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Effects of Rising Sea-Levels on Coastal Marsh Migration and Carbon Sequestration Along the Georgia Coast

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An abstract of

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Abstract

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Climate change and resulting sea-level rise pose an enormous threat to coastal wetlands via increased inundation and erosion. Any coastal wetland loss is critical because of their role in climate change mitigation as they serve as a highly productive carbon sink. Using elevation data, sea-level rise modeling, and existing carbon stock data, this paper explores the extent of habitat loss and subsequent loss in carbon storage on the Georgia coast under three sea-level rise scenarios. This analysis found that critical coastal habitats, freshwater forests, freshwater emergent wetlands, and salt marshes, all saw significant area loss under all three scenarios, while less productive habitats expanded. Carbon storage also decreased significantly as a result of habitat loss. This information is crucial in evaluating coastal protection policy and mitigating damages caused by rising sea-levels.

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Introduction

Carbon dioxide emissions have reached a critical threshold where simply reducing the amount of carbon entering the atmosphere is no longer sufficient if we want to avoid irreversible harm to the planet. Carbon must now be actively removed from the atmosphere or other carbon sinks in addition to reducing emissions. The world's oceans act as one of the most significant carbon sinks, capturing around 31% of carbon emissions annually (Gruber et al. 2019). It is therefore vital to maximize the potential of marine ecosystems as a carbon sink. Unfortunately, there is still significant damage to the marine systems due to the amount of carbon entering. Carbon lowers the pH of the oceans through a process known as ocean acidification in which carbon dioxide reacts with water, forming carbonic acid. Since preindustrial times, the average ocean pH has decreased from 8.2 to 8.1. While this may seem inconsequential, this corresponds to a 25% increase in ocean acidity (EPA 2016). Increased acidity subsequently disrupts nutrient cycling and directly interferes with sensitive marine life such as corals and shellfish (Ekstrom et al. 2015; Parker et al. 2013). Therefore, finding strategies to mitigate these effects is crucial.

Because of these threats, there has been an increased focus on removing carbon from marine systems. Many possible strategies have been discussed, such as direct carbon capture from seawater, ocean alkalization, and micro/macro algae cultivation (Rau 2009; Paquay and Zeebe 2013; Gao et al. 2022). But none of these artificial strategies has gained much traction when compared to the benefits of maintaining blue carbon ecosystems.

Blue carbon ecosystems primarily refer to coastal wetlands such as mangrove forests, seagrass beds, and salt marshes (NOAA 2021). These systems are characterized by dominant vegetation and aquatic soils that are particularly effective as storing carbon for long periods of time. Though wetlands only account for around 5-8% of the world surface, up to an estimated

30% of soil carbon is stored in these systems, demonstrating that wetland soils are far more efficient and effective at storing carbon (Nahlik and Fennessy 2016). Much like terrestrial ecosystems, blue carbon ecosystems can store carbon in the "short-term" in vegetation biomass such as grasses and roots. But more importantly, their "long-term" carbon storage vastly outdoes that of terrestrial ecosystems (Mcleod et al. 2011). The burial rate in salt marshes is estimated to be 218 ± 24g $m^{-2}y^{-1}$, more than 40 times higher than that of the average terrestrial forest (Mcleod et al. 2011). Carbon storage in the soil is by far the most significant sink in salt marshes accounting for 99% of stored carbon, whereas above ground biomass only accounts for 1% (Alongi 2020).

Dense and anoxic soils allow for a much higher organic matter accumulation rate, and a significantly lower decomposition rate, allowing carbon to stay stored in its sediments for thousands of years (Osland et al. 2018; Nahlik and Fennessy 2016).

Unfortunately, wetland coverage has been consistently decreasing for centuries. Compared to the 1700s, total wetland area has reduced by more than 50%, with about 60,000 acres of coastal wetlands specifically lost each year (EPA 2013). Most of this land has been used for land development projects, which are energy intensive and release massive amounts of carbon. By continuously developing wetlands, the United States is steadily losing one of its most effective and reliable carbon sinks, which only looks to exacerbate the climate crisis even more.

Land development is not the only threat to coastal wetlands. Rising sea levels threaten to submerge huge areas of the coast, vastly reducing the amount of space available to wetlands. Based on recent projections, sea levels could rise up to two meters along the east coast by the end of the century, almost certainly occupying land that is currently a coastal wetland (Kopp et al. 2014).

There are many factors that could contribute two how much sea-level rise the east coast sees this century. Because there is a wide range of possible sea-level rise, three scenarios, which consider the range of human intervention, were chosen. These three predictions are based on three IPCC Representative Concentration Pathways (RCP) scenarios: RCP 8.5, RCP 4.5 and RCP 2.6. RCP scenarios predict trends of atmospheric greenhouse gas concentrations based on variations in human behavior. RCP 8.5 details a "business as usual" situation in which there is no serious climate intervention. This largely describes a worst case scenario and would result in the highest sea-level rise. RCP 4.5 details an intermediate scenario. The IPCC expects this to be the most probable scenario in which there is a peak in emissions in 2040 before an eventual decline. RCP 2.6 is a "very stringent" pathway in which global emission reaches 0 by 2100. By reducing emissions at this rate, global temperature rise can be kept below 2 degrees C by 2100. Predictably, the RCP 8.5 scenario results in the highest global average sea-level rise and RCP 2.6 results in the lowest average sea-level rise.

In the United States, Georgia has one of the most well protected and preserved salt marsh coasts, largely thanks to efforts of Eugene Odom, see Table 1. Known as the "Father of Modern Ecology", Odom was a pioneer of environmental education. He, and his students, led efforts to oppose land developers from touching the Georgia coastal wetlands, and this persistence ultimately led to the passage of the Coastal Marshlands Protection Act of 1970 (Harris 1970). Since then, Georgia's coasts have been extremely well preserved, and have been the location of many soil carbon analyses which have evaluated soil carbon concentration, above and below ground carbon biomass, depth, and other variables (Loomis and Craft 2010; Krauss et al. 2018; Nahlik and Fennessy 2016). This information makes the Georgia coast an effective location to study carbon dynamics.

Figure 1. Map Depicting Current wetland coverage in Georgia, taken from US Fish and Wildlife Service.

Historically, if given the proper conditions, marshes have demonstrated the ability to migrate inland at a rate faster than sea-level rise (Kirwan et al. 2010; Schuerch et al. 2018). In general, marsh loss is due to excessive inundation, meaning the marshes do not have enough time to properly migrate. However, marsh migration rates depend on several factors including vertical sediment accumulation rate and available space for migration. For instance, sediment accumulation rates are significantly influenced by vegetation (Langston et al., 2021). Anthropogenic structures pose another barrier to marsh migration. Urban areas or coastal structures such as seawalls can also inhibit a marsh from effectively migrating inland (Kirwan et al. 2010). Because of their healthy condition, Georgia's coastal marshes may not all be lost to sea-level rise. Effective coastal protections have preserved large areas of the coast, providing ample inland area for marsh migration. Recently, Cabin Bluff became the last undeveloped portion of the Georgia coast to become protected, guaranteeing tens of thousands of acres of protected land to be available for inland marsh migration (TNC 2020).

Considering these factors, the National Oceanic and Atmospheric Administration developed a marsh migration model to predict new geographic areas that are likely locations for future marshes, as well as areas of concern where marshes may be lost. Existing carbon stock data will be used to estimate average carbon storage for each present habitat. Using that information, this analysis seeks to evaluate the carbon sequestration potential of new Georgia marshes under different sea-level rise scenarios.

Methods

Sea-Level Rise Estimates

The NOAA sea-level change calculator was used to estimate local sea level rise in Georgia. The calculator uses the nearest tidal gauge information and critical elevation inputs to calculate prediction curves. Based on the NOAA calculator, the northern coast would be slightly more affected by sea-level rise in all three scenarios (see Table 1). The NOAA sea-level change calculator does not have a site projection for the south coast of Georgia, but does include a site projection for Fernandina Beach, a site in north Florida just a few miles beyond the border with Georgia. In this location, the worst-case scenario corresponds with an increase of around four and a half feet. The intermediate scenario projects just over one foot, and the best-case scenario project just over zero feet. There is a noticeable, but not hugely significant difference in the local sea level rise projections between the northern and southern parts of the coast.

Based on the predictions, the following LSL rise scenarios were chosen (feet):

	Georgia Coast North (Fort Pulaski)	Georgia Coast South (Fernandina Beach)
RCP 8.5	5	4.5
RCP 4.5	2	1
RCP 2.6	1	0

Table 1. Local sea-level rise estimates for the Georgia coast based on the NOAA sea-level rise calculator.

Using these estimations, sea-level rise and marsh migration maps were taken at these LSL benchmarks for the coast of Georgia (NOAA).

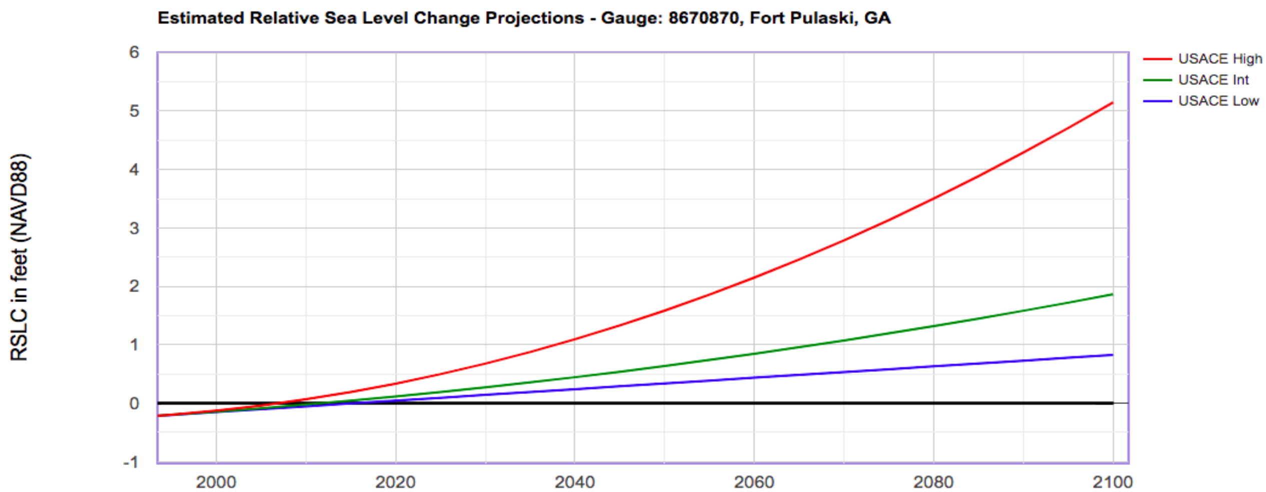

Figure 2a. Sea-level rise projections on the north Georgia coast, Fort Pulaski. From NOAA Sea-Level Rise calculator.

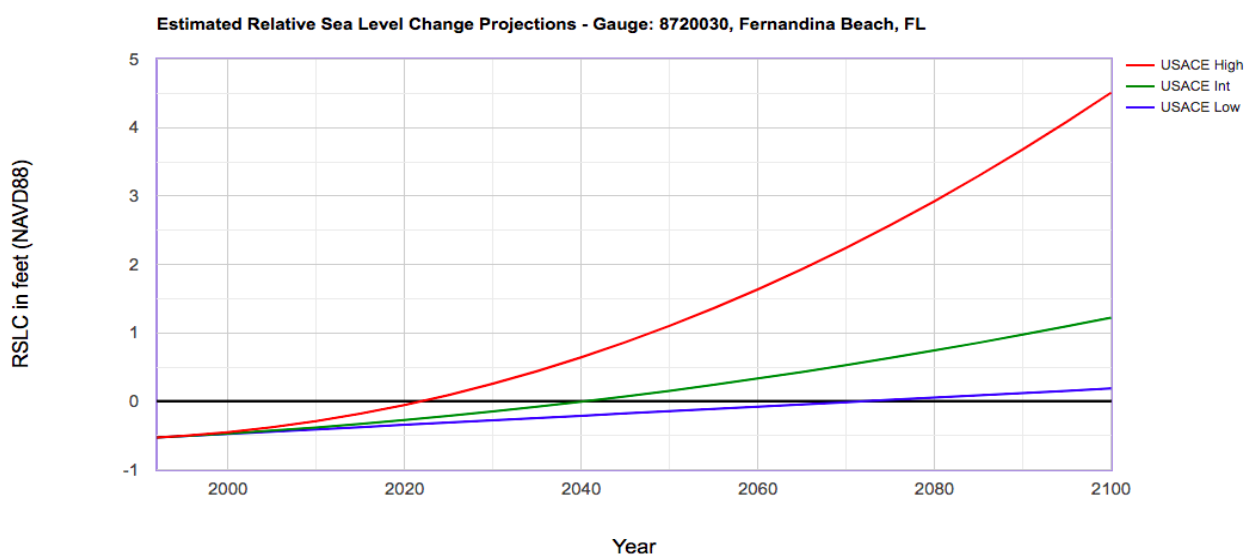

Fig 2b. Sea-level rise projections for the South Georgia coast, Fernandina Beach. From NOAA Sea-Level Rise calculator.

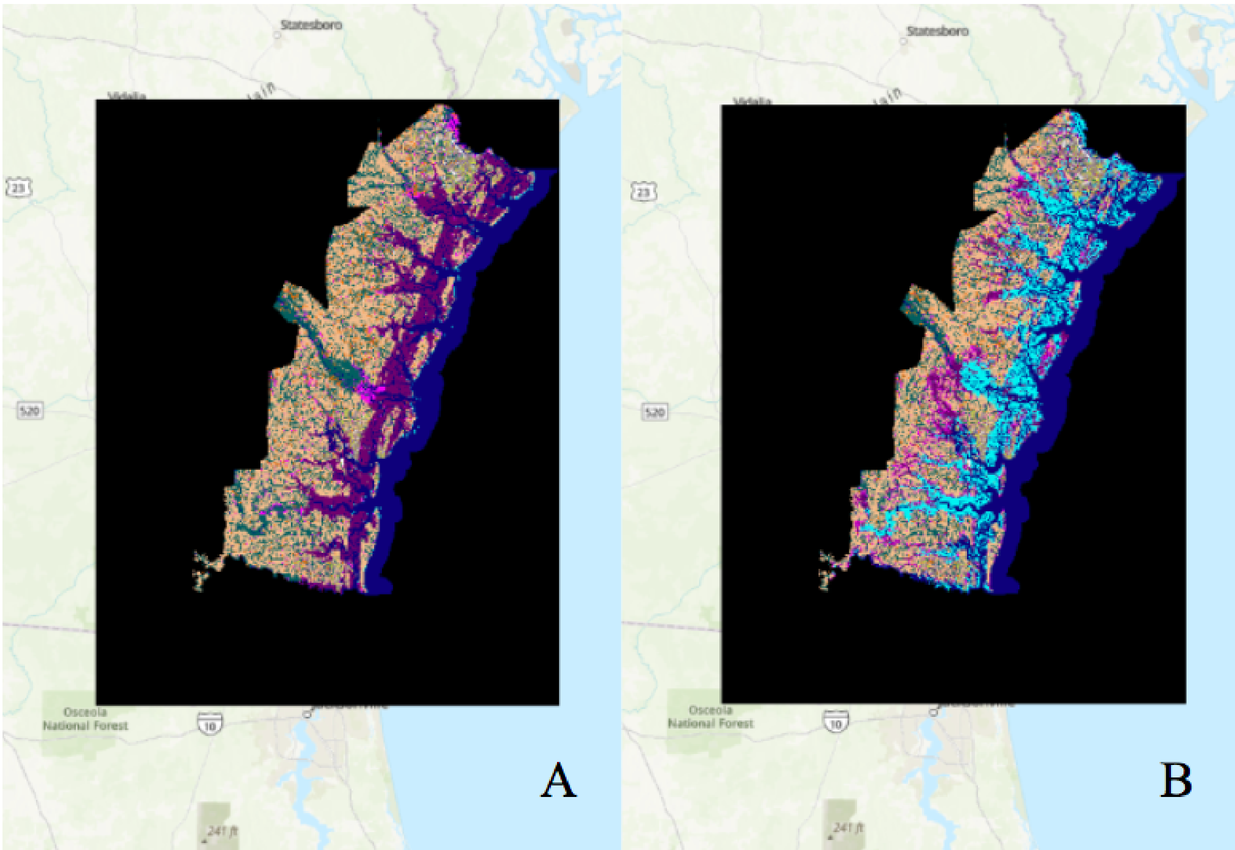

Figure 3. Sample marsh migration maps taken from NOAA Marsh Migration Model. Image A shows 0 feet of sea-level rise. Image B shows 5 feet of sea-level rise. Different colors represent different habitats.

Marsh Migration Estimates

Marsh migration estimates were based on the NOAA Sea Level Rise (SLR) Viewer's Marsh Migration Map. The NOAA Marsh Migration map takes into account the following variables: Sea level rise values, Tidal surfaces in NAVD88 values, Freshwater Wetlands Upland Boundary (FWUB), Digital Elevation Model (DEM), Accretion Rates, and Wetland Habitat Data. However, the user is only able to manipulate the relative sea level values, the other model components are non user-defined. Although accretion is able to be manipulated in the viewer application, accretion rates are not manipulated in the data download. Specific sea-level rise maps were chosen consistent with the estimates in Table 1. Georgia coastal data was specifically downloaded from the NOAA Sea-level rise database. Sea-level rise measurements were kept in imperial unit measurements because the NOAA Marsh Migration viewer data only included maps at half-foot increments. Resulting maps show the new geographic reach of each habitat type under the SLR scenario, accounting for inland wetland migration and loss of wetlands on the seaward edge.

The downloaded NOAA Raster data was then uploaded to ArcGIS for visualization (Figure 3). Using the Zonal Statistics and Table tool, habitat cover at each scenario was calculated in m^2. These values were converted to km^2 and represented in Tables 4a and 4b.

Soil measurements

Soil carbon data was collected from published literature. Four studies that had site locations in Georgia that measured carbon stock, soil bulk density, and sample core depth were included in the dataset. The data was taken from: Loomis and Craft (2010), Krauss et al (2018), NWCA 2011, and NWCA 2016. Previous studies have also examined vegetative biomass as an additional carbon stock (Radabaugh 2017). Prior studies only consider soil carbon as a part of this measure and evaluate vegetation and above ground biomass independently, thus this analysis does the same. (Radabaugh 2017).

The initial search for soil carbon data came from the Coastal Carbon Atlas which is a synthesis of coastal wetland information. Location parameters were set to Georgia and data type was set to carbon stock to only identify sites that included the relevant information. All studies that included sites in the Coastal Carbon Atlas were included as a part of my site data (See Appendix A for full site information).

Ecosystem type was also recorded if given, however this information was only included for the Craft et al (2010) and Krauss et al (2018) analyses. The NWCA data only included site latitude and longitude information. Therefore, the coordinates of all sites from NWCA were input to the US Fish and Wildlife Service National Wetlands Inventory to identify the habitat type of each site. Habitat classifications varied between the National Wetlands Inventory and the Loomis and Craft (2010) and Krauss et al (2018) papers, therefore, I translated the habitat classifications into a single definition for each of the four focal habitat types: Freshwater forest, freshwater emergent wetland, salt marsh, and brackish. These classifications were based on salinity ranges and vegetation types (Table 2).

Habitat Conversions

Habitat Classification for Present Analysis	**Source**	**Definition**	**Original Paper Habitat Classification**
Freshwater forest	Krauss 2018	"Salinity ≤0.5 psu"	Tidal freshwater
Freshwater forest	Craft 2010	"Long-term salinity <0.5 practical salinity units (psu)"	Tidal freshwater forested wetland
Freshwater forest	National Wetlands Viewer	"Salinity due to ocean-derived salts less than 0.5 ppt." "an area with 50 percent areal coverage of trees over a shrub layer with a 60 percent areal coverage would be classified as Forested Wetland"	Palustrine Forested Wetland
Freshwater forest*	National Wetlands Viewer	"Salinity due to ocean-derived salts less than 0.5 ppt." "area with 20 percent areal coverage of trees over the same (60 percent) shrub layer"	Palustrine Scrub/Shrub Wetland
Freshwater Emergent Wetland	National Wetlands Viewer	"Salinity due to ocean-derived salts less than 0.5 ppt." Dominated by emergent vegetation	Palustrine Emergent Wetland
Brackish	Krauss 2018	"Salinity 0.5–5.0 psu"	Salt-Stressed
Brackish	Craft 2010	"Salinity between 0.5 and 15 psu"	Brackish
Salt Marsh	Craft 2010	"Salinity >15 psu"	Salt Marsh
Salt Marsh	National Wetlands Viewer	"deepwater tidal habitats" Salinity equivalent to open ocean (~30+ ppt)	Estuarine and Marine Wetlands

Table 2. Habitat conversion table defining how habitats are classified in this analysis compared to how they are defined in the original paper. Palustrine scrub/shrub wetlands are grouped together with freshwater forests. Both habitat types are freshwater dominated with percentage of vegetation cover being the key difference. Since this analysis does not consider above ground biomass as a part of the calculation, it was appropriate to group these habitats together.

The following map was created to visualize the availability of soil carbon data from existing data surveys. Each point represents a specific location with carbon stock data. The colors correspond with a specific author/study. Site data includes carbon stock, latitude, longitude, year, and any relevant unit conversions.

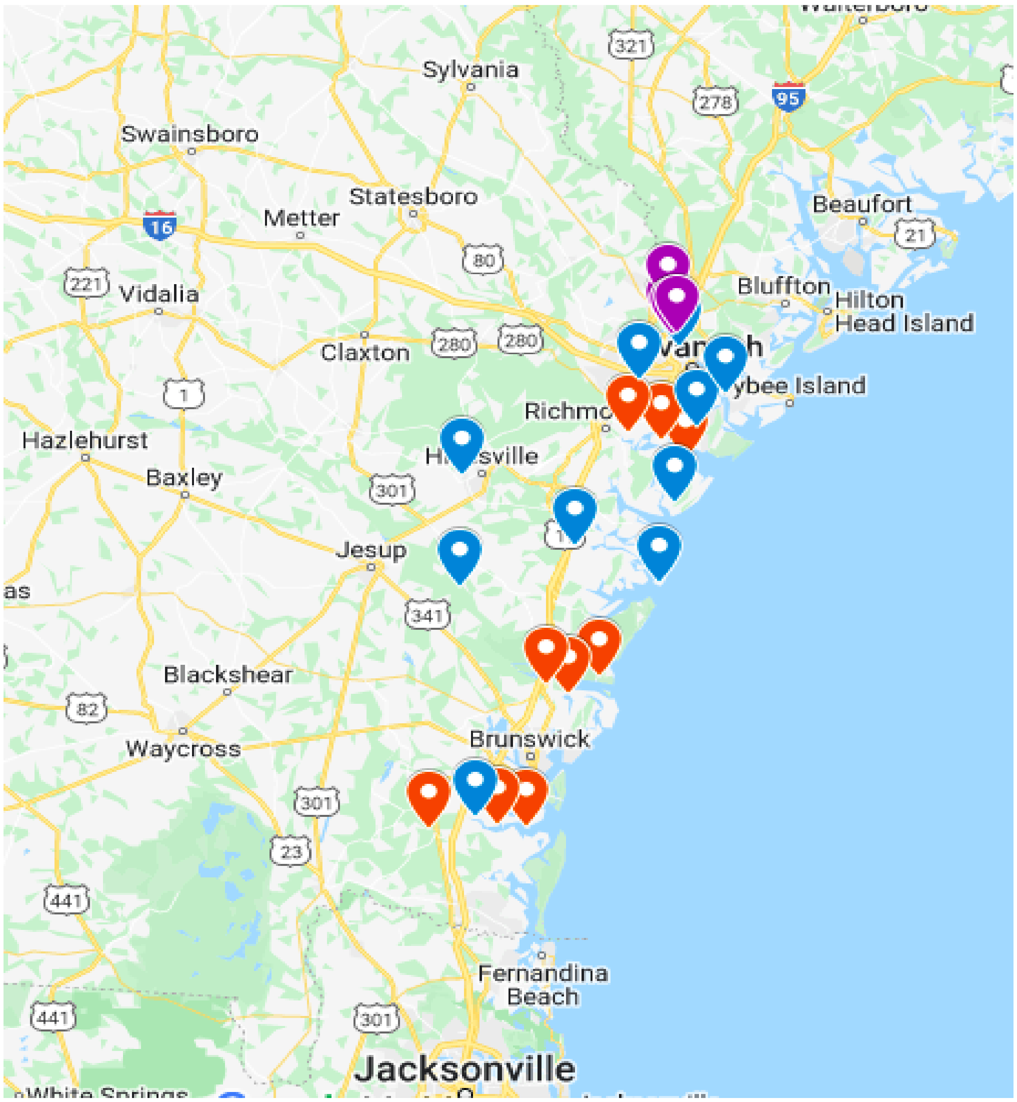

Figure 4. Map indicating all sites used in compiling site data for all relevant habitat types. Blue sites: NWCA 2011/NWCA 2016. Red sites: Craft 2010. Purple sites: Krauss 2018. Based on the above map and the NWI classifications, the sites fall into the following categories: Freshwater forest/shrub wetland (10 sites), Estuarine and marine wetland (6 sites), Brackish (6 sites) and Freshwater emergent wetland (2 sites).

Carbon Storage Projections

The existing carbon stock data from the current marsh regions is used to estimate the carbon stock potential of new marsh regions after marsh migration. The average and SD of carbon stocks were calculated for each habitat type. All soil stock data collected from Craft 2010, Krauss 2018, NWCA 2011, and NWCA 2016 was converted to Mg/km^2 at a depth of 1 meter as a standard measure of carbon per unit volume (Fourqurean).

Carbon storage inputs from table 3 were used in the model to estimate carbon sequestration totals of new marshland. The marsh migration maps were broken down into habitat type, based on the NOAA definitions, using ArcGIS. Using Table 2, these habitat types were then reclassified into one of the four habitat types used in this analysis.

New area totals were multiplied by the existing average soil carbon quantities for the corresponding habitat type (Craft et al. 2009, SLAMM). Soil depths were assumed to be 1 meter, consistent with standard practice (Fourqurean). This gave an estimate of the total carbon that would be sequestered in the new marsh areas. Since the site information is not universal, a range with low and high end estimates were calculated to fully capture the possible variation in carbon sequestration.

Habitat Type	**Average Value of Carbon Storage g/cm^3**	**Standard Deviation**	**Sample Size**	**Sources**
Freshwater forest/shrub wetland	0.034	0.016	10	Krauss 2018 Craft 2010 NWCA16
Estuarine and marine wetland	0.037	0.027	6	Craft 2010 NWCA16
Brackish	0.024	0.004	6	Craft 2010 Krauss 2018
Palustrine Emergent Wetland	0.028	0.005	2	NWCA16

Table 3. Additional site data. The four habitat types of the carbon stock sites are recorded in the first column, followed by the average carbon storage g/cm^3 estimate and standard deviation. The sample size is also included based on the habitat conversions from Table 3. Sources where each habitat type is found is recorded in the final column.

Results

Marsh Migration Estimates

	5 Feet SLR	**2 Feet SLR**	**1 Foot SLR**	**0 Feet SLR**
Palustrine Freshwater Forest	981 (Δ -598)	1170 (Δ -409)	1234 (Δ -345)	1579
Palustrine Scrub/ Shrub Wetland	219 (Δ -114)	260 (Δ -73)	273 (Δ -60)	333
Estuarine and Marine Wetland	614 (Δ -877)	1629 (Δ +138)	1678 (Δ +187)	1491
Brackish	263	225	228	NA
Palustrine Emergent Wetland	250 (Δ 0)	209 (Δ -41)	203 (Δ -47)	250
Unconsolidated Shore	1598 (Δ +1555)	365 (Δ +322)	243 (Δ +200)	43
Open Water	2284 (Δ +344)	2054 (Δ +114)	1979 (Δ+ 39)	1940

Table 4a. Area calculations for seven habitats under three LSL rise scenarios consistent with NOAA Sea Level Rise calculator estimates of the North Georgia coast. All are in km^2 units. Values in the table represent the area coverage at that sea-level rise and do not indicate the relative difference from 0 feet of sea-level rise. In parentheses are the relative change in habitat coverage relative to 0 feet of sea level rise. A positive sign (+) indicates habitat gained, and a negative sign (-) indicates habitat lost. Brackish habitats were not present in the 0 feet SLR, so there is no baseline condition to compare to.

Lower Coast Area Estimates

	4.5 Feet SLR	**1 Foot SLR**	**.5 Foot SLR**	**0 Feet SLR**
Palustrine Freshwater Forest	1013 (Δ -566)	1234 (Δ -345)	1263 (Δ -316)	1579
Palustrine Scrub/ Shrub Wetland	225 (Δ -108)	273 (Δ -60)	281 (Δ -52)	333
Estuarine and Marine Wetland	681 (Δ -801)	1678 (Δ +187)	1651 (Δ +160)	1491
Brackish	254	228	234	NA
Palustrine Emergent Wetland	240 (Δ -10)	203 (Δ -47)	201 (Δ -49)	250
Unconsolidated Shore	1524 (Δ 1481)	243 (Δ +200)	233 (Δ +190)	43
Open Water	2212 (Δ -272)	1979 (Δ+ 39)	1941 (Δ +1)	1940

Table 4b. Area calculations for seven habitats under three LSL rise scenarios consistent with NOAA Sea Level Rise calculator estimates of the South Georgia coast. All are in km^2 units. Values in the table represent the area coverage at that sea-level rise and do not indicate the relative difference from 0 feet of sea-level rise. In parentheses are the relative change in habitat coverage relative to 0 feet of sea level rise. A positive sign (+) indicates habitat gained, and a negative sign (-) indicates habitat lost. Brackish habitats were not present in the 0 feet SLR, so there is no baseline condition to compare to.

Upper Coast Carbon Estimates (Mg stored per habitat)

	5 Feet SLR	2 Feet SLR	1 Foot SLR	0 Feet SLR
Freshwater forest/shrub wetland	4.12E+07 (Δ -2.45E+07)	4.91E+07 (Δ -1.66E+07)	5.18E+07 (Δ -1.39 E+07)	6.57E+07
Freshwater emergent wetland	7.00E+06 (Δ 3 E+04)	5.85E+06 (Δ -1.12 E+06)	5.69E+06 (Δ -1.28 E+06)	6.97E+06
Estuarine and marine wetland	2.29E+07 (Δ -3.28 E+07)	6.09E+07 (Δ +3.4 E+06)	6.27E+07 (Δ +7 E+06)	5.57E+07
Brackish	6.31E+06	5.40E+06	5.47E+06	NA

Table 5a. Carbon storage calculations for five habitats under three LSL rise scenarios consistent with NOAA Sea Level Rise calculator estimates of the South Georgia coast. All are in Mg units. In parentheses are the relative change in habitat coverage relative to 0 feet of sea level rise. A positive sign (+) indicates habitat gained, and a negative sign (-) indicates habitat lost. Brackish habitats were not present in the 0 feet SLR, so there is no baseline condition to compare to.

Net Carbon Losses (Mg)

5 Feet SLR	2 Feet SLR	1 Foot SLR
-5.727 E+07	-1.432 E+07	-8.18 E+06

Table 5b. Calculations of the total carbon losses based on adding the respective gains and losses in each habitat type.

Lower Coast Carbon Estimates (Mg stored per habitat)

	4.5 Feet SLR	**1 Foot SLR**	**.5 Foot SLR**	**0 Feet SLR**
Freshwater forest/shrub wetland	4.26E+07 (Δ -2.31 E+07)	5.18E+07 (Δ -1.39 E+07)	5.31E+07 (Δ -1.26 E+07)	6.57E+07
Freshwater emergent wetland	6.71E+06 (Δ -2.6 E+05)	5.69E+06 (Δ -1.28 E+06)	5.64E+06 (Δ -1.33 E+06)	6.97E+06
Estuarine and marine wetland	2.55E+07 (Δ -3.02 E+07)	6.27E+07 (Δ +7 E+06)	6.17E+07 (Δ +6 E+06)	5.57E+07
Brackish	6.11E+06	5.47E+06	5.61E+06	NA

Table 5c. Carbon storage calculations for five habitats under three LSL rise scenarios consistent with NOAA Sea Level Rise calculator estimates of the South Georgia coast. All are in Mg units. In parentheses are the relative change in habitat coverage relative to 0 feet of sea level rise. A positive sign (+) indicates habitat gained, and a negative sign (-) indicates habitat lost. Brackish habitats were not present in the 0 feet SLR, so there is no baseline condition to compare to.

Net Carbon Losses (Mg)

4.5 Feet SLR	**1 Foot SLR**	**.5 Feet SLR**
-5.356 E+07	-8.18 E+06	-7.93 E+06

Table 5d. Calculations of the total carbon losses based on adding the respective gains and losses in each habitat type.

Marsh Cover Results

Based on the habitat cover trends from Tables 4a and 4b, habitat cover in freshwater forested/shrub wetlands, palustrine scrub/shrub wetlands, and estuarine and marine wetlands are all expected to decrease significantly by the end of the century, with losses up to 38%, 34% and 59% respectively, under the worst case scenario (Figure 5). In contrast, brackish habitats and palustrine emergent wetlands will remain relatively stable and unconsolidated shores, which offer very little productivity compared to wetlands, are expected to increase over 3500% if Georgia sees five feet of sea-level rise. Worse yet, rising sea-levels could result in nearly 350 km^2 of coastland turning into open water.

Under a best-case or middle-of-the-road scenario, freshwater forests and estuarine/marine wetlands, despite losing hundreds of square kilometers, would stay as the dominant habitat types on the coast, which they currently are under the status quo. As projections worsen, both habitats see continual losses, culminating in unconsolidated shores being the dominant habitat type under a worse case scenario. As sea-levels continue to rise, salt marshes will continue to migrate inland, occupying lands that are currently classified as transition wetlands or freshwater wetlands. This transition happens very quickly under just a foot of sea-level rise. As seen in Tables 4a and 4b, salt marshes actually see area expansion within one or two feet of sea-level rise, quickly occupying current freshwater forest areas. Once this transition takes place however, there is little further area for salt marshes to encroach. If sea-levels rise beyond a few feet, salt marsh migration then becomes outpaced, losing large amounts of land to unconsolidated shores or open waters. The rate of marsh migration in both freshwater marshes and saltwater marshes is vastly outpaced by area loss due to sea-level rise.

Carbon Storage Results

Based on the calculations in Tables 3b and 3d, coastal wetlands are expected to lose significant amounts of carbon, over 5 x 10^7 Mg (55,115,565 metric tons) in the worst case analysis and 1.4 x 10^7 Mg in the middle of the road scenario. Unsurprisingly, the freshwater forests and estuarine wetlands, which observed the greater habitat loss after 5 feet of rise, also observed the greater carbon loss (Figure 6). Per Table 5, these two habitat types had the two greatest carbon storage rates, meaning that excessive losses in these habitats is especially troublesome.

Discussion

These marsh cover findings are consistent with previous results on Georgia wetland/salt marsh loss. Using the Sea-Levels Affecting Marsh Migration (SLAMM) model, Craft estimates that freshwater wetlands will decrease by 39% and saltwater wetlands will decrease by up to 45% (Craft et al. 2009). However, it is important to note that Craft uses different sea-level rise scenarios wherein the maximum sea-level rise is 89 cm (~2.7 feet) which is well below the maximum estimated used in this analysis. This discrepancy can be explained by using different sea-level rise models and Craft et al (2009) relying on estimates from over a decade ago. Still, per Tables 4a and 4b, the majority of habitat loss or gain occurs under the first few feet of sea-level rise, consistent with the results of Craft et al (2009).

The replacing habitats, primarily unconsolidated shores, can also store carbon, but this analysis did not include any stocks from sites that fall into that category. Furthermore, unconsolidated shores sequester carbon at a significantly lower rate because of the lack of vegetation, meaning that accretion rates are slowed, and there is no direct input of organic matter into the soil. As the wetlands transition into unconsolidated shores or open waters, vegetation is lost, and the sediments are exposed to more oxygen. This allows for more microbial activity, such as decomposition, which releases carbon gas emissions (Sandi, 2021). As aforementioned, this may contribute to a loss of 5×10^7 Mg of carbon, equivalent to the annual emission of approximately 45 million gas consuming cars.

It is important to note that while using a 1 meter depth for soil analysis is standard practice because the significant majority of carbon is stored in the upper layers, there is still carbon stored in deeper soils, suggesting that the estimates in Tables 4a and 4b may be slight underestimates of the total carbon stored in those systems.

There are several aspects of the model that would need to be reconsidered in a future study. First is the unpredictability with sea-level rise estimates specifically because the sea-level rise estimates used in this analysis are based on an estimate at the very northern coast and southern coast. Although the values observed in the NOAA sea-level rise calculator are consistent with the estimate range from the Georgia Department of Natural Resources, an additional estimate point at the center of the coast would have made the estimate more accurate (Gambill et al 2020). In addition, sea-level rise estimates were rounded to the nearest half foot since the NOAA Sea Level Rise (SLR) Viewer Marsh Migration Model works on half-foot intervals. The Marsh Migration model utilizes Digital Elevation Model (DEM) data to map marsh migration which does not fully capture perfect coastal resolution. The NOAA Sea Level Rise (SLR) Viewer Marsh Migration model also assumes that the current conditions will remain as it pertains to potential changes in coastal geography, meaning that factors such as new infrastructure and coastal storm impacts are not included as a part of this project's predictions. Some coastal structures are designed as specific responses to sea-level rise and could impact how sea-level rise interacts with habitats on a very local level.

The NOAA Sea Level Rise (SLR) Viewer Marsh Migration model uniformly applies a single accretion rate across a study site. Accretion rates vary drastically due to a combination of factors including location within tidal elevation or proximity to other streams, even within a single habitat and geographic location (Langston et al., 2021). Accretion rates are highly variable in Georgia (Langston et al., 2021), and thus, are another variable that must be further considered when evaluating how marsh migration may change over the next century. Because of difficulty in obtaining accretion rate data for an entire region, the NOAA Sea Level Rise (SLR) Viewer Marsh Migration model does not capture variation in accretion rates. As a part of the user parameters, the user can choose between four possible accretion rates: 0 mm, 2mm, 4mm, and 6mm. However, the model applies a single accretion rate in its data download that the user cannot choose. This accretion rate is applied to the entire region. For instance, the “All Uplands” category is treated with the same accretion rate as “Estuarine Wetlands” even though this would be inaccurate. This would likely limit the amount of space that the model makes available to inland marsh migration, suggesting that the reported area calculations are underestimated.

Accretion rates can vary depending on elevation and marsh proximity from tidal channels (Langston et al., 2021). Furthermore, sediment accretion is higher in areas with more tidal inundation, generally lower elevations. Organic accretion is dependent on plant productivity, meaning that elevations that support more plant biodiversity and productivity also have the greatest organic accretion rates (Langston et al., 2021). Among *Spartina* species, organic matter deposition is a stronger predictor of accretion rates than mineral deposition. This also means that organic matter limits accretion rates more than mineral deposition (Hill and Anisfeld 2015). Studies focused on the Northeast, Gulf, and West coasts agree that organic matter deposition plays a more significant role in accretion rate than mineral deposition (Hill and Anisfeld 2015). Crosby et al (2017) finds a latitudinal gradient. They find that northern marshes rely more on organic matter deposition, whereas southern marshes rely more on sediment capture.

Unfortunately, this analysis, as well as the prior literature confirms that the rate of soil accretion, and subsequent migration, is being far outpaced by sea-level rise and soil erosion. The NOAA Sea Level Rise (SLR) Viewer Marsh Migration model’s assumption of a constant accretion rate over the next century may be inaccurate. Accretion rates are likely to change over the next century. For instance, changes in weather patterns or in the frequency of major weather events such as hurricanes can both lower accretion rates. Man-made infrastructures, such as dams or seawalls can reduce sediment supply, likewise reducing accretion rates (Langston et al. 2021.; Kirwan and Megonigal 2013). If accretion rates were a manipulatable input in this model, running each sea-level rise scenario with multiple realistic accretion rates would most accurately represent the range of possible marsh migration scenarios. Georgia's historical coastal accretion rate is approximately 1.55 mm/year, but under a more extreme LSL Rise scenario, increases to 6.27 mm/year (Langston et al. 2021). Accretion rate will continue to increase as sea-level rise increases. However, the gap between the rates grows as sea-level rise rates become more extreme (Langston et al. 2021). Therefore, wetland migration would be most able to keep up with sea-level rise under the least-extreme scenario, which would allow for the outcomes at 1 or 2 feet of sea-level rise to materialize. A future study would also apply an accretion rate aspect to understand how accretion rates in different habitats would also affect the wetland's ability to migrate.

Based on the results in this study and prior literature, salt marsh migration seems to be able to keep up with sea-level rise under less extreme scenarios. This is largely due to the ability for vegetation to migrate quickly. Vegetation type also plays a significant role in accretion rates. Above-ground accretion is dependent on plant shoots to slow water velocity and allow sediments to settle. Below-ground plant biomass directly adds organic material to the soil (Kirwan and Megonigal 2013). Both of these factors rely on the species and density of the vegetation present. Certain vegetation types can thrive under LSL scenarios, increasing sediment accumulation and biomass (Kirwan et al. 2010). In particular, common marsh grasses in the *Sporobolus* and *Spartina* genuses have shown to accelerate sediment deposition and allow for faster vertical migration under minimal sea-level rise scenarios (Hill and Anisfeld 2015). However, within *Spartina*, accretion rates in *Spartina patens* dominated areas were more severely limited by sediment supply when compared to *Spartina alterniflora* (Hill and Anisfeld 2015). *Spartina alterniflora* demonstrated a much greater ability for mineral and sediment accumulation when compared to *Spartina patens*, another common salt marsh plant. Furthermore, the accretion rates for *Spartina alterniflora* were greatest in the mid-marsh, suggesting that migration rates inland may be fastest under immediate sea-level rise (Hill and Anisfeld 2015). However, after excessive submergence, the vegetation common in marshlands are not able to survive (Sandi et al. 2021). Between the different habitat types, various plant species are more adapted to certain environments. For coastal wetlands, relative salinity is often the driving factor. In Georgia, *Spartina alterniflora* dominates salt marshes, *Juncus roemerianus* dominates brackish, and *Zizaniopsis mileacea* dominates freshwater marshes (Craft et al. 2009).

Salt marsh migration into existing wetlands, and rising sea-levels also suggests that coastal vegetation will be exposed to greater salinity levels than they may be used to, as well as more frequent inundation. *Spartina alterniflora and maritima* plants demonstrated the fastest stem growth when in low salinity conditions (0 and 15 ppt), consistent with freshwater wetlands or brackish habitats (Adams 1995). At extreme salinity scenarios (55 and 75 ppt) these significantly reduced stem growth as well as signs of salt stress such as rolled leaves and necrosis (Adams 1995). Although the extreme salinity scenarios are higher than the *Spartina* would likely see in nature, they still demonstrate a sensitivity to increased salinity levels, with an ideal salinity range of 0-20 ppt for optimum growth (Adams 1995). Since the salt marshes in this analysis are classified as having a range that extends beyond 20 ppt, it is likely that *Spartina* would be exposed to salinity levels that would inhibit their growth with additional sea level rise.

Spartina species may not be able to respond to increased temperatures and sea-level rise uniformly either. Northern *Spartina alterniflora* demonstrated a weakened ability to adapt.

Rising sea-levels slowed the biomass accumulation rate in northern marshes, which would slow their accretion rate and subsequent marsh building (Crosby 2017). Furthermore, northern *Spartina alterniflora* had a higher mortality rate under increased temperatures when transplanted to southern latitudes (Crosby 2017). This would suggest that northern marshes are additionally susceptible to extreme warming patterns.

Saltwater marshes, when compared to freshwater marshes, have significantly less plant diversity than freshwater marshes, resulting in lower decomposition rates and organic matter accumulation rates (Craft 2007; Odum 1988). Marsh migration threatens to reduce freshwater marsh areas in favor of salt marshes, expanding areas that have reduced carbon accumulation rates (Odum 1988). After synthesizing the existing data on carbon stocks, the results challenge the prior knowledge. Instead of finding that the freshwater marshes stored more carbon, the carbon stock data in this analysis instead suggest that salt marshes are more productive. Craft comes to the same conclusion, also noting that the greater ecosystem service in salt marshes was unexpected (Craft 2007). There were a couple of sites in the salt marsh category that had a significantly higher carbon stock recorded- resulting in a much higher standard deviation. Based on the predictions from Craft and Odum, the recorded carbon stocks at these sites may have come from particularly productive areas that are well above the average.

Ultimately, any loss of coastal marshes will reduce soil carbon stocks. Based on the Marsh migration model, the rate of marsh migration into available land will not be able to keep up with the rate of marsh loss due to sea-level rise. Unconsolidated shores and open waters are significantly less efficient at storing carbon than. Furthermore, newly established marshes have lower carbon sequestration rates than older marshes, further decreasing storage potential (Fagherazzi et al. 2020).

NOAA's Sea-level change calculator finds that Georgia's immediate neighbors, South Carolina and Florida should expect to see similar sea-level rise outcomes, with a "middle-of-the-road" outcome of 1-2 feet, and a worst-case scenario of approximately 4-5 feet. However, other areas of the southeast may be more susceptible to sea-level rise. For instance, coastal Louisiana's "middle-of-the-road" outcome is approximately 3.5 feet, with a worst-case scenario of 7 feet. Similar results can be seen along the Texas coast. Georgia (and South Carolina) appear to be the least affected by sea-level rise out of any state in the southeast. With the other state expecting either equal or worse sea-level rise outcomes, it is likely that all the other states will see significant losses in their coastal wetland area, subsequently seeing losses in the ecologic and economic services associated with coastal ecosystems. Furthermore, Georgia's well protected, and largely undeveloped, coasts help support some inland marsh migration. Other states in the region do not have this same flexibility, meaning that inland marsh migration would likely be reduced.

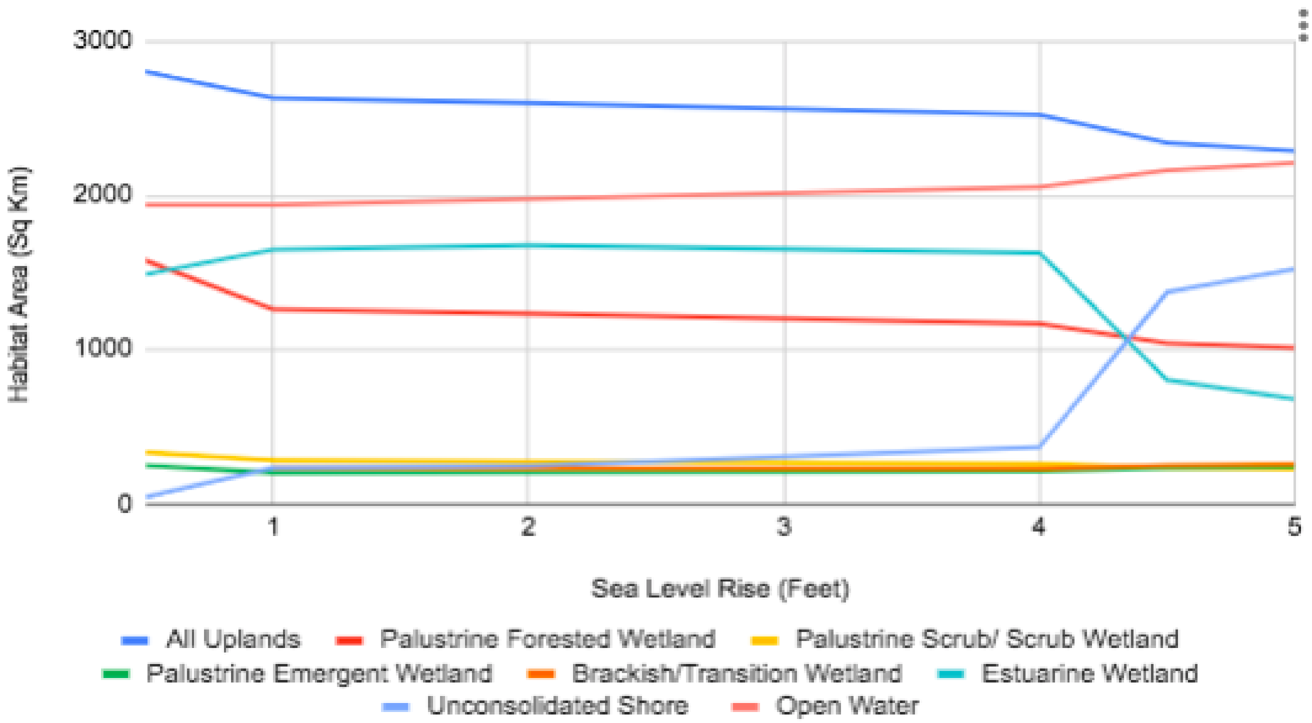

Figure 5. Line graph demonstrating the change in habitat area for eight habitat types. Sea-level rise is depicted on the x-axis considering changes up to five feet.

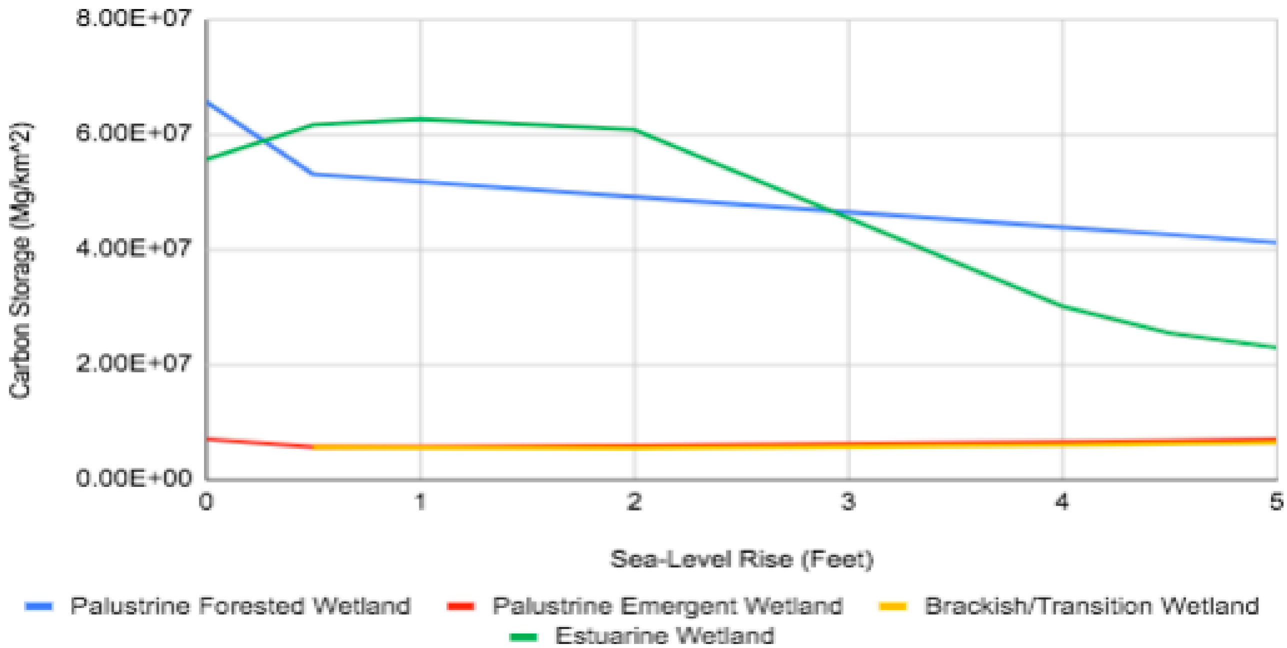

Figure 6. Line graph demonstrating the change in carbon storage area for four habitat types. Sea-level rise is depicted on the x-axis considering changes up to five feet.

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Appendix A: Site Data

Site Number	**Site Name**	**Paper/Study**	**Habitat**	**Carbon Stock (g/cm^3)**
1	Savannah River (Upper)	Krauss 2018	Tidal Freshwater Forest	0.05738
2	Savannah River (Middle)	Krauss 2018	Salt Marsh (Salt Stressed)	0.09296
3	Savannah River (Lower)	Krauss 2018	Salt Marsh (Salt Stressed)	0.07382
4	Savannah River (Marsh)	Krauss 2018	Salt Marsh (Salt Stressed)	0.032486
5	Ogeechee	Craft 2010	Freshwater	0.05738
6	Ogeechee	Craft 2010	Brackish	0.0195
7	Ogeechee	Craft 2010	Salt Marsh	0.02257
8	Altamaha	Craft 2010	Freshwater	0.026634
9	Altamaha	Craft 2010	Brackish	0.02845
10	Altamaha	Craft 2010	Salt Marsh	0.020054
11	Satilla	Craft 2010	Freshwater	0.025144
12	Satilla	Craft 2010	Brackish	0.023275
13	Satilla	Craft 2010	Salt Marsh	0.02271
14	NWCA16-1995	NWCA16	Estuarine Wetland	0.020265
15	NWCA16-1996	NWCA16	Freshwater Emergent Wetland	0.0279135
16	NWCA16-1997	NWCA16	Freshwater Forest	0.0315895
17	NWCA16-1998	NWCA16	Estuarine Wetland	0.028247
18	NWCA16-1999	NWCA16	Freshwater Forest	0.016296
19	NWCA16-2000	NWCA16	Freshwater Forest	0.0256
20	NWCA16-2003	NWCA16	Freshwater Emergent Wetland	0.020288

21	NWCA16-2006	NWCA16	Freshwater Forest	0.0571265
22	NWCA16-2014	NWCA16	Estuarine Wetland	0.0162735
23	NWCA16-2016	NWCA16	Estuarine Wetland	0.0162735
24	NWCA16-2019	NWCA16	Freshwater Forest	0.024104
25	NWCA16-2026	NWCA16	Freshwater Forest	0.022314

Site information for the sites included in figure 4. Site information includes the name, study of origin, habitat type, and carbon storage measured as g/cm^3.