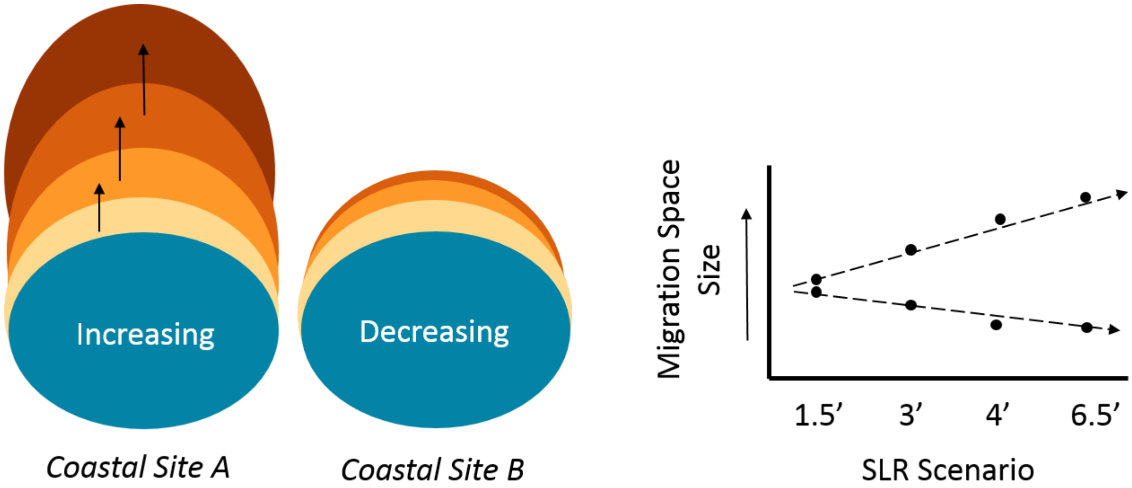


Figure 3.7. Migration space trend. The diagram shows the 1.5 to 6.5-foot SLR scenarios for two sites. Site A has moderate migration space under the 3-foot scenario but its migration space increases over later scenarios. The site on the right has the same size migration space for the 1.5-foot scenario, but the migration space decreases with each subsequent scenario. The chart shows how the trend would appear in the regression analysis.



Buffer Area

The natural and agricultural land immediately surrounding the tidal complex is an important component of a site because it influences the condition and ecological processes occurring in the tidal complex and its migration space. We referred to these lands as "buffer area" and we measured their extent, quality, and naturalness. A large intact buffer area allows coastal systems to interact with surrounding terrestrial and freshwater systems, and the condition of the buffer influences the water quality, sediment transport, species migrations, and dynamic processes within the migration space and tidal complex. A tidal complex hemmed in by development and having a small, degraded, homogenous buffer area is presumably less resilient than a complex with a large, natural, and ecologically heterogeneous buffer, because the complex has limited options for rearrangement and interactions. The buffer area also represents potential migration space beyond a sea level rise scenario of 6.5 feet. Initially, we focused solely on natural land cover, however; discussion and input from the steering committee highlighted the importance of including agricultural lands, particularly poorly drained farm land, as a potential influence on marsh migration patterns in the future.

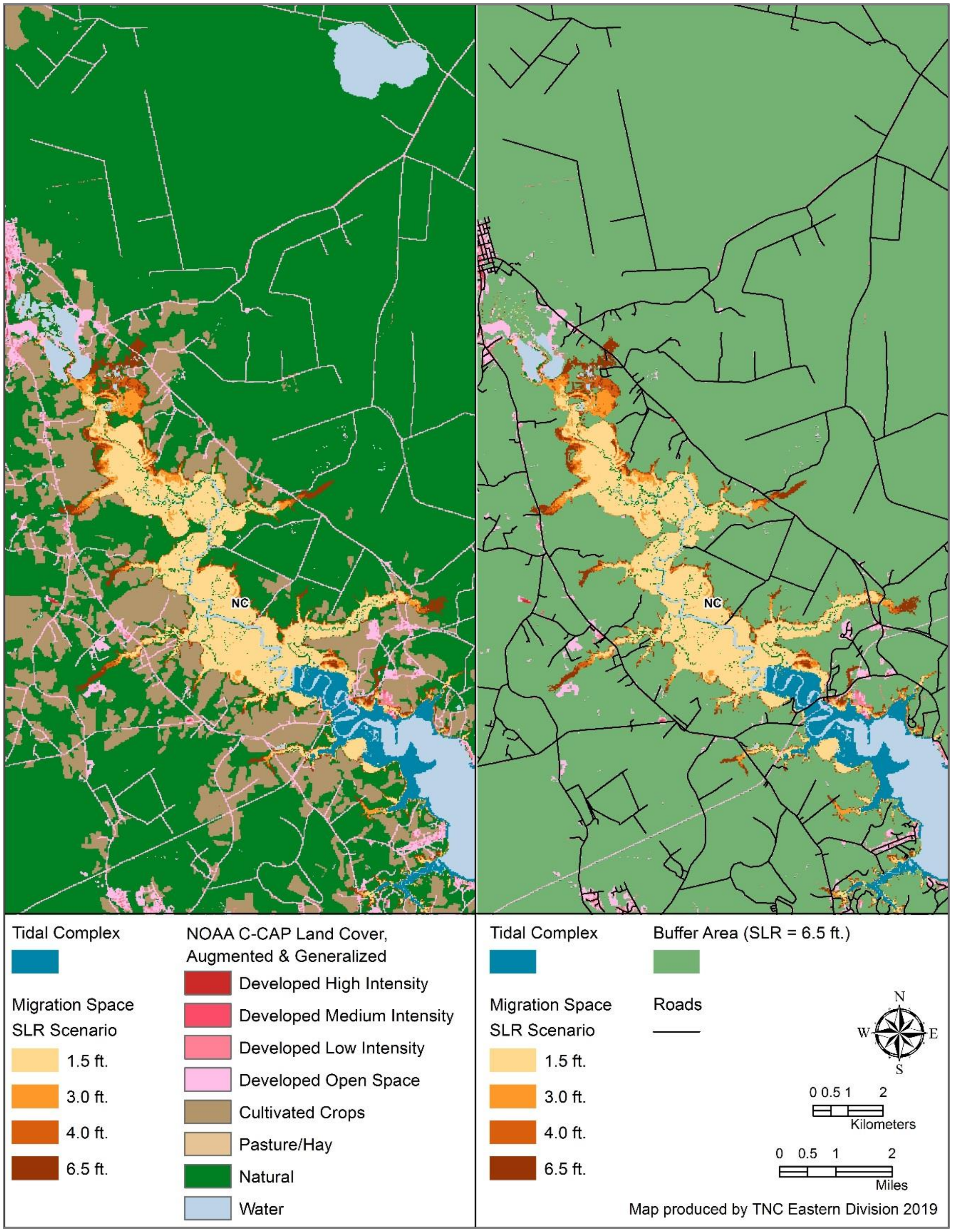
Mapping Buffer Area

To delineate the buffer area for each tidal complex and its migration space, we selected natural cover and agricultural land cover, including hay and pasture, from an augmented version of the NOAA 2010 C-CAP land cover grid (Figure 3.8). The augmented C-CAP had more information on railroads as well as minor and residential roads than the standard version. We then used a series of masks to remove all pixels likely to be underwater in each of the four SLR scenarios, and we also removed any cells in the buffer area that had been mapped as tidal complex or migration space. The remaining pixels of natural and agricultural land cover were region-grouped using an eight-neighbor rule and converted to a polygon.

For each SLR scenario, discrete buffer polygons that intersected accessible marsh migration space polygons were selected and then attributed with a unique ID, acreage, and perimeter. We used the accessible marsh migration space instead of the geophysical migration space because the buffer areas themselves were derived from the augmented NOAA 2010 C-CAP grid, which was also used to delineate the accessible migration space units. Next, the output from a one-to-many spatial join in ArcGIS was restructured and aggregated in R (R Core Team, 2018) to link each buffer area polygon with the accessible migration space unit that it intersected. As some of the buffer area polygons were quite large, there were cases where a tidal complex had no migration space but did have buffer area. To account for this, the spatial linkage was repeated between the buffer area units and the tidal complex units. Both linkages were done for each of the four SLR scenarios.

With the buffer area units linked to the accessible migration space and tidal complex units, several cumulative attributes were then calculated for each buffer area. These included the total tidal complex acreage, count of tidal complexes, total accessible migration space acreage, and accessible migration space count.

Figure 3.8. Buffer area. The map on the left shows the augmented NOAA 2010 land C-CAP cover where natural land classes (forest, shrub/scrub, wetlands, etc.) are shown in green, agricultural land is brown, and developed lands are in shades of red. The map on the right shows how the land cover data, with roads and railroads added, translated to the buffer area around the tidal complex and its migration space (orange shades).



CHAPTER

4

COASTAL SHORELINE REGIONS

To facilitate comparisons between similar types of ecosystems and estuaries, we divided the study area into four coastal shoreline regions associated with discrete geographic stretches of shoreline that share similar processes and dominant estuary types (Figure 4.1). Stratifying the results within the shoreline regions allowed us to account for systematic variation in processes, geomorphology, habitat types, and species use, and thus make fair comparisons of resilience characteristics within regions of similar estuary types as opposed to comparing across types. For example, we compared South Atlantic coastal lagoons to each other and not to the heavily flushed riverine systems in the Piedmont basins. Our goal was to identify the most resilient areas for each type of shoreline.

The Coastal Shoreline Regions (CSRs) were created by aggregating Coastal Shoreline Units (CSUs) developed for the South Atlantic Bight Marine Assessment (Conley et al. 2017), by estuarine type. The CSUs were based on USGS Watershed Boundary Dataset 10-digit Hydrologic Unit watersheds. These were augmented with the Estuarine and Coastal Drainage Area watersheds from the NOAA Coastal Assessment Framework (NOAA, 2007), and with information on natural features, current patterns and local knowledge. CSUs were assigned an estuary type based on the Coastal Marine Ecological Classification Standard (CMECS) categorization (Madden et al. 2009). The CMECS classification focuses on estuary size, shape, and flushing in dictating processes within an estuary and the adjacent coastal area. Three CMECS estuary types were used in the South Atlantic: 1) river-dominated estuaries, 2) lagoonal estuaries, and 3) island archipelago. Given the limited variation in CMECS types found in the region, the decision was made to divide the river-dominated estuary type into Coastal Plain and Piedmont basins. This distinction, described by Dame et al. (2000), represents the variation in freshwater flow, watershed drainage, and proportion of wetlands.

The coastal shoreline regions, from north to south were:

South Atlantic Lagoons (538 sites)

This shoreline region includes lagoons, sloughs, barrier island estuaries, and tidal inlets from Albemarle Sound south to the Florida Keys. Lagoons tend to be shallow and mostly enclosed with reduced ocean exchange. They have very high surface to volume ratios and can be quiescent in terms of wind, current, and wave energy, although many in this region are more energetic. This shoreline region consists of the huge Outer Banks area of North Carolina that contains Pamlico Sound, the largest embayed estuary in the world, the narrow arcuate shoreline marshes in southern North Carolina and South Carolina, and the long, connected barrier island complex that runs from Jacksonville Florida to the Keys.

Piedmont Basin River-Dominated (303 sites)

Sites in this shoreline region receive significant inflows of freshwater as a result of an extensive upstream watershed that frequently contributes a substantial load of suspended sediments. These estuaries are associated with major river systems and have a relatively smaller proportion of the watershed covered by wetlands. These river-dominated estuaries are linear and seasonally turbid, especially in upper reaches, and can be subjected to high current speeds. Harbors and estuaries of the larger rivers are depositional environments and typically have deltas, spits, and sand bars. The estuaries are highly flushed, with a wide and variable salinity range, and seasonally stratified. They have moderate surface to volume ratios, high watershed to water area ratios, and have very high wetland to water area ratios.

Coastal Plain River-Influenced (163 sites)

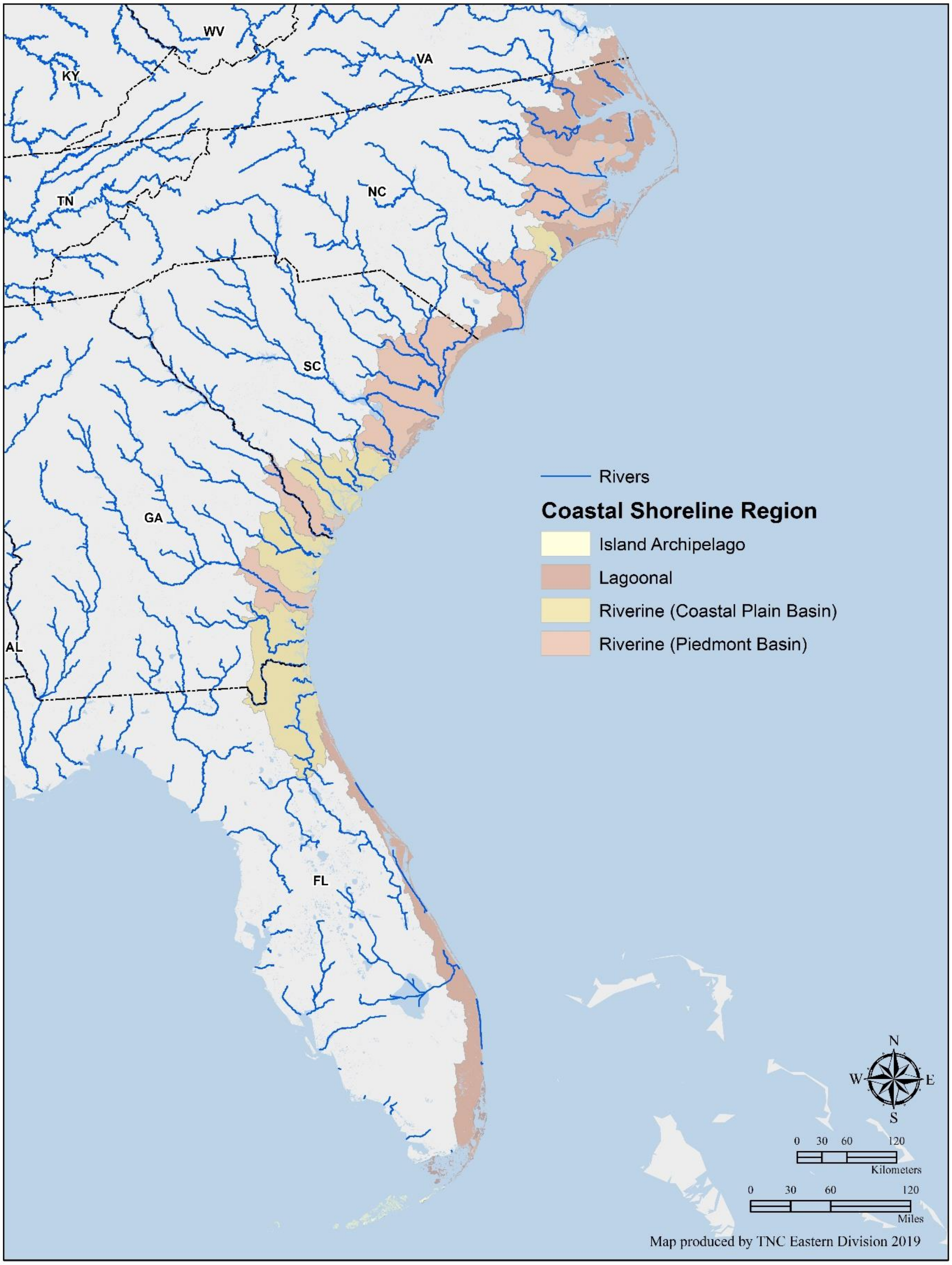
This CSR is comprised of smaller river basins with watersheds entirely contained within the Coastal Plain. These systems have highly variable discharge rates and low loads of suspended sediments. A larger proportion of the watershed is covered by wetlands, and these estuaries generally contain a more extensive saline zone due to the lack of significant freshwater inflow (Dame et al. 2000). Like other river-dominated estuaries, they tend to be linear and seasonally turbid, especially in the upper reaches, and can be subjected to high current speeds. The estuaries are depositional environments with deltas, spits, and sand bars and are moderately highly flushed, with a variable salinity range. They have moderate surface to volume ratios, high watershed to water area ratios, and have very high wetland to water area ratios.

Island Archipelago (223 sites)

This unique shoreline region is a coral cay archipelago (i.e., an island formed from sediments derived from the reef on which it sits) located off the southern coast of Florida. Consisting of only two limestone-based island archipelago sites, the islands of the middle keys form a long narrow arc, and the islands of the lower keys are perpendicular to the line of that arc. The Lower Keys are surrounded by open water areas with primarily limestone-based tidal flats. Mangrove swamps and rocky barren scrub-shrub habitats on limestone dominate the vegetated intertidal habitats.

The shoreline regions are geographic areas where the coasts and estuaries are dominated by a set of processes and geomorphology, but not every site within a CSR necessarily reflects the dominant type. The regions typically include a range of variation including small river-dominated sites and a few lagoon-like sites where sand accumulates.

Figure 4.1. Coastal Shoreline Regions (CSRs).



CHAPTER

5

ESTIMATING SITE RESILIENCE

This section describes the concepts and methods we used to estimate the resilience of a coastal site. We define “site resilience” as the ability of a site to support biological diversity and ecological functions even as it changes in response to climate change and SLR (Anderson et al. 2016). We expect coastal sites to change dramatically over the next century with new tidal habitats forming and migrating into the adjacent low lands where suitable migration space is available, and much of the existing marsh converting to open water. Identifying places where conservation can succeed, and restoration actions to help sites adapt to change, are necessary steps in sustaining the diversity and functions of coastal habitats.

In this study, we estimate a site’s resilience to SLR based on its physical characteristics and the condition of ecological processes that facilitate habitat migration. Physical characteristics change slowly and are expected to endure under both current and future climates, making them a useful template for conservation planning. By evaluating the physical and condition characteristics of each site, we can identify the sites with relatively more options for migration and rearrangement. A site with extensive high-quality migration space, supplied with adequate sediment and freshwater, and surrounded by natural buffer area offers more chances for rearrangement and adaptation than a site with little migration space, starved for sediment, and flanked by roads and development. We can reasonably call the first site more “resilient” and the second site more “vulnerable” based on the measurable differences in options for adaptation. Admittedly, we do not know exactly how natural changes will play out at either site, because predicting the precise amount and spatial arrangement of each individual component in the future depends on thousands of specific climatic, hydrologic, and biotic changes, and there are large uncertainties about each of these.

To identify the measurable factors with the greatest influence on site resilience, we examined over 25 potential attributes. For each attribute, we clarified the mechanism by which it increased options for adaptation, and we tested whether we could consistently measure the attribute across the study area with the precision needed to make realistic judgment about the site. We narrowed the attribute list down to 13 physical and condition characteristics that have a quantifiable effect on the resilience of a site and could be adequately mapped at a regional scale (Box 5.1). Some of these factors apply directly to the tidal complex and its migration space and some to the buffer area, and they are not all equal in influence. We present the 13 attributes in the next sections, focusing first on the tidal complex and migration space, and second on the buffer area.

Box 5.1. Physical and condition attributes to assess resilience of coastal sites.
Condition attributes are shown in italics.

Tidal Complex and Migration Space	Buffer Area
Physical Attributes • Amount of migration space • Diversity and evenness of tidal classes • Shared upland edge with migration space (%) • Size of current tidal complex	Physical Attributes • Adjusted buffer area size • Diversity of coastal landforms (first 1 km) • Acreage of maritime highlands
Condition Attributes • *Undeveloped upland marsh edge (%)* • *Positive sediment balance* • *Good water quality index* • *Minimal freshwater flow alteration*	Condition Attributes • *Connectedness of wetlands (first 1 km)* • *Natural cover (%) (first 1 km)*

Tidal Complex and Migration Space

This section focuses on identifying and mapping characteristics of the tidal complex and its migration space that increase a site's ability to adapt to SLR. Characteristics of the migration space are particularly critical to resilience because it represents the future distribution of the tidal complex, whereas characteristics of the current tidal complex are less influential because under most SLR scenarios the current complexes are unstable and expected to degrade or convert entirely to open water. Our model of site resilience addresses both the physical structure of the site and the condition of the components that could sustain the tidal complex and facilitate movement into a site's migration space. Because the factors are unequal in their degree of influence, we used a weighting scheme to give more weight to factors hypothesized to have a large influence on site resilience and less weight to factors likely to have less influence, when we combined factors into a single index (Box 5.2 and Figure 5.1).

Box 5.2. Tidal complex and migration space attributes and data sources.

Physical Characteristics

Amount of Migration Space (Weight = 5): A large migration space is an essential condition for a large tidal complex in the future that supports robust species populations, allows for ecological processes, and is less susceptible to degradation. We both measured this quantitatively and applied a threshold to ensure a minimum size. Data source: NOAA SLR Viewer data

Tidal Class Variety and Evenness (Weight = 3): Future estuarine habitats in the migration space are a function of the tidal classes that the space encompasses. Many tidal classes with relatively similar abundances offer options for a variety of habitats. Data source: NOAA SLR Viewer data

Shared Upland Edge between Migration Space and Tidal Complex (Weight = 2): The migration of tidal habitats into the adjacent lowlands is facilitated by migration space directly adjacent to the upland edge of existing marshland. Data sources: augmented NOAA 2010 C-CAP, NOAA SLR Viewer data

Size of Existing Tidal Complex (Weight = 2): The size of the tidal complex is likely to influence its ability to migrate as large complexes provide large sources of biotic material. Data source: augmented NOAA 2010 C-CAP

Condition Characteristics

Developed Upland Edge (Weight = 5): Tidal complexes with development and roads along their upland edge have less access to their migration space and a lower likelihood of upland migration. Data sources: augmented NOAA 2010 C-CAP

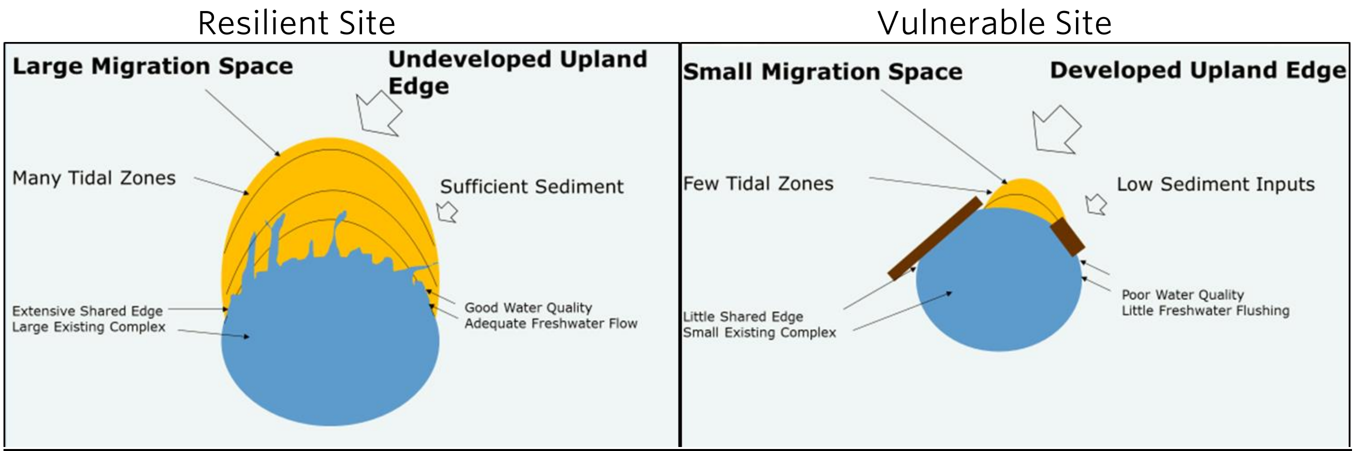
Sediment Balance (Weight = 2): Watershed-derived sediment is a key source of tidal wetland accretion and declines have resulted in tidal wetland declines. Data source: Schuerch et al. 2018

Water Quality Index (Weight = 1): Excessive nutrient inputs can reduce sediment and organic matter accumulation and weaken root systems, reducing resilience. Data source: EPA StreamCat WCHEM

Flow Alteration (Weight = 1): Freshwater inflow is necessary for healthy and productive coastal estuaries and influences plant composition. Data source: EPA StreamCat

Data Source References: **NOAA SLR Viewer Data** (Herold pers. comm., 2018), **augmented NOAA C-CAP 2010** (NOAA, 2017; U.S. Census Bureau, 2017b), **EPA StreamCat WCHEM** (Johnson et al. 2019), **EPA StreamCat** (Hill et al. 2016)

Figure 5.1. Tidal complex and migration space characteristics that increase resilience. Characteristics of a resilient site are shown on the left and contrasted with a vulnerable site on the right. Factors with a strong influence are listed in bold and located above factors with less influence.



Physical Characteristics

The physical characteristics of a site determine if suitable land is available to support the migration of tidal habitats, and the probability that colonizers will be able to access and utilize the migration space. These factors focus on the size, shape, diversity, and configuration of the migration space. For all the physical characteristics, we assumed that a large range increased resilience because variation and flexibility increase the options for adaptation. For example, a large migration space that encompasses a range of tidal classes offers more possibilities for sustaining diversity than a small migration space with one tidal class. The condition of the site and its migration space is also important and is addressed separately in an upcoming section focused on the processes that enable or facilitate the migration of the tidal complex to its new space.

The physical attributes described below are arranged in order of influence. For each, we first describe how the attribute contributes to the site's resilience and then we explain the data sources and methods through which we mapped the attribute. The attributes were ordered with respect to their direct importance to site resilience, and then weighted on a numeric scale from 1 to 5 to reflect their influence, with 5 indicating the greatest influence. Among the steering committee, there was unanimous agreement on the order of importance and high agreement on the numeric weights. The numeric weights were used as a multiplier when combining factors to give more weight to factors with more influence: 5 (very high), 4 (high), 3 (moderate), 2 (low) and 1 (very low). The numeric weight is listed in parentheses after each attribute.

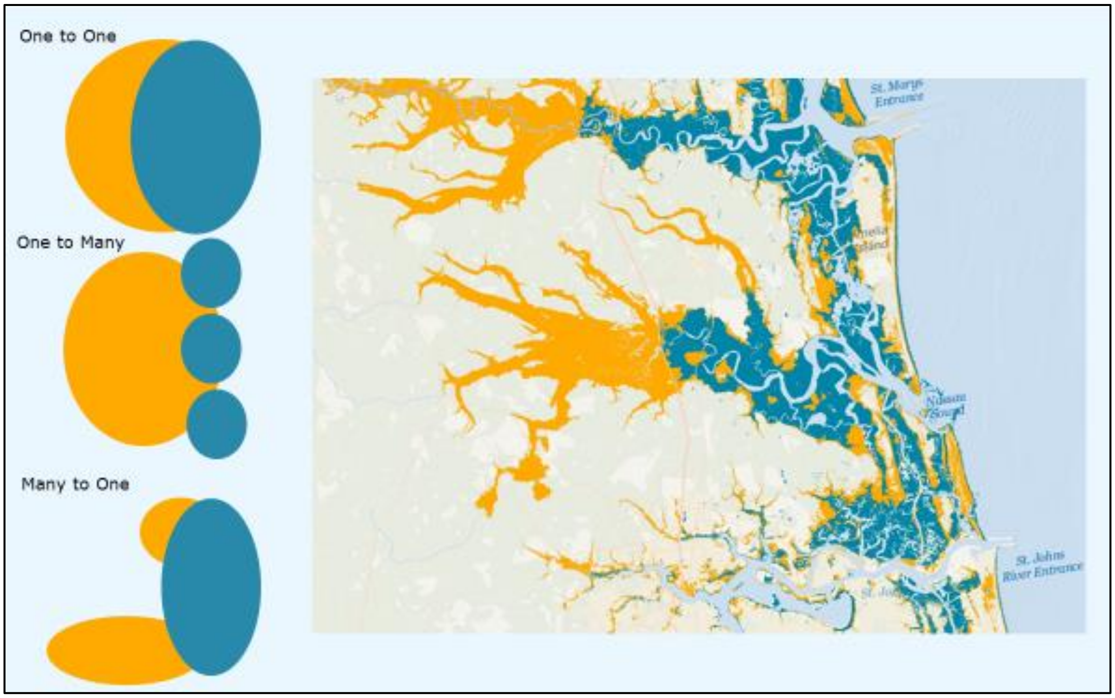
Physical Characteristics of the Migration Space

SIZE OF MIGRATION SPACE (WEIGHT = 5): A large migration space is an essential condition for a large tidal complex in the future, although we don't know how closely the space and the future size will correlate. In fact, most of the other physical and condition attributes we describe are aimed at identifying the sites where the migration space is most likely to fully transition to new tidal habitat. Large areas of tidal habitat are more resilient because they sustain demographic and ecological processes that inherently require space within which to operate and support robust populations of keystone species such as saltmarsh grasses. Large marshes store more carbon, provide more storm buffer and are less susceptible to degradation from stochastic events, and they are also more likely to host rare species such as Saltmarsh Sparrow (*Ammodramus caudacutus*). Tidal complexes with small migration spaces are vulnerable if inundation levels reach the expected 2 to 6.5 feet, because existing tidal marshes will be stressed for oxygen and will likely degrade or disappear.

The relationship between a tidal complex and its migration space is complicated. A single tidal complex may have many non-contiguous regions of associated migration space and they may vary in size. Our estimate of total size is defined as the sum of all migration space units adjacent to the tidal complex (Figure 5.2). Additionally, estimates of migration space vary depending on the SLR scenario, and at higher scenarios, some portions may be inundated. Thus, total size for any scenario is based on the total of previous scenarios minus the amount converted to open water.

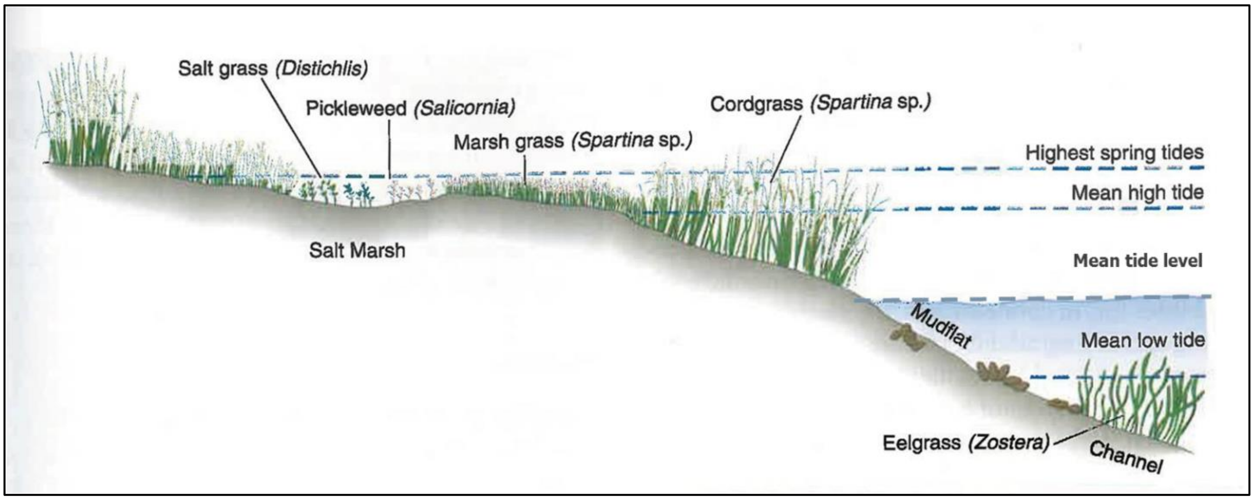
We differentiated between the absolute size of the migration space and the size of the accessible migration space (area available for establishment of new habitat). The absolute size is the total area physically able to accommodate new habitat and the accessible size is the amount remaining after accounting for existing roads and railroads (see Chapter 3). We use both measures in the integration of the factors (see upcoming "Integration of Physical and Condition Characteristics" section) as there is uncertainty about the permanency of road barriers once an area becomes inundated with water.

Figure 5.2. Tidal complex and migration space association. At the upper end of the two large rivers the relationship between existing marsh and migration space is almost one-to-one. Toward the center of the marsh are areas where the current marsh will likely disassociate into many smaller marshes (many to one). In a few places, some small complexes could unite under one migration space (one to many).



<u>TIDAL CLASSES VARIETY AND EVENNESS (WEIGHT = 3):</u> The types and proportion of estuarine habitats expected to occur in the migration space are partially a function of the type and proportion of tidal classes the space encompasses. The NOAA marsh migration data relates tide levels to ecological thresholds and the upper boundaries of various habitats: open water is bounded by mean low water (MLW), unconsolidated shore is bounded by mean tide level (MTL), salt marsh is bounded by mean high water (MHW), and brackish marsh is bounded by mean high water in spring (MHWS, Figure 5.3). Although there is disagreement among scientists as to how perfectly these tidal thresholds match observable habitat transitions, there is agreement that having many evenly distributed tidal classes within the migration space offers the potential for a larger variety of habitats in the future.

Figure 5.3. Tidal classes and habitats. Credit: Clemson University



Tidal classes were calculated by reclassifying the predicted habitat types in NOAA's SLR Viewer marsh migration data into four classes: 1) unconsolidated shore, 2) estuarine marsh, 3) brackish/transitional marsh, 4) palustrine wetlands. For each migration space unit, we counted the total number of classes, and the area of each. We then calculated Simpson's evenness index as a measure of the diversity and evenness of tidal classes using the following formula:

Calculate Simpson's diversity index as:

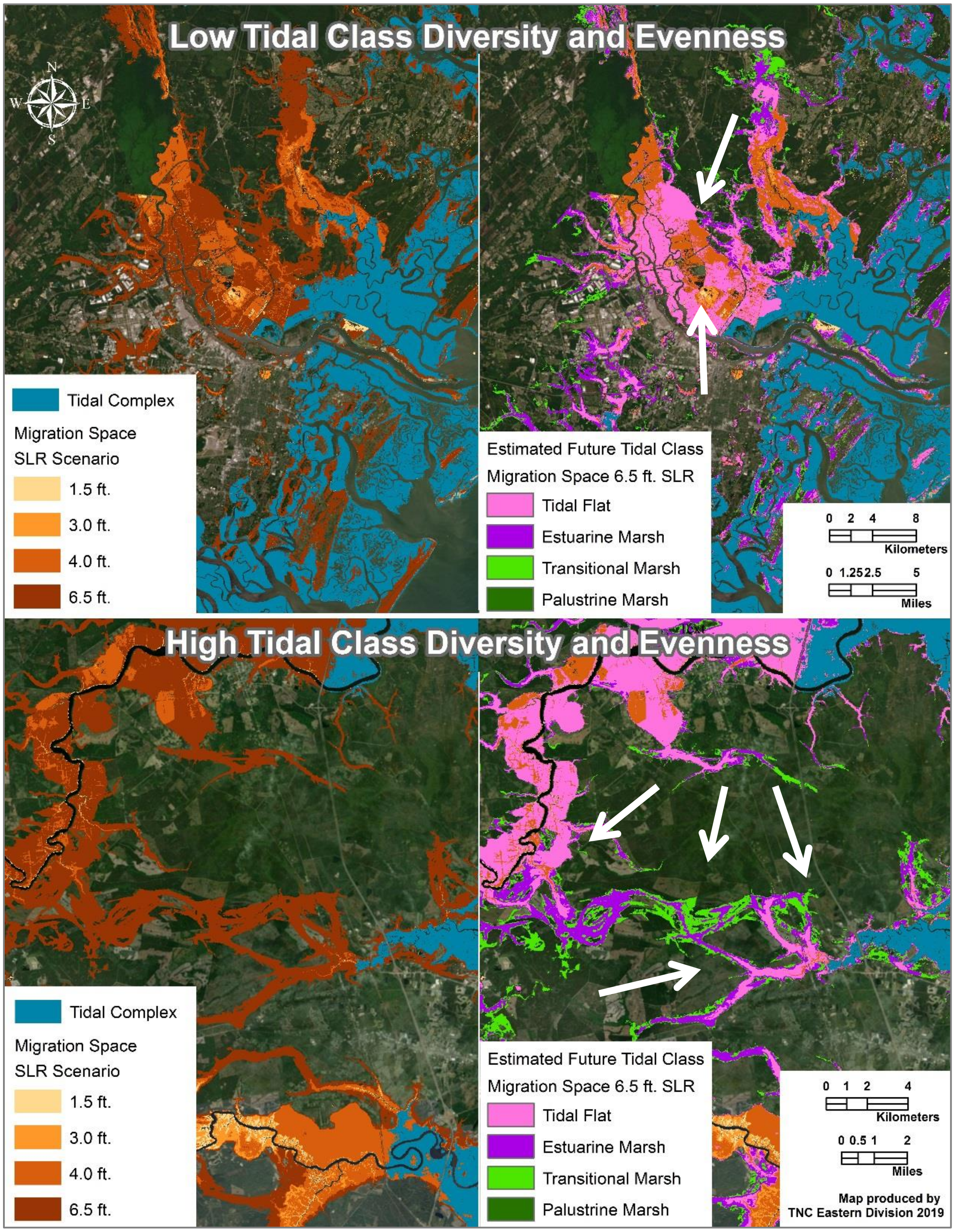
$D = (1/ \sum p_i^2)$ where pi is the proportional representation of each habitat.

Calculate Simpson's Evenness as:

$E = D/D_{max}$ where D_{max} is the maximum possible number of habitats

We gave more weight to the MHW (salt marsh) and MHWS (brackish marsh) tidal classes, as the MTL (unconsolidated shore) subtidal class could easily shift to permanently submerged. At the same time, the sand and mud flats mapped as unconsolidated shore provide a distinct type of habitat that enhances the diversity of a site. To balance these competing demands, we calculated the proportion of unconsolidated shore in each migration space unit. If the proportion of unconsolidated shore was greater than half (0.50), we penalized the evenness value by the non-unconsolidated shore proportion. For example, if a site had an evenness score of 0.69 because it had a somewhat equitable distribution of all four tidal classes, but 52% of the unit was unconsolidated shore, the final evenness score was calculated as 0.69 * (1- 0.52) = 0.33. This allowed us to discount the tidal variability of migration space units that were predominantly unconsolidated shore and unlikely to provide much marsh habitat as SLR increases, yet also value this unique habitat when it was one piece of a complex habitat mosaic (Figure 5.4).

Figure 5.4. Migration space tidal class diversity and evenness. The top panel shows a site whose 6.5-ft. migration space scores low for tidal class diversity and evenness as it is likely to be comprised primarily of unconsolidated shore (pink color). The lower panel shows a site predicted to have several evenly-distributed classes for the 6.5-ft. scenario. White arrows highlight the 6.5-ft. migration space areas (shown in dark orange in left panels). More tidal classes in the migration space will likely translate to more wetland habitats in the future.

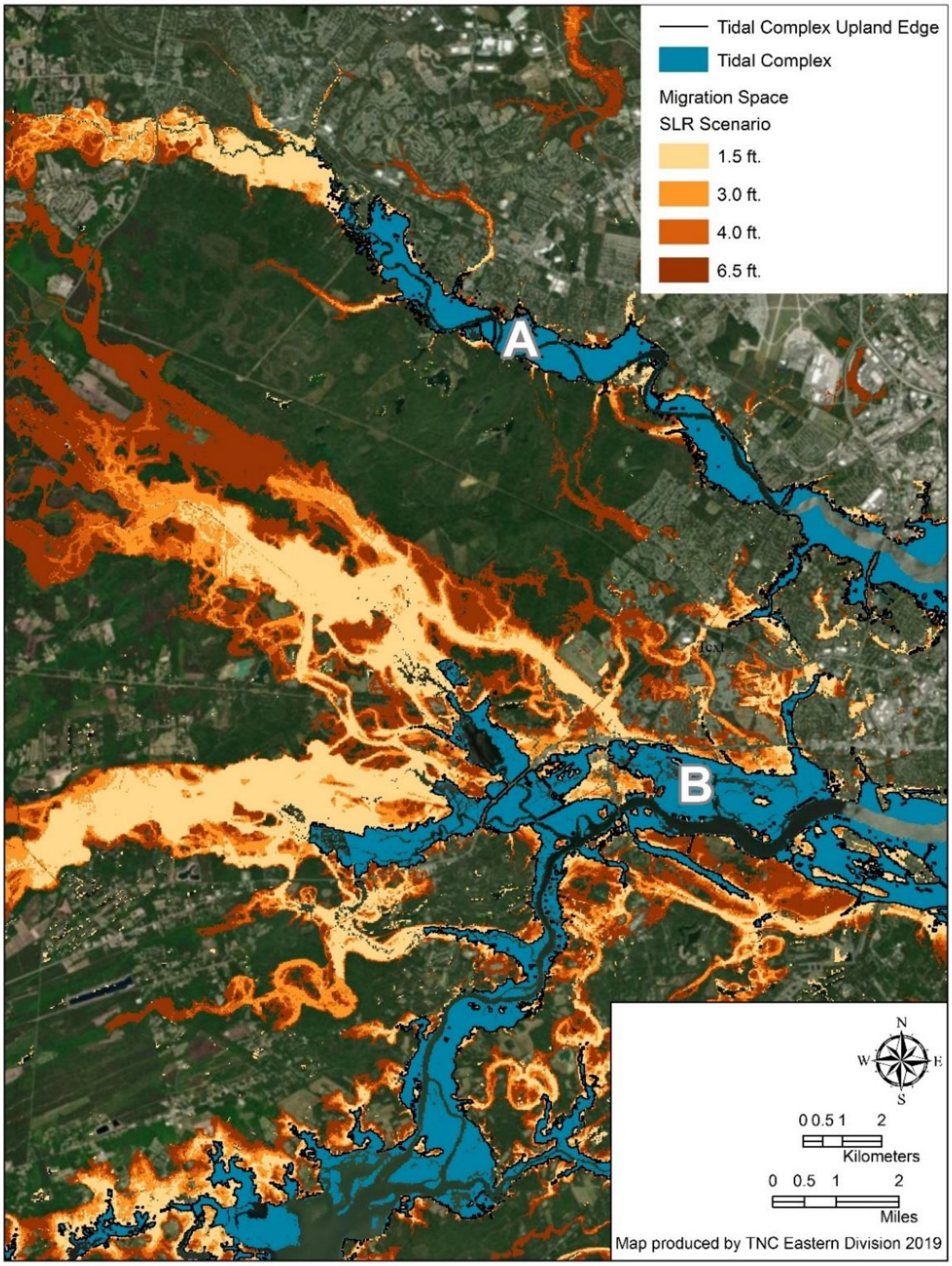


<u>SHARED UPLAND EDGE (WEIGHT = 2):</u> The migration of existing tidal habitats into the adjacent lowlands is facilitated by having migration space directly adjacent to the existing habitats. Having a high proportion of a tidal complex's upland edge shared with its migration space helps ensure that all regions of the tidal complex and all types of habitat have direct access to the migration space (Figure 5.5 B). It was not uncommon to have a relatively large patch of migration space touch only a small part of the existing complex, especially if the migration space was associated with a small river inlet. In these cases, migration could be hampered as not all the existing complex has easy access to the migration space (Figure 5.5 A).

To map the shared upland edge, we first identified the upland edge of each tidal complex in a GIS by removing all seaward edges based on an ocean/water grid derived from NOAA's 2010 C-CAP land cover grid. The resulting tidal complex upland edge was then spatially intersected with the migration space units, and the output was set to a polyline. We calculated the length of the polyline output, the shared upland edge, from the intersection analysis. Lastly, for each complex, we divided the shared upland edge by the total upland edge length to calculate the percent of upland edge shared with migration space.

While the tidal complexes did not change with SLR scenario in our analysis, the migration space configuration did change with each sea level rise scenario. Accordingly, the shared edge was only calculated for the first SLR scenario in which a complex was adjacent with its migration space and served as the baseline connection for the other SLR scenarios.

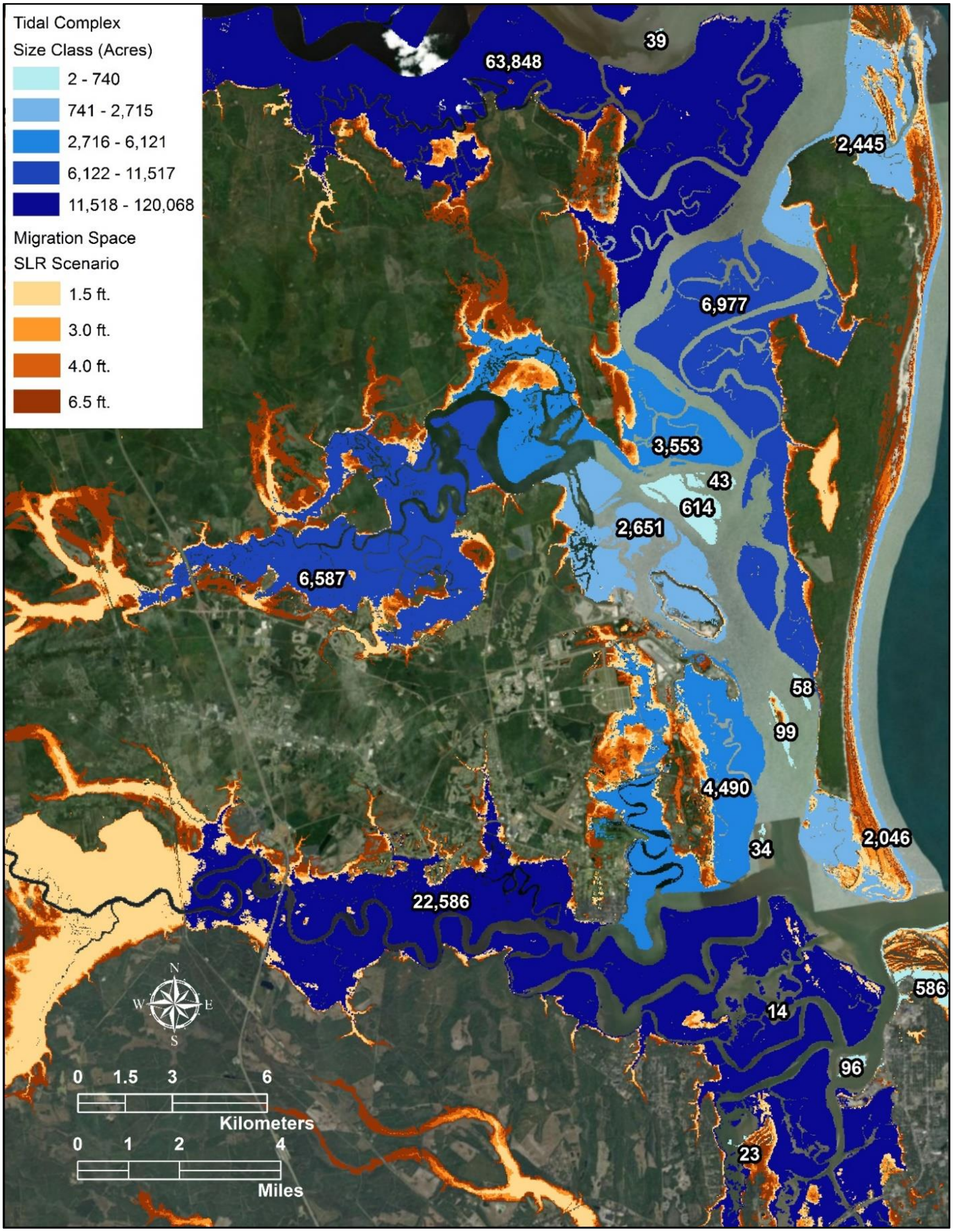
Figure 5.5. Shared upland edge between a tidal complex and its migration space. Examples of different spatial relationships between the upland edge (black line) of tidal complexes and their migration space, and the resulting differences in shared upland edge percentages. At site A, only 34% of the marsh's upland edge is shared with migration space, as most of the future marsh area is located at the far end of the tidal complex. In contrast, site B should have better access to its migration space as 62% of its upland edge is adjacent to migration space.



Physical Characteristics of the Existing Tidal Complex

SIZE OF EXISTING TIDAL COMPLEX (WEIGHT = 2): The size of the existing tidal complex (Figure 5.6) is likely to influence its ability to migrate because large complexes provide large sources of biotic material such as propagules and rhizomes. We gave this metric a low weight for influence, however, because most tidal complexes are already decreasing in size due to inundation and are not stable over the next century (Ganju et al. 2017). Researchers have found that aboveground and belowground biomass of *Spartina sp*. decreases exponentially with increased flood duration and higher salinities, and that even subtle increases in sea level may lead to substantial reductions in productivity and organic accretion (Snedden et al. 2015).

Figure 5.6. Tidal complex size. The map shows different tidal complexes ranging in size from very small (14 acres) to very large (>60K acres).



Condition Characteristics

The condition factors are characteristics that increase the probability of a tidal complex moving into its migration space and establishing new habitat. While the physical factors focus on the size and geometry of the migration space, the condition factors focus on the processes that enable the migration or formation of new tidal habitats. Migration of a tidal complex can be obstructed by many things: development, barriers, degraded substrate, an inadequate sediment supply, or poor water quality that hampers normal vegetation growth. The condition metrics are designed to help determine if the migration space is usable, and whether the expected ecological processes are functioning. In our model, a tidal complex with an undeveloped upland edge and sediment surplus whose migration space has good water quality and minimal flow alteration has the enabling conditions needed to facilitate migration.

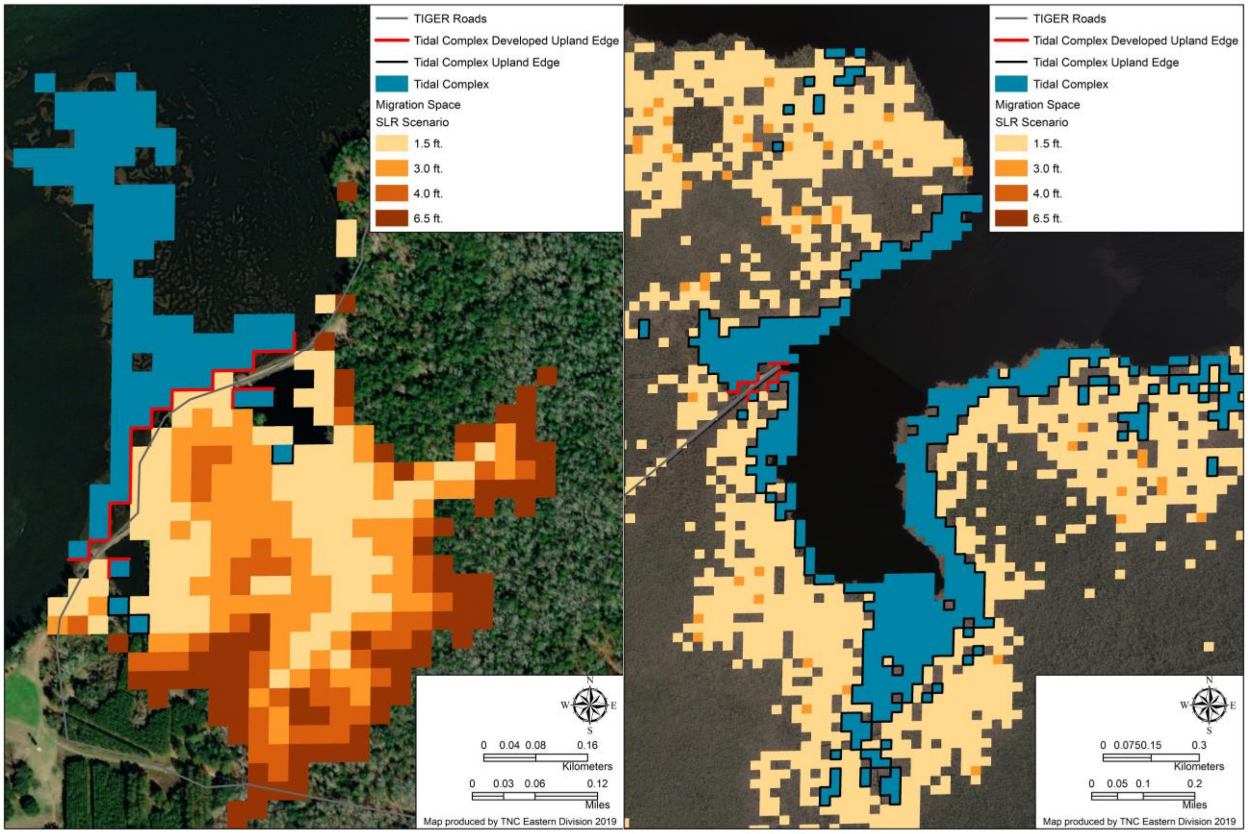
The condition attributes described below are arranged in order of influence. For each, we first describe how the attribute contributes to the site's resilience and then we explain the data sources and method through which we mapped the attribute. The condition attributes were ordered with respect to their direct importance to site resilience, and then weighted on a numeric scale from 1 (low influence) to 5 (high influence). Among the steering committee, there was unanimous agreement on the order of importance and high agreement on the numeric weights. The numeric weights were used as a multiplier when combining factors to give more weight to factors with more influence: 5 (very high), 4 (high), 3 (moderate), 2 (low) and 1(very low). The numeric weight is listed in parentheses after each attribute.

Current Condition Characteristics of the Existing Tidal Complex

<u>DEVELOPED UPLAND EDGE (WEIGHT = 5):</u> Tidal complexes with a large portion of their landward edge flanked by roads, buildings, parking lots or other anthropogenic barriers will have limited to no access to their migration space and will be unable or severely restricted in their ability to migrate upland.

We first created a development polygon by extracting all developed pixels, including roads and railroads, from the augmented NOAA 2010 C-CAP land cover grid and converting those pixels to a polygon. We used the National Bridge Inventory (NBI) geospatial data (Federal Highway Administration, 2017) to remove bridges as these are unlikely to prevent marsh migration. We then intersected the upland edge of each tidal complex with the development polygon to calculate the percent of a complex's total upland edge that was developed (Figure 5.7).

Figure 5.7. Tidal complex developed upland edge. In the left image, the upland edge of the tidal complex is mostly developed (red) with a road (gray) likely separating the complex from its migration space. The right image shows a complex with a mostly undeveloped edge (black). We used the percent of a complex's upland edge that was developed to assess the potential of a marsh to access its migration space.



<u>SEDIMENT INPUT (WEIGHT = 2):</u> Watershed-derived sediment is a key source of tidal wetland accretion. However, because marshes build vertically, lateral erosion can lead to rapid marsh loss. In fact, declines in sediment delivery due to agriculture and dams have played a major role in tidal wetland declines (Weston, 2014). A sediment surplus may result in either vertical growth and/or lateral expansion, while a sediment deficit may result in drowning and/or lateral contraction. Many sites in the Eastern US are exhibiting a sediment deficit, with half of them having projected lifespans of less than 350 years at current rates of sea-level rise and sediment availability (Ganju et al. 2017).

To assess and map tidal complex sediment levels, we obtained a spatially explicit global sediment balance dataset from a recent study by Schuerch and colleagues (2018). The study aimed to estimate the future response of global coastal wetlands to sea-level rise using a global model that considers both the ability of coastal wetlands to build up vertically by sediment accretion, and the accommodation space, (e.g. migration space) which they defined as the vertical and lateral space available for fine sediments to accumulate and be colonized by wetland vegetation. Seaward wetland loss through inundation is counteracted by a large tidal range and a high sediment availability, as both these variables increase the resilience of coastal wetlands to drowning through vertical sediment accretion processes. They summarize this in a wetland adaptability score indicating a reduction in the loss of wetlands where tidal range and sediment availability are high.

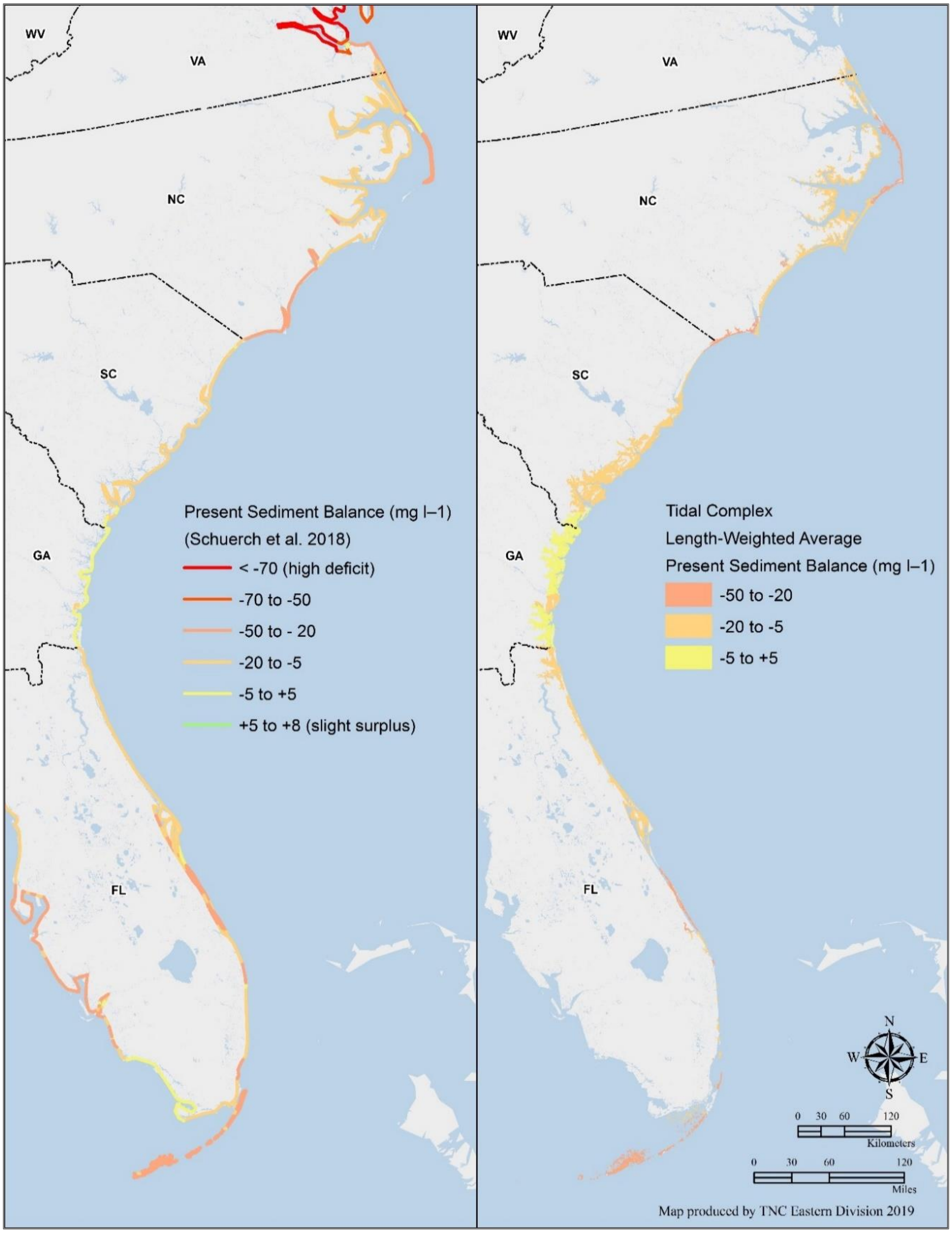
In their paper and accompanying data, Schuerch et al. (2018) develop a spatially explicit estimate of wetland adaptability based on a linear relationship between sediment availability and wetland drowning, where the slope of the linear relationship depends on tidal range. They estimate sediment availability as the difference between two mapped values in global datasets:

- The suspended sediment concentration needed for coastal wetlands to build up vertically under current SLR rates, and
- The actual total suspended matter concentration derived from satellite data (http://globcolour.info).

The needed sediment concentration was compiled from meta-data analyses by Kirwan et al. (2016) and Crosby et al. (2016), and includes measurements of vertical marsh elevation changes from 57 marsh sites across Europe, Australia and North America, with the majority of the data originating on the Eastern US coast. This was combined with global tidal range data derived from Pickering et al. (2017) to calculate the wetland adaptability score for every coastline segment. When divided by the estimated suspended matter concentrations, the results indicate the degree to which the sediment supply is insufficient relative to the expected need or if it is in deficit or surplus (Figure 5.8).

We used a Euclidean allocation algorithm to spatially link the shoreline sediment balance data to the tidal complex units, and then calculated an area-weighted average sediment balance for each tidal complex.

Figure 5.8. Estimated sediment balance for the project area. The left image shows the sediment balance (Schuerch et al. 2018) for the South Atlantic coastline. The right image shows the tidal complex estimated sediment balance after using an area-weighted average to assign the sediment balance data to the tidal complex units.



Current Condition Characteristics of the Migration Space

WATER QUALITY INDEX (WEIGHT = 1): Excessive nutrient inputs are the single largest pollution problem impacting US coastal waters (Howarth et al. 2000), and eutrophication results in systems with lower dissolved oxygen, less ability to adapt, and consequently lower resilience. Nitrogen has emerged as a focal nutrient in salt marshes because nitrogen eutrophication can reduce organic matter accumulation by increasing rates of decomposition and hindering sediment accretion, limiting increases in marsh elevation (Olcott, 2011). Nutrient loading also leads to weakened root systems and reduced geomorphic stability (Deegan et al. 2012).

To estimate and map the nitrogen loading for each tidal complex and migration space we investigated several existing models including the USDA Soil & Water Assessment Tool (SWAT) model, the USGS SPARROW 2002 Total Nitrogen model, the InVEST nutrient model, and EPA's Stream Catchment (StreamCat) water quality index. After examining the results of these models and considering the age of the underlying datasets, we selected the EPA StreamCat water chemistry metric to estimate water quality based on total nitrogen, total phosphorus, and turbidity.

The EPA's StreamCat 2.1 is a package of landscape metrics that have been calculated for 2.6 million streams and their catchments in the lower 48 states (Hill et al. 2016). Results are summarized for stream catchments and for cumulative watersheds and linked to the National Hydrography Dataset (NHDPlus v.2, USEPA & USGS, 2012). Johnson et al. (2019) recently revised the StreamCat water chemistry (WCHEM) variable which integrates multiple facets of the overall chemical integrity of a watershed. They used a random forest model to spatially estimate the National Rivers and Stream Assessment water quality index (WQlz), based on actual measurements of total nitrogen, total phosphorus, and turbidity. They found a 0.62 correlation with known WQlz index values. Although this data set performed well against actual water quality measurements, it may not capture temporal variability in the chemical species sampled over a large spatial area. However, the results looked quite reasonable for the region of interest (Figure 5.9).

For each sea level rise scenario, we linked the StreamCat revised water quality index to each migration space unit using a proportionally weighted index based on the cumulative drainage-area of each flowline and/or catchment (Figure 5.10).

Figure 5.9. Water quality index for the South Atlantic. The left image shows the EPA StreamCat revised water quality index value (Johnson et al. 2019) for NHDPlus v2 catchments in the South Atlantic. The right map shows the water quality values rolled up to the migration space units using a drainage-area weighted average approach.

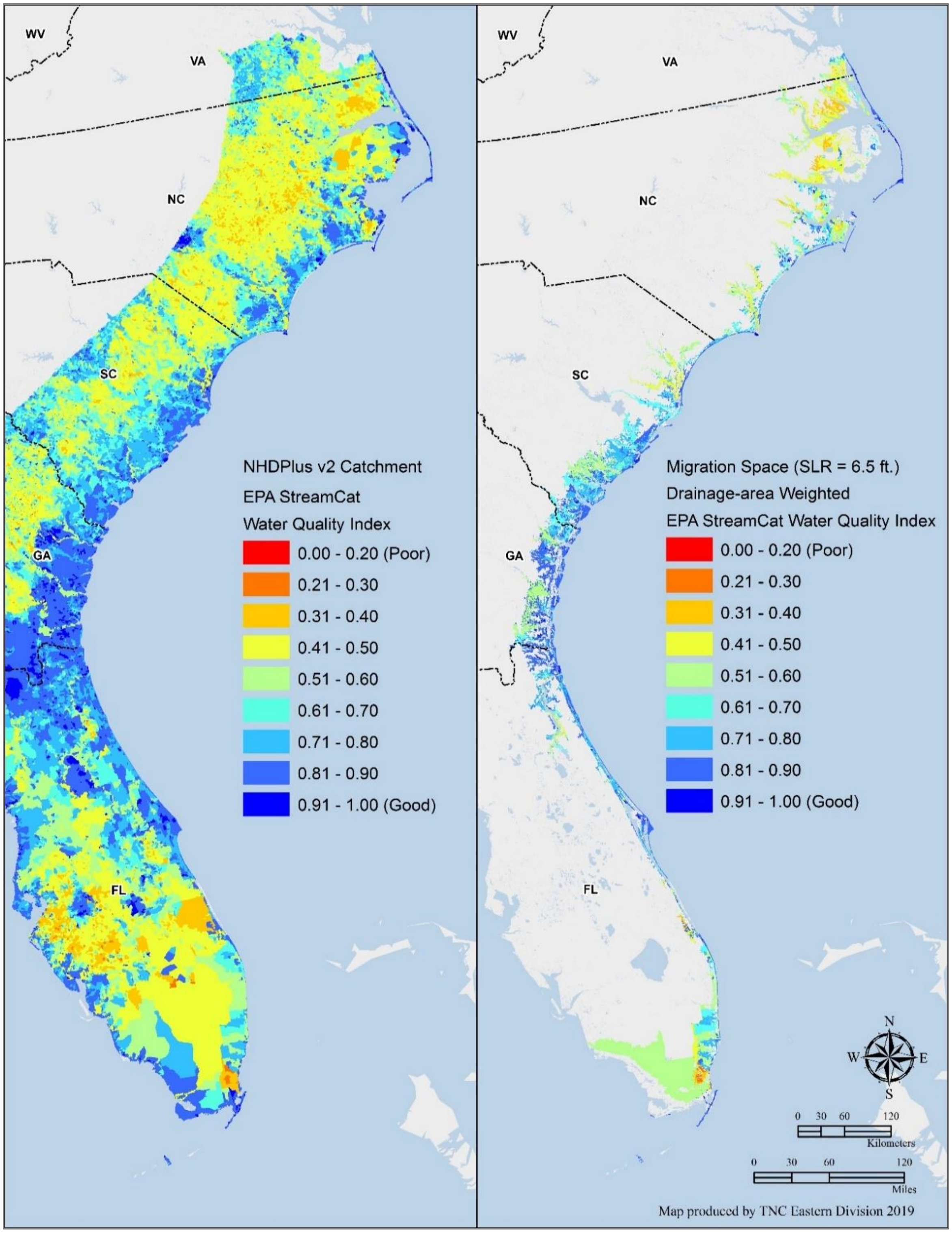
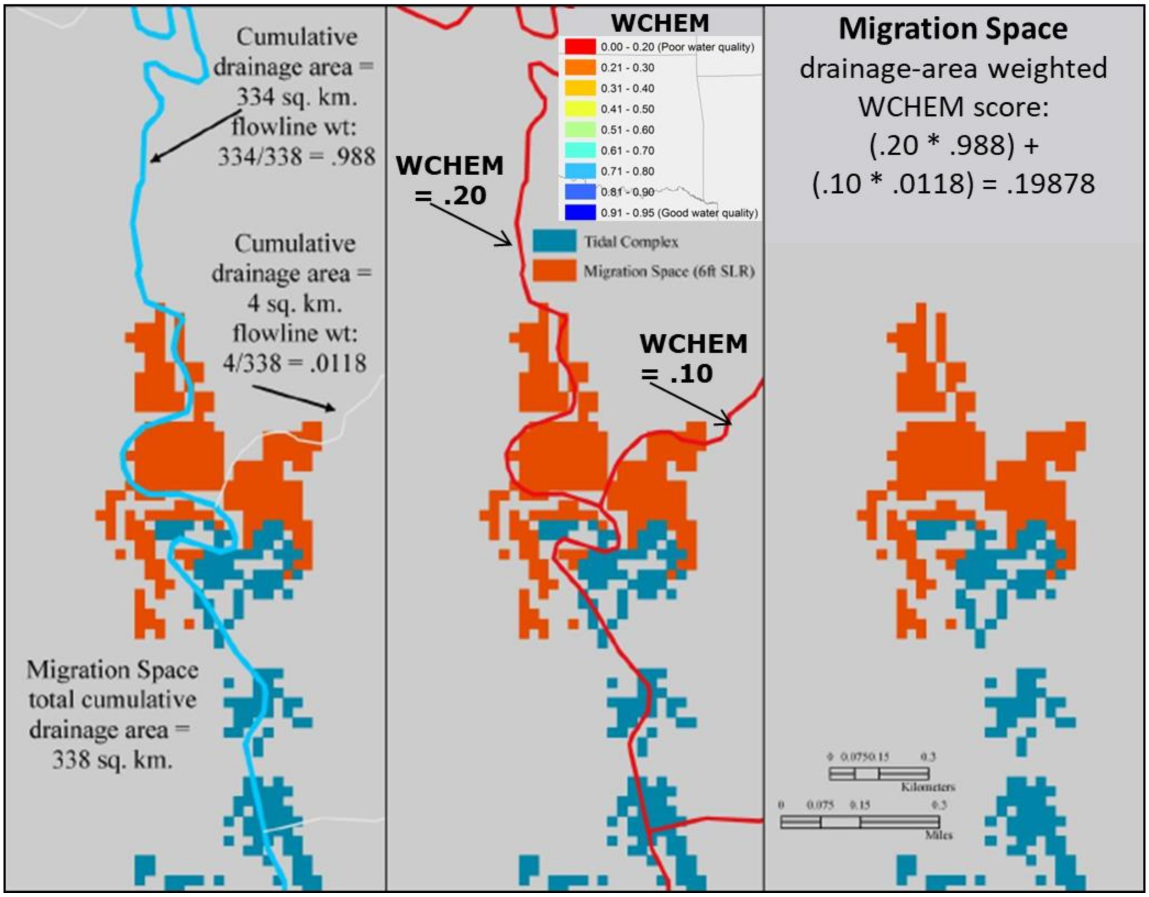


Figure 5.10. Drainage-area weighted average approach. Illustration of the approach that uses the cumulative drainage-area of NHDPlus v2 flowlines or catchments to translate hydrologically-based condition attributes to a migration space unit.

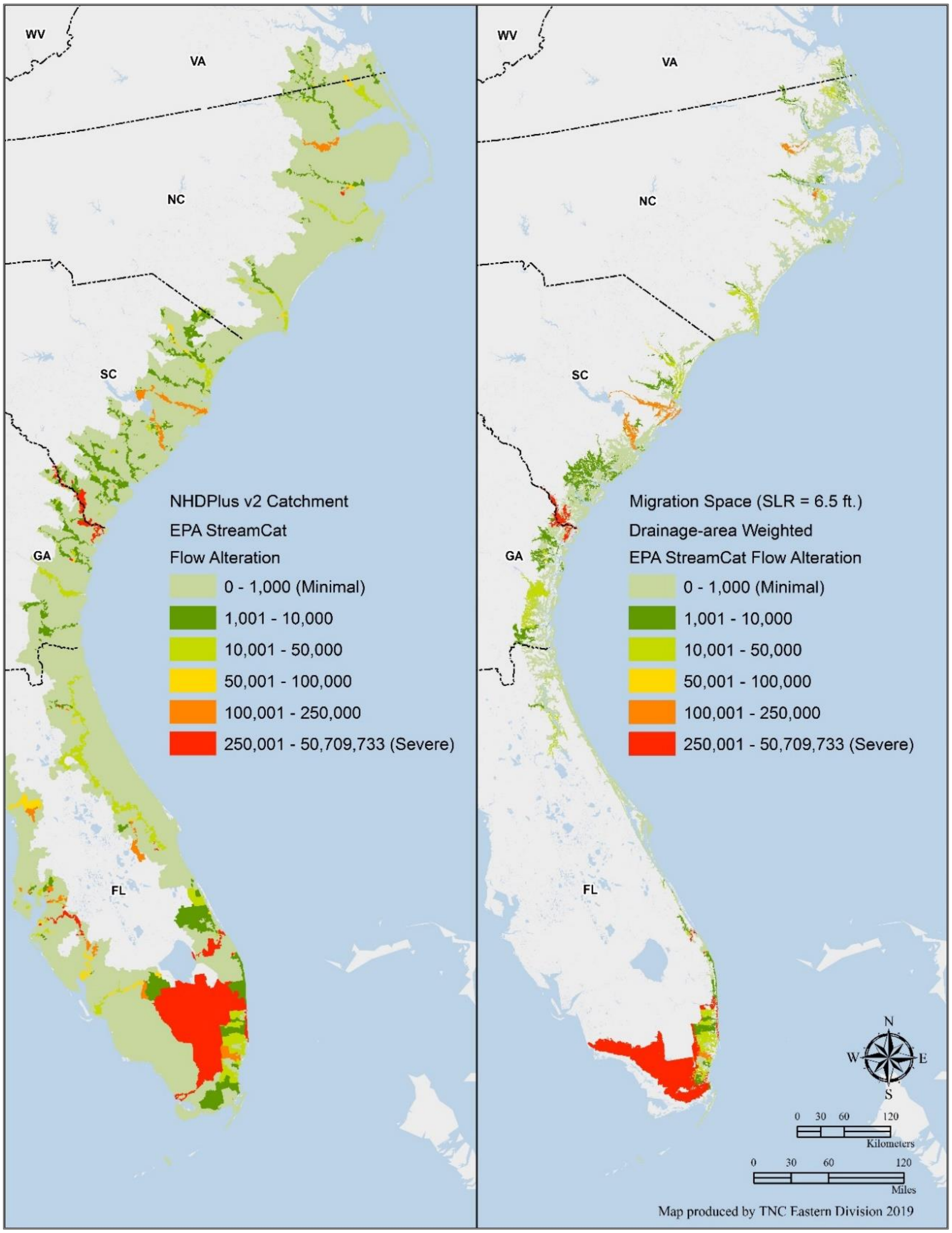


FRESHWATER FLOW ALTERATION (WEIGHT = 1): Freshwater inflow is necessary for healthy and productive coastal estuaries and strongly influences the role and abundance of plant composition in tidal wetlands. In drier coastal zones, relatively small changes in rainfall could produce comparatively large landscape-scale changes in the abundance of foundation plant species that would affect some ecosystem goods and services. Whereas a drier future would result in a decrease in the coverage of foundation plant species, a wetter future would result in an increase in foundation plant species coverage (Osland et al. 2014). Freshwater supply must compete with upstream demands from farms, cities, and industry, consequently many coastal sites receive less freshwater than would be expected under natural conditions with the delivery of freshwater altered in timing and quantity. We assumed that sites with natural or less altered flows would be more resilient to environmental and climatic changes because the flow sustains the expected transitions and migration of current tidal complexes into the migration space (White & Kaplan, 2017).

As for the previous water quality metric, we opted to use EPA's StreamCat dataset to assess the degree of flow alteration in each watershed contributing to the migration space. StreamCat calculates a variable indicating the percent of normal volume of all reservoirs per unit area of watershed (m^3/km^2). Cooper et al. (2017) used a similar measure to assess flow alteration nationally with good success. The StreamCat variable was calculated using the National Anthropogenic Barrier Dataset (NABD). The NABD is based on the 2009 National Inventory of Dams (NID) with revisions that include 1) dam removals that occurred after development of the 2009 NID and 2) the identification of duplicate dam records along state boundaries attributed to the 1:100,000 scale National Hydrography Dataset Plus Version 1 stream network. A limitation of this metric is that only larger dams are included.

The results reveal patterns in the region that are easily interpretable as they relate closely to the locations and densities of large dams (Figure 5.11). We linked the StreamCat flow alteration variable to each unit of migration space using a proportionally weighted index based on the cumulative drainage-area of each flowline (Figure 5.10).

Figure 5.11. Watershed flow alteration. The left image shows the EPA StreamCat watershed flow alteration value (Hill et al. 2016) for NHDPlus v2 catchments in the South Atlantic. Areas of high flow alteration have a larger amount of dam storage relative to their watershed area. The right-hand image shows the flow alteration score calculated for the migration space units using a drainage-area weighted average.



Integration of Physical and Condition Characteristics:

The final score for the tidal complex and its migration space was calculated for each site using a weighted sum of the physical and current condition characteristics along with a migration space threshold and an adjustment for accessible migration space.

Weighted Sums

To put the metrics onto a standard scale, each individual variable was converted to a Z-score (standard normal distribution) relative to its coastal shoreline region (CSR). To do this, we examined the distribution of each variable within each CSR. If the distribution was normal, we calculated the mean and standard deviation and used these to transform the values to standard normal (value – mean / standard deviation). If the distribution was skewed or otherwise distorted, we used various transformations to convert it to a normal distribution, or used non-parametric techniques to calculate a Z-rank score based on the order, rank, and number of the values.

When all the variables were on the same scale, we applied the following variable weights agreed upon by our steering committee.

<u>Physical Options</u>
- Size of Migration Space (5)
- Tidal Classes (3)
- Shared Upland Edge (2)
- Size of Complex (2)

Weighted Sum = Physical Score

<u>Current Condition</u>
- Developed Upland Edge (5)
- Sediment Balance (2)
- Water Quality Index (1)
- Flow Alteration (1)

Weighted Sum = Condition Score

A score was calculated for each theme using the following equations:

*Physical Score = (5*MS + 3*TC+ 2*SE+ 2*SC)/12*

Where MS = size of migration space Z-score, TC = tidal class Z-score, SE = shared upland edge Z-score, and CS = size of complex Z-score

*Condition Score = (5*DE + 2*SB+ 1*WQ+ 1*FA)/9*

Where DE = developed upland edge Z-score, SB = sediment balance Z-score, WQ = water quality Z-score, and FA = flow alteration Z-score

Site Score
If a site's migration space met one of the two migration space thresholds described below, the physical and condition score were weighted equally and summed to calculate a site score as follows:

(Physical Score + Condition Score)/2

However, if a site's migration space did not meet one of the two migration space thresholds, we weighted the physical score three times as much as the condition score to prevent sites in excellent condition, but with little migration space, from having inflated resilience scores:

*(3*Physical Score + 1*Condition Score)/4*

<u>MIGRATION SPACE THRESHOLD:</u> When we initially weighted the physical and condition scores equally, we noticed that some sites with very little or no migration space could still score high in our combined score if their tidal complex was very large and their condition characteristics were high scoring. This did not make sense as the existing tidal complexes have nowhere to go or will be reduced to a few acres. Thus, to account for the overwhelming importance of migration space, we imposed a minimum size threshold for a site to rank as resilient. We wanted to make it explicit that even if a site had all the other physical attributes and intact condition, with little migration space, the tidal complex is unlikely to be present in the future, and thus cannot be considered resilient to sea level rise. We did not want to penalize small sites that will likely increase in size. After studying the data, we developed the following criteria:

- Criterion 1: A resilient site's migration space size must be greater than average relative to its coastal shoreline region

OR

- Criterion 2: A resilient sites average migration space size must be at least as big as the existing complex and predicted to increase in size, and not on a barrier island with a downward trend in size

<u>ACCESSIBILITY OF MIGRATION SPACE:</u> We also applied an adjustment to the physical score based on the accessibility of a site's migration space. As described previously, some areas of migration space are fragmented by paved roads that may be barriers in the future, at least at some stages of inundation and migration. To incorporate the accessibility of the migration space into the physical score, we calculated two physical scores using the weights and approaches described above, with the only difference being the migration space size variable. Again, the accessible

migration space size was delineated after removing all roads while the original 'geophysical' migration space did not include major roads and development. Physical Score One (PS1) used the geophysical migration space size, and Physical Score 2 (PS2) used the accessible migration space size. For each site, we calculated the difference between the two scores (PDIFF), and measured the percent of a site's 'geophysical' migration space that is accessible as:

*PERMS = (Geophysical MS/Accessible MS) * 100.*

Where MS = Migration Space and PERMS = the percent of the migration space that is accessible.

For each coastal shoreline region, we regressed the physical score difference (PDIFF) against the PERMS variable. In the South Atlantic, this relationship explained between 23% and 37% of the variance in scores, although the coefficients were very small (range 0.005 – 0.010) indicating a small but significant influence. The shoreline region values were:

- Lagoons: adj. R^2 = 0.37, coeff. = 0.009
- Riverine (Coastal Plain): adj. R^2 = 0.37, coeff. = 0.005
- Riverine (Piedmont Basin): adj. R^2 = 0.37, coeff. = 0.010
- Island Archipelago: adj. R^2 = .23, coeff. = 0.005

Using this information, we adjusted the physical score downwards where appropriate using the following equation:

*Physical score – (((100 – PERMS) * regression coefficient) * the adjusted R^2)*

This adjustment had the effect of decreasing the score a maximum of less than one-half (0.4) standard deviation in sites with road-fragmented migration space and had no effect on sites with unfragmented migration space.

Buffer Area

This section focuses on the characteristics of the buffer area surrounding the tidal complex and migration space, and specifically on characteristics that sustain the migrating tidal complex and provide options for species to move and interact with other natural systems. Identification of the buffer area is recognition that the coastal sites occur within a larger landscape, and the quality and condition of the land surrounding each site can affect its long-term resilience. Tidal complexes interact with their inland surroundings through species movement, nutrient and water flow, wind movement and atmospheric cooling. These processes depend on both the physical structure of the buffer area (e.g., size, landforms) and the condition of the buffer area (e.g., natural cover, connectivity among wetlands). As part of the resilience estimates, we calculated several physical and condition characteristics for the buffer area and weighted them based on their expected influence on resilience (Box 5.3, Figure 5.12).

Box 5.3. Buffer area attributes and data sources.

Physical Characteristics

Adjusted Buffer Area Size (Weight = 5): A large buffer area provides space for species populations to breed, disperse and migrate, and to accommodate flood and wind disturbances. The size of the buffer was adjusted to reflect how well it buffered its associated migration space. Data sources: augmented NOAA 2010 C-CAP, NOAA SLR Viewer data.

Landform Diversity (Weight = 5): A diversity of coastal landforms in lands immediately adjacent to the tidal complex and migration space provides more options for species adaptation as they create more habitats and microclimates. Data source: TNC landform model

Acreage of Maritime Highlands (Weight = 5): Areas of intact uplands surrounded by low wetlands will likely remain functional in the face of sea level rise and may become islands in the future, creating terrestrial refugia that could be conservation objectives themselves. Data sources: DEM, augmented NOAA 2010 C-CAP

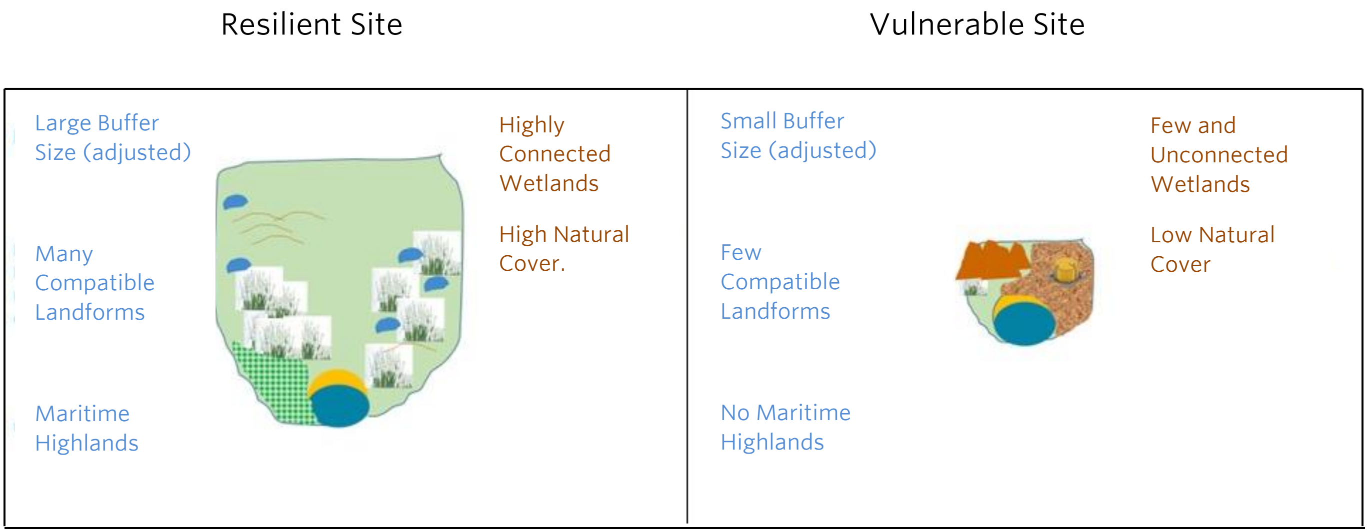
Condition Characteristics

Wetland Connectedness (Weight = 5): Dense and connected wetlands in the first 1km of buffer area create a permeable landscape that allows for interactions among freshwater, brackish, and saltmarsh species. Data sources: TNC landform model, UMASS Resistant Kernel Model

Percent Natural Cover (Weight = 5): Natural areas in the immediately adjacent buffer area (first 1 km) allow the system to interact with other marshes, swamps, forests, and grasslands. Areas in agriculture were included in the buffer because they are permeable to movement and will likely revert to marsh, but because they are intensively managed, often treated with chemicals, and regularly replanted, they do not provide the range of options for native species that natural cover does. Data source: augmented NOAA 2010 C-CAP

Data Source References: **NOAA SLR Viewer data** (Herold pers. comm., 2018), **augmented NOAA 2010 C-CAP land cover** (NOAA, 2017; U.S. Census Bureau, 2017b), **TNC landform model** (Anderson et al. 2016), **DEM** (USGS, 2016), **UMASS Resistant Kernel Model** (Compton et al. 2007).

Figure 5.12. Buffer area characteristics that increase resilience. Characteristics of a buffer area expected to improve coastal resilience are shown on the left and are contrasted with a buffer area that is unlikely to improve resilience on the right. Physical factors are listed in blue and condition factors in brown. The tidal complex is shown as a blue circle at the base.



Physical Characteristics

Resilience characteristics in the buffer area are those that increase the probability that the migrating tidal complex will be nested in a larger landscape that sustains ecological processes. The buffer area's physical characteristics include an index of its size and migration space buffering, landform diversity, and the acreage of maritime highlands. For each of these variables, we assumed that a larger amount or a higher diversity increased resilience by increasing the available habitats, microclimates and options for adaptation. For example, a large buffer area with a range of coastal landforms and maritime highlands can sustain a wider diversity of species.

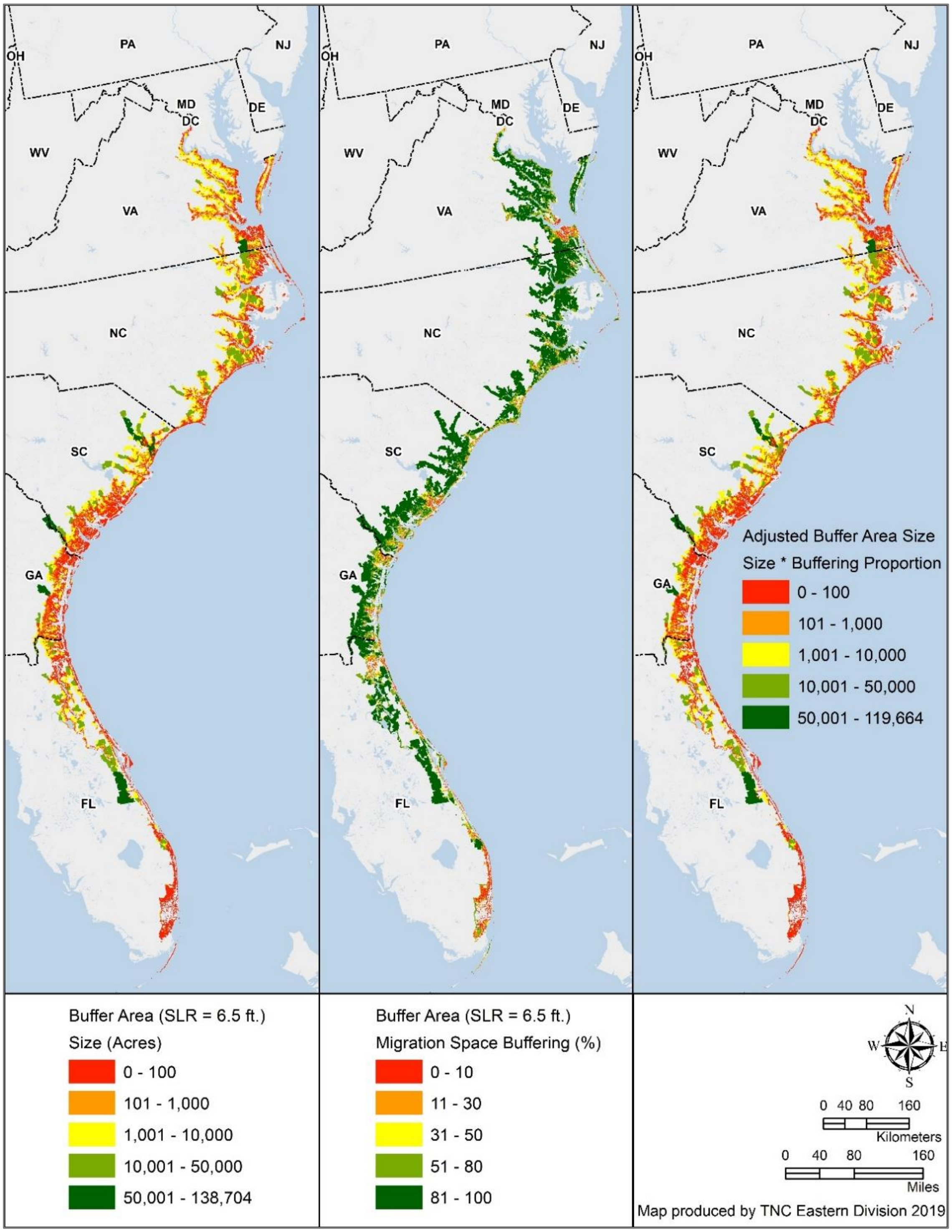
<u>ADJUSTED BUFFER AREA SIZE (WEIGHT = 5):</u> A buffer area provides space for species populations to breed, disperse and migrate, and to accommodate flood and wind disturbances. As the sea level rises, the ecological interactions between the coastal zone and the adjacent terrestrial and freshwater systems will become more critical and thus resilience increases with the size of the surrounding and intact buffer area.

As described in Chapter 3, a one-to-many spatial join was used to link each buffer area polygon with each migration space unit and/or tidal complex unit that it intersected. With the buffer area units linked to the migration space and tidal complex units, the cumulative size of all intersecting buffer areas was calculated for each tidal complex. As most buffer areas were relatively large, we also wanted to include a measure of how much of the area immediately surrounding the migration space is buffered versus developed. To do this, we used a Euclidean allocation algorithm in a GIS to calculate the proportion of the 1-km area around each migration space, available to be buffer area (i.e., is not predicted to be inundated, is not existing marsh, and is not migration space), that is actually buffered. We then multiplied a site's buffer area size by the proportion of migration space buffering as follows:

Buffer Area Size (Adjusted) = Buffer Area (acreage) * Migration Space Buffering (proportion from 0 to 1)

This adjustment (Figure 5.13) appropriately penalized buffer areas whose shape did not buffer much of the migration space and did not penalize buffer area units that safeguarded a large amount of migration space.

Figure 5.13. Adjusted buffer area size. The left panel shows buffer areas assigned to one of five size classes. The center panel shows the percentage of the 1-km area surrounding the migration space that is buffered by the buffer areas. The right panel shows the resulting adjusted buffer area size after multiplying by the migration space buffering proportion (center panel values/100).



LANDFORM DIVERSITY (WEIGHT = 5): A diversity of landforms in land immediately adjacent to the tidal complex and migration space, the first 1 km of the buffer area (Figure 5.14) provides more options for species adaptation in response to SLR because a variety of landforms equates to a variety of habitats and microclimates. For example, depressions, flats, slope bottoms, and hummocks all create complexity and microtopography in the landscape and redistribute moisture and temperature. Landforms compatible with tidal habitats are arguably the most important to the coastal wetlands as they could support species that utilize both fresh and salt water.

We developed a spatially comprehensive map of 17 landform types at a 30-m scale for the entire Eastern US and then extracted seven types that are compatible with coastal wetlands for this analysis (Anderson et al. 2016). Details on the creation of the landform map can be found in Anderson et al. (2016), and the original map can be viewed at http://maps.tnc.org/resilientland/

To measure landform diversity, we tabulated the variety of landforms within a 100-acre circle around each pixel based on seven landform types compatible with tidal habitats: dry flat, moist flat, wet flat, valley/toeslope, gentle slope, hilltop flat, and open water. Then, we calculated the mean landform variety score in the first 1 km of each buffer area for both migration space and tidal complex units (Figure 5.15). We restricted the analysis to the first 1-km of buffer area for each migration space to ensure we focused on the region most likely to interact with the coastal wetlands. To perform this, we calculated a 1-km Euclidean distance from each migration space for each SLR scenario, and then recoded all distances greater than 0 as 1. We then spatially combined the re-classed Euclidean distance output with the buffer grid for each SLR scenario and used a Lookup operation in ArcGIS to set the value of the combination grid to the unique ID of each buffer area. We repeated this same process for the tidal complexes.

MARITIME HIGHLANDS (WEIGHT = 5): As a complement to the landform diversity score, we also identified buffer areas that contained maritime “highlands” – areas of intact uplands surrounded by low wetlands. Although the highlands do not provide space for coastal systems, they will likely remain functional in the face of SLR and may become islands in the future, creating terrestrial refugia that could be conservation objectives themselves. We delineated maritime highlands as lands in natural cover that were greater than 4 meters in elevation (13 feet) and surrounded by a low elevation landscape (< 4 m), and tabulated the acreage of maritime highlands in each buffer area (Figure 5.16). Intact maritime highlands are relatively rare in this region as few exist and many are already developed.

Figure 5.14. First 1 km of buffer area. Several of the buffer area metrics were only calculated for the first 1 km of the buffer area. The image below shows this zone in gray for a coastal site.

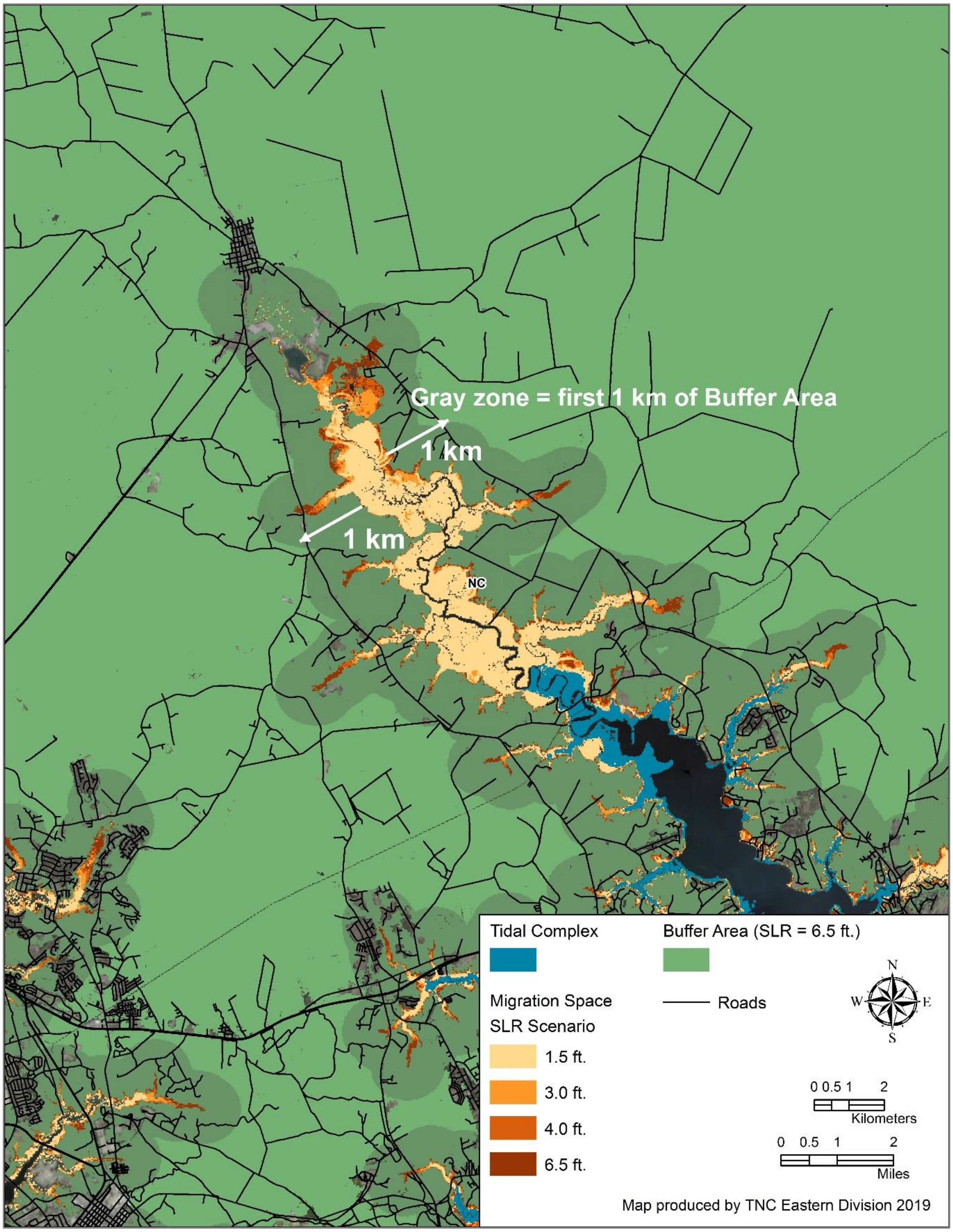


Figure 5.15. Landform variety in first 1 km of buffer area. The left panel shows the coastal landforms from which landform variety in a 100-acre circle around each pixel was calculated. The right panel shows the mean landform variety found in the first 1 km of each buffer area.

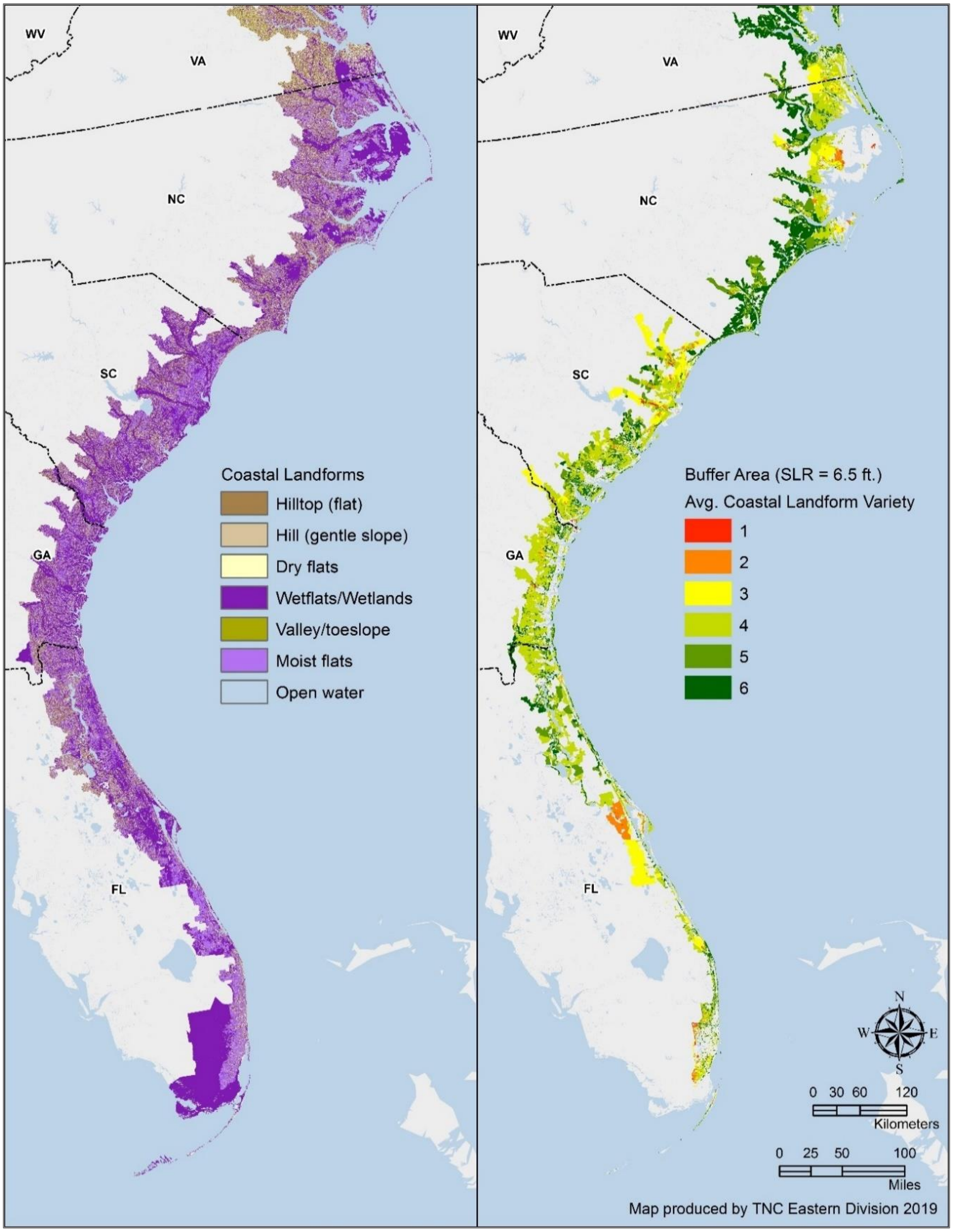
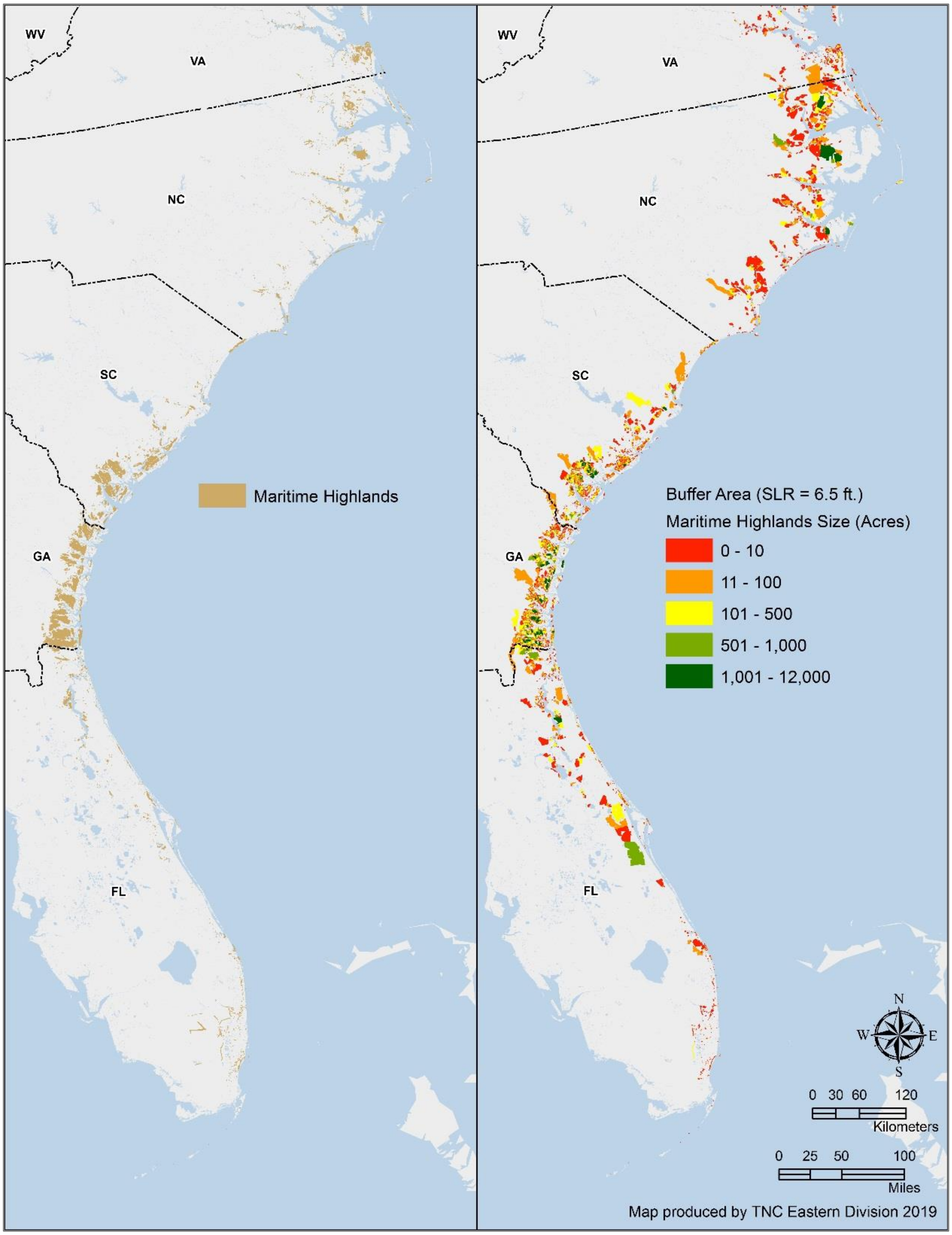


Figure 5.16. Acreage of maritime highlands in the buffer area. The left panel shows the location of maritime highlands across the project area, with the greatest concentrations in coastal Georgia and southern South Carolina. The right panel shows the total acreage of maritime highlands found in each buffer area.



Condition Characteristics:

We measured the condition of the buffer area based on the connectedness of its wetlands and the proportion of it in natural cover. Our assumption was that an intact natural buffer with highly connected wetlands offers more options for adaptation than an agricultural buffer with a few isolated wetlands.

WETLAND CONNECTEDNESS (WEIGHT = 5): This metric measured the density and connectivity among wetlands in the first 1 km of buffer area. A permeable wetland landscape allows for extensive interactions among species that require some degree of freshwater inundation or tolerate a mixture of fresh and salt water. There is strong agreement among scientists that the more connected the landscape is, the more it can facilitate expected range shifts and community reorganization (Heller & Zavaleta, 2009).

We used resistant kernel analysis to map wetland local connectedness. This analysis was developed by Brad Compton using software written by the UMASS CAPS program (Compton et al. 2007). Connectedness refers to the connectivity of a focal cell to its ecological neighborhood when it is viewed as a source. The results can reveal the extent that ecological flows outward from the focal cell are impeded or facilitated by the surrounding landscape. To calculate connectedness, each cell of a resistance grid is coded with a resistance weight based on land cover, road class, or landform. The theoretical spread of a species or process outward from a focal cell is a function of the resistance values of the neighboring cells and their distance from a focal cell out to a maximum distance of three kilometers (the recommended distance determined by the software developer).

To identify and map connected wetlands within the buffer area, we used a resistance grid based on landforms. Landforms compatible with coastal wetlands (open water, wet flat, moist flat, dry flat, valley and toeslope, gentle slope, hilltop flat) were given low resistance weights, while developed land and incompatible landforms (sideslope, steep slope, summit, ridge) were assigned high resistance weights (Table 5.1). We increased the grid cell size from 30 m to 90 m to run the local connectedness analysis on the resistance surface which allowed us to run the analysis with a reasonable processing time because the CAPS software program is computationally intensive. We averaged the resistance weight values (Table 5.1) of the 30-m cells to the 90-m cells, resulting in a grid of 90-m cells for the project area where each cell was scored with a local connectivity value from 0 (least connected) to 100 (most connected). Lastly, we calculated the average local connectedness score in the first 1 km of each buffer unit under each SLR scenario (Figure 5.17).

Table 5.1. Resistance weights used in the local connectedness model. Small weights indicate landforms that are compatible with coastal wetlands.

Landform	**Resistance**
Steep slope (cool/warm aspect)	10
Cliff	10
Summit/ridgetop	5.5
Slope crest	7.5
Hilltop (flat)	3.5
Hill (gentle slope)	3.5
Sideslope (cool/warm)	5.5
Dry flats	1.5
Wet flats	1
Valley/toeslope	2
Moist flats	1.25
Flat at the bottom of a steep slope	1
Cove/footslope (cool/warm aspect)	3.5
Open water	1.5
Development	20

PERCENT NATURAL COVER (WEIGHT = 5): This metric measured the naturalness of the land cover within the first 1 km of the buffer area. Natural areas immediately adjacent to the migration space and tidal complex allow the coastal systems to interact with freshwater marshes and swamps, coastal forests, and native grasslands, supporting species like marsh hawks and mink that use a mosaic of habitats to meet their resource needs. Areas that are currently in agriculture were included in the buffer because they are permeable to movement by many species and, once inundated; they will likely revert to marsh. However, because agriculture is often intensively managed, treated with chemicals, and regularly replanted, these areas do not provide the range of options for native species that natural cover does.

To measure percent natural cover, we tabulated the area of natural land cover in the first 1 km of each buffer area using the augmented NOAA 2010 C-CAP land cover dataset. The 1-km boundaries were delineated for the landform variety metric as previously described (Figure 5.18).

Figure 5.17. Wetland connectedness in first 1 km of buffer area. The left panel shows the wetland connectedness values across the project area. The right panel shows the average wetland connectedness score in the first 1 km of each buffer area.

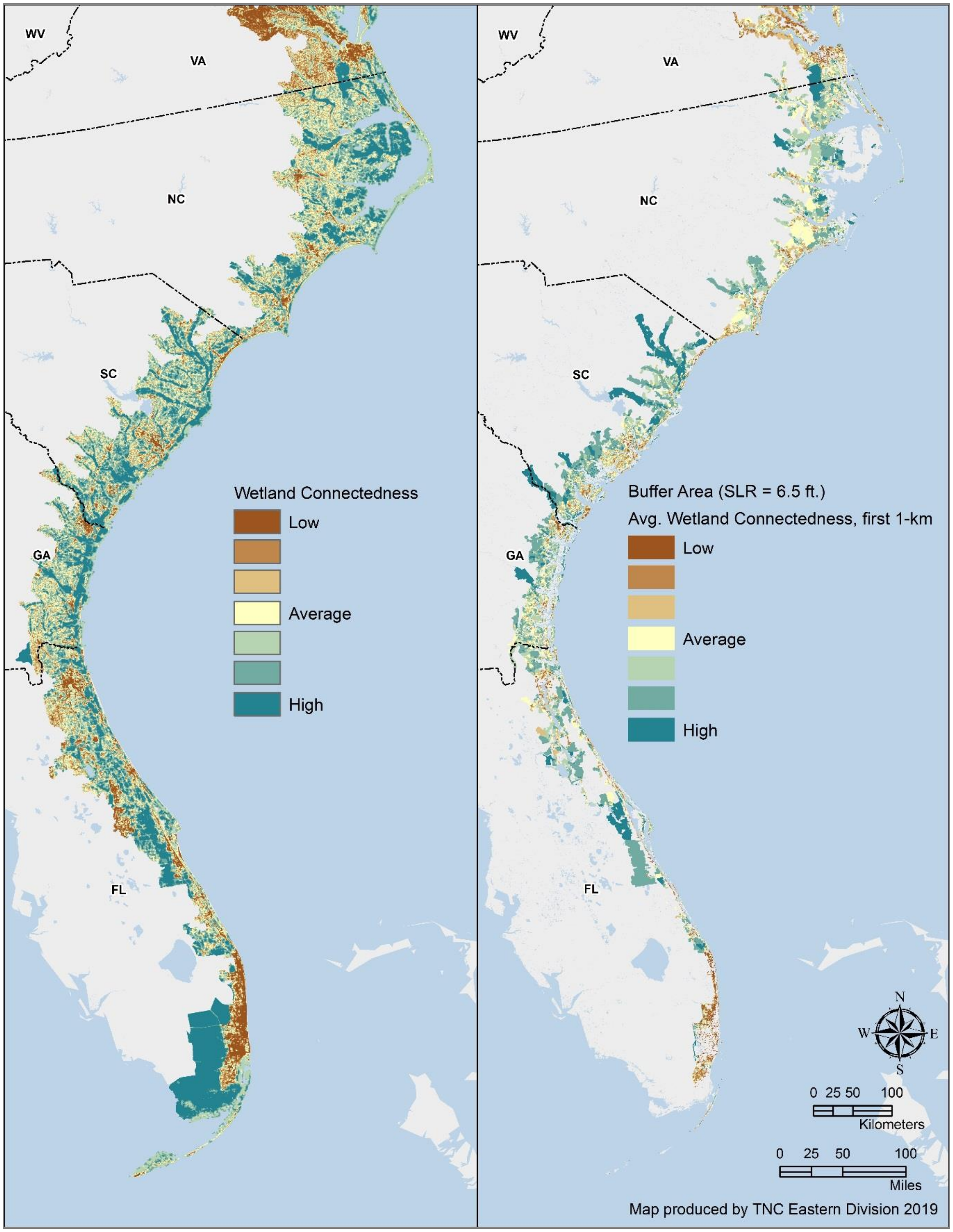
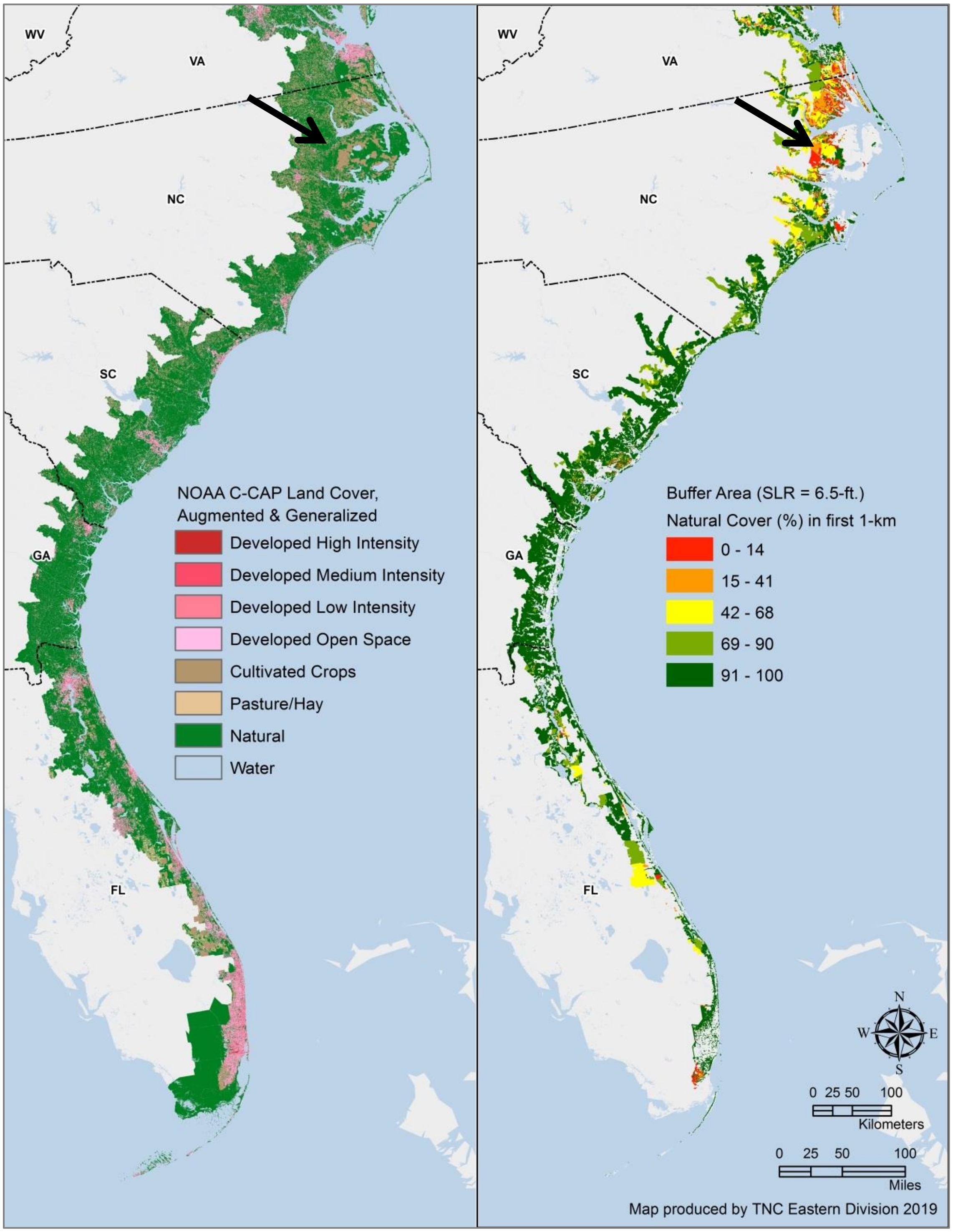


Figure 5.18. Natural land cover in the first 1 km of the buffer area. The left image shows generalized land cover classes from the augmented NOAA 2010 C-CAP dataset. The right image shows the percent of each buffer area comprised of natural cover. The black arrow highlights a buffer area with large amounts of agricultural land that scored low for natural cover.



Integration of Physical and Condition Characteristics

The final score for the buffer area was calculated for each site as a weighted sum of the two categories: physical options and current condition as shown below:

Physical Options
- BS: Adjusted Buffer Area Size (5)
- VL: Variety of Landforms (5)
- MH: Amt Maritime Highlands (5)

___

Weighted Sum = Physical Score
*(BS*5 + VL* 5 + MH 5)/15*

Current Condition
- WC: Wetland Connectedness (5)
- PN: Natural Cover (5)

___

Weighted Sum = Condition Score
*(WC*5 + PN* 5)/10*

The final Buffer Score = (Physical score + Condition score)/ 2

Resilience Scores

We calculated a Site Resilience Score (a.k.a. Resilience Score) for each site as the weighted sum of the site score (90%) based on the physical and condition characteristics (with appropriate thresholds and adjustments), and the buffer area score (10%).

Tidal Complex / Migration Space (90%)
- Physical Options
  - Size of Migration Space (5)
  - Tidal Classes (3)
  - Shared Upland Edge (2)
  - Size of Complex (2)
- Current Condition
  - Developed Upland Edge (5)
  - Sediment Balance (3)
  - Water Quality Index (1)
  - Flow Alteration (1)

___

= Site Score

Buffer Area (10%)
- Physical Options
  - Adjusted Buffer Area Size (5)
  - Variety of Landforms (5)
  - Maritime Highlands (5)
- Current Condition
  - Wetland Connectedness (5)
  - Natural Cover (5)

___

= Buffer Area Score

RESILIENCE SCORE

*Site Resilience = 0.90*Site Score + 0.10*Buffer Area Score*

The final scores are in standard normal units (z-scores) relative to the site's coastal shoreline region (river-dominated, lagoonal, etc.). To create the final scores, we calculated the mean and variance of site resilience scores within each coastal shoreline region (z-scores have a mean of 0 and standard deviation of 1). Use of this scheme assumed that the scores followed a normal distribution with a mean and standard deviation that accurately summarized the data. Rank based z-scores were used where the distribution of raw scores did not approximate a normal distribution or could not be transformed into a normal distribution. We grouped the scores into the following categories, which are used throughout the results section and serve as the legend for the various maps:

- Far Above Average (>2 standard deviations) - Most Resilient
- Above Average (1- 2 standard deviations) - More Resilient
- Slightly Above Average (0.5 to 1 standard deviations) - Somewhat Resilient
- Average (-0.5 to 0.5 standard deviations) - Average
- Slightly Below Average (-0.5 to -1 standard deviations) - Somewhat Vulnerable
- Below Average (-1 to -2 standard deviations) - More Vulnerable
- Far Below Average (<-2 standard deviations) - Most Vulnerable

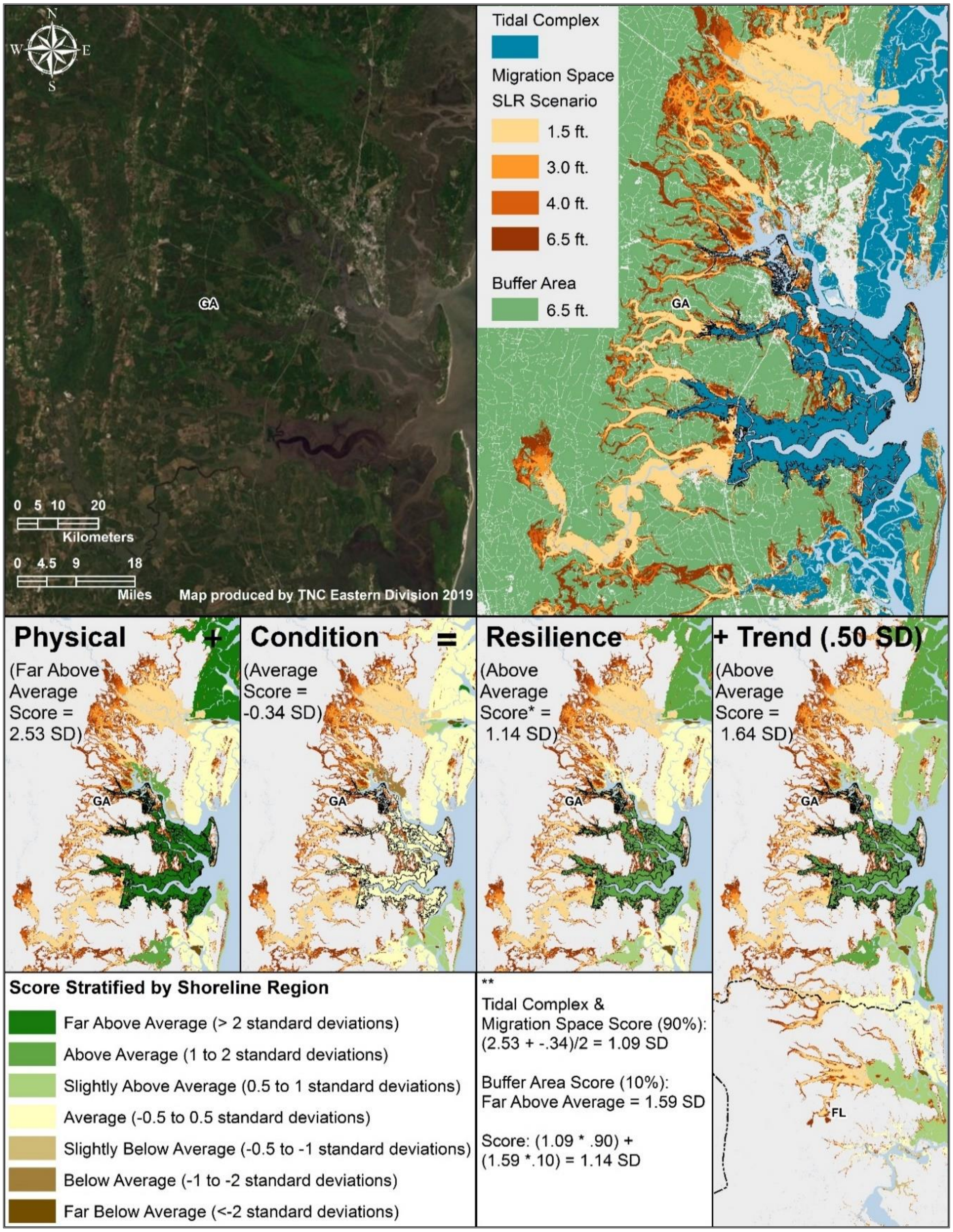
Following this scheme ensured that the results were seamless across the South Atlantic coast and allows comparisons with our terrestrial resilience analysis.

The results we present focus on both the 6.5-foot scenario, and the 6.5-foot scenario with trend, as these provide the most comprehensive estimate of a site's resilience over the next century. However, we calculated scores for each of the four SLR scenarios, and these results are available to download from the project web site.

Resilience with Trend

Some sites show an increasing trend in their migration space where the amount of area gets larger within each SLR scenario. We used linear regressions to identify sites with a statistically significant ($p < 0.05$) relationship between the sea level rise scenarios (1.5 – 6.5 ft.) and migration space size. Sites with a significant migration space trend were assigned to one of three trend categories: increase, decrease, no change. Sites whose migration space showed an increasing trend were awarded an additional 0.50 SD points to their estimated resilience score, shown in the data as "resilience score with trend." The remaining sites with no significant positive relationship between migration space size and SLR scenario were not penalized. The use of 0.50 SD to calculate the resilience score with trend ensured that these sites received an increase but could not change by more than one resilience class. Figure 5.19 uses a tidal complex in Georgia to illustrate how the final resilience scores were calculated.

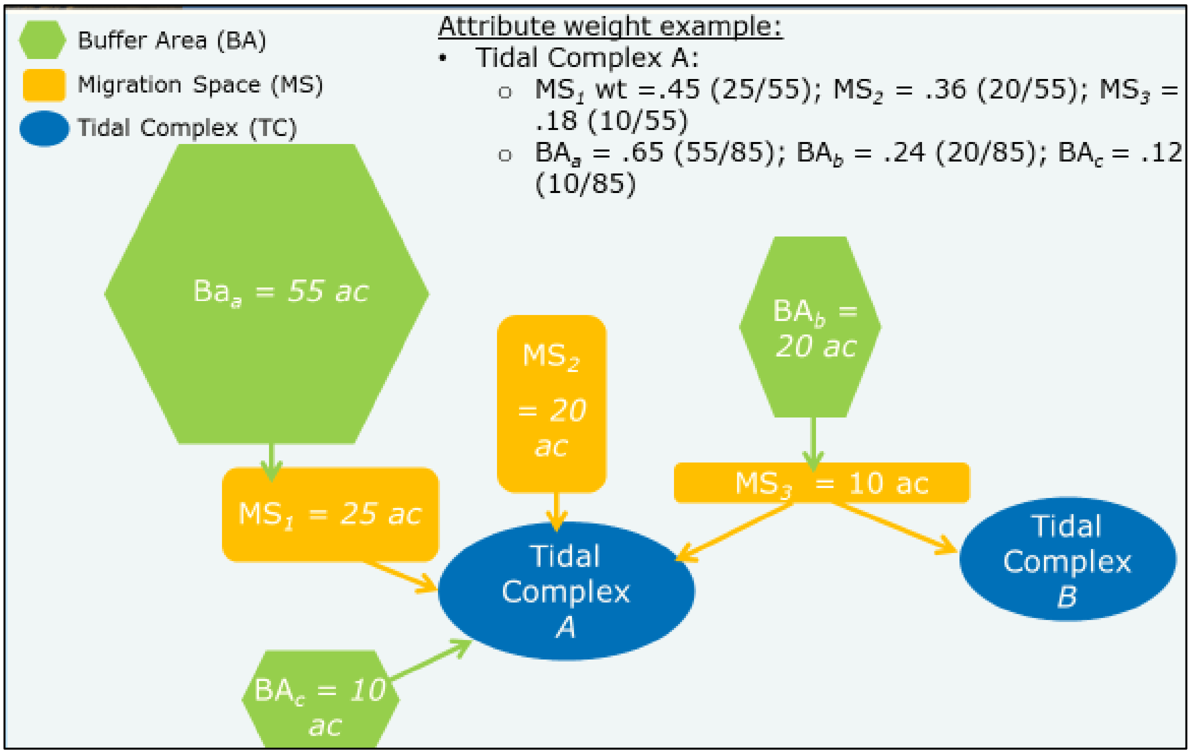
Figure 5.19. Calculating estimated resilience. This image shows the process used to estimate the resilience score for a large tidal complex, outlined in black, in St. Andrew Sound in southern Georgia. This site met the migration space size thresholds, so the physical and condition scores were weighted equally.



Spatial Integration

We have described the analysis process as if each tidal complex had its own migration space and buffer area. In reality, different tidal complexes often share the same migration space and buffer area, and one tidal complex can potentially have several migration space units. To address this, we used a spatial model that assigned the influence of each component in proportion to the spatial extent of each component for the focal tidal complex. For example, if a tidal complex had two migration space units, one covering 75% of the total migration space area and the second covering 25% of the area, the attributes of the first would be weighted by 0.75 and the characteristics of the second would be weighted by 0.25 when combined into a final score for the site (Figure 5.20).

Figure 5.20. Spatial integration of attributes. Approach used to calculate physical and condition attribute values for the tidal complex unit.



Additional Characteristics to Inform Conservation and Management Strategies

After calculating estimated resilience scores, we calculated the following attributes to provide additional information that might be useful in prioritizing conservation and management actions in the migration space of resilient tidal complexes, and that might provide more insight into the current marsh and its surroundings.

Securement

As migration space represents potential future habitat for important and productive coastal systems, we examined how much of this critical land is already in permanent protection. Using a spatial dataset of secured lands in the Eastern US (Eastern Conservation Science, 2017), we extracted all parcels that were permanently protected from development (GAP status 1, 2, or 3, Crist et al. 1998). We overlaid the selected secured lands with the migration space polygons and tidal complexes to calculate the percent securement of each unit. We also examined the percent securement by each estimated resilience class for each SLR scenario.

Migration Space Future Development

Development is perhaps the greatest and most permanent threat to natural systems. In the US between 1982 and 2001, more than 34 million acres of open space were lost to development, about 6000 acres per day or 4 acres a minute. In addition to habitat destruction, high-density development of natural habitats can transform a landscape by changing local hydrology, increasing recreation pressure, and introducing invasive species either by design or by accident (e.g., introduced by vehicles). Moreover, urbanization and fragmentation are inextricably linked since the dispersal and movement of forest plants and animals are disrupted by development and roads. We used future development predictions to examine the risk of development by 2100 in migration space units. We extracted pixels that were modeled to be developed in 2100 in the 30-m Land Transformation Model (LTM) Version 3, developed by the Human-Environment Modeling and Analysis Laboratory at Purdue (Tayyebi et al. 2013), and that were not currently in permanent protection. We then calculated the percent of each migration space unit that was expected to be developed by 2100. This information can be used by natural resource managers to understand the potential for development in important migration space areas.

CHAPTER

6

RESULTS

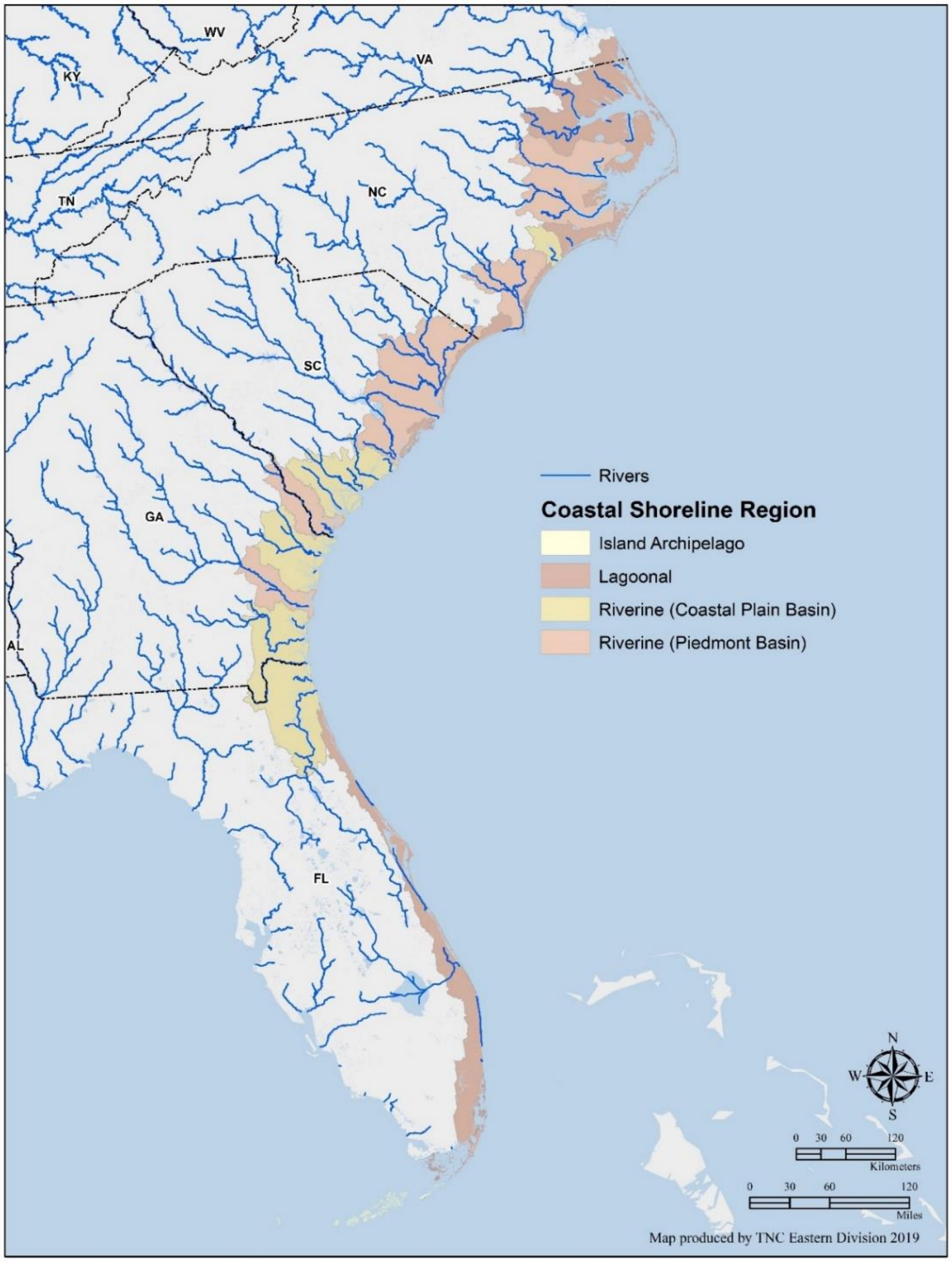
This section presents the results of the 6.5-foot SLR scenario by coastal shoreline region. We calculated the physical, condition, and final resilience scores for each site under each sea level rise scenario, and we show the 6.5-foot scenario in this section as it identifies the sites likely to be robust to the most extreme events. While site-specific results vary by coastal shoreline region, the migration space of many sites increased from the 1.5-foot SLR scenario to the 6.5-ft. scenario. In the results presented here, these sites scored more resilient than sites whose migration space declined with increasing inundation.

This region currently has more than 1.2 million acres of estuarine wetland sites but could lose up to 77% of these existing estuarine habitats under 6.5 feet of sea level rise (Marcy et al. 2011). However, our analysis identifies hundreds of resilient sites where estuarine habitats could potentially increase in size through landward migration, and whose cumulative migration space area totals more than 1.7 million acres. Even without the Everglades, cumulative migration space totals 715,000 acres and with conservation and management these resilient sites could offset almost 80% of the estimated estuarine habitat loss, providing critical habitat for birds and wildlife, and buffering people from the effects of storms and floods. With the Everglades, the total estuarine wetland area could potentially increase in the future

Six and a half feet of SLR is well within the realm of possibility in the next century. Based on the latest peer-reviewed research on global mean sea level rise that considers the possibility of rapid ice melt in Greenland and Antarctica, an interagency team led by NOAA recently revised the lower and upper bounds of their global and regional sea level rise scenarios for 2100 (Sweet et al. 2017). The previous scenarios ranged from 0.65– 6.5 ft. but the six new scenarios now range from 1.0 to 8.2 ft. (0.2 - 2.0 m up to 0.3 - 2.5 m). The report also found that along all US coasts except Alaska, relative sea level is expected to be greater than the global average under several of the scenarios. Furthermore, recent studies suggest that the US Atlantic coast is particularly vulnerable to sea level rise due to enhanced warming and slowing of the Atlantic Ocean circulation (Krasting et al. 2016; Saba et al. 2016; Sallenger et al. 2012), as well as high subsidence rates relative to global rates (Karegar et al. 2016). Regardless of the exact increase in Atlantic Ocean levels by 2100, seas will continue to rise beyond 2100 and it is critical that conservation and restoration actions be undertaken now to prepare for this future reality.

This section summarizes the 6.5-foot scenario results for the South Atlantic geography, and includes results stratified by the four coastal shoreline regions as well as the raw (unstratified) results for the full region (Figure 6.1).

Figure 6.1. Full project area with Coastal Shoreline Regions (CSRs).



Full Region

This project was designed to create consistent and credible estimates of resilience for all sites within each CSR. We used the shoreline regions as our primary geographic units because they are ecologically consistent and contain less heterogeneity than the arbitrary boundary of the project area. Thus, the within-CSR results identify the sites that are most resilient within a given type of shoreline, and avoid comparing, for example, an island archipelago site to a riverine-influenced site. Comparisons across shoreline regions can provide useful context for interpreting the within-CSU results, and we present them here also.

Tidal Complex Units

Our methods identified 1,232 coastal sites in the project area that had a minimum of two acres of tidal marsh. The Lagoonal CSR had the largest number of sites (538), and the Coastal Plain Riverine CSR had the smallest number (163). For all CSRs, the second smallest size class, 3-10 acres, was the most common (Figure 6.2). The Coastal Plain Riverine CSR featured the largest site in the region, located in the state of Georgia, encompassing over 120,000 acres. The Coastal Plain Riverine CSR had an average tidal site size that was significantly larger than the other CSRs (Table 6.1). The Island Archipelago region had the smallest average site size, followed, not closely, by the Riverine Piedmont Basin. The Lagoonal and Coastal Plain Riverine regions had more of the large size classes than the other CSRs, reflecting both the physical setting and land use patterns within the four CSRs (Figure 6.3 and Figure 6.4).

Figure 6.2. Frequency of tidal site class by CSR. Small size classes are shown in white and light blue colors that transition to dark blues as the tidal complex size increases.

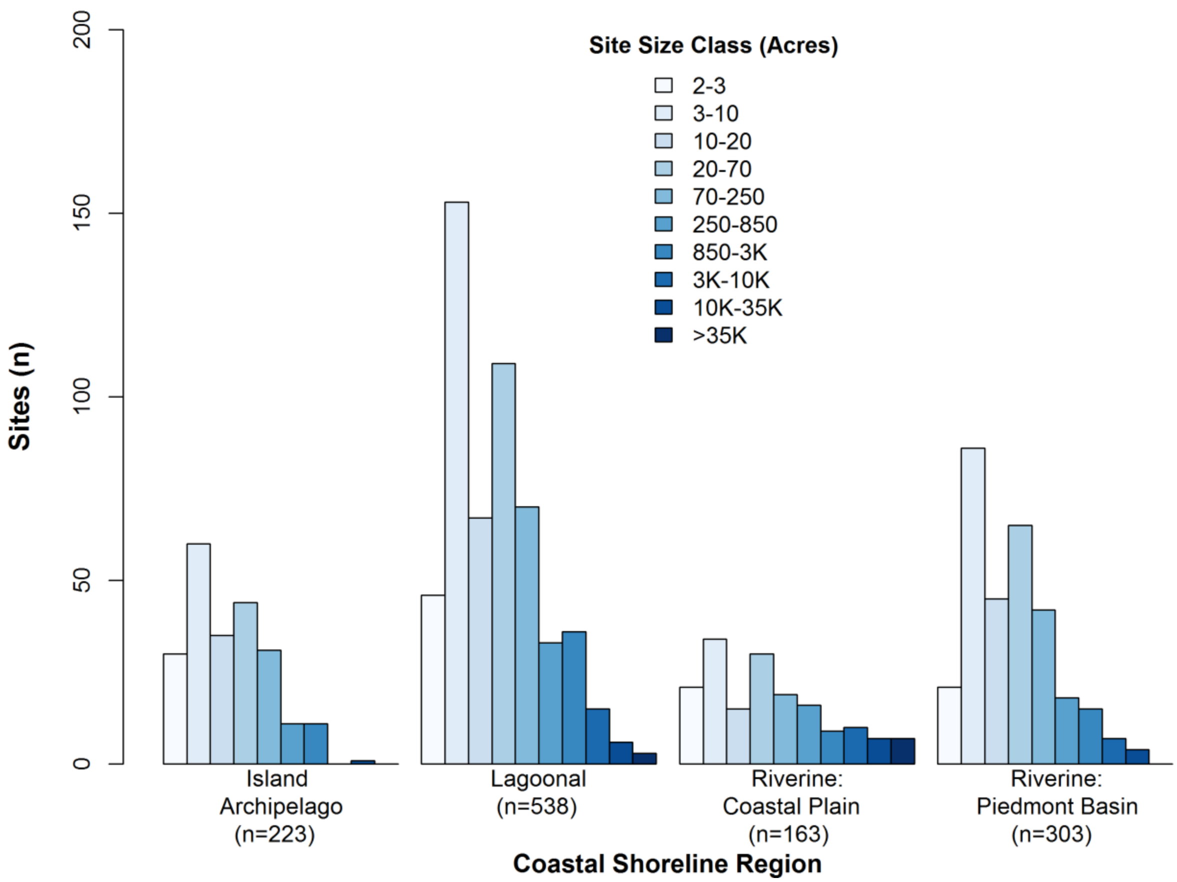


Table 6.1. Summary statistics for tidal site size by CSR.

	Tidal Site Size (Acres)				
Coastal Shoreline Region	**1st Quartile**	**Median**	**Mean**	**3rd Quartile**	**Max**
Island Archipelago	5.45	14.01	173.22	60.94	10,284.40
Lagoonal	6.67	21.02	830.37	98.13	56,554.80
Riverine (Coastal Plain)	6.67	35.69	3,785.06	379.68	120,068.00
Riverine (Piedmont Basin)	6.78	19.79	468.93	91.85	29,753.10

Figure 6.3. Physical settings and land use characteristics of the full region.

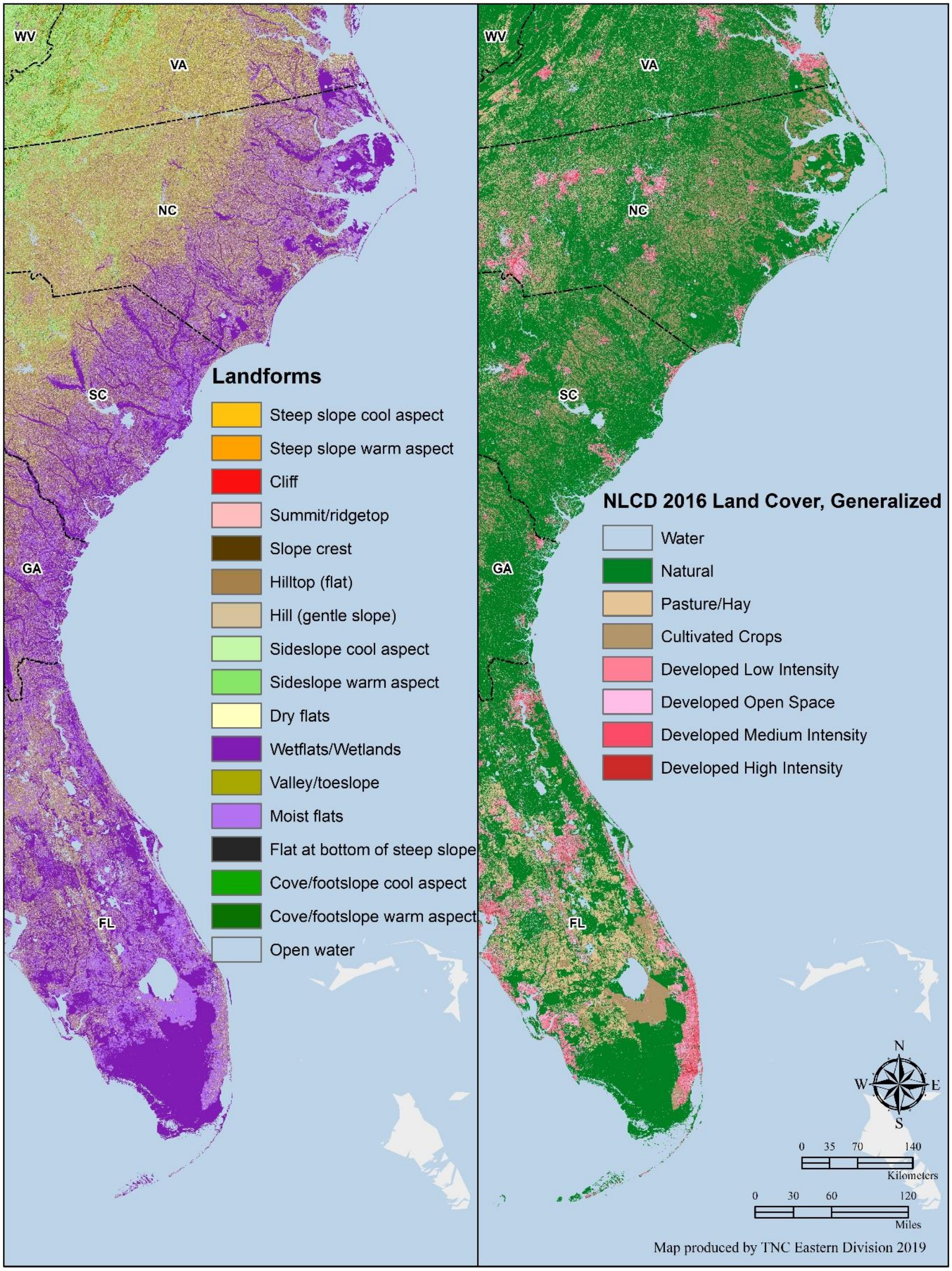
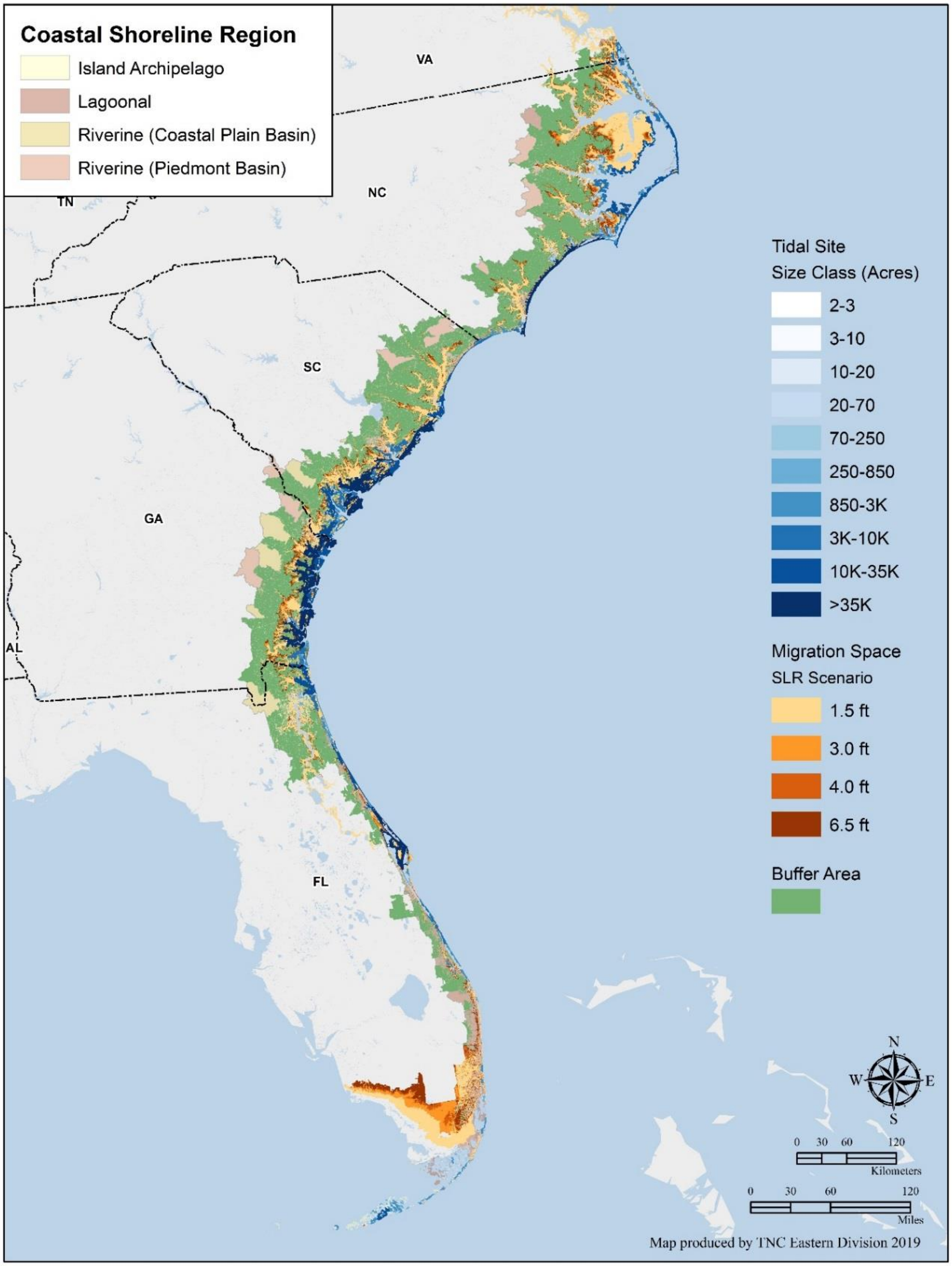


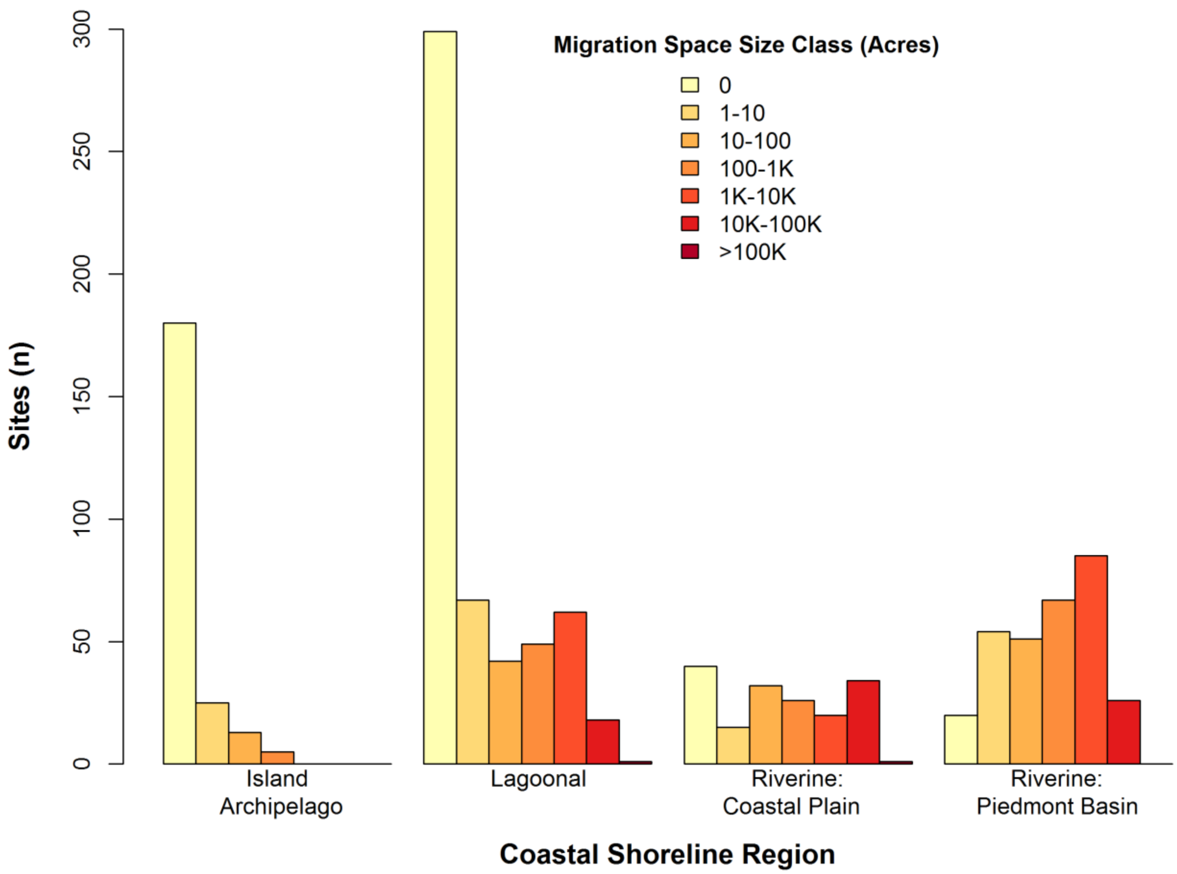
Figure 6.4. Tidal complex, migration space, and buffer area units. The color of the tidal complex unit reflects its size class (n=10), while the color of the migration space indicates the SLR scenario (n=4).



Migration Space Units

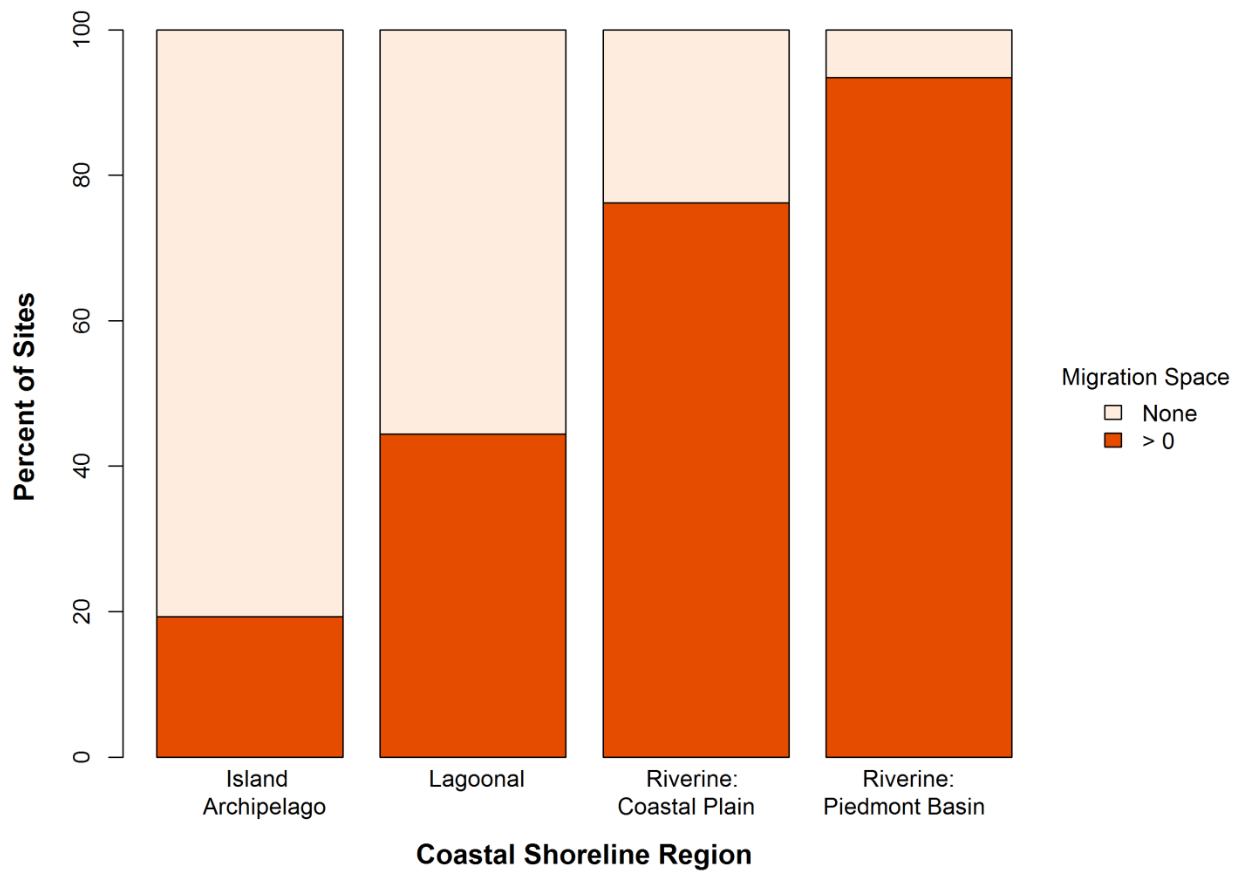
Of the 1,232 coastal sites, 693 (56%), had migration space (Figure 6.5). Of the four CSRs, the Piedmont Basin had the greatest number of large migration space size classes, followed by the Lagoonal and Coastal Plain Riverine regions (Figure 6.5). With the exception of the Piedmont Basin, sites with no migration space comprised the most frequent class in the CSRs.

Figure 6.5. Frequency of migration space size class by CSR. Small migration space size classes are shown in light yellow shades that transition to darker oranges as the migration space size increases.



The percentage of sites with migration space varied substantially by CSR (Figure 6.6). The two Riverine regions had the highest percentage, with 93% of sites in the Piedmont Basin having migration space and 76% in the Coastal Plain. In the Island Archipelago region, only 19% of the sites had migration space, reflecting the region's insular setting.

Figure 6.6. Percent of sites with migration space by CSR.



The Coastal Plain Riverine CSR had the largest average migration space size while the Island Archipelago region had the smallest (Table 6.2). Excluding the large migration space in the Everglades of Florida, which encompassed over 1 million acres, the Coastal Plain Riverine CSR had the largest migration space at almost 103,000 acres. A Spearman's rank-order correlation showed site size and migration space size were somewhat positively correlated and this relationship was statistically significant (r_s = 0.33, $p < 0.0001$).

Table 6.2. Summary statistics for migration space size by CSR.

	Migration Space (Acres)				
Coastal Shoreline Region	**1st Quartile**	**Median**	**Mean**	**3rd Quartile**	**Max**
Island Archipelago	0.00	0.00	5.07	0.00	222.40
Lagoonal	0.00	0.00	3,387.88	73.84	1,023,800.00
Riverine (Coastal Plain)	1.00	83.95	14,135.00	5,332.14	102,780.16
Riverine (Piedmont Basin)	11.12	283.11	3,882.28	6,385.17	34,971.51

Buffer Area Units

Less than half of the sites, 517 (42%), had land-based buffer area (Figure 6.7). The buffer size pattern was quite variable by CSR and reflects the different types of sites and their larger geographic settings. For example, the Lagoonal and Island Archipelago regions had more sites without buffer area than with, due to the insular nature of many of the tidal wetlands in both of these regions. In fact, the mean size of buffers in the Island Archipelago was very small, less than 1 acre. Sites in the riverine regions typically had moderate to large buffer areas, with most sites being buffered. The Coastal Plain Riverine region had the largest mean buffer size as well as the largest buffer area in the South Atlantic (Table 6.3). There was a moderate positive relationship between site size and buffer area size ($r_s = 0.31$, $p < 0.001$).

Figure 6.7. Frequency of buffer area size class by CSR.

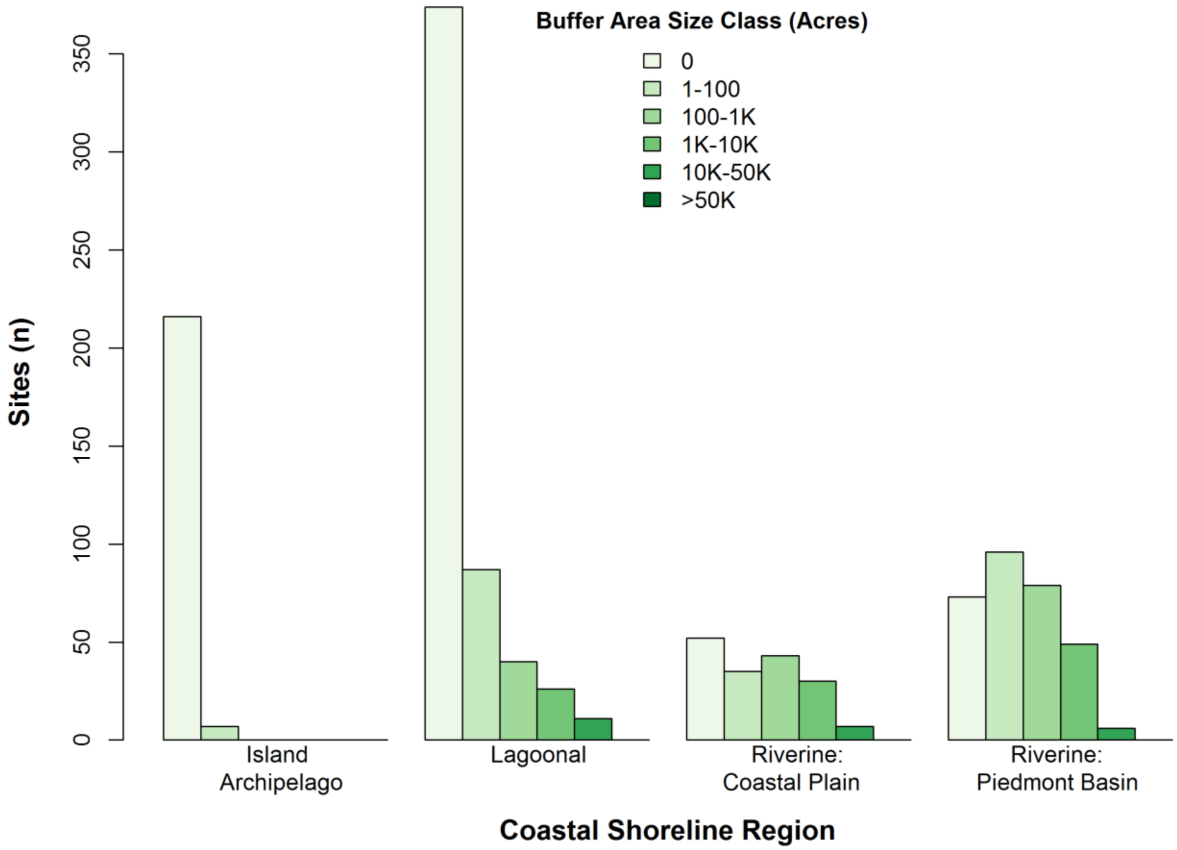


Table 6.3. Summary statistics for buffer area size by CSR.

	Buffer Area (Acres)				
Coastal Shoreline Region	**1st Quartile**	**Median**	**Mean**	**3rd Quartile**	**Max**
Island Archipelago	0.00	0.00	0.08	0.00	8.67
Lagoonal	0.00	0.00	559.09	4.17	25,031.84
Riverine (Coastal Plain)	0.00	83.84	2,022.04	802.96	73,724.94
Riverine (Piedmont Basin)	0.67	54.04	932.31	572.22	24,441.83

Physical and Condition Scores

The estimated resilience score for a coastal site consists of the weighted sum of its condition and physical components, with weighting dependent on a site's cumulative amount of migration space (see "Integration of Physical and Condition Characteristics" section in Chapter 5 for more details). The physical and condition characteristics of a site and its migration space account for 90% of the resilience score while the buffer area score (condition and physical, weighted equally) comprises the remaining 10%. The final estimated resilience was stratified by CSR to ensure that sites were compared within an ecological context. However, we calculated unstratified physical, condition, and resilience scores to understand the results and regional patterns. Figure 6.8 shows the geographic distribution of the unstratified physical scores and Figure 6.9 shows the top ten highest scoring sites for unstratified physical characteristics. As the regional map in Figure 6.8 shows, there was a cluster of high scoring sites along the South Carolina and Georgia coasts, reflecting a flat and wet, largely undeveloped landscape that is predicted to provide large areas for marsh migration at 6.5 feet of sea level rise.

There were other spatial clusters of "Above Average" sites evident at the regional scale, including Pamlico Sound in North Carolina and an area north of Palm Coast in northern Florida. The focal site in Figure 6.9 is a complex of tidal wetlands around the Satilla and Little Satilla Rivers in Jekyll and St. Andrew Sounds in southern Georgia. The marsh was very large (64K acres, "Far Above Average") with an extremely large migration space of almost 103K acres that ranked "Above Average" for the project area. The marsh shared approximately 60% of its border with its migration space, which was "Slightly Above Average" for the full region. The site's migration space scored "Slightly Above Average" for estimated future tidal class diversity and evenness. The site had a large buffer area of 34,000 acres immediately adjacent to a large proportion of the migration space, ranking "Above Average" for the project area.

Without stratification, the Lagoonal and Island Archipelago regions had the greatest proportion of low scoring sites for physical characteristics, and the two riverine regions had the greatest proportion of high scoring sites. Stratification ensured that all sites in a shoreline region were only compared to other sites in that same shoreline region, allowing the best physical sites in each region to rise to the top. As the stratified results map shows (Figure 6.10), the sites that scored high for unstratified physical characteristics remained high (green), but new high scoring sites are visible in the Island Archipelago and Lagoonal regions. Table 6.4 shows the number of sites in each stratified physical class.

For the unstratified condition scores, high-scoring sites are sprinkled across the full project area (Figure 6.11). There are no large geographic clusters as there were for the high scoring physical sites, showing that the condition scores are largely independent of the site's geophysical characteristics. The top ten highest scoring sites for the full region are clustered largely in Georgia with a couple in South Carolina and North Carolina (Figure 6.12). The focal site highlighted in Figure 6.12 is a marsh complex near St. Catherine's Sound in northern coastal Georgia. The site's upland edge had no development ("Far Above Average"), a low sediment deficit (-1.8 mg/l, "Above Average"), and its migration space had "Above Average" water quality and no flow alteration. The high scoring physical sites in Georgia and South Carolina had at least one condition challenge and none scored "Far Above Average" for unstratified condition.

The stratified map shows the sites in the best condition for each shoreline region, even those that had low scoring sites for condition at the full regional scale (Figure 6.13 and Table 6.5). The differences between the two maps are relatively subtle, suggesting that in the South Atlantic region, the average condition of coastal sites is relatively similar among the different shoreline regions.

Figure 6.8. Estimated physical score, not stratified by shoreline region. Sites in green scored greater than "Average" and have physical characteristics hypothesized to increase resilience including a large migration area with a diversity of tidal classes that are evenly distributed. Sites in yellow have "Average" physical characteristics. Sites in brown scored less than "Average" and are expected to respond poorly to sea level rise.

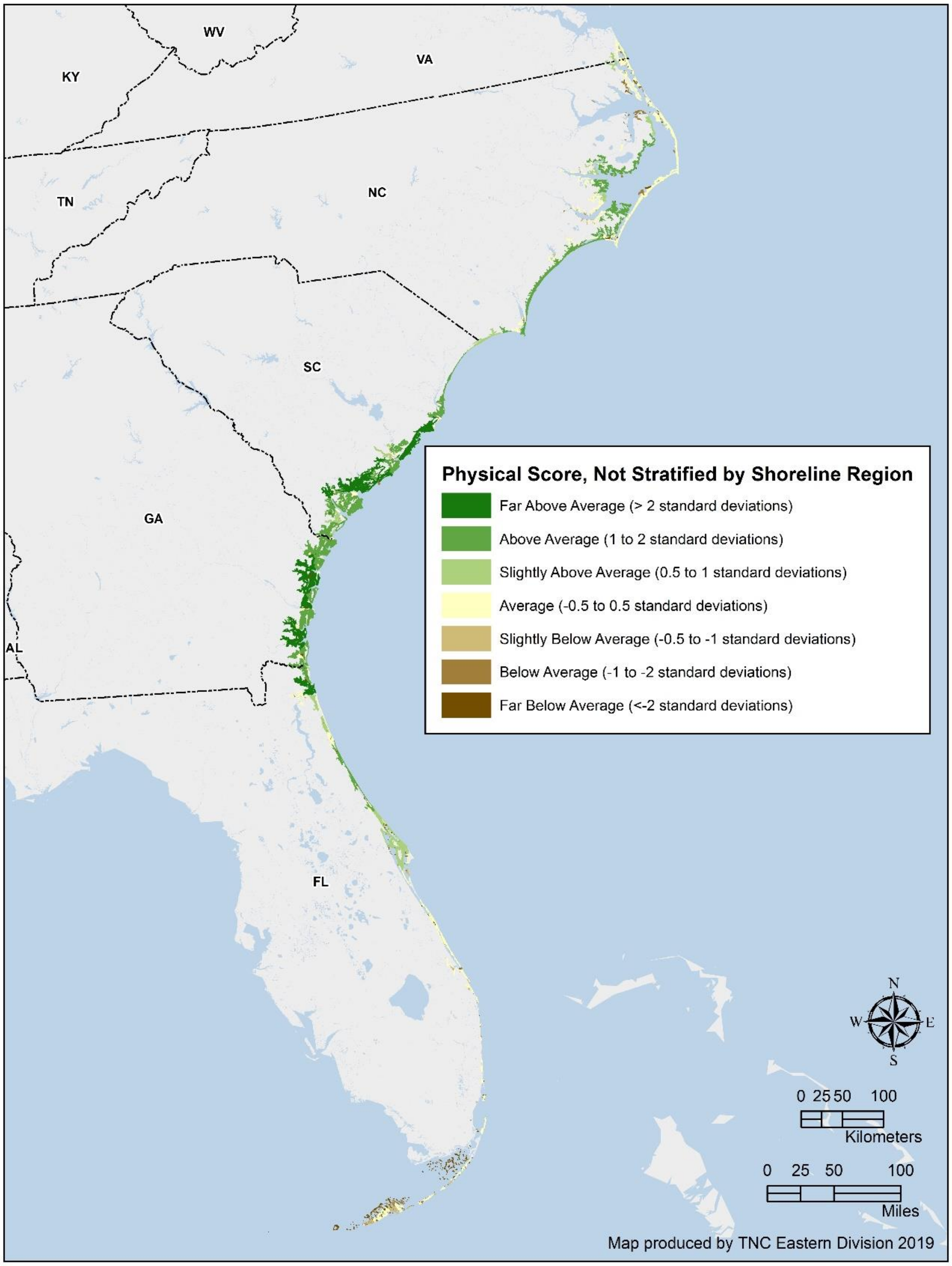


Figure 6.9. Top ten highest scoring sites for physical characteristics, not stratified by shoreline region. The focal site is a complex of tidal wetlands around the Satilla and Little Satilla Rivers in Jekyll and St. Andrew Sounds in southern Georgia. The site is very large (64K acres) with an upland edge that is mostly shared (60%, "Slightly Above Average") with its large "Above Average" migration space (103K acres).

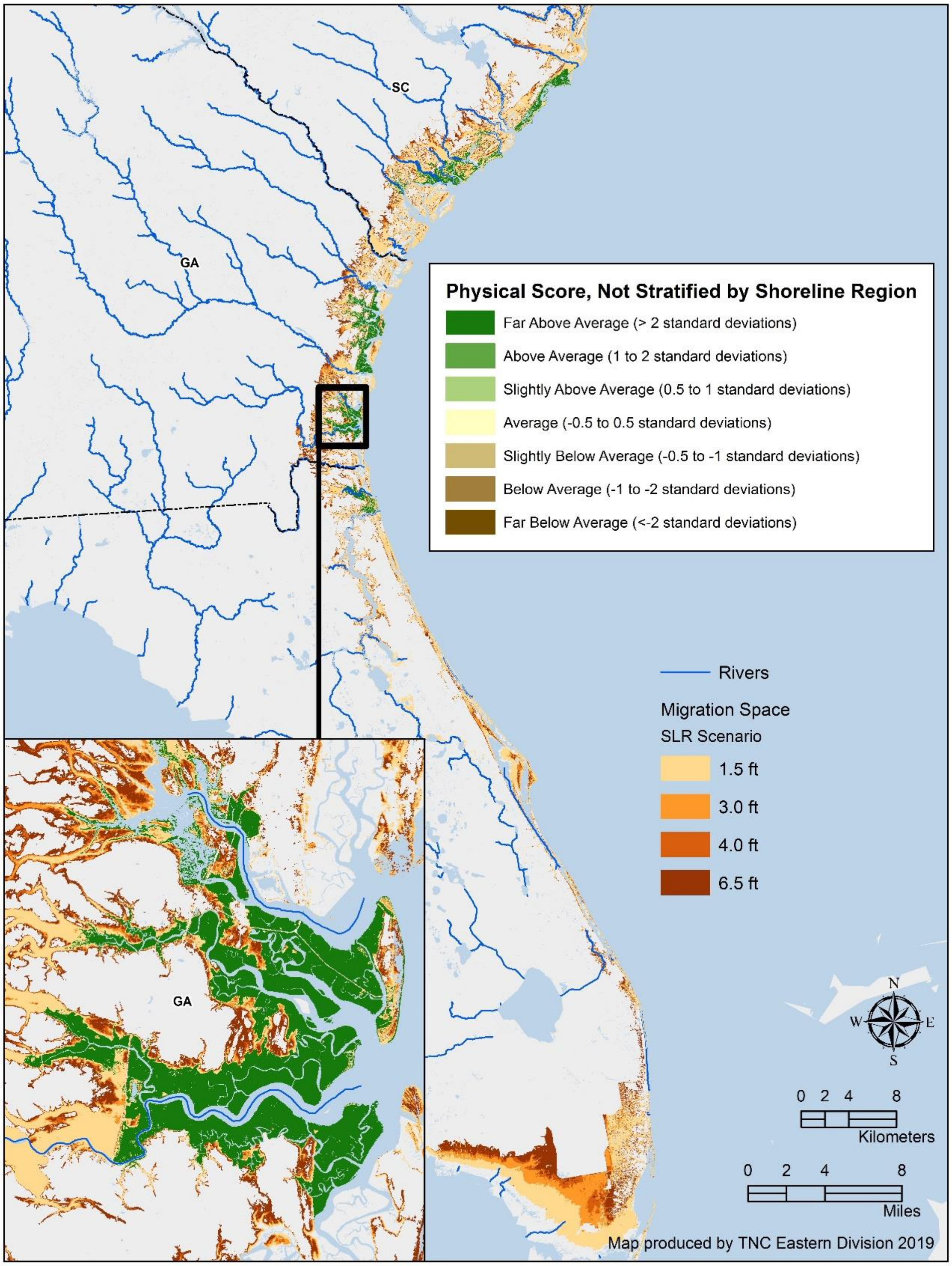


Figure 6.10. Estimated physical score, stratified by shoreline region. Sites in green scored greater than "Average" and have physical characteristics hypothesized to increase resilience, including a large migration area with a diversity of tidal classes that are evenly distributed. Sites in yellow have "Average" physical characteristics relative to all the units in the CSR. Sites in brown scored less than "Average" and are estimated to respond poorly to sea level rise.

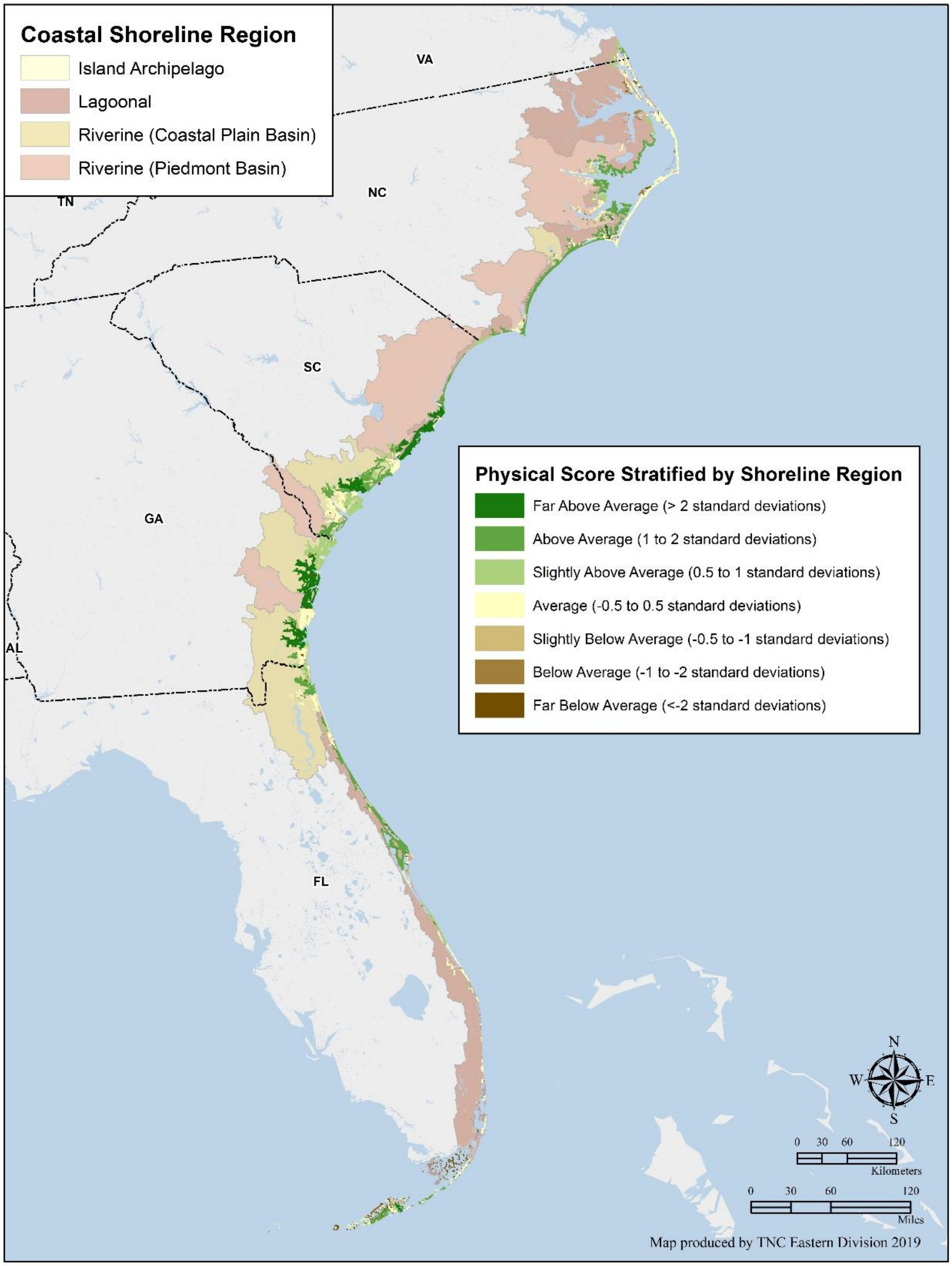


Figure 6.11. Estimated condition score, not stratified by shoreline region. Sites in green scored greater than "Average" and are estimated to be in good condition based on a low amount of development along their upland edge, a positive or slightly negative sediment balance, and migration space with good water quality and unaltered flows. Sites in yellow are "Average." Sites in brown scored less than "Average" and are estimated to be in poor condition.

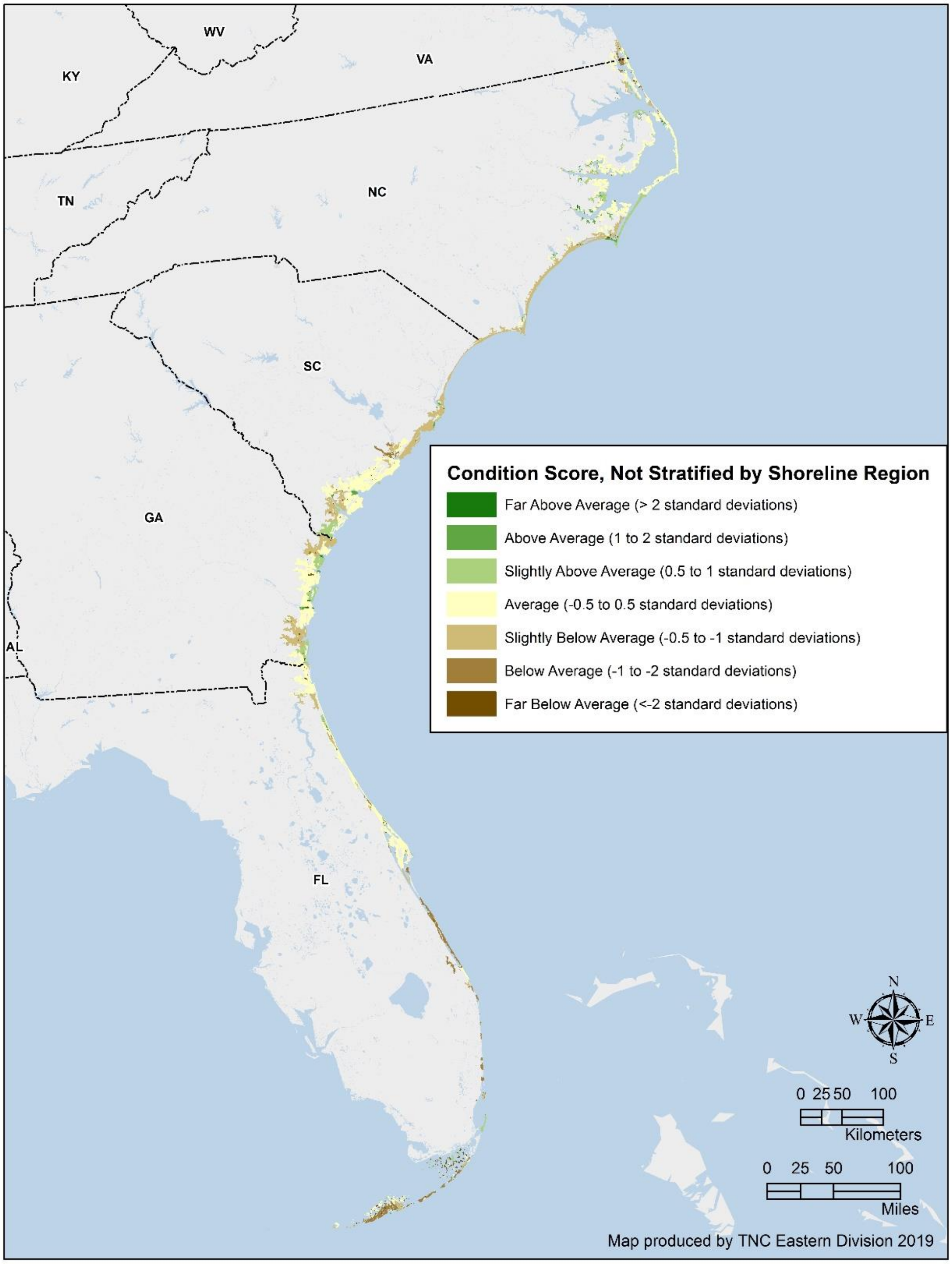


Figure 6.12. Top ten highest scoring sites for condition characteristics, not stratified by shoreline region. The focal site is near St. Catherine's Sound along the northern Georgia coastline. The site had a completely undeveloped upland edge, very low sediment deficit (-1.8 mg/l), and its migration space, while only "Average" in size at 300 acres, occurred in a catchment with good water quality and no flow alteration.

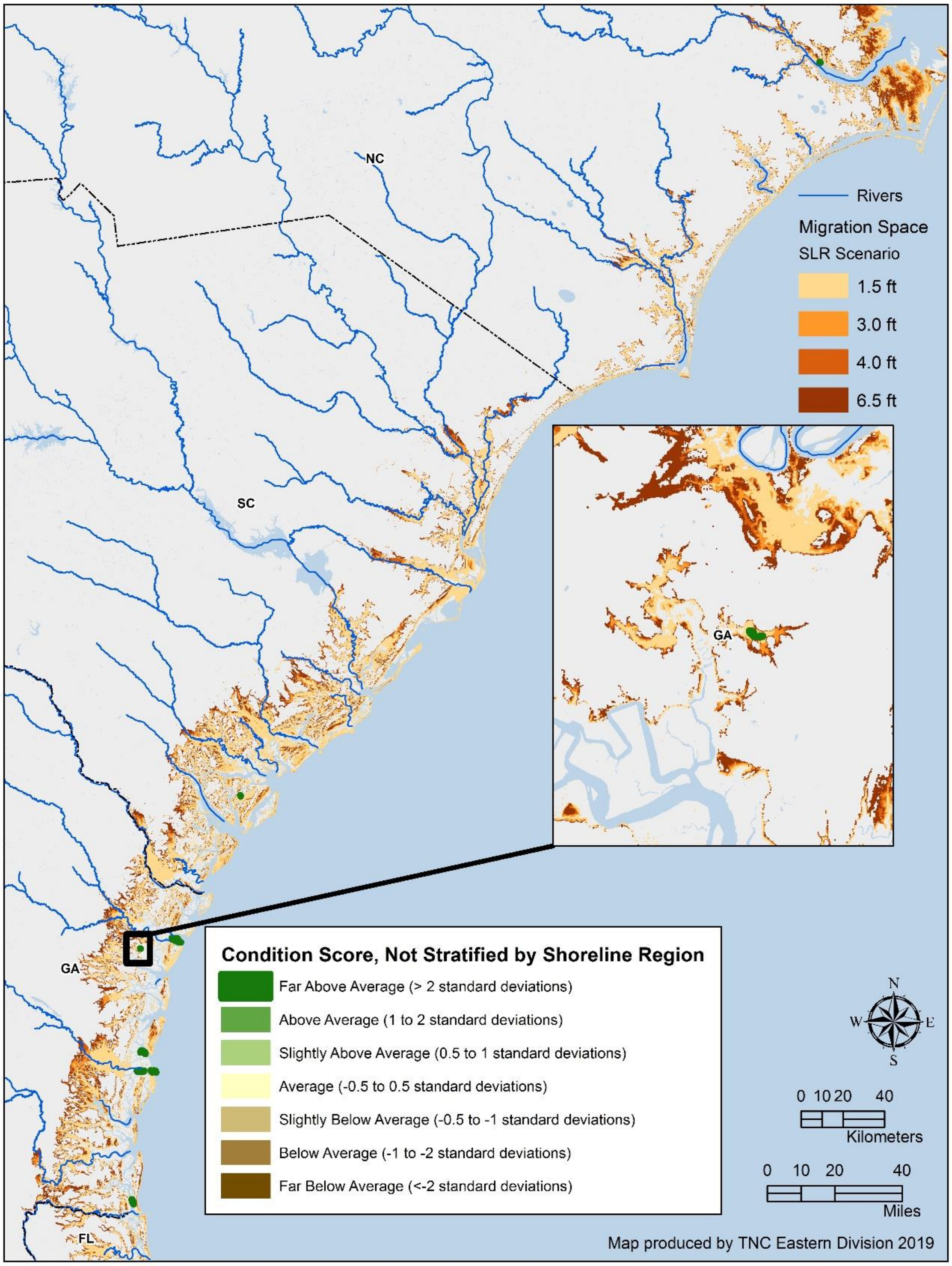


Figure 6.13. Estimated condition score, stratified by shoreline region. Sites in green scored "Above Average" and are estimated to be in good condition based on a low amount of development along their upland edge, a positive or slightly negative sediment balance, and migration space with good water quality and unaltered flows. Sites in yellow are "Average." Sites in brown are "Below Average" and are estimated to be in poor condition.

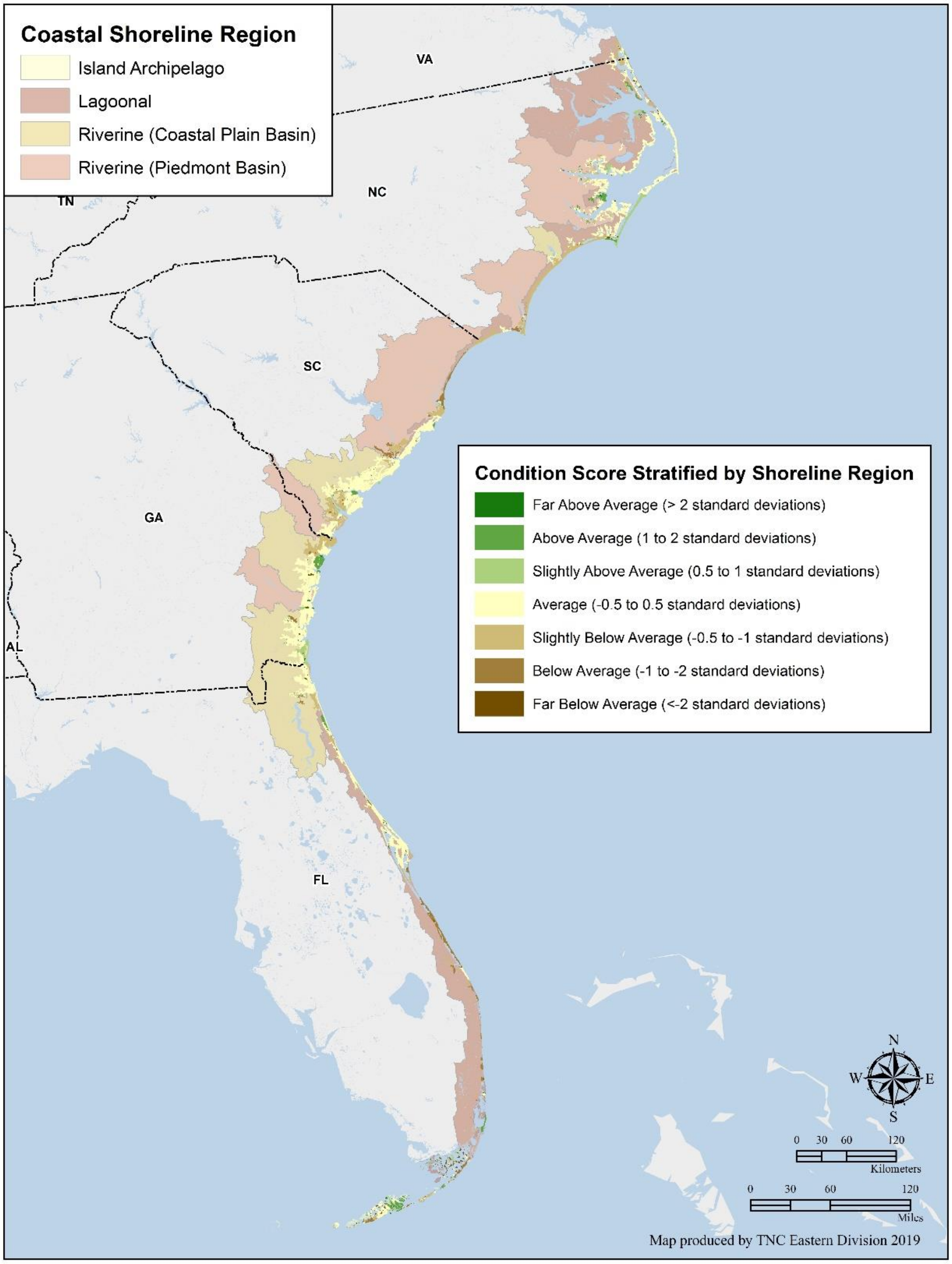


Table 6.4. Frequency of stratified physical scores for the 6.5-foot sea level rise scenario. The percentage of sites in each physical class by CSR is shown in parentheses.

Physical Score	Island Archipelago	Lagoonal	Riverine (Coastal Plain)	Riverine (Piedmont Basin)
Far Above Average	1 (0%)	3 (1%)	3 (2%)	4 (1%)
Above Average	8 (4%)	26 (5%)	13 (8%)	24 (8%)
Slightly Above Average	4 (2%)	21 (4%)	19 (11%)	23 (8%)
Average	30 (13%)	134 (25%)	53 (32%)	137 (45%)
Slightly Below Average	11 (5%)	49 (9%)	21 (13%)	55 (18%)
Below Average	9 (4%)	43 (8%)	19 (11%)	41 (14%)
Far Below Average	160 (72%)	262 (49%)	40 (24%)	19 (6%)

Table 6.5. Frequency of stratified condition scores for the 6.5-foot sea level rise scenario. The percentage of sites in each condition class by CSR is shown in parentheses.

Condition Score	Island Archipelago	Lagoonal	Riverine (Coastal Plain)	Riverine (Piedmont Basin)
Far Above Average	4 (2%)	8 (1%)	3 (2%)	7 (2%)
Above Average	26 (12%)	51 (9%)	19 (11%)	41 (14%)
Slightly Above Average	30 (13%)	55 (10%)	21 (13%)	46 (15%)
Average	61 (27%)	143 (27%)	52 (31%)	114 (38%)
Slightly Below Average	17 (8%)	55 (10%)	21 (13%)	45 (15%)
Below Average	22 (10%)	51 (9%)	17 (10%)	41 (14%)
Far Below Average	63 (28%)	175 (33%)	35 (21%)	9 (3%)

Sites in the Piedmont Basin Riverine region had a strongly normal distribution with most sites scoring "average" for condition as a small percentage of sites in the "Far Below Average" or "Far Above Average" category (Table 6.5). Sites in the Lagoonal region were skewed towards poor condition, and Island Archipelago sites, unsurprisingly, had the worst physical attributes due to the absence of migration space for many insular sites in this region. Table 6.6 shows no sites scored "Far Above Average" for both physical and condition characteristics, and only one site scored "Far Above Average" for physical and "Above Average" for condition. This relationship held true for the unstratified results where only ten sites scored "Above Average" for both physical and condition characteristics. As sites without migration space scored poorly for both physical and condition characteristics, there was a positive correlation between the condition and physical scores ($r = 0.54$, $p < 0.0001$).

Table 6.6. The number of sites in each physical and condition score category, stratified. A two-by-two frequency table shows the count of sites occurring in each physical and condition class combination. Physical classes are by row and condition classes are by column. Boxes shaded in gray indicate sites with the same physical and condition score class. For example, only six sites scored "Above Average" for both physical and condition characteristics.

	Condition Class						
Physical Class	**Far Above Average**	**Above Average**	**Slightly Above Average**	**Average**	**Slightly Below Average**	**Below Average**	**Far Below Average**
Far Above Average	0	1	0	7	2	1	0
Above Average	0	7	8	42	9	5	0
Slightly Above Average	1	15	6	21	18	6	0
Average	17	55	38	131	57	56	0
Slightly Below Average	3	29	15	32	23	34	0
Below Average	1	16	24	38	11	21	1
Far Below Average	0	14	61	99	18	8	281

Estimated Resilience Score

At the scale of the whole study areas, small to medium-size sites in southern Florida's Island Archipelago region scored poorly when compared to large sites with ample migration space in Georgia, South Carolina, and North Carolina's Pamlico Sound area largely due to lack of migration space (Figure 6.14). The greater than "Average" sites were largely clustered in South Carolina and Georgia, where sites had "Above Average" physical and "Above Average" to "Slightly Above Average" condition scores. As noted in the previous section, regardless of stratification, no sites scored "Far Above Average" for both physical and condition characteristics, with most "Far Above Average" and "Above Average" physical sites having "Average" condition characteristics.

The ten sites with the highest unstratified resilience scores are shown in Figure 6.15. The site highlighted in Figure 6.15 is in St. Helena Sound along the southern coast of South Carolina. This site featured a large marsh (47K acres, "Far Above Average" for the full region) with an expansive migration space (82K acres, "Above Average"). Approximately 64% of the marsh's upland edge was shared with migration space ("Above Average"). The site scored "Average" for condition with a low amount of developed upland edge (4%, "Slightly Above Average"), "Average" flow alteration, "Average" water quality, and a small estimated sediment deficit ("Above Average"). The site's buffer area was "Above Average" for physical characteristics and "Slightly Above Average" for condition with a large buffer area (27K acres, "Above Average"), substantial acreage of maritime highlands (1.5K acres, "Above Average"), "Average" landform diversity (4.5), “Average” natural cover (94%, which compared to other fully intact buffer areas, was only “Average”), and “Above Average” wetland connectedness.

The average tidal complex size of the top ten highest scoring sites for unstratified resilience was 18K acres (min = 5, max = 120K, median = 41, SD = 37K), and the complexes shared an average of 74% of their upland edge with migration space. These sites had an average migration space size of 34K acres (min = 252, max =87K, median = 7K, SD = 36K). Average condition characteristics included low development of the upland edge (1.34%), low sediment deficits (-8 mg/l), low to moderate flow alteration, and moderately good water quality index scores (0.75).

The estimated resilience scores stratified by coastal shoreline region are mapped in Figure 6.16, with the distribution of resilience classes by CSR shown in Table 6.7. Comparing the unstratified scores (Figure 6.15) to the stratified scores (Figure 6.16), one can see how stratification alters some of the scores either upward, as in southern North Carolina, or downward in parts of the Keys, by forcing sites to be in one of seven resilience classes in each CSR. This approach highlights those sites likely to be the most resilient in their respective region while also identifying those likely to be the most vulnerable.

Migration space size was significantly and positively correlated with the physical score, while the condition score had a small negative correlation with tidal complex size, and small positive correlations with both migration space variables (Table 6.8).

Figure 6.14. Estimated resilience score, not stratified by shoreline region. This map shows the estimated resilience score for the 6.5-foot sea level rise scenario. The map shows sites that are above (green) or below (brown) the mean for the project area. Sites in green scored greater than "Average" and are estimated to be more resilient based on their physical and condition characteristics. Sites in yellow are "Average." Sites in brown scored less than "Average" and are estimated to be vulnerable to sea level rise and climate change.

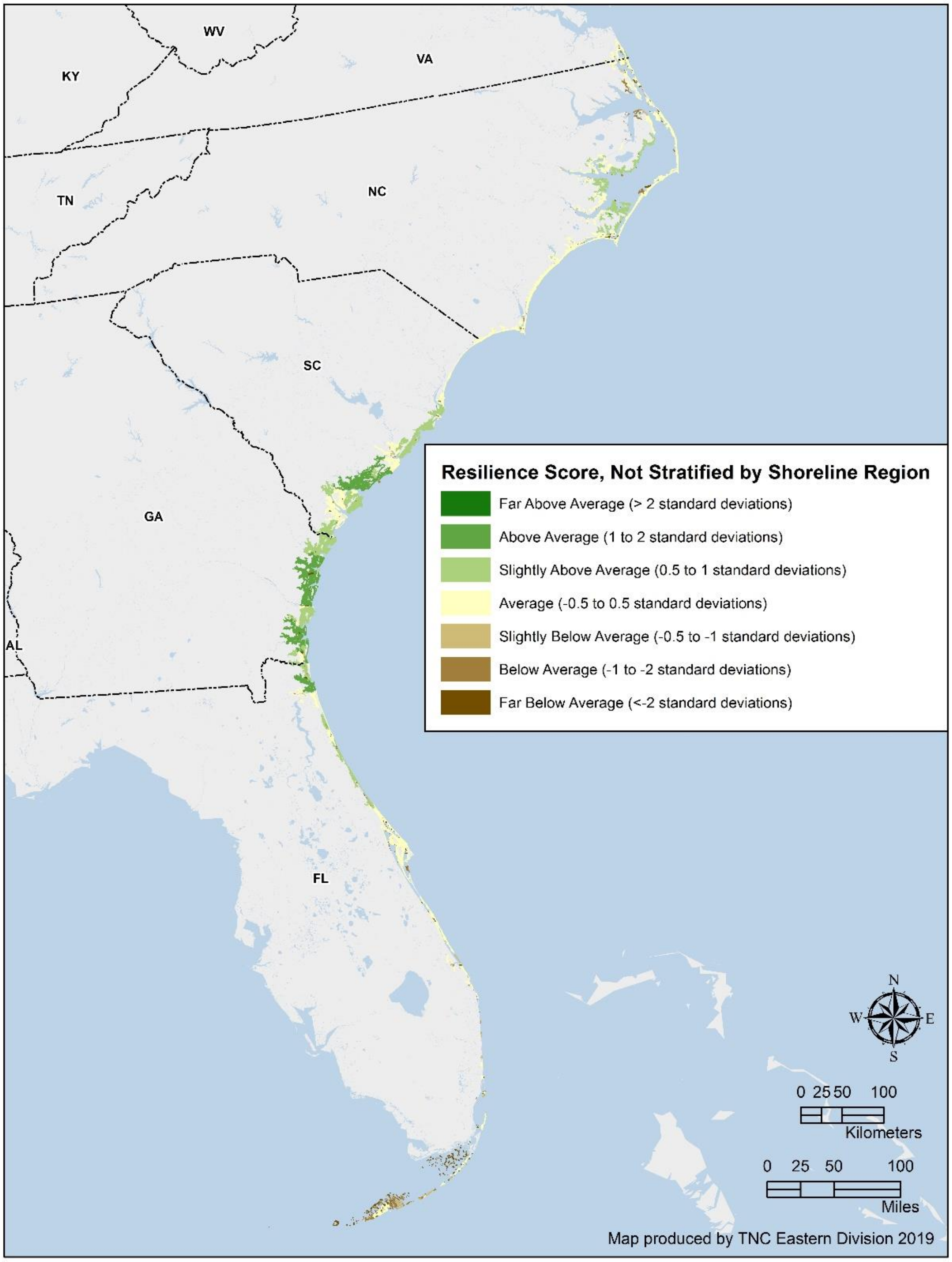


Figure 6.15. The top ten highest scoring sites in the full region, not stratified by shoreline region. The ten sites with the highest unstratified estimated resilience scores in the project area are shown. A tidal marsh in Helena Sound on the southern coast of South Carolina is highlighted in the map. The marsh was "Far Above Average" in size at 47K acres, and 64% of its upland edge was immediately adjacent to migration space. The migration space was "Above Average" in size at 82K acres. The site had "Average" water quality and flow alteration, low development of its upland edge, and a relatively small sediment deficit. The buffer area was "Above Average" in size, maritime highland acreage, and wetland connectivity, with mostly natural land cover and "Average" landform diversity.

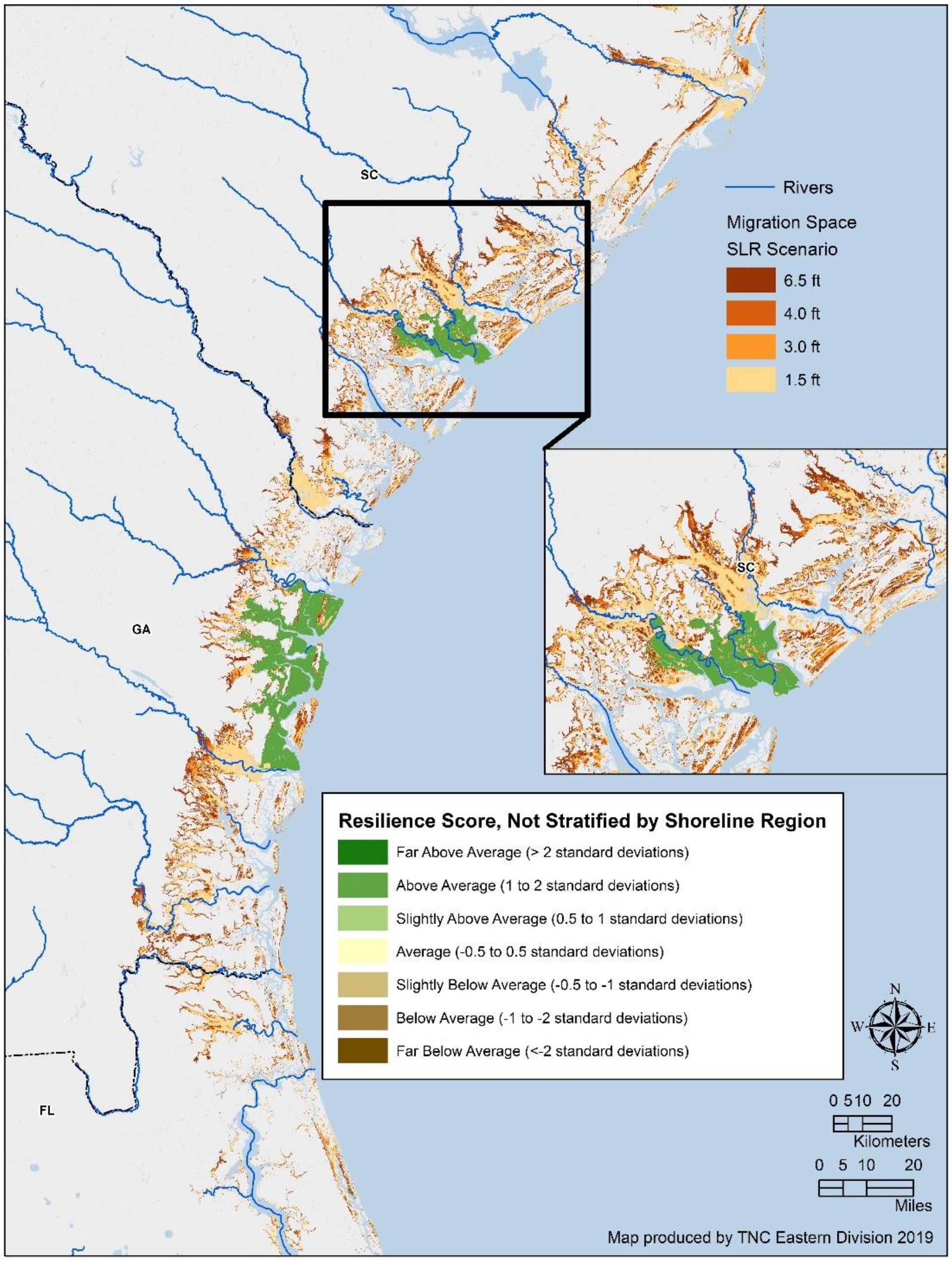


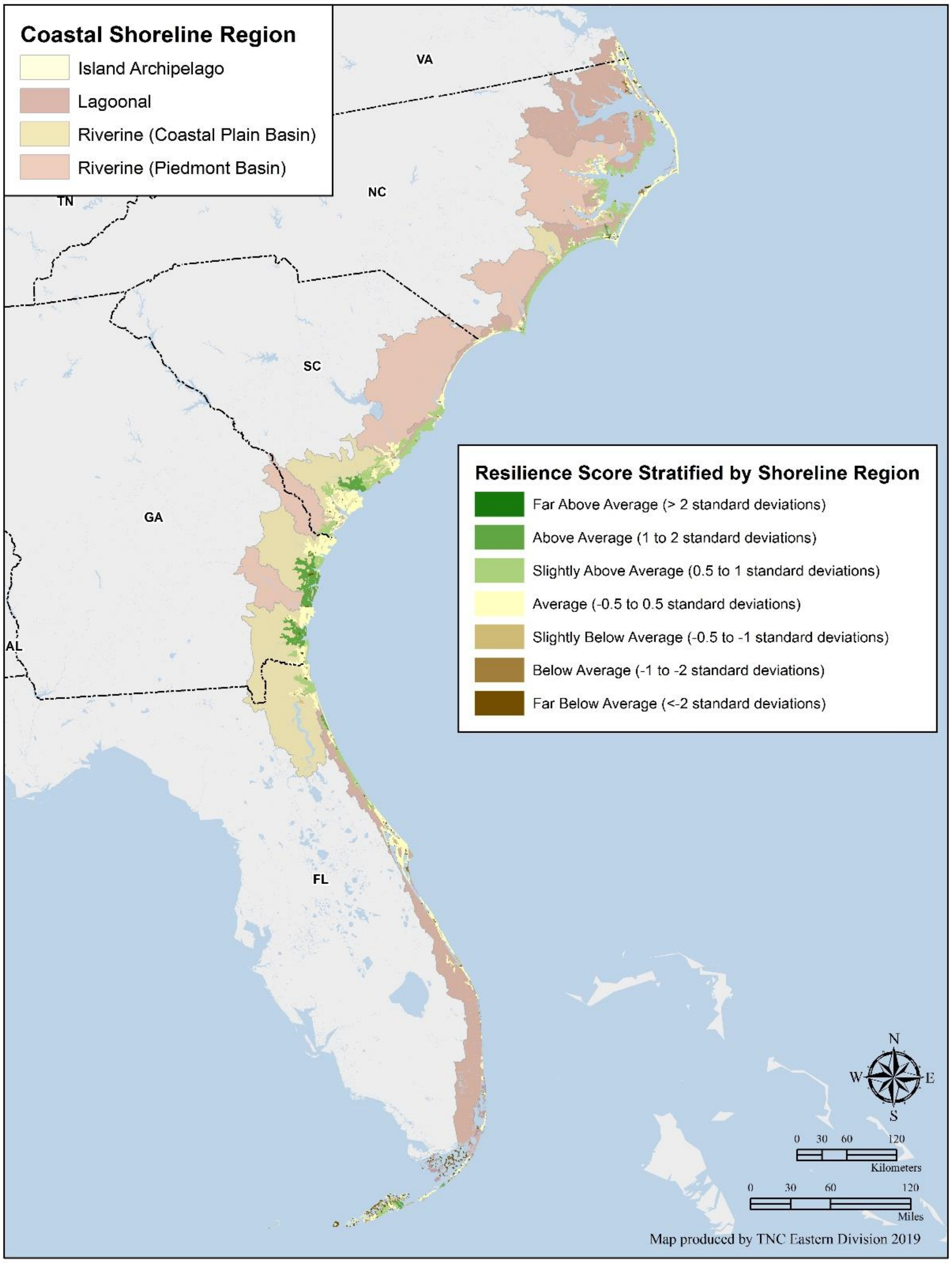
Table 6.7. Frequency of stratified resilience scores for the 6.5-foot sea level rise scenario.

Resilience Score	Island Archipelago	Lagoonal	Riverine (Coastal Plain)	Riverine (Piedmont Basin)
Far Above Average	0	0	0	0
Above Average	3	13	6	2
Slightly Above Average	2	32	18	20
Average	20	126	66	180
Slightly Below Average	27	51	25	58
Below Average	12	55	15	28
Far Below Average	159	261	38	15

Table 6.8. Relationship between resilience components and analysis unit size. Spearman correlation coefficients between the stratified physical, condition, and estimated resilience scores and the size (acres) of the tidal complex, geophysical migration space, and accessible migration space, after removing complexes with no migration space. A star indicates a significant ($p \leq .05$) relationship.

	Tidal Complex Size	Geophysical Migration Space Size	Accessible Migration Space Size
Physical Z-score	0.505*	0.770*	0.618*
Condition Z-score	-0.085*	0.144*	0.089*
Resilience Z-score	0.374*	0.719*	0.649*

Figure 6.16. Estimated resilience score, stratified by shoreline region. This map shows the estimated resilience score for the 6.5-foot sea level rise scenario. The map shows sites that are above (green) or below (brown) the mean relative to each CSR. Sites in green scored greater than "Average" and are estimated to be more resilient based on their physical and condition characteristics. Sites in yellow are "Average." Sites in brown scored less than "Average" and are estimated to be vulnerable to sea level rise and climate change.



Trends in Migration Space Size

All shoreline regions experienced an increase in average migration space from 1.5 to 6.5-ft. of sea level rise, except for the Island Archipelago region which showed a slight decline (Figure 6.17). The Coastal Plain Riverine region showed the largest increase of the CSRs, followed by the Lagoonal and Piedmont Basin Riverine regions with both showing small net increases, although the trend is very weak.

Linear regressions identified 644 sites with a statistically significant ($p \leq 0.05$) relationship between the sea level rise scenarios (1.5 – 6.5 feet) and migration space size. Of those sites with a significant relationship, 25% had increasing migration space, but the majority (66%) had no discernible trend (Figure 6.18). For the sites with a significant and increasing trend, the Lagoonal region had the greatest mean increase in size (+ 3749 acres), followed by the Coastal Plain Riverine region (+ 2806 acres, Table 6.9). Island Archipelago sites had the smallest mean decline in migration space size (-1 acres) likely due to the small amount of migration space in this region. The Piedmont Basin Riverine region had the largest mean decrease (-1114 acres) suggesting that while these sites are relatively resilient to low levels of SLR, available migration space declines after four feet.

Across all sites, 165 had migration space that showed an increasing trend, and these were awarded an additional 0.50 SD points to their estimated resilience score (shown in the dataset as “resilience score with trend.”) The remaining 479 sites with no significant positive relationships between migration space size and SLR scenario were not penalized. The map in Figure 6.19 shows the spatial distribution of the stratified resilience scores with the trend analysis incorporated. The award was restricted such that site scores could not increase by more than one resilience class (Table 6.10). After incorporating migration space trend, 114 complexes moved up a class (Figure 6.20, Table 6.10).

Figure 6.17. Mean migration space size by sea level rise scenario for each shoreline region.

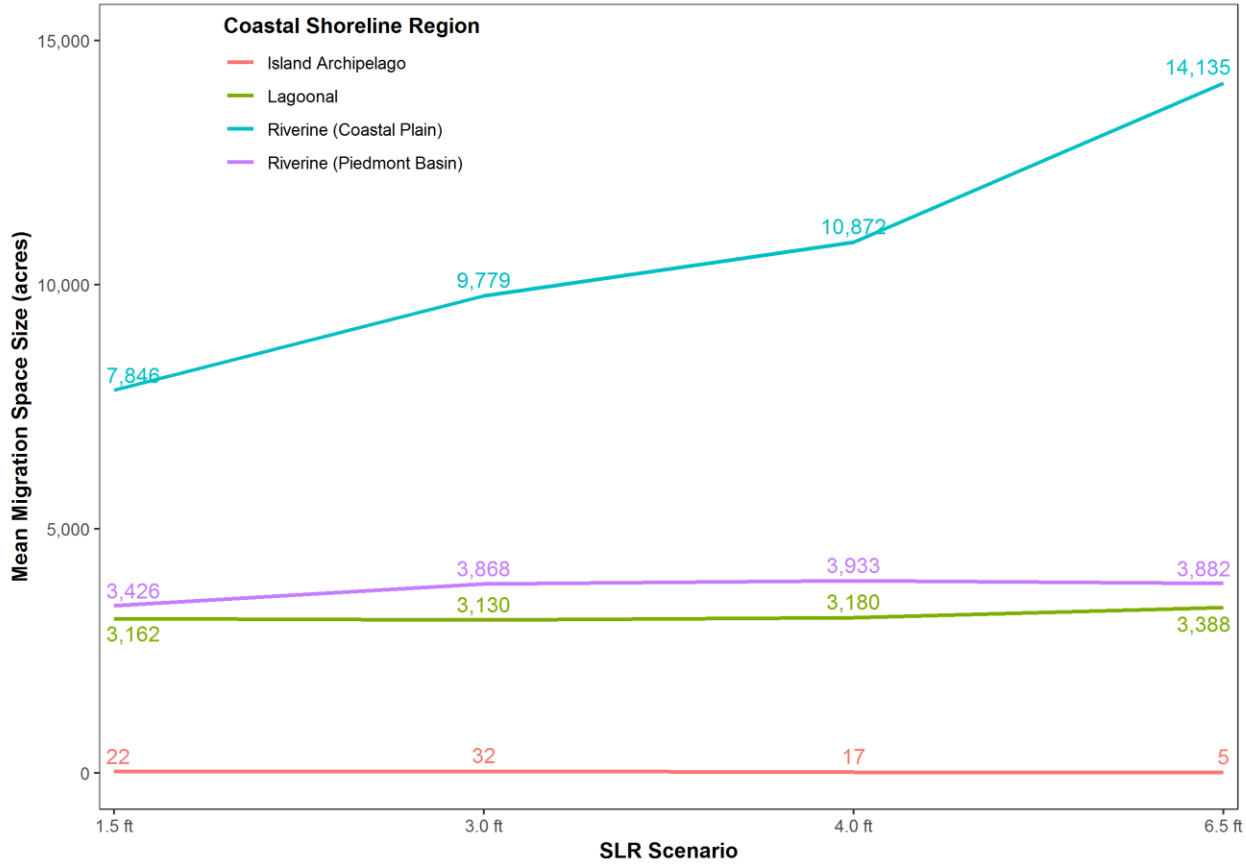


Table 6.9. Significant migration space trend by CSR. The number of sites with a significant ($p \leq .05$) relationship between sea level rise scenario ($\geq$ 1.5 feet) and migration space size. The mean change in migration space size (acres) for each CSR is shown in parentheses next to the count of sites in each category.

Trend direction	Island Archipelago	Lagoonal	Riverine (Coastal Plain)	Riverine (Piedmont Basin)
Decrease	3 (-1)	21 (-163)	7 (-12)	13 (-1114)
Increase	0	33 (+3749)	72 (+2806)	60 (+544)

Figure 6.18. Migration space size trend by shoreline region. The percent of sites in each CSR with an increasing or decreasing migration space trend is shown in the stacked bar plot.

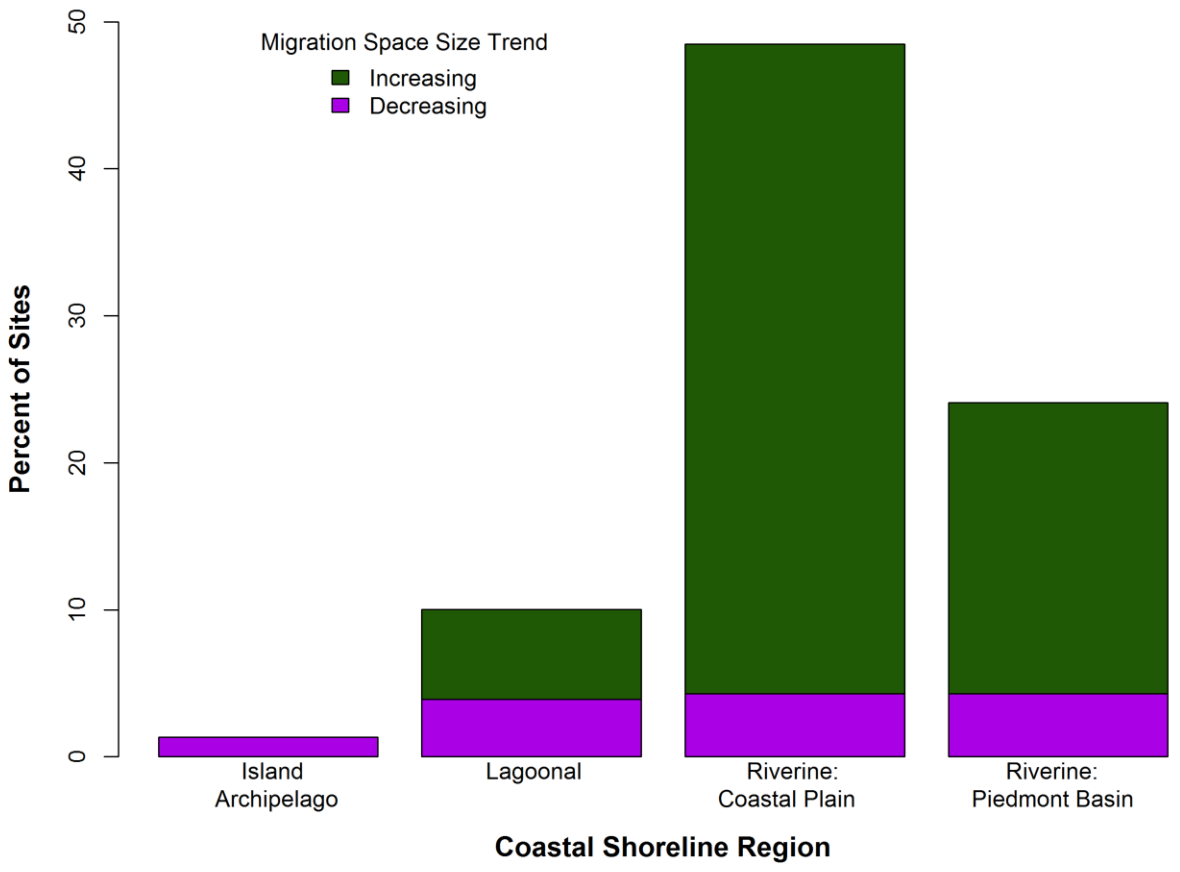


Table 6.10. The change in resilience class after incorporating the trend in migration space size. Sites whose migration space showed a significant increase ($p \leq .05$) from the 1.5 to 6.5-foot sea level rise scenario received an additional 0.50 standard deviation units to their score. The green boxes highlight the number of sites whose class improved when the migration space trend was incorporated.

	Resilience with Trend						
Resilience Class	**Far Above Average**	**Above Average**	**Slightly Above Average**	**Average**	**Slightly Below Average**	**Below Average**	**Far Below Average**
Far Above Average	0	0	0	0	0	0	0
Above Average	0	24	0	0	0	0	0
Slightly Above Average	0	28	44	0	0	0	0
Average	0	0	59	333	0	0	0
Slightly Below Average	0	0	0	24	137	0	0
Below Average	0	0	0	0	3	107	0
Far Below Average	0	0	0	0	0	0	473

Table 6.11. Frequency of stratified resilience scores with migration trend for the 6.5-foot sea level rise scenario.

Resilience with Trend Score	Island Archipelago	Lagoonal	Riverine (Coastal Plain)	Riverine (Piedmont Basin)
Far Above Average	0	0	0	0
Above Average	3	21	20	8
Slightly Above Average	2	33	31	37
Average	20	121	49	167
Slightly Below Average	27	48	15	50
Below Average	12	54	15	26
Far Below Average	159	261	38	15

Figure 6.19. Estimated resilience score with migration space trend. This map shows the estimated resilience score after incorporating the trend in migration space size for the 6.5-foot sea level rise scenario. Sites whose migration space showed a significant increase ($p \leq 0.05$) from the 1.5 to 6.5-foot SLR received an additional 0.50 standard deviation units to their score.

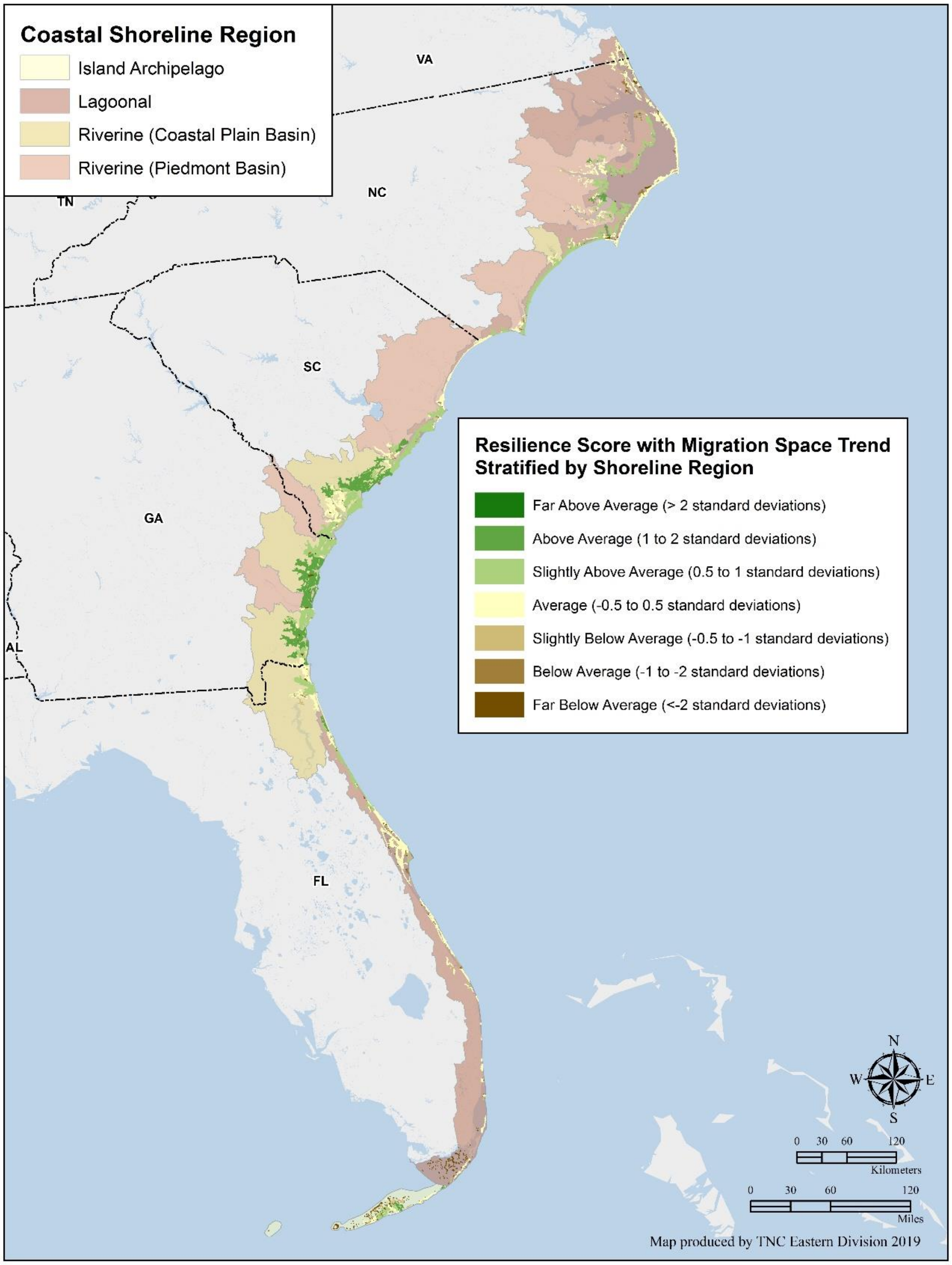
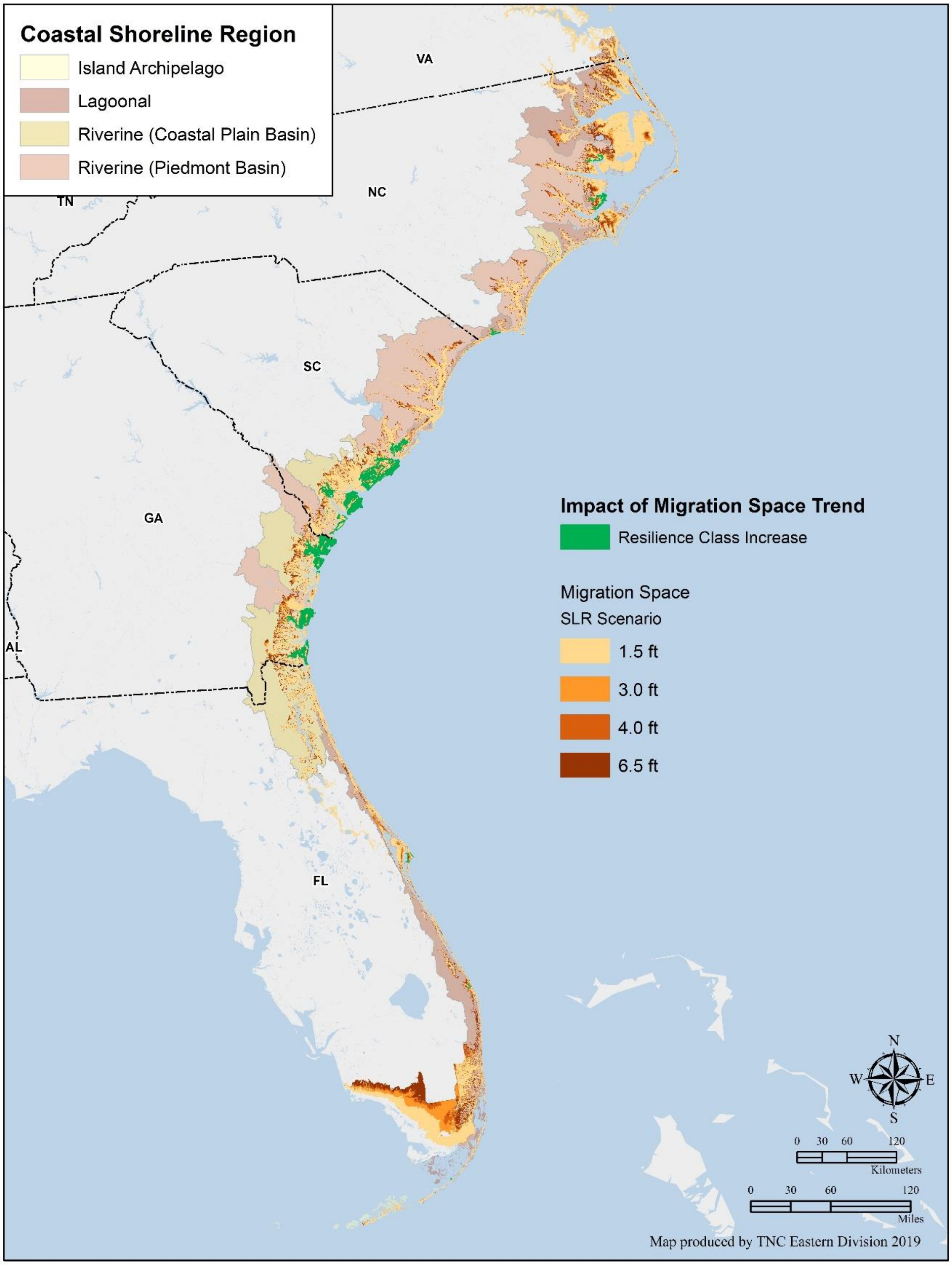


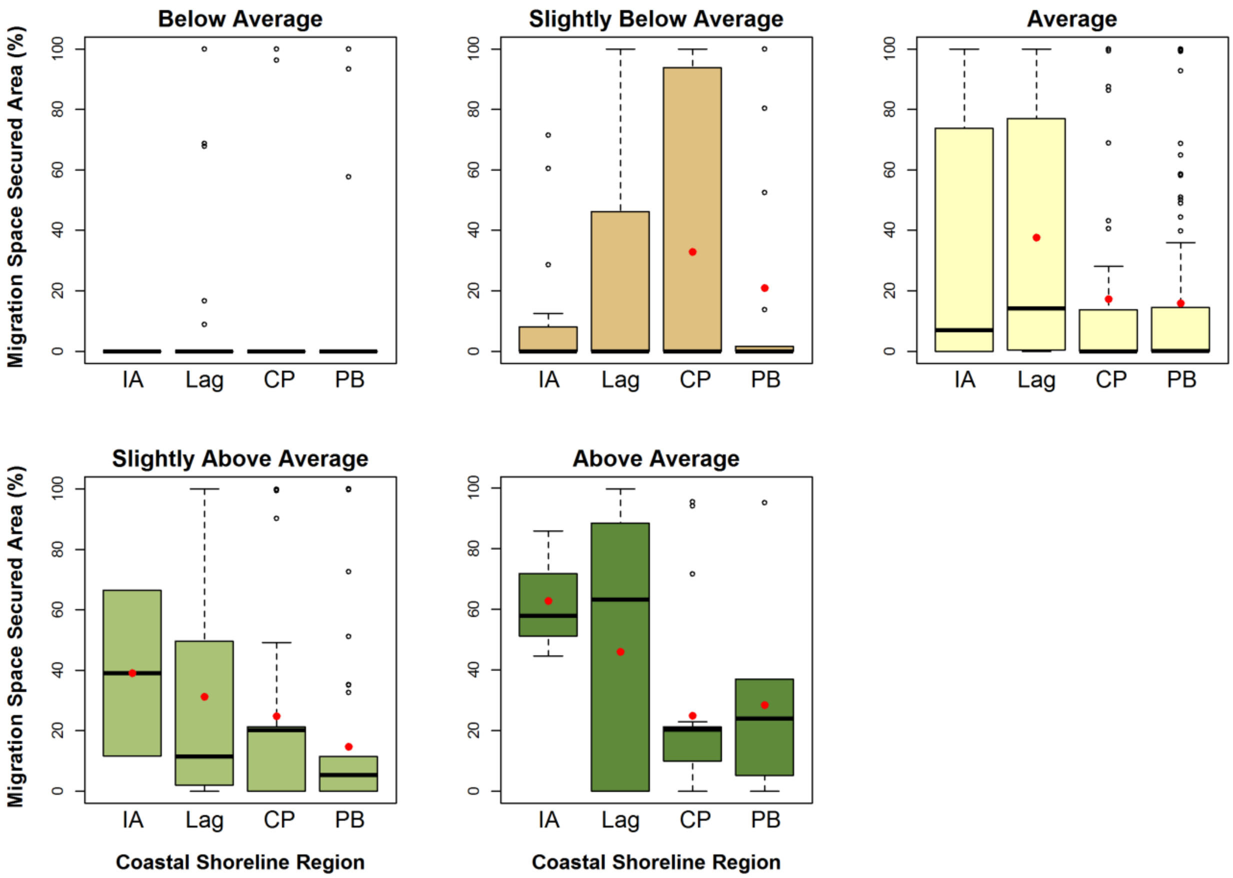
Figure 6.20. Estimated resilience class changes after incorporating migration space trend. This map shows the sites whose estimated resilience class increased (n=114) after incorporating the increasing trend in migration space size for the 6.5-foot sea level rise scenario.



Migration Space Securement

The amount of a site's total migration space that was already secured against conversion to development (GAP status 1-3) varied by CSR and resilience category, with the Island Archipelago and Lagoonal sites having the highest percentage of secured resilient migration space (Figure 6.21). The worst scoring sites, "Far Below Average," are not shown in Figure 6.21 as these sites had very little, if any, migration space, thus this category always had the lowest average percent secured.

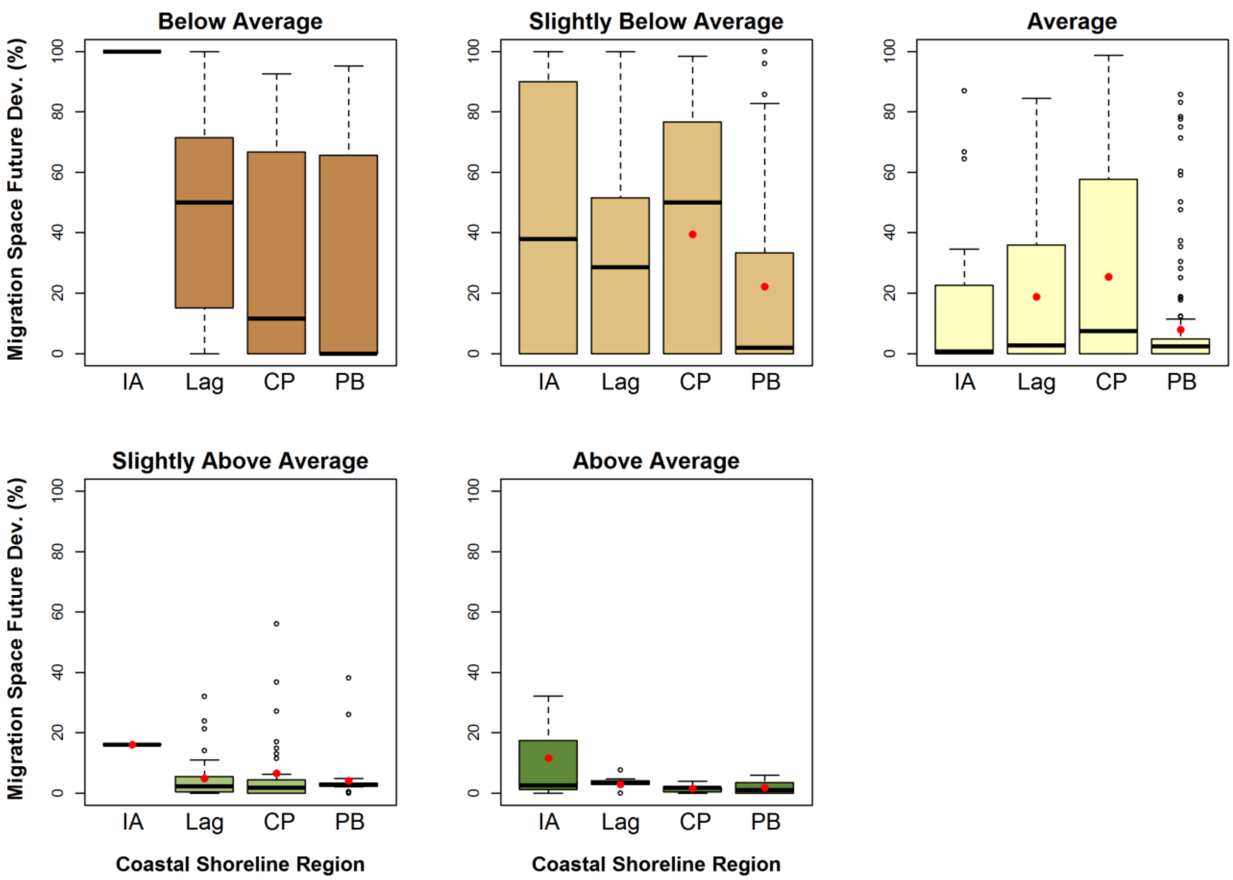
Figure 6.21. Amount (%) of migration space in permanent protection for each CSR by estimated resilience class. A boxplot with the distribution of migration space securement (%) by CSR is shown for each estimated resilience class. The mean percent secured is denoted by a red circle. The resilience classes are shown using our standard z-score color palette.



Migration Space and Future Development

The migration space of more vulnerable sites is predicted to be at greater risk of development than the migration space of resilient sites, likely due to the vulnerable sites being located in or near more fragmented and urban landscapes (Figure 6.22). For the most part, future development is most likely to occur in the migration space of sites that scored less than "Average." Unfortunately, the limited migration space for resilient sites in the Island Archipelago is at greater risk of development than the migration space of resilient sites in other coastal regions.

Figure 6.22. Amount (%) of migration space predicted to be developed by 2100 for each CSR by estimated resilience class. For each CSR, the boxplot shows the distribution of migration space future development (%) by resilience class with the mean denoted by a red circle. The resilience classes are shown using our standard z-score color palette.



CHAPTER

7

DISCUSSION

In this study, we estimated the relative resilience of individual coastal sites based on the amount and quality of each site's migration space and buffer area. The results identify the places that could potentially retain species and ecological functions under rising sea levels because they have both the physical characteristics needed to allow the tidal complex to migrate and the conditions needed to support and facilitate such migration. Sites that ranked high for resilience typically: 1) had extensive, diverse, unfragmented, and easily-accessed migration space; 2) were relatively well supplied with sediment and high-quality freshwater; and 3) were surrounded by a natural buffer area. These sites offer more options for rearrangement and continued productivity than sites that lack these characteristics, and we hypothesize that they will be relatively more resilient to sea level rise. Although there is ample and accumulating evidence demonstrating that these conditions can lead to migration of the tidal complex and the development of new coastal habitats, we do not know for certain that this will occur, nor do we know the specifics of how each site will adapt and transform.

A recent study of long-term trends in a Gulf of Mexico tidal marsh found that at a regional scale, tidal marsh migration was able to outpace sea level rise. In the Big Bend area of Florida's Gulf Coast, Raabe and Stumpf (2016) compared nineteenth century topographic sheets with satellite imagery and found marsh migration led to a net gain of 25,946 acres (105 km^2) of marsh, a 23% increase over a 120-year period during which the study region experienced increased tidal amplitude and an average SLR rate of 1.5 mm/year. While 10,626 acres (43 km^2) of tidal marsh were lost to open water at the shoreline, the expansion of tidal habitats into adjacent forested lowlands offset this loss by a factor of three. The authors conclude that despite low sediment inputs and increasing sea levels, this region's coastal marshes were able to expand because they exist in a relatively undeveloped landscape with limited hydrologic modifications and have access to a large and intact migration space. The authors also note some additional characteristics that may have increased marsh resilience, including a low-energy environment and an underlying karst substrate that is less prone to erosion than unconsolidated sediments. Similar to the authors' conclusions, our Gulf of Mexico regional assessment identified the Big Bend tidal complex as likely to be resilient due to its large and accessible migration space and relatively good condition (notably scoring low for sediment inputs).

Another recent analysis examined tidal wetland changes in the Chesapeake Bay region of the US, an area experiencing some of the highest relative SLR rates in the world (Schieder et al. 2018). The results showed that since the late 1800s, the study region experienced a small net gain of 1,700 acres (7 km^2) of marsh, a 2% increase, due primarily to marsh migration into adjacent lowlands. While there was a net gain across the region, marsh changes were quite variable by map unit (individual topographic sheet). For example, in the Cape Charles, Virginia map unit, roughly 90% of marshes were lost, but the Potomac River, Maryland map unit saw a 400% increase in marsh area. In addition, some areas, such as the Blackwater River, had low quality topographic sheets and were unable to be examined in the analysis. Using projections for the entire region, the authors conclude that roughly 100,000 acres (400 km^2) of new marsh have been created from the drowning of adjacent uplands since the late 1800s. Marsh migration rates were weakly correlated with slope and development of the adjacent migration space, suggesting other processes also likely contributed to this expansion.

A look at the Blackwater National Wildlife Refuge, a well-studied site within the Chesapeake Bay region, shows how local site-specific conditions and management can impact marsh migration. Tide gauges in this region show that sea level has risen by over a foot since 1938, and analysis of aerial photos documented a corresponding loss of 5,028 acres (20 km^2) of tidal marsh in the refuge over the subsequent 68-year period (Lerner et al. 2013). During the same period, the refuge gained 2,949 acres (12 km^2) of new marsh through upslope migration of tidal marsh into the migration space that became available as sea levels rose. Although these observations confirm that the tidal complex is migrating and new tidal marsh is forming, the concern is that the emerging area of new marsh is not keeping pace with losses of existing marsh and could result in a net loss of both marsh habitat and associated saltmarsh-dependent birds.

Marsh loss in the Blackwater NWR was primarily due to inundation, but it was exacerbated by nutria (*Myocastor coypus*), a large semi-aquatic rodent that consumes vegetation and creates erosion-promoting channels (Lerner et al. 2013). Similarly, in South Carolina, vegetation-feeding periwinkle snails (*Littorina littorea*) have been found to transform healthy marsh to mudflats in a matter of months under a regime of increased inundation, and the consequent lack of snail predators such as blue crabs and turtles. Increased periwinkle feeding may be a factor in salt marsh loss from South Carolina to Texas since 2000 (Brown University, 2005). Managers emphasize that at Blackwater, strategies aimed at facilitating marsh migration had to be complemented by strategies to slow marsh loss such as managing herbivores and/or spreading thin layer sediment across the marsh surface. A recent study of marsh bird occupancy at the forest-marsh interface of tidal marshes in the Albemarle-Pamlico Peninsula of North Carolina highlights the potential of prescribed fire as a strategy to facilitate marsh migration (Taillie & Moorman, 2019). Fire appeared to increase bird diversity as the authors found that the occupancy of clapper/king rail (*Rallus crepitans/elegans*) was greater at sites that had experienced high fire frequency in the past decade, and the occupancy of all focal taxa was higher in areas that had vegetation characteristics consistent with fire effects, including lower density of herbaceous plants and shorter woody vegetation.

One method of potentially slowing wetland loss is to artificially supply sediments to subsiding marshes. Known as thin-layer sediment application, this method aims to help subsiding marshes accrete sediment by spraying a sediment slurry under high pressure over the marsh surface. The technique was developed in Louisiana, which leads the United States in coastal wetland loss, and has since been applied at many sites on the Gulf and Atlantic coasts. The ability of this approach to prevent loss appears uncertain, but some studies show promising short-term results (Ray, 2007). A two-year study on Masonboro Island in North Carolina (Leonard et al. 2002; Croft et al. 2006) found that deteriorated marsh plots increased their elevation by 8.5 cm after sediment treatments, while treated reference plots increased by 10 cm. They found a corresponding increase in the mean stem density of *Spartina sp.* across all plots. In Venice Louisiana, sites that received moderate amounts of dredged material (5-12 cm) still had better vegetative growth and soil conditions than reference marshes seven years after the treatment (Mendelssohn & Kuhn, 2003). Other studies in Georgia (Reimold et al. 1978) and Louisiana (Cahoon & Cowan, 1987; LaSalle, 1992) have indicated that response is sensitive to depth of deposition, slope of the marsh surface, wave action, timing of storm events, and time since application. A recent global study assessing the ability of coastal wetlands to build up vertically by sediment accretion or laterally by migration, found that the resilience of global wetlands is primarily driven by the availability and accessibility of migration space (Schuerch et al. 2018). Collectively, the studies suggest that thin layer sediment applications are unlikely to offset the persistent long-term effects of sea level rise but may be useful in alleviating short-term marsh losses or in facilitating the migration of marshes into their migration space. Accordingly, the Tampa Bay Regional Council, in conjunction with EA Engineering, has suggested that an initial target site for thin-layer spreading be areas where marsh migration is not possible (EA Engineering, 2018).

Our results are based on site level attributes that could be mapped consistently at a regional scale. This approach allows for accurate comparisons among sites but can limit the utility of the dataset in making fine-scale, within-site decisions. We recommend the study be used as a screening tool for exploring the region, making decisions among sites, and grasping the magnitude and spatial distribution of the SLR challenge. The data sets that underlie this study all have a degree of error even though they were carefully reviewed by our team and inspected by our steering committee to ensure consistency. Once a planner decides where to work, local data and field surveys will be necessary before proceeding.

Our goal was to make this study as objective and transparent as possible, but subjectivity was inevitably introduced into the analysis at several points. Foremost among these was the relative weighting of individual resilience factors with respect to their influence on resilience. Although there was strong agreement among our team of coastal experts, we decided to explore the sensitivity of the results to the weighting scheme and to the inclusion or exclusion of certain datasets by running the data with different weighting schemes and comparing the results. We found that many of the same sites continually emerged in the same order along the resilience spectrum, especially at the two ends. Presumably, the physical and condition characteristics of the resilient sites were so distinct from the vulnerable sites that the patterns were detected even with variable or imperfect data (e.g., large migration space in natural setting versus no migration space and hemmed in by development). Sites where the subjective schemes had the most effect where those that scored close to "average" because differences between or among similar sites were more easily influenced by small data changes.

Going forward, we plan to integrate the results of this study with our terrestrial resilience map and web tools (Anderson et al. 2016). The terrestrial study identified climate resilient sites for land conservation, but did not address the coastal zone, which was masked-out on the final maps. Both studies were designed to help users make informed decisions when facing large uncertainties about climate and SLR. However, they are not intended to replace basic conservation principles such as the importance of coastal reserves, reducing direct threats, managing land appropriately, and using natural resources in a sustainable way.

We expect the coastal sites to change dramatically over the next century with our familiar tidal marsh and tidal flats migrating onto the adjacent lowlands and much of the existing marsh converting to open water. Identifying those places where conservation actions could succeed and managing those sites to adapt to change is a first step in sustaining the diversity and natural services of our coastal systems. Further, the results from this study can be used to identify potential sites for restoration, defined as sites that have the physical characteristics needed to accommodate marsh migration but that score low for their condition characteristics. Users can explore the data to see if the low condition score indicates a lack of sediment, poor water quality, anthropogenic barriers to marsh migration, and/or freshwater flow alteration that could be improved by strategies aimed to address the source of the problem or problems at a particular site. We hope that this study and the accompanying tools prove useful to planners and conservationists in identifying where to focus conservation action, and what strategies to employ.

CHAPTER

8

ROLLOUT MEETINGS & FEEDBACK

Rollout Meetings

To facilitate the use of this study for better conservation planning, we have been communicating the results through a variety of channels. We created an online mapping tool, a strategy story map, and a new web page to highlight the study on TNC's Conservation Gateway. The report and final datasets for all four scenarios (29 datasets in all) are posted on the web page along with full metadata. In the next few months, we will be adding the results to our existing Resilient Land Mapping tool (http://maps.tnc.org/resilientland/). The mapping tool is designed to support land acquisition, management, and restoration decisions for conservation under a changing climate. The tool allows web users to zoom-in to an area of interest and view the results in detail while comparing them with satellite images or topographic maps. Users can import a shapefile or draw a polygon around areas of interest and generate statistics about the area related to its climate resilience. The tool is used by The Nature Conservancy for making decisions about land acquisition and management and is also used by over one hundred NGOs and the USFWS for similar reasons. We will also be posting the data on TNC's shared forum for community-based coastal conservation: http://coastalresilience.org

In addition to the tools and written materials, we completed five web-based trainings and three face-to-face workshops, with three more in-person meetings and two web-based meetings scheduled for November 2019 and January 2020. To date, these workshops have attracted over 100 participants, including members from 11 state agencies, five federal agencies, ten local governments, 24 NGOs, 12 academic or funding institutions, and 11 engineering firms.

In these forums, we presented the findings, taught users how to interpret the project results and use the web tools, explained the significance of local resilient sites, highlighted local vulnerabilities and threats, and convened a dialog around the conservation and management of these coastal resources. The meetings were led by TNC regional staff in conjunction with state-based TNC staff who will follow up with local organizations and actions. Invites and selection of participants was done by local staff by identifying stakeholders likely to incorporate this information into their planning. Selected stakeholders included city and/or town planners, local land trusts, and state agency staff plus a smattering of academic leaders, funding institutions, federal agency staff, and engineers.

The objectives of the meetings were to ensure that local entities: 1) became familiar with the study and products; 2) understood the value and significance of their coastal resources; and 3) discussed potential strategies and actions needed to sustain their coastal systems. We received helpful feedback on the project deliverables and web tools which we incorporated into the final project data package, web mapping tool, and a story map to identify conservation and restoration strategies to sustain the natural benefits of coastal habitats in the face of rising sea levels (see "Conservation, Restoration, and Management Strategies" section for more details). Additionally, we facilitated discussions focused on innovative policy actions such as prioritizing sites for repeat flooding buy-out programs if they fall within important migration space areas. We also had broad discussion about the obvious vulnerabilities of economically-stressed communities situated within the sea level rise zones. We hoped to motivate local communities to develop a coastal management plan based on resilient coastal sites, but we have follow-up work to achieve that goal.

A sample agenda from the South Carolina workshop is included below (Figure 8.1); other workshops had a very similar structure. This workshop was in Charleston, South Carolina and was cosponsored by the Land Trust Alliance and the Open Space Institute. The agenda included a presentation of the study, interactive time with the web tool, and case studies on the use of buy-outs and community rating systems as conservation tools from the City or Charleston, Ducks Unlimited, The Nature Conservancy, and the Kennebec Estuary Land Trust.

Figure 8.1. Sample rollout meeting agenda. Agenda from the Charleston, South Carolina workshop about coastal land protection in a changing climate, held June 4, 2019.

Land Trust Alliance
Together, conserving the places you love

The Nature Conservancy

OPEN SPACE INSTITUTE

Staying Above Water: Land Protection in a Changing Climate

Supporting a diversity of plants and wildlife in a changing climate

June 4, 2019, 10 AM to 3:00 PM

The School House, 720 Magnolia Road, Charleston, South Carolina

Workshop Goals

- Understand underlying concepts of coastal resilience.
- Gain experience with online mapping tools.
- Understand where to protect coastal land in the face of rising sea levels and storm surges.
- Explore how to consider land use planning and zoning in the context of changing coastal habitats.
- Learn how others are integrating coastal resilience into land protection decisions.

Meeting Agenda

10:00 am	Welcome, introductions and workshop goals: Maria Whitehead, Open Space Institute & Kelly Watkinson, Land Trust Alliance
10:30 am	Characteristics of Coastal Resilient Sites: Mark Anderson, The Nature Conservancy
11:30 am	Coastal adaptation and land protection in South Carolina • Community Rating System Explorer for prioritizing land protection: Liz Fly, The Nature Conservancy • Buyouts and managing land assets: Stephen Julka, City of Charleston • The role of land trusts in buyout acquisitions: Ducks Unlimited
12:15 pm	Lunch Break
1:00 pm	TNC Coastal Viewer & Interactive Exercise: Mark Anderson, The Nature Conservancy
2:00	Application and Implementation: Ruth Indrick, Kennebec Estuary Land Trust
2:40	Question & Discussion
3:00 pm	Adjourn

Workshops & Webinars

We completed three workshops and we have three more scheduled. Similarly, we have completed three webinars and have at least two more scheduled.

<u>Completed Workshops:</u>
Low Country Conservation Workshop: May 2019
South Carolina Resilient Coastal Sites Workshop: June 2019
Gulf Coast Resilient Coastal Sites Workshop: September 2019

Upcoming Workshops:
Georgia Climate Conference: November 2019
Southeast Climate Adaptation Science Center Symposium: November 2019
Florida Resilient Coastline Program: 2020

Completed Webinars:
South Atlantic Landscape Conservation Cooperative: October 2018
Mobile Bay National Estuary Program Implementation Committee: June 2019
North Carolina Natural and Working Lands Coastal Habitat Subcommittee: July 2019

Upcoming Webinars:
South Atlantic Landscape Conservation Cooperative: November 2019
The Nature Conservancy Southeast Field Offices: Anticipated December 2019

Participants

Through the outreach meetings and webinars, we reached participants from a wide variety of organizations, including:

State Agencies

- ACE Basin/SC DNR
- AL DCNR: Division of Marine Resources
- AL DCNR: State Lands
- Alabama Dept. of Enviro. Mgmt.
- Alabama DOT
- Louisiana DNR
- Louisiana Wildlife Federation
- NC Dept. of Environmental Quality
- NC Division of Marine Fisheries
- SC Dept. of Natural Resource

Federal Agencies and Programs

- Mobile Bay National Estuary Program
- Environmental Protection Agency
- US Department of Agriculture
- US Fish and Wildlife Service
- Weeks Bay National Estuary Research Reserve

City and Municipal Districts

- Baldwin Co Soil and Water Cons.
- Beaufort County Community Dev. Dept.
- Beaufort County Open Land Trust
- Charleston County Zoning & Planning Dept.
- City of Charleston, Office of Resilience & Emergency Mgmt.
- City of Mobile
- City of Orange Beach
- City of Spanish Fort
- Lowcountry Council of Governments
- Mobile County

NGO's

- 3MC Partnership
- AL Coastal Foundation
- Audubon
- Coastal Conservation League
- Conservation Voters of SC
- Defenders of Wildlife
- Ducks Unlimited
- East Cooper Land Trust
- Edisto Island Open Land Trust
- Florida's Nature Coast Conservancy
- Galveston Bay Foundation
- Gulf Coast Partnership
- Land Trust Alliance
- Land Trust for Louisiana
- Lowcountry Land Trust
- Mississippi Wildlife Foundation
- Mobile Baykeeper
- Open Space Institute
- Pee Dee Land Trust
- Pelican Coast Conservancy
- Southern Environmental Law Center
- Tall Timbers
- The Conservation Fund
- The Nature Conservancy
- The SC Environmental Law Project
- Trust for Public Land
- Winyah Rivers Alliance

Engineering Firms

- Allen ES
- Anchor QEA
- Ecology & Environment
- Geosyntec
- GMC
- Moffatt & Nichol
- Payne Environmental
- Stantec
- Tetra Tech
- Thompson Engineering
- Volkert
- WOOD

Other

- Clemson University, Dept. of Forestry & Environmental Conservation
- Mobile Area Water and Sewer System
- National Fish and Wildlife Foundation
- Nicholas Institute for Environmental Policy Solutions -Duke University
- Northern GOM Sentinel Site Cooperative;
- Western Carolina University

Incorporating Feedback

Conservation, Restoration, and Management Strategies

Datasets

Through the meetings and webinars, we received substantial feedback on the project's products and tools. In response, we developed several additional data layers to help users prioritize the migration space of resilient coastal sites. For each migration space unit, we first assigned the highest resilience score of all the tidal complex units with which it was associated. We pulled out migration space areas with above average resilience scores (>0.5 SD) and then examined their size class distribution. We also calculated additional attributes for these areas such as percent of the migration space permanently protected from development, percent expected to be developed by 2100, and population density of urban areas within 1-km. Many different queries can be run with these resilient migration space attributes. For example, a user might want to find all resilient migration space units over 1,000 acres in size that have a high percentage of area predicted to be developed by 2100. We also incorporated the results of various queries into the strategies story map (see section below) and a subset are included in the project web tool to illustrate ways the data can be used to answer different questions.

The focus of many restoration and protection efforts will be on the migration space, but feedback indicated that some users would prefer to work with smaller tidal complex units. To calculate results for a whole set of new tidal complexes was not feasible, but we were able to break the tidal complexes into smaller units so users can work with these if they desire. These units are still linked to their larger unit via a common ID and can be used to identify smaller marsh areas that are associated with large unsecured migration space units for example. We incorporated these smaller units into the final data package and web map tool.

Conservation Strategies Story Map

Of primary interest to the stakeholders was how the results could be used to address specific questions or to develop place-based strategies that address marsh migration. In response to these concerns, and to feedback from the meetings, we developed some new data and a conservation strategies story map that demonstrates different ways the results can be used to address a range of issues and questions. The story map is available here: http://arcg.is/0Wym1L

In the story map, the strategies are grouped into two sections as follows:

1) Conserving Coastal Systems: Land Protection, Future Development, Management, Restoration, Productivity, Long-Distance Migrations, Fragmenting Roads
2) Investing in Natural Solutions to Protect People and Nature: Urban Areas, Impoverished Areas, Repetitively Flooded Areas

Here is a brief summary of the content under each heading.

CONSERVING COASTAL SYSTEMS

Prioritizing Land Protection

Due to their outstanding value for people and nature, many of our coastal marshes are protected by public or private conservation. Unfortunately, land immediately surrounding the marsh is often unprotected, or already developed, leaving nowhere for the marsh to migrate as sea levels rise. By focusing land acquisition on each site's migration space – land that could receive and support coastal habitats under rising seas - we can provide a stage on which future habitats can adapt and thrive. The story map shows resilient coastal sites (> "Average" score) and their migration space overlain by a dataset of lands permanently protected from conversion.

Influencing Future Development
Development is perhaps the most permanent threat to natural systems. When development occurs on the boundary of a coastal marsh, or directly in the marsh's migration space, it leaves nowhere for the marsh to migrate as the sea level rises. We estimated the risk of migration space loss for each coastal site's migration space using a model that predicts future development. The story map shows future urban land projected to occur in the unprotected migration space of resilient marshes by 2100.

Identifying Restoration Priorities
Even in sites with relatively large amounts of migration space, the ability of habitats to migrate may be undermined by four common problems: 1) barriers to upland marsh migration, 2) low sediment inputs, 3) poor water quality due to excess nutrients like nitrogen and phosphorus, and 4) altered freshwater flows. Each of these conditions can be improved by local conservation and management efforts that increase a system's resilience. The story map shows coastal sites with greater than “Average” physical properties but “Average” or less than “Average” condition characteristics, and the color of the tidal complex indicates the most pressing condition issues of those we measured.

Maintaining Coastal Productivity
Acre-for-acre, tidal marshes are among the most productive ecosystems known. The current productivity of a coastal site may be estimated from the extent of its vegetated habitats. To estimate the future productivity of coastal sites, we determined if a site’s migration space was expected to be larger, smaller, or the same size as the existing tidal complex. The story map shows sites predicted to have decreased productivity (migration space area is smaller than current marsh) and sites expected to have increased productivity (migration space area is the same size as the current marsh or larger) for 6.5 feet of sea level rise.

Locating Long-Distance Marsh Migrations
In some coastal sites, the migration space available to the current marsh is mostly concentrated at one end. In effect, the current marsh “disappears,” and new marsh establishes in a completely different place linked only by a small connection. If the physical and condition characteristics are good, the marsh may still be ranked as resilient, because it has somewhere to go, not because it will be there in the future. The story map classifies current marshes by that distance to show which marshes have relatively longer distances to migrate. For each site, the tidal complexes are divided into smaller pieces that allow a user to see which marsh areas are closest to a particular migration space area. This dataset (disaggregated tidal complexes) is available in the final data package.

Finding Potentially Fragmenting Roads
Our measure of geophysical migration space includes the impacts of development and major roads, but some of that might not be accessible if you included all major, secondary, and residential roads as well as railroads. We created a metric of "accessible migration space" and compared it to the total geophysical migration space. This story map shows roads by the potential gain in accessible migration space that mitigation or retirement of the road might provide, with the important caveat that the road may not actually split the migration space into different units or may be completely inundated in the future and not a barrier to migration.

INVESTING IN NATURAL SOLUTIONS TO PROTECT PEOPLE AND NATURE

Nature-based solutions use natural systems and/or processes to address hazards such as storm surge, flooding, and erosion. These approaches can lead to both a healthier environment and stronger communities by reducing flood risk and flood damages, improving water quality, and enhancing habitat for wildlife, recreation, and tourism. For more information on Natural Solutions, visit TNC's Coastal Resilience Program and Naturally Resilient Communities.

Urban Areas
The coastal zone is the most densely populated area of the US. Estimates suggest the US coastal population will reach almost 134 million by 2020, exposing more of the population to the detrimental impacts of intense storms such as Hurricane Sandy. In some areas, salt marshes, beaches, and other natural ecosystems can help buffer human communities from flooding and storm impacts, providing a natural solution for people that also ensures habitat for plants and wildlife. The story map shows resilient coastal sites and their migration space areas that are within 1 km of urban areas. Natural coastal protection is site-dependent and local conditions should always be evaluated, but this screening analysis can identify promising areas for more detailed investigation.

Impoverished Areas
Numerous studies have highlighted the disproportionate impact that climate change and sea level rise are expected to have on vulnerable populations in the Southeastern US. Economically disadvantaged communities face increased challenges in preparing for, responding to, and recovering from climate disasters. It is harder for people in poverty to retreat from areas expected to be inundated, and vulnerable communities may need additional resources to protect and manage future marsh areas to accommodate rising seas. The predominance of "heirs' property" designations for land owned by African Americans without legal title in low-income communities in the South poses another challenge for populations vulnerable to sea level rise. The story map shows one measure of social vulnerability, the percent of the population in US

Census tracts whose income is below the Federal poverty line in the last 12 months, based on the US Census 2017 American Community Survey 5-year estimates. The census tracts are superimposed with migration space so users can identify important migration space in impoverished areas.

Repetitively Flooded Areas
Flooding is the most common and costliest natural disaster in the US. NOAA's 2018 annual report on high tide flooding in the US found the national frequency continued to accelerate, due largely to increasing relative sea levels at Eastern US and Gulf Coast locations. FEMA recently released the National Flood Insurance Program (NFIP) redacted claims dataset that includes the generalized geographic locations of claims since 1970. We processed over 1.2 million records and found that the migration space of resilient marshes frequently had a high number of locations with multiple claims since 1970. The story map shows the total number of NFIP claims since 1970 that intersected the migration space of resilient marshes. This data could be used to make natural resource management decisions such as identifying migration space areas with multiple NFIP claims as potential candidates for buy-out programs.

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EXISTING STUDIES REVIEWED

Table A1-1. Studies reviewed for "Resilient Coastal Sites in the South Atlantic" and "Resilient Coastal Sites in the Gulf of Mexico"

	Geography				
Project Name	**US**	**GOM**	**SA**	**State**	**Citation and Website**
Incorporating Future Change into Current Conservation Planning: Evaluating Tidal Saline Wetland Migration Along the U.S. Gulf of Mexico Coast		Y			Enwright et al. 2015; http://dx.doi.org/10.3133/ds969
Gulf Coast Vulnerability Assessment		Y			Watson et al. 2015; https://gulfcoastprairielcc.org/science/science-projects/gulf-coast-vulnerability-assessment/
NOAA Living Shoreline Projects	Y				https://www.habitatblueprint.noaa.gov/storymap/ls/index.html
NC DMF Coastal Habitat Protection Plan: Strategic Habitat Areas			Y	NC	http://portal.ncdenr.org/web/mf/habitat/shas
Migratory Species in the Gulf of Mexico Large Marine Ecosystem: Pathways, Threats and Conservation		Y			Brenner et al. 2016b; http://www.migratoryblueways.org/
NFWF South Atlantic Regional Coastal Resilience Assessment	Y		Y		Report: http://www.nfwf.org/coastalresilience/Documents/regional-coastal-resilience-assessment.pdf; Web tool: https://resilientcoasts.org/#Home
NFWF Gulf Coast Regional Coastal Resilience Assessment	Y	Y			Report: http://www.nfwf.org/coastalresilience/Documents/regional-coastal-resilience-assessment.pdf Web tool: https://resilientcoasts.org/#Home
Strategic Conservation Assessment (SCA) for Gulf Lands		Y			https://www.fws.gov/southeast/news/2017/04/strategic-conservation-assessment-will-help-guide-gulf-conservation/

Table A1-1. Studies reviewed for "Resilient Coastal Sites in the South Atlantic" and "Resilient Coastal Sites in the Gulf of Mexico"

	Geography				
Project Name	**US**	**GOM**	**SA**	**State**	**Citation and Website**
Hazard Vulnerability Assessment Tool (HVA)			Y		Alexander et al. 2015; https://scholarworks.uno.edu/cgi/viewcontent.cgi?article=1002&context=resilience, http://www.gsaaportal.org/learn/topic/hazard_vulnerability_assessment
Evaluation of Regional SLAMM Results to Establish a Consistent Framework of Data and Models, Prepared for the Gulf Coast Prairie Landscape Conservation Cooperative		Y			Warren Pinnacle Consulting, Inc., 2015; http://warrenpinnacle.com/prof/SLAMM/GCPLCC/
Sea Level Rise Modeling for the SAMBI Designing Sustainable Landscapes Project			Y		Rubino, 2009; http://www.basic.ncsu.edu/dsl/slr.html
Coastal habitats shield people and property from sea-level rise and storms (Coastal Hazard Index)	Y				Arkema et al. 2013; https://www.nature.com/articles/nclimate1944
Coastal Resilience	Y				http://coastalresilience.org/
South Atlantic Bight Marine Assessment (SABMA)			Y		Conley et al. 2017; http://nature.ly/marineSAtlanticBightERA
Reducing Flood Risk in the GOM through strategic land conservation		Y			Shepard et al. 2016; https://www.conservationgateway.org/ConservationPractices/Marine/crr/library/Documents/TNC_open_spaces_2016.pdf
A Land Conservation Vision for the Gulf of Mexico Region: An Overview		Y			http://www.gbrtrust.org/documents/publications/LandTrustAllianceConservationVisionPublication.pdf

Table A1-1. Studies reviewed for "Resilient Coastal Sites in the South Atlantic" and "Resilient Coastal Sites in the Gulf of Mexico"

	Geography				
Project Name	**US**	**GOM**	**SA**	**State**	**Citation and Website**
National Assessment of Coastal Vulnerability to Sea Level Rise: Preliminary Results for the US Atlantic Coast	Y				Thieler & Hammar-Klose, 1999; https://pubs.usgs.gov/of/1999/of99-593/
Evaluating coastal landscape response to sea-level rise in the northeastern United States—Approach and methods	NE				Lentz et al. 2015; http://dx.doi.org/10.3133/ofr20141252
Using a Bayesian Network to Predict Shoreline-Change Vulnerability to Sea-Level Rise for the Coasts of the United States	Y				Gutierrez et al. 2014; http://dx.doi.org/10.3133/ofr20141083
National Assessment of Shoreline (broken out by geographic subregions, including GOM and SE Atlantic)	Y				Himmelstoss et al. 2017; https://doi.org/10.3133/ofr20171015
National Assessment of Hurricane-Induced Coastal Erosion Hazards: Gulf of Mexico Update		Y			Doran et al. 2016; http://pubs.usgs.gov/of/2013/1130
National Assessment of Hurricane-Induced Coastal Erosion Hazards: Southeast Atlantic Coast			Y		Stockdon et al. 2013; https://pubs.usgs.gov/of/2013/1130/
NOAA Sea Level Rise Viewer	Y				https://coast.noaa.gov/slr/
NOAA National Storm Surge Hazard Maps	Y				http://noaa.maps.arcgis.com/apps/MapSeries/index.html?appid=d9ed7904dbec441a9c4dd7b277935fad&entry=1
Expansion of Tidal Marsh in Response to Sea-Level Rise: Gulf Coast of Florida, USA				FL	Raabe & Stumpf, 2016; https://doi.org/10.1007/s12237-015-9974-y

Table A1-1. Studies reviewed for "Resilient Coastal Sites in the South Atlantic" and "Resilient Coastal Sites in the Gulf of Mexico"

	Geography				
Project Name	**US**	**GOM**	**SA**	**State**	**Citation and Website**
The Contribution of Mangrove Expansion to Salt Marsh Loss on the Texas Gulf Coast				TX	Armitage et al. 2015; https://doi.org/10.1371/journal.pone.0125404
Prioritization of Critical Marsh Conservation and Restoration Areas based on Future Sea-level Rise Scenarios in Copano and San Antonio Bays, Texas Area				TX	Brenner et al. 2016a; http://www.glo.texas.gov/coastal-grants/_documents/grant-project/15-032-final-rpt.pdf
Adding Dynamic Information to Resiliency Planning: Identifying and Reducing Future Conflicts from Wetland Migration due to SLR				GA	Kramer & Samples, 2017; http://gwri.gatech.edu/sites/default/files/files/docs/2017/kramersamplesgwrc2017.pdf
Salt Marsh Zonal Migration and Ecosystem Service Change in Response to Global Sea Level Rise: A Case Study from an Urban Region				TX	Feagin et al. 2010; http://www.ecologyandsociety.org/vol15/iss4/art14/
Historic sediment accretion rates in a Louisiana coastal marsh and implications for sustainability				LA	Smith, 2009; http://digitalcommons.lsu.edu/gradschool_theses/2139
Coastal wetland response to sea-level rise in a fluvial estuarine system				FL	Alizad et al. 2016; https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016EF000385
Tidal hydrodynamic response to sea level rise and coastal geomorphology in the Northern Gulf of Mexico				AL,FL	Passeri, 2015; https://stars.library.ucf.edu/etd/1429/

Table A1-1. Studies reviewed for "Resilient Coastal Sites in the South Atlantic" and "Resilient Coastal Sites in the Gulf of Mexico"

	Geography				
Project Name	**US**	**GOM**	**SA**	**State**	**Citation and Website**
Predicting Coastal Retreat in the Florida Big Bend Region of the Gulf Coast under Climate Change Induced Sea-Level Rise				FL	Doyle et al. 2003; https://pubs.er.usgs.gov/publication/70201524
Physical and Program Options for the Inland Migration of Louisiana's Coastal Wetlands in Response to Relative Sea Level Rise				LA	Beck et al. 2012; https://hdl.handle.net/10161/5239.
Shifting Coastal Wetland Communities in North Carolina: An Historical Spatial Analysis of Alligator River National Wildlife Refuge				NC	Hodgkiss, 2011; http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1017.9670&rep=rep1&type=pdf
Predicting the retreat and migration of tidal forests along the northern Gulf of Mexico under sea-level rise		Y			Doyle et al. 2010
Sea-level rise and drought interactions accelerate forest decline on the Gulf Coast of Florida, USA				FL	Desantis et al. 2007
Sea-Level Rise, Inundation, and Marsh Migration: Simulating Impacts on Developed Lands and Environmental Systems				FL	Linhoss et al. 2015
The dynamic effects of sea level rise on low-gradient coastal landscapes: A review	Y				Passeri et al. 2015; doi:10.1002/2015EF000298

Table A1-1. Studies reviewed for "Resilient Coastal Sites in the South Atlantic" and "Resilient Coastal Sites in the Gulf of Mexico"

	Geography				
Project Name	**US**	**GOM**	**SA**	**State**	**Citation and Website**
Assessing Coastal Squeeze of Tidal Wetlands				ME	Torio & Chmura, 2013
Assessing tidal marsh resilience to sea-level rise at broad geographic scales with multi-metric indices	Y				Raposa et al. 2016
Salt marsh persistence is threatened by predicted sea-level rise	Y				Crosby et al. 2016; https://www.brown.edu/Research/Sax_Research_Lab/Documents/PDFs/Crosby%20et%20al.%202016%20-%20salt%20marsh%20persistence%20and%20sea%20level%20rise.pdf
Overestimation of marsh vulnerability to sea level rise	Y				Kirwan et al. 2016; Read more at https://phys.org/news/2016-02-salt-marshes-persist-seas.html#jCp
Spatial response of coastal marshes to increased atmospheric CO2	Y				Ratliff et al. 2015
Forest resistance to SLR prevents landward migration of tidal marsh	NE				Field et al. 2016

APPENDIX

II

SCORING METHODS

Z-scores

In order to identify resilient and vulnerable sites in each Coastal Shoreline Region (CSR), we transformed each metric to standardized normalized scores (z-scores) so that each had a mean of zero and a standard deviation of one. A z-score is calculated using the following formula:

$$z = (X - \mu) / \sigma$$

where z is the z-score, X is the value of the CSR attribute, μ is the mean of the attribute for all sites in the CSR, and σ is the standard deviation of the attribute for all sites in the CSR. The resultant z-score indicates how many standard deviations a particular site is from the CSR mean for a variable. For example, a site with a z-score of 1 indicates that the value for this attribute is 1 standard deviation greater than the attribute mean of all sites in the CSR.

Rank-based Z-scores

An assumption of standardized normal scores is that the data come from a normal distribution. Many of the CSR attribute values were not normally distributed and various approaches to transform the CSR attributes to a normal distribution were unsuccessful. We thus used rank-based z-scores which do not require a normal distribution. To calculate a rank-based z-score, we used the following steps:

1. Rank the attribute values from lowest to smallest
2. Compute a percentile for each attribute value in the dataset as follows:
    a. 100(i-0.5)/n where i is the rank and n is the sample size
3. For each percentile, calculate the inverse of the standard normal cumulative distribution function to determine how many standard deviations from the mean that particular percentile is on a normal distribution.

The resultant rank-based z-scores are interpreted in the same manner as standard z-scores. That is, a rank-based z-score of 1 indicates that the site value for this attribute is 1 standard deviation greater than the attribute mean for all the sites in that CSR.

We assigned all z-score and all rank-based z-scores to one of seven categories (Table A2-1).

Table A2-1. Z-score classes with corresponding abbreviations and colors used in the report and spatial data.

Z-score Class	Figure Color	Value Range
Far Above Average (FAA)		> 2 standard deviations
Above Average (AA)		1 to 2 standard deviations
Slightly Above Average (SAA)		0.5 to 1 standard deviations
Average (A)		-0.5 to 0.5 standard deviations
Slightly Below Average (SBA)		-0.5 to -1 standard deviations
Below Average (BA)		-1 to -2 standard deviations
Far Below Average (FBA)		< -2 standard deviations

APPENDIX III

DATA SOURCES & METHODS

SOFTWARE

- *ArcGIS 10.5.1*: Unless specified otherwise, all spatial analyses were conducted in ArcGIS 10.5.1.
- *R*: All statistical analyses, data aggregation, and data restructuring were conducted in R. R Core Team (2018).

CREATION OF ANALYSIS UNITS

Unit: Tidal Complex

Data Sources:

- Land Cover: 30-m NOAA 2010 Coastal Change Analysis Program (C-CAP; NOAA, 2017), https://coast.noaa.gov/ccapftp/#/
- Roads/Railroads: 2017 TIGER/Line roads and railroads (U.S. Census Bureau, 2017b)
- Wetlands: National Wetland Inventory (NWI, USFWS 2015) https://www.fws.gov/wetlands/data/State-Downloads.html
  - May 2015: downloaded dataset compiled by USFWS for the United States and its Territories, then projected to NAD83 Albers
- US Mainland: OpenStreetMap Land Polygons (large polygons not split)
  - April 2018: downloaded zip file called "land-polygons-complete-4326" from https://osmdata.openstreetmap.de/data/land-polygons.html.

Analysis Steps:

1. Download NOAA 2010 C-CAP data by state: Virginia, North Carolina, South Carolina, Georgia, and Florida
2. Merge state selections and project to NAD83 Albers
3. To add roads and railroads to NOAA 2010 C-CAP land cover data:
   - Download TIGER/Line roads
     - Extract the following road types:
       - Major roads

            - Minor roads
            - Residential roads
        - Project to NAD83 Albers
        - Assign code (value = 30) to identify TIGER/Line roads
        - Convert to 30-m grid, snap to projected C-CAP land cover grid
    - Download TIGER/Line railroads
        - Project to NAD83 Albers
        - Assign code (value = 40) to identify lines as railroads
        - Convert to 30-m grid, snap to projected C-CAP grid
    - Burn gridded roads and railroads into C-CAP land cover grid
2. Select the following C-CAP classes from the land cover grid:
        - 16 = Estuarine Forested Wetland
        - 17 = Estuarine Scrub/Shrub Wetland
        - 18 = Estuarine Emergent Wetland
        - 19 = Unconsolidated Shore
3. Create discrete tidal complex units by grouping all estuarine and unconsolidated shore pixels within 150 meters of each other into discrete units as follows:
    - Run Euclidean distance with maximum distance of 100 meters from each C-CAP estuarine and unconsolidated pixel from Step 4 above
    - Assign a value of 1 to all Euclidean distance values <= 75
        - 75 meters was selected because any two cells near each other will have a 75-m distance out and this sums to 150 m which has some support in the literature (Faber-Langendoen et al. 2012; Mitchell et al. 2013; King County, WA 2019)
    - Region group grid using 8-neighbor rule
    - Extract region grouped grid by the estuarine and unconsolidated shore pixels (grid output from step 4 above)
    - Convert extracted grid to polygon
    - Dissolve polygon by gridcode
    - Calculate standard metrics for tidal complex
        - ID = assign region group ID
        - Acres = calculate geometry operation in ArcGIS to calculate acreage of each discrete unit
        - Perimeter (km) = calculate geometry operation in ArcGIS to calculate length of each discrete unit in kilometers
4. Assess area of unconsolidated shore in each tidal complex unit:
    - Tabulate area of C-CAP 2010 estuarine and unconsolidated shore classes within each tidal complex
    - Calculate acreage of estuarine classes (C-CAP values = 16, 17, 18)
    - Calculate acreage of unconsolidated shore (C-CAP value = 19)
5. Select tidal complex units with at least two acres of estuarine marsh:

- Query to select tidal complexes with >= 2 acres of estuarine marsh (NOAA C-CAP classes 16, 17, and 18)

6. Remove tidal complex units that were probably misclassified
    - Using USFWS NWI Wetlands Type categories, calculate percentage of NWI wetland type in each tidal complex unit.
    - Calculate dominant type based on area
    - Using NWI data, satellite imagery, and detailed state land cover datasets (where available), manually review all units where estuarine wetland is not the dominant type
    - Remove tidal complex units that do not appear to be tidal wetlands based on manual review
    - Code remaining tidal complex units as 100 and convert to grid to remove these areas from the migration space grid (see Migration Space Unit section next)
7. For each SLR scenario, link tidal complexes to marsh migration space through spatial intersection operation and calculate total migration space acreage. See Step 9 of the migration space delineation steps for details.
    - Geophysical migration space
    - Accessible migration space
8. For each SLR scenario, calculate estimated future productivity:
    - Divide total migration space acreage by tidal complex acreage to get proportion of tidal complex that could be replaced by migration space
        - Calculate for both geophysical and accessible migration space units
9. Assign South Atlantic Coastal Shoreline Regions (CSR) to tidal complex units:
    - Tabulate area of each CSR type
    - Assign dominant CSR for a tidal complex
10. Distinguished tidal complexes on the US mainland versus tidal complexes associated with barrier islands
    - Ran spatial intersection between tidal complex units and the US mainland polygon to identify complexes on the US mainland.
    - As some of the tidal complexes were linked to both barrier islands and the US mainland, manually reviewed these and made assignment based on where the majority of the complex occurred.
    - Calculated attribute field called “MAINLAND” where a value of 1 indicates mainland tidal complexes and a value of 0 denotes island complexes.
11. Calculate metrics for the tidal complex units using migration space and buffer area units (see migration space and buffer area sections on the following pages for details)

Unit: Disaggregated Tidal Complexes

Data Sources:

- Land Cover: 30-m NOAA 2010 C-CAP (NOAA, 2017) https://coast.noaa.gov/ccapftp/#/
- Roads/Railroads: 2017 TIGER/Line roads and railroads (U.S. Census Bureau, 2017b)
- Original Tidal Complex Units: Tidal complex units created as described in section on previous page.

Analysis Steps:

1. Select the following C-CAP classes from the land cover grid:
    - 16 = Estuarine Forested Wetland
    - 17 = Estuarine Scrub/Shrub Wetland
    - 18 = Estuarine Emergent Wetland
    - 19 = Unconsolidated Shore
2. Create smaller discrete tidal complex units by grouping all NOAA 2010 C-CAP estuarine and unconsolidated shore pixels within 60 meters of each other into discrete units as follows:
    - Run Euclidean distance with maximum distance of 100 meters from each C-CAP estuarine and unconsolidated pixel from Step 4 above
    - Assign a value of 1 to all Euclidean distance values <= 30
        - 30 meters was selected because any two cells near each other will have a 30-m distance out and this sums to 60 m, which is only 40% of the original distance rule of 150 m.
    - Region group the resulting grid using an 8-neighbor rule
    - To match the footprint of the original tidal complex units, extract the region grouped grid by the final tidal complex units from the steps on the previous page.
    - Convert the extracted grid to polygon
        - dissolve polygon by GRIDCODE (region group ID)
    - To link disaggregated tidal complex units to their original tidal complex unit, run union between the original tidal complex units and dissolved polygon of disaggregated tidal complex units.
    - Join the attribute table from the original tidal complex units with the disaggregated tidal complex units by TC_ID so the attribute fields are the same. Add the following two fields to identify the disaggregated tidal complex units and their area (acreage).
        - DATC_ID = unique ID for disaggregated tidal complex unit. The TC_ID shows the original complex to which this polygon belonged.
        - DATC_Acres = area (acres) of disaggregated tidal complex unit.

Unit: Migration Space

Data Sources:

- <u>NOAA Marsh Migration Data:</u> 10-m raster NOAA Sea Level Rise (SLR) Viewer marsh migration data, with no accretion rate, for all SLR scenarios from 0.5-ft. to 10.0-ft. Latest and fully revised data for VA, NC, SC, GA, and FL was provided by Nate Herold at NOAA via ftp January 24, 2018.

Analysis Steps:

Part 1: Delineate migration space from NOAA marsh migration data

1. Create ArcGIS Model Builder tool to iterate through each state workspace and combine each 1-10-ft. (in .50-ft. increments) scenario with the baseline grid to identify pixels that changed from baseline.
    a. Include ½ foot scenarios
    b. Remove existing salt marsh and other tidal habitat pixels (C-CAP values 16 – 19)
    c. Only select pixels that ended up as unconsolidated shore (C-CAP = 19), salt marsh (C-CAP = 18), and brackish/transitional marsh (C-CAP = 17)
    d. Run the model for each state in the project area
2. For each state and SLR scenario, project the model output to NAD83 Albers and resample to 30-m (snap to NOAA 2010 C-CAP land cover grid).
3. For each SLR scenario, merge all the resampled and projected state grids
4. Delineate geophysical migration space:
    a. Ensure no existing tidal complex units are in the migration space by removing tidal complex units (converted to 30-m grid and coded as 100)
    b. Ensure no developed pixels are in the migration space. Remove developed pixels in NOAA 2010 C-CAP land cover.
        i. C-CAP values = 2, 3, 4, 5
2. To create migration space unit polygons with unique IDs that will be maintained regardless of SLR scenario, region group the final migration space grid using an 8-neighbor rule
    a. Convert region grouped grid to polygon and dissolve by GRIDCODE
3. Delineate full migration space for each individual SLR scenario
    a. Extract individual scenarios from region-grouped migration space grid above
    b. Convert each scenario with its region grouped ID to poly:
        i. Dissolve region grouped poly by GRIDCODE (unique ID for each migration space polygon):
    c. For each SLR scenario, add the following attributes:
        i. MS_ID (= GRIDCODE)
        ii. MS_Acres
        iii. MS_Perim (km)
        iv. SLR (ft.)

4. Calculate accessible migration space from geophysical migration space (by removing development, excluding bridges):
    a. Remove development, leveed areas, and tidal complex units
        i. Con developed/roads (values = 2,3,4,5, 30 (roads), and 40 (railroads)) to 100
        ii. Mosaic to new raster and set 100 to Null
    b. To create migration space unit polygons with unique IDs that will be maintained regardless of SLR scenario, region group the final migration space grid using an 8-neighbor rule
        i. Convert region grouped grid to polygon and dissolve by GRIDCODE
    c. Delineate full migration space for each individual SLR scenario
        i. Extract individual scenarios from region grouped migration space grid above
        ii. Convert each scenario with its region grouped ID to poly:
            1. Dissolve region grouped poly by GRIDCODE (unique ID for each migration space polygon):
        iii. For each SLR scenario, add the following attributes:
            1. MS_ID (= GRIDCODE)
            2. MS_Acres
            3. MS_Perim (km)
            4. SLR (ft.)
5. For each SLR scenario, run spatial join (one-to-many between) tidal complex unit shapefile and migration space unit shapefiles based on intersection. This output will be used to calculate the total migration space acreage for each tidal complex.
    a. Run for geophysical migration space units
    b. Run for accessible migration space units
6. Write and run R script to link tidal complex units and migration space units to calculate the total migration space and count of migration space units for each tidal complex at each SLR scenario using the .dbf from the one-to-many joins from Step 8 above, and the relationship between each tidal complex and its connected migration space ID's at SLR = 1.5 ft. Also calculate the total tidal complex acreage and count of tidal complex units for each migration space unit for each SLR scenario.
    a. Run for geophysical migration space units
    b. Run for accessible migration space units
7. Write and run R script to calculate migration space area weights to roll up attributes to the tidal complex based on the relationship between each tidal complex and its associated migration space units. For example, if a tidal complex had two migration space units, one covering 75% of the total migration space area and the second covering 25% of the area, the attributes of the first

would be weighted by 0.75 and the characteristics of the second would be weighted by 0.25 when combined into a final score for the site.

   a. Run for geophysical migration space
   b. Run for accessible migration space

Unit: Buffer Area

Data Sources:

- Land Cover: 30-m NOAA 2010 C-CAP (NOAA, 2017), https://coast.noaa.gov/ccapftp/#/
- Roads/Railroads: 2017 TIGER/Line roads and railroads (U.S. Census Bureau 2017b)
- HUC 10 Watersheds: Watershed Boundary Dataset (WBD) shapefile from the NHDPlus v2 National data. "WBDSnapshot_National.shp" from the "NHDPlusV21_NationalData_WBDSnapshot_Shapefile_08.7z" downloaded May 2016 from http://www.horizon-systems.com/NHDPlus/V2NationalData.php
- Elevation: National Elevation Dataset (NED; USGS, 2016)
    - Downloaded individual 1-degree arc second tiles for the continental US from /vdelivery/Datasets/Staged/Elevation/1/IMG
    - Tiles were merged together and resampled to 30-m grid. Projected to Albers Equal-Area Conic (North America). DEM was filled and was filled and then a low-pass filter was used to smooth abrupt changes in elevation.

Analysis Steps:

1. Create mask to restrict buffer area units to HUC 10 watersheds that intersect tidal complex units and migration space units.
   a. Intersect HUC 10 watersheds with augmented migration space grid (converted to poly) that intersects tidal complex units.
2. Create grid of potential buffer area by extracting natural and agricultural land cover from the NOAA 2010 C-CAP land cover grid with TIGER/Line roads and railroads added. Set mask to HUC 10 watersheds from Step 1.
   a. Select natural land cover classes and set to 1
      i. C-CAP values = 8,9,10,11,12,13,14,15,16,17,18,19,21,22,23
   b. Select agricultural and pasture land cover classes and set to 2
      i. C-CAP values = 6, 7
3. To prevent inclusion of buffer area pixels that are likely to be inundated for a particular sea level rise scenario, create a sea level rise mask. For each of the four SLR scenarios, code 30-m DEM pixels with elevation values (in meters) less than or equal to the scenario, as 100.

4. To prevent inclusion of tidal complex and migration space pixels in the buffer area, create grid of tidal complex units and for each SLR scenario, a grid of accessible migration space units, each coded as 100.
5. For each SLR scenario, mosaic the following grids together and only retain any natural and agricultural land cover remaining after removal of tidal complexes, accessible migration space, leveed areas, and sea level rise masks:
    a. Tidal complex (100)
    b. Accessible migration space (100)
    c. SLR mask (100)
    d. Potential buffer area (agricultural and natural cover) [values = 1, 2]
6. For each SLR scenario, region group remaining buffer space using 8-neighbor rule:
    a. convert to polygon and dissolve by grid code (region group ID)
    b. calculate the following fields:
        i. Buff_ID: GRIDCODE field
        ii. Buff_Acr: calculate area (acreage) using Geometry
        iii. Buff_Perim: calculate perimeter (km) Geometry
        iv. SLR: SLR scenario
7. Spatially link buffer area units to accessible migration space units. For each SLR scenario,
    a. spatial join (one to many) the accessible migration space units shapefile to the buffer area units shapefile
    b. write and run R script to calculate total accessible migration space acreage and number of accessible migration space units for each buffer area unit, and to calculate total buffer area acreage and number of buffer area units for each accessible migration space unit.
8. Spatially link buffer area units to the tidal complex units.
    a. relationship 1: Spatially link buffer area units to tidal complex units via a tidal complex's accessible migration space units. For each SLR scenario,
        i. output (.dbf table) from spatial join (one to many) between the accessible migration space units shapefile and the buffer area units shapefile
        ii. output (.dbf table) from spatial join (one to many) between the accessible migration space units shapefile and the tidal complex units shapefile (see migration space unit delineation steps on previous page)
    b. relationship 2: Link buffer units to tidal complex units (no accessible migration space unit to connect the tidal complex to the buffer area unit). Note that some tidal complexes have very little to no migration space but lots of buffer space. For each SLR scenario,
        i. spatial join (one to many) the tidal complex units shapefile to the buffer area units shapefile

   c. write and run R script to restructure and aggregate outputs from above three spatial joins to calculate total tidal complex acreage and number of tidal complex units for each buffer unit, and to calculate total buffer area acreage and number of buffer area units for each tidal complex.
   d. Using outputs from the three spatial joins, write and run R script to calculate buffer area area-weights to roll up attributes to the tidal complex. For example, if a tidal complex had two buffer area units, one covering 75% of the total buffer area and the second covering 25% of the area, the attributes of the first would be weighted by 0.75 and the characteristics of the second would be weighted by 0.25 when combined into a final score for the site.
9. For each SLR scenario, create final buffer area unit shapefile with the following additional fields from the above analyses:
   a. TC_Acres: total area (acreage) of tidal complex units associated with the buffer area unit
   b. TC_Cnt: total number of tidal complex units associated with the buffer area unit
   c. MS_Acres: total area (acreage) of accessible migration space units associated with the buffer area unit
   d. MS_Cnt: total number of accessible migration space units associated with the buffer area unit

STRATIFICATION UNITS

Unit: Coastal Shoreline Regions (CSRs)

Data Sources:

- South Atlantic Coastal Shoreline Units: South Atlantic Bight Marine Assessment (SABMA, Conley et al. 2017). The United States Geologic Survey (USGS) Watershed Boundary Dataset (WBD)10-digit Hydrologic Units (HUCs) were used as the base for CSU watershed delineation. The WBD dataset was augmented with the Estuarine and Coastal Drainage Area watersheds from the NOAA Coastal Assessment Framework (NOAA, 2007), information on natural features and current patterns, and local knowledge. The result was a continuous string of 39 CSUs that covered the SABMA project area. The SABMA subregion stratification (Mid-Atlantic, Carolinian and Floridian) was applied to the CSUs in order to account for variation in climate, habitat types and species use within South Atlantic Bight estuaries moving from the temperate systems of North Carolina to the subtropical systems in Florida. CSUs were assigned an estuary type based on the Coastal Marine Ecological Classification Standard (CMECS) categorization (Madden et al. 2009). Building upon the Environmental Protection Agency's Classification Framework for Coastal Systems (Burgess et al. 2004), three CMECS estuary types were used in the South Atlantic: 1) river-dominated estuaries, 2) lagoonal estuaries, and 3) island archipelago. Given the limited variation in CMECS types found in the region, the decision was made to divide the river-dominated estuary type into Coastal Plain and Piedmont basins. This distinction, described by Dame et al. (2000), represents the variation in freshwater flow, watershed drainage, and proportion of wetlands. Further subdivision of the lagoonal estuaries was considered; however, the inclusion of South Atlantic subregions as part of the characterization accounts for the core variation from north to south. In the end, the CSUs of the South Atlantic Bight Marine Assessment were sorted into the following types: Lagoonal Estuaries (19 CSUs), River-dominated Estuaries (18 CSUs) [9 Coastal Plain Basins and 9 Piedmont River Basins], and Island Archipelago (2 CSUs).

- HUC 8, HUC 10, and HUC 12 watersheds: Watershed Boundary Dataset (WBD, NRCS 2016) downloaded Sept. 2016 from http://datagateway.nrcs.usda.gov

Analysis Steps:

1. Aggregated and dissolved the 39 SABMA Coastal Shoreline Units by estuary type ("CSU_TYPE") field.
2. The initial estuarine type assignments were reviewed and approved by the project steering committee during the second steering committee call.
3. For consistency, we addressed occasional boundary anomalies by filling out incomplete HUC 12 watersheds or removing small portions of incomplete HUC 12 watersheds
4. Lastly, in southern Florida, a small portion of the South Atlantic Lagoonal CSR fell within the boundary of HUC-8 03090202 and was removed as this area is in our "Resilient Coastal Sites in the Gulf of Mexico US" project.

TIDAL COMPLEX PHYSICAL ATTRIBUTES

Attribute: Tidal Complex Size

- See previous section on creation of tidal complex units

Attribute: Tidal Complex Shared Upland Edge (%) with Migration Space

Data Source:

- Land Cover: 30-m NOAA 2010 C-CAP (NOAA, 2017), https://coast.noaa.gov/ccapftp/#/

Analysis Steps:

1. Identify upland edge of each tidal complex as follows:
    a. Create ocean/water grid from NOAA's 2010 C-CAP land cover dataset. Assign ocean/water pixels to 1, non-water to 2
        i. water (C-CAP value = 21)
        ii. aquatic bed (C-CAP value = 23)
    b. Convert ocean/water grid to polygon
        i. gridcode 1 = water
        ii. gridcode 2 = land
    c. Spatially intersect tidal complex polygon with ocean/water polygon, line is output
    d. Erase all ocean/water lines
    e. Calculate length (LAND_KM) of remaining upland edge polylines (km)
2. For each SLR scenario***, spatially intersect landward tidal complex lines with migration space units, line is output
    i. calculate NEW_Length field (km)
    ii. summarize NEW_Length field by Tidal Complex ID (gridcode)
    iii. (shared length (km) / total length of tidal complex upland edge (LAND_KM)) * 100
    iv. ***run intersection for initial SLR = 1.5 and then for each scenario to find tidal complex units that don't have migration space until later scenarios.

MIGRATION SPACE PHYSICAL ATTRIBUTES

Attribute: Migration Space Size

- See earlier section on creation of migration space units

Attribute: Tidal Height Classes Variety and Evenness

- NOAA Marsh Migration Data: 10-m raster NOAA Sea Level Rise (SLR) Viewer marsh data, with no accretion rate for all SLR scenarios from 0.5-ft. to 10.0-ft. Latest and fully revised data for FL, AL, MS, LA, and TX was provided by Nate Herold at NOAA via ftp on January 24, 2018.

Analysis Steps:
Part 1: Convert NOAA marsh migration data to tidal class categories

1. For each state and SLR scenario, convert NOAA SLR marsh migration data to one of four tidal class categories as follows:
    a. Unconsolidated shore (grid value = 1). C-CAP land cover class = 19
    b. Estuarine marsh (grid value = 2). C-CAP land cover class = 18
    c. Brackish/Transitional marsh (grid value = 3). C-CAP land cover class = 17
    d. Palustrine wetlands (grid value = 4). C-CAP land cover classes = 13,14,15
    e. All other values = NoData
2. For each SLR scenario, merge, resample to 30 m, and project all the grids together, snap to NOAA 2010 C-CAP land cover grid.

Part 2: Calculate Tidal Class Diversity and Evenness in the Migration Space Units

1. For each SLR scenario, tabulate area of each tidal class in the migration space units
2. For each SLR scenario, use R script to calculate proportion of each tidal class in each migration space unit
    a. Square proportions and sum
    b. Take reciprocal = Simpsons D
    c. Evenness = D / total number of habitats:
    d. 1 = equal distribution
    e. Min = 1 / Dmax
    f. If unconsolidated proportion > .50, multiply the evenness value by (1- the unconsolidated shore proportion)
    g. If unconsolidated proportion <= .50, leave evenness value as is
3. For each SLR scenario, use the migration space area-based weights (calculation of these described in migration space unit delineation section on previous pages) for each tidal complex to roll up the values to the tidal complex units.

BUFFER AREA PHYSICAL ATTRIBUTES

Attribute: Adjusted Buffer Area Size

Data Sources:

- <u>Buffer Area Size (acreage)</u>: see earlier section on creation of buffer area units sand size attribute
- <u>Accessible Migration Space:</u> see previous section on creation of accessible migration space units

Analysis Steps:

Part 1: Assess how well the accessible migration space is buffered by an associated buffer area unit.

1. For each SLR scenario (n=4):
    a. Run Euclidean Allocation of accessible migration space with a maximum distance of 1 kilometer
    b. From Euclidean Allocation grid, remove tidal complexes, accessible migration space units, inundated pixels, and leveed areas
        i. Mosaic following grids into a removal mask:
            1. Tidal complex pixels set to 0
            2. Inundated pixels from DEM set to 0
            3. Leveed areas set to 0
            4. Accessible migration space pixels set to 0
            5. To be on safe side, all accessible migration space SLR scenarios below the selected SLR scenario set to 0
    b. Set the buffer area unit pixels to 1
    c. Use Map Algebra to set all 0 values to null in the accessible migration allocation grid from Step 1a above
2. For each 1-km accessible migration space ID with the above components removed (output from Step 1c), run Tabulate Area to calculate area of buffer area units (set as 1) in each 1-km zone.
3. For each 1-km accessible migration space ID with the above components removed (output from Step 1c), run Geometry to calculate area of each zone.
4. In R, run script to calculate the percentage of the 1-km area outside of each accessible migration space unit that is buffered:
    a. MSBUFF = (BUFF_AREA from Step 2/ ZONE_AREA from Step 3) * 100
5. In R, run script to roll up the migration space buffering values to the buffer area units:
    a. Join accessible migration space buffering table from Step 4 to the accessible migration space buffer weights (generated during creation of buffer area units)
    b. For each buffer area unit ID, sum the total 1-km area, sum the total 1-km buffered area, and calculate the % of the total 1-km area that is buffered.

Part 2: Calculate adjusted buffer area size

1. For each SLR scenario (n=4):
    a. Adjusted Buffer Area Size = Buffer Size (acres) * percent migration space buffering

Attribute: Landform Variety in the first 1 km of the Buffer Area

Data Source:

- Landforms: 30-m landform model (Anderson et al. 2016) with 17 classes developed for the project area

Analysis Steps:

2. Select landforms compatible with coastal processes and systems:
    a. Hilltop (flat)
    b. Hill (gentle slope)
    c. Dry flats
    d. Wet flats
    e. Valley/toeslope
    f. Moist flats in upland land cover
    g. Open water
3. To address correlation between landform variety and buffer size, calculate landform variety for 100-acre circular area within project area using Focal Statistics with:
    a. Neighborhood Shape = circle
    b. Radius = 358.908800 meters
4. Relationship 1: Accessible migration space units and buffer area units
    a. For each accessible migration space SLR scenario polygon, run Euclidean distance (30 m, snap to NOAA C-CAP 2010), max distance of 1-km
    b. For each Euclidean distance output, Con to set 0 values to Null and all other values to 1
    c. Combine the Euclidean distance Con output with the buffer grid for each SLR scenario
    d. Run a Lookup on the combine grid to set the raster value to the buffer ID (gridcode)
    e. Calculate Zonal Mean of the landform variety 100-acre grid using the Lookup grid buffer ID as the zone
5. Relationship 2: Tidal complex units and buffer area units (since there were buffer units that only intersected tidal complexes (i.e., did not intersect the accessible migration space of tidal complexes), do the following steps:
    a. For the tidal complex polygon, run Euclidean distance (30 m, snap to NOAA 2010 C-CAP), max to 1000 m
    b. For the Euclidean distance output, Con to set 0 values to Null and all other values to 1

   c. Combine the Euclidean distance Con output with the buffer grid for each SLR scenario
   d. Run Lookup on the combine grid to set the raster value to the buffer ID (gridcode)
   e. Calculate Zonal Mean of the landform variety 100-acre grid using the Lookup grid buffer ID as the zone
6. As there are two sets of landform variety means:
   a. Run R script to combine the two sets of buffer 1-km mean values for each SLR scenario to ensure that a buffer area's relationship with a tidal complex is not counted more than once (i.e., a buffer unit that is immediately adjacent to a tidal complex but is also linked to the tidal complex via the accessible migration space).
7. For each SLR scenario, use the buffer area units' area-based weights for each tidal complex to roll up the values to the tidal complex unit

Attribute: Acreage of Maritime Highlands in the Buffer Area

Data Sources:

- <u>Elevation:</u> National Elevation Dataset (NED; USGS, 2016)
  - Downloaded individual 1-degree arc second tiles for the continental US from /vdelivery/Datasets/Staged/Elevation/1/IMG
  - Tiles were merged together and resampled to 30-m grid. Projected to Albers Equal-Area Conic (North America). DEM was filled and was filled and then a low-pass filter was used to smooth abrupt changes in elevation.
- <u>Land Cover:</u> 30-m NOAA 2010 C-CAP (NOAA, 2017), https://coast.noaa.gov/ccapftp/#/
- <u>Roads/Railroads:</u> 2017 TIGER/Line roads and railroads (U.S. Census Bureau, 2017b)

Analysis Steps:

1. Identify high elevation lands (>= 4 m) embedded in a low elevation landscape (< 4 m):
   a. Identify lowlands:
      i. Assign a value of 1 to all elevation values < 4 meters
      ii. Convert grid values = 1 to a polygon shapefile
   b. Pull out highlands enclosed by lowlands:
      i. Run Union on lowlands polygon, do not allow gaps. Not allowing gaps creates polygons for the highland areas (>=4 m) that are completely surrounded by lowland polygons (i.e., donut holes).
      ii. Select donut hole polygons (those surrounded by lowland pixels) where ID = 0
      iii. Calculate unique ID field (FID + 1)

2. Convert selected highland areas to grid using ID field, snap to C-CAP land cover grid
3. Using C-CAP land cover grid with roads/railroads burned in, remove developed and agricultural land from maritime highlands
4. Convert remaining maritime highland grid to polygon
    a. Dissolve by gridcode (ID)
5. Summarize the area of maritime highland in each buffer area
    a. Tabulate area of maritime highlands in each buffer area unit
6. For each SLR scenario, use the buffer area units' area-based weights for each tidal complex to roll up the values to the tidal complex unit

PHYSICAL SCORE CALCULATIONS

Tidal Complex and Migration Space (Site) Unadjusted Physical Score
The unadjusted physical score for the tidal complex and its migration space was calculated for each site using a weighted sum of the current physical characteristics.

Weighted Sums
To put the metrics onto a standard scale, each individual variable was converted to a Z-score (standard normal distribution) relative to its coastal shoreline region (CSR). To do this, we examined the distribution of each variable within each CSR. If the distribution was normal, we calculated the mean and standard deviation and used these to transform the values to standard normal (value – mean / standard deviation). If the distribution was skewed or otherwise distorted, we used various transformations to convert it to a normal distribution or used non-parametric techniques to calculate a Z-rank score based on the order, rank and number of the values.

When all the variables were on the same scale, we applied the variable weights agreed upon by our steering committee.

Attribute Weights
Each attribute was given a rank with respect to its importance for site resilience, and each was weighted on a numeric scale from 1 to 5 in terms of its influence and importance. The numeric weights were used as a multiplier when combining factors, with the objective of giving more weight to factors with more influence. The numeric weights were: 5 - very high, 4 - high, 3 - moderate, 2 - low, and 1 - very low.

Physical Options
Size of Migration Space (5)
Tidal Classes (3)
Shared Upland Edge (2)
Size of Tidal Complex (2)
____
Weighted Sum = Physical Score

The tidal complex and migration space unadjusted physical score was calculated using the following equation:

*Site Unadjusted Physical Score = ((Migration Space Size * 5) + (Migration Space Tidal Class Evenness & Diversity * 3) + (Tidal Complex Size * 2) + (Tidal Complex Shared Upland Edge * 2)) / 12*

Given the importance of migration space, migration space thresholds were applied to the unadjusted physical score:

1) A tidal complex's migration space total size must be greater than average, relative to its Coastal Shoreline Region. OR

2) A tidal complex with average migration space size that is at least as big as the existing complex and is predicted to increase in size (future migration space size trend) and is not on a barrier island
that shows a downward trend in size.

For tidal complex units that did not meet one of the above thresholds, if the unit's unadjusted physical z-score was greater than 0, it was assigned a value of 0. This was to ensure that sites without adequate migration space did not receive inflated physical scores due to high scores for their tidal complex variables (size and shared upland edge).

Each site's unadjusted physical z-score was converted to a new set of standardized normalized values (z-scores) using a z-rank procedure, after removing the very low scoring sites (essentially sites without any migration space or with very poor scores for all their physical attributes). The very low sites were manually assigned a z-score of -3.5 SD and then combined with the new set of z-scores.

Tidal Complex and Migration Space (Site) Final Physical Score:
<u>Accessibility of Migration Space</u>: We also applied an adjustment to the physical score based on the accessibility of a site's migration space. As described previously, some areas of migration space are fragmented by paved roads that may be barriers in the future, at least at some stages of inundation and migration. To incorporate the accessibility of the migration space into the physical score, we calculated two physical scores using the weights and approaches described above, with the only difference being the migration space size variable. Again, the accessible migration space size was delineated after removing all roads while the original 'geophysical' migration space did not include major roads and development.

Physical Score One (PS1) used the geophysical migration space size (as described above), and Physical Score 2 (PS2) used the accessible migration space size. As was done for the geophysical migration space-based score, each site's unadjusted physical z-score (PS2) was converted to a new set of standardized normalized values (z-scores) using a z-rank procedure, after removing the very low scoring sites (essentially sites without any accessible migration space or with very poor scores for all their physical attributes). The very low sites were manually assigned a z-score of -3.5 SD and then combined with the new set of z-scores.

For each site, we calculated the difference between the two scores (PDIFF) and measured the percent of a site's 'geophysical' migration space that is accessible as:

*PERMS = (Geophysical MS/Accessible MS) * 100*

where MS = Migration Space and PERMS = the percent of the migration space that is accessible.

For each coastal shoreline region, we regressed the physical score difference (PDIFF) against the PERMS variable. In the South Atlantic, this relationship explained between 23% and 37% of the variance in scores, although the coefficients were very small (range 0.005 – 0.010) indicating a small but significant influence. The shoreline region values were:

- Lagoons: adj. R^2 = 0.37, coeff. = 0.009
- Riverine (Coastal Plain): adj. R^2 = 0.37, coeff. = 0.005
- Riverine (Piedmont Basin): adj. R^2 = 0.37, coeff. = 0.010
- Island Archipelago: adj. R^2 = .23, coeff. = 0.005

Using this information, we adjusted the physical score downwards where appropriate using the following equation:

*Physical score – (((100 – PERMS) * regression coefficient) * the adjusted R^2)*

This adjustment had the effect of decreasing the score a maximum of less than one-half (0.4) standard deviation in sites with road-fragmented migration space and had no effect on sites with unfragmented migration space.

Buffer Area Physical Score

The physical score for the buffer area was calculated for each site as a weighted sum of the physical options.

Buffer Area Physical Options

Adjusted Buffer Area Size (5)
Variety of Landforms (5)
Acreage of Maritime Highlands (5)

____

Weighted Sum = Buffer Area Physical Score

The buffer area physical score was calculated using the following equation:

*Buffer Area Physical Score = ((Adjusted Buffer Area Size * 5) + (Variety of Landforms * 5) + (Acreage of Maritime Highlands * 5)) / 15*

TIDAL COMPLEX CONDITION ATTRIBUTES

Attribute: Developed Upland Edge Percent

Data Sources:

- Land Cover: NOAA 2010 C-CAP (NOAA, 2017), https://coast.noaa.gov/ccapftp/#/
- Roads/Railroads: 2017 TIGER/Line roads and railroads (U.S. Census Bureau, 2017b)
- Bridges: National Bridge Inventory (NBI; FHWA, 2017) is a collection of information (database) describing the more than 610,000 of the Nation's bridges located on public roads, including Interstate Highways, U.S. highways, State and county roads, as well as publicly-accessible bridges on Federal lands.
    - March 2019: downloaded zip file named "National_Bridge_Inventory_NBI_Bridges" from Homeland Infrastructure Foundation-Level Data at https://hifld-geoplatform.opendata.arcgis.com/

Analysis Steps:

1. Identify upland edge of each tidal complex as follows:
    a. Create ocean/water grid from NOAA's C-CAP 2010 land cover dataset. Assign ocean/water pixels to 1, non-water to 2
        i. water (C-CAP value = 21)
        ii. aquatic bed (C-CAP value = 23)
    b. Convert ocean/water grid to polygon
        i. gridcode 1 = water
        ii. gridcode 2 = land
    c. Spatially intersect tidal complex polygon with ocean/water polygon, line is output
    d. Erase all ocean/water lines
    e. Calculate length of remaining upland edge polylines (km)
2. Create polygon of developed lands (including roads and railroads)
    a. Convert bridge data to 30-m grid, snap to land cover grid
    b. Mosaic bridges grid to the NOAA 2010 C-CAP land cover grid, augmented with TIGER/Line roads and railroads
    c. Select following developed pixels from the augmented NOAA 2010 C-CAP land cover grid. Bridges were not treated as developed pixels because they are unlikely to prevent marsh migration.
        i. Developed, high intensity lands (C-CAP value = 2)
        ii. Developed, medium intensity lands (C-CAP value = 3)
        iii. Developed, low intensity lands (C-CAP value = 4)
        iv. Developed, open space (C-CAP value = 5)
        v. TIGER/Line roads and railroads
    d. Convert developed pixels to polygon

3. Identify upland edge that is developed or immediately adjacent to development/roads.
    a. Spatially intersect tidal complex upland lines with developed/roads polygon, line is output
    b. For each line segment, calculate length of developed upland edge (DEV_KM)
    c. Run Summary Statistics to calculate total LAND_KM and total DEV_KM for each tidal complex ID
    d. For each tidal complex ID, calculate percentage of the landward edge with development: (DEV_KM/LAND_KM) * 100

Attribute: Sediment Balance

Data Source:

- <u>Sediment Balance Data:</u> Present-day global sediment balance (mg/l) for shorelines in the Eastern US and Gulf of Mexico US from the author of a recently published study (Schuerch et al. 2018). The dataset shows the difference between the suspended sediment concentration needed for coastal wetlands to build up vertically with current SLR rates and the actual total suspected matter concentration derived from satellite data (GlobColour). A positive value in the dataset indicates coastlines with a sediment surplus while negative values indicate a deficit.

Analysis Steps:

1. Project the sediment balance shoreline data to NAD 1983 Albers
2. Spatially link the projected sediment balance shoreline data to the tidal complex units:
    a. Run a 30-m Euclidean Allocation of shoreline segment unique IDs to calculate, for each pixel, the nearest shoreline segment based on Euclidean distance.
    b. Extract the resulting Euclidean allocation grid by a 30-m grid of the tidal complex units.
    c. For each tidal complex unit ID, tabulate the area of each shoreline segment ID.
3. In R, calculate the proportion of each shoreline segment that intersected a tidal complex unit to generate shoreline segment area-weights to roll-up the sediment balance data to the tidal complex units.
4. In R, join the sediment balance data to the shoreline segment-area weights by unique shoreline segment ID. For each tidal complex unit, calculate the average sediment balance based on the proportion that each shoreline segment spatially intersected with the tidal complex unit.

MIGRATION SPACE CONDITION ATTRIBUTES

Attribute: Water Quality Index

Data Sources:

- Water Quality Index model (WCHEM): EPA StreamCat (Hill et al. 2016) revised water chemistry index (Johnson et al. 2019), https://www.epa.gov/national-aquatic-resource-surveys/streamcat
- Catchments: NHDPlus v2 National Data (USEPA & USGS 2018), http://www.horizon-systems.com/NHDPlus/V2NationalData.php

Analysis Steps:

Part 1: Process water quality index data (WCHEM variable)

1. Download the EPA's StreamCat ICI_IWI_v2.1 data (.csv) for the following HydroRegions: 03S (South Atlantic South) and 03N (South Atlantic North)
2. Merge the HydroRegion .csv files into a single .dbf table.
3. Download the NHDPlus v2 National Data geodatabase (NHDPlusV21_National_Seamless.gdb)
   a. From the NHDPlusCatchment feature class, select the smoothed NHDPlus catchments (CatchmentSP_Albers) that intersected the project area boundary.
   b. Project the selected smoothed catchments to NAD 1983 Albers
4. Join the merged .dbf table to the selected smoothed NHDPlus catchments by the COMID attribute field in the water chemistry .dbf table and the FEATUREID attribute field in the smoothed NHDPlus catchments. Export the joined data to a new shapefile.

Part 2: Translate the NHDPlus catchment water quality values to the migration space units, and then roll up the migration space values to the tidal complex units.

1. Calculate drainage-area weights for the migration space units using both NHDPlus v2 National Data flowlines and smoothed catchments (both flowlines and catchments are used to ensure that the spatial relationship between a migration space unit and the NHD data is captured).
   a. Select NHDPlus v2 flowlines and smoothed catchments with their cumulative drainage area attribute (DivDASqKM) that intersect the project area. Project the selected flowlines and smoothed catchments to NAD 1983 Albers.
   b. For each SLR scenario, run a spatial join (one to many) between the migration space units and NHDPlus v2 flowlines.
   c. For each SLR scenario, run a spatial join (one to many) between the migration space units and NHDPlus v2 smoothed catchments.
   d. In R, for each SLR scenario, process the one-to-many tables resulting from the spatial joins and select all unique combinations of migration space units and flowline/catchment IDs (COMIDs). For each migration space unit, summarize the total cumulative drainage area (DivDASqKM) of

flowlines/catchments that spatially intersect each migration space and name this value "TotDA." For each flowline/catchment COMID linked to a migration space unit, calculate the proportion of the total cumulative drainage area (TotDA) the flowline/catchment comprises: (DivDASqKM/ToTDA). The resulting values are the drainage-area weights for each flowline/catchment COMID and migration space relationship.

2. In R, for each SLR scenario, run script to calculate the average water quality index value (WCHEM) of each migration space unit using the catchment/flowline drainage-area weights from Step 1d.
3. In R, for each SLR scenario, run script to roll up the migration space water quality index values to the tidal complex units using the migration space area-based weights for each tidal complex.

Attribute: Freshwater Flow Alteration

Data Sources:

- Flow Alteration Variable (NABD_NrmStorWs): EPA StreamCat (Hill et al. 2016) Normal (most common) volume of all reservoirs (NORM_STORA in NID) per unit area of watershed (cubic meters/square km) based on the National Anthropogenic Barrier Dataset (NABD), https://www.epa.gov/national-aquatic-resource-surveys/streamcat
- Catchments: NHDPlus v2 National Data (USEPA & USGS 2018), http://www.horizon-systems.com/NHDPlus/V2NationalData.php

Analysis Steps:

Part 1: Process flow alteration data

1. Download the EPA's StreamCat NABD data (.csv) for the following HydroRegions: 03S (South Atlantic South) and 03N (South Atlantic North)
2. Merge the HydroRegion .csv files into a single .dbf table.
3. Download the NHDPlus v2 National Data gdb (NHDPlusV21_National_Seamless.gdb)
    a. From the NHDPlusCatchment feature class, select the smoothed NHDPlus catchments (CatchmentSP_Albers) that intersected the project area boundary.
    b. Project the selected smoothed catchments to NAD 1983 Albers
4. Join the merged .dbf table to the selected smoothed NHDPlus catchments by the COMID attribute field in the NABD .dbf table and the FEATUREID attribute field in the smoothed NHDPlus catchments. Export the joined data to a new shapefile.

Part 2: Translate the NHDPlus catchment flow alteration values to the migration space units, and then roll up the migration space values to the tidal complex units.

1. Calculate drainage-area weights for the migration space units using both NHDPlus v2 National Data flowlines and smoothed catchments (both flowlines

and catchments are used to ensure that the relationship between a migration space unit and the NHD data is captured).

   a. Select NHDPlus v2 flowlines and smoothed catchments with their cumulative drainage area attribute (DivDASqKM) that intersect the project area. Project the selected flowlines and smoothed catchments to NAD 1983 Albers.
   b. For each SLR scenario, run a spatial join (one to many) between the migration space units and NHDPlus v2 flowlines.
   c. For each SLR scenario, run a spatial join (one to many) between the migration space units and NHDPlus v2 smoothed catchments.
   d. In R, for each SLR scenario, process the one-to-many tables resulting from the spatial joins and select all unique combinations of migration space units and flowline/catchment IDs (COMIDs). For each migration space unit, summarize the total cumulative drainage area (DivDASqKM) of flowlines/catchments that spatially intersect each migration space and name this value "TotDA." For each flowline/catchment COMID linked to a migration space unit, calculate the proportion of the total cumulative drainage area (TotDA) the flowline/catchment comprises: (DivDASqKM/ToTDA). The resulting values are the drainage-area weights for each flowline/catchment COMID and migration space relationship.

2. In R, for each SLR scenario, run script to calculate the average flow alteration value (NABD_NRM_Stor) of each migration space unit using the catchment/flowline drainage-area weights from Step 1d.
3. In R, for each SLR scenario, run script to roll up the migration space flow alteration values to the tidal complex units using the migration space area-based weights for each tidal complex.

BUFFER AREA CONDITION METRICS

Attribute: Local Wetland Connectedness in first 1 km of Buffer Area

Data Sources:

- Model: Resistant kernel analysis (Compton et al. 2007)
- Landforms: 30-m landform model (Anderson et al. 2016) with 17 classes for the project area
- Land Cover: augmented version of NLCD 2011 (Homer et al. 2015) published in Anderson et al. (2016)

Analysis Steps:

1. Create resistance grid where each cell is coded with a resistance weight based on the slope and land position of that cell.
    a. Flatter areas (less slope) and/or areas that are lower (lower land position) are more likely to facilitate the connectedness of wetlands.
2. Experiment with a variety of focal distances, select 1km as it best represents flow of wetlands
3. To run the local connectedness analysis on the resistance surface, increase the grid cell size from 30 m to 90 m
4. Aggregate the 30 m cells to the 90 m cells using the average of the 30 m resistance weights (table below).
5. Output grid of 90-m cells where each cell was scored with a local connectivity value from 0 (least connected) to 100 (most connected).

Landform	code	Resistance
Steep slope (cool/warm aspect)	3/4	10
Cliff	5	10
Summit/ridgetop	11	5.5
Slope crest	13	7.5
Hilltop (flat)	21	3.5
Hill (gentle slope)	22	3.5
Sideslope (cool/warm)	23/24	5.5
Dry flats	30	1.5
Wet flats	31	1
Valley/toeslope	32	2
Moist flats	39	1.25
Flat at the bottom of a steep slope	41	1
Cove/footslope (cool/warm aspect)	43/44	3.5
Open water	50	1.5
Development		20

6. For each SLR scenario, run Zonal Mean to calculate the average local connectedness for each buffer unit

7. For each SLR scenario, use the buffer area units' area-based weights for each tidal complex to roll up the values to the tidal complex unit

Attribute: Percent Natural Cover in first 1 km of Buffer Area

Data Source:

- Land Cover: NOAA 2010 C-CAP (NOAA, 2017), https://coast.noaa.gov/ccapftp/#/
- Roads/Railroads: 2017 TIGER/Line roads and railroads (U.S. Census Bureau, 2017b)

Analysis Steps:

1. Relationship 1: Accessible migration space units and buffer area units
   a. For each accessible migration space SLR scenario polygon, run Euclidean distance (30 m, snap to NOAA C-CAP 2010), max distance of 1-km
   b. For each Euclidean distance output, Con to set 0 values to Null and all other values to 1
   c. Combine the Euclidean distance Con output with the buffer grid for each SLR scenario
   d. Run a Lookup on the combine grid to set the raster value to the buffer ID (gridcode)
   e. Tabulate area of agriculture and natural land using the Lookup grid buffer ID as the zone
   f. Using the tabulate area results, calculate percent of agricultural and natural land cover in the first 1-km buffer area
2. Relationship 2: Tidal complex units and buffer area units (since there were buffer units that only intersected tidal complexes (i.e., did not intersect the accessible migration space of tidal complexes), do the following steps:
   a. For the tidal complex polygon, run Euclidean distance (30 m, snap to NOAA 2010 C-CAP), max to 1000 m
   b. For the Euclidean distance output, Con to set 0 values to Null and all other values to 1
   c. Combine the Euclidean distance Con output with the buffer grid for each SLR scenario
   d. Run Lookup on the combine grid to set the raster value to the buffer ID (gridcode)
   e. Tabulate area of agriculture and natural land using the Lookup grid buffer ID as the zone
   f. Using the tabulate area results, calculate percent of ag and natural land cover in the first 1-km buffer area
3. As there are two sets of percent natural values:
   a. Run R script to combine the two sets of buffer 1-km mean values for each SLR scenario to ensure that a buffer area's relationship with a tidal

complex is not counted more than once (i.e., a buffer unit that is immediately adjacent to a tidal complex but is also linked to the tidal complex via the migration space).

4. For each SLR scenario, use the buffer area units' area-based weights for each tidal complex to roll up the values to the tidal complex unit

CONDITION SCORE CALCULATIONS

Tidal Complex and Migration Space (Site) Condition Score

The final condition score for the tidal complex and its migration space was calculated for each site using a weighted sum of the current condition characteristics.

Weighted Sums

To put the metrics onto a standard scale, each individual variable was converted to a Z-score (standard normal distribution) relative to its coastal shoreline region (CSR). To do this, we examined the distribution of each variable within each CSR. If the distribution was normal, we calculated the mean and standard deviation and used these to transform the values to standard normal (value – mean / standard deviation). If the distribution was skewed or otherwise distorted, we used various transformations to convert it to a normal distribution or used non-parametric techniques to calculate a Z-rank score based on the order, rank and number of the values.

When all the variables were on the same scale, we applied the variable weights agreed upon by our steering committee.

Attribute Weights

Each attribute was given a rank with respect to its importance for site resilience, and each was weighted on a numeric scale from 1 to 5 in terms of its influence and importance. The numeric weights were used as a multiplier when combining factors, with the objective of giving more weight to factors with more influence. The numeric weights were: 5 - very high, 4 - high, 3 - moderate, 2 - low, and 1 - very low.

Current Condition

Developed Upland Edge (5)
Sediment Balance (2)
Water Quality Index (1)
Flow Alteration (1)

____

Weighted Sum = Condition Score

The tidal complex and migration space condition score was calculated using the following equation:

*Site Condition Score = ((Tidal Complex Upland Edge Development * 5) + (Tidal Complex Sediment Balance * 2) + (Migration Space Water Quality * 1) + (Migration Space Flow Alteration * 1)) / 9*

Each site's condition score was converted to a new set of standardized normalized values (z-scores) using a z-rank procedure, after removing the very low scoring sites (essentially sites without any migration space or with very poor scores for all their condition attributes). The very low sites were manually assigned a z-score of -3.5 SD and then combined with the new set of z-scores.

Buffer Area Condition Score

The condition score for the buffer area was calculated for each site as a weighted sum of the current condition characteristics.

<u>Buffer Area Current Condition</u>

Wetland Connectedness (5)
Percent Natural Cover (5)

____

Weighted Sum = Buffer Area Condition Score

The buffer condition score was calculated using the following equation:

*Buffer Area Condition Score = ((Buffer Area Wetland Connectedness * 5) + (Buffer Area % Natural Land Cover * 5)) / 10*

ESTIMATED RESILIENCE CALCULATIONS

Tidal Complex and Migration Space (Site) Resilience Score
The resilience score for the tidal complex and its migration space was calculated for each site as a weighted sum of the two categories: physical options and current condition using the following equation:

Site Resilience Score = (Tidal Complex & Migration Space Final Physical Score + Tidal Complex & Migration Space Condition Score) / 2

Buffer Area Resilience Score
The resilience score for the buffer area was calculated for each site as a weighted sum of the two categories: physical options and current condition using the following equation:

Buffer Area Resilience Score = (Buffer Area Physical Score + Buffer Area Condition Score) / 2

Each buffer area's resilience score was converted to a new set of standardized normalized values (z-scores) using a z-rank procedure, after removing the very low scoring units. The very low units were manually assigned a z-score of -3.5 SD and then combined with the new set of z-scores.

Final Site Resilience Score
We calculated a final resilience score for each site as the weighted sum of the site resilience score (90%) based on the physical and condition characteristics (with appropriate thresholds and adjustments), and the buffer area resilience score (10%).

*Final Site Resilience Score = (0.90*Site Resilience Score) + (0.10*Buffer Area Resilience Score)*

The final scores are in standard normal units (z-scores) relative to the site's coastal shoreline region (river-dominated, lagoonal, etc.). We grouped the scores into the following categories, which are used throughout the results section and serve as the legend for the various maps:

- Far Below Average (<-2 standard deviations) - Most Vulnerable
- Below Average (-1 to -2 standard deviations) - More Vulnerable
- Slightly Below Average (-0.5 to -1 standard deviations) - Somewhat Vulnerable
- Average (-0.5 to 0.5 standard deviations) - Average
- Slightly Above Average (0.5 to 1 standard deviations) - Somewhat Resilient
- Above Average (1- 2 standard deviations) - More Resilient
- Far Above Average (>2 standard deviations) - Most Resilient

ADDITIONAL MIGRATION SPACE ATTRIBUTES

Attribute: Migration Space Percent Securement

Data Source:

- Secured Lands: dataset of secured areas for the Eastern US (Eastern Conservation Science, 2017)

Analysis Steps:

1. Select secured lands with GAP status of 1,2, or 3
2. For each SLR scenario, tabulate area of secured lands in the geophysical migration space and calculate percent of the migration space in securement
3. For each SLR scenario, use the migration space area-based weights for each tidal complex to roll up the migration space percent securement values to the tidal complex unit

Attribute: Migration Space Percent Future Development (2100)

Data Sources:

- Future Land Cover: Land Transformation Model (LTM) Version 3 developed by the Human-Environment Modeling and Analysis Laboratory at Purdue (Tayyebi et al. 2013)
- Secured Lands: dataset of secured areas for the Eastern US (Eastern Conservation Science, 2017)

Analysis Steps:

1. Select LTM 2100 land cover data (us_2100_urbv3)
2. Convert TNC internal secured lands (GAP status 1-3) to a 30-m raster, snap to LTM 2100 grid
3. Remove all secured lands from the future development grid.
4. For each SLR scenario, tabulate area of future development for the migration space and calculate % of migration space expected to be developed in 2100
5. For each SLR scenario, use the migration space area-based weights for each tidal complex to roll up the migration space flow alteration values to the tidal complex unit