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Natural Resource Stewardship and Science

Marine Vulnerability Assessment of Cumberland Island National Seashore

Determining the vulnerability of marine habitats at Cumberland Island National Seashore to climate change stressors

Natural Resource Report NPS/CUIS/NRR—2016/1281

ON THIS PAGE
Salt flat in high marsh of Cumberland Island National Seashore
Photograph by: Program for the Study of Developed Shorelines, Western Carolina University

ON THE COVER
Tidal creek and shellfish beds at Cumberland Island National Seashore
Photograph by: Program for the Study of Developed Shorelines, Western Carolina University

Marine Vulnerability Assessment of Cumberland Island National Seashore

Determining the vulnerability of marine habitats at Cumberland Island National Seashore to climate change stressors

Natural Resource Report NPS/CUIS/NRR—2016/1281

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Executive Summary

The impacts of climate change resulting from elevated levels of atmospheric carbon and manifested primarily through increasing global temperatures are affecting coastal and marine habitats and are anticipated to become more significant in the coming decades. Sea-level rise (SLR) and changes in ocean chemistry make coastal habitats among the most vulnerable. The National Park Service (NPS), managing almost 12,000 km of shoreline, has an urgent need to better understand, characterize, and forecast the effects of climate change for mitigation and management purposes.

The goal of this project is to develop a methodology framework for assessing the vulnerability of NPS-managed marine habitats, beginning with a pilot project at Cumberland Island National Seashore (CUIS). This framework employs an assessment approach in which vulnerability is defined as the sum of exposure (the magnitude of the stressor), sensitivity (how strongly a system is affected by the stressor), and adaptive capacity (the potential to adjust in response to the stressor).

Nine marine habitats within CUIS, including marine nearshore subtidal, intertidal beach, low salt marsh, salt flats, high fringing salt marsh, shellfish beds, tidal mud flats, tidal creeks, and estuarine nearshore subtidal, were identified, delineated and assessed for their vulnerability to four climate change-related stressors: SLR, temperature change, salinity change, and ocean acidification. For each habitat-stressor combination, exposure, sensitivity, and adaptive capacity were rated on a qualitative scale of low-medium-high.

Results for combined stressor vulnerability at CUIS show SLR to be the most significant climate-related stressor and shellfish beds to be the most vulnerable habitat. This habitat is highly exposed to all stressors except ocean acidification, and is moderately sensitive to all four stressors. High fringing salt marsh (the narrow and sporadic zone between the expansive low salt marsh and the uplands) is also among the most vulnerable habitats at CUIS due to its high sensitivity to SLR, small area coverage, and reduced adaptive capacity from decreased migration potential. Changes in salinity and sea level would likely reduce the overall suitability for the growth of high fringing salt marsh species (i.e., *Juncus roemerianus*) as well as increase competition, particularly with the ubiquitous low marsh species *Spartina alterniflora*.

In addition to climate change-related stressors, non-climate stressors were also considered. The primary non-climate stressors impacting CUIS marine habitats include feral horses, erosional impacts of boat wakes, and water quality degradation resulting from development and upstream contamination. This vulnerability assessment serves as a foundation upon which effective strategies for managing CUIS marine resources and habitats vulnerable to both climate and non-climate stressors can be developed and implemented.

Summarized Major Findings:

- Nine marine habitats of interest were chosen at CUIS, as well as four climate change stressors of interest (SLR, ocean acidification, salinity change, and temperature change).
- The metrics of vulnerability (exposure, sensitivity, and adaptive capacity) were used to assess the overall climate change risk of habitats of interest at CUIS.
- Salt flats are most vulnerable to salinity change as the vegetation in this zone is dependent on high interstitial salinity.
- Tidal creeks and estuarine nearshore subtidal habitats are most vulnerable to temperature change due to existing problems with high summer water temperatures leading to low dissolved oxygen.
- Estuarine nearshore subtidal habitat is likely most vulnerable to temperature change as it already experiences issues with this stressor.
- Sea-level rise is likely the most significant climate-related stressor at CUIS, and the high fringing salt marsh is the habitat most vulnerable to SLR, due to small area coverage and reduced adaptability from decreased migration potential.
- Shellfish beds are the most vulnerable habitat overall at CUIS (all stressors combined equally). Shellfish have the potential for a moderate sensitivity to all four stressors of interest.
- The high fringing salt marsh is potentially the most vulnerable habitat, considering SLR is likely the most significant stressor at CUIS. This habitat is limited in area and confined to more specific conditions. Habitat migration is also partially hindered by terrestrial habitat.
- The confidence level for the metric of vulnerability scores can be used to help focus resources for adaptation strategies within CUIS. Vulnerable habitats with a high confidence level are a reasonable place to start adaptation planning.
- Physical or intrinsic adaptive capacity should be considered as well as the extrinsic or "management-based" adaptive capacity. The adaptation strategies for some stressors may limit or enhanced the overall adaptive capacity of a habitat.
- Interactions between the climate change stressors of interest (as well as other climate threats) are inevitable, but are hard to predict. Sea-level rise and salinity are two stressors that have a clear link. With increased SLR, salinity will also increase in most of the marine environments at CUIS.

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List of Terms & Acronyms

CUIS – Cumberland Island National Seashore
CVI – Coastal Vulnerability Index (from USGS)
DO – Dissolved Oxygen
DNR – Department of Natural Resources
FL – Florida
GA – Georgia
GIS – Geographic Information Systems
I&M – Inventory and Monitoring Program (NPS)
ENS – Estuarine Nearshore Subtidal (Habitat of Interest)
HFSM – High Fringing Salt Marsh (Habitat of Interest)
MNS – Marine Nearshore Subtidal (Habitat of Interest)
MSL – Mean Sea Level
MLLW – Mean Lower Low Water
NC – North Carolina
NPCA – National Park Conservation Association
NOAA – National Oceanic and Atmospheric Administration
NPS – National Park Service
OA – Ocean Acidification
PSDS – Program for the Study of Developed Shorelines
SLR – Sea-Level Rise
SECN – Southeast Coast Network
U.S. – United States
USGS – United States Geological Survey
WCU – Western Carolina University
WA – Washington state

Introduction

Purpose of Study

Over the next century, climate change will pose a serious threat to natural environments, cultural resources, and infrastructure along coastlines around the globe. Climate change factors will also present many challenges for the National Park Service (NPS) and public land managers. Increasing ocean temperatures and sea-level rise (SLR) will significantly alter the landscape of low-lying coastal parks. Climate-related changes will also increase the risk of coastal hazards such as erosion and storm impacts.

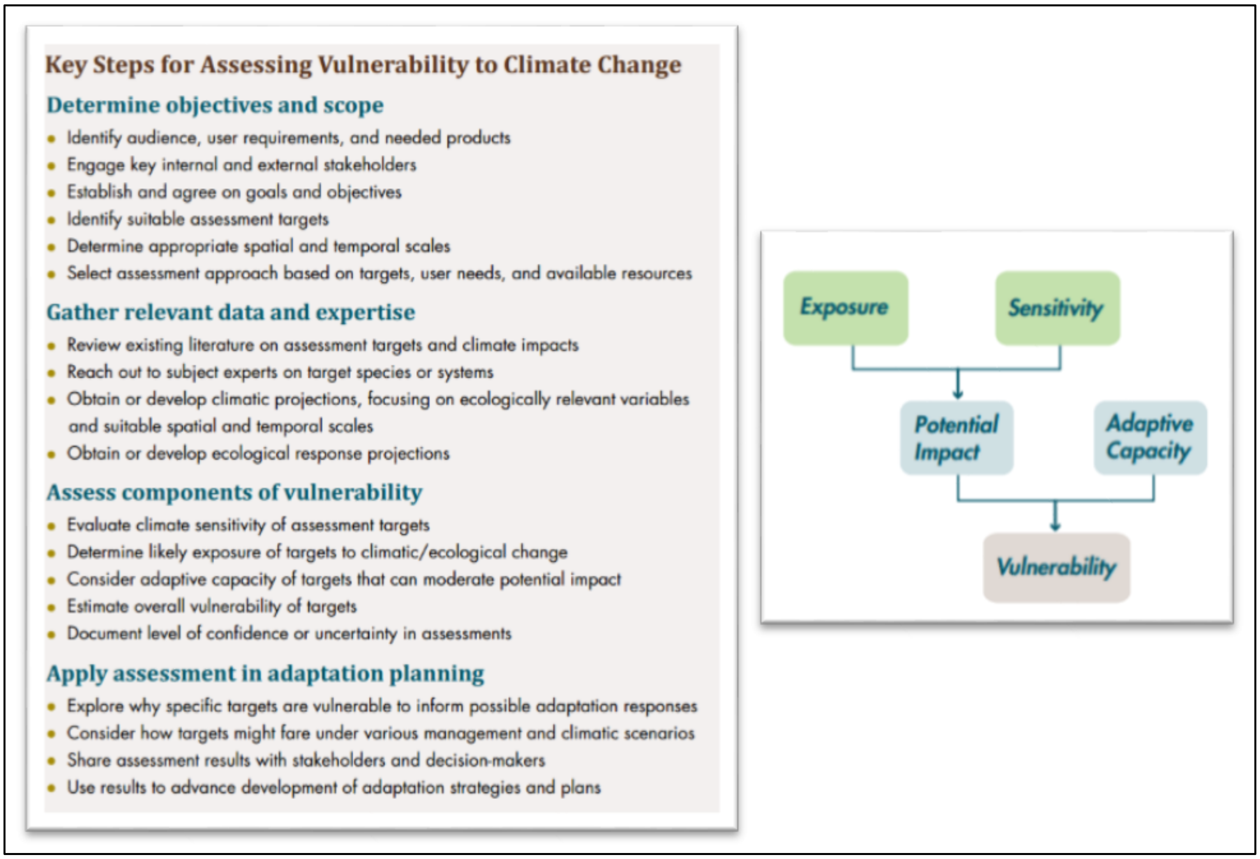
The increasing risk of climate-related change has prompted the NPS to begin an assessment of the vulnerability and adaptability of resources within our national parks. One area of concern for coastal parks is effects on critical marine environments such as salt marshes, oyster beds, and coral reefs. Climate change is likely to have significant implications for these types of marine ecosystems. Marine climate stressors such as SLR, water temperature, and salinity could not only negatively affect the natural environment but also affect the economy and livelihood of those who depend on marine resources. This concern has prompted a collaborative study between the NPS and the Program for the Study of Developed Shorelines (PSDS) at Western Carolina University (WCU), focusing on vulnerability of NPS marine environments to climate change.

The National Park System contains 88 units on the ocean and Great Lakes, each with a unique set of coastal and marine resources that are being impacted by climate change. This project was designed to explore general methods of determining climate change vulnerability of marine environments, primarily using existing data and research. Cumberland Island National Seashore (CUIS) was chosen as a pilot park to test these methods. This framework can then be applied within other coastal parks across the nation.

Vulnerability assessments, like this one, are the first step in climate change adaptation. It is necessary to understand the risk of a system to climate impacts before adaptation strategies can be implemented. The National Wildlife Federation (in conjunction with the NPS, the United States Geological Survey [USGS], U.S. Fish and Wildlife Service, the National Oceanic and Atmospheric Administration [NOAA], and other agencies) published a document related to climate change vulnerability and adaptation in 2011 (*Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessments*, Glick et al., 2011). This document serves as a guidebook for managers to use in planning and interpreting climate change vulnerability assessments, and describes four key steps for assessing vulnerability to climate change: 1) determine objective and scope, 2) gather relative data and expertise, 3) assess components of vulnerability, and 4) apply assessment in adaptation planning (Figure 1). All four keys steps (Figure 1) outlined by Glick et al. (2011) were utilized as part of this climate change vulnerability assessment. Vulnerability is described as having three components: exposure, sensitivity, and adaptive capacity (Glick et al., 2011); exposure and sensitivity are discussed as the “potential impact” of the stressor, and the adaptive capacity as how the system responds or copes with the impacts of the stressor (Figure 1). These three “metrics” or components were adopted for this study and make up the basic framework for the CUIS vulnerability assessment.

Objectives, Scope, and Background Research

The key objective of this study was to assess the vulnerability of marine habitats at CUIS to climate change stressors using existing literature, data, and research. Four climate change stressors were chosen (SLR, ocean acidification, salinity change, and temperature change) as well as nine habitats (see section on habitats of interest). Our assessment was focused on the current and short term (decadal scale) climate change vulnerability of these habitats and is not meant to provide vulnerability over the long term (century scale) or during extreme/rapid stressor change scenarios. A significant portion of this assessment was focused on gathering relevant data and expertise (the second step of the National Wildlife Federation guidebook); previous research and data collection was the principal source of information for assessing the metrics of vulnerability (Figure 1; Glick et al., 2011).



Key Steps for Assessing Vulnerability to Climate Change

Determine objectives and scope

- Identify audience, user requirements, and needed products
- Engage key internal and external stakeholders
- Establish and agree on goals and objectives
- Identify suitable assessment targets
- Determine appropriate spatial and temporal scales
- Select assessment approach based on targets, user needs, and available resources

Gather relevant data and expertise

- Review existing literature on assessment targets and climate impacts
- Reach out to subject experts on target species or systems
- Obtain or develop climatic projections, focusing on ecologically relevant variables and suitable spatial and temporal scales
- Obtain or develop ecological response projections

Assess components of vulnerability

- Evaluate climate sensitivity of assessment targets
- Determine likely exposure of targets to climatic/ecological change
- Consider adaptive capacity of targets that can moderate potential impact
- Estimate overall vulnerability of targets
- Document level of confidence or uncertainty in assessments

Apply assessment in adaptation planning

- Explore why specific targets are vulnerable to inform possible adaptation responses
- Consider how targets might fare under various management and climatic scenarios
- Share assessment results with stakeholders and decision-makers
- Use results to advance development of adaptation strategies and plans

Figure 1. Two figures from National Wildlife Federation assessment guidance document (Glick et al., 2011). Left: List of key steps for Assessing Vulnerability to Climate Change. Right: Diagram relating the key components of vulnerability.

The primary audience for this type of assessment is managers and decision-makers at the park level, which is meant to provide guidance and information regarding the relative vulnerability of different marine habitats within one particular unit, in this case, CUIS. In other words, the results for this vulnerability assessment are CUIS-specific and are not relevant to other NPS locations. While the scope for this pilot project was focused on comparing marine habitats *within* CUIS, this vulnerability assessment framework and methodology could be transferred to a different geographic scale (regional or NPS-wide). For example, this methodology could be used to assess the relative vulnerability (to one or more stressors) of the same habitat between different parks, which may be more useful on the regional or national level of the NPS.

Cumberland Island National Seashore

Cumberland Island is a barrier island located in southeastern Georgia (GA) just north of the border with Florida (FL) (Figure 2). Cumberland Island is approximately 28 km in length with 283 km of shoreline and an area of almost 150 km^2, including 43 km^2 of marine and estuarine waters. A large portion of the island is part of the national seashore, managed by the NPS. However, the island is also managed by several other entities, including the state of GA and several private owners. The intertidal and subtidal zones are managed by the Coastal Resources Division of the GA Department of Natural Resources (DNR). Due to the complicated nature of inholdings and jurisdiction, all areas of Cumberland Island within the CUIS boundary (including the surrounding marshes and tidal creeks) were included as part of this study and were treated uniformly regardless of management or jurisdiction. Also, any further mention of Cumberland Island in this document refers to both the island proper as well as Little Cumberland Island to the north (Figure 2).

Unlike the long, linear, wave-dominated barrier islands that make up much of FL and the Carolinas, Cumberland Island is a mixed-energy barrier island, with almost 2 meters of tidal range (Hoyt et al., 1964) and seasonal storms controlling coastal processes (Hayes, 1994; Graham, 2009). Cumberland Island is more curved and wider than its wave-dominated counterparts; the island is over 4 km wide in some locations. Relatively stable inlets separate Cumberland from Jekyll Island to the north and Amelia Island, FL to the south. The southern inlet, St. Mary's River, is approximately 1 km wide, and is constrained on both sides by man-made jetties. However, the Satilla River Inlet to the north is more natural, with a wide channel (~4 km) comprised of extensive sand shoal deposits (Figure 2).

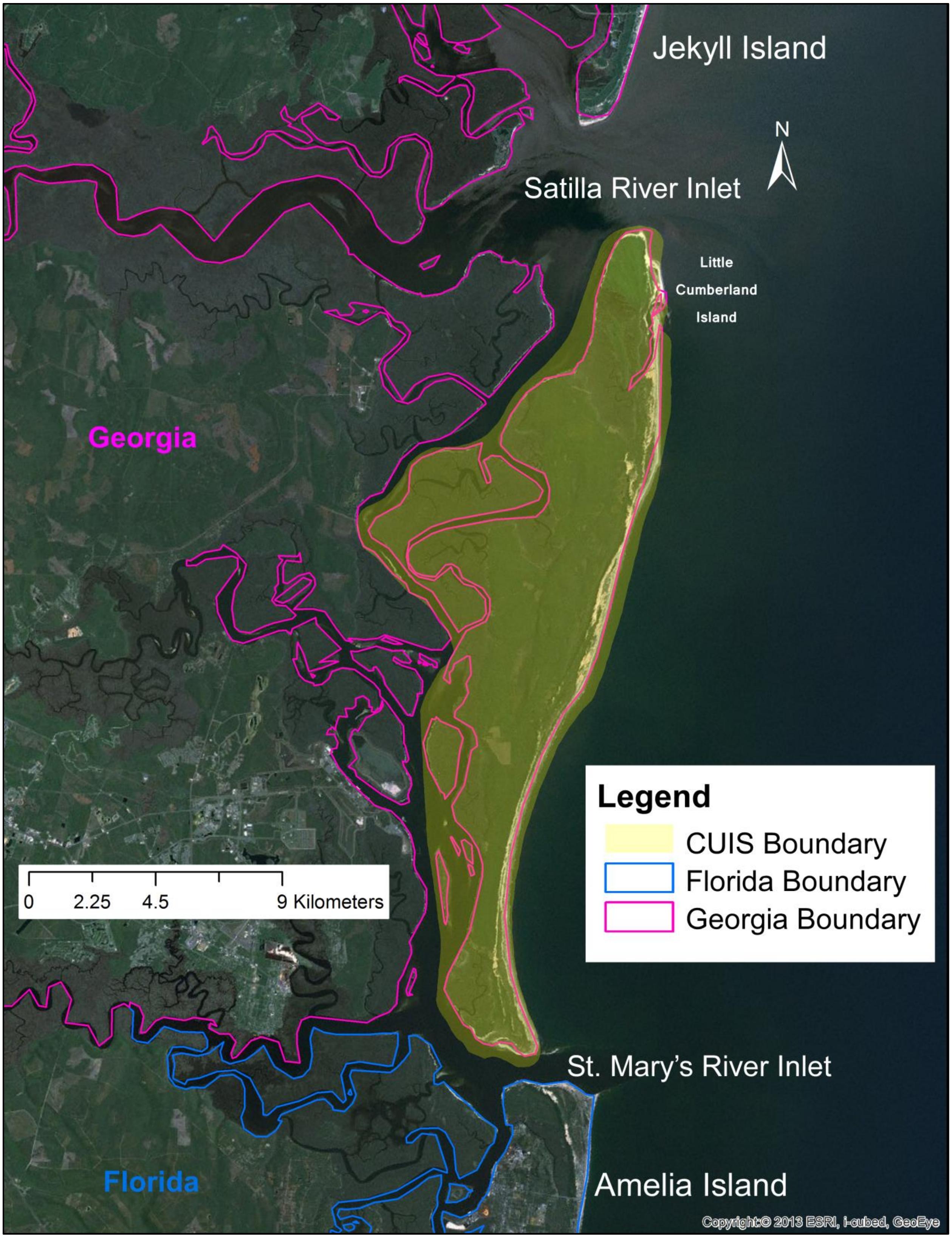


Figure 2. Location map of study area: Cumberland Island National Seashore (CUIS) and vicinity.

Geology of Cumberland Island

The central core of Cumberland Island was formed approximately 40,000 years ago during the Pleistocene (Oertel, 1979; Griffin, 1982; Dilsaver, 2004; Alber et al., 2005). At this time, global sea level was falling as glaciers expanded over the continents; this cooling trend continued until its peak at the last glacial maximum, around 20,000 years ago (Yokoyama et al., 2000). Then, as climate warmed and the large continental glaciers retreated, the resulting rise in sea level added additional sediments onto the exterior of the existing Pleistocene barrier island. These Holocene sediments (about 4,000–5,000 years ago) make up the outer portions (i.e., beaches, primary dunes, active spits, and marshes) of modern day Cumberland Island (Hoyt et al., 1964; Dilsaver, 2004; Alber et al., 2005).

Most of Cumberland Island has the typical cross-section of a large, stable barrier island. On the seaward side near the Atlantic Ocean is the modern dune and beach environment (Figure 3). Due to storms and horse grazing, there are varying degrees of stability within dune systems on the island, regardless of their height and vegetation. In general, the active beaches and dunes are continuously shifting and changing in width and height, with some dunes on the island growing quite large: up to 12 m above mean sea level (MSL). At the same time, significant portions of these large dunes are inactive, having become vegetated over time. To the west of the dunes is extensive maritime forest, which has formed on top of Pleistocene relict beach ridges and deposits, and comprises a wide section of the island's interior. Finally, the westernmost portion of Cumberland Island is made up of tidally-influenced salt marshes, tidal creeks, and mudflats (Figure 3). Some cross-sections of the island differ slightly from this model. For example, some of the dune fields in the extreme northern and southern portions of the island are replaced by active and relict sand spit deposits.

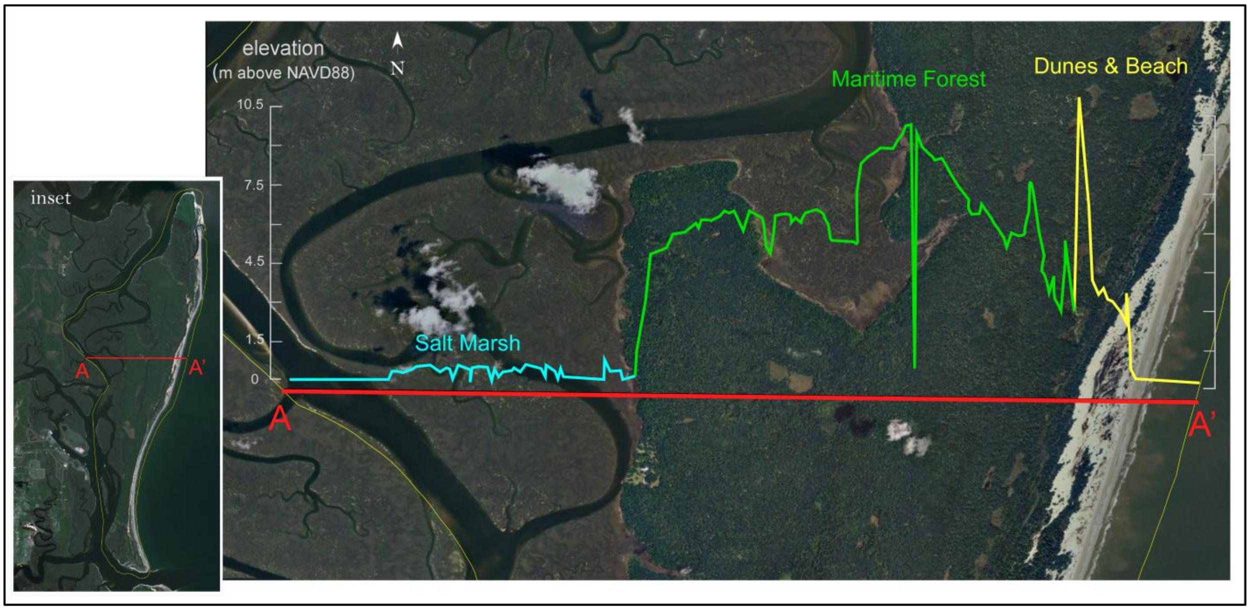


Figure 3. Elevation profile across the central portion of CUIS. Profile elevation data was generated in ArcGIS using the 2010 GA Topographic LiDAR. Inset map shows the location of the profile within CUIS.

Human History of Cumberland Island

Cumberland Island has at least 4,000 years of documented human history. Archaeological investigations have uncovered numerous cultural and pre-historic resources such as shell middens and mounds, primarily from the Timucuan American Indians (Dilsaver, 2004). Physical and ecological modifications to the island began to occur in the 16th and 17th centuries, with the arrival of Spanish and British explorers. Historical structures from this time can also be found, including forts and slave quarters.

American settlers established plantations on Cumberland Island following the Revolutionary War, which further altered the landscape, introducing both non-native crops as well as livestock. Many of the historic structures from this time (later 1800's to early 1900's) are still preserved today, including mansions and lodgings utilized by wealthy families such as the Carnegies (Figure 4A). In fact, a number of the private inholdings that exist today within CUIS boundaries belong to heirs of wealthy families that inhabited the island during this time.

The national seashore (CUIS) itself was not officially established by Congress until 1972 (NPCA, 2009). Since then, much of the island has recovered from the changes caused by agriculture and plantations. Maritime forest has taken over much of the once farmed land. However, feral horses and pigs are still widespread on the island today and can cause damage to the natural landscape (Figure 4B).

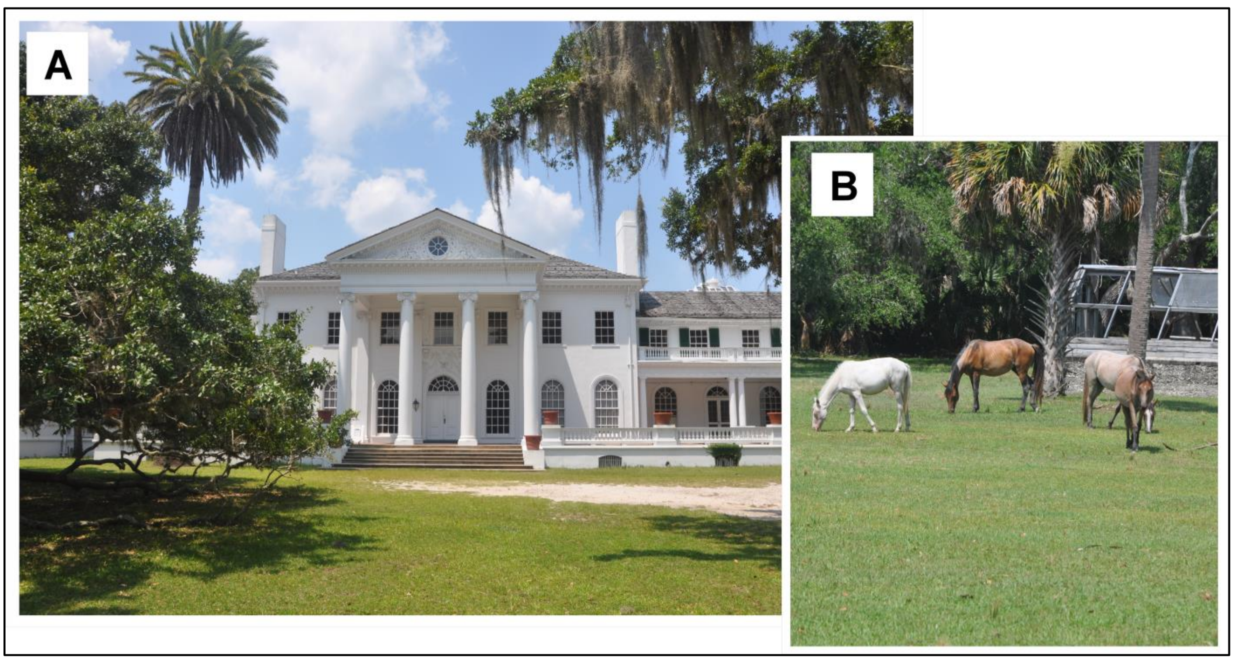


Figure 4. A) Plum Orchard mansion, located on the sound side of CUIS; the mansion was built by Lucy Carnegie for her son in 1898. B) Feral horses grazing on the grounds of CUIS. Photos courtesy of PSDS at WCU.

Vulnerability Assessment Research

Vulnerability studies exhibit a great deal of variation in scope (environmental, socioeconomic, and ecological), scale (e.g., species, habitat, regional, national), and stressors (SLR, coastal erosion, etc.). Most studies focus on the environmental aspects of vulnerability, i.e., the physical processes and responses of the study area to the stressor. Some studies also address the ecological aspects (i.e., the biological processes and responses to the stressor) and socioeconomic aspects (Table 1). Many environmental studies address some ecological issues, such as the effects of stressors on certain key habitat types, but do not assess ecosystem responses to stressors in much detail. Vulnerability assessments, both national and international, commonly use a qualitative scoring system (Tables 1 and 2)—typically a five "level" scale such as very high, high, vulnerable, low, and very low (e.g., Gornitz et al., 1994; Diez et al., 2007; Pendleton et al., 2010; Yin et al., 2012; Manomet Center & National Wildlife Federation, 2013; see Tables 1 and 2). Such qualitative assessments often provide broader and more comparative analyses (e.g., Pendleton et al., 2004-2007; Bilkovic et al., 2009), while quantitative studies typically focus on specific stressors and/or ecosystems and the potential for change over time (e.g., Osland et al., 2013). Most vulnerability assessments utilize a combination of quantitative methods and data, as well as qualitative comparative rankings.

Climate change vulnerability studies commonly examine one or more climate stressors. On a national scale, Monahan and Fisichelli (2014a) assessed the climate change exposure of 289 NPS units (including CUIS) by examining the sensitivity to climate stressors such as temperature and precipitation in the context of the historical range of variability. Within coastal areas, the most frequently assessed climate stressor is SLR, as this has the potential for the greatest effect on coastal communities and ecosystems due to loss of land from inundation. Halpern et al. (2007) found that SLR was the most impactful of several climate stressors. Specifically at CUIS, studies have examined stressors such as SLR (Pendleton et. al., 2005-CUIS), temperature and precipitation (Monahan and Fisichelli, 2014b), and potential hurricane flooding (Stockdon et. al., 2007). Other commonly addressed stressors include water temperature, salinity, ocean acidification (OA), and dissolved oxygen (DO) (Table 1).

Many NPS assessments of coastal climate change susceptibility have focused on the exposure and sensitivity of physical habitats to SLR (e.g., Pendleton et al., 2005-CUIS). They have not addressed other climate stressors on marine resources, such as biological/ecological components of habitats, and the habitats' inherent capacities to adapt to climate-related changes. Recent studies that have addressed these broader issues have taken place outside of the NPS, primarily internationally (Tables 1 and 2).

More recently, marine vulnerability assessments have borrowed from the risk management field, employing a framework where vulnerability takes into account exposure, sensitivity, and adaptive capacity (Smit and Wandel, 2006). This approach considers a system's potential to adjust in response to climate-related changes. Notable examples using this framework for marine vulnerability are assessments of climate change impacts on Australia's Great Barrier Reef (Marshall and Johnson, 2007) and Canada's Pacific coast (Okey et al., 2012).

National Park Service Marine Vulnerability Assessments

The NPS, as well as many other Department of the Interior (DOI) agencies, has adopted a consistent framework for conducting vulnerability assessments for natural and built environments (Glick et al., 2011). The NPS defines climate change vulnerability as "the extent to which a species, habitat or ecosystem is susceptible to harm from climate change impacts" (Glick et al., 2007; Schneider et al., 2007). The definition also includes the three previously mentioned "metrics" that should be considered for any vulnerability assessment: exposure, sensitivity, and adaptive capacity. These three metrics were used within this study and are defined as follows (Glick et al., 2011):

- **Exposure** refers to how much of a change in climate and climate associated problems a species or system is likely to experience.
- **Sensitivity** refers to the degree to which a species, habitat, or ecosystem is likely to be affected by or responsive to those changes.
- **Adaptive capacity** refers to the ability of a species, habitat, or ecosystem to accommodate or cope with climate change impacts with minimal disruption.

The physical susceptibility of NPS properties to SLR has been examined in a qualitative fashion (Table 1). Pendleton et al. (2004 to 2007), in a joint project by the NPS and the USGS, produced a series of studies assessing the threat of SLR to coastal areas within the NPS (including CUIS) using a Coastal Vulnerability Index (CVI) (based on prior work by Gornitz et al., 1994, Shaw et al., 1998, and Thieler and Hammar-Klose 1999). In these assessments, the term "vulnerability" was roughly equivalent to the combined "exposure and sensitivity" terms used herein. The threat imposed by SLR was assessed primarily from a geological/physical perspective and did not address ecological issues or the potential adaptive capacity of different habitats.

Pendleton et al. (2004 to 2007) calculated the CVI based on ratings of six geological and physical process variables: geomorphology, historical shoreline change rate, regional coastal slope, relative sea level change, mean significant wave height, and mean tidal range. The CVI was calculated as the square root of the product of the ratings (each on a scale of 1–5) divided by the number of variables. The CVI was used to assess the relative susceptibility of beach areas within parks, rather than among parks. The rating system for each variable was not necessarily consistent for each park; it was dependent on what values were typical of that variable in the region (e.g., compare the system for CUIS [Pendleton, et al., 2004-CUIS] with that for the National Park of American Samoa [Pendleton et al., 2004-NPSA]). For studies with the same or similar rating systems, the calculated CVIs may be comparable. Geomorphology, shoreline change, and significant wave height typically had the strongest influence on calculated CVI, as these variables exhibited the most variation within the park.

Non-NPS National Marine Vulnerability Assessments

Several studies of non-NPS areas in the United States (U.S.) have used the Gornitz et al. (1994) and Thieler and Hammar-Klose (1999) CVI in some form (Table 1). Other studies have addressed vulnerability qualitatively (Table 2); qualitative studies typically incorporate many types of data on exposure and sensitivity to climate stressors but do not produce a numerical value for vulnerability.

Several of these studies employ the vulnerability = exposure + sensitivity + adaptive capacity (V = E + S + AC) framework methodologically, if not numerically (Table 1a and Table 1b).

Osland et al. (2013) developed models to predict how climate change could cause change in wetlands species within the southern U.S. Specifically, they found that more frequent and intense extreme winter events could have a detrimental effect on salt marsh ecosystems and subsequently accelerate the poleward migration of mangrove forests (Osland et al., 2013).

Table 1a. Select marine vulnerability assessments for the U.S. from NPS sources.

Authors	Year	Place (s)	Stressors	Method	Scope
USGS varied authors, primarily Pendleton et al. and Hammar-Klose et al.	2003 to 2007	CACO, GUIS, OLYM, CUIS, DRTO, CAHA, FIIS, VIIS, PAIS, ASIS, NPSA, CHIS, GATE, GOGA, WAPA, FIIS	SLR	CVI	physical
Stockdon & Thompson	2007	FIIS	hurricane flooding	storm-impact scaling model	physical
Stockdon et al.	2007	CUIS	hurricane flooding	storm-impact scaling model	physical
Monahan and Fisichelli	2014b	CUIS	temperature, precipitation	quantitative	physical, ecological

Table 1b. Select marine vulnerability assessments for the U.S. from non-NPS sources.

Authors	Year	Place (s)	Stressors	Method	Scope
Gornitz et al.	1994	Southeast USA	SLR	CVI	physical
Cooper et al.	2008	New Jersey	SLR	inundation model	physical
Pendleton et al.	2010	Northern Gulf of Mexico	SLR	CVI	physical
Bilkovic et al.	2009	Virginia	SLR, temp., salinity	qualitative	physical, ecological
Manomet Center & National Wildlife Federation	2013	Northeast USA	climate change	qualitative	ecological
Osland et al.	2013	Southeast USA	climate change	quantitative	ecological
Ekstrom et al.	2015	USA	OA	qualitative	social; physical exposure

The U.S. study most relevant to the present CUIS study is a vulnerability assessment of the estuarine tidal waters and wetlands of Virginia (Chesapeake Bay) by Bilkovic et al. (2009). The goal of this assessment was to predict climate-driven changes due to SLR, temperature, salinity, and human development. The authors modeled projections based on a range of climate scenarios, resulting in predicted "shifts" in the various habitats. This included temperature effects on the distribution of eelgrass (not present in CUIS), the invasion of tropical species (a potential issue for CUIS), and the timing of temperature-based spawning cues (a potential issue in the nursery habitats of CUIS). They predicted that salinity gradients will shift upstream with SLR, changing the relative areal coverage of different salinity-controlled habitats (Bilkovic et al., 2009).

International Marine Vulnerability Assessments

There have been many SLR susceptibility studies outside of the U.S., several of which use the CVI (Gornitz et al., 1994; Thieler and Hammar-Klose, 1999) (Table 2). There have also been a few studies that address ecological vulnerability to various climate change variables. Sheaves et al. (2007), as part of an expansive vulnerability assessment of marine resources in the Great Barrier Reef region (east coast of Queensland state, Australia), examined ecological vulnerability of the Coastal Ecosystem Mosaic, a diverse group of coastal and estuarine habitats. The Great Barrier Reef Coastal Ecosystem Mosaic contains many similar habitats to those found at CUIS, including beaches, salt marshes, and estuarine wetlands. This vulnerability assessment discussed the V = E + S + AC framework, although no vulnerability metrics were specifically calculated. Sheaves et al. (2007) also addressed a variety of climate-related stressors, including SLR, OA, and changes in temperature and salinity. Weather changes (rainfall and severe weather events) were also incorporated, and the potential effects of freshening (due to increased rainfall and runoff) and salinization (due to SLR) on brackish and freshwater wetlands, respectively, were discussed in detail (Sheaves et al., 2007). They found that climate-driven changes in the Coastal Ecosystem Mosaic are likely to be unpredictable in direction and extent, and that the ecosystems face particular stress from SLR.

In a comprehensive assessment of the Galápagos Islands (Larrea and Di Carlo, 2011), Banks et al. (2011) examined the threats of SLR, temperature change, precipitation, and OA on marine habitats (Table 2). The assessment addresses exposure and sensitivity, but not adaptive capacity. Although Galápagos contains some similar habitats to those of CUIS, these specific habitats are not examined in detail. In contrast to the patterns observed regionally, sea surface temperatures and sea level have not risen recently around Galápagos, although rainfall has increased over the last century. OA is considered the most serious threat, due to the abundance of coral reefs in the area; the reefs will likely not survive given the expected pH conditions by the end of the 21st century. Changes in upwelling patterns are also of concern for this area (Banks et al., 2011).

Okey et al. (2012) performed a similar vulnerability assessment of habitats on Canada's Pacific coast to climate change using the V = E + S + AC framework (Table 2). The report addressed a variety of climate-related stressors (including temperature, salinity, OA, and SLR, in addition to other climate- and weather-related variables) for a range of habitats (including estuaries, salt marshes, and tidal flats) and taxonomic groups (particularly benthic invertebrates and commercial fish species) (Okey et al., 2012). The authors preliminarily calculated relative climate impact scores (exposure plus sensitivity) for temperature change, OA, and changes in ultraviolet radiation. Using exposure data from various sources and sensitivity data derived from surveys of experts in Teck et al. (2010), the calculated impact scores were highest for intertidal habitats, as all three stressors (temperature, acidification, and UV) tend to have higher impacts in shallower waters. Adaptive capacity was not integrated into the metrics; it was addressed as a human management issue rather than an inherent property of the habitats themselves (Okey et al., 2012). Like Sheaves et al. (2007), the authors concluded that although some long-term trends are predictable (e.g., sea level will rise), other climate stressors are more difficult to predict in terms of direction and magnitude (e.g., sea surface temperature).

Table 2. Select international marine vulnerability assessments.

Authors	Year	Place (s)	Stressors	Method	Scope
Sheaves et al.	2007	Great Barrier Reef CEM, Australia	extreme weather events, SLR, rainfall, water temperature, OA	E+S+A, qualitative	ecological, physical
Diez et al.	2007	Buenos Aires Province, Argentina	SLR	CVI	physical
Eliot et al.	1999	Alligator Rivers Region, Australia	climate change, SLR	qualitative	physical, ecological
Abuodha and Woodroffe	2010	Illawarra coast, Australia	SLR	CVI	physical
Li et al.	2004	China	relative SLR, coastal wetland renewal, coastal erosion, coastal flooding	qualitative	physical, socioeconomic
Yin et al.	2012	China	SLR	CVI	physical
Muehe and Neves	1995	Brazil	SLR	qualitative	physical, socioeconomic
Kont et al.	2003	Estonia	SLR	modeling, qualitative	physical
Paskoff	2004	France	SLR	qualitative	physical
Dwarakish et al.	2009	Karnataka state, India	SLR	CVI	physical
Kumar et al.	2010	Orissa state, India	SLR	CVI	physical
Nageswara et al.	2008	Andhra Pradesh, India	SLR	CVI	physical
Snoussi et al.	2008	Eastern coast of Morocco	SLR	qualitative	physical, socioeconomic
Frihy	2003	Nile River Delta, Egypt	SLR	qualitative	physical
Okey et al.	2012	Pacific coast of Canada	SLR, temperature, salinity, ocean pH, oxygen, runoff, etc.	E+S+A, qualitative	ecological
Nicholls and Hoozemans	1996	Mediterranean coasts	SLR	qualitative	physical, socioeconomic

Table 2 (continued). Select international marine vulnerability assessments.

Authors	Year	Place (s)	Stressors	Method	Scope
Nunn and Mimura	1997	Pacific islands	SLR	qualitative	physical, socioeconomic
Alpar	2009	Turkey	SLR	qualitative	physical
Banks et al.	2011	Galapagos Islands	temperature, precipitation, ocean pH, upwelling	qualitative	ecological

CUIS Research & Monitoring

Cumberland Island is experiencing SLR in line with regional observations of the U.S. Atlantic coast (Zervas, 2009). Relative SLR at nearby Fernandina Beach, FL is approximately 2.01 mm/year; SLR ranges between 2 and 4 mm/year along the Atlantic coasts of the southeast and mid-Atlantic states (Zervas, 2009; NOAA Tides and Currents, Sea Level Rise). Pendleton et al. (2004-CUIS) assessed the susceptibility of the seaward shore of CUIS to SLR based on six geological and physical factors: geomorphology, historical shoreline change rate, regional coastal slope, relative sea level change, mean significant wave height, and mean tidal range. Of nearly 30 km (18.5 miles) of shoreline that was evaluated, 22% was classified as being very highly vulnerable to SLR, 28% was classified as highly vulnerable, 28% was classified as moderately vulnerable, and 22% was classified as being of low vulnerability (Pendleton et al., 2004-CUIS).

The Southeast Coast Network (SECN) monitors the “vital signs” for 20 units within the southeastern region, including CUIS. These vital signs are related to categories including air and climate, geology and soils, water, biological integrity, human use, and ecosystem patterns and processes (DeVivo et al., 2008). This monitoring is described regularly within the NPS Natural Resources Data Series Reports. For example, at CUIS, vegetation community monitoring was conducted in 2009 as part of the vital signs program. Thirty locations were chosen for vegetation sampling of the canopy, shrub, and groundcover (Byrne et al., 2012). However, this vegetation monitoring was focused on the terrestrial upland and did not sample the marine habitats within the current study. One of the most significant data sources for this assessment was the coastal water and sediment quality monitoring that was part of the vital signs program. This monitoring analyzed the daily and seasonal water quality within the estuarine intertidal zone at CUIS and provided data on pH, DO, salinity, temperature, and nutrients (DeVivo et al., 2008). The fixed-station water-quality monitoring station was particularly useful, as it provides continuous water quality data (DO, salinity, temperature, pH, and turbidity) from a point within Cumberland Sound (Rinehart et al., 2013).

Cumberland Sound experiences considerable seasonal fluctuation in pH, primarily from changes in precipitation and discharge (ranging from 7.0 to 8.4 between 2011 and 2012) (Wright et al., 2012; Rinehart et al., 2013). These seasonal ranges are greater than the average magnitude of pH decrease expected from OA over the next 100 years globally (a decrease of 0.4 pH units from 8.1) (Feely et al., 2004). Similarly, salinity within Cumberland Sound varies over the course of the year, with extremes of 14 to 38 ppt (parts per thousand) observed (Wright et al., 2012; Rinehart et al., 2013). Temperature also varies seasonally (water 52º to 88º F in 2012, Rinehart et al., 2013; and air 47º to

85º F in 2011, Wright et al., 2012). These changes (pH, salinity, and temperature) are all primarily due to fluctuations in precipitation and upstream river discharge.

In 2005, a coastal water resource assessment by Alber et al. (2005) analyzed the watershed conditions at CUIS. The authors reviewed a wide variety of coastal water quality data, primarily from the GA DNR and the Environmental Protection Agency (EPA), to determine the current state of the coastal water resources at CUIS. Alber et al. (2005) summarized the water quality related to DO, dissolved nutrients, bacteria, and other contaminants. DO, which is associated with water temperature, salinity, and vertical stratification, ranged from below 2 mg/L to above 9 mg/L from 2000 to 2004 (Alber et al., 2005). Low DO conditions (less than or equal to 4 mg/L) are frequently observed in Cumberland Sound (16% of observations between March of 2000 and December of 2004), with most of these low DO conditions occurring in the spring and summer months. These events have been shown to be detrimental to estuarine and marine organisms. Alber et al. (2005) also discussed potential problems along the sound shoreline related to nutrients, fecal bacteria, metal contamination, and toxic compounds. Finally, this study also provided a detailed review and discussion of the park habitats, including the marine habitats of interest from the current study.

The NPS's Inventory and Monitoring Program (I&M) has conducted primary resource assessments focused on air, water, soil, and vegetation monitoring at CUIS. The I&M program is also completing an inventory of "basic" natural resources, among them vegetation maps, species occurrences, geological resources, and air quality. Figure 5 shows the most recent status of these inventories within the SECN. As of 2011, all inventories were completed at CUIS, with the exception of the geological resources and the vegetation map inventories (NPS, 2011).

Status of Inventories in Southeast Coast Network Parks

Inventory	CAHA	CALO	CANA	CASA	CHAT	CONG	CUIS	FOCA	FOFR	FOMA	FOPU	FOSU	HOBE	KEMO	MOCR	OCMU	TIMU
Air Quality Data	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Air Quality Related Values	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Base Cartography Data	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Baseline Water Quality Data	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Climate Inventory	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Geologic Resources Inventory	◡	◡	◡	◡	×	◡	◡	◡	◡	◡	◡	◡	×	×	●	×	◡
Natural Resource Bibliography	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Soil Resources Inventory	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Species Lists	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Species Occurrence and Distribution	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Vegetation Map Inventory	◡	◡	◡	◡	◡	●	◡	◡	◡	◡	◡	◡	◡	◡	◡	◡	◡
Water Body Location and Classification	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

Legend
- ● Complete
- ◡ In Progress
- × Not Yet Scheduled

Natural Resource Bibliography Inventories also complete at CHPI, FORA, and WRBR.

Figure 5. NPS Status of Inventories within the Southeast Coast Network Parks, including CUIS. Figure from NPS, 2011 (SECN Program Summary).

The National Park Conservation Association (NPCA) also conducted a resources assessment or "State of the Parks" report for CUIS in 2009, which focused on natural and cultural resources (NPCA, 2009). In this report, resources were rated based on NPCA: Center for State of the Parks comprehensive assessment methodology, which rates each general resource on a scale of 0 to 100. Overall, the natural resources received a "fair" rating of 74; the lowest rating for natural resources was given to *Ecosystem Measures: Species Composition and Condition* (Figure 6). The primary issues discussed for natural resources at CUIS were related to non-native species (e.g. feral hogs and horses), air quality, and water quality, as well as loss of salt marshes and other nearshore habitats due to human development. The threat of SLR was also discussed, emphasizing that inundation of salt marshes, saltwater intrusion, erosion, and amplified storm impacts could become increasingly important in the future. In comparison, the cultural resources at CUIS received an overall "poor" rating (55), especially those resources related to ethnography, which was given the lowest rating (Figure 6).

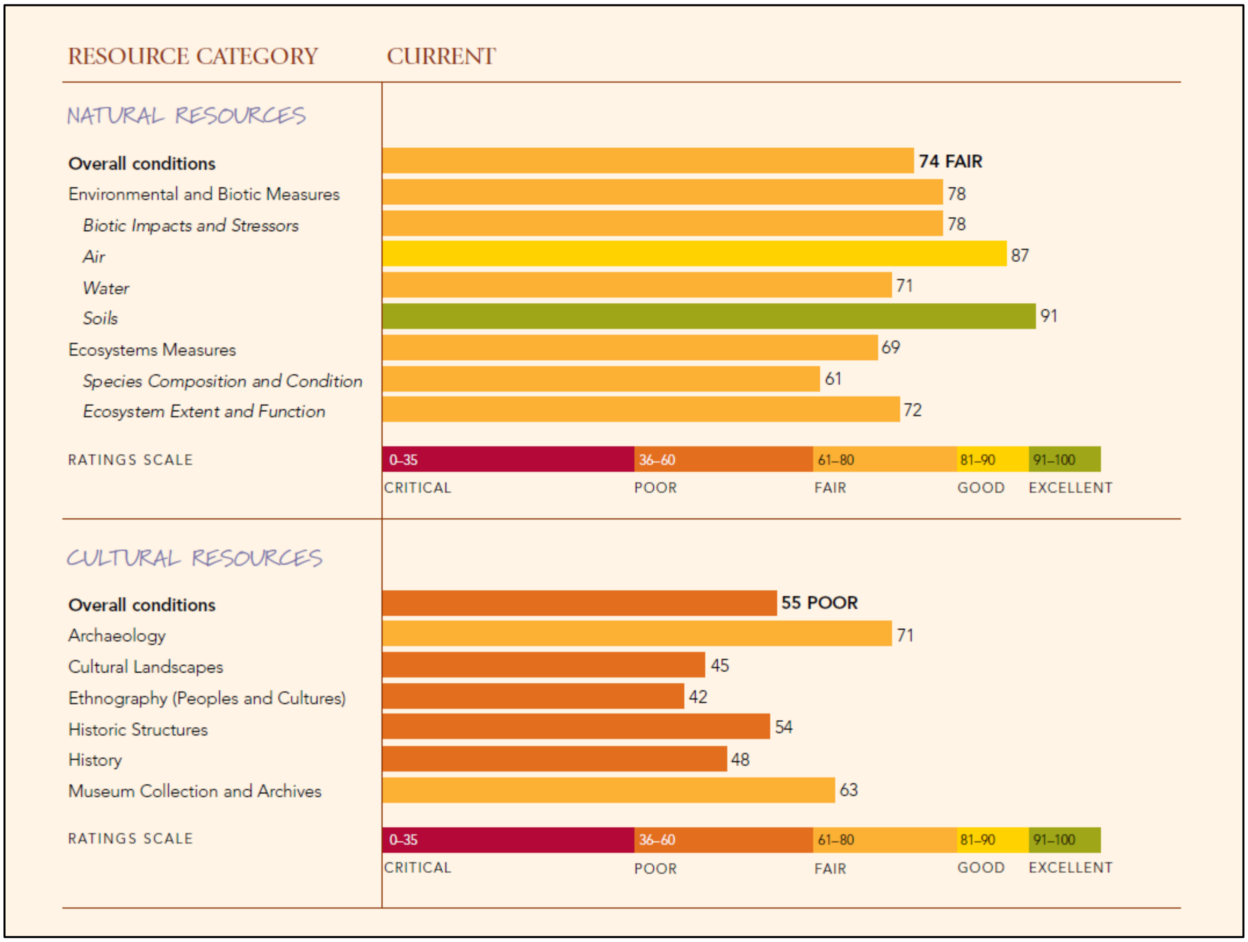


Figure 6. National Park Conservation Association Resources Assessment ratings for CUIS. Figure from NPCA, 2009.

Nearshore Marine Habitats of Interest

Nine marine habitats/environments of interest were defined for CUIS. These environments include only those within the intertidal and subtidal zones surrounding the island. Each of the habitats was also classified using NOAA's Coastal and Marine Ecological Classification Standard (CMECS), and these results can be found in Appendix A. We will use more generic terms for each habitat of interest within the main text of this document. The physical properties and common species of each of the nine environments for CUIS are described below. Results and observations from field visits to a number of these habitats will be described in the next section of the document, as well as further photographs and illustrations of the habitats at CUIS (Figures 11 to 15).

Marine Nearshore Subtidal (MNS)

The marine nearshore subtidal (MNS) habitat at CUIS is comprised of areas that are permanently submerged below low tide on the ocean (east) side of the island. Although the habitat and species within the MNS zone spans a large area offshore, only a narrow portion lies within the actual CUIS boundary (Figure 2). The offshore region at CUIS, which is part of the South Atlantic Bight (concave shoreline from Cape Hatteras NC to central FL), is characterized by relatively low slopes, shallow water, high tidal amplitude, and low energy (Pendelton et al., 2004-CUIS). Sediments within the MNS zone are moving generally from north to south in the direction of longshore transport with reversals near the inlets. These sediments are commonly fine to moderate sized sands, with little shell material due to the low wave energy (heights typically less than 1 foot) (Giles and Pilkey, 1965). Extensive sand bars/shoals often form within this habitat in GA.

The MNS habitat is home to numerous commercially significant fish, shellfish, and other seafood species. For example, between 1972 and 2013, an average of over 4 million pounds of shrimp was harvested each year in GA, with a yearly average commercial value of over $14 million (GA DNR, Coastal Resource Division, 2013). Other economically important marine species in GA include hard blue crab (*Callinectes sapidus*), red drum (*Sciaenops ocellatus*), black sea bass (*Centropristis striata*), southern flounder (*Paralichthys lethostigma*), and black drum (*Pogonias cromis*) (GA DNR, Coastal Resource Division, 2013).

Common marine mammals near Cumberland Island are the pilot whale (*Globicephala macrorhynchus*) and the Atlantic bottlenose dolphin (*Tursiops truncates*) (Johnson et al., 1974). Florida manatees (also known as West Indian manatees; *Trichechus manatus*) have also been sighted but are not considered common (Johnson et al., 1974). The marine waters offshore of CUIS are also frequented by the federally threatened loggerhead sea turtle (*Caretta caretta*).

Intertidal Beach

Sandy beaches are landforms at the marine/terrestrial interface formed by unconsolidated sands. Functionally, the land and seaward boundaries of sandy beaches are conventionally defined as the limits of active sand transport and exchange, i.e., the limits of the littoral active zone (Schacher et al., 2008). For this study, the intertidal beach habitat is defined as land on the ocean (east) side of the seashore below water at high tide and above water at low tide. The intertidal beach at CUIS, similar to the MNS habitat, is characterized by relatively low slopes (Figure 7A). In GA, beach sand is derived from nearby rivers and the adjacent MNS environment, and is considerably finer than beaches to the north and south due to low wave energy (Giles and Pilkey, 1965). In general, the intertidal beaches at CUIS are wide, a result of the low wave energy, fine sediment, and a tidal range over 2 meters (Alber et al., 2005).

Within the intertidal beach substrate, physical factors such as temperature, water saturation, salinity, oxygen concentration, levels of free CO_2, water hardness, light, and concentration of organic materials vary markedly (Riedl and McMahan, 1974). These factors generally exhibit rhythmic variations with tidal, day/night, and seasonal cycles. For example, the amount and characteristics of interstitial water are determined by interactions of the ocean (tides), evaporation and precipitation, and seasonal variations in groundwater input. Most of these factors contribute to controlling the distribution of organisms in the intertidal, but perhaps the most important are degree of desiccation, salinity, and sediment characteristics.

Sands on the intertidal beach are home to the following species: surf crabs (*Albunea* spp.), ghost shrimp (*Callianassa* spp.), coquina clams (*Donax* spp.), mole crabs (*Emerita talpoida*), sand dollars (*Mellita isometra*), ghost crabs (*Ocypode quadrata*), lettered olives (*Oliva sayana*), moon snails (*Polinices duplicatus*), and polychaete worms (Alber et al., 2005; Hymel, 2009). Shorebirds such as skimmers/terns/gulls (family *Laridae*), shearwaters (family *Procellariide*), and sandpipers (family *Scolopacidae*) use the intertidal beach for nesting and foraging. Federally-threatened species including piping plovers (*Charadrius melodius*) and loggerhead sea turtles (*Caretta caretta*) also visit the CUIS intertidal beach.

Low Salt Marsh

Salt marshes are commonly found on low energy estuarine shorelines, where there is mixture of fresh and saline water input. At CUIS, low salt marsh (Figures 7C to E) makes up the majority of land on the west side of the island. Plants in this habitat must be tolerant of the harsh conditions that come with regular flooding as well as variable salinity and temperature. Along most of the east coast of the U.S. (including GA and CUIS), this habitat is comprised primarily of the cordgrass species *Spartina alterniflora*, which contributes a large amount of decaying organic debris to the system (Hoyt et al, 1964). Sediments are primarily organic and muddy, but coarser sediments can be found within this habitat, particularly on the tidal creek levees formed at the edges of the marsh (Wiegert and Freeman, 1990). Back-barrier erosion can have significant impacts on low salt marsh habitat, resulting from both natural and human processes (Jackson et al., 2007).

Salt marshes in GA constitute approximately one-third of all salt marshes on the U.S. Atlantic seaboard (Schoettle, 1993) and are extremely important natural and economic resources, serving as a nursery for commercially significant fish, shellfish, and crustaceans. Local invertebrates that use the salt marsh are blue crabs (*Callinectes sapidus*), marsh snails (*Ilyanassa obsoleta*), periwinkle snails (*Littoraria irrorata*), mud snails (*Melampus bidentatus*), stone crabs (*Menippe mercenaria*), mud crabs (*Panopeus spp*.), wharf crabs (*Sesarma cinereum*), and fiddler crabs (*Uca* spp.) (Johnson et al., 1974; Alber et al., 2005). Marshes behind Cumberland Island are critical habitat areas for wood storks (*Mycteria americana*), federally listed as endangered, and other birds such as herons and egrets (family *Ardeidae*) (Alber et al., 2005).

Salt Flats

Salt flats (also known as salt pans) are sandy, barren zones where infrequent flooding and high evaporation lead to pore space salinities over 100 ppt (Wiegert and Freeman, 1990). Salt flats are commonly found between low salt and high marsh zones at CUIS (Figure 7B). These salt flats have more porous and sandy soils than other marsh habitats, factoring into the overall high amount of evaporation (Teal, 1958).

It has been suggested that salt flats can form when storms bring coarser sediments into the marsh, increasing the salinity, and then killing existing marsh vegetation (i.e., *Spartina alterniflora*). Increased interstitial salinity caused by porous substrate can increase competition from more salt-tolerant species or even restrict any vegetation from colonizing (Wiegert and Freeman, 1990). High salinities restrict plant life to a few salt-tolerant taxa, notably saltwort (*Batis maritima*) and glasswort (*Salicornia depressa*). At the centers of salt flats, extreme salinity precludes any plant growth, creating barren patches. Invertebrate species utilize this zone, including marsh snails (*Ilyanassa obsoleta*), periwinkle snails (*Littoraria irrorata*), and fiddler crabs (*Uca* spp.).

High Fringing Salt Marsh (HFSM)

The high fringing salt marsh (HFSM) habitat (Figure 7C) is found at a slightly higher elevation than the low marsh and is only inundated during the highest tides such as the spring tide. Pore space salinities are commonly lower than other marsh zones (Wiegert and Freeman, 1990). This habitat is not as widespread as low salt marsh habitat and is usually found at the fringes of the intertidal zone near the terrestrial upland. Sediments in the high marsh tend to be more compacted and have more sand content than the mud-rich low marsh habitat (Teal, 1958). The primary plant species found in this zone is black needlerush *(Juncus roemerianus*), which prefers less frequent flooding and more stable salinity than its low marsh counterpart, *Spartina alterniflora.* Other common plants include saltgrass (*Distichlis spicata*), sea oxeye (*Borrichia frutescens*), and spike grass (*Uniola sessiliflora*) (Johnson et al., 1974; Alber et al., 2005).

Similar to low salt marsh, invertebrates are common and include blue crabs (*Callinectes sapidus*), marsh snails (*Ilyanassa obsoleta*), periwinkle snails (*Littoraria irrorata*), mud snails (*Melampus bidentatus*), stone crabs (*Menippe mercenaria*), mud crabs (*Panopeus spp*.), wharf crabs (*Sesarma cinereum*), and fiddler crabs (*Uca* spp.).

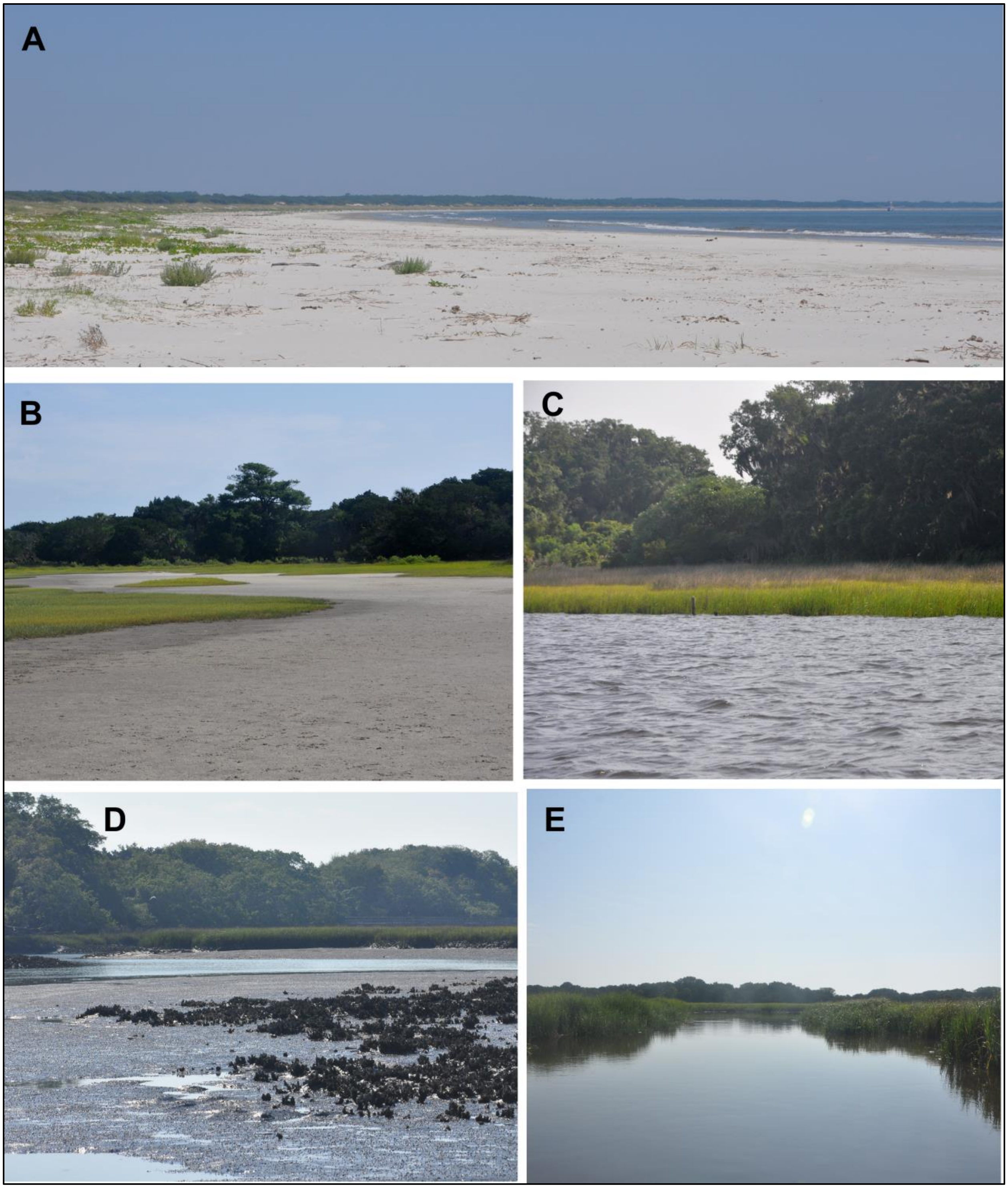


Figure 7. Marine habitats at CUIS. A) Intertidal beach and marine nearshore subtidal habitat (looking north). B) Salt flat habitat, both vegetated and non-vegetated. C) Low salt marsh (green vegetation) and high fringing salt marsh (brown vegetation) at high tide. D) Tidal mudflats, tidal creek, low salt marsh, and shellfish beds at low tide. E) Tidal creek and low salt marsh habitat at high tide.

Tidal Mud Flats

Tidal mud flats are part of the lower intertidal zone below any salt marsh vegetation and above the water at low tide (Figure 7D). They are typically level, border the estuary, and are alternately submerged and exposed to the air by changing tidal levels. Mud flats along the GA coast are characterized by a wide range of grain sizes (primarily organic-rich muds), as well as physical and sedimentary structures (Howard and Frey, 1985).

Mud flats commonly consist of a soggy substrate made up of clay and silt that is deposited during slack tide, the brief period between flood tide and ebb tide during which water is not flowing. Only the upper layers of this muddy substrate contain oxygen. The deeper layers contain decaying organic matter that gives off a hydrogen sulfide gas at low tide, which causes the faint rotten egg smell typical of anaerobic sediments (Olsen, 2014).

The mud of a tidal flat is characteristically rich in dissolved nutrients and plays host to a diverse biotic assemblage ranging from microscopic organisms found adhering to and living within interstitial spaces of sediment particles to large epibenthic forms such as crabs, fish, and wading birds (Dineen, 2014). Bioturbation is common within GA mud flats, particularly from polychaetes, amphipods, bivalves, and anemones (Howard and Frey, 1985). In addition, phytoplankton and algae grow on the surface of the mud and attach to hard surfaces such as old shells or logs (Olsen, 2014). Collectively tidal mud flats are of great importance to large numbers of invertebrates and fish, supporting complex estuarine food webs and providing resting and feeding areas to many indigenous and migratory birds (Dineen, 2014).

Shellfish Beds

Shellfish beds are patches of hard substrate formed primarily by oysters (Figure 7D) in the intertidal estuarine waters near CUIS (Harris, 1980). The beds are commonly both completely submerged and exposed in the region due to the high tidal range. These shellfish are keystone organisms, controlling the biota and physical structure of estuarine areas and are thus valuable for determining the health of an ecosystem. As filter feeders, shellfish improve water quality and decrease the amount of plankton in the system.

The eastern oyster (*Crassostrea virginica*), in particular, is an important substrate former (including at CUIS), creating hard surfaces for other organisms, such as ribbed mussels (*Geukensia [aka Modiolus] demissa*), and providing habitat to a variety of fish and invertebrates (Bergquist et al., 2006). Hard clams (*Mercenaria mercenaria*) and the eastern oyster (*Crassostrea virginica*) are both commercially harvested from the CUIS area (Alber et al., 2005).

Tidal Creeks

Tidal creeks are an important connection between the estuaries and the salt marshes at CUIS (Figure 7E). The network of channels allows tidal waters to flow into the marsh, providing critical nutrients, oxygenated water, and sediment (Schoettle, 1993). When the tide ebbs, it flushes the system of deposits from inland tributaries (Alber et al., 2005). Within this study, there is overlap between the top portion of the tidal creeks (that which is exposed at lower tide levels) and the tidal mud flats habitat. There is also a section of the tidal creeks habitat that is not regularly exposed (the areas below low tide levels).

Tidal creeks provide marsh access to free-swimming species such as killifish (*Fundulus heteroclitus*) and grass shrimp (*Palaemonetes pugio*), which are permanent residents. Silver perch (*Bairdella chrysura*) and spot (*Leiostomus xanthurus*) inhabit the creeks only during the early stages of their life (Alber et al., 2005). The Atlantic bottlenose dolphin (*Tursiops truncates*) and the FL manatee (*Trichechus manatus*) can also be found in tidal creeks during warm summer months (Johnson et al., 1974).

Estuarine Nearshore Subtidal (ENS)

The estuarine nearshore subtidal habitat (ENS) is comprised of the deeper portions of tidal creeks and the estuary on the west side of Cumberland Island. To be consistent with the geographic information systems (GIS) portion of this research, we characterized the ENS at those areas deeper than 4 meters below MLLW (mean lower low water). These creeks and estuaries are inundated at even the lowest spring tides. Most of this habitat is comprised of Cumberland Sound, not all of which is within the technical boundaries of the seashore. The Intracoastal Waterway runs through this habitat and, therefore, is subjected to intermittent dredging for shipping channels.

Due to high turbidity, there is no submerged aquatic vegetation within the sound. However, numerous fish and marine mammals inhabit the ENS zone and this habitat is extremely important for local and regional fisheries. Also seen in these subtidal zones are the Atlantic bottlenose dolphin (*Tursiops truncates*) (Johnson et al., 1974) and the FL manatee (*Trichechus manatus*).

Climate Change Stressors of Interest

Stress resulting from a rapidly changing climate is likely to be greater along the coast due to the added impact of SLR on marine habitats and organisms. Although different climate change-related stressors will pose a variety of threats to marine habitats within coastal NPS units, the four most substantial climate stressors were defined for this study at CUIS: SLR, OA, and changes in salinity and temperature. In order to provide results that are actionable within a meaning planning cycle for the NPS, we examined the short-term trends in these climate stressors, and determined the relative vulnerability of the different environments on a decadal timescale (Table 3).

When assessing the vulnerability of natural habitats to climate-related stressors, it is helpful to know how a stressor might change over time, how two or more stressors may interact, and whether a stressor's impact will be chronic and somewhat predictable (such as a gradual increase in SLR or OA) or episodic and unpredictable (such as dramatic, but temporary, changes in salinity and temperature resulting from extreme weather events). For example, while a salt marsh will experience chronic erosion as sea levels steadily rise, corals suffer bleaching episodically (albeit permanently) when temperature events exceed the tolerance of the corals' photosynthetic symbionts (Hoegh-Guldberg, 1999). On the other hand, changes in salinity can be detrimental to a salt marsh, due to extreme (but ephemeral) events such as fresh water influx from a hurricane (Day et al., 2007). The likely mechanism of impact for each stressor was identified and considered when assessing the vulnerability of each habitat to each climate change stressor of interest.

Sea-Level Rise (SLR)

One of the most significant changes that will occur in our coastal zones as climate changes is increasing sea levels. Resources (natural and cultural) and infrastructure in many coastal parks are already threatened by SLR (Scavia et al., 2002; Peek et al., 2014). Satellite imaging between 1993 and 2010 provides a global average SLR of 3.2 mm per year (IPCC, 2013). In the current century, the rate of SLR is expected to increase, and the most recent IPPC projects a rise between 0.28 and 0.98 m by the end of the 21st century (Table 3; IPCC, 2013). Two major contributors to rising seas are increased melting of continental ice and thermal expansion of seawater due to warming air and ocean temperatures, respectively (IPCC, 2013). The relative SLR rates vary between different coastal NPS units depending on local and regional conditions. Fernandina Beach, FL (just south of CUIS) currently has an average SLR trend of 2.02 mm per year (Table 3; NOAA Tides and Currents, Sea Level Rise). Within this document, any further mention of SLR is referring to relative SLR at CUIS.

SLR leads to the inundation of coastal land, more specifically, the coastal zonation (e.g., subtidal, intertidal, supratidal) moves landward. With sufficient and compatible accommodation space, this may result in a simple migration of coastal habitats, with no net loss or gain in habitat area or quality. However, factors such as slope, sediment supply, adjacent habitats, and even the rate of SLR may lead to habitat degradation, biodiversity loss, and net loss of certain habitat types with net expansion of other habitat types.

Ocean Acidification (OA)

The U.S. EPA defines pH as the measure of a substance's acid-alkaline balance (EPA, 2012). Ranging from 0 (extremely acidic) to 14 (extremely alkaline), the pH scale is centered at 7, which is considered neutral (McKenna, 2013; EPA, 2012). Overall acidification (pH decrease) of oceans occurs when carbon dioxide (CO_2) reacts with seawater, producing carbonic acid (NRDC, 2009; McKenna, 2013). Since the beginning of the Industrial Revolution (mid-1800s), carbon dioxide in the atmosphere has increased by 25%, and concentrations are expected to increase at an even higher rate in the next few decades (Feely et al., 2009). Current ocean pH is around 8.1 and is expected to decline 0.4 pH units by 2100 (Table 3; Feely et al., 2004; 2009; Orr et al., 2005).

Many organisms are likely to be affected by the expected decrease in ocean water pH. This is especially true for organisms that use calcium carbonate ($CaCO_3$) to build their shells or skeletons, such as corals and shellfish. The decreased availability of carbonate caused by OA makes it more difficult for these organisms to grow. Increased CO_2 concentration can also interfere with organisms' ability to regulate internal pH and may have unanticipated impacts on the development and ecology of marine organisms.

In the past several years, there has been a rapid increase in the awareness of the effects of the acidification of our nation's ocean waters. Ocean waters provide vital resources, including food, recreation, transportation, and many others; these resources contribute substantially to local, regional, and the national economy. In response to this awareness, Congress passed the Federal Ocean Acidification Research and Monitoring Act in 2009. This Act is focused on developing a research plan that will direct "Federal research and monitoring on OA that will provide for an assessment of the impacts of OA on marine organisms and marine ecosystems and the development of adaption and mitigation strategies to conserve marine organisms and marine ecosystems" (Interagency Working Group of Ocean Acidification, 2012).

Brackish waters can also experience large variations in pH, as they have a low buffering capacity (Dickinson et al., 2012). In 2011, pH values on the sound side of Cumberland Island ranged from 7.0 to 8.4 (Wright et al., 2012). In 2012, pH values were similar, with a range from 7.17 to 8.43; a low monthly average of 7.6 was recorded in the summer, while the high monthly average of 8.2 was recorded in December (Rinehart et al., 2013). Although these estuarine pH changes are not technically considered part of the OA climate change stressor, they are significant for the evaluation of overall habitat vulnerability and will be discussed in the results portion of this document.

Temperature Changes

Many aquatic ecosystems are highly sensitive to water temperatures. Within the estuarine environment, water temperature can be a good proxy for the health of the system. Most species can only live in waters of a certain temperature range, and major fluctuations can remove those species from the environment. Other physical and ecological processes are also influenced by water temperatures, for example, the amount of DO in water is directly affected by temperature. Warmer waters cannot hold as much oxygen as cooler waters, and a lack or low amount of oxygen can be detrimental for plant and animal species. Warm waters can also increase the likelihood of algal blooms. Blooms, caused by the rapid reproduction of microorganisms such as cyanobacteria, dinoflagellates, or diatoms, may produce toxins that harm other marine organisms or humans (via consumption of contaminated shellfish). The decomposition of algae after a bloom can further aggravate the system and cause hypoxic (depleted oxygen) conditions. Temperature changes can also affect vertical stratification and water column mixing within estuaries and sounds. Increased water column stratification can further aggravate the detrimental low DO or hypoxic events seen within estuaries and sounds (e.g., Stanley and Nixon, 1992; Howarth et al., 2011; Simpson et al., 2011).

Continuous monitoring conducted by the NPS on the sound side of Cumberland Island yielded water temperatures ranging from 50.2° to 88.6° F during 2011 and 2012; the highest overall water temperatures for both years were from July (Wright et al., 2012; Rinehart et al., 2013). The temperature of estuarine waters is dependent on many factors, including freshwater influx, tidal mixing, and changes in air temperature.

Salinity Changes

Rapid changes in salinity do not allow species sufficient time to adapt, placing stress on local populations. Also, as with temperature, salinity changes can influence vertical water column stratification, increasing the likelihood of low DO events (e.g., Kuo and Neilson, 1987). Average open ocean water has a salinity of 35 ppt (Alber et al., 2005; NOAA, 2008). Water just offshore of CUIS is often lower than the average, dropping to around 30 ppt in the spring with increased river discharge (Alber et al., 2005). In 2012, salinity readings on the sound side of CUIS ranged from 14.8 to 37.6 ppt. The lowest reading (14.8 ppt) in 2012 was in July, correlating with high rainfall totals from Tropical Storm Debby (Rinehart et al., 2013). In 2011, when there were no major storms, the salinity values ranged from 30.5 to 38.2 ppt (Wright et al., 2012). The salinity of estuarine waters is dependent on several factors, including precipitation, evaporation, daily tides, and the amount of freshwater influx (Table 3). Open ocean water is more consistent in terms of salinity, but the same factors can affect the salinity of nearshore marine waters. In marsh habitats the salinity is variable; the low salt marsh often has salinity values that range from 0.5 to 32 ppt, and the salt flat habitat can have an interstitial salinity over 100 ppt (Wiegert and Freeman, 1990).

Table 3. Trends and scenarios for climate change stressors analyzed. The decadal change values serve as general guidelines for the time frame examined at CUIS.

Parameter	**Trend**[1]	**Long-Term Change (2100)**[2]	**Current Working Rate**[3]	**Decadal Change (10 years)**[4]
SLR	Increase (rise)	0.28 – 0.98 m	2.02 mm/year	20 mm
OA	Decrease (in pH)	7.7 pH units, decrease of 0.4	0.0014 to 0.0024 pH units/year	0.02 pH units
Temperature	Variable, increase likely	Rates uncertain	Rates uncertain	Rates uncertain
Salinity[5]	Variable	Trend & rates uncertain	Trend & rates uncertain	Trend & rates uncertain

1 = general direction of change

2 = expected change in stressor by the year 2100 (SLR rate from IPCC, 2013; OA rate from Feely et al. 2004)

3 = current rate of change (SLR rate from NOAA Tides & Currents; OA rate from IPCC, 2013)

4 = conservative change estimate calculated using the current rate multiplied by 10 years

5 = Salinity trends and rates depend largely on precipitation patterns. Long-term (2100) and decadal scale (10 year) change depends on ratio of drought years/wet years during that period. Years of drought = more saline waters, years with high precipitation = more fresh water.

Marine Habitat GIS Delineation

The marine resources and habitats of interest for this study make up a significant portion of CUIS; however, the percentage that each environment makes up within the boundaries of the park is not currently known. Therefore, the approximate percentage of a subset of the habitats of interest in this study was delineated using various methods and previous data collection efforts. Field verification of species and habitat characteristics was also conducted by PSDS in July of 2014. These efforts were focused on the identification of species present within these habitats as well as any geologic or physical features of significance. Methods, descriptions, and results from the GIS analysis are described in the following sections.

Habitat Categories

Because of the complex nature and large number of habitats of interest defined for CUIS, several of the environments were combined for the GIS analysis. For example, it was not possible to differentiate between HFSM, low marsh, and salt flats using existing data (aerial photography) from the area. Additional analysis of remote sensing data, such as infrared or thermal imagery, could help to distinguish these more intricate habitats.

For this part of the study, the three marsh habitat categories were combined into one designation called “salt marsh” (only for the GIS delineation). Similarly, tidal creeks, tidal mud flats, and oyster reefs are all found in the same general geomorphic setting within the park and were combined into one category called “tidal flats.” Table 4 further describes the grouping of habitats for the GIS analysis.

Table 4. Combined habitats of interest delineated using GIS methods (only combined for this section)

GIS Delineation Habitat Name	Original Habitats of Interest Name
Marine Nearshore Subtidal	Marine Nearshore Subtidal
Intertidal Beach	Intertidal Beach
Salt Marsh	Low Salt Marsh + Fringing High Marsh + Salt Flats
Tidal Flats	Tidal Creeks + Tidal Mud Flats + Oyster Reefs
Estuarine Nearshore Subtidal	Estuarine Nearshore Subtidal

GIS Data Sources

Several existing pieces of GIS data were utilized as a baseline for the GIS delineation of habitats within CUIS. All of these data, including sources, can be found within Table 5. The *Unpublished Morphogenetic Map of CUIS and Vicinity* is a GIS data layer that was based on research and mapping conducted for NPS by Parkinson and Latiolias (2011) (Figure 8, Table 5). This GIS data product is comprised of a digital map of morphogenetic features, or “geologic features by categories related to form (structure) and development (origin)” (Parkinson and Latiolias, 2011). These data were used as a “first step” in the delineation of habitats within the GIS framework. Another significant resource for the habitat delineation, as well for the original habitat of interest designation, was the C-CAP Southeast Region 2010 Land Cover data (Figure 7).

Table 5. GIS data sources for habitat delineation

Data Type	Data Name	Publisher/Author	Data Source
Aerial Imagery	GA National Parks – CIR Orthophoto Tile 17RMP455975	U.S. Geological Survey	NPS Inventory and Monitoring; Joe DeVivo
Aerial Imagery	ESRI_Imagery_World_2D	ESRI	http://goto.arcgisonline.com/maps/ESRI_Imagery_World_2D
Units of Cumberland Island	Unpublished Digital Morphogenetic Map of CUIS and Vicinity, GA	RWParkinson Inc., and MDA Information Systems, Inc. (and Dynamac Corporation)	NPS; https://irma.nps.gov/App/Reference/Profile/2181280
Land Cover	C-CAP Southeast Region 2010-Era Land Cover	NOAA's Ocean Service, Coastal Services Center	NOAA; http://www.csc.noaa.gov/landcover
LiDAR DEM	2010 GA Topographic LiDAR	NOAA Coastal Services Center, Coastal GA Regional Development Center	Chester Jackson, GA Southern
Park Boundary	NPS Boundaries and Centroids	NPS WRD Ocean and Coastal Resources Branch (OCRB)	NPS; https://irma.nps.gov/App/Reference/Profile/2195122

GIS Methods

The delineation of habitats on CUIS began with inserting all appropriate data into an ArcMap (v.10.1) GIS document. The unpublished morphogenetic units (Figure 8, Table 5) were the foundation for all marine habitats of interest from this study. All GIS analysis was done in ArcMap 10.1 using the NAD1983/UTM Zone 17N horizontal coordinate system. The LiDAR data used a vertical datum of NAVD88. Table 6 describes the general workflow for each of the marine habitats of interest investigated in this study.

As with every analysis, there is error associated with the delineation of the habitats. The goal behind the delineation of these habitats was to improve upon the currently available data (in this case the morphogenetic units) and to provide the NPS with an *approximate* percentage of each habitat of interest for CUIS.

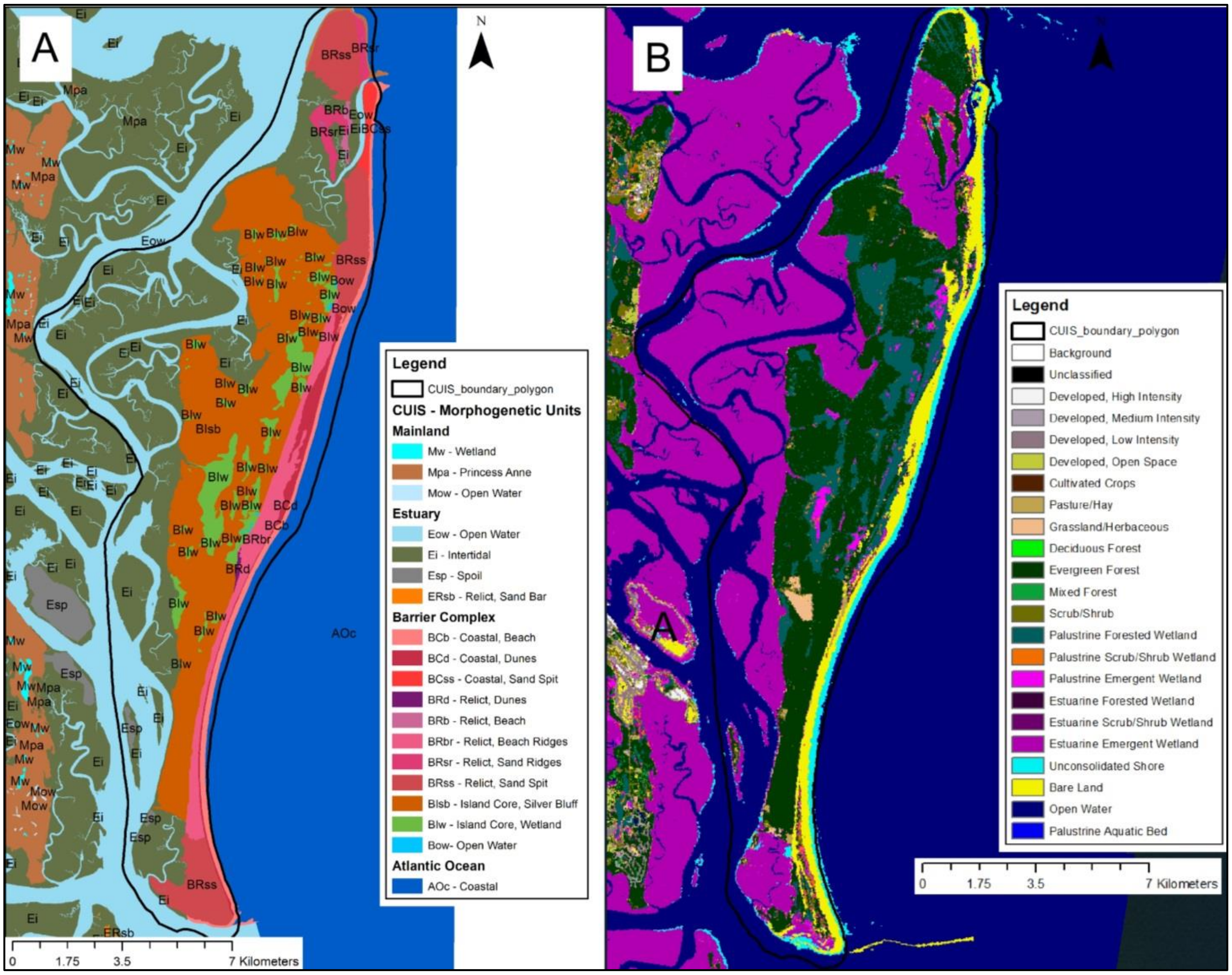


Figure 8. Examples of existing GIS data utilized in the marine habitat delineation for CUIS. A) Morphogenetic units of CUIS (Parkinson and Latiolias, 2011) and B) 2010 GA Landcover data (NOAA).

Table 6. Workflow and morphogenetic unit utilized for the GIS delineation of habitats within CUIS.

Habitat	Morphogenetic Unit*	Work Flow**
Marine Nearshore Subtidal	Atlantic Ocean (AOc); margin of ocean basin extending from mean low water to fair weather wave base	AOc was used as a starting point for delineation of marine nearshore subtidal, some locations were smoothed and the file was also clipped to the CUIS boundary layer obtained from the NPS.
Intertidal Beach	Barrier Complex: Coastal, Beach (BCb); gently sloping surface of unconsolidated sediments (e.g., sand and gravel) accumulating in high energy zone of breaking waves at the land-sea interface and extending from low tide to toe of coastal dunes, sea cliffs, or other distinct change in slope or physiography.	BCb was used as starting point; eastern boundary with AOc (above) was kept, with some smoothing. The western boundary for intertidal beach was recreated, as original BcB morphogenetic unit extends out of the intertidal zone to the toe of the dunes. New boundary on western side of intertidal beach is the wet/dry line, representing the high tide line, and was digitized from aerial photography.
Salt Marsh	Estuary, Intertidal (Ei); Zones within or along the margin of the estuary wherein the substrate is permanently wet and/or intermittently water-covered; may be vegetated or barren.	Ei was used as a starting point for the salt marsh and tidal creek habitat delineations. Both of these habitats are enveloped within the Ei morphogenetic unit.
Tidal Flats	Estuary, Intertidal (Ei); Zones within or along the margin of the estuary wherein the substrate is permanently wet and/or intermittently water-covered; may be vegetated or barren.	The salt marsh unit was differentiated from the tidal creek unit by digitizing the boundary between the intertidal muds and the vegetated intertidal zones, using aerial imagery (see Table 2). The vegetated portion of the Ei morphogenetic unit was delineated as salt marsh and the barren, muddy portion of this unit was delineated as tidal creek (which includes tidal flats and oyster reefs). Some barren locations that were located in the higher marsh zones were actually salt flats and are included in the salt marsh habitat.
Estuarine Nearshore Subtidal	Estuarine Open Water (EOw): Typically channel features with depths greater than – 4 feet MLLW (Mean Lower Low Water).	EOw was used as a proxy for the estuarine nearshore subtidal habitats; some locations were smoothed and the EOw was clipped to the CUIS boundary layer obtained from the NPS.

*Morphogenetic unit utilized for habitat delineation, with description of original morphogenetic unit taken from (Parkinson and Latiolias, 2011)

** Description of work flow within ArcMap, with a description of the edits made to original morphogenetic layer

GIS Results

A total of 36,433 acres in the CUIS area were included as part of the GIS delineation. Over half (55%) of the land area is comprised of marine/estuarine intertidal and subtidal habitats (Table 7). The intertidal and subtidal zones comprise approximately 32% and 23% of the total area of CUIS, respectively. The salt marsh habitat was the most widespread of the delineated habitats, making up almost half of the total marine habitat area (9,250 acres, 46% of Marine Habitat) (Table 7, Figure 9).

Most of the salt marsh habitat is likely low marsh, comprised primarily of *Spartina alterniflora*. We estimate (from aerial analysis and field study) that HFSM and salt flats habitats make up less than 20% of the total salt marsh GIS category. Intertidal beach makes up the smallest percent of the marine habitat area (4%) as well as overall on CUIS (2%) (Table 7).

Table 7. Percentage of each habitat delineated for CUIS using GIS.

Habitat Name	Area (acres)	% of Marine Habitat	% of CUIS
Marine Nearshore Subtidal	1,786	9%	5%
Intertidal Beach	795	4%	2%
Salt Marsh	9,250	46%	25%
Tidal Flats	1,675	8%	5%
Estuarine Nearshore Subtidal	6,420	32%	18%
Marine Habitat Totals	19,926	100%	55%
Upland	16,507	n/a	45%
CUIS Totals	36,433	n/a	100%

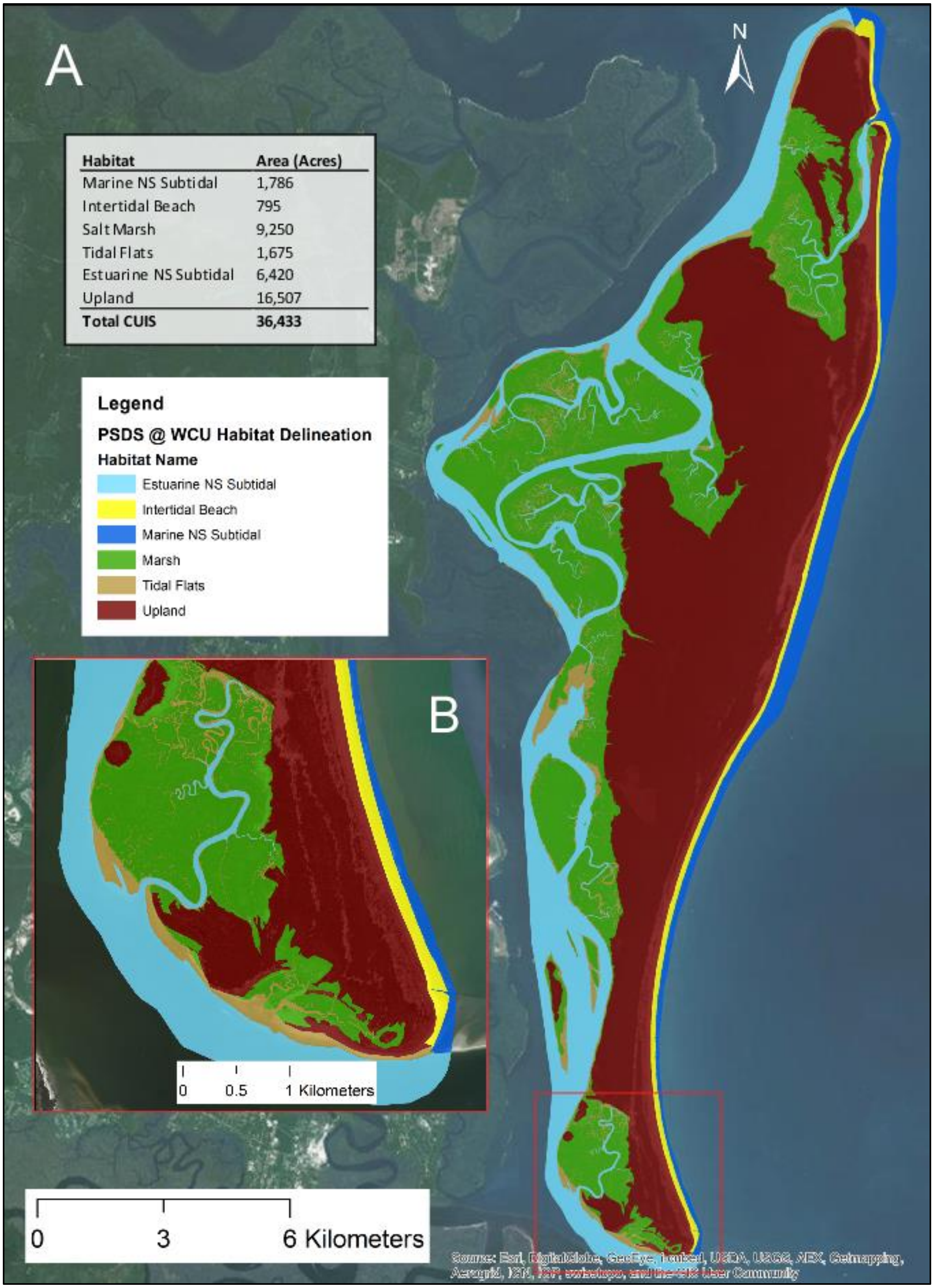


Figure 9. A) Complete CUIS GIS habitat delineation results with area (in acres) of each. The upland habitat included any land area not in the marine habitats. B) Zoomed in example of GIS delineation in the southern portion of CUIS.

Field Work

Field work was conducted at Cumberland Island in July of 2014, primarily on the sound side of the island. This field work was focused on identifying different species and conditions of the habitats of interest defined in this study, as well as field checking and verifying the results of the GIS habitat delineation (Table 7, Figure 9). Site visit locations were chosen based on data and knowledge obtained during the GIS delineation. Due to the resolution of the aerial imagery, some areas and habitats at CUIS were hard to distinguish prior to visiting. This is especially true on the sound side of the island throughout the salt marshes, tidal flats, and tidal creeks. Therefore, representative locations were chosen for each habitat, as well as locations in which the habitat was unknown or unclear (Figure 10).

Upon arrival at these pre-selected locations, species observed were identified and the habitat and environment was described and defined. Photographs were taken, as well as general field observations and geographic location data. Some of the pre-selected field sites could not be visited, primarily due to access reasons. The following sections describe the field work results and Table 8 summarizes the species noted in each habitat.

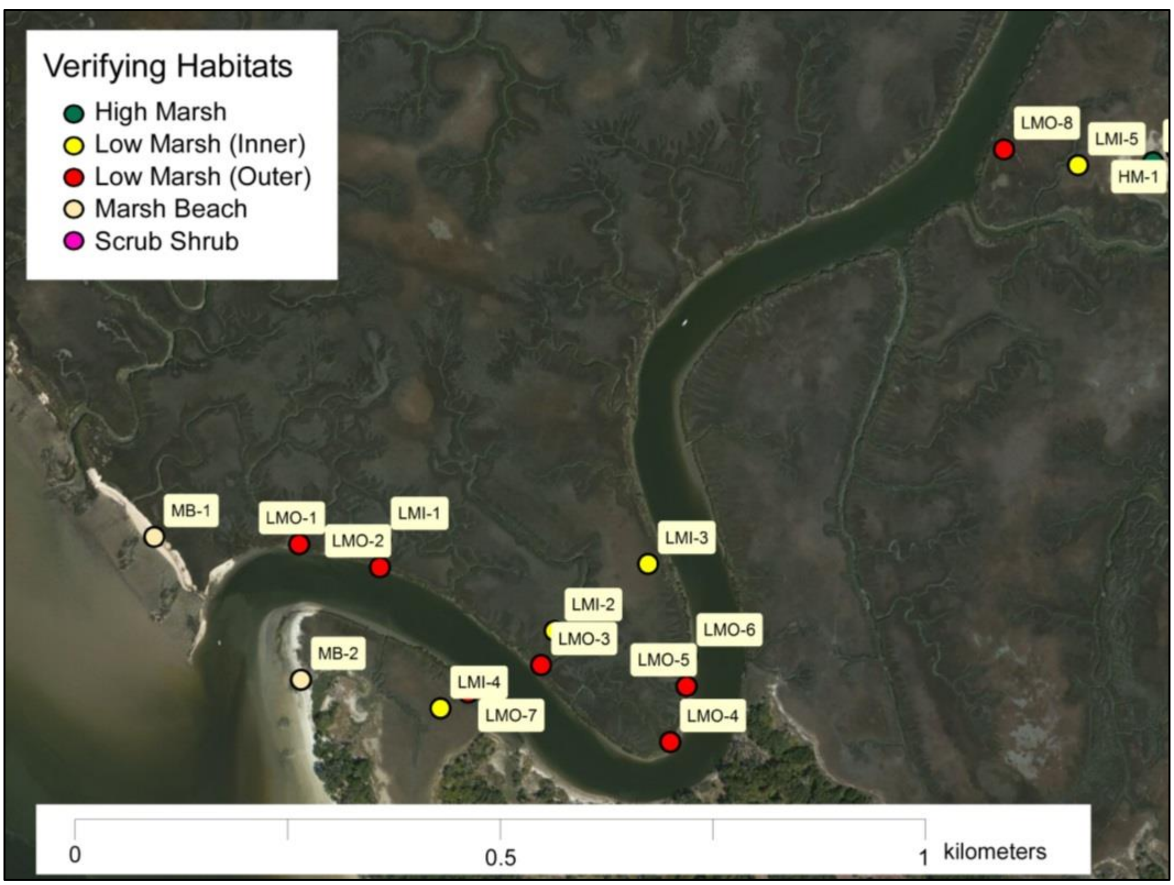


Figure 10. Example of locations of interest selected prior to visit for field work investigations. Location is on the southwest estuarine side of CUIS.

Table 8. Species observed during field visit to CUIS in July of 2014.

Habitat Name	**Species Observed**
Low Marsh	smooth cordgrass (*Spartina alternaflora),* sea oxeye (*Borrichia frutescens* , saltwort (*Batis maritima*), mud snail (*Melampus bidentatus*), periwinkle snail (*Littorina irrorata*), mud fiddler crab (*Uca pugnax*), roseate spoonbill (*Platalea ajaja*), great blue heron (*Ardea herodias*), great egret (*Ardea alba*)
High Marsh	saltwort (*Batis maritima*), sea oxeye (*Borrichia frutescens*), black needlerush (*Juncus roemerianus*), glasswort (*Salicornia depressa)*, salt grass (*Distichlis spicata*), marsh lavender (*Limonium carolinianum),* mud snail (*Melampus bidentatus*)*,* mud fiddler crab (*Uca pugnax*), roseate spoonbill (*Platalea ajaja*), great blue heron (*Ardea herodias*), great egret (*Ardea alba*)
Salt Flats	saltwort (*Batis maritima*), glasswort (*Salicornia depressa*)
Tidal Creeks Tidal Flats Oyster Beds	eastern oyster (*Crassostrea virginica*), ribbed mussel (*Modiolus demissus*), mud snail (*Melampus bidentatus*), mud fiddler crab (*Uca pugnax*), roseate spoonbill (*Platalea ajaja*), great egret (*Ardea alba*), great blue heron (*Ardea herodias*)
Intertidal Beach	Coquina clams (*Donax sp*.), gull species (*Larus* spp.), brown pelican (*Pelecanus occidentalis*)

Low Salt Marsh

The majority of salt marsh at CUIS is comprised of the cordgrass species *Spartina alterniflora* (Table 8). There is a zonation of the low marsh based on elevation. Next to the tidal creeks is a slightly higher elevation marsh "levee" where *Spartina alterniflora* is often over a meter tall. This increased elevation also allows for other species, including saltwort (*Batis maritima*) and sea oxeye (*Borrichia frutescens*), to colonize adjacent to the tidal creeks (Figure 11). In the central portions of the low marsh the elevation decreases slightly, and *Spartina alterniflora* is the primary species present. Numerous bird species were observed around the low marsh, including roseate spoonbills (*Platalea ajaja*) and great blue herons (*Ardea herodias*) (Figure 12A).

Sediments in the low marsh at CUIS were primarily organic muds, but coarser material was present on both the marsh levees and estuarine beaches. The estuarine beaches were comprised of a mixture of sandy sediments and shell hash (likely oysters). Abundant mud fiddler crabs (*Uca pugnax*) were observed in the low marsh (Figure 12C).

High Fringing Salt Marsh & Salt Flats

The HFSM habitat of CUIS comprises less area than the *Spartina alterniflora* low marsh. It is typically at a higher elevation bordering the upland habitat and, therefore, inundated less often. Several sites representing this zone were visited at high tide (during July of 2014), and in all instances, water was not present above the ground surface. A small amount of short *Spartina alterniflora* was present in the high marsh, particularly near the fringe of the low marsh. There is a much wider variety of salt-tolerant plant species within the HFSM.

Field observations throughout the marshes of CUIS show a zonation of species typical to this part of GA and to the southeastern U.S., with *Spartina alterniflora* as the primary low marsh species and black needlerush (*Juncus roemerianus)* comprising much of the HFSM (Figure 13A). However, many of the sites visited contained a more complex zonation (Figure 13B-D); in these areas the characteristic zonation was interrupted by a mixture of non-vegetated salt flats and more salt-tolerant species such as glasswort (*Salicornia depressa)* and saltwort (*Batis maritima).* Sea oxeye (*Borrichia frutescens)* and salt grass *(Distichlis spicata)* were also widespread throughout the higher marsh zone, particularly near the outer edges of the low marsh. Large numbers of mud fiddler crabs (*Uca pugnax*) were also observed in all zones of the marsh, including the salt flats (Figure 12C). A typical cross-section of the estuarine environments at CUIS (as noted during field work), including the marsh habitats, is depicted in Figure 14.

It is also important to note that *Spartina alterniflora* was present (even if in very small amounts) in most marsh zones. It dominates the low marsh but appears to be growing in less abundance in both the HFSM and portions of the salt flats. Conversely, the salt-favoring species (i.e., *Salicornia depressa* and *Batis maritima)* were rarely seen outside of the salt flats and only in locations with slightly higher elevations (less flooded). *Juncus roemerianus* was even more restricted and only found in the highest elevation portions of the marsh (bordering the terrestrial upland).

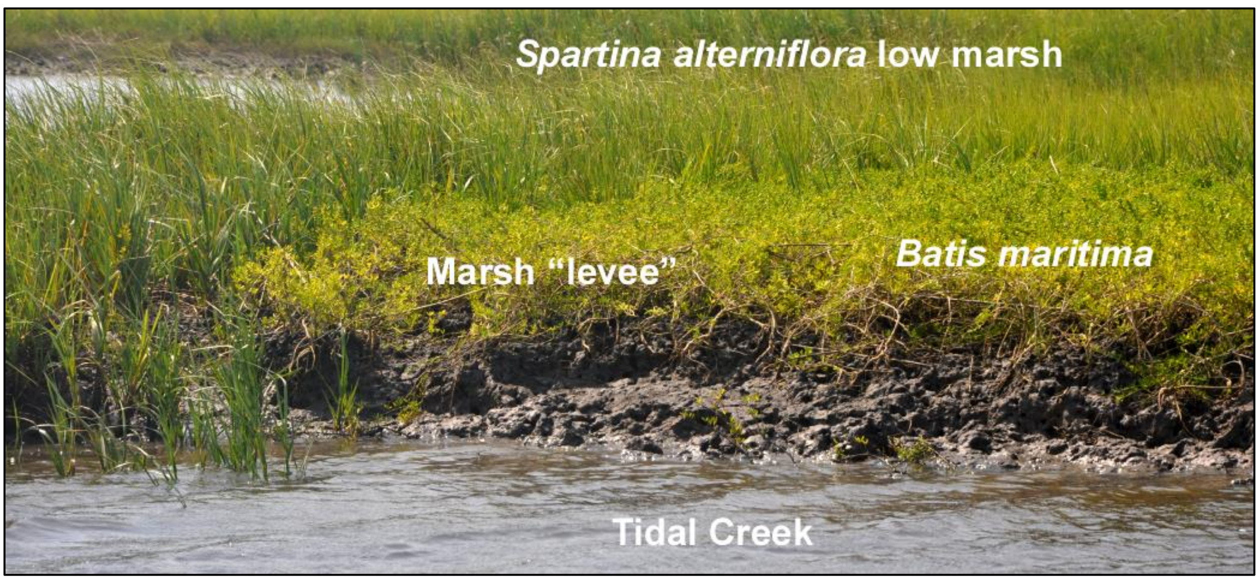


Figure 11. Low marsh at CUIS, with typical species *Spartina alterniflora* and also marsh "levee" colonized by higher marsh species *Batis maritima*. Photo courtesy of PSDS at WCU.

Tidal Creeks, Oyster Beds and Tidal Mud Flats

The tidal creeks, oyster beds, and tidal mud flats were all observed during the field visit to CUIS. Due to the high tidal range (up to 2 meters), the majority of these zones were submerged at high tide. However, as the tide retreated, a portion of each zone was uncovered. Thick, sandy mud was present within these zones, and the two most common species noted were the eastern oyster (*Crassostrea virginica*) and the ribbed mussel (*Modiolus demissus*) (Figure 12A-B). Two marine mammals, the Atlantic bottlenose dolphin (*Tursiops truncates*) and the FL manatee (*Trichechus manatus*) were also briefly spotted swimming in the tidal creeks (Figure 12D). Mud fiddler crabs (*Uca pugnax*) and numerous bird species were also present in this zone (Figure 12C).

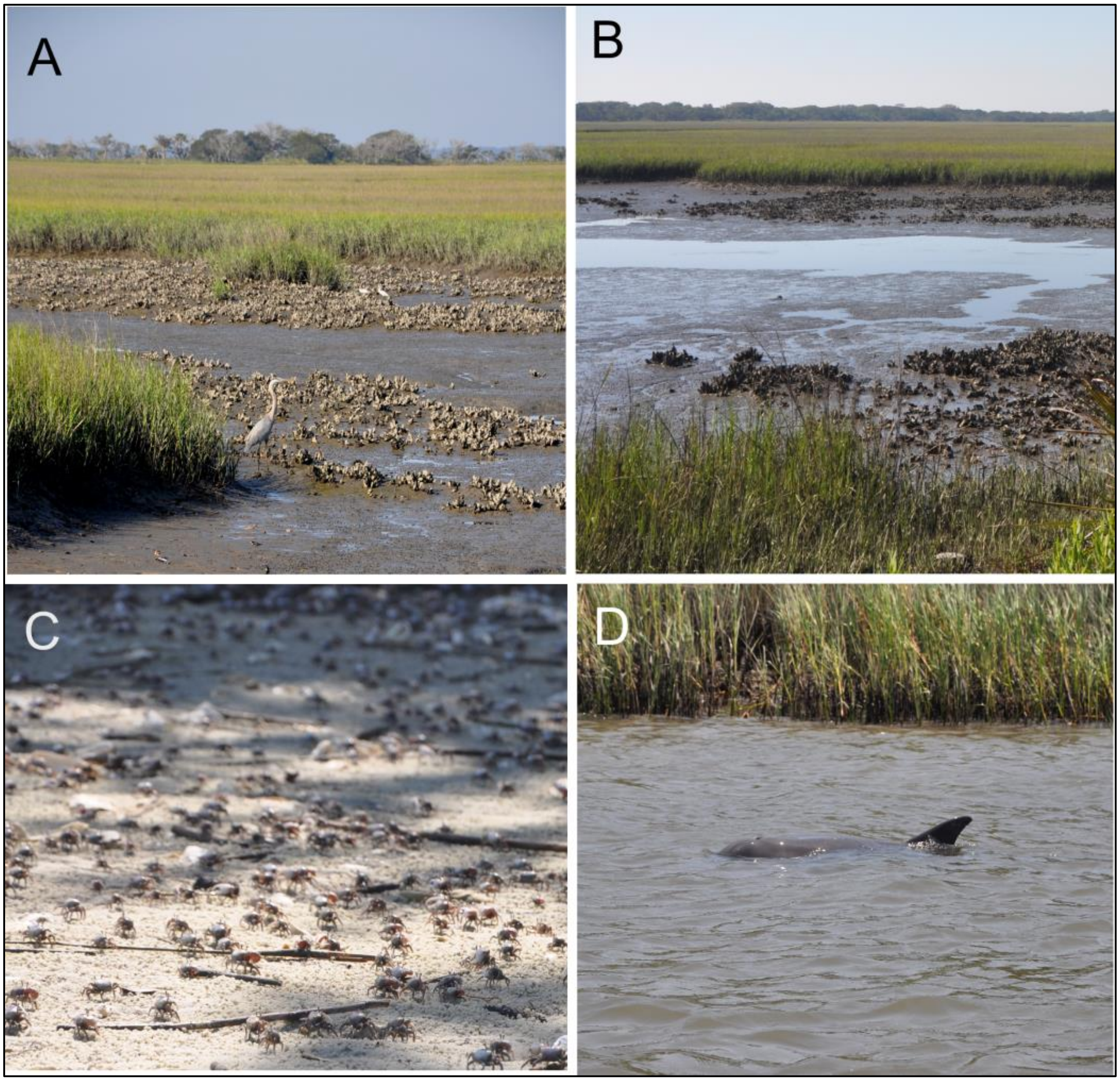


Figure 12. Example of the habitats observed at CUIS. A) Low marsh, oyster beds, and tidal flats at low tide; species seen here are the eastern oyster (*Crassostrea depressa*) and the great blue heron (*Ardea herodias*). B) Shellfish beds and tidal flats at low tide. C) Fiddler crabs (*Uca pugnax*) in the marsh. D) The Atlantic bottlenose dolphin (*Tursiops truncates*) swimming in the tidal creek habitat. All photos courtesy of PSDS at WCU.

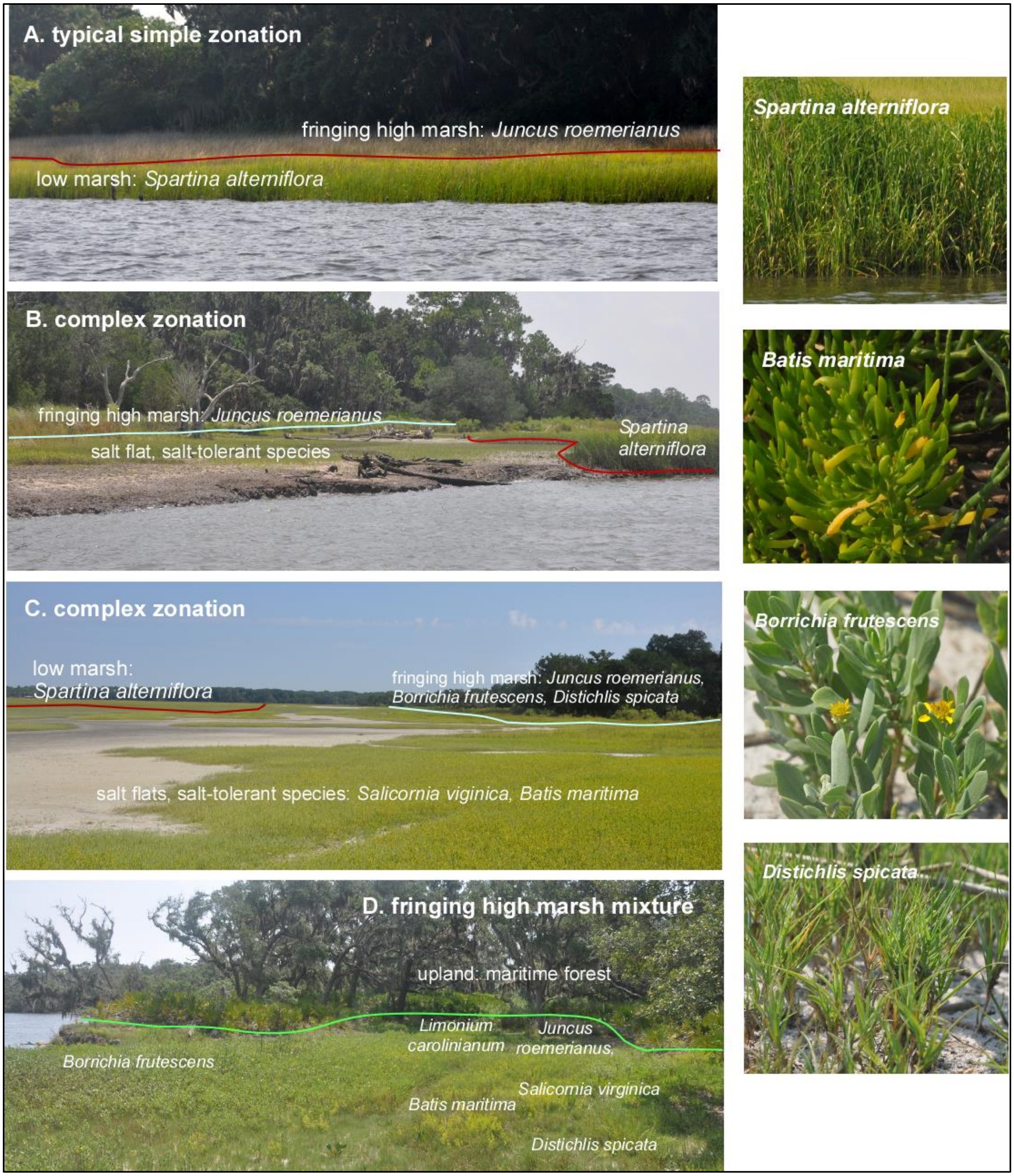


Figure 13. Salt marsh zonation and characteristic species observed during field work in July of 2014. A) Typical simple southeastern U.S. salt marsh zonation observed at CUIS. B, C) Complex zonation observed in many locations across CUIS. D) High marsh with a mixture of species interlaced together. Zoomed photos to the right are actual observed plants found at CUIS. All photos courtesy of PSDS at WCU.

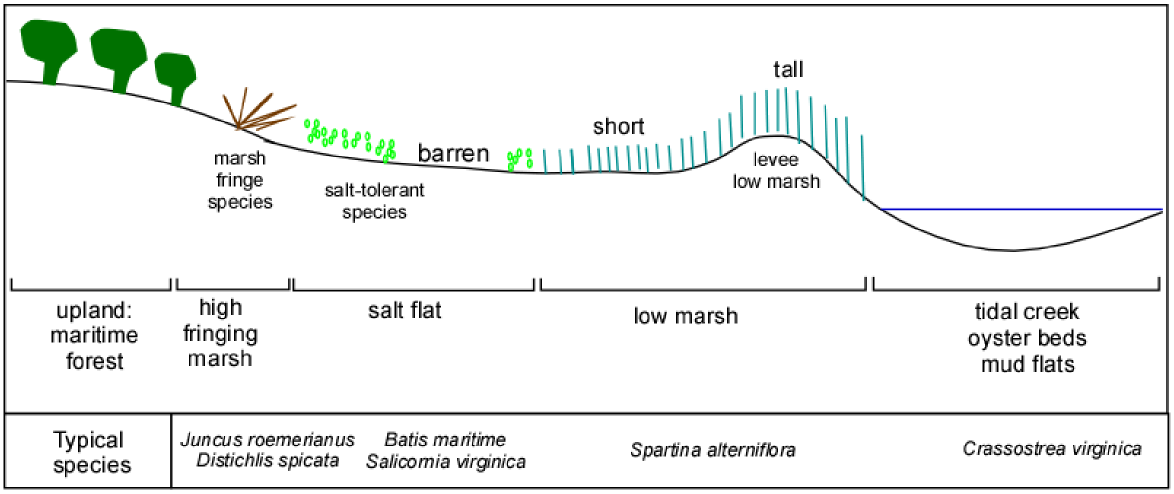


Figure 14. Simplified cross-section of the estuarine intertidal zone at CUIS, including common species.

Intertidal Beach

The intertidal beach at CUIS is fairly wide (over 100 m), particularly north of the St. Mary's River Inlet jetty in the southern part of the island (Figure 2, Figure 15A). While sand is accreting in this southern location, some portions of the shoreline have experienced erosion. Figure 15C shows a section of the beach in the central portion of the island that experienced erosion into the dunes during a storm in the spring of 2012 (prior field visit). Overall, wave energy across the island is low, and the sediments are primarily fine to medium sized sands with low shell content. Observed species in this habitat include several species of gull (*Larus* spp.), brown pelicans (*Pelecanus occidentalis*), and varied species of coquina clams (Figure 15B). The intertidal beach is bordered on the upland side (to the west) by a combination of active and inactive aeolian dunes, relict beach ridges, and relict sand spits.

Figure 15. Images illustrating the intertidal beach habitat at CUIS. A) Wide intertidal beach in the southern portion of the island. B) Seagulls foraging in the intertidal zone of the island. C) Erosion into the dunes in the central portion of the island in spring of 2012 (taken during a past visit to CUIS). All photos courtesy of PSDS at WCU.

Climate Change Vulnerability Assessment

For this analysis, vulnerability was assessed using the metrics (components) of vulnerability described in the National Wildlife Federation conservation guidebook compiled by numerous DOI agencies, including the NPS, USGS, US Fish and Wildlife, and NOAA (Glick et al., 2011). For each habitat, qualitative scores were given for the metrics of vulnerability to each of the stressors. Our assessment was focused on the current and short term (decadal scale) climate change vulnerability of these habitats in order provide results that are actionable within a meaningful planning cycle. Thus, this report is not meant to provide the vulnerability of these marine habitats over the long term (century scale) or during extreme or rapid stressor change scenarios.

Most of the habitats at CUIS have a relatively high physical adaptive capacity to gradual changes, especially to SLR. For example, a salt marsh can migrate with SLR, if the change occurs slowly. However, with a rapid shift in the direction or magnitude of the stressor (e.g. SLR) the adaptation could be entirely different. The sensitivity and adaptive capacity values are in reference to the current rate (or amount) of change for each stressor, or changes expected in the near future. The physical or intrinsic adaptive capacity (e.g., the ability of a habitat to migrate) was the primary consideration for the adaptive capacity scores within this analysis. Discussion of the adaptive capacity beyond the intrinsic factors can be found in a subsequent section (Intrinsic versus Extrinsic Adaptive Capacity).

Vulnerability Framework & Methods for Each Stressor

For this study a simple qualitative scale (1 = low, 2 = medium, 3 = high) was used to score each metric of vulnerability for all habitat-stressor combinations. The values were summed for each stressor and possible outcomes range between 3 and 9, with total stressor vulnerability rankings as follows:

- 3 or 4 = low vulnerability
- 5 = moderate-low vulnerability
- 6 = moderate vulnerability
- 7 = moderate-high vulnerability
- 8 or 9 = high vulnerability

Most vulnerability studies, whether physical, ecological, or socioeconomic, use a similar five “level” qualitative (as compared to quantitative) scoring system (e.g., Gornitz et al., 1994; Diez et al., 2007; Pendleton et al., 2010; Yin et al., 2012; Manomet Center for Conservation Sciences and National Wildlife Federation, 2013). Using a more quantitative approach implies a level of certainty that is not appropriate for the variable data quality and quantity related to climate change stressors at CUIS (or other NPS units). Below is a description of the framework that was used for assigning qualitative values for each metric of vulnerability. The rationale for determining the exposure, sensitivity, and physical adaptive capacity of each stressor is described but is only meant to provide the general foundation used during internal discussions about each habitat. A more complete description for each rating score is provided in the following results section.

Sea-Level Rise (SLR)

Exposure

All of the marine habitats of interest at CUIS were considered highly exposed to SLR. The physical location of each of these environments is extremely near, or at, sea level. All of these habitats would directly experience the impacts of changes in sea level in the coming decades.

Sensitivity

Species that are dependent on partial or full subaerial exposure to carry out normal functions (e.g., metabolism, reproduction, growth/productivity, etc.) or that would encounter increased predation or competition under higher sea level are considered more sensitive to SLR. Habitats that contain more sensitive species are overall more sensitive. The presence of sensitive species is related to tidal height; subtidal areas (always inundated) have low sensitivity, low intertidal areas (frequently submerged) have moderate sensitivity, and high intertidal areas (less frequently submerged) have high sensitivity. Additionally, habitats that cover a smaller area are likely more sensitive, as their constituent species are more dependent on particular environmental conditions. The SLR sensitivity of each habitat is relative to the current rate of SLR. Any significant increase in this rate could potentially shift the sensitivity values (Table 3).

Adaptive capacity

Highly adaptive habitats contain species that have the potential to grow or move vertically or horizontally, or remain in the same place under new conditions. Highly adaptive species tend to have high reproductive rates, growth rates, or are mobile. Most of the habitats at CUIS have a moderate or high adaptive capacity to the current rate of SLR (or even a moderate acceleration) due to the potential for migration. However, this adaptability would likely decrease if there was a sudden or rapid acceleration of SLR.

Ocean Acidification (OA)

Exposure

Exposure to OA is a function of proximity to and mixing with the open ocean. Variability of pH not associated to climate change-related OA was not considered as pH can fluctuate greatly with changes in freshwater discharge/runoff (freshwater is more acidic than seawater) and amount of coastal eutrophication. These fluctuations are largely independent from OA.

Sensitivity

Habitats most sensitive to pH changes are those with currently narrow pH ranges and which contain species that are sensitive to pH. Organisms that are sensitive to pH include calcifying organisms (calcification is strongly influenced by pH, carbonate concentration, and CO2 concentration) and larval organisms. Habitats that already experience large pH fluctuations (those closer to the sound and thus freshwater input) are likely less sensitive to gradual shifts in pH from OA, as they already experience seasonal and precipitation related shifts in pH from high discharge and rainfall events. Some species may be more sensitive to pH changes from OA during periods of coastal eutrophication. Coastal waters can reach organism threshold levels with a combined effect from climate change-related OA and local coastal eutrophication.

Adaptive capacity

It is difficult to separate species' adaptive capacity to pH changes from their sensitivity to pH. Habitats that already experience large pH fluctuations (those closer to the sound and thus freshwater input) are more likely to adapt to the pH changes associated with OA. Habitats with less pH fluctuation (marine habitats) may be less able to adapt. We assume that the adaptive capacity of most of the habitats within CUIS is reasonably high, as most nearshore marine habitats experience pH fluctuations throughout the year. However, it is not known how long-term trends in pH, extreme pH, or OA combined with non-climate pH changes may affect the ecosystem here.

Salinity Changes

Exposure

Climate-related salinity changes are likely to be caused by several interacting influences of seawater mixing, freshwater discharge/runoff, and evaporation, all of which can fluctuate naturally or under human influence. The most exposed habitats are at the confluence of these variables: changes in one or more may result in changes to the average salinity, stratification, salinity extremes, and/or patterns of salinity fluctuation. Thus, lower intertidal habitats and estuarine habitats are more highly exposed to salinity changes, whereas marine and higher intertidal habitats have lower exposure.

Sensitivity

Organisms with narrow salinity tolerances are more sensitive to salinity changes. It is likely that organisms that live in habitats with broad salinity ranges are less sensitive to salinity change, although extreme changes may be significant at the fringe of some habitats (i.e., the low marsh). It is currently unclear whether the habitats of interest at CUIS will be more sensitive to average changes in salinity over time, or to more frequent and/or intense seasons or extreme events (for salinity, high discharge events such as storms, or drought conditions). More likely, organisms will become sensitive to a combination of the long-term and short-term changes in salinity.

Adaptive capacity

Adaptive capacity is largely a function of the habitat's potential to move to more favorable salinity conditions. Mobile organisms, as well as organisms with high reproductive rates or broad dispersal, are better able to migrate to areas that suit their salinity tolerance.

Temperature Changes

Exposure

Temperature fluctuations are a function of ocean temperature, temperature of freshwater discharge, and air temperature. Habitats at the confluence of these variables are the most exposed to temperature changes. Habitats along the southeast coast of the U.S. are particularly exposed to the shifts that are likely to occur between the tropic and temperate zones as climate continues to change (Osland et al., 2013).

Sensitivity

Organisms with narrow temperature ranges are more sensitive to temperature. Although most organisms are accustomed to seasonal variation in temperature, many species depend on temperature cues for life history events such as spawning or migration; these organisms may be more sensitive to temperature changes, as such changes could disrupt precisely timed behaviors. Organisms that experience narrower temperature ranges (e.g., those living in deeper water) may be more sensitive to temperature fluctuation. Organisms may also be indirectly sensitive to temperature change if they are sensitive to low DO conditions, which are more likely to occur in warmer water. Many habitats are also sensitive to climate extremes, for example, the southeastern U.S. is expected to experience a tropicalization of coastal zones with future climate change, as certain tropical habitats migrate poleward at the expense of temperate habitats (e.g. mangroves replacing salt marshes; Osland et al., 2013).

<u>Adaptive capacity</u>

More highly adaptive organisms are either less sensitive to changes in temperature regime or are able to migrate to more favorable temperatures. A habitat's adaptive capacity for temperature change may also be reduced by the increased risk of low DO conditions and phytoplankton blooms that can be triggered by high temperatures. Note: it is likely there are no habitats in CUIS controlled by temperature; it is more an issue of individual creatures' tolerances.

Direction of Change for Stressors

Both SLR and OA are climate change stressors that have a predictable outcome in terms of direction in the future. It is known that in the near future, sea level is going to rise and ocean water pH is going to decrease. However, it is important to note that for both water temperature and salinity, the changes that will occur in the future will not likely be unidirectional and will be more unpredictable (Sheaves et al., 2007; Teck et al., 2010). Instead, the "change" for these stressors may be related to the magnitude and duration of seasonal and extreme events, which is harder to predict (although it is likely that temperature will primarily increase). For example, prolonged precipitation in the area would cause an increase in river discharge into Cumberland Sound, thus causing a decrease in the salinity of the water entering the low salt marsh. However, if the area were to experience prolonged periods of drought, the waters of Cumberland Sound (and in the low marsh) would increase in salinity with more evaporation. It is unclear if gradual changes over time or increased seasonal/extreme events (for temperature and salinity) will have more of an impact on the habitats and organisms.

Confidence Level

Each value given for the metrics of vulnerability (exposure, sensitivity, and adaptive capacity) was also given a qualitative (low-medium-high) confidence level. These confidence levels were based on a combination of factors, including our confidence in the available science and input from reviewers of the document. The climate change vulnerability of some habitats and species has been studied (e.g., salt marshes and *Spartina alterniflora*). Other environments, such as tidal mud flats, have little research related to climate change impacts on organisms, especially specific to this region. In general, habitat-stressor combinations with little to no research were given a low confidence level, and combinations with extensive research were given a high confidence rating. For example, little research has been conducted on how OA is affecting this region of the U.S., and therefore, most of the values assigned for this stressor were given a low or moderate confidence level. Conversely to this, the effects of SLR on salt marshes have been studied across the globe, which increased the confidence level given for these values. The confidence level is displayed for each habitat-stressor combination in the tables in the following sections. Exposure ratings were also given a higher confidence level overall, as this metric is more dependent on the physical position of the habitat, a factor that is moderately easy to assess.

Metrics of Vulnerability: Results

Each habitat of interest was investigated separately to determine vulnerability to the four climate change stressors of interest. Our interpretation of each habitat's vulnerability to each stressor incorporates relevant previous research and data collection. Also, the justification of our results for each NPS metric of vulnerability (sensitivity, exposure, adaptive capacity) is described. These metrics are not weighted; there is an assumption that all three metrics have equal significance in determining the total vulnerability. An important note about this assumption, and our metric values, is that when a habitat has a low exposure to a stressor, the sensitivity and adaptive capacity values are less meaningful, as it is more unclear how these habitats will react if they become more exposed over time. In addition, it is important to note that for this study, the low-medium-high ratings given for each metric are relative to other habitat-stressor combinations within CUIS, not relative to other locations. When compared to other areas of the U.S. or other coastal NPS units, the results for the vulnerability of each habitat would change. However, with some adjustments, this same methodology could be utilized to compare the vulnerability of specific habitats in other units. Because this study and document is intended to be used by local park managers, we have focused specifically on CUIS and the internal vulnerability of each of the habitats of interest. The total vulnerability values are summed for each stressor, and possible outcomes range between 3 and 9, with total stressor vulnerability ranking as follows: 3–4 = low; 5 = moderate–low, 6 = moderate, 7 = moderate–high, 8–9 = high. Tables 9–17 give the habitat specific results for the metrics of vulnerability for each climate stressor.

1. Marine Nearshore Subtidal (MNS): Climate Change Vulnerability

The MNS habitat is highly exposed to SLR, as it is physically located near current sea level. However, it is fully submerged, and will remain so with any rise in sea level. These changes in sea level (over the next few decades) are not expected to significantly influence organisms within this fully submerged habitat. There are no substantial beds of submerged aquatic vegetation that depend on sufficient light penetration (Alber et al., 2005). Organisms within this habitat are likely to tolerate the changes that come with rising sea level, so sensitivity to SLR is rated low and adaptive capacity is rated high (Table 9). Rising sea level may even expand this habitat as intertidal areas are inundated.

The MNS habitat is in direct contact with the open ocean, and is thus highly exposed to changes in ocean pH and carbonate equilibrium of the open ocean (Table 9). The organisms in this habitat are most likely accustomed to relatively stable pH, CO_2, and carbonate concentrations (in contrast to estuarine habitats, where these variables fluctuate). These organisms will likely be moderately sensitive to these OA changes. Different groups of organisms, and different stages of development, have different capacities to regulate H^+ and CO_2 concentrations in bodily tissues (Byrne, 2011), but marine organisms tend to have more restricted tolerances than estuarine organisms. Coastal eutrophication, which is common in this region, can enhance the effects of OA, as well as reducing the ability of sea water to buffer further acidification (Cai et al., 2011). A combination of low pH from eutrophication and climate change-related OA could cause coastal waters to reach or go above intertidal organism threshold levels (Feely et al., 2010). Carbonate shell makers must also contend with reduced carbonate concentrations, which make shell accretion more difficult. There is great variation in how different organisms respond to changes in water chemistry associated with OA, even among related organisms (Branch et al., 2013). Thus, adaptive capacity is rated moderate (Table 9).

Salinity is somewhat variable in the MNS habitat, but is more stable and consistently marine compared with the estuarine habitats at CUIS. The MNS habitat has low exposure to salinity change (Table 9), as salinity in this habitat is primarily controlled by ocean conditions, with less influence from freshwater discharge, runoff, and evaporation. SLR may lead to even more consistently marine conditions. Because most of the organisms in this habitat are accustomed to low fluctuations in salinity, changes in salinity (increase, decrease, or increased variability) may exceed the tolerances of these organisms (moderate sensitivity). The organisms likely have a moderate adaptive capacity for salinity change; some species need to migrate to or colonize areas with more suitable conditions.

Subtidal waters are less susceptible to changes in water temperature than intertidal waters. The MNS habitat's exposure to changes in air temperature and freshwater discharge temperature will likely be moderated by the relative stability of ocean water temperature. Although many organisms are sensitive to temperature, particularly during reproduction and early development (Byrne, 2011), this is more of a concern in estuarine nursery habitats. Organisms that cannot tolerate temperature changes have the potential to move to higher or lower latitudes or deeper or shallower waters (Byrne, 2011). At the same time, the migration of species into new habitats will inevitably have some impact, particularly when moving to new climate zones.

Table 9. Raw scores for Exposure, Sensitivity, and Adaptive Capacity of the Marine Nearshore Subtidal to SLR, OA, Salinity, and Temperature. Also included are the total non-weighted vulnerability scores. Confidence level for each score is assigned using number of asterisks (1= lowest confidence, 3 = highest confidence).

	Climate Stressor			
Vulnerability Metric	**SLR**	**OA**	**Salinity**	**Temp.**
Exposure	high (3) ***	high (3)**	low (1) ***	low (1) ***
Sensitivity	low (1) **	moderate (2) **	moderate (2) **	moderate (2) **
Adaptive Capacity	high (1) **	moderate (2) *	moderate (2) **	high (1) ***
Total	**moderate-low (5)**	**moderate-high (7)**	**moderate-high (5)**	**low (4)**

2. Intertidal Beach: Climate Change Vulnerability

Because the intertidal beach is already impacted by ocean tides, waves, storms, and changes in sea level, it was considered highly exposed to SLR (Table 10). Sensitivity of the intertidal beach to SLR, however, is considered low since this habitat is already inundated and flooded on a regular basis (by tides), and gradual changes resulting from SLR will have little negative impact (especially compared to the influence occurring from increased storm activity). This is not true for urbanized coastlines, where the natural landward migration of the shoreline and beach zone is hindered by human development (Schlacher et al., 2007; 2008). In this case, the undeveloped nature of Cumberland Island greatly enhances the ability of the intertidal beach to migrate and adapt to a rise in sea level. In addition, the organisms found in the intertidal beach are highly specialized, resilient, and are likely able to easily adapt to a gradual increase in SLR (Schoeman et al., 2014).

The intertidal beach was given a high exposure to OA because it is directly impacted by ocean waters. OA will primarily affect carbonate shell forming organisms within the intertidal beach habitat and studies have shown that with reduced carbonate concentrations, shell accretion can become more difficult for many organisms (Feely et al., 2004; Orr et al., 2005; Fabry et al., 2008). However, most of these studies are focused in tropical regions (i.e., Langdon and Atkinson, 2005), high latitudes (Fabry et al., 2008), or within specific locations such as Puget Sound, WA (Feely et al., 2010). Although the intertidal beach at Cumberland Island has calcifying organisms, a lack of OA-related studies focusing on the GA coastline suggests that this stressor may not yet be having substantial effects in this region. However, like the MNS habitat, the effects of OA may be amplified by coastal eutrophication. This amplification could cause a low pH threshold level for some organisms to be reached (Feely et al., 2010). As a result, we classified the sensitivity of the intertidal beach to OA as moderate (Table 10). Even though a modest increase in OA is anticipated in CUIS over the next century, this change, in conjunction with a lack of scientific data on the impacts of such an increase for this region, leads to an adaptive capacity classification of moderate.

Exposure of the intertidal beach to changes in salinity is deemed low since the primary attributes that affect salinity, such as increases/decreases in fresh water input resulting from changes in river discharges, are primarily located on the western side of CUIS. Because organisms living in the intertidal beach are most acclimatized to ocean salinity with occasional pulses of freshwater from high discharge events such as storms, they are likely to be more sensitive and less adaptive than estuarine environments to major shifts in salinity and received moderate ratings for both of these metrics (Table 10).

Exposure of the intertidal beach to changes in water temperature is deemed moderate since these changes result mainly from variations in precipitation and freshwater input that primarily affects habitats on the estuarine side of CUIS. The sensitivity of the intertidal beach to changes in temperature is considered low, and the adaptive capacity is considered high, since this habitat is already regularly exposed to seasonal, and often extreme, fluctuations in air and water temperature. Average monthly air temperatures in the region ranged from 47° to 85° F in 2011 (Wright et al., 2012).

One significant organism that depends on specific beach sand temperatures is sea turtles. However, turtles nest just above the intertidal zone, and therefore, are not technically part of this habitat. While that is the case, it is important to note that temperature changes will affect sea turtle nesting. With an increase in water temperature, there could be a shift in the timing of nesting (warmer water leads to earlier nesting) as well as a change in the length of the season (Hawkes et al., 2007; 2009). Temperature changes can also reduce the success of incubation as most turtles prefer temperatures between 25° and 35°C (Georges et al., 1994; Kaska et al., 1998; Hawkes et al., 2009). Shifts in temperature also control the sex of the embryo, as warmer temperatures lead to more females (Oz et al., 2004; Rees and Margaritoulis, 2004; Zbinden et al., 2007; Schmid et al., 2008; Hawkes et al., 2007; 2009). Among the CUIS habitats of interest, the MNS habitat has the highest overall vulnerability to OA (moderate-high). Due primarily to low exposure, the MNS is less vulnerable (moderate to low) to salinity and temperature changes.

Table 10. Raw scores for Exposure, Sensitivity, and Adaptive Capacity of the Intertidal Beach to SLR, OA, Salinity, and Temperature. Also included are the total non-weighted vulnerability scores. Confidence level for each score is assigned using number of asterisks (1= lowest confidence, 3 = highest confidence).

	Climate Stressor			
Vulnerability Metric	**SLR**	**OA**	**Salinity**	**Temp.**
Exposure	high (3)***	high (3)***	low (1)***	moderate (2)***
Sensitivity	low (1)***	moderate (2)**	moderate (2)**	low (1)***
Adaptive Capacity	high (1)***	moderate (2)**	moderate (2)**	high (1)***
Total	**moderate-low (5)**	**moderate-high (7)**	**moderate-low (5)**	**low (4)**

3. Low Salt Marsh: Climate Change Vulnerability

The low salt marsh was given a high exposure rating for all climate change stressors with the exception of OA (Table 11). The low salt marsh habitat is extremely low in the intertidal zone, and lies just adjacent to the estuarine waters of the tidal creeks and Cumberland Sound. Because of this position relative to sea level, the low salt marsh will experience the direct and indirect impacts of SLR and, therefore, was given a high rating for exposure for this stressor. As previously mentioned, the salinity and water temperature variations that will likely result from climate change are a function of seaward (ocean), landward (riverine), and atmospheric factors. The low salt marsh is physically positioned in areas experiencing direct impacts from both of these locations and thus was given a high rating for exposure to salinity and water temperature. As exposure to OA is a function of proximity to and mixing with the open ocean only, the low marsh was given a low rating for exposure to OA (Table 11).

Overall, the low salt marsh was given low scores for sensitivity and high scores for adaptive capacity for all climate change stressors (Table 11). The low salt marsh is extremely expansive within CUIS (Table 6), and *Spartina alterniflora* is easily the most dominant and widespread nearshore plant species. Each day, the low salt marsh is subjected to over 2 meters (6 feet) of water level change. At low tide, the entire marsh, including the muddy organic soil, is exposed. During high tide, the low marsh is almost completely submerged by the waters of Cumberland Sound. Therefore, it is likely that the species living in this habitat at CUIS have a low sensitivity to gradual changes related to SLR. At the same time, this habitat is extremely flat and low in elevation, and a major change, or an accelerated rate of change, could cause negative impacts on low marsh species. Consequently, the low marsh was given a moderate sensitivity to SLR.

While the low salt marsh was given a moderate rating for SLR sensitivity, this *Spartina alterniflora* dominated zone will likely have a high adaptive capacity to changes in sea level (Table 11). During periods of SLR, salt marshes adapt by migrating upland, accreting vertically (by accumulating organic matter and trapping inorganic sediments), or a combination of both (Mitsch and Gosselink, 2000). If a marsh is bordered by land that is incompatible for migration (i.e., major changes in elevation, rocky cliffs, or human development) the marsh may be at risk for submergence during rising sea level. To avoid this drowning, the marsh elevation must remain at equilibrium with sea level by the accumulation of sediments (Mitsch and Gosselink, 2000). There have been major losses of coastal wetlands (i.e., low salt marsh) in regions with a high relative rate of SLR (e.g., Louisiana) that are also deprived of sediment for vertical accumulation (Cahoon and Reed, 1995; Day et al., 2001; Barras et al., 2003; Nicholls et al., 2007; 2011). Significant salt marsh loss can also be attributed to increasing urbanization and development, which not only directly destroys wetlands, but can also cause indirect impacts such as the loss of accommodation space for migration as sea level rises (Lee et al., 2006; Sheaves et al., 2007).

In places like CUIS, where the natural environment is fairly unrestricted and the adjacent lands are suitable, the low salt marsh has the potential to migrate inland (in this case, into the higher marsh zones) as sea level rises. CUIS also has a large tidal range and moderate sediment supply, characteristics which have been shown to substantially increase the SLR adaptability of salt marshes (Simas et al., 2001; Morris et al., 2002; Kirwan et al., 2010) by increasing the likelihood that the marsh will gain elevation (through accretion) at a rate sufficient to keep pace with SLR. These factors led to the conclusion that the low salt marsh at CUIS will likely have a high adaptive capacity to SLR. Schile et al. (2014) modeled the effects of SLR on salt marshes and found that low marshes may reach a tipping point and convert into mudflats, but only at the most extreme SLR scenario (180 cm/century) and within areas that have a low sediment supply. In all other cases, the model showed low marsh species keeping up with SLR by accretion and/or migration inland (Schile et al., 2014). In New England marshes, *Spartina alterniflora* and other low marsh species have been replacing the high marsh species by migrating inland since the late 19th century (Donnelly and Bertness, 2001), corresponding to a time of recorded SLR acceleration.

Over the course of the year, the low salt marsh at CUIS experiences fairly wide fluctuations in pH (7.0 to 8.4) from the waters of Cumberland Sound (2011 to 2012; Wright et al., 2012; Rinehart et al., 2013), and *Spartina alterniflora* has been shown to grow in soils with pH values ranging from 3.7 to 7.9 (USDA Plants Database Website). The normal seasonal fluctuations in pH in these estuarine waters (from discharge and precipitation variations) are greater than the expected ocean water pH change over the next 100 years (reduction of 0.4 pH units from 8.1; Feely et al., 2004). Therefore, it is likely that low salt marsh species (primarily *Spartina alterniflora*) have a low sensitivity to more gradual changes in pH (Pennings et al., 2005; Brown et al., 2006; Touchette et al., 2009) and will also easily adapt (high adaptive capacity) to these longer term changes incurring from climate change-related OA.

Similar to pH, the low salt marsh is currently subjected to large fluctuations in salinity (ranging from 14 to 38 ppt in 2011 and 2012) during the year (Wright et al., 2012; Rinehart et al., 2013). *Spartina alterniflora* has been shown to have a moderate to high tolerance for high salinities and can survive regular flooding by waters ranging from fresh to above normal ocean salinity (USDA Plants Database Website). Experiments have also shown that *Spartina alterniflora* is able to survive stress from periods of flooding, drought, and increased salinity (Brown and Pezeshki, 2007), as well as efficiently out-competing higher marsh species under most conditions (Pennings et al., 2005). This tolerance of water level and salinity changes by low marsh species justifies the low sensitivity and high adaptive capacity given for salinity (Table 11). It is important to note that hypersaline conditions can decrease the primary production of *Spartina alterniflora* (Nestler, 1977; Wiegert et al., 1983; Dame and Kenny, 1986; Howes et al., 1996; Brown et al., 2006), and extreme long-term increases in salinity, especially during drought conditions, could cause plant mortality (Brown et al., 2006).

Spartina alterniflora is common along the entire east coast of the U.S., in areas with varied climates and water temperatures (Figure 16). Seasonal water temperatures can also vary over 30°F within Cumberland Sound during the year (ranging from 52° to 88°F, 2012 data; Rinehart et al., 2013). Therefore, this habitat likely has a low sensitivity and a high adaptive capacity to changes in water temperature (Table 11).

Table 11. Raw scores for Exposure, Sensitivity, and Adaptive Capacity of the Low Salt Marsh to SLR, OA, Salinity, and Temperature. Also included are the total non-weighted vulnerability scores. Confidence level for each score is assigned using number of asterisks (1= lowest confidence, 3 = highest confidence).

	Climate Stressor			
Vulnerability Metric	**SLR**	**OA**	**Salinity**	**Temperature**
Exposure	high (3) ***	low (1) ***	high (3) ***	high (3) ***
Sensitivity	moderate (2) **	low (1) *	low (1) **	low (1) **
Adaptive Capacity	high (1) ***	high (1) *	moderate (2) **	high (1) **
Total	**moderate (6)**	**low (3)**	**moderate (6)**	**moderate-low (5)**

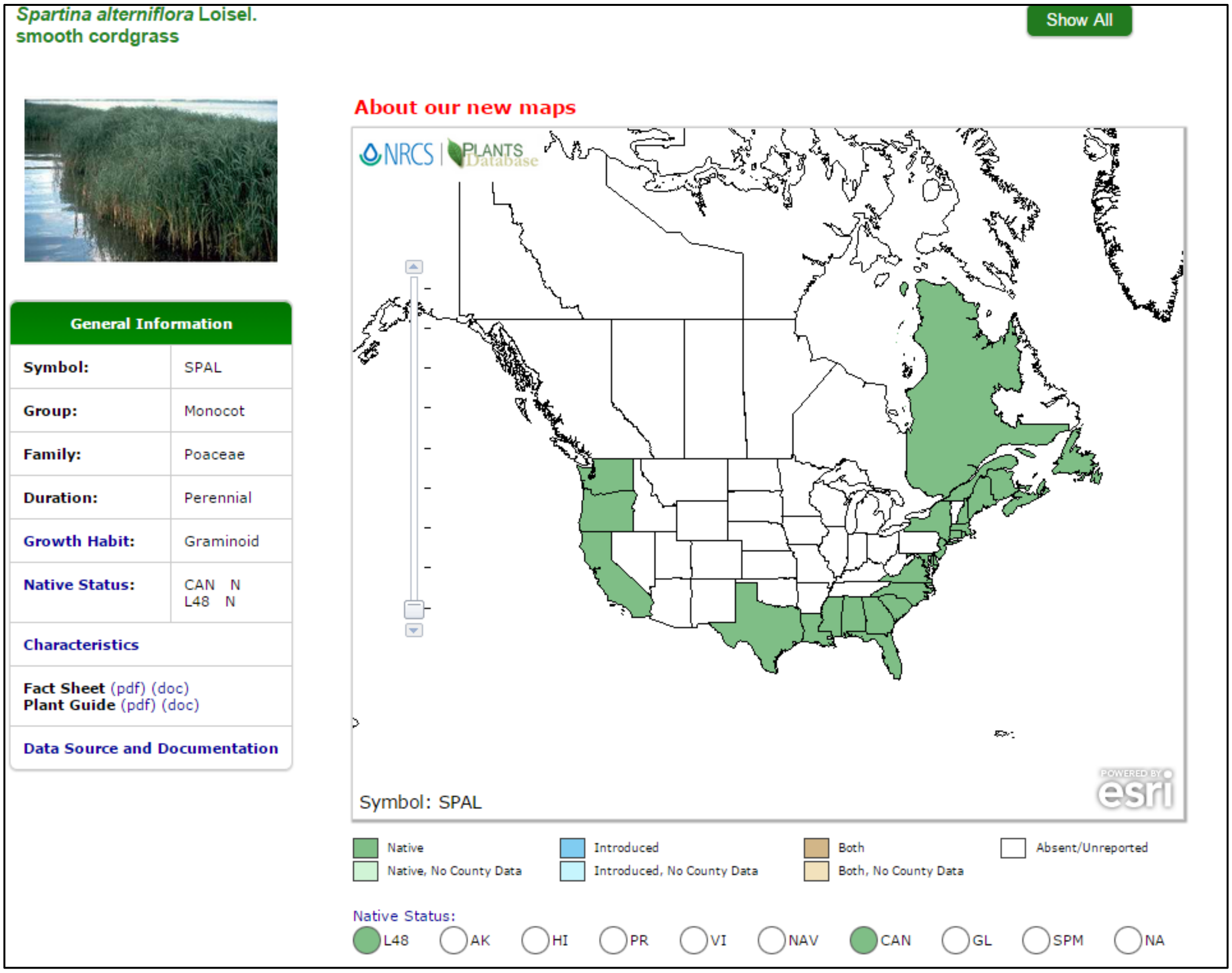


Figure 16. Distribution map of *Spartina alterniflora* within North America. Figure from USDA Plants database: http://plants.usda.gov/core/profile?symbol=SPAL

4. Salt Flats: Climate Change Vulnerability

The salt flats (also referred to as salt pans) were given a high rating for exposure to SLR due to a low position within the intertidal zone (Table 12). This habitat is situated further inland than the low salt marsh (Figures 13 and 14) and is only flooded intermittently by tides (5 to 10% frequency; Wiegert and Freeman, 1990). Evaporation in these areas after flooding (as well as porous sediments) leads to high interstitial salinity (commonly between 40 and 120 ppt; Wiegert and Freeman, 1990). Elevated pore space salinity in these zones causes most of the habitat to be barren of vegetation, as well as discouraging more competitive (but lower salinity tolerant) species, such as *Spartina alterniflora*, from populating. Rising sea level would likely cause these sparsely vegetated zones to become more frequently flushed with estuarine water, lowering the pore space salinity and reducing the evaporation period. With low salinity, the soils could become more favorable for additional vegetation; over time, the low salt marsh species would likely migrate into, and take over, the salt flat habitat. In fact, *Spartina alterniflora* was noticed growing in portions of the salt flat habitat at CUIS (mixed within more salt-tolerant species) during a field visit in the summer of 2014. These factors led to a moderate designation for sensitivity to SLR (Table 12). Similar to the low salt marsh, however, the salt flats will likely have a high adaptive capacity and migrate inland (towards the high marsh zone) as sea level rises (with sufficient accommodation space).

This habitat was given a moderate rating for exposure to salinity due to its slightly higher elevation relative to current sea level (Table 12). However, the salt flat is, by definition, controlled by salinity, and thus was given a high sensitivity to salinity changes. If the salinity were to decrease with more flooding (as sea level rises), species more compatible with this range in salinity (i.e., *Spartina alterniflora*) would likely begin to take over and convert this habitat to low marsh (Pennings et al., 2005). As sea level rises and salinity changes, the salt flats have the potential to establish within higher elevation marsh zones (moderate adaptive capacity).

The salt flat environment does not sit directly on Cumberland Sound, nor does it normally have direct influence from ocean waters. OA will most affect habitats with a direct connection to the ocean; consequently, the salt flat habitat was given a low exposure to this climate stressor (Table 12). Two primary water sources affect the salt flat habitat: water from Cumberland Sound and rain water. As mentioned previously, Cumberland Sound has pH values that can range seasonally from 7.0 to 8.4 (Wright et al., 2012; Rinehart et al., 2013), a wider range than expected in the ocean over the next century. Rain water that affects this habitat is also slightly acidic (commonly around 6.0). This range of pH already affecting the salt flats led to a low sensitivity for OA and a moderate adaptive capacity (Table 12).

Water temperature changes related to climate are controlled primarily by ocean water temperature, freshwater discharge/input, and air temperature (evaporation). Because this habitat is formed in part due to high amounts of evaporation, but is less influenced by freshwater input or ocean waters, it was given a moderate exposure to temperature (Table 12). Unless air temperature decreases a substantial amount to reduce evaporation, it is not likely that this habitat will be sensitive to temperature changes and will likely be able to adapt to the temperature changes that ensue.

Table 12. Raw scores for Exposure, Sensitivity, and Adaptive Capacity of the Salt Flats to SLR, OA, Salinity, and Temperature. Also included are the total non-weighted vulnerability scores. Confidence level for each score is assigned using number of asterisks (1= lowest confidence, 3 = highest confidence).

	Climate Stressor			
Vulnerability Metric	**SLR**	**OA**	**Salinity**	**Temperature**
Exposure	high (3) ***	low (1) ***	moderate (2)***	moderate (2) ***
Sensitivity	moderate (2) **	low (1)*	high (3) **	low (1) **
Adaptive Capacity	high (1) ***	moderate (2)*	moderate (2) **	high (1) **
Total	**moderate (6)**	**low (4)**	**moderate-high (7)**	**low (4)**

5. High Fringing Salt Marsh (HFSM): Climate Change Vulnerability

The HFSM has a high exposure to SLR as it is located within the intertidal zone (Table 13). The HFSM habitat fringes the terrestrial upland environment and is inundated during higher tides (e.g., spring tides). Over time, SLR will likely cause the lower intertidal habitats (low salt marsh, salt flats) to migrate inland into the HFSM. This higher elevation marsh is limited in area compared to the other estuarine habitats; we estimate that the HFSM makes up less than 10% of the total salt marsh at CUIS (for salt marsh coverage, see table 7). The small area of the HFSM suggests that the species within this habitat have a specific set of conditions for growth and those conditions are only met in a limited area of CUIS. One of the conditions controlling this growth is likely the position of the marsh substrate relative to sea level. *Juncus roemerianus*, one of the primary HFSM species within this habitat, appears to be sensitive to SLR as it is only found growing in locations lacking regular flooding (Wiegert and Freeman, 1990). For the HFSM to adapt, it must either keep up with SLR by accreting sediment, or migrate into the adjacent terrestrial upland (Mitsch and Gosselink, 2000).

Donnelly and Bertness (2001) found that marshes in New England have been converting rapidly from high marsh species to lower marsh species (*Spartina alterniflora*) over the past few centuries, coincident with accelerated rates of SLR. Their study suggests that more frequent flooding (from tides) was the root cause of the shift from high marsh to low marsh. Of all of the estuarine intertidal habitats, the HFSM will likely be least successful in migrating inland as the accommodation space is more limited. The HFSM sits just adjacent to the terrestrial upland, and in many locations, the elevation of this upland habitat may be too high for the marsh to populate successfully, hindering migration. Because of the sensitive nature of HFSM species to conditions such as water level and salinity, as well as the limited coverage and unsuitable accommodation space, this habitat was given a high sensitivity and a moderate adaptive capacity to SLR (Table 13).

OA will not likely affect the HFSM (low exposure) due to no direct connection to ocean waters. The species within this habitat will not likely be disturbed by changing pH values, as they already are being subjected to rain water and estuarine water with lower values on a regular basis. The primary species, *Juncus roemerianus*, can also grow in a wide range of pH values (between 4.0 and 7.0, USDA Plant Fact Sheet). These factors led to the low sensitivity and moderate adaptive capacity values for OA (Table 13).

As sea level rises, the HFSM will become more frequently inundated by tides, which will also begin to increase the salinity of this zone. However, this zone does not sit directly adjacent to Cumberland Sound, and therefore, was given a moderate rating for exposure to salinity. High marsh species at CUIS, such as *Juncus roemerianus*, are present in a moderate range of salinities (Pennings et al., 2003; Touchette, 2006). At the same time, many studies have shown that salinity (and water level) stress plays an important role in the distribution of high marsh species, especially as it relates to increased competition (Wiegert and Freeman, 1990; Pennings et al., 2005; Touchette et al., 2009). *Juncus roemerianus* (and other high marsh species) may physically be able to grow and survive in higher salinity zones, but will likely not be as widespread due to competition from more salt-tolerant species such as *Spartina alterniflora*, implying that competition is a major control on the species distribution of the high marsh. As salinity increases, the high marsh must migrate to less saline zones within the upland (or accrete enough sediment to attain a proper elevation) to retain the same area coverage. These aspects of the HFSM suggest a moderate sensitivity and adaptive capacity to salinity.

Water temperature changes related to climate are controlled primarily by ocean water temperature, freshwater discharge/input, and air temperature. This habitat is aerially exposed most of the time, but is less influenced by estuarine and ocean water than lower elevation zones; thus, it was given a moderate exposure to temperature. Seasonal water temperatures can also vary over 30°F within Cumberland Sound (ranging from 52° to 88°F, 2012 data; Rinehart et al., 2013), and HFSM species (e.g., *Juncus roemerianus*) are also found throughout the southeastern U.S. (USDA Plant Fact Sheet). Therefore, this habitat likely has a low sensitivity and a high adaptive capacity to changes in water temperature.

Table 13. Raw scores for Exposure, Sensitivity, and Adaptive Capacity of the High Fringing Salt Marsh to SLR, OA, Salinity, and Temperature. Also included are the total non-weighted vulnerability scores. Confidence level for each score is assigned using number of asterisks (1= lowest confidence, 3 = highest confidence).

	Climate Stressor			
Vulnerability Metric	**SLR**	**OA**	**Salinity**	**Temp.**
Exposure	high (3)***	low (1)***	moderate (2)***	moderate (2)***
Sensitivity	high (3) **	low (1)*	moderate (2) **	low (1) **
Adaptive Capacity	moderate (2)**	moderate (2)*	moderate (2) **	high (1)**
Total	**high (8)**	**low (4)**	**moderate (6)**	**low (4)**

6. Tidal Mud Flats: Climate Change Vulnerability

Due to the proximity of mud flats to tidal creeks and extremely low elevation within the intertidal zone, tidal mud flats were considered highly exposed to SLR (Table 14). A natural response of a rising sea level is that a portion of the current tidal flat area will be submerged and affected by waves and erosion (Natural Resources Canada, 2007). Marsh and tidal mud flat collapse can occur because of the positive feedback between marsh boundary erosion, tidal mud flat bed erosion, and wave generation in tidal flats. As a result, marsh erosion widens nearby tidal flats, thereby increasing wave energy and promoting further erosion in a runaway effect (Mariotti and Fagherazzi, 2013). SLR enhances this process by deepening tidal flats and increasing the sediment flux from tidal flats to salt marshes. Similar to the low salt marsh, the entire mud flat zone is exposed during low tide and is almost completely submerged by the waters of Cumberland Sound during high tide. Consequently, tidal mud flats were given a moderate sensitivity to SLR. The ability of tidal mud flats to adapt to SLR is analogous to the low marsh in that this zone will likely migrate upland with increasing SLR. As a result, tidal mud flats received a high rating for adaptive capacity. It is important to note, once again, that a sudden or rapid change in the rate of SLR could potentially change the sensitivity and/or adaptive capacity of the tidal mud flats.

Even though tidal mud flats are regularly flooded, fluctuations in pH will result primarily from changes in fresh water flow regimes related to riverine and precipitation inputs. As a result, tidal mud flats have a low exposure to OA (Table 14). Sensitivity of tidal mud flats to OA is also considered low due to the wide fluctuations in pH that this habitat already experiences from the waters of

Cumberland Sound (Wright et al., 2012; Rinehart et al., 2013). One study indicates that some crustaceans (copepods) living in environments prone to elevated CO_2 levels, such as mudflats, may be less sensitive to future acidification (Pascal et al., 2010). Due to their low exposure and low sensitivity to OA, tidal mud flats are considered to be highly adaptive to future increases in OA.

Because salinity is dependent upon multiple freshwater sources and inputs, tidal mud flats are highly exposed to changes in salinity (Wright et al., 2012; Rinehart et al., 2013). However, because tidal mud flats already experience significant episodic, seasonal, and temporal fluctuations in salinity, they have a low sensitivity and will likely be highly adaptable to anticipated future changes in salinity (Table 14).

The temperature of tidal mud flats is dependent on the input of freshwater, as well as changes in air temperature. Because the temperature of tidal mud flats is influenced by multiple inputs including warming oceans and increased/decreased river inputs, as well as changes in precipitation resulting from climate change, tidal mud flats are highly exposed to changes in temperature. While tidal mud flats are highly exposed to changes in temperature, habitats and organisms in tidal mud flats already experience significant seasonal temperature variations (Wright et al., 2012). This habitat, therefore, is considered to have a low sensitivity and high capacity to adapt to future increases in air or water temperature (Table 14).

Table 14. Raw scores for Exposure, Sensitivity, and Adaptive Capacity of the Tidal Mud Flats to SLR, OA, Salinity, and Temperature. Also included are the total non-weighted vulnerability scores. Confidence level for each score is assigned using number of asterisks (1= lowest confidence, 3 = highest confidence).

	Climate Stressor			
Vulnerability Metric	**SLR**	**OA**	**Salinity**	**Temp.**
Exposure	high (3)***	low (1)***	high (3)***	high (3)***
Sensitivity	moderate (2)**	low (1)***	low (1)**	low (1)***
Adaptive Capacity	high (1) **	high (1)***	high (1)**	high (1)**
Total	**moderate (6)**	**low (3)**	**moderate-low (5)**	**moderate-low (5)**

7. Shellfish Beds: Climate Change Vulnerability

Shellfish beds are highly exposed to SLR, as they are located in the low intertidal and thus have the potential to be permanently inundated by sufficient SLR (Table 15). The shellfish beds are considered to have moderate sensitivity to SLR because oysters do not need periodic aerial exposure (many oyster beds are fully subtidal), but increased or permanent submergence may increase predators, parasites, and/or competition for resources (DeAlteris, 1988). Increased sea level may also lead to salinity changes that might necessitate upstream migration (DeAlteris, 1988). Oysters are good colonizers, so the adaptive capacity of shellfish beds to SLR is high. Larval oysters depend on sufficient hard substrate to settle, but once started, an oyster patch can grow rapidly. Shellfish beds are more likely to be affected indirectly by increasingly marine salinity that comes with SLR (see discussion below); as long as appropriate substrate is available for larval oysters, and overharvesting doesn't limit shell base on which to grow, the habitat should be able to migrate upstream and/or grow vertically with rising sea level (DeAlteris, 1988).

Shellfish beds are located on the estuarine side of the island. Current and future pH fluctuations from freshwater input (7.0 to 8.4 in Cumberland Sound from 2011 to 2012; Wright et al., 2012; Rinehart et al., 2013) will likely outweigh any influence from decreased ocean pH from OA (a decrease of 0.4 pH units from 8.1; Feely et al., 2004), indicating low exposure to OA. However, as carbonate shell formers, oysters are moderately sensitive to acidification (Barton et al., 2012; Gazeau et al., 2013). Acidification has the potential to disrupt the formation of carbonate shell material (due to the reduced availability of CO_3^- ion in seawater, or to changes in metabolism related to pH regulation) and to dissolve already formed shell (Barton et al., 2012; Gazeau et al., 2013). Because estuarine oysters already encounter frequent pH fluctuation, they may be less sensitive than fully-marine shell forming organisms (such as reef forming corals). For example, embryonic oysters develop normally at pH 6.75 to 8.75 (Kennedy and Breisch, 1981). Similarly, because oysters already encounter greater variability in pH than that predicted for OA, they have a moderate capacity to adapt to the slight decrease in pH from the influence of climate change-related reduced ocean pH. However, under conditions of extreme low-pH stress (e.g., pH near 6.0 or below), it may be difficult for oyster beds to migrate to more favorable pH conditions, if such areas are even present. It is important to note that extremely low pH conditions may not be reached by climate change-related OA alone within this area, but in combination with other sources of acidification (e.g., upstream or precipitation sources, coastal eutrophication) organism threshold levels may be reached more frequently. These interactions may worsen the impact of these stressors, and therefore, increase the vulnerability of these habitats.

As an estuarine intertidal habitat, shellfish beds are already exposed to variations in salinity from submergence, evaporation, and freshwater input. Thus, shellfish beds are highly exposed to changes in salinity (increased, decreased, or greater or lesser variability) from any or all of these factors. Oysters are moderately sensitive to salinity; they are tolerant of variable salinity, with an optimal range of 10 to 28 ppt (Wilson et al., 2005) and an upper limit of 35 ppt (Buroker, 1983). Extreme low salinity (less than 6 ppt) may limit larval recruitment (Wilson et al., 2005) and can reversibly reduce or stop feeding in adults (Kennedy and Breisch, 1981). Extended periods of normal marine salinity (~35 ppt) can allow predators and parasites to take hold in shellfish bed habitats (Turner, 1985; DeAlteris, 1988). Shellfish beds were given a high adaptive capacity to salinity changes. If salinity becomes intolerably low, or if predators/parasites exclude oysters in normal marine conditions, oysters will likely colonize new, more suitable habitats (DeAlteris, 1988). Shellfish beds tend to move upstream with the salinity changes that come with SLR; vertical growth and upstream migration should be possible as long as overharvesting does not limit shell base on which the bed builds (DeAlteris, 1988).

As an intertidal habitat, shellfish beds are highly exposed to variation in both surface water and air temperature (Table 15). Water temperature in shellfish beds is influenced by both the temperature of freshwater discharge and by air temperature, but with probably little influence from open ocean temperature. Shellfish beds were given a moderate sensitivity to temperature changes. *Crassostrea* *virginica* experience temperatures from -1°C to 36°C throughout their geographic range, with an optimum temperature for respiration and feeding at about 24° to 26°C (Kennedy and Breisch, 1981). High temperatures have also been linked to an increase in disease for *Crassostrea virginica* along the Atlantic and Gulf coasts of the U.S. (Cook et al., 1997; Motes et al., 1998; Ford and Smolowitz, 2007). Oyster beds are also indirectly sensitive to temperature via its relationship with episodes of hypoxia or anoxia. Low DO events can reduce or prevent larval recruitment, in some cases leading to total settlement failure (Baker and Mann, 1992). Low DO can reversibly reduce or prevent growth, but adult oysters can survive such conditions for days or even weeks (Baker and Mann, 1992). Low DO events are an issue in Cumberland Sound and surrounding deeper tidal creeks (Alber et al., 2005). Considering the temperature extremes experienced by *Crassostrea virginica* in its latitudinally broad geographic range, changes in temperature due to climate change are unlikely to limit oysters' ability to maintain shellfish beds. If shellfish beds do encounter persistent intolerable temperature conditions, oysters may colonize more appropriate habitat. Low DO conditions (hypoxia or anoxia) may reduce the success of larval recruitment, but adult oysters have a much greater tolerance for low DO; recovery of oyster beds is likely unless low DO events are extreme in severity and duration (Baker and Mann, 1992). With high exposure and moderate sensitivity to SLR and temperature changes, the shellfish bed habitat has moderate overall vulnerability to these stressors. Due to high exposure to salinity and moderate adaptive capacity to OA, overall vulnerability to these stressors is moderate-low (Table 15).

Table 15. Raw scores for Exposure, Sensitivity, and Adaptive Capacity of Shellfish Beds to SLR, OA, Salinity and Temperature. Also included are the total non-weighted vulnerability scores. Confidence level for each score was assigned using number of asterisks (1= lowest confidence, 3 = highest confidence).

	Climate Stressor			
Vulnerability Metric	**SLR**	**OA**	**Salinity**	**Temp.**
Exposure	high (3)***	low (1) ***	high (3) ***	high (3) ***
Sensitivity	moderate (2) **	moderate (2) **	moderate (2) ***	moderate (2)**
Adaptive Capacity	high (1) ***	moderate (2) **	high (1) ***	high (1) **
Total	**moderate (6)**	**moderate-low (5)**	**moderate-low (5)**	**moderate (6)**

8. Tidal Creeks: Climate Change Vulnerability

Because tidal creeks are connected to, and directly influenced by, the rise and fall of ocean tides, they are highly exposed to SLR. However, portions of some tidal creeks that never become fully exposed under normal tidal fluctuations have a lower exposure to SLR since they are continually inundated. This combination of exposure in tidal creeks leads to an overall ranking of moderate for exposure to SLR (Table 16). Unlike salt marshes and tidal mud flats, however, habitats and organisms confined within tidal creeks are subtidal, and impacts resulting from SLR will be minor. Thus, tidal creeks are classified as having a low sensitivity, and are highly adaptive, to SLR (Table 16).

Even though tidal creeks are connected to ocean waters by inlets, fluctuations in pH result primarily from changes in fresh water flow regimes related to riverine and precipitation inputs. As a result, tidal creeks have a moderate exposure to OA (Table 16). Monitoring data from Cumberland Sound shows that these creeks are already experiencing a wider range of pH values (7.1 to 8.4 in 2012) than the expected contribution from climate change-related OA (Rinehart et al., 2013). Therefore, the sensitivity of tidal creeks to OA is considered low due to anticipated minor changes in OA in conjunction with the dominance of non-ocean forcing freshwater input mechanisms. Tidal creeks would also likely be highly adaptive to future increases in OA as these changes are predicted to be gradual and less than the current pH range within tidal creek waters.

Salinity of tidal creeks is also highly dependent on the input of freshwater. Salinity in the sound, for example, varied from 14 to 37 ppt in 2012 (Rinehart et al., 2013). Because salinity is dependent upon multiple freshwater sources and inputs, tidal creeks are highly exposed to future salinity changes. However, because tidal creeks already experience significant episodic, seasonal, and temporal fluctuations in salinity, they have a low sensitivity, and are highly adaptable to anticipated future changes in salinity (Table 16).

One possible exception to the low sensitivity and high adaptive capacity of tidal creeks to salinity might be during extended drought periods. Between 1998 and 2002, there was an outbreak of a parasitic dinoflagellate (*Hematodinium*) that has been shown to prevent the blood cells of crabs from holding oxygen, causing mortality. According to the GA DNR and the NOAA’s Sapelo Island research site, crabs are more susceptible to this parasite in higher salinity regimes in estuarine waters (Alber et al., 2005).

The temperature of tidal creeks is highly dependent on the input of freshwater, as well as changes in air temperature. Because the temperature of tidal creeks is influenced by multiple sources/inputs including warming oceans and increased/decreased river inputs, as well as changes in precipitation resulting from climate change, tidal creeks are considered highly exposed to changes in temperature (Table 16). This habitat, and the organisms residing within, already experiences significant seasonal air and water temperature fluctuations; water temperatures within Cumberland Sound ranged from 52 to 88°F in 2012 data (Rinehart et al., 2013) and average monthly air temperature in the region was between 47° and 85°F in 2011 (Wright et al., 2012). Since this habitat already experiences a wide variation in air and water temperature, it is moderately sensitive, and moderately able to adapt to anticipated additional increases in both.

Changes in precipitation and weather patterns resulting in higher air and water temperatures could exacerbate or increase the number of episodes of low DO, especially within Cumberland Sound and the larger tidal creeks. These low DO events, which cause harmful algal blooms and subsequent fish kills, have been recorded already in portions of Cumberland Sound (Alber et al., 2005; NPCA, 2009). In many cases however, these tidal creeks experience significant temperature fluctuations without causing detrimental impacts; organisms in tidal creeks should be able to adapt to gradual temperature shifts, as many of these species have broad latitudinal ranges and persist in much warmer and much colder environments. This combination suggests that these tidal creeks likely have a moderate sensitivity to temperature changes (Table 16). In terms of adaptability, certain organisms may move or migrate to more favorable temperature conditions (e.g., by moving to deeper, cooler waters). However, the occurrence of these low DO events has led to fish kills, suggesting that some fish may not be able to adapt quickly to increases in the severity or duration of low DO episodes. This led to a moderate ranking for adaptive capacity of tidal creeks to temperature (Table 16).

Table 16. Raw scores for Exposure, Sensitivity, and Adaptive Capacity of Tidal Creeks to SLR, OA, Salinity and Temperature. Also included are the total non-weighted vulnerability scores. Confidence level for each score using number of asterisks (1= lowest confidence, 3 = highest confidence).

	Climate Stressor			
Vulnerability Metric	**SLR**	**OA**	**Salinity**	**Temp.**
Exposure	high (3)**	moderate (2)***	high (3)***	high (3)***
Sensitivity	low (1)***	low (1)***	low (1)***	moderate (2)**
Adaptive Capacity	high (1)***	high (1)***	high (1)**	moderate (2)**
Total	**moderate-low (5)**	**low (4)**	**moderate-low (5)**	**moderate-high (7)**

9. Estuarine Nearshore Subtidal: Climate Change Vulnerability

The ENS habitat is just below the intertidal zone and therefore has a high exposure to SLR (Table 17). As with the MNS habitat, changes in sea level are not expected to impact the ENS negatively (low sensitivity and high adaptive capacity). Bottom waters are already too turbid to support submerged aquatic vegetation such as seagrass (Alber et al., 2005) so increased depth is not likely to harm current bottom dwellers. This habitat may in fact expand, as rising sea level inundates intertidal areas. Organisms that are light-limited may migrate landward to slightly shallower water.

The deeper, non-intertidal parts of the estuarine area may experience greater influence from changes in ocean chemistry than the intertidal areas (where freshwater discharge is the major contributor to changes in chemistry); however, the ENS already experiences greater fluctuations in pH (from 7.0 to 8.4 in 2011 to 2012; Rinehart et al., 2013) due to freshwater discharge than are expected with OA (reduction of 0.4 pH units from current 8.1; Feely et al., 2004). As estuarine organisms already encounter changes in pH greater than those expected due to OA, their sensitivity to OA is low (Table 17). Organisms that are tolerant of pH fluctuations should have a high capacity to adapt to slight, long-term, pH changes due to OA.

The ENS habitat is highly exposed to temperature variation from freshwater discharge and ocean water. This stressor of greatest concern for the ENS habitat due to its relationship with water column stratification and low DO. Cumberland Sound experiences a wide range of DO levels, from below 2 mg/L to above 9 mg/L from 2000 to 2004 (Alber et al., 2005). Low DO conditions (less than or equal to 4 mg/L) are most frequent during the spring and summer (Alber et al., 2005). Although the organisms in the ENS habitat do experience a wide range of temperature (water temperature in Cumberland Sound varied from 52° to 88 ºF in 2012; Rinehart et al., 2013) and DO conditions, the system is rated as moderately sensitive to temperature changes (Table 17). Extremely low DO conditions can cause physiological stress or death among sensitive organisms (Diaz and Rosenberg, 1995). Although mobile organisms (e.g., fish and crustaceans) can often move to escape stressful conditions, sessile organisms are limited in their response. Thus, adaptive capacity to temperature is moderate (Table 17).

With influence from seawater and freshwater discharge, the ENS habitat is highly exposed to potential salinity changes from both sources. Most likely, salinity will become more consistently marine as a result of SLR. Salinity changes (like temperature) can also contribute to water column stratification which can affect levels of DO. However, estuarine organisms, being adapted to fluctuating salinity, are not highly sensitive (directly) to salinity changes, but some organisms do require particular, albeit broad, salinity ranges. Organisms may adapt to salinity changes by migrating to more favorable conditions. This would likely entail migration upstream as marine salinity conditions move upstream with SLR.

Due to a combination of high exposure and moderate sensitivity and adaptive capacity, temperature is the stressor of greatest concern in the ENS habitat (moderate-high vulnerability). Low sensitivity and high adaptive capacity yield lower vulnerability (low to moderate-low) for SLR, OA, and salinity (Table 17).

Table 17. Raw scores for Exposure, Sensitivity, and Adaptive Capacity of Estuarine Nearshore Subtidal to SLR, OA, Salinity and Temperature. Also included are the total non-weighted vulnerability scores. Confidence level for each score is assigned using number of asterisks (1= lowest confidence, 3 = highest confidence).

	Climate Stressor			
Vulnerability Metric	**SLR**	**OA**	**Salinity**	**Temp.**
Exposure	high(3) ***	moderate (2) **	high (3) ***	high (3) ***
Sensitivity	low (1) ***	low (1) ***	low (1) **	moderate (2) *
Adaptive Capacity	high (1) ***	high (1) **	high (1) ****	moderate (2) **
Total	**moderate-low (5)**	**low (4)**	**moderate-low (5)**	**moderate-high (7)**

Climate Change Stressors: Results

The following section describes the overall vulnerability of the habitats at CUIS to each specific climate stressor; the combined metric scores (exposure, sensitivity, adaptive capacity) were used to rank the habitats in order of vulnerability. Results are displayed without weighting the metrics and, therefore, there is an assumption that all three metrics have equal significance in determining the total vulnerability. An important note about this assumption, and our metric values, is that when a habitat has a low exposure to a stressor, the sensitivity and adaptive capacity values are less meaningful, as it is more unclear how these habitats will react if they become more exposed over time. It must also be mentioned again that the values assigned for these climate change stressors and habitats are specific to CUIS and, therefore, should only be compared to each other.

SLR Vulnerability

Based on the data and research from the region, SLR is likely the most significant climate change stressor affecting the habitats of interest within this study. This is especially true for the intertidal environments, which are the most vulnerable habitats to changes in future sea level. All of the marine habitats in this study are highly exposed to sea-level change, as they are all physically positioned near current sea level. Halpern et al. (2007) evaluated the vulnerability of marine habitats to a variety of threats (using expert opinion and literature) and found that globally, SLR is considered the greatest threat to intertidal ecosystems. Also, there are clear, measured trends of the rate of sea level change (IPCC, 2013; NOAA Tides and Currents, Sea Level Rise) and these changes have clearly defined impacts on marine habitats and resources, including land submergence, salt water intrusion and erosion (Reed, 1990; Nicholls et al., 1999; Leatherman et al., 2000; Fitzgerald et al., 2008; Nicholls and Cazenave, 2010).

Results for the SLR stressor show the HFSM as the most vulnerable habitat, followed by low salt marsh, tidal mud flats, shellfish beds, and salt flats all with the same score (Table 18). In New England, it has been noted that SLR has caused loss of high marsh habitat due to the encroachment of low marsh species as conditions (salinity and flooding frequency) have changed (Donnelly and Bertness, 2001). The NPS has also reported significant back-barrier erosion in some locations of CUIS, partly within the marshes and mud flats. This erosion is likely exacerbated by changing sea levels within this region (Alber et al., 2005; Graham, 2009), and will continue this trend of increased erosion with further SLR.

Table 18. SLR vulnerability for all habitats of interest at CUIS, sorted by total score (high to low).

	Metrics of Vulnerability			
Habitat	**Exposure (1=low)**	**Sensitivity (1= low)**	**AC (1=high)**	**SLR Total Score**
High Fringing Salt Marsh	3	3	2	8
Low Salt Marsh	3	2	1	6
Tidal Mud Flats	3	2	1	6
Shellfish Beds	3	2	1	6
Salt Flats	3	2	1	6
Intertidal Beach	3	1	1	5
Tidal Creeks	3	1	1	5
Marine Nearshore Subtidal	3	1	1	5
Estuarine Nearshore Subtidal	3	1	1	5

While the low marsh is near the top of the vulnerability ranking for SLR, the adaptive capacity is high. Most studies agree that with moderate rates of SLR, low marshes will be able to keep pace with the rise in water by the vertical accumulation of sediment or by migrating inland; this is especially true in regions with a high tidal range and adequate sediment supply (Simas et al., 2001; Morris et al., 2002; Kirwan et al., 2010), similar to CUIS. However, a rapid or sudden increase in the rate of SLR could alter the high adaptability of coastal marshes. Many studies discuss a "tipping point" or "threshold rate," at which coastal marshes will become submerged due to an inability to keep up with the pace of SLR (Orson et al., 1985; Reed, 1990; Morris et al., 2002; Fitzgerald et al., 2008; Kirwan et al., 2010).

The two subtidal habitats (marine nearshore and estuarine nearshore) are the least vulnerable to SLR. The subtidal habitats are not likely going to be significantly affected by changes in SLR (over the next few decades), as these zones are already permanently submerged. Therefore, it is reasonable that these environments are the least vulnerable to this stressor.

OA Vulnerability

Although studies have shown the OA is causing negative impacts to marine species in many locations across the globe (i.e., Langdon and Atkinson, 2005; Fabry et al., 2008; Feely et al., 2010), measurable impacts have not yet been documented in the U.S. southeast. It is also not likely that OA will have a significant effect on the estuarine habitats at CUIS, as they are already subject to seasonal precipitation related fluctuations in pH far lower than any predictions for climate-change related OA. Even within the marine habitats at CUIS, OA has not yet been researched for potential impacts to organisms within these environments. Similar uncertainty about OA and how it will affect marine habitats was also noted in the Halpern et al. (2007) vulnerability evaluation study, and there was a low certainty (in terms of affects) among experts for all climate change factors. Modeling from a recent study of the OA vulnerability and adaptation of US shellfisheries (Ekstrom et al., 2015) show that along the GA coast, the *sublethal threshold levels* for bivalve larvae (like oysters) will not be reached until after 2099 (the longest time frame in the study). Because of this, OA is assumed to be the least significant climate change stressor overall, at least in the short term.

Within this analysis, the MNS and intertidal beach habitats are the most vulnerable to OA, as they are the only two with a high exposure to this stressor (Table 19). Both of these habitats are in direct contact with the open ocean and are highly exposed to any climate change-related OA that occurs. Compared to the estuarine habitats, the organisms are more accustomed to stable pH; any carbonate shell making organisms could potentially be impacted (Byrne, 2011). There has not yet been any documented OA sensitivity for organisms living along the southeast coast of the U.S. However, organisms in these marine habitats may begin to see the effects of the long-term change in ocean pH as it combines with short-term, pH changes such as those related coastal eutrophication. Climate change-related OA will likely amplify and intensify any impacts of local changes in pH, which could cause organism threshold levels to be reached in these coastal ocean waters (Feely et al., 2010).

The least vulnerable habitats to OA are the low salt marsh and tidal mud flats, as they have a low exposure to this stressor, as well as not being sensitive to these changes. All of the estuarine habitats (with the exception of shellfish beds) have a low sensitivity to OA, as they already experience major fluctuations in pH from estuarine, riverine and atmospheric inputs, and these inputs far outweigh any OA related changes in pH. At the same time, it is not known whether a long-term average decrease in pH (from ocean-related changes) will be more or less significant than the seasonal (precipitation-related) low pH events. Potentially, there may be organisms that are able to adapt to these seasonal shifts in pH, but not able to adapt to a long-term gradual (and permanent) decrease. It is also possible that low pH from seasonal and discharge related events combined with long-term OA could create conditions that are not suitable for organisms.

Shellfish beds are likely the most OA sensitive estuarine environment at CUIS. Like the shell forming organisms in the intertidal beach and ENS habitats, shellfish in Cumberland Sound could be affected by climate change-related OA, especially when combined with other more local sources of low pH (Ekstrom et al., 2015) such as coastal eutrophication.

Table 19. OA vulnerability for all habitats of interest at CUIS, sorted by total score (high to low).

	Metrics of Vulnerability			
Habitat	**Exposure (1=low)**	**Sensitivity (1= low)**	**AC (1=high)**	**OA Total Score**
Marine Nearshore Subtidal	3	2	2	7
Intertidal Beach	3	2	2	7
Shellfish Beds	1	2	2	5
Salt Flats	1	1	2	4
High Fringing Salt Marsh	1	1	2	4
Tidal Creeks	2	1	1	4
Estuarine Nearshore Subtidal	2	1	1	4
Low Salt Marsh	1	1	1	3
Tidal Mud Flats	1	1	1	3

Salinity Change Vulnerability

Salinity changes at CUIS are variable depending on the sources: SLR will bring increased salinity into many of the intertidal habitats, especially the marshes and salt flats. Separate from SLR induced changes to these marine habitats, additional salinity changes will occur from variations in freshwater discharge following periods of increased rainfall or drought. The salt flats, low salt marsh, HFSM and shellfish beds were determined to be the most vulnerable habitats to salinity changes (Table 20).

The salt flats have the highest score for vulnerability to salinity changes. The plants within these salt flats depend on the high interstitial salinity to limit competition (Wiegert and Freeman, 1990). If the salinity of this habitat becomes lower and more suitable for vegetation, possibly due to an increase in tidal flushing, it is likely that more competitive species (likely *Spartina alterniflora)* will begin to grow. Similar to the salt flats, the species in the HFSM are controlled by salinity (and also flooding). If the salinity in these zones begins to increase, the habitat will become more suitable for more salt-tolerant species.

The low marsh is vulnerable to salinity because it is situated where it is exposed to both sources of change (SLR and freshwater input). However, while the low salt marsh is exposed to both sources of salinity change, it is less likely to experience extremely high pore space salinity, as it is more frequently flushed with estuarine waters and less subject to evaporation. Pennings et al. (2005) suggest that in lower latitudes (like the GA coast) marsh plant zonation is more controlled by salinity stress than in other parts of the U.S.

The rest of the habitat at CUIS displayed the same total score for salinity vulnerability at CUIS (Table 20). However, two of these habitats, intertidal beach and MNS, received a low score for exposure, as they are not in a location that is majorly threatened by salinity changes from SLR or discharge (compared to the estuarine habitats). Tidal creeks, ENS, shellfish beds, and tidal mud flats were all considered highly exposed to salinity changes, but due to the range of salinities already experienced in these environments, were given low ratings for sensitivity and high for adaptive capacity.

Table 20. Salinity vulnerability for all habitats of interest at CUIS, sorted by total score (high to low).

	Metrics of Vulnerability			
Habitat	**Exposure (1=low)**	**Sensitivity (1= low)**	**AC (1=high)**	**Salinity Total Score**
Salt Flats	2	3	2	7
High Fringing Salt Marsh	2	2	2	6
Low Salt Marsh	3	1	2	6
Shellfish Beds	3	2	1	6
Marine Nearshore Subtidal	1	2	2	5
Intertidal Beach	1	2	2	5
Tidal Mud Flats	3	1	1	5
Tidal Creeks	3	1	1	5
Estuarine Nearshore Subtidal	3	1	1	5

Temperature Change Vulnerability

Temperature changes are likely the second most significant stressor for the habitats of interest at CUIS (Table 21). The overall trends and extremes in temperature are still not as clear as SLR, but changes could cause significant problems, particularly for the estuarine habitats. The waters of Cumberland Sound are already being negatively affected by increasing water temperature, especially during the summer months. Warmer waters increase the likelihood of stratification and low DO events; these events are already present within the deeper tidal creeks and estuarine habitats near CUIS (Alber et al., 2005). Because they are exposed and sensitive to these changes in temperature, the tidal creeks and the ENS habitats display the highest overall vulnerably to temperature. Any increase in water temperature during the summer months could increase the frequency and duration of these low DO events. Anoxic or hypoxic conditions in the water can cause physiological stress or death among sensitive organisms (Diaz and Rosenberg, 1995). Although mobile organisms (e.g., fish and crustaceans) can often move to escape these conditions, migration causes stress and favorable habitat may not be available. Sessile organisms are limited in their response.

Table 21. Temperature vulnerability for all habitats of interest at CUIS, sorted by total score (high to low).

	Metrics of Vulnerability			
Habitat	**Exposure (1=low)**	**Sensitivity (1= low)**	**AC (1=high)**	**Temperature Total Score**
Tidal Creeks	3	2	2	7
Estuarine Nearshore Subtidal	3	2	2	7
Shellfish Beds	3	2	1	6
Low Salt Marsh	3	1	1	5
Salt Flats	2	1	2	5
Tidal Mud Flats	3	1	1	5
Marine Nearshore Subtidal	1	2	1	4
Intertidal Beach	2	1	1	4
High Fringing Salt Marsh	2	1	1	4

Overall Habitat Vulnerability for CUIS

The total climate change stressor vulnerability scores assigned in the previous section were summed for each habitat-stressor combination, and the overall vulnerability ranking of habitats at CUIS were determined based on these values (Table 22). This overall stressor assessment shows the most at-risk habitats of interest at CUIS are the shellfish beds, HFSM and salt flats. The lowest ranking habitats at CUIS were low salt marsh and tidal mud flats. These summed results are based on an assumption that all four stressors (SLR, OA, salinity and temperature) are currently affecting all habitats at CUIS equally. We acknowledge that this is not the case at CUIS (or for any location), however, there is not sufficient data to allow for an accurate estimate of the percentages at which each stressor is affecting these marine habitats. Another assumption for these results is that that the climate change stressor will continue to affect these habitats in the future.

This overall ranking does not take into account all the interactions between climate stressors and non-climate stressors, which can increase their severity and potentially affect the relative vulnerabilities of habitats. The lack of data and information also limits the ability to assess impacts on certain habitats. As a result, precise comparisons of vulnerability among habitats and stressors are difficult to make. These factors are discussed later in this section.

Table 22. Overall climate change stressor vulnerability scores and ranking of habitats at CUIS.

Habitat	Stressor	Raw Scores			Totals		Overall Habitat Vulnerability Rank (1=highest)
		Exposure (1=low)	Sensitivity (1= low)	Adaptive Capacity (1=high)	Totals for Each Stressor	Total Score All Stressors	
Shellfish Beds	SLR	3	2	1	6	23	1[A]
	OA	1	2	2	5		
	Salinity	3	2	1	6		
	Temp.	3	2	1	6		
Salt Flats	SLR	3	2	1	6	22	2[B]
	OA	1	1	2	4		
	Salinity	2	3	2	7		
	Temp.	2	1	2	5		
High Fringing Salt Marsh	SLR	3	3	2	8	22	2[B]
	OA	1	1	2	4		
	Salinity	2	2	2	6		
	Temp.	2	1	1	4		
Marine Nearshore Subtidal	SLR	3	1	1	5	21	3[C]
	OA	3	2	2	7		
	Salinity	1	2	2	5		
	Temp.	1	2	1	4		
Intertidal Beach	SLR	3	1	1	5	21	3[C]
	OA	3	2	2	7		
	Salinity	1	2	2	5		
	Temp.	2	1	1	4		
Tidal Creeks	SLR	3	1	1	5	21	3[C]
	OA	2	1	1	4		
	Salinity	3	1	1	5		
	Temp.	3	2	2	7		
Estuarine Nearshore Subtidal	SLR	3	1	1	5	21	3[C]
	OA	2	1	1	4		
	Salinity	3	1	1	5		
	Temp.	3	2	2	7		
Low Salt Marsh	SLR	3	2	1	6	20	4[D]
	OA	1	1	1	3		
	Salinity	3	1	2	6		
	Temp.	3	1	1	5		

A = Highest ranked habitats for combined vulnerability (also highlighted in red).
B = High ranked habitats for combined vulnerability (also highlighted in orange).
C = Moderate ranked habitats for combined vulnerability (also highlighted in Yellow).
D = Low ranked habitats for combined vulnerability (also highlighted in green).
E = Lowest ranked habitats for combined vulnerability (also highlighted in blue).

Table 22 (continued). Overall climate change stressor vulnerability scores and ranking of habitats at CUIS.

Habitat	Stressor	Raw Scores: Exposure (1=low)	Raw Scores: Sensitivity (1= low)	Raw Scores: Adaptive Capacity (1=high)	Totals: Totals for Each Stressor	Totals: Total Score All Stressors	Overall Habitat Vulnerability Rank (1=highest)
Tidal Mud Flats	SLR	3	2	1	6	19	5[E]
	OA	1	1	1	3		
	Salinity	3	1	1	5		
	Temp.	3	1	1	5		

A = Highest ranked habitats for combined vulnerability (also highlighted in red).

B = High ranked habitats for combined vulnerability (also highlighted in orange).

C = Moderate ranked habitats for combined vulnerability (also highlighted in Yellow).

D = Low ranked habitats for combined vulnerability (also highlighted in green).

E = Lowest ranked habitats for combined vulnerability (also highlighted in blue).

Without weighting the stressors, the shellfish beds had the highest overall value for vulnerability based on the four climate change stressors of interest. These shellfish beds are highly exposed to all of the stressors except OA, and are at least moderately sensitive to all four climate stressors. Although the shellfish beds do not currently have a high exposure to OA, studies have shown that shellfish (primarily oyster) development can be hindered by increasing levels of pH from OA, especially coupled with reduced salinity and temperature as well as combined with coastal eutrophication (Barton et al., 2012; Barros et al., 2013; Ko et al., 2014). Because these shellfish beds are exposed to most of the stressors and sensitive to all of the stressors, they had the greatest overall total for vulnerability within CUIS.

By taking into consideration that SLR is likely the most significant climate change stressor at CUIS, we suggest that the HFSM is the most vulnerable habitat overall. Compared to the low salt marsh, the HFSM is more sensitive to changes from both SLR and salinity, as the organisms (primarily plant species) within these environments are more influenced by these stressors. HFSM plants prefer to grow in smaller range of pore space salinities and water levels, especially compared to the low marsh cordgrass, *Spartina alterniflora*, which can tolerate and adapt to a wider range of salt concentrations and endure large daily tidal fluctuations. Pennings et al. (2005) investigated both the high and low marsh at Sapelo Island, GA and found that *Juncus roemerianus* did not occur naturally in the low or intermediate marsh (the *Spartina alterniflora* zone). Further experiments with the two marsh species found that *Juncus roemerianus* performed poorly when transplanted to the lower marsh zones, suggesting that the lower limit of the species was set by physical stress from this environment (likely salinity and flooding).

Also adding to the vulnerability of the HFSM, is its relatively small areal extent and reduced accommodation space for migration into the upland terrestrial habitats. The lower intertidal zones (mud flats, low salt marsh, and salt flats) have more suitable accommodation space than the HFSM, as these habitats can migrate into the adjacent intertidal zone. The HFSM, however, must migrate into the terrestrial upland habitat, much of which significantly higher in elevation at CUIS, or is part of cultural landscapes within the park. These restrictions cause a type of coastal “squeeze” on the HFSM. The estuarine side of the high marsh is being lost due to increasing water level, salinity and competition, and the terrestrial side of the marsh is not migrating or adding area at a sufficient pace to keep up with the overall loss. This reduces the adaptive capacity (and raises the vulnerability) of the HFSM (Table 22). Other locations in the U.S. have found that with SLR, the lower marsh species like *Spartina alterniflora* are replacing those in the higher marsh (Donnelly and Bertness, 2001).

The habitats with the lowest overall vulnerability were tidal mud flats and low salt marsh (Table 22). Tidal mud flats have a low vulnerability in part because the organisms within this habitat will not likely experience significant affects from changes in OA, salinity or temperature. Some studies have suggested that tidal mud flats may actually expand during times of rising sea level. Both low salt marsh and tidal flats are highly adaptive to most of the climate-related stressor, which decreases the overall vulnerability of these habitats.

Although each climate change stressor was evaluated individually, the different stressors will undoubtedly interact with each other. Additionally, there are further climate concerns that will affect the region besides the four stressors of interest within this study, many of which are connected with the stressors chosen (e.g., changes in precipitation, which affects salinity and temperature). For simplicity, the metrics of vulnerability were primarily assessed independent of interactions with other stressors.

One significant interaction is between SLR and salinity. As sea level increases, more saline waters will encroach into many of these habitats. For example, the HFSM has a high overall vulnerability because of this interaction. The primary vegetation in this zone, *Juncus roemerianus,* could potentially survive with just an increase in salinity. However, in conjunction with rising seas, lower marsh species may become more suited for this habitat. Salt marsh plants can also be impacted by precipitation and salinity interactions, particularly the combination of severe drought and high salinity (Brown et al., 2006). Temperature changes and salinity changes are also connected. With an increase in air water temperature, evaporation is higher, causing increased water and pore space salinity in these habitats. This can also occur during periods of drought, reducing the freshwater inputs and leading to increase salinity in estuarine habitats. Although placing a value on these interactions is difficult when using the metrics of vulnerability, their impact on overall vulnerability is nonetheless significant because all of these climate stressors will have interactions with each other, as well as other stressors to these environments. Because these interactions are hard to assess, the overall vulnerability rankings of these habitats could be artificially low.

Confidence Level Results

Even though we have calculated combined climate change stressor vulnerability scores and ranked habitat vulnerability at CUIS, the availability of scientific data and research makes us inherently more (or less) confident in certain findings. For example, due to a richness of knowledge, research and data on SLR and intertidal habitats, we have a higher level of confidence in the following habitat/stressor combinations and anticipated impacts:

- Intertidal Beach/SLR (moderate to low impact)

- Intertidal Beach/Temp (low impact)
- Mud Flats/OA (low impact)
- Shellfish Beds/Salinity (moderate impact)
- Tidal Creeks/OA (low impact)
- Estuarine Nearshore Subtidal/SLR (moderate to low impact)

Conversely, due to a lack of analytic and technical data, our confidence is lowest for the following habitat/stressor combinations and anticipated impacts:

- Marine Nearshore Subtidal/OA (moderate to high impact)
- Low Salt Marsh/OA (low impact)
- Salt Flats/OA (low impact)
- High Fringing Salt Marsh/OA (low impact)

A number of assumptions and conclusions can be made from these findings. The most apparent is a lack of confidence regarding the potential long-term impacts of OA on several CUIS habitats. Although we have a higher degree of confidence that OA will have a lower impact on mud flats and tidal creeks based primarily on exposure, a paucity of research on the potential long-term impacts of OA leads to less confidence in stating OA will have similarly low impacts elsewhere within CUIS. Due to the availability of a significant volume of research on SLR and estuarine habitats, however, we are confident that the impacts of SLR to the intertidal beach and ENS in CUIS will be low, and we are similarly confident that increases in salinity will have a moderate impact on shellfish beds.

Our findings regarding confidence can be used to prioritize the allocation of funding and target future research needs and efforts. For example, we are generally more confident about vulnerability of habitats at CUIS to SLR compared to other stressors. Therefore, a habitat with high vulnerability to SLR (like the HFSM) should be a priority for short-term monitoring, research, and adaptation planning. We are less confident about the impacts of OA on these CUIS habitats, particularly combined with the risk of interactions with non-climate pH stressors (such as coastal eutrophication). Because we are less confident about this stressor (primarily because of the lack of data), we feel this would be a starting point for new research or long-term monitoring at CUIS or within the region.

Intrinsic versus Extrinsic Adaptive Capacity

There are two different aspects of adaptive capacity that must be addressed when working with managed natural environments such as NPS lands. The first is intrinsic, or natural, adaptive capacity, which is defined by the ability of an ecosystem, habitat, or species to naturally migrate or shift as climate changes. Natural resources also have an extrinsic, or management-based, adaptive capacity in which the ability to change and acclimate is dictated through human action, such as the development and implementation of a resource management plan. Extrinsic adaptive capacity, which can improve or reduce a resource’s adaptive ability, is often dictated by technology, funding, and governance. This analysis focused on the intrinsic adaptive capacity of natural resources and habitats in CUIS.

SLR: Much of the research involving extrinsic adaptation strategies to climate change, both within and external to the NPS, is devoted to SLR. Salt marsh restoration, living shorelines, erosion protection, and other adaptation strategies are already being applied in many locations in response to SLR. For example, the NPS has recently completed a two acre salt marsh restoration project in Jamaica Bay area of Gateway National Recreation Area in New York (Rafferty et al., 2011). Shellfish restoration projects are also common across the country from NC to WA (Brumbaugh et al., 2006).

An intriguing "bi-modal" strategy for SLR adaptation that can be implemented by park managers (including those at CUIS) is to allow intertidal habitats to migrate naturally. This extrinsic adaptation option is not always practical for more urban parks where space is limited, but, within more natural parks such as CUIS, allowing intertidal habitats to intrinsically adapt may be one of the most successful, and least expensive, forms of adaptation available.

Salinity and Temperature: While there are no park-level management actions directly targeting salinity and temperature changes, adaptation strategies that can help mitigate the *effects* of these changes are available.

One of the primary effects of salinity and temperature changes near CUIS is an increased risk of water column stratification and detrimental low DO (hypoxic) events within estuarine environments. Low DO events within Cumberland Sound are partially controlled by high nutrient input, most of which comes from external, upstream sources. Reducing this nutrient input could measurably decrease the number and/or severity of hypoxic events. Although the park does not contribute significantly to nutrient loading in the Sound when compared to other sources, such as upstream municipal effluent, the NPS could work with regional stakeholders to help reduce the amount of nutrients entering Cumberland Sound.

OA: Some regions of the U.S., particularly in the Pacific Northwest, are already experiencing a decrease in shellfish production related to the upwelling of cold acidified waters (Washington State Blue Ribbon Panel on Ocean Acidification, 2012). As a result, management strategies designed to enhance the ability of coastal resources to adapt to changes in OA concentrate on the impact of OA to intertidal habitats and shellfish production. Adaptation strategies for wild shellfish, for example, are currently focused on increased research and monitoring of OA, as well as reducing the input of land-based pollutants that can enhance acidification (such as eutrophication from nitrogen and organic carbon runoff).

Ekstrom et al. (2015) point out that along the east coast of the US, marine ecosystems are at risk to OA primarily due to high local levels of eutrophication. Even so, little information on the potential impacts of OA along the southeastern U.S. coast exists, and adaptation strategies targeting southeastern coastal habitats are limited.

Similar to salinity and temperature adaptation, OA adaptation at CUIS could include working with local and regional partners to limit the amount of runoff and pollutants entering Cumberland Sound.

Continued monitoring of pH levels, as well as research focused on the effects of lower pH on local habitats such as shellfish beds, may also prove highly beneficial.

Non-Climate Change Stressors at CUIS

While this study focuses on analyzing the vulnerability to climate change-related stressors, it is important to note that non-climate-related stressors have had, and will continue to have, major impacts on marine resources in CUIS. Primary non-climate stressors impacting marine environments in CUIS include feral horses, regional development including three superfund sites and two paper mills, channel dredging, historic land use (including agriculture, timber harvesting, diking, and channelization and construction), and shoreline stabilization (Table 23).

Recent estimates by the NPCA (2009) indicate there are 200 feral horses currently roaming Cumberland Island. These horses graze intensely on salt marsh grasses, exacerbating erosion and degrading water quality and habitat for wildlife. They also destabilize sand dunes, trample shorebird nests, and adversely affect water quality and wetlands habitat.

The hydrology of the island has also been altered through the years as plantation managers channelized streams and redirected flow for agriculture. More recently, the closure of the Durango paper mill in neighboring St. Mary's, GA has had an unintended impact on water resources and habitat within the park. When it was operating, the paper mill drew millions of gallons of water per day from the deep artesian aquifer that underlies the area. Since the plant no longer operates, water flow has been renewed at eight artesian wells within the park, which were dug long before the park was created and never capped properly. This spillage has created habitat that the park must decide how to manage (NPCA, 2009).

Pollution sources in the vicinity of the park include waste facilities, industrial sites, and continuing commercial and residential development. Agricultural runoff and superfund sites on the mainland, and possibly runoff from the island itself, contribute to high levels of mercury in the waters surrounding the island. The Satilla River and the St. Mary's River, both of which drain into Cumberland Sound, contain segments where mercury is a parameter of concern. In addition, high mercury concentrations have been found in fish and shellfish tissues collected in lower Cumberland Sound. Water demands by urban centers in the area are taxing the aquifer, and there is evidence of saltwater intrusion within the surficial aquifer at some locations to the north in the Brunswick area (NPCA, 2009).

As more people move near CUIS, it spurs development that includes large waterfront homes and marinas, built directly west of the park. This, in turn, brings new sources of air, water, and noise pollution, as well as an increased likelihood of wildlife disturbance. Significant bird populations that forage, roost, and/or nest on the island's southern tip, for example, may be disturbed by an increase in unauthorized boat landings and visitation to that area. In addition, endangered sea turtles and manatees that travel the waters between the island and the mainland will be at greater risk of being hit by vessels.

Greater boat traffic can also increase marsh edge erosion resulting from more frequent and larger wakes, and lead to additional landings on the island's western shoreline, which may adversely affect marine and intertidal resources and narrow tidal creeks (Graham, 2009). Increased noise pollution from boat traffic could also have negative impacts on marine animals within the park.

In addition to these wildlife-related concerns about development, there are three rivers on the mainland that drain into the waters surrounding Cumberland Island, and as regional development increases, those rivers will deliver greater amounts of contaminants to the waters surrounding the park, affecting other water quality measures such as temperature and turbidity. Other potential stressors include over-fishing and shellfish over-harvesting (NPCA, 2009).

Natural coastal processes at CUIS are negatively impacted by a jetty at the south end of the island. The jetty was constructed as a barrier to the southward downdrift transport of sand and to keep the tidal inlet open for ship traffic. The southern tip of the island (Pelican Banks) is growing while Fort Clinch State Park, across the inlet on Florida's Amelia Island, is losing sand. As a result, the state of Florida would like to transport the sand on Pelican Banks to Fort Clinch State Park (Graham, 2009).

A Pleistocene clay layer beneath a historic seawall built to protect the shoreline at the Ice House Museum contains cobbles that have eroded from the seawall. Back-barrier erosion occurs at about 0.5 to 1 m (1.6 to 3.3 ft) per year, while cut-bank erosion at the end of the seawall (approximately 2.4 m (8 ft) per year) has undercut trees that have toppled onto the shore (Graham, 2009).

Many of these non-climate stressors will likely be exacerbated by climate change, and vice versa. For example, erosion from increased rates of SLR will be worsened by anthropogenic landscape modifications such as inlet dredging and increased boat wakes. These interactions between the non-climate and climate change stressors will likely play a significant role in the overall vulnerability of these habitats in both the short and long term. The following section will discuss some of these interactions and the result on the overall vulnerability of the marine habitats of CUIS.

Non-Climate Stressors & Interactions with Climate Change

While non-climate stressors will continue to impact marine habitats in CUIS, interactions between non-climate stressors and climate change are likely to exacerbate these impacts by amplifying some stressors and reducing the adaptive capacity of certain species/habitats (Sheaves et al., 2007). Erosion of the estuarine shoreline resulting from an acceleration in SLR, for example, might result in anthropogenic landscape modifications such as increased dredging and a demand for shoreline stabilization projects.

Table 23 shows the primary non-climate stressors affecting each CUIS habitat (column 2) and the current degree to which they pose a threat to that habitat (column 3). For example, increased nutrient inputs from upstream, non-CUIS sources, in conjunction with an increase in water temperature, will likely result in more low DO events, algal blooms, and fish kills in the ENS habitat of CUIS (Alber et al., 2005). Non-climate impacts to the CUIS intertidal beach, on the other hand, are expected to be minor. Although anthropomorphic influences resulting from channel dredging and shoreline stabilization structures currently exist, future human manipulation of the CUIS shoreline is expected to be minimal and pose a low threat to the intertidal habitat. As a result, the ENS habitat received a high rating for non-climate stressors, while the intertidal beach received a low rating.

Table 23. Primary non-climate stressors at CUIS for each habitat of interest, with stressor level, and potential interaction with climate change stressors.

Habitat	Primary Non-Climate Stressors	Current Non-Climate Stressor Threat Level	Potential Increase in Climate Change Stressor Vulnerability
Marine Nearshore Subtidal	• dredging, engineering structure • overfishing • invasive water species/competition	low	low increase in vulnerability
Intertidal Beach	• dredging, engineering structure • over-fishing • invasive water species/competition	low	low increase in vulnerability
Low Salt Marsh	• dredging, engineering structure • increased boat wake • animal modifications: plant trampling, defecation, ingestion • invasive land species • water/soil contamination	high	high increase in vulnerability: SLR stressor
Salt Flats	• animal modifications: plant trampling, defecation, ingestion • invasive land species/competition	moderate	moderate increase in vulnerability: SLR & salinity
High Fringing Salt Marsh	• animal modifications: plant trampling, defecation, ingestion • invasive land species/competition	moderate	moderate increase in vulnerability: SLR & salinity
Tidal Mud Flats	• animal modifications: plant trampling, defecation • invasive land species/competition • water/soil contamination: fertilizers, effluent, pesticides	high	moderate increase in vulnerability: SLR & salinity
Shellfish Beds	• animal modifications: plant trampling, defecation • over-harvesting • water/soil contamination	high	high increase in vulnerability: temperature & salinity
Tidal Creeks	• dredging, engineered structures • overfishing • invasive water species/competition • water/soil contamination	high	high increase in vulnerability: temperature
Estuarine Nearshore Subtidal	• dredging, engineered structures • overfishing • invasive water species/competition • water/soil contamination	high	high increase in vulnerability: temperature

In addition, since non-climate stressors can increase the overall vulnerability (exposure, sensitivity, or adaptive capacity) of certain habitats, the table also includes an estimate of the potential increase in vulnerability each habitat may experience as a result of the interaction between non-climate and climate change stressors (column 4).

These assessments were based on literature review of issues at CUIS, and a low threat rating does not mean a habitat is not being affected by non-climate stressors. A low rating signifies that, relative to other habitats of interest, a threat is not as high or has not been documented as thoroughly. Aquatic habitats and habitats that are regularly inundated, including the low salt marsh, tidal mud flats, shellfish beds, tidal creeks, and the ENS, are considered highly threatened by non-climate stressors, including nutrients, pesticides, and fecal coliform resulting primarily from upstream municipal and industrial effluent (Alber et al., 2005). As the island is largely undeveloped forest and wetlands, there are no real sources of pollution on Cumberland Island itself. However, the large feral horse population represents a source of organic material to the water resources of the island, particularly tidal creeks and marshes (Alber et al., 2005).

In the larger region, both point and nonpoint sources of pollution can be introduced via either the Satilla or the St. Mary's rivers, both of which empty into Cumberland Sound to the west of the island. The Crooked River, which has a much smaller watershed, also drains from the mainland into the Sound. There are a total of 29 federally regulated National Pollutant Discharge Elimination System (NPDES) permittees in the region: 16 in Glynn County (almost all of which are industrial facilities located in and around Brunswick); nine in Camden County itself (the largest of which, Durango-Georgia Paper, is no longer active) and four in Nassau County, FL. Although there are no current areas in Camden County listed on the Georgia 303(d) list, there are seven regions not meeting designated uses in Glynn County, all of which are attributed (at least in part) to industrial sources (Georgia EPD 2002a; Georgia EPD 2002b).

It is expected that non-climate change stressors will make four habitats (low salt marsh, shellfish beds, tidal creeks, and ENS) more vulnerable to climate change stressors. Low salt marsh, in particular, provides a good example of the potential interaction between climate and non-climate stressors, and how they might work together to increase vulnerability.

While SLR is likely to increase marsh bank erosion, extensive dredging and wakes resulting from more and bigger boats could greatly enhance the impacts of SLR, thereby resulting in significantly higher marsh erosion rates. Another example is an increase in the vulnerability of the low salt marsh to SLR resulting from feral horses which have been shown to remove up to 98% of the aboveground standing stock of *Spartina alterniflora* in heavily grazed marshes (Turner, 1987). Because accretion of sediment in marshes is a function of the density of grasses present to trap particles (Gleason et al., 1979), heavily grazed marshes may be more susceptible to erosion and storm damage. Thus, intensive grazing could create conditions that speed the loss of marsh habitat. Species distributions on the marsh may also be altered by heavy grazing, permitting *Salicornia depressa*, which is unpalatable to horses, to dominate (Reimold et al., 1975).

Major Findings

Vulnerability Assessment Framework for Marine Habitats within National Parks

- Nine marine-influenced habitats of interest were chosen at CUIS: marine nearshore subtidal (MNS), intertidal beach, low salt marsh, salt flats, high fringing salt marsh (HFSM), shellfish beds, tidal mud flats, tidal creeks, and estuarine nearshore subtidal (ENS).
- Four climate change stressors of interest were chosen: sea-level rise (SLR), ocean acidification (OA), salinity change, and temperature change.
- Metrics of vulnerability (exposure, sensitivity, and adaptive capacity) were used to assess the overall climate change risk of habitats of interest at CUIS.
- Each metric was rated on qualitative low-medium-high (also numeric, 1-2-3) scale based on currently available data and research. Metric ratings are specific to CUIS.
- Metric results were combined to estimate an overall vulnerability for each stressor.
- Overall combined stressor vulnerability was calculated by summing the values for all stressors within each habitat. This combined vulnerability assumes all stressors are equal in significance for the park.
- The vulnerability assessment is based on current effects and potential decadal scale changes within the habitats of interest.

Habitat Specific Vulnerability Results

- MNS and intertidal beach: most vulnerable to OA (moderate-high). Both habitats are highly adaptive to SLR.
- Low salt marsh: most vulnerable to SLR and salinity, but only moderate value, as this habitat has potential to migrate to more suitable location.
- Salt flats: most vulnerable to salinity changes, due to the fact that species present are controlled by salinity.
- HFSM: most vulnerable to SLR (high) and a moderate vulnerability to salinity. The vulnerability is due to potential hindrances to the migration of this habitat into the upland.
- Tidal mud flats: most vulnerable to SLR (moderate).
- Shellfish beds: most vulnerable to both SLR and temperature (moderate for both).
- Tidal creeks: most vulnerable to temperature, already experiences issues with low DO in deeper creeks.
- ENS: most vulnerable to temperature, as it is already having issues with low DO in Cumberland Sound.

Stressor Specific Vulnerability Results

- SLR is likely the most significant climate-related stressor at CUIS.

- SLR: HFSM is the most SLR-vulnerable habitat at CUIS, due to small area coverage and reduced adaptability from decreased migration potential.
- OA: MNS and intertidal beach are tied for the most OA vulnerable habitats at CUIS, primarily because they are the only highly exposed habitats to this stressor.
- Salinity changes: Salt flats are the most salinity change-vulnerable habitat at CUIS. The vegetation in this zone is dependent on high interstitial salinity.
- Temperature changes: Tidal creeks and ENS zones are tied for the most temperature change-vulnerable habitats at CUIS, due to existing problems with high summer water temperatures and low DO. The ENS habitat is slightly more vulnerable, as it currently experiences the most issues.

Overall Habitat Vulnerability

- Shellfish beds are the most vulnerable habitat overall at CUIS using metrics of vulnerability for all four stressors. Shellfish have the potential for a moderate sensitivity to all four stressors of interest.
- HFSM is potentially the most vulnerable habitat, considering SLR is the most significant stressor at CUIS. This habitat is limited in area and confined to more specific conditions. Migration is also partially hindered by terrestrial habitat.
- The confidence level for the metric of vulnerability scores can be used to help focus resources for adaptation strategies within CUIS. Vulnerable habitats with a high confidence level are a reasonable place to start adaptation planning.
- Not only should the physical or intrinsic adaptive capacity be considered, but also the extrinsic or "management-based" adaptive capacity. The adaptation strategies for some stressors may limit or enhanced the overall adaptive capacity of a habitat.
- Interactions between the climate change stressors of interest (as well as other climate threats) are inevitable, but they are hard to predict. SLR and salinity are two stressors that have a clear link. With increased SLR, salinity will also increase in most of the marine environments at CUIS.
- Although only marine habitats were analyzed as part of this study, it is important to note that upland and nearshore freshwater habitats at CUIS may also be vulnerable to the climate change stressors evaluated (e.g., salt water intrusion into upland habitats with SLR).

Non-Climate Stressors at CUIS

- Primary non-climate stressors: feral horses, regional development including three superfund sites and two paper mills, channel dredging, diking, channelization, construction, shoreline stabilization, water pollutants, and over-fishing/harvesting.
- Non-climate stressors will likely be further exacerbated by climate change, and vice versa.
- Interaction between the non-climate and climate change stressors will play a significant role in the overall vulnerability of CUIS habitats in both the short and long term.

- Animal modifications (primarily horse vegetation trampling and ingestion) to the intertidal estuarine habitats (particularly the marsh habitats) will add to the overall vulnerability, especially as it relates to SLR stress (erosion) on the edges of these habitats.
- Water contamination from upstream sources (particularly nutrients), as well as high summer temperatures, has led to low DO events within the estuarine water surrounding CUIS. Any additional increase in water temperature from climate change could increase the frequency and severity of these events, with possible effects to ENS, tidal creeks, and shellfish beds.

Summary and Next Steps

This project was initiated to develop a framework for assessing the relative vulnerability of marine habitats within the NPS units to climate change. CUIS was selected as a pilot park, and a framework was developed and implemented to assess the likelihood that climate-induced variation will have an adverse effect on intertidal and subtidal habitats.

The result of this effort is a synthesis document that evaluates the vulnerability of park resources within its bioregional context and provides two essential types of information needed for climate change adaptation planning:

1. Identifying which species/habitats are likely to be most strongly affected by climate change.
2. Understanding why they are likely to be vulnerable.

Determining the resources that are most vulnerable enables managers to better set priorities for conservation action, while understanding why they are vulnerable provides a basis for developing appropriate management and conservation responses (Glick et al, 2011).

Figure 17 provides a comprehensive framework for adaptation planning, and indicates how vulnerability assessments can fit into and support that process. Elements of this framework draw from a number of existing conservation planning frameworks including The Nature Conservancy's Conservation by Design and the U.S. Fish and Wildlife Service's Strategic Habitat Conservation framework (Glick et al, 2011). The CUIS habitat vulnerability assessment presented in this report achieved Goal 1 (Identify Conservation Targets) and Goal 2 (Assess Vulnerability to Climate Change). Future steps that can be taken to manage CUIS marine resources vulnerable to climate change involve the identification and implementation of management options (Goals 3 and 4).

Figure 17. Conservation goals as described in the National Wildlife Federation document on vulnerability assessments. Figure 1.1 from Glick et al., 2011.

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Appendix A: Coastal and Marine Ecological Classification Standard (CMECS) of CUIS Habitats

Marine Nearshore Subtidal: CMECS Classification

Biogeographic Setting

- Realm: Temperate North Atlantic
- Province: Warm Temperate Northwest Atlantic
- Ecoregion: Carolinian

Aquatic Setting

- System: Marine
- Subsystem: Nearshore
- Tidal Zone: Subtidal

Water Column Component

- Water Column Layer: Marine Nearshore Surface Layer
- Salinity Regime: Euhaline Water
- Temperature Regime: Warm Water

Geoform Component

- Tectonic Setting: Passive Continental Margin
- Physiographic Setting: Continental/Island Shelf
- Geoform Origin: Geologic
- Level 1 Geoform: Beach
- Level 1 Geoform Type: Barrier Beach/Tide Dominated Beach

Substrate Component

- Substrate Origin: Geologic
- Substrate Class: Unconsolidated Mineral Substrate
- Substrate Subclass: Fine
- Substrate Group: Sand
- Substrate Subgroup: Medium Sand

Biotic Component

- Biotic Setting: Benthic/Attached Biota
- Biotic Class: Faunal Bed
- Biotic Subclass: Soft Sediment Fauna

Intertidal Beach: CMECS Classification

Biogeographic Setting

- Realm: Temperate North Atlantic
- Province: Warm Temperate Northwest Atlantic
- Ecoregion: Carolinian

Aquatic Setting

- System: Marine
- Subsystem: Nearshore
- Tidal Zone: Intertidal

Water Column Component

- Water Column Layer: Marine Nearshore Surface Layer
- Salinity Regime: Euhaline Water
- Temperature Regime: Warm Water

Geoform Component

- Tectonic Setting: Passive Continental Margin
- Physiographic Setting:
- Geoform Origin: Geologic
- Level 1 Geoform: Beach
- Level 1 Geoform Type: Barrier Beach/Tide Dominated Beach

Substrate Component

- Substrate Origin: Geologic
- Substrate Class: Unconsolidated Mineral Substrate
- Substrate Subclass: Fine Unconsolidated Substrate
- Substrate Group: Sand
- Substrate Subgroup: Medium Sand

Biotic Component

- Biotic Setting: Benthic/Attached Biota
- Biotic Class: Faunal Bed
- Biotic Subclass: Soft Sediment Fauna

Low Salt Marsh: CMECS Classification

Biogeographic Setting

- Realm: Temperate North Atlantic
- Province: Warm Temperate Northwest Atlantic
- Ecoregion: Carolinian

Aquatic Setting

- System: Estuarine
- Subsystem: Coastal
- Tidal Zone: Intertidal

Water Column Component:

- Water Column Layer: Marine Nearshore Surface Layer
- Salinity Regime: Mesohaline/Polyhaline Water
- Temperature Regime: Warm Water

Geoform Component

- Tectonic Setting: Passive Continental Margin
- Physiographic Setting: Sound
- Geoform Origin: Geologic
- Level 1 Geoform: Marsh Platform
- Level 2 Geoform: Flat
- Level 2 Geoform Type: Tidal Flat

Substrate Component

- Substrate Origin: Geologic
- Substrate Class: Unconsolidated Mineral Substrate
- Substrate Subclass: Fine Unconsolidated Substrate
- Substrate Group: Sandy Mud

Biotic Component

- Biotic Setting: Benthic/Attached Biota
- Biotic Class: Emergent Wetland
- Biotic Subclass: Emergent Tidal Marsh
- Biotic Group: Low and Intermediate Salt Marsh
- Biotic Community: *Spartina alterniflora* Carolinian Zone Herbaceous Vegetation

Salt Flats: CMECS Classification

Biogeographic Setting

- Realm: Temperate North Atlantic
- Province: Warm Temperate Northwest Atlantic
- Ecoregion: Carolinian

Aquatic Setting

- System: Estuarine
- Subsystem: Coastal
- Tidal Zone: Intertidal

Water Column Component: N/A

Geoform Component

- Tectonic Setting: Passive Continental Margin
- Physiographic Setting: Sound
- Geoform Origin: Geologic
- Level 1 Geoform: Flat
- Level 1 Geoform Type: Back-Barrier Flat

Substrate Component

- Substrate Origin: Geologic
- Substrate Class: Unconsolidated Mineral Substrate
- Substrate Subclass: Fine Unconsolidated Substrate
- Substrate Group: Muddy Sand

Biotic Component

- Biotic Setting: Benthic/Attached Biota
- Biotic Class: Emegent Wetland
- Biotic Subclass: Vegetated Tidal Flats
- Biotic Group: Vegetated Salt Flat and Panne
- Biotic Community: *Batis maritima* Dwarf-shrubland/ *Salicornia depressa,/ Spartina alterniflora* Herbaceous Vegetation

High Fringing Salt Marsh: CMECS Classification

Biogeographic Setting

- Realm: Temperate North Atlantic
- Province: Warm Temperate Northwest Atlantic
- Ecoregion: Carolinian

Aquatic Setting

- System: Estuarine
- Subsystem: Coastal
- Tidal Zone: Intertidal

Water Column Component: N/A

Geoform Component

- Tectonic Setting: Passive Continental Margin
- Physiographic Setting: Sound
- Geoform Origin: Geologic
- Level 1 Geoform: Marsh Platform
- Level 2 Geoform: Flat
- Level 2 Geoform Type: Tidal Flat

Substrate Component

- Substrate Origin: Geologic
- Substrate Class: Unconsolidated Mineral Substrate
- Substrate Subclass: Fine Unconsolidated Substrate
- Substrate Group: Muddy Sand

Biotic Component

- Biotic Setting: Benthic/Attached Biota
- Biotic Class: Emergent Wetland
- Biotic Subclass: Emergent Tidal Marsh
- Biotic Group: High Marsh
- Biotic Community: *Juncus roemerianus* Herbaceous Vegetation

Tidal Mud Flats: CMECS Classification

Biogeographic Setting

- Realm: Temperate North Atlantic
- Province: Warm Temperate Northwest Atlantic
- Ecoregion: Carolinian

Aquatic Setting

- System: Estuarine
- Subsystem: Coastal
- Tidal Zone: Intertidal

Water Column Component:

- Water Column Layer: Estuarine Nearshore Surface Layer
- Salinity Regime: Mesohaline-Polyhaline Water
- Temperature Regime: Warm Water

Geoform Component

- Tectonic Setting: Passive Continental Margin
- Physiographic Setting: Sound
- Geoform Origin: Geologic
- Level 1 Geoform: Flat
- Level 1 Geoform Type: Tidal Flat

Substrate Component

- Substrate Origin: Geologic
- Substrate Class: Unconsolidated Mineral Substrate
- Substrate Subclass: Fine Unconsolidated Substrate
- Substrate Group: Mud

Biotic Component

- Biotic Setting: Benthic/Attached Biota
- Biotic Class: Faunal Bed
- Biotic Subclass: Soft Sediment Fauna

Shellfish Beds: CMECS Classification

Biogeographic Setting

- Realm: Temperate North Atlantic
- Province: Warm Temperate Northwest Atlantic
- Ecoregion: Carolinian

Aquatic Setting

- System: Estuarine
- Subsystem: Coastal
- Tidal Zone: Intertidal

Water Column Component:

- Water Column Layer: Estuarine Nearshore Surface Layer
- Salinity Regime: Mesohaline-Polyhaline Water
- Temperature Regime: Warm Water

Geoform Component

- Tectonic Setting: Passive Continental Margin
- Physiographic Setting: Sound
- Geoform Origin: Biogenic
- Level 1 Geoform: Flat
- Level 1 Geoform Type: Tidal Flat
- Level 2 Geoform: Mollusk Reef
- Level 2 Geoform Type: Patch Mollusk Reef

Substrate Component

- Substrate Origin: Biogenic Substrate
- Substrate Class: Shell Substrate
- Substrate Subclass: Shell Reef Substrate
- Substrate Group: Oyster Reef Substrate

Biotic Component

- Biotic Setting: Benthic/Attached Biota
- Biotic Class: Reef Biota
- Biotic Subclass: Mollusk Reef Biota
- Biotic Group: Attached Oysters
- Biotic Community: Attached *Crassostrea*

Tidal Creeks: CMECS Classification

Biogeographic Setting

- Realm: Temperate North Atlantic
- Province: Warm Temperate Northwest Atlantic
- Ecoregion: Carolinian

Aquatic Setting

- System: Estuarine
- Subsystem: Coastal
- Tidal Zone: Intertidal

Water Column Component

- Water Column Layer: Estuarine Nearshore Surface Layer-Lower Water Column
- Salinity Regime: Mesohaline-Polyhaline Water
- Temperature Regime: Warm Water

Geoform Component

- Tectonic Setting: Passive Continental Margin
- Physiographic Setting: Sound
- Geoform Origin: Geologic
- Level 1 Geoform: Channel
- Level 2 Geoform: Tidal Channel/Creek

Substrate Component

- Substrate Origin: Geologic
- Substrate Class: Unconsolidated Mineral Substrate
- Substrate Subclass: Fine Unconsolidated Substrate
- Substrate Group: Sandy Mud

Biotic Component

- Biotic Setting: Benthic/Attached Biota
- Biotic Class: Faunal Bed
- Biotic Subclass: Soft Sediment Fauna

Estuarine Nearshore Subtidal: CMECS Classification

Biogeographic Setting

- Realm: Temperate North Atlantic
- Province: Warm Temperate Northwest Atlantic
- Ecoregion: Carolinian

Aquatic Setting

- System: Estuarine
- Subsystem: Coastal
- Tidal Zone: Subtidal

Water Column Component:

- Water Column Layer: Estuarine Nearshore Surface Layer-Lower Water Column
- Salinity Regime: Mesohaline-Polyhaline Water
- Temperature Regime: Warm Water

Geoform Component

- Tectonic Setting: Passive Continental Margin
- Physiographic Setting: Sound
- Geoform Origin: Geologic
- Level 1 Geoform: Channel

Substrate Component

- Substrate Origin: Geologic Geologic
- Substrate Class: Unconsolidated Mineral Substrate
- Substrate Subclass: Fine Unconsolidated Substrate
- Substrate Group: Muddy Sand

Biotic Component

- Biotic Setting: Benthic/Attached Biota
- Biotic Class: Faunal Bed
- Biotic Subclass: Soft Sediment Fauna

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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