Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Waccamaw NWR

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June 2013

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) suggested that global sea level will increase by approximately 30 cm to 100 cm by 2100 (IPCC 2001). Rahmstorf (2007) suggests that this range may be too conservative and that the feasible range by 2100 is 50 to 140 cm. Rising sea levels may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat "migration" as salt marshes transgress landward and replace tidal freshwater and irregularly-flooded marsh (Park et al. 1991).

In an effort to plan for and potentially mitigate the effects of sea-level rise on the U.S. National Wildlife Refuge System (Refuge System), the U. S. Fish and Wildlife Service (FWS) uses a variety of analytical approaches, most notably the SLAMM model. FWS conducts some SLAMM analysis in-house and, more commonly, contracts the application of the SLAMM model. In most cases Refuge System SLAMM analyses are designed to assist in the development of comprehensive conservation plans (CCPs), land acquisition plans, habitat management plans, and other land and resource management plans.

This is the second application of SLAMM to Waccamaw NWR. The first application of SLAMM to the refuge, carried out in 2008, did not include LiDAR-derived elevation data and elevations were taken from a 1974 contour map. The current application uses a bare-earth LiDAR elevation data obtained in 2008 - 2009 and a wetland layer derived from aerial photos taken in 1994 and 2006.

Model Summary

Changes in tidal marsh area and habitat type in response to sea-level rise were modeled using the Sea Level Affecting Marshes Model (SLAMM 6) that accounts for the dominant processes involved in wetland conversion and shoreline modifications during long-term sea level rise (Park et al. 1989; www.warrenpinnacle.com/prof/SLAMM).

Successive versions of the model have been used to estimate the impacts of sea level rise on the coasts of the U.S. (Titus et al. 1991; Lee et al. 1992; Park et al. 1993; Galbraith et al. 2002; National Wildlife Federation & Florida Wildlife Federation 2006; Glick et al. 2007; Craft et al. 2009).

Within SLAMM, there are five primary processes that affect wetland fate under different scenarios of sea-level rise:

- **Inundation:** The rise of water levels and the salt boundary are tracked by reducing elevations of each cell as sea levels rise, thus keeping mean tide level (MTL) constant at zero. The effects on each cell are calculated based on the minimum elevation and slope of that cell.
- **Erosion:** Erosion is triggered based on a threshold of maximum fetch and the proximity of the marsh to estuarine water or open ocean. When these conditions are met, horizontal erosion occurs at a rate based on site- specific data.

- **Overwash:** Barrier islands of under 500 meters (m) width are assumed to undergo overwash during each specified interval for large storms. Beach migration and transport of sediments are calculated.
- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the fresh water table to rising sea level close to the coast.
- **Accretion:** Sea level rise is offset by sedimentation and vertical accretion using average or site-specific values for each wetland category. Accretion rates may be spatially variable within a given model domain and can be specified to respond to feedbacks such as frequency of flooding.

SLAMM Version 6.0 was developed in 2008/2009 and is based on SLAMM 5. SLAMM 6.0 provides backwards compatibility to SLAMM 5, that is, SLAMM 5 results can be replicated in SLAMM 6. However, SLAMM 6 also provides several optional capabilities.

- Accretion Feedback Component: Feedbacks based on wetland elevation, distance to channel, and salinity may be specified. This feedback is used where adequate data exist for parameterization.
- Salinity Model: Multiple time-variable freshwater flows may be specified. Salinity is estimated and mapped at MLLW, MHHW, and MTL. Habitat switching may be specified as a function of salinity. This optional sub-model is not utilized in USFWS simulations, although a freshwater polygon was applied to Waccamaw NWR (see methods section for further detail).
- Integrated Elevation Analysis: SLAMM will summarize site-specific categorized elevation ranges for wetlands as derived from LiDAR data or other high-resolution data sets. This functionality is used in USFWS simulations to test the SLAMM conceptual model at each site. The causes of any discrepancies are then tracked down and reported on within the model application report.
- Flexible Elevation Ranges for land categories: If site-specific data indicate that wetland elevation ranges are outside of SLAMM defaults, a different range may be specified within the interface. In USFWS simulations, the use of values outside of SLAMM defaults is rarely utilized. If such a change is made, the change and the reason for it are fully documented within the model application reports.
- Many other graphic user interface and memory management improvements are also part of the new version including an updated *Technical Documentation*, and context sensitive help files.

For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 6.0 *Technical Documentation* (Clough et al. 2010). This document is available at http://warrenpinnacle.com/prof/SLAMM

All model results are subject to uncertainty due to limitations in input data, incomplete knowledge about factors that control the behavior of the system being modeled, and simplifications of the system (Council for Regulatory Environmental Modeling 2008). Site-specific factors that increase or decrease model uncertainty may be covered in the *Discussion* section of this report.

Sea Level Rise Scenarios

Some SLAMM 6 predictions are obtained using SLR estimates from the Special Report on Emissions Scenarios (SRES) published by the Intergovernmental Panel on Climate Change (IPCC). All IPCC scenarios describe futures that are generally more affluent than today and span a wide range of future levels of economic activity, with gross world product rising to 10 times today's values by 2100 in the lowest, to 26-fold in the highest scenarios (IPCC 2007). Among the IPCC families of scenarios, two approaches were used, one that made harmonized assumptions about global population, economic growth, and final energy use, and those with an alternative approach to quantification. This is important to keep in mind as not all of the IPCC scenarios share common assumptions regarding the driving forces of climate change.

In this model application, the A1B scenario mean and maximum predictions are applied. Important assumptions were made in this scenario: reduction in the dispersion of income levels across economies (i.e. economic convergence), capacity building, increased cultural and social interactions among nations, and a substantial reduction in regional differences in per capita income, primarily from the economic growth of nations with increasing income (Nakicenovic et al. 2000). In addition, the A1 family of scenarios assumes that the future world includes rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Given today's global economic and political climate, as well as environmental and ecological constraints, these may not be feasible assumptions for the future.

In particular, the A1B scenario assumes that energy sources will be balanced across all sources, with an increase in use of renewable energy sources coupled with a reduced reliance on fossil fuels (Nakicenovic et al. 2000). Given this A1B scenario, the IPCC WGI Fourth Assessment Report (IPCC 2007) suggests a likely range of 0.21 m to 0.48 m of SLR by 2090-2099 "excluding future rapid dynamical changes in ice flow." The IPCC-produced A1B-mean scenario that was run as a part of this project falls near the middle of this estimated range, predicting 0.39 m of global SLR by 2100. A1B-maximum predicts 0.69 m of global SLR by 2100. However, other scientists using the same set of economic growth scenarios have produced much higher estimates of SLR as discussed below.

Recent literature (Chen et al. 2006; Monaghan et al. 2006) indicates that eustatic sea level rise is progressing more rapidly than was previously assumed. This underestimation may be due to the dynamic changes in ice flow omitted within the IPCC report's calculations, and a consequence of overestimating the possibilities for future reductions in greenhouse gas emissions while concurrently striving for economic growth.

A recent paper in the journal *Science* (Rahmstorf 2007) suggests that, taking into account possible model error, a feasible range of 50 to 140 cm by 2100. This work was recently updated and the ranges were increased to 75 to 190 cm (Vermeer and Rahmstorf 2009). Pfeffer et al. (2008) suggests that 2 m by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. A recent US intergovernmental report states "Although no ice-sheet model is currently capable of capturing the glacier speedups in Antarctica or Greenland that have been observed over the last decade, including these processes in models will very likely show that IPCC AR4 projected SLRs for the end of the 21st century are too low" (Clark 2009). A recent paper by

Grinsted et al. (2009) states that "sea level 2090-2099 is projected to be 0.9 to 1.3 m for the A1B scenario…" Grinsted also states that there is a "low probability" that SLR will match the lower IPCC estimates.

The variability of SLR predictions presented in the scientific literature illustrates the significant amount of uncertainty in estimating future SLR. Much of the uncertainty may be due to the unknown future of the drivers climate change, such as fossil fuel consumption and the scale of human enterprise. In order to account for these uncertainties, and to better reflect these uncertainties as well as recently published peer-reviewed measurements and projections of SLR as noted above, SLAMM was run not only assuming A1B-mean and A1B-maximum SLR scenarios, but also for 1 m, 1.5 m, and 2 m of eustatic SLR by the year 2100 as shown in Figure 1.

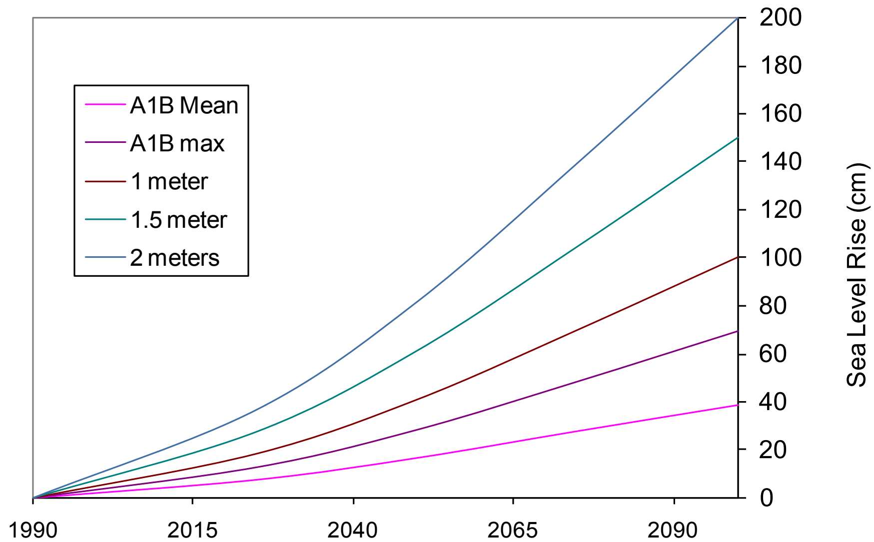


Figure 1. Summary of SLR scenarios utilized.

Data Sources and Methods

Wetland layer.

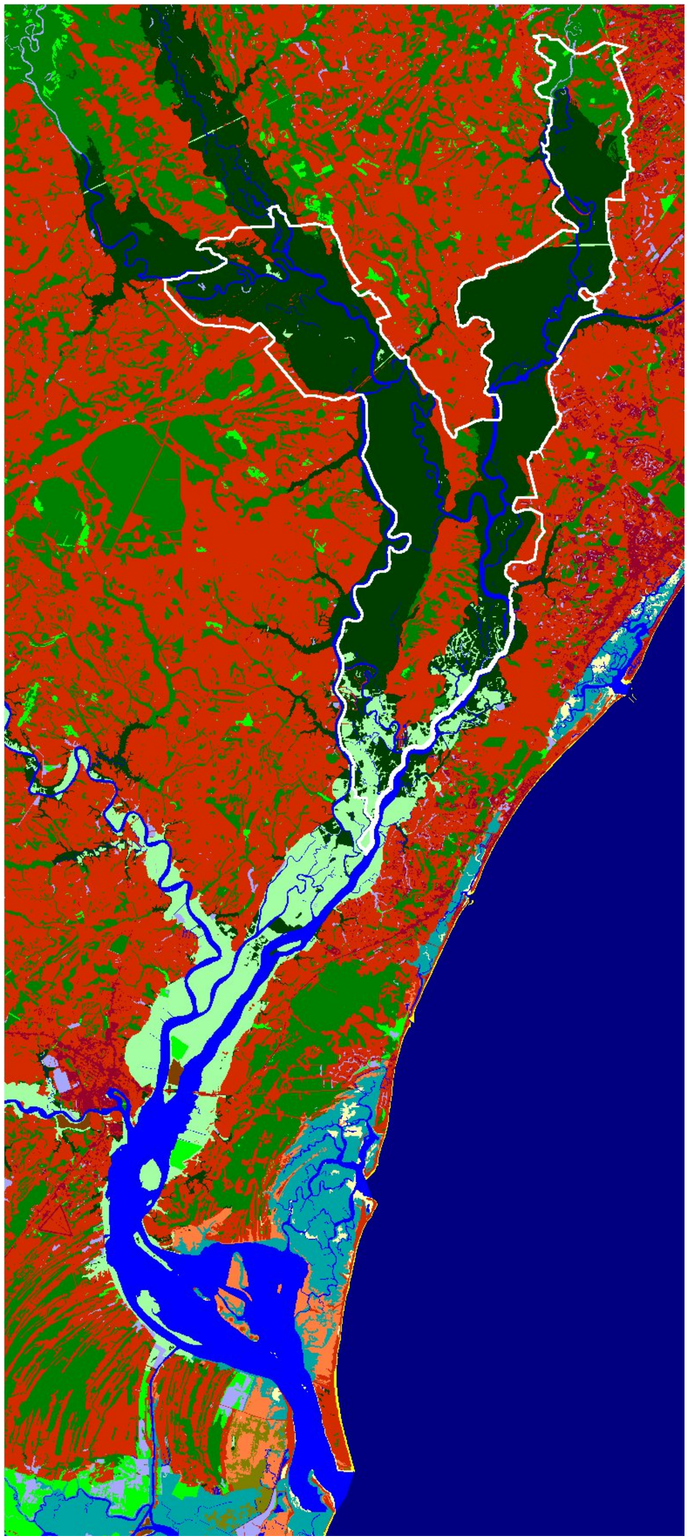


Figure 2 shows the most recent available wetland layer derived primarily from NWI surveys dated 1994 and 2006. Converting the surveys into 10 m x 10 m cells indicated that the approximately 57,808 acre Waccamaw NWR (approved acquisition boundary including water) is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Tidal Swamp	38115	66
	Undeveloped Dry Land	9168	16
	Swamp	4313	7
	Riverine Tidal	3179	5
	Tidal-fresh marsh	2756	5
	Inland Open Water	155	<1
	Inland Fresh Marsh	107	<1
	Developed Dry Land	11	<1
	Cypress Swamp	4	<1
	Total (incl. water)	**57808**	**100**

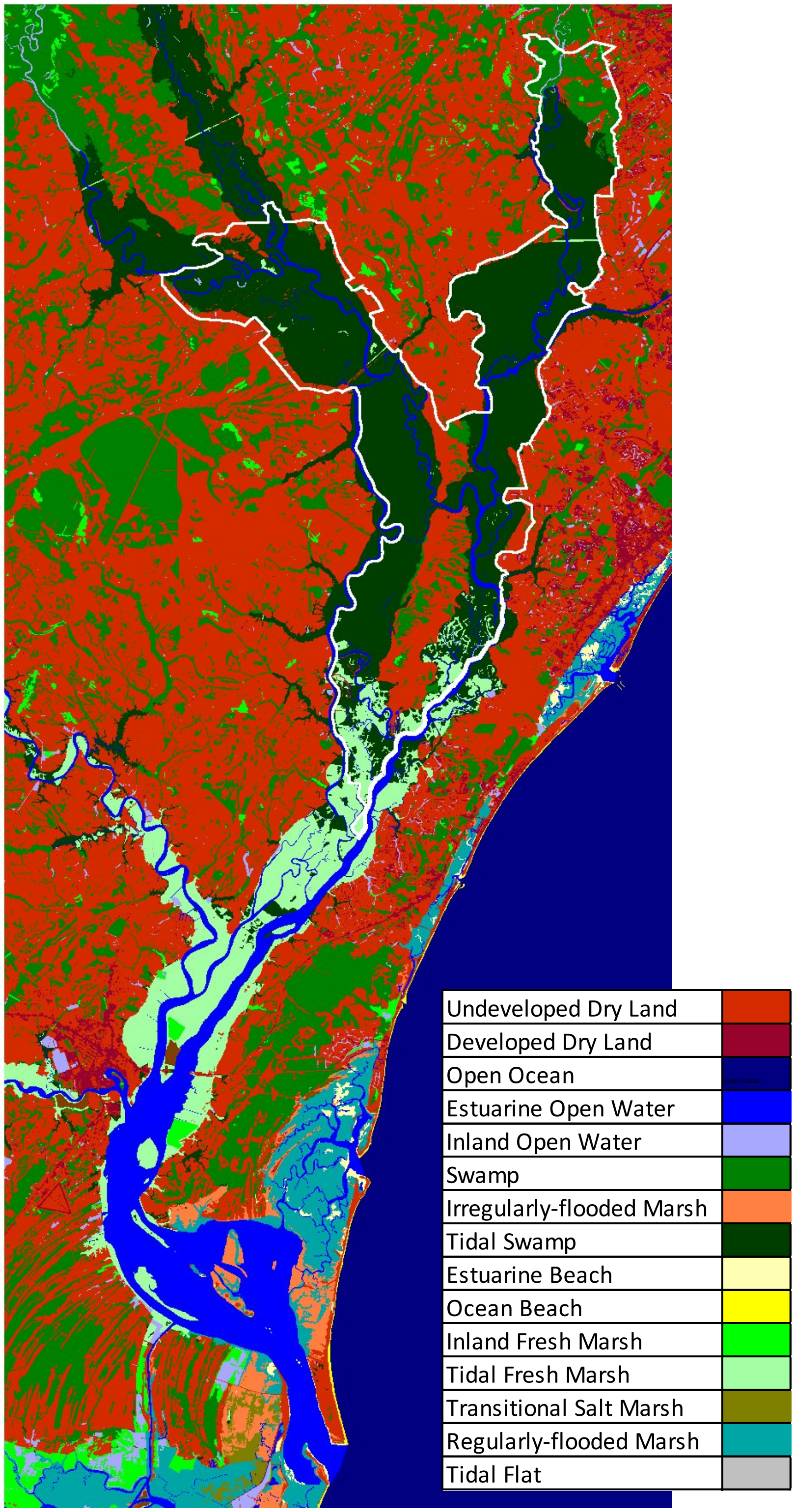
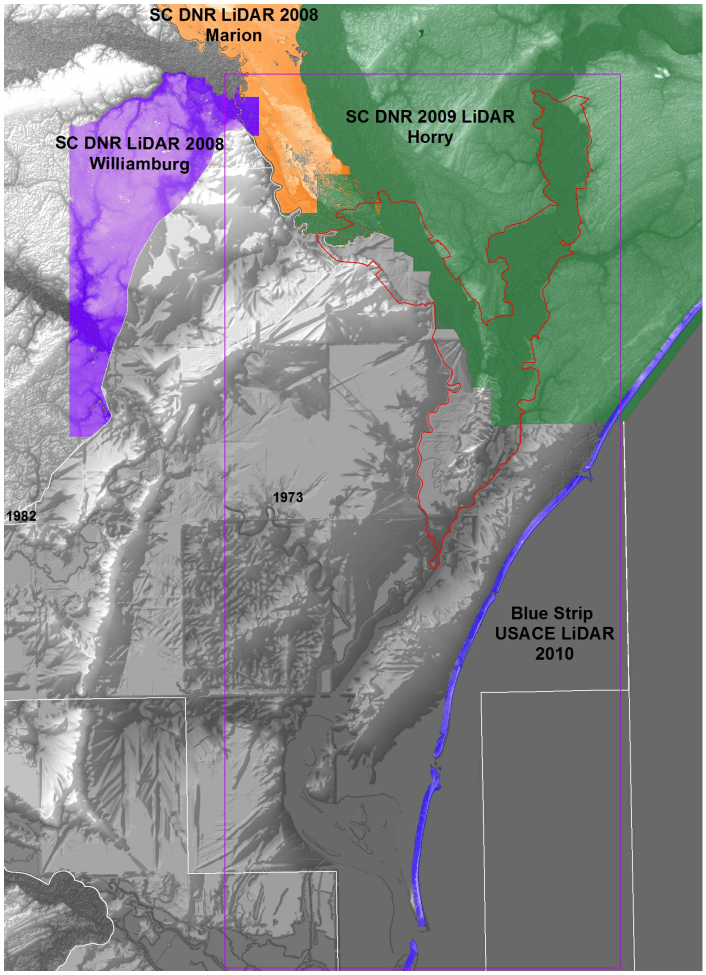


Figure 2. NWI coverage of the study area. Approved refuge boundaries are indicated in white.

Elevation Data. The elevation layer covering the northeastern half of the refuge area is based on bare-earth LiDAR data collected in 2008 - 2009 by the South Carolina Department of Natural Resources.

LiDAR data were not available for the southwestern half of the refuge therefore NED contour data dated 1973 were used.



Dikes and Impoundments. According to the National Wetland Inventory, most of the wetlands protected by dikes or impoundments are outside the refuge, as shown in Figure 3. In addition, the connectivity algorithm was used in this simulation to capture the effects of any natural or man-made impoundments that may not have been marked as diked in the National Wetland Inventory. The connectivity module of SLAMM ensures that dry land only converts to wetland if there is an unimpeded path from open water to the dry land in question.

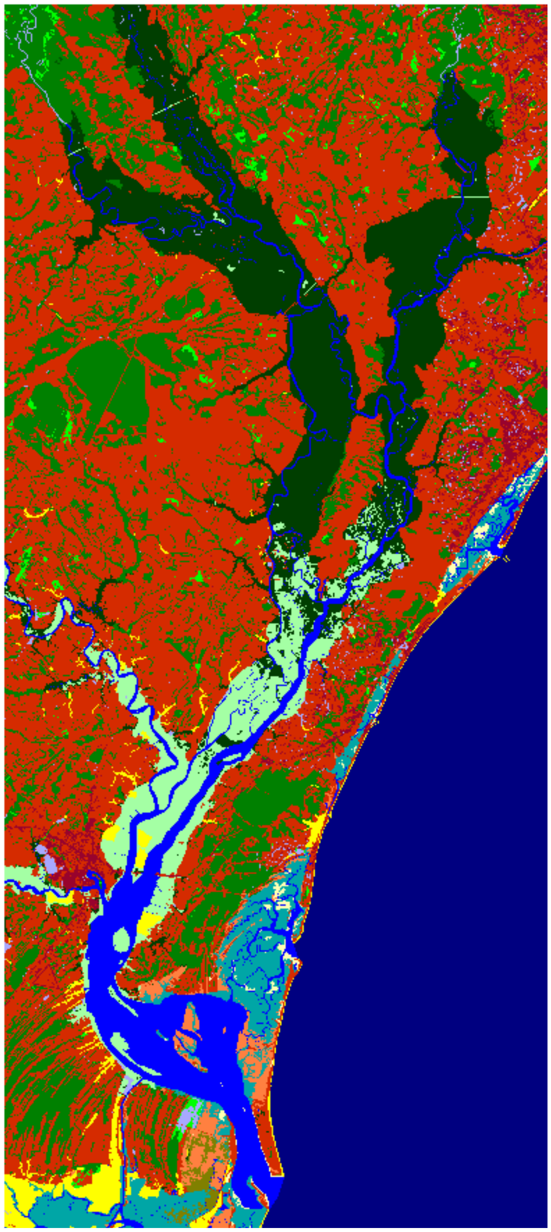


Figure 3. Dikes and impoundments within the study area marked in yellow.

Historic sea level rise rates. The historic trend for relative sea level rise rate applied is 4.09 mm/yr, the average of the values measured at Springmaid Pier, SC (NOAA gauge # 8661070). This rate is higher than the global (eustatic) SLR for the last 100 years (approximately 1.7 mm/yr), potentially indicating regional subsidence or some other factor causing SLR to be higher than the global average.

Tide Ranges. Two values of great diurnal range (GT) were estimated for the Waccamaw NWR study area. Upstream areas were assigned a GT of 0.6 m, while the remaining study area was assigned a value of 1.4m (as shown in Figure 4 using information from NOAA tidal datum stations. The data applied are shown in Table 1.

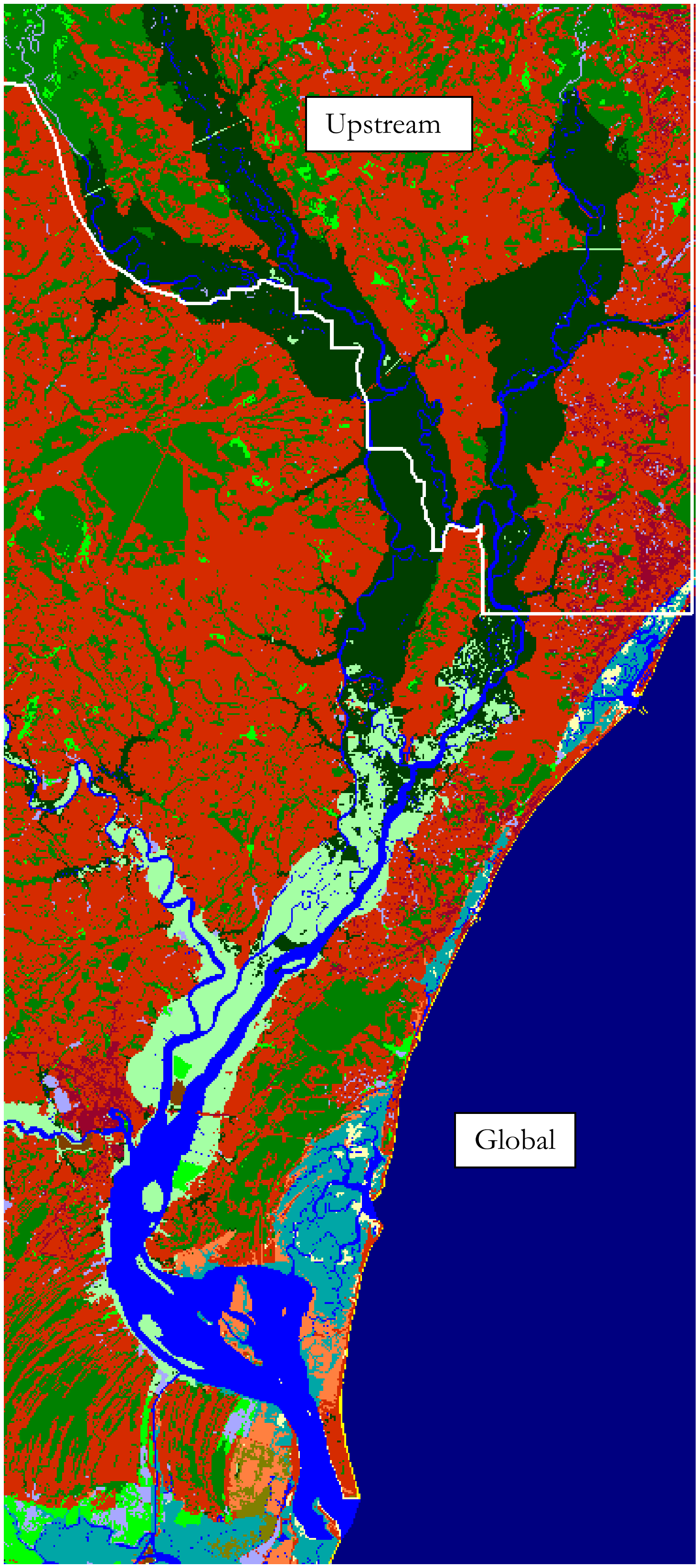


Figure 4. GT subsites.

Table 1. NOAA Tidal Datums used to derive GT

Station	GT	Site Name	Subsite
8660983	0.717	Socastee Bridge, SC	Upstream
8661139	0.746	Bucksport, Waccamaw River, SC	Upstream
8661093	0.578	Yauhannah Bridge, Pee Dee River, SC	Upstream
8661299	0.345	Lower Topsaw Landing, Pee Dee River, SC	Upstream
8661703	1.122	Sandy Island, Thoroughfare Creek, SC	Global
8661991	1.169	Hagley, Waccamaw River, SC	Global
8662953	1.159	Windsor Plantation, Black River, SC	Global
8662931	1.208	Waccamaw River Entrance, SC	Global
8661593	0.803	Winea Plantation, Black River, SC	Global
8662216	1.337	Cumberland, Sampit River, SC	Global
8662549	1.256	South Island Ferry, Winyah Bay, SC	Global
8662746	1.305	Winyah Bay, South Island Plantation, SC	Global
8662299	1.596	Clambank Creek Dock, Goat Island, SC	Global
8662245	1.561	Oyster Landing (N. Inlet Estuary), SC	Global
8662071	1.165	Pawleys Inlet, Wards Dock, SC	Global
8661989	1.352	Bennetts Dock, SC	Global
8662006	1.674	Pawleys Island Pier, Atlantic Ocean, SC	Global
8661684	1.509	Oaks Creek, Upper End, Murrells Inlet, SC	Global
8661609	1.474	Oaks Cr. Inlet, Murrells Inlet, SC	Global
8661559	1.481	Smiths Dock, Murrells Inlet, SC	Global
8661582	1.455	Divines Dock, Murrells Inlet, SC	Global
8661529	1.476	Capt. Alexs Marina, Murrells, SC	Global

Salt elevation. This parameter within SLAMM designates the boundary between wet and dry lands or saline wetlands and fresh water wetlands. Based on regional data for this application, salt elevation was estimated at 1.6 Half Tide Units (HTU), corresponding to 0.45 m above MTL in the upstream areas and 1.0 m in the remaining study area.

Accretion rates. Accretion rates in regularly-flooded and irregularly-flooded marshes were set to 1.9 mm/year and 4.3 mm/yr respectively. Rates in tidal fresh and inland fresh marshes to 4.8 mm/year. These values were derived from studies conducted in Georgia marshes (Craft 2008) and are the same as those used in the 2008 application of SLAMM 5 to Waccamaw NWR.

Erosion rates. Horizontal erosion of marshes and swamps occurs in SLAMM only at the wetland-to-open-water interface and only when adequate open water (fetch) exists for wave setup. Due to a lack of site-specific data, erosion rates for swamps and marshes were set to the SLAMM defaults of 1 m/yr and 2 mm/yr, respectively, while tidal flat erosion was set to 6 m/yr as used in the previous application of SLAMM 5 to Waccamaw NWR.

Model Timesteps. Model forecast data is output for years 2025, 2050, 2075 and 2100 with the initial condition date set to 2006, the most recent wetland data available.

Elevation correction. MTL to NAVD88 correction is quite variable over the study area (ranging from -0.16m to 0.70 m). Therefore a raster of elevation corrections was created using the NOAA VDATUM software and incorporated into model simulations.

Refuge boundaries. Modeled USFWS refuge boundaries for South Carolina are based on Approved Acquisition Boundaries as published on the USFWS National Wildlife Refuge Data and Metadata website. The cell-size used for this analysis is 10 m.

Input subsites and parameter summary. Table 2 summarizes all SLAMM input parameters for the study area. Values for parameters with no specific local information were kept at the model default value.

Table 2. Summary of SLAMM input parameters for Waccamaw NWR.

Parameter	Global	Upstream	Notes
NWI Photo Date (YYYY)	1994/2006	1994/2006	Variable based on subsite
DEM Date (YYYY)	1973	2008/2009	Variable based on subsite
Direction Offshore [n,s,e,w]	East	East	
Historic Trend (mm/yr)	4.09	4.09	
Historic Eustatic Trend (mm/yr)	1.7	1.7	
MTL-NAVD88 (m)	N/A	N/A	Cell-by-cell values applied
GT Great Diurnal Tide Range (m)	1.34	0.6	
Salt Elev. (m above MTL)	1.00	0.45	
Marsh Erosion (horz. m /yr)	2	2	Used in previous SLAMM application
Swamp Erosion (horz. m /yr)	1	1	Used in previous SLAMM application
T.Flat Erosion (horz. m /yr)	6	6	Used in previous SLAMM application
Reg.-Flood Marsh Accr (mm/yr)	1.9	1.9	Used in previous SLAMM application
Irreg.-Flood Marsh Accr (mm/yr)	4.3	4.3	Used in previous SLAMM application
Tidal-Fresh Marsh Accr (mm/yr)	4.8	4.8	Used in previous SLAMM application
Inland-Fresh Marsh Accr (mm/yr)	4.8	4.8	Used in previous SLAMM application
Mangrove Accr (mm/yr)	0	0	SLAMM Default
Tidal Swamp Accr (mm/yr)	1.1	1.1	SLAMM Default
Swamp Accretion (mm/yr)	0.3	0.3	SLAMM Default
Beach Sed. Rate (mm/yr)	0.5	0.5	SLAMM Default
Freq. Overwash (years)	25	25	Used in previous SLAMM application
Use Elev Pre-processor [True,False]	TRUE where no LiDAR data available FALSE where LiDAR data available		

Freshwater Flow. In order to better represent the marsh dynamics in the refuge, a freshwater flow polygon was designated, as shown in Figure 5. In this region the habitat-switching flowchart built in to SLAMM is modified to account for the predominance of fresh-water flow. In the modified flow chart, when categories fall below their lower elevation boundary, Dry Land and Swamp convert to Tidal Swamp, Tidal Swamp converts to Tidal-fresh marsh, and Tidal-fresh marsh converts to Irregularly-Flooded Marsh. In comparison, when no freshwater influence is defined, Swamp converts directly to Irregularly-Flooded (brackish) Marsh as high-salinity water is assumed.

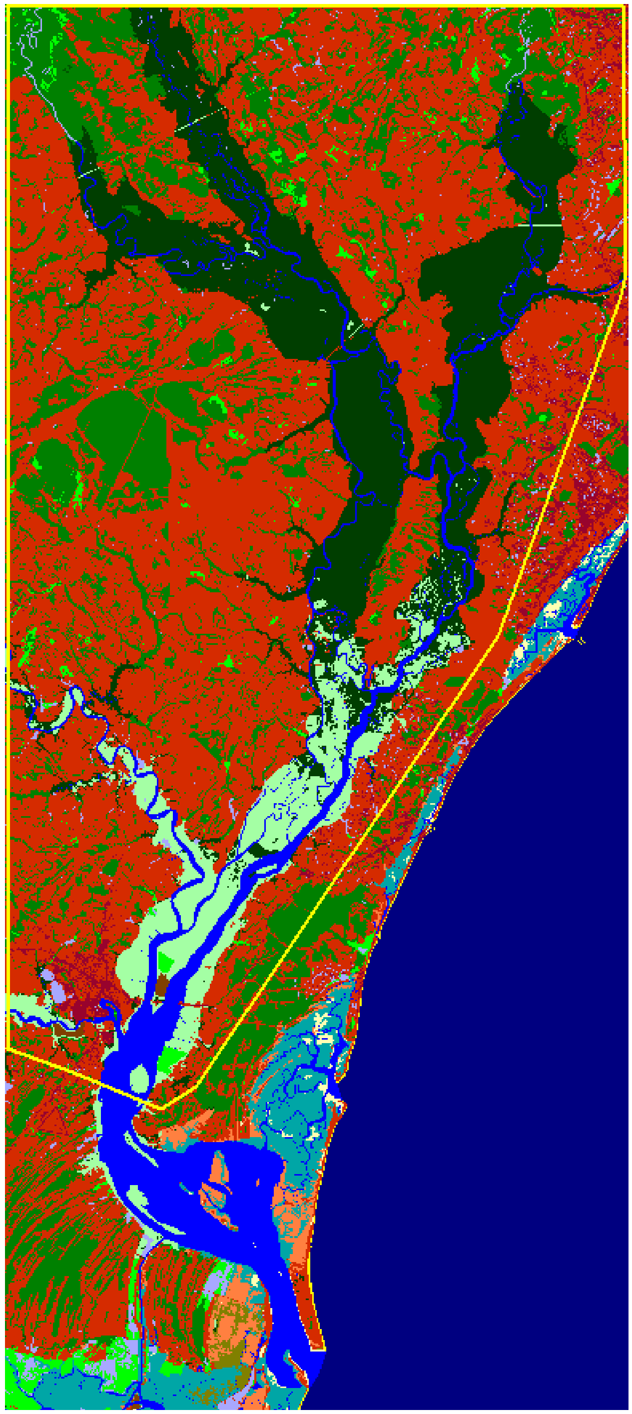


Figure 5. Extent of polygon drawn to delinate the zone of freshwater influence (in yellow).

Changes to the SLAMM conceptual model

Based on the areas with LiDAR elevation data, the SLAMM conceptual model was adjusted to better represent the locations of certain landcover types in the tidal frame. The minimum elevations of Tidal-fresh marsh and Tidal Swamp were decreased based on the 5th percentiles of the LiDAR-derived elevations of these categories.

Calibration of the initial conditions

Initially, SLAMM simulates a "time zero" step, in which the consistency of model assumptions for wetland elevations is validated with respect to available wetland coverage information, elevation data and tidal magnitudes. Due to DEM and wetland layer uncertainty, simplifications within the SLAMM conceptual model, or other local factors, some cells may immediately fall below their lowest allowable elevation category and would be converted by the model to a different land cover category. For example, an area categorized in the wetland layer as swamp that would be regularly inundated according to its elevation and tidal information will be converted to a tidal marsh. These cells represent outliers on the distribution of elevations for a given land-cover type. Generally, a threshold tolerance of up to 5% change is allowed for in major land cover categories in SLAMM analyses.

In the case of Waccamaw NWR, several changes to wetland layer were noted at time zero. As shown in Figure 6, a large portion of the tidal swamp in the refuge is converting to tidal-fresh marsh. These changes are occurring due to lower elevations in the LiDAR data layer. These changes appear to be "corrections" to the initial NWI layer, as they are observed in the Google Earth satellite imagery shown in Figure 7.

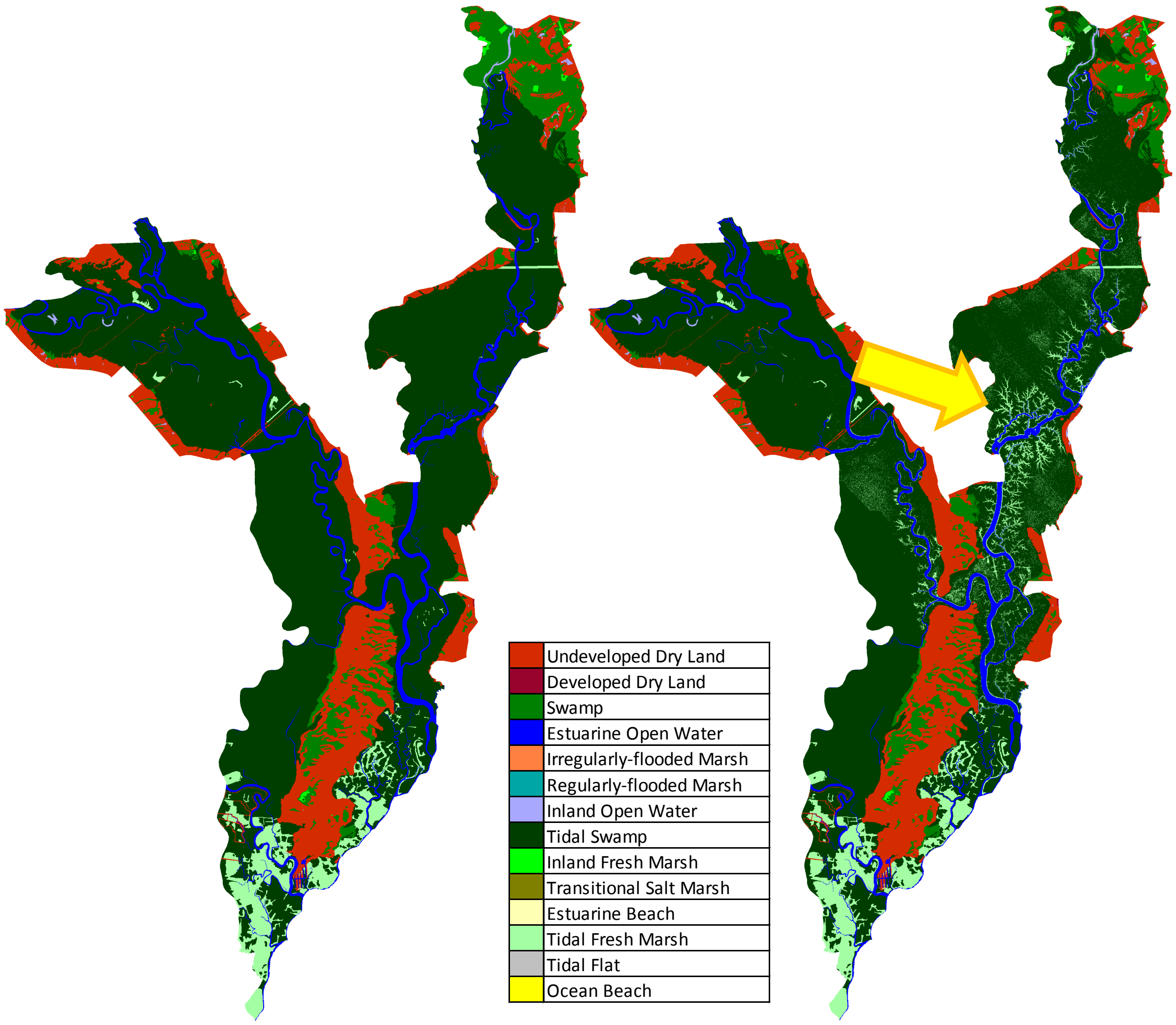


Figure 6. Initial NWI layer (left) and SLAMM time zero 2006 projection. Yellow arrow indicates the area shown in Google Earth Map.

Figure 7. Google Earth Map showing tributaries within tidal swamp

Based on these results, predicted gains and losses of wetland categories are made with respect to the coverage predicted by SLAMM at time zero. These results are summarized in the following table as "SLAMM 2006".

Land cover type	Areas (acres) NWI 2006	Areas (acres) SLAMM 2006
Tidal Swamp	38115	37272
Undeveloped Dry Land	9168	9082
Swamp	4313	3346
Riverine Tidal	3179	3179
Tidal-fresh marsh	2756	4661
Inland Open Water	155	155
Inland Fresh Marsh	107	73
Developed Dry Land	11	11
Cypress Swamp	4	4
Tidal Flat	0	4
Regularly Flooded Marsh	0	22
Total (incl. water)	**57808**	**57808**

Results

Percentage losses by 2100 for each land-cover type given different SLR scenarios are presented in Table 3. As discussed above, land-cover losses are calculated in comparison to the "time zero" or "SLAMM 2006" wetland coverage.

Table 3. Predicted loss rates of land categories by 2100 given simulated scenarios of eustatic SLR at Waccamaw NWR.

Land cover category	2006 coverage (acres)	Land cover loss by 2100 for different SLR scenarios				
		0.39 m	0.69 m	1 m	1.5 m	2 m
Tidal Swamp	37278	55%	65%	75%	86%	91%
Undeveloped Dry Land	9082	3%	5%	6%	9%	11%
Swamp	3346	32%	41%	46%	50%	53%
Tidal-fresh marsh	4676	-20%	-23%	-42%	-39%	11%
Inland Fresh Marsh	73	7%	28%	38%	45%	50%
Developed Dry Land	11	0%	0%	0%	6%	14%

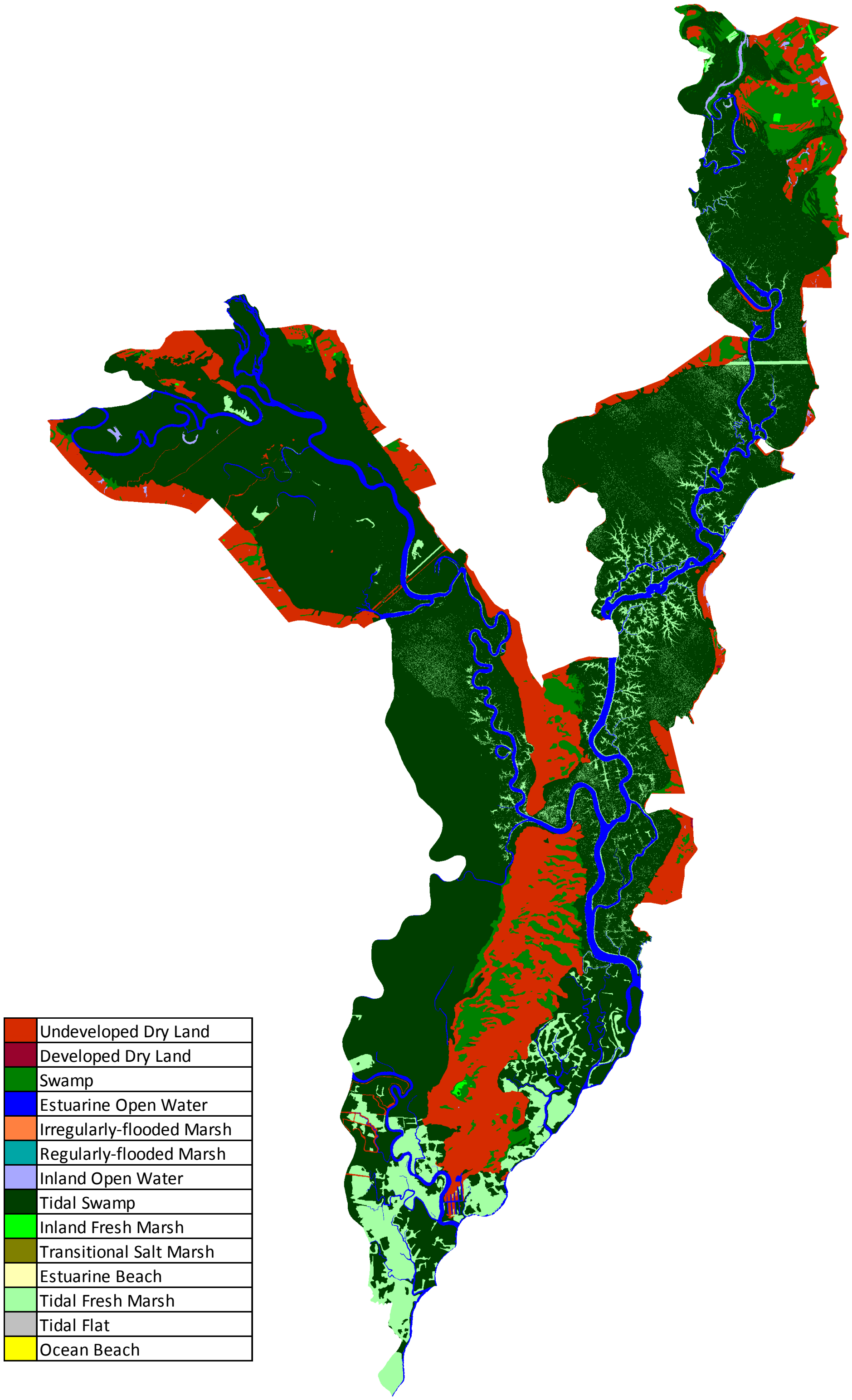
The refuge is primarily tidal swamp, with 66% of the refuge currently covered by this wetland type according to the initial NWI wetland layer. SLAMM simulations suggest that tidal swamp will be seriously impacted by accelerated SLR, with more than 50% of this wetland type lost under the most conservative SLR scenario examined (IPCC A1B Mean, 0.39m by 2100). Under the 1 m by 2100 scenario, 75% of tidal swamp in the refuge is predicted to have converted to other wetland types.

The SLAMM conceptual model predicts that tidal swamp converts to tidal-fresh marsh under higher frequency of inundation, and the statistics for tidal-fresh marsh show increases in this habitat type in Table 3 (as noted by the negative values). Therefore the loss of tidal swamp leads to increases in tidal-fresh marsh at SLR scenarios below 2 m by 2100, with a maximum increase under the 1 m by 2100 scenario. Swamp and Inland Fresh Marsh also appear vulnerable to accelerated SLR, but to a somewhat lesser extent, with losses of 46% and 38% of these habitats, respectively, under 1 m of SLR by 2100.

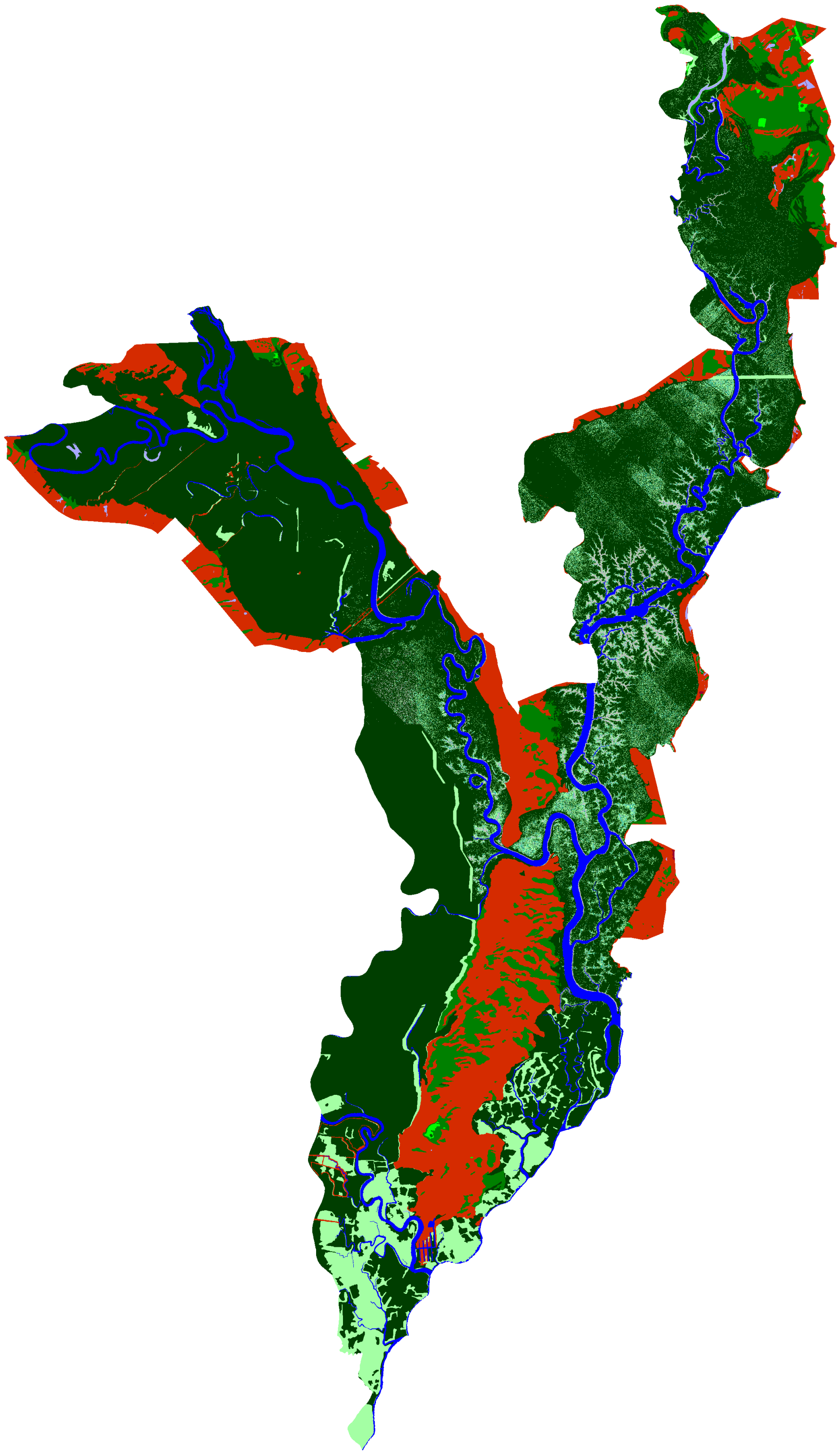
Waccamaw NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

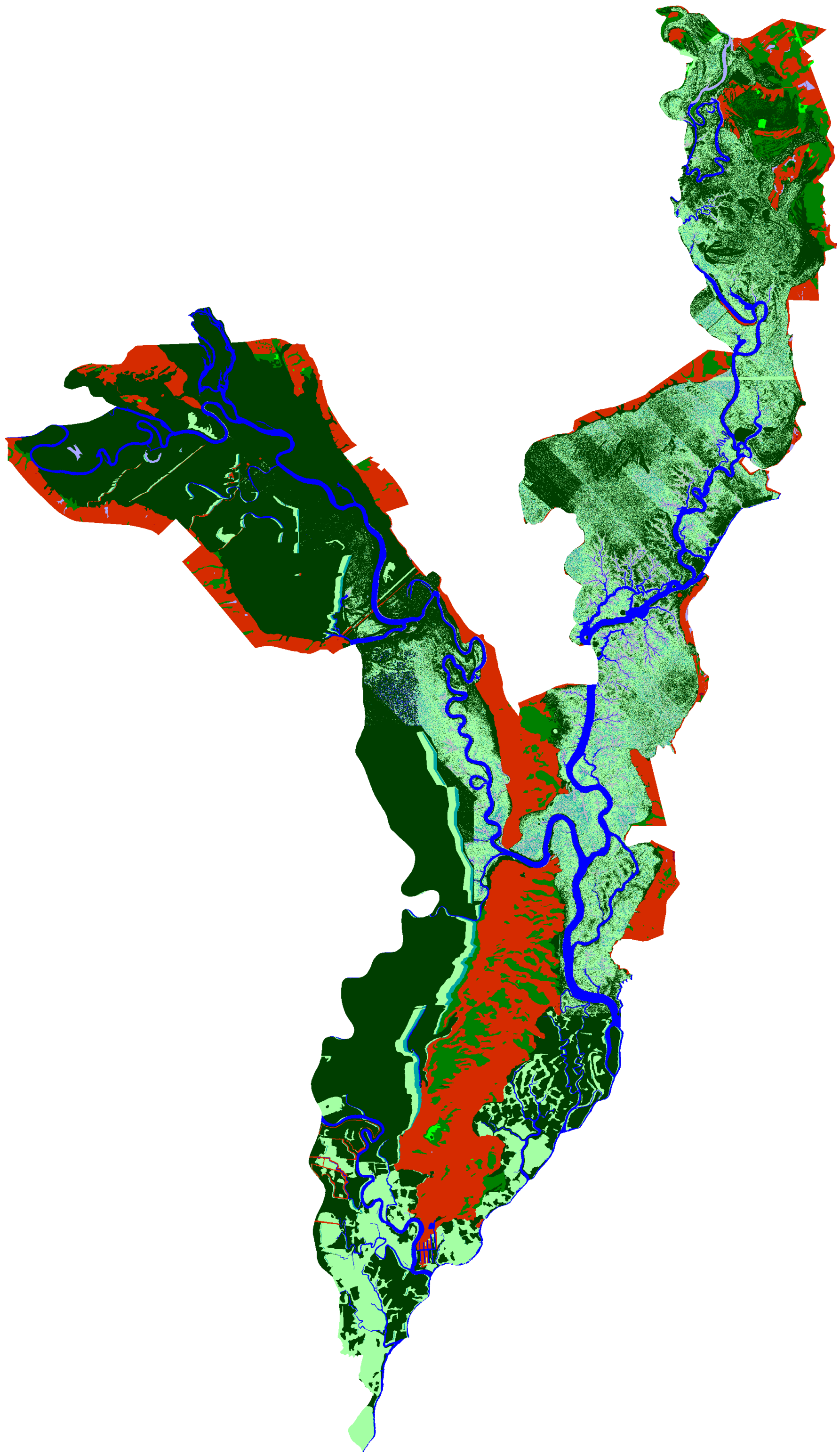
		Initial	2025	2050	2075	2100
	Tidal Swamp	38115	34917	25836	19369	16697
	Undeveloped Dry Land	9168	9056	9001	8924	8829
	Swamp	4313	3214	2753	2442	2261
	Riverine Tidal	3179	3159	1487	1301	1211
	Tidal-fresh marsh	2756	5633	12372	9589	5604
	Inland Open Water	155	155	143	92	89
	Inland Fresh Marsh	107	73	71	70	68
	Developed Dry Land	11	11	11	11	11
	Cypress Swamp	4	4	4	4	4
	Tidal Flat	0	996	2050	9629	14474
	Estuarine Open Water	0	125	2259	3595	6822
	Regularly Flooded Marsh	0	463	1821	2782	1737
	Total (incl. water)	**57808**	**57808**	**57808**	**57808**	**57808**



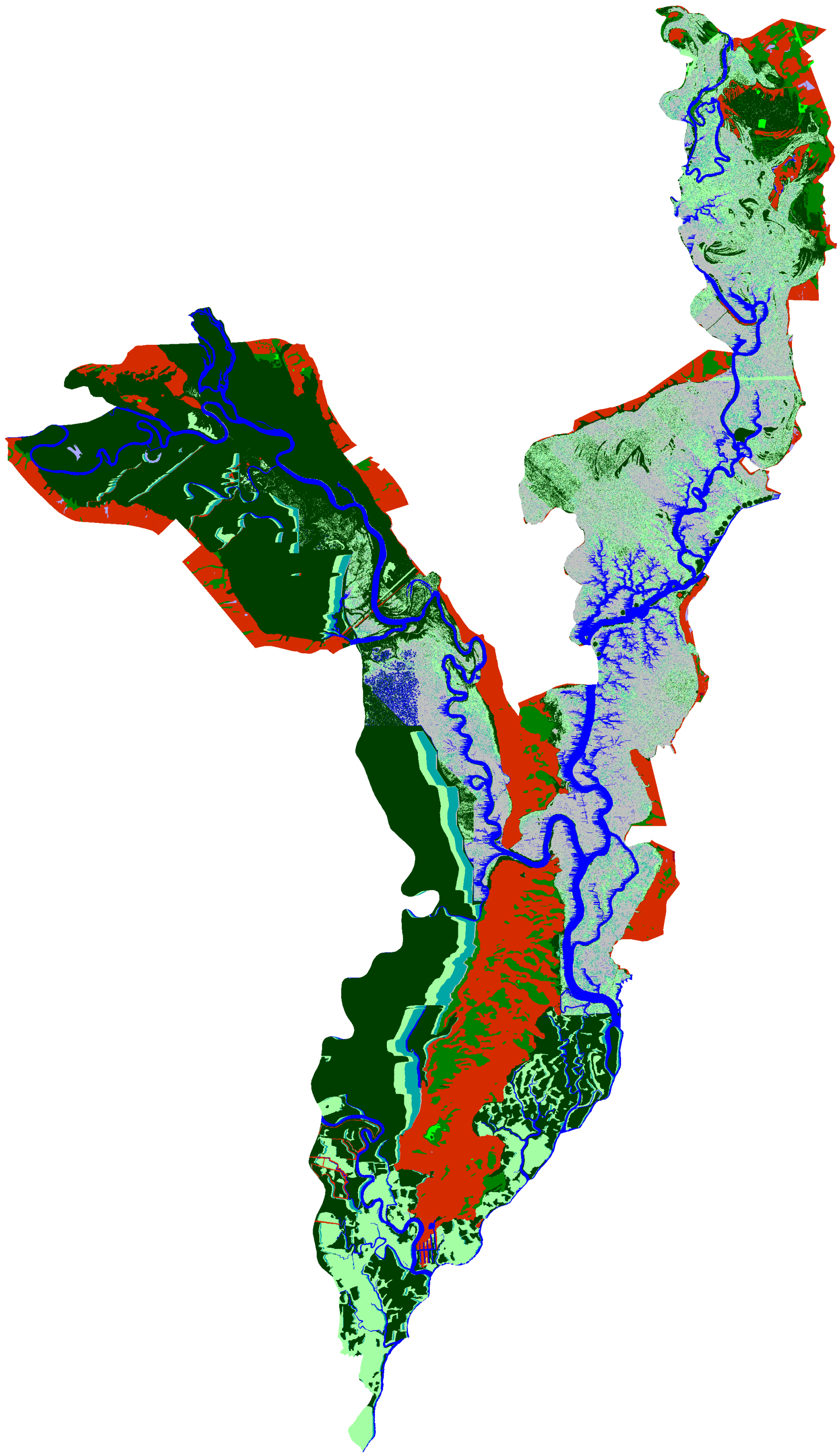
Waccamaw NWR, SLAMM 2006.



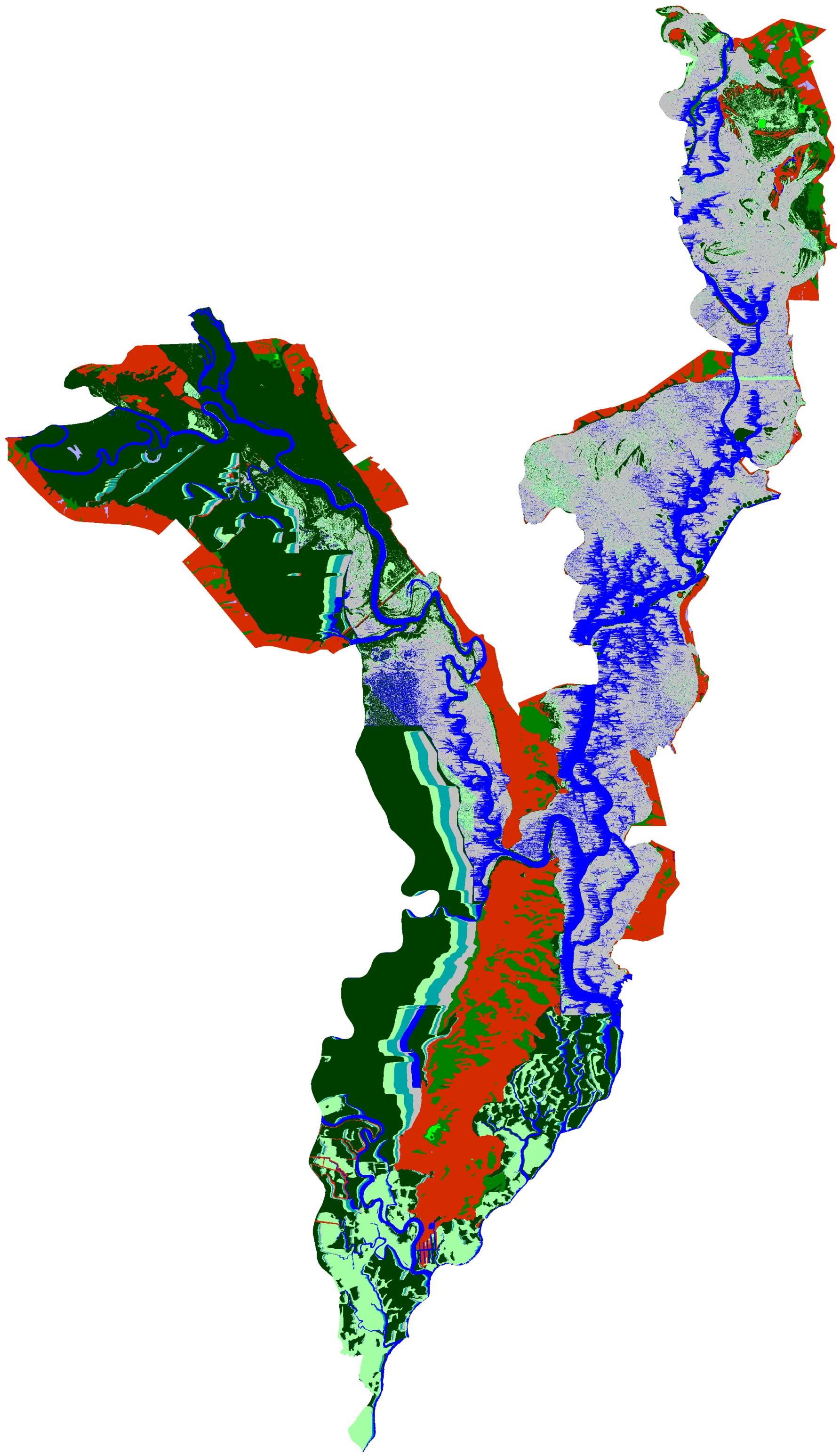
Waccamaw NWR, 2025, Scenario A1B Mean, 0.39 m SLR



Waccamaw NWR, 2050, Scenario A1B Mean, 0.39 m SLR by 2100.



Waccamaw NWR, 2075, Scenario A1B Mean, 0.39 m SLR by 2100.

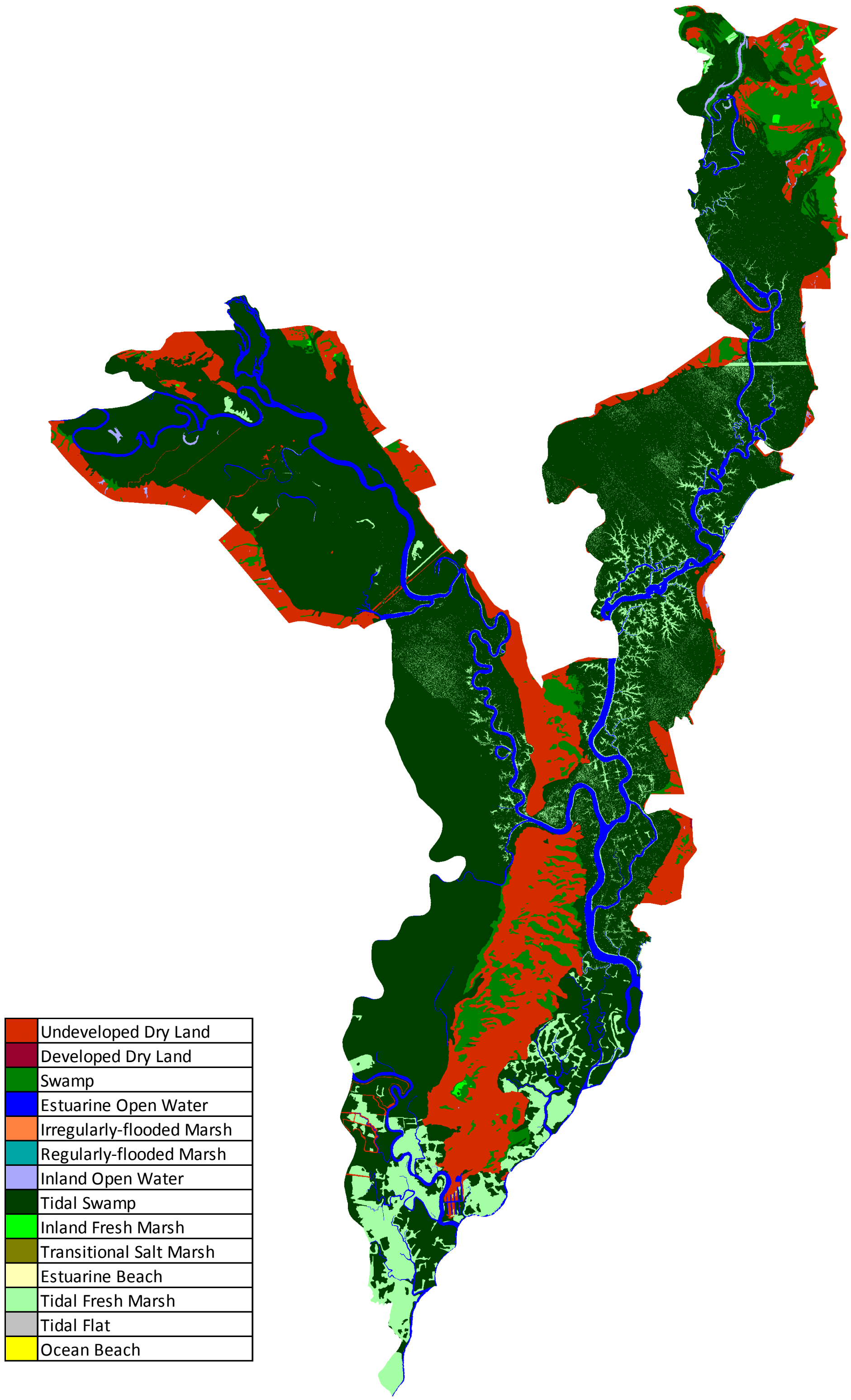


Waccamaw NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.

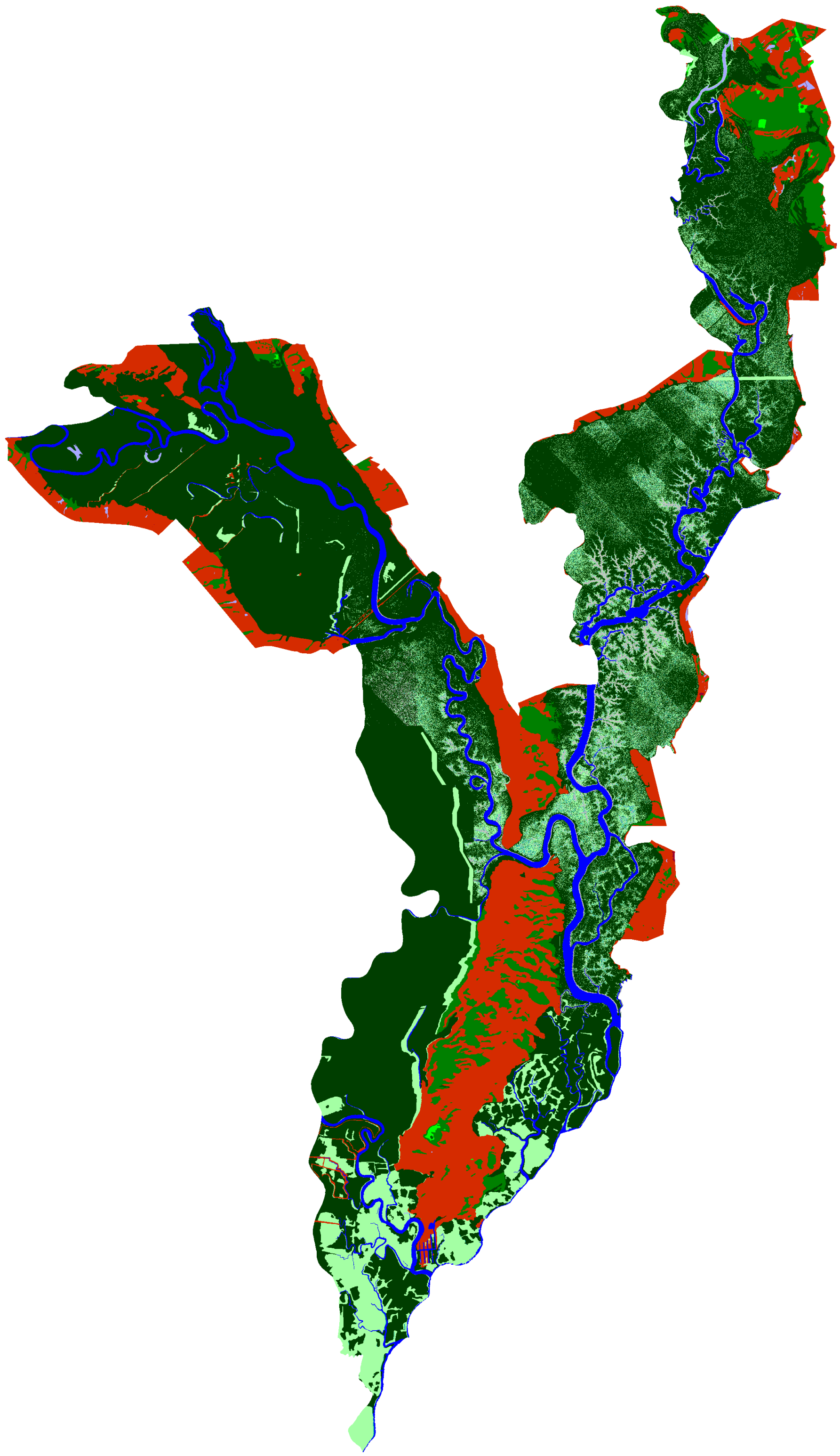
Waccamaw NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

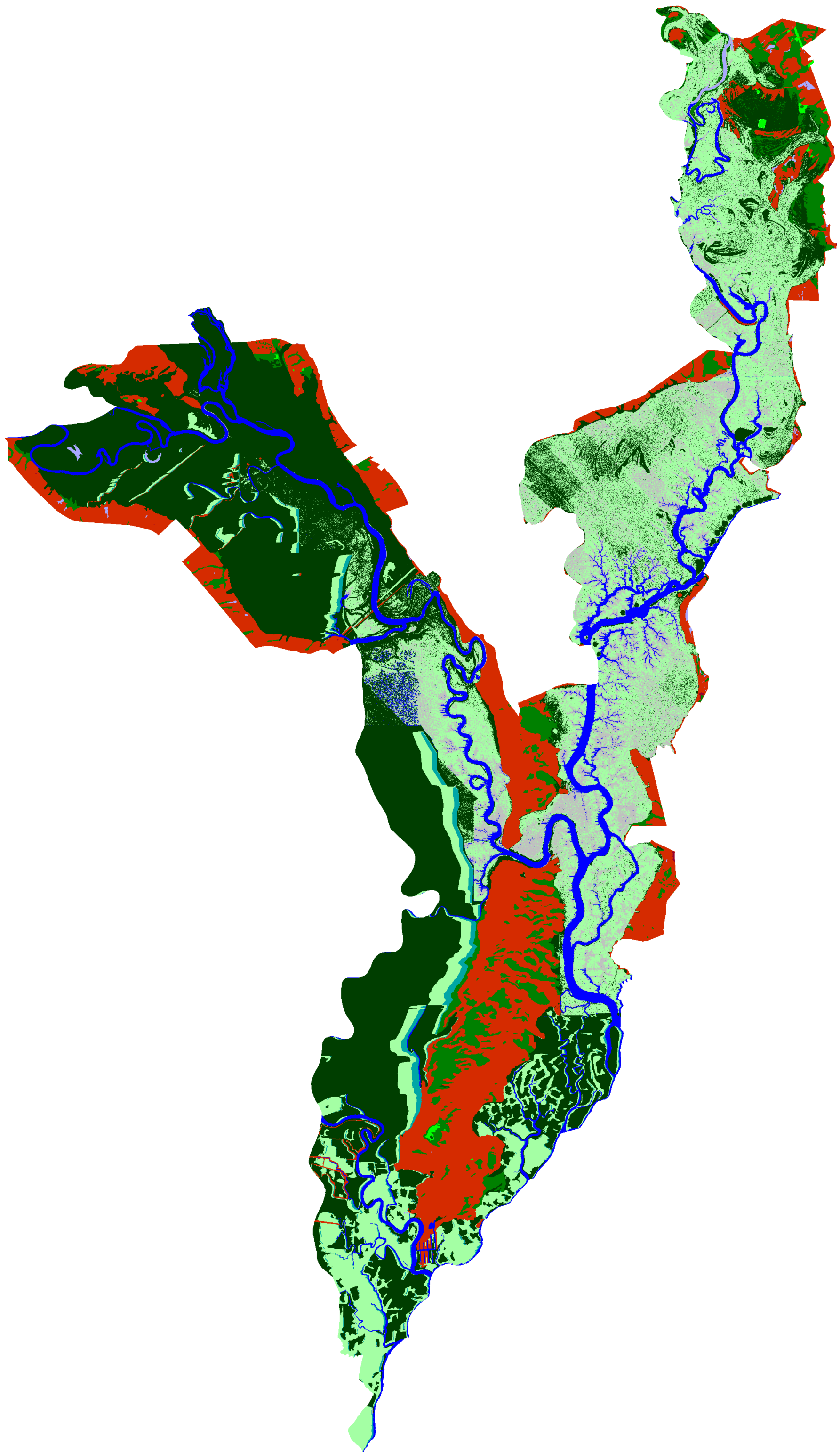
		Initial	2025	2050	2075	2100
	Tidal Swamp	38115	33193	20814	16052	12968
	Undeveloped Dry Land	9168	9048	8962	8820	8657
	Swamp	4313	3176	2564	2240	1977
	Riverine Tidal	3179	3158	1464	1258	1120
	Tidal-fresh marsh	2756	7052	15773	7680	5761
	Inland Open Water	155	155	142	91	88
	Inland Fresh Marsh	107	71	68	61	52
	Developed Dry Land	11	11	11	11	11
	Cypress Swamp	4	4	4	4	4
	Tidal Flat	0	1220	4749	14289	6083
	Estuarine Open Water	0	140	2585	6761	20589
	Regularly Flooded Marsh	0	579	671	540	498
	Total (incl. water)	**57808**	**57808**	**57808**	**57808**	**57808**



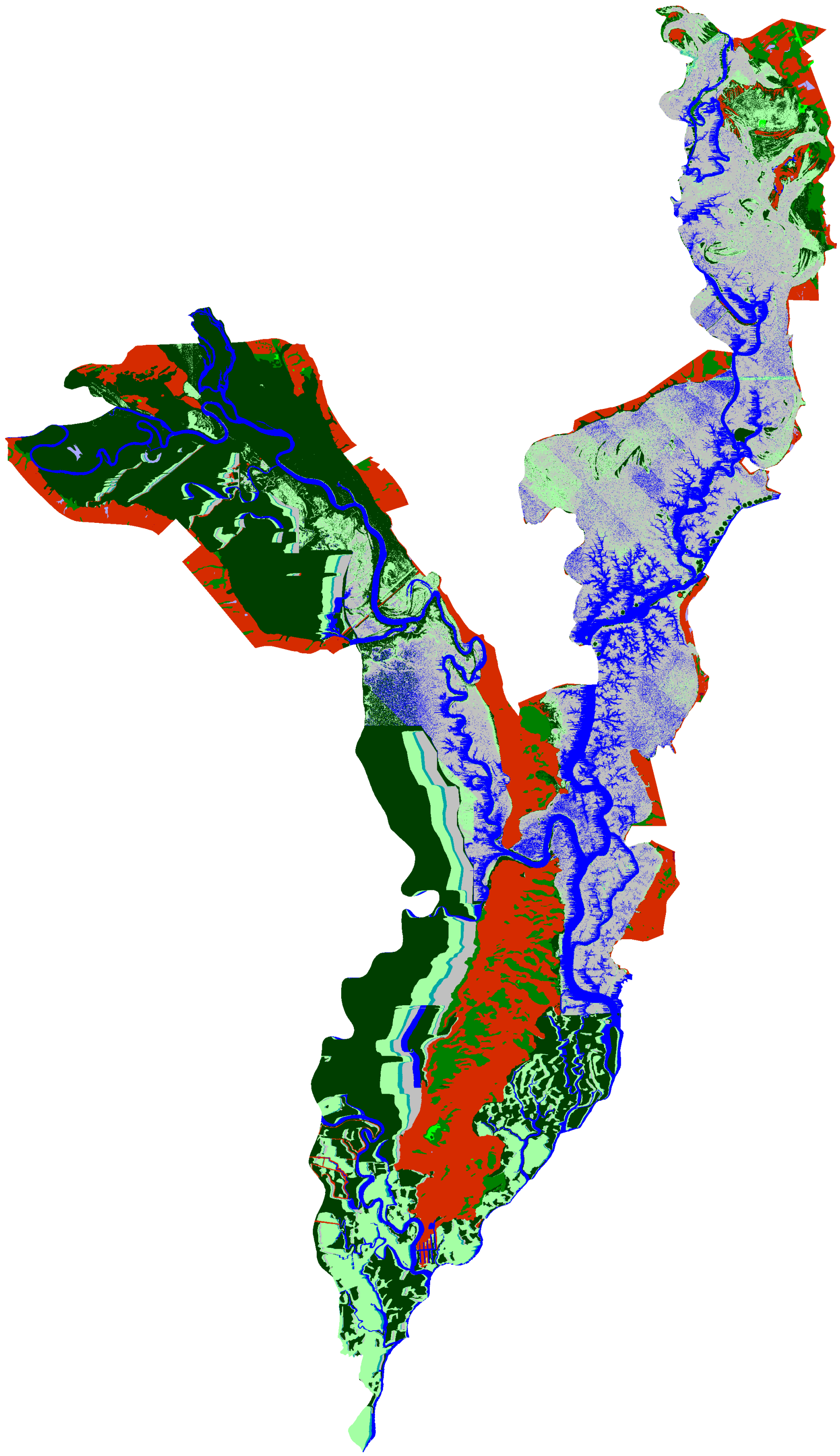
Waccamaw NWR, SLAMM 2006.



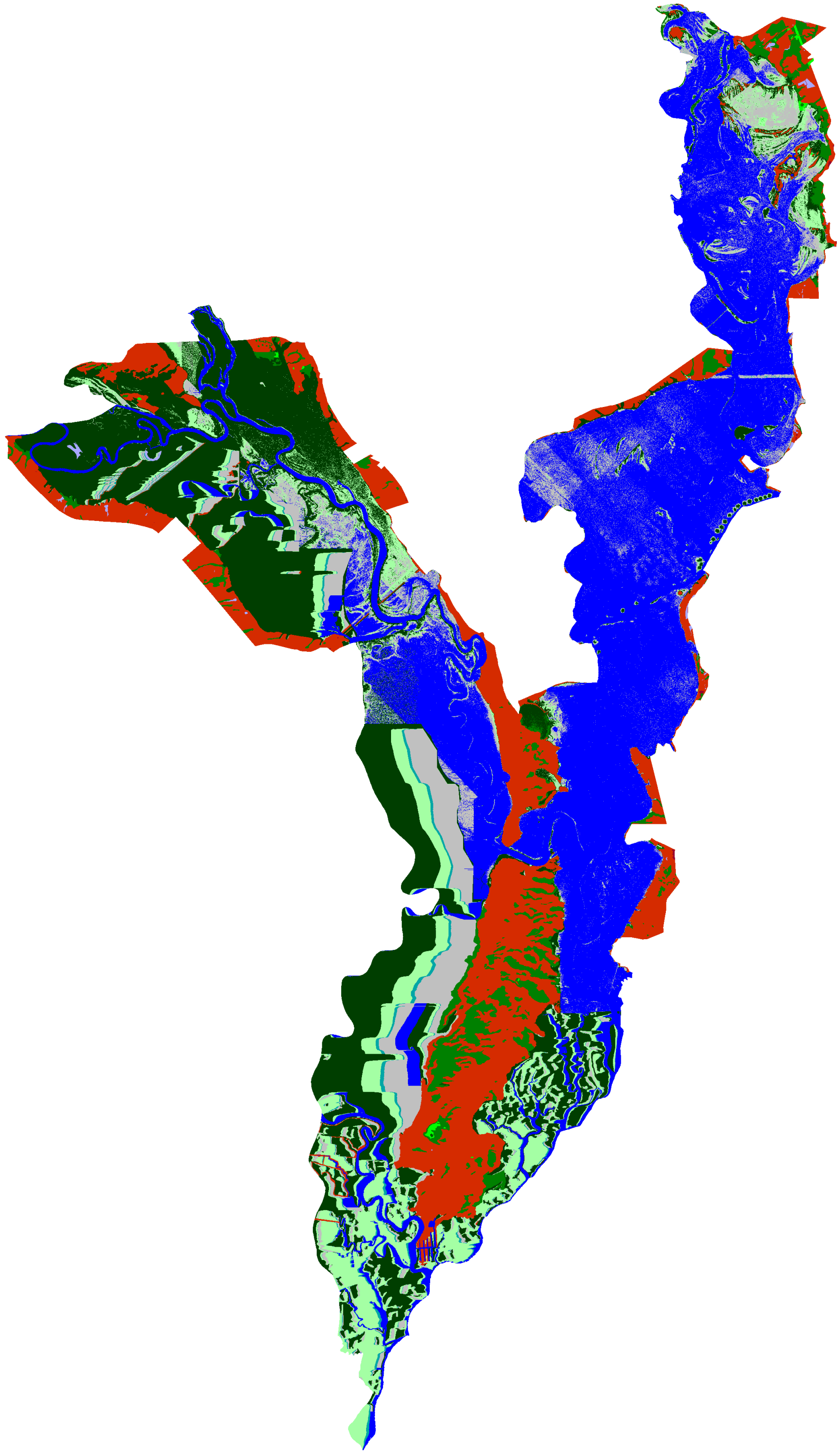
Waccamaw NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



Waccamaw NWR, 2050, Scenario A1B Maximum, 0.69 m SLR by 2100.



Waccamaw NWR, 2075, Scenario A1B Maximum, 0.69 m SLR by 2100.

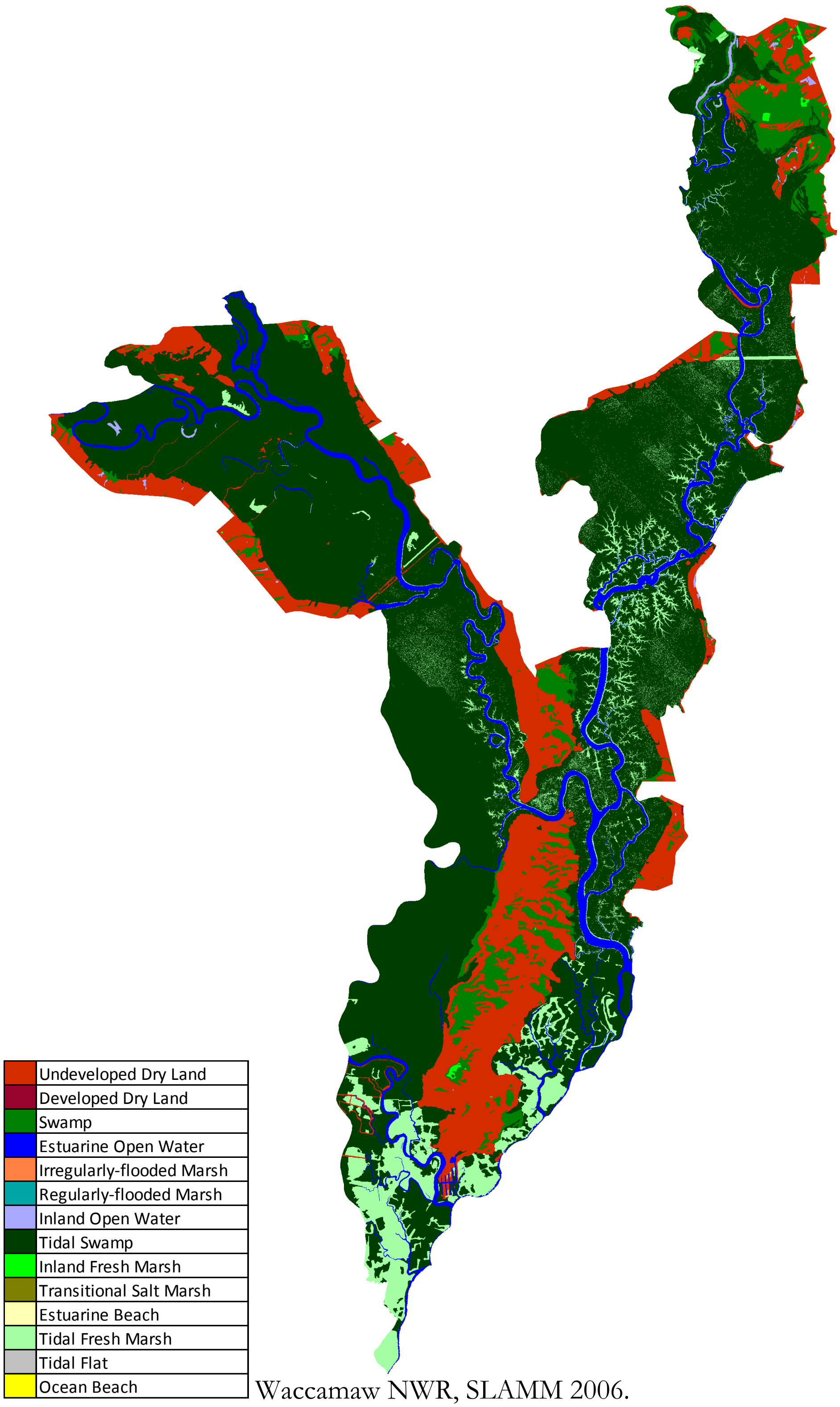


Waccamaw NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.

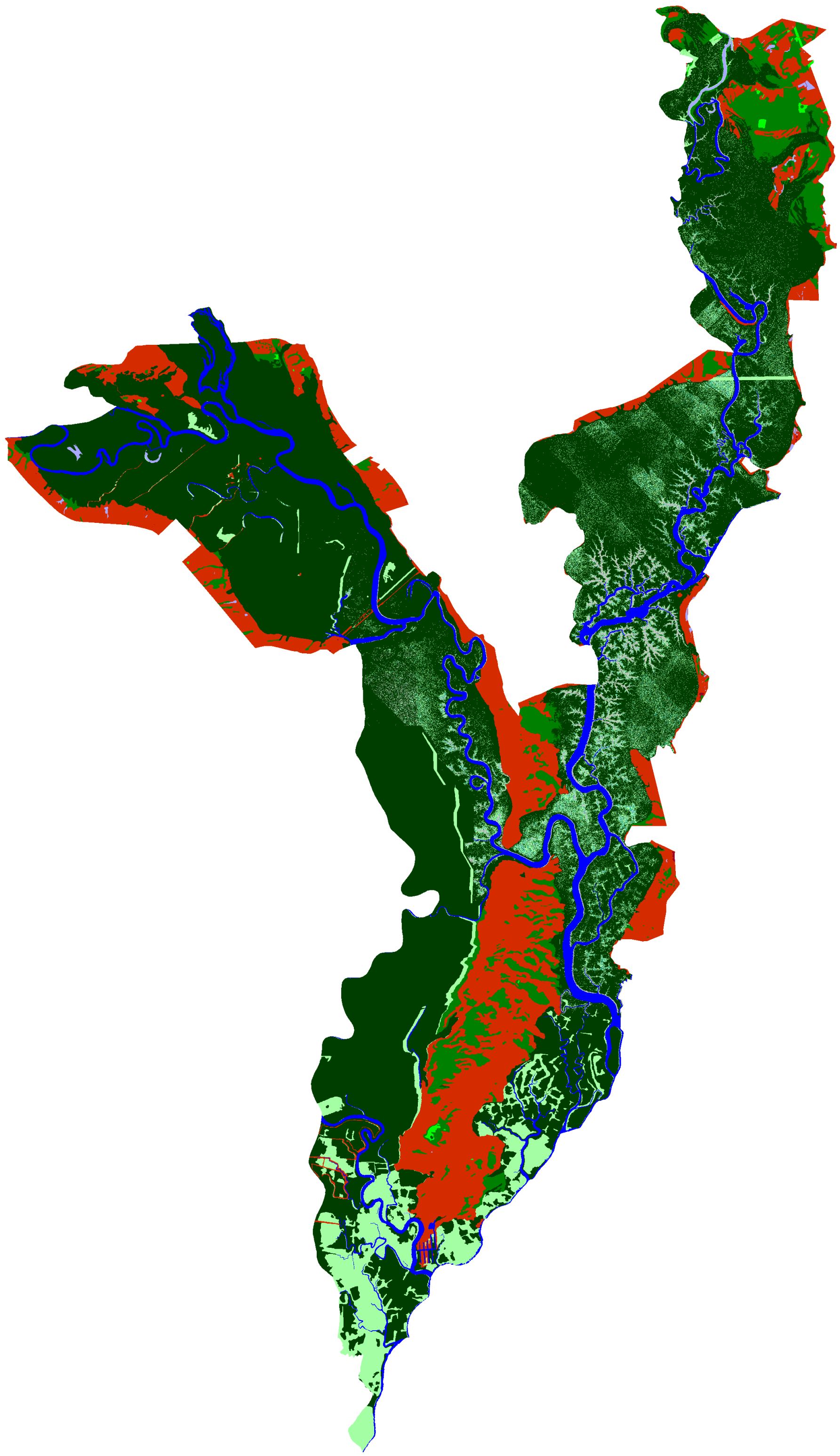
Waccamaw NWR
1 m eustatic SLR by 2100

Results in Acres

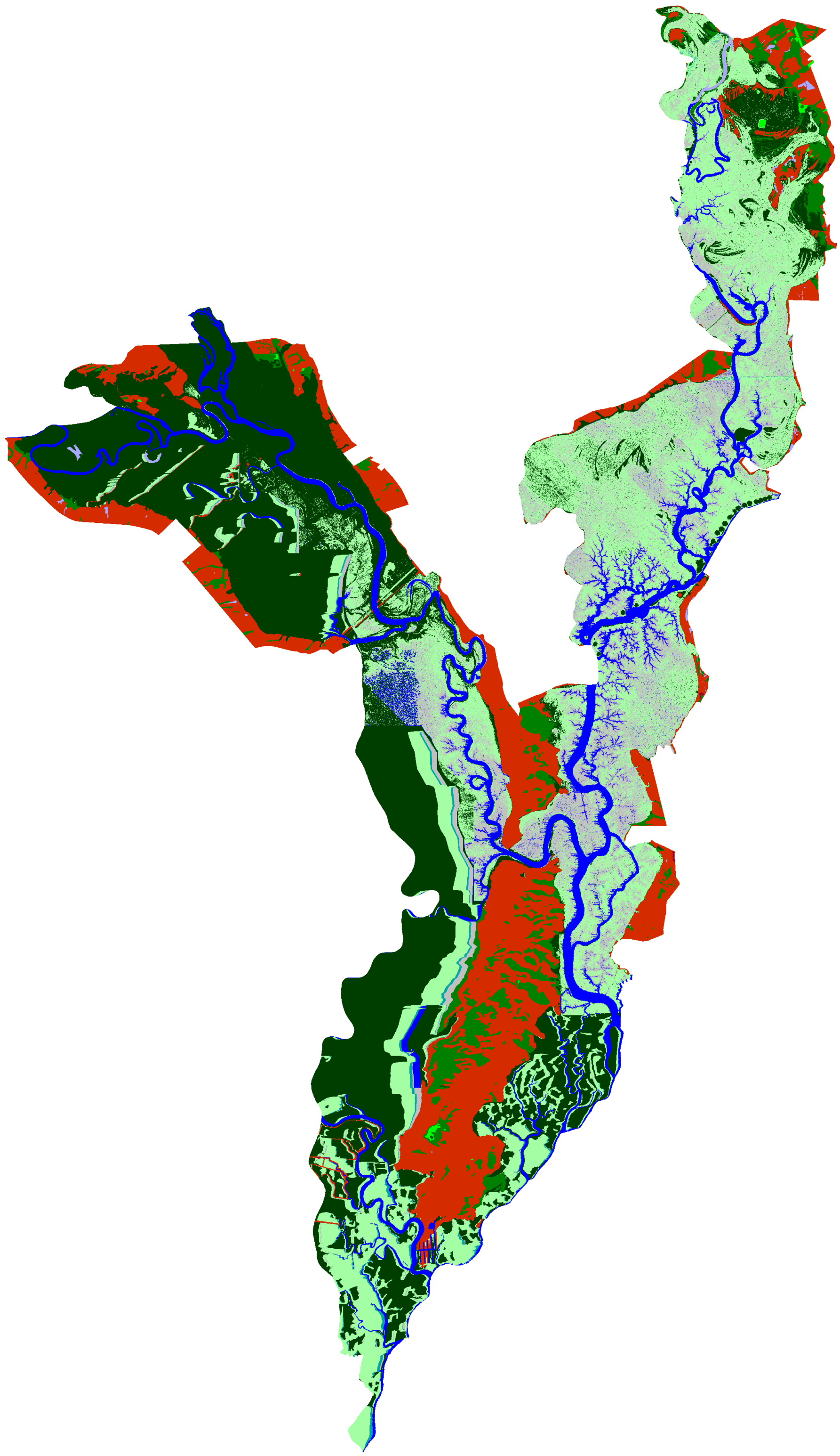
		Initial	2025	2050	2075	2100
	Tidal Swamp	38115	30945	18278	13658	9295
	Undeveloped Dry Land	9168	9038	8914	8700	8504
	Swamp	4313	3008	2408	2028	1812
	Riverine Tidal	3179	3158	1436	1246	1086
	Tidal-fresh marsh	2756	9442	15937	7391	6623
	Inland Open Water	155	155	142	90	87
	Inland Fresh Marsh	107	70	64	51	45
	Developed Dry Land	11	11	11	11	11
	Cypress Swamp	4	4	4	4	4
	Tidal Flat	0	1498	6873	13123	6509
	Estuarine Open Water	0	154	3362	11341	23668
	Regularly Flooded Marsh	0	326	380	164	165
	Total (incl. water)	**57808**	**57808**	**57808**	**57808**	**57808**



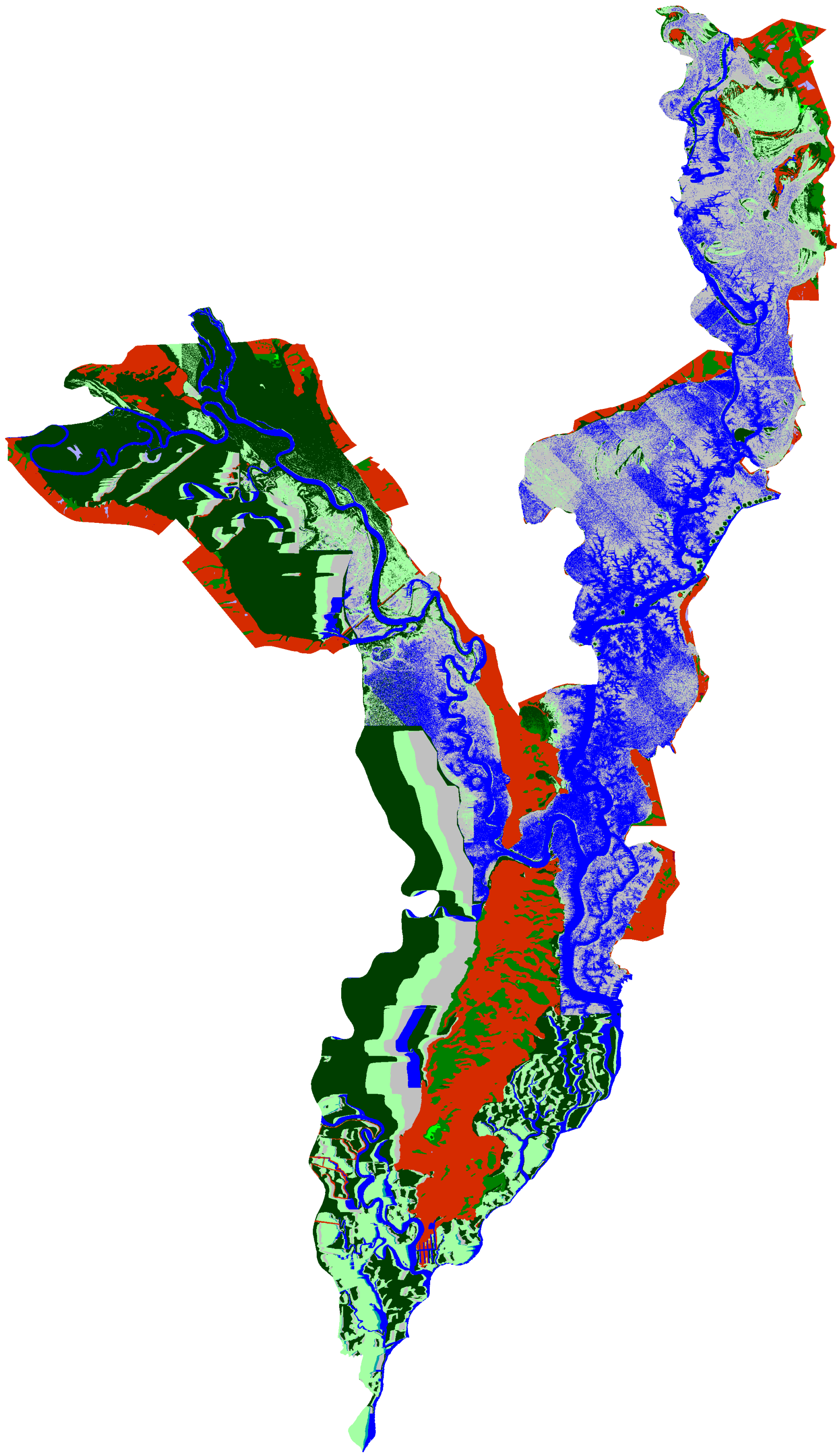
Waccamaw NWR, SLAMM 2006.



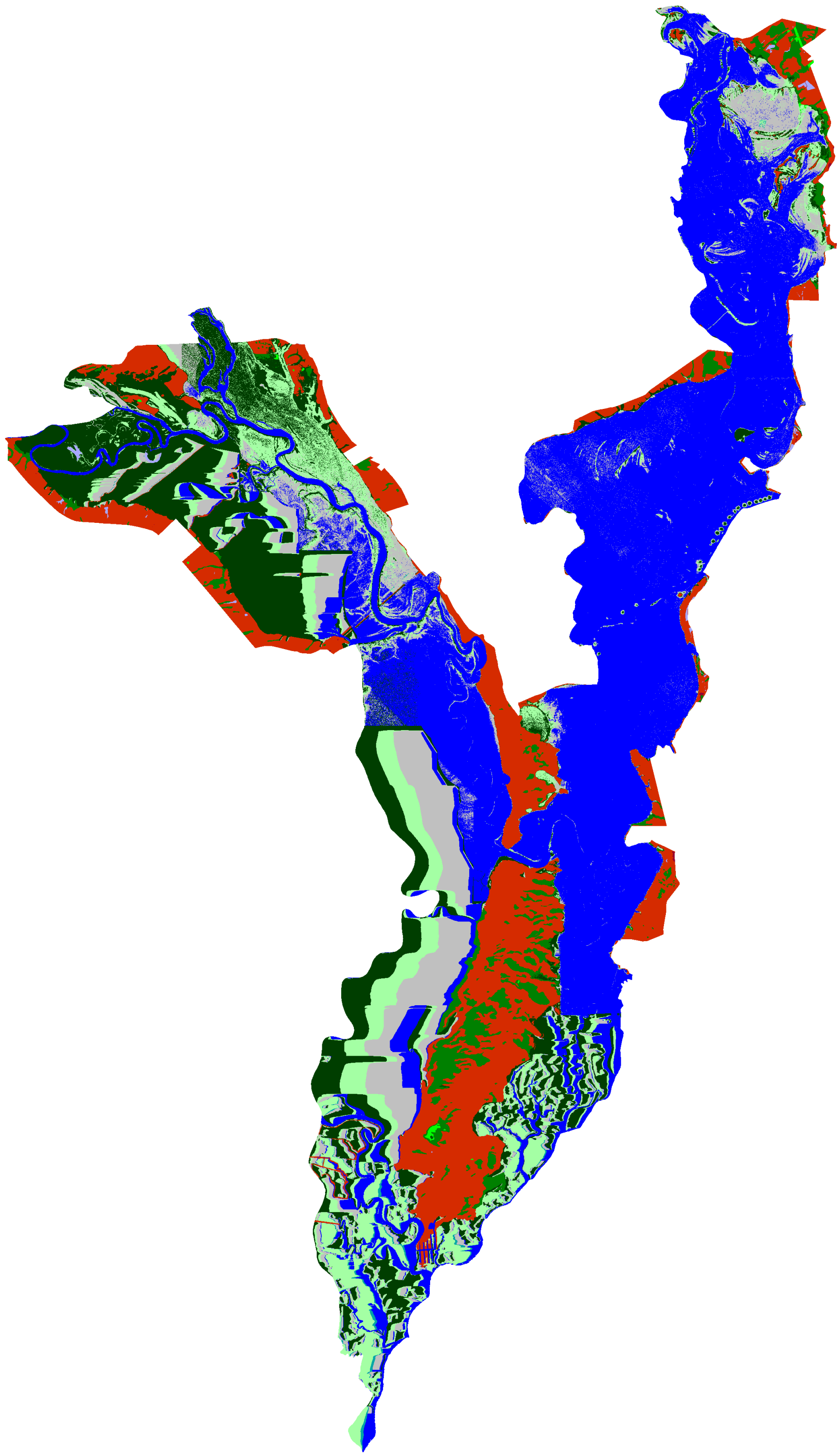
Waccamaw NWR, 2025, 1 m SLR by 2100.



Waccamaw NWR, 2050, 1 m SLR by 2100.



Waccamaw NWR, 2075, 1 m SLR by 2100.

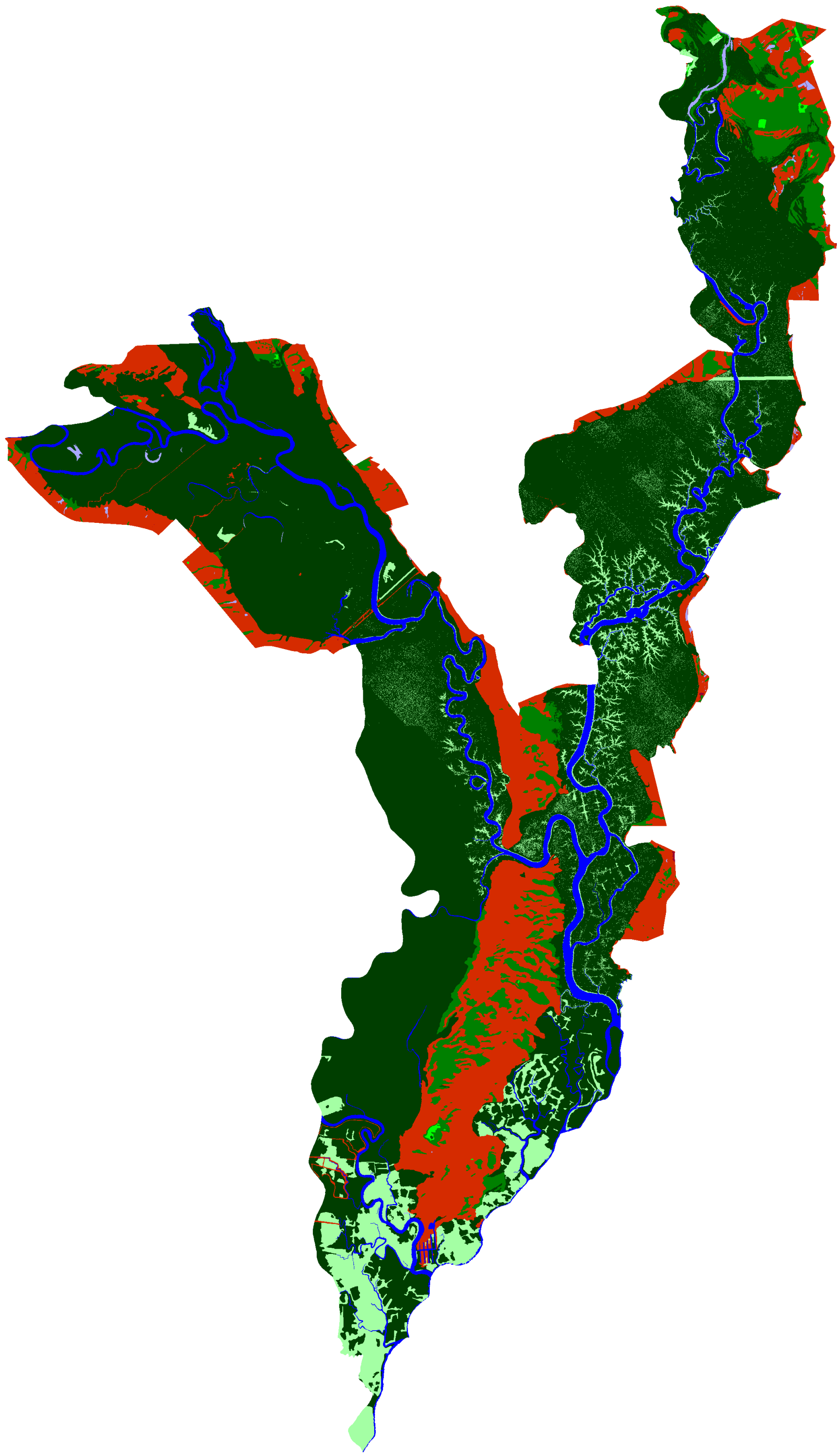


Waccamaw NWR, 2100, 1 m SLR by 2100.

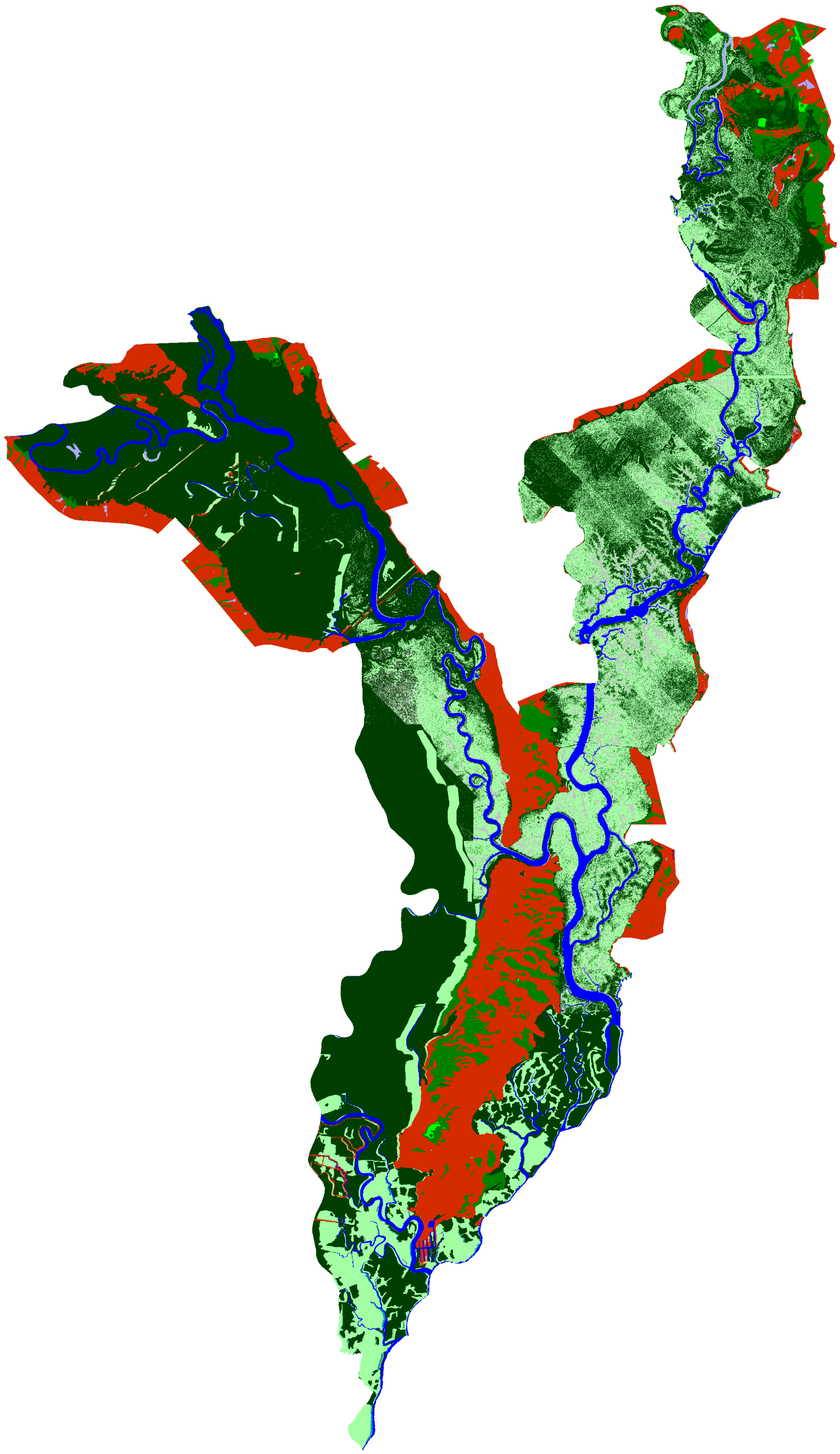
Waccamaw NWR
1.5 m eustatic SLR by
2100

Results in Acres

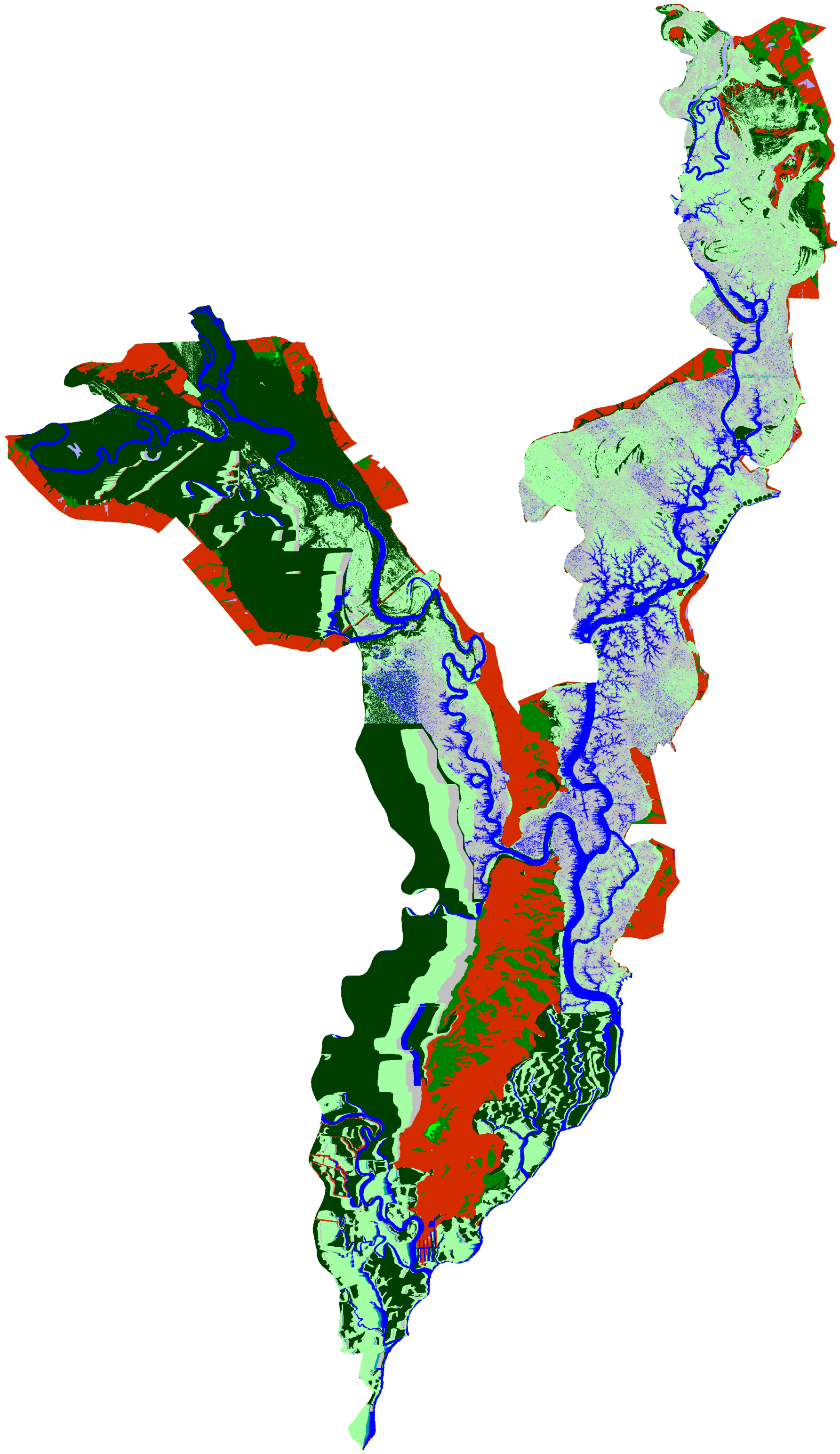
		Initial	2025	2050	2075	2100
	Tidal Swamp	38115	26843	15720	9883	5087
	Undeveloped Dry Land	9168	9019	8819	8532	8247
	Swamp	4313	2849	2233	1834	1664
	Riverine Tidal	3179	3157	1411	1214	905
	Tidal-fresh marsh	2756	13654	14227	8268	6478
	Inland Open Water	155	155	142	89	87
	Inland Fresh Marsh	107	69	53	44	40
	Developed Dry Land	11	11	11	11	11
	Cypress Swamp	4	4	4	4	4
	Tidal Flat	0	1755	10450	11878	6393
	Estuarine Open Water	0	176	4576	15892	28740
	Regularly Flooded Marsh	0	115	162	160	153
	Total (incl. water)	**57808**	**57808**	**57808**	**57808**	**57808**



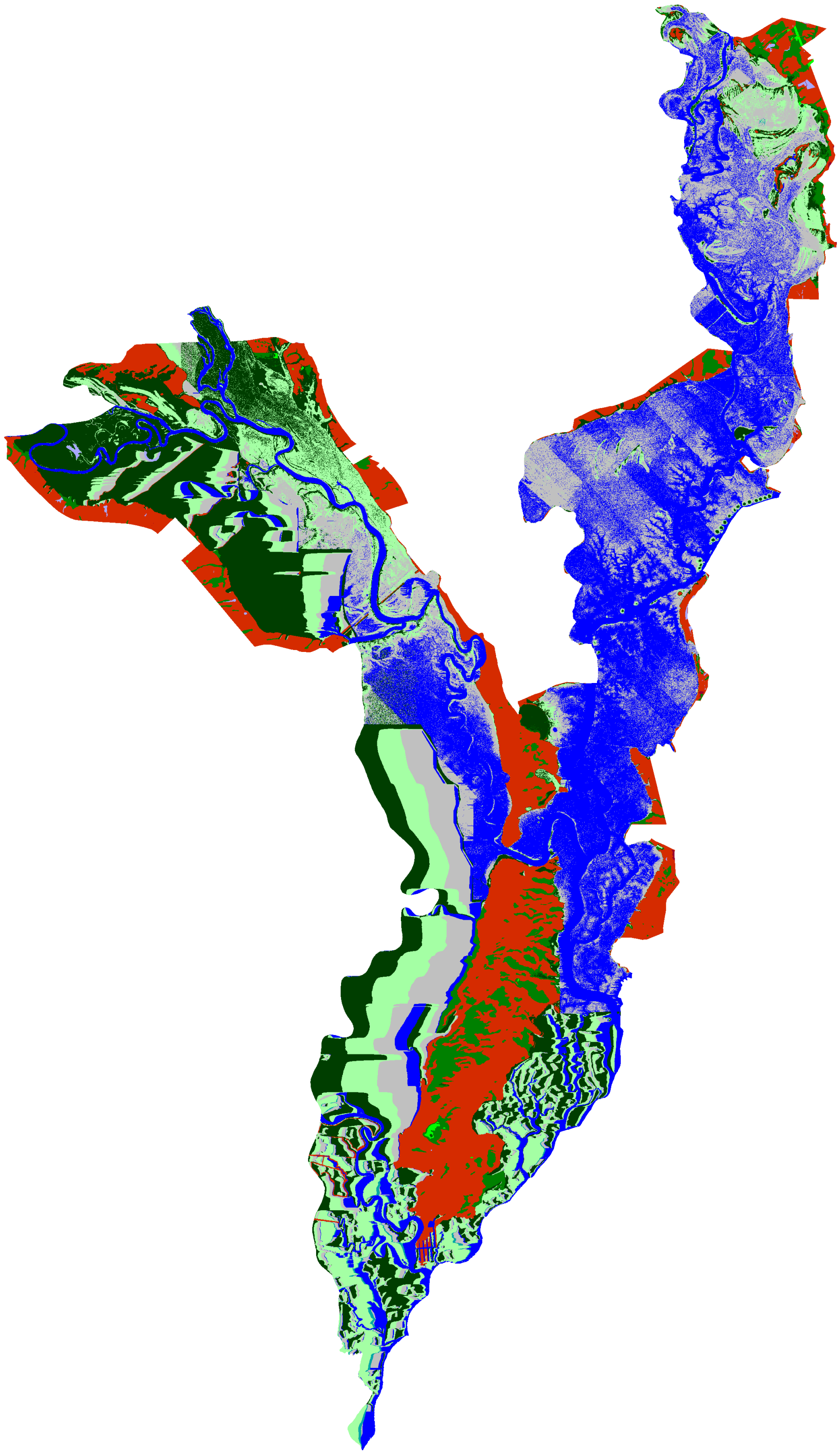
Waccamaw NWR, SLAMM 2006.



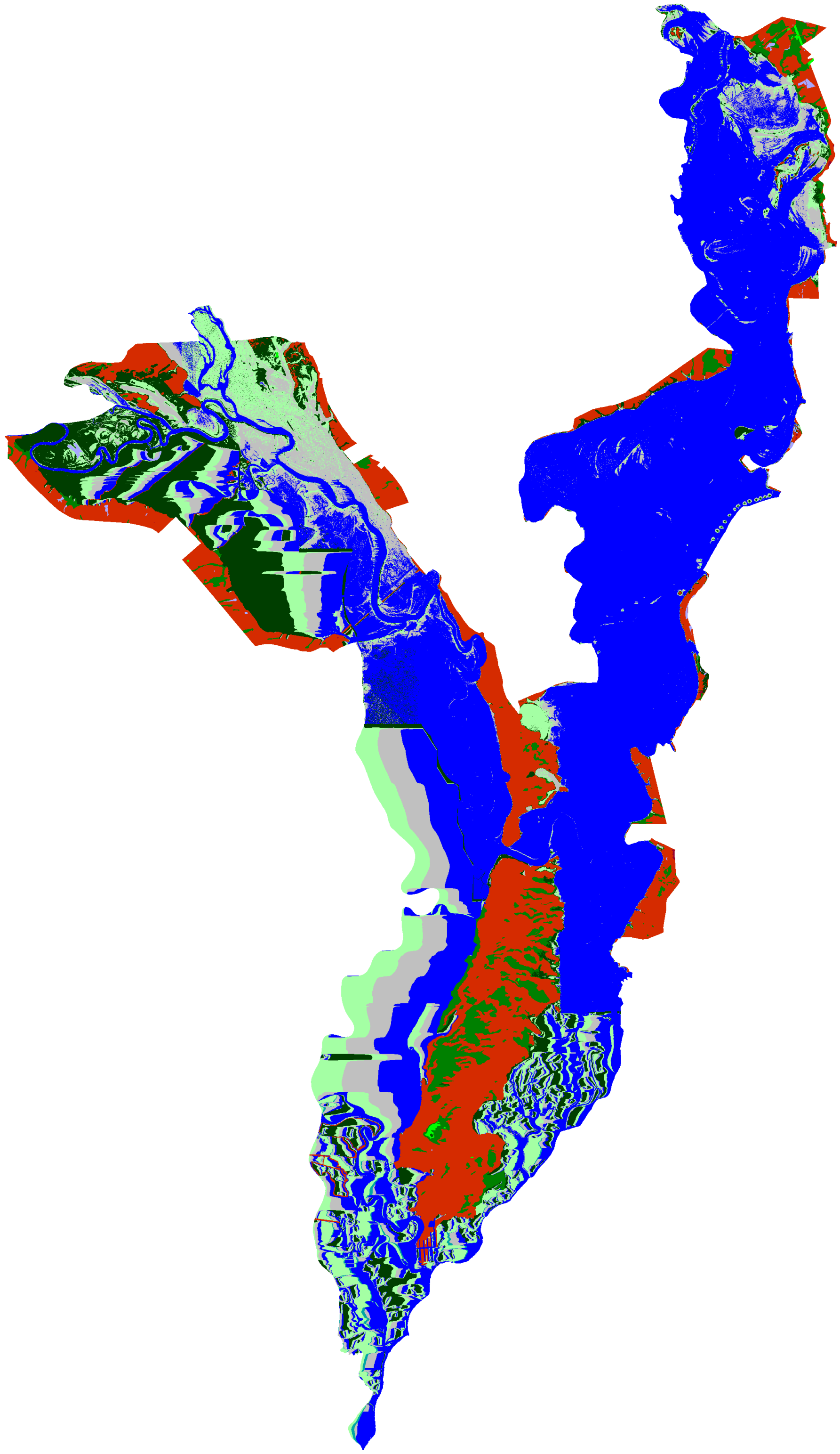
Waccamaw NWR, 2025, 1.5 m SLR by 2100.



Waccamaw NWR, 2050, 1.5 m SLR by 2100.



Waccamaw NWR, 2075, 1.5 m SLR by 2100.

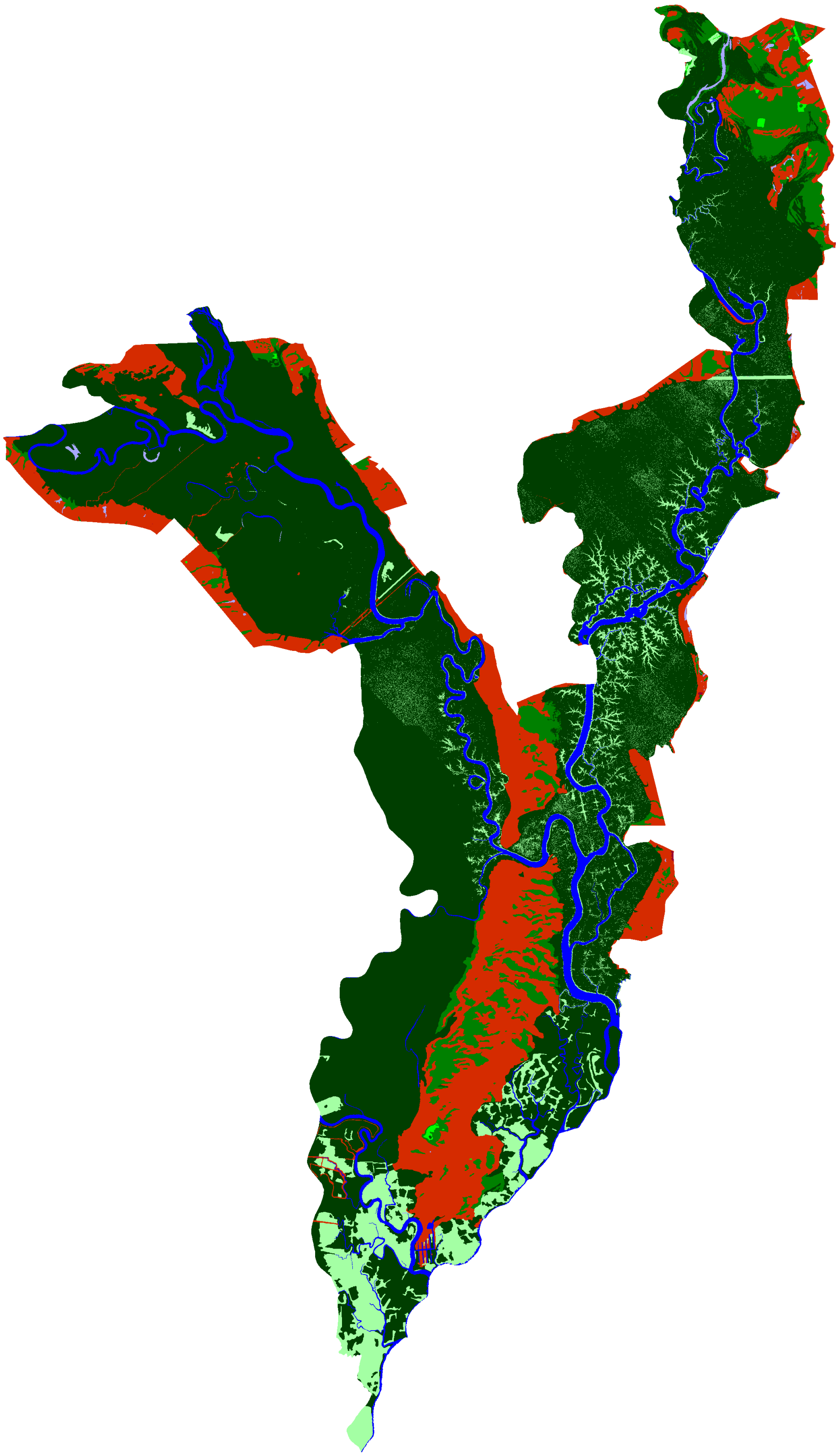


Waccamaw NWR, 2100, 1.5 m SLR by 2100.

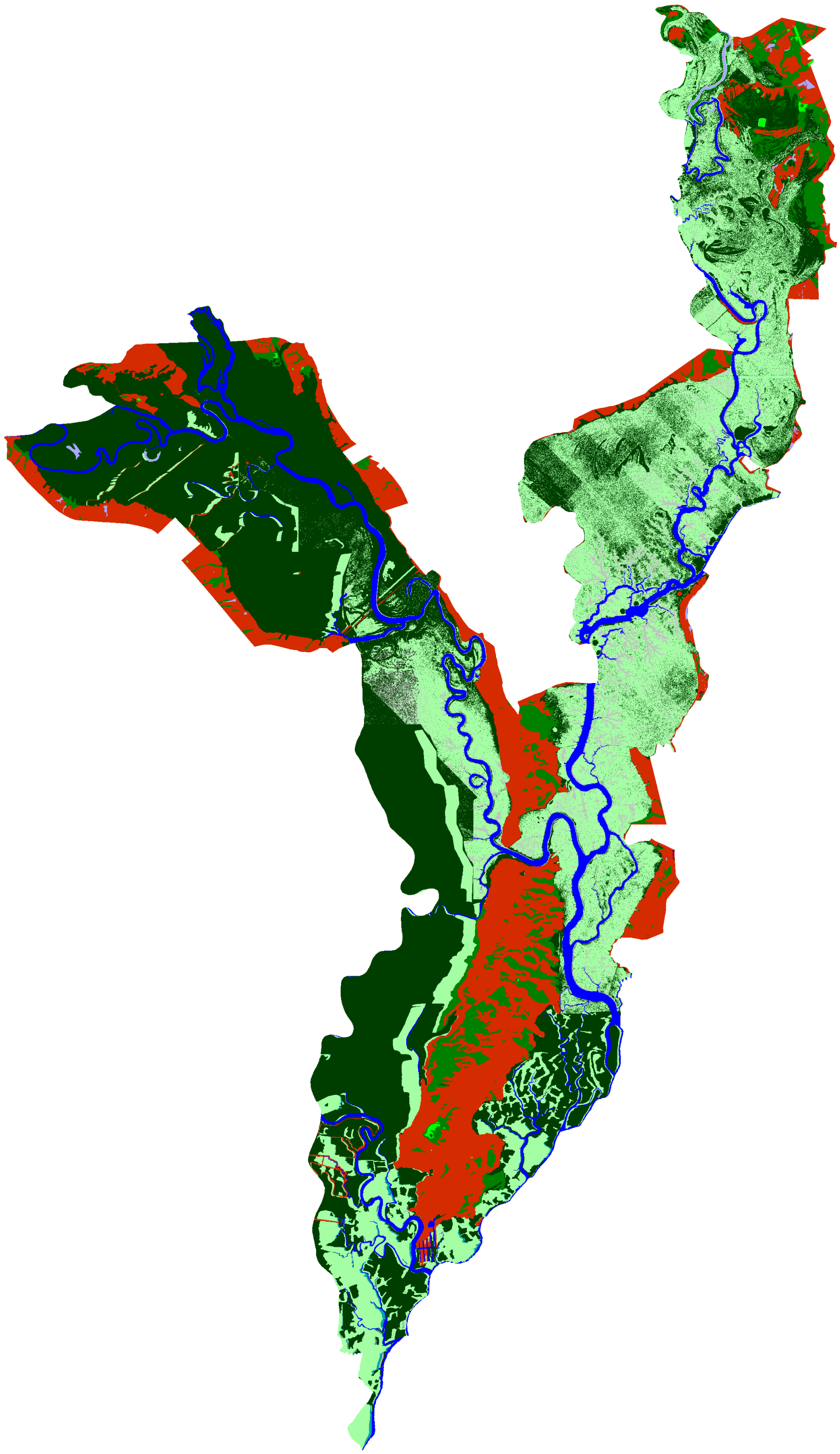
Waccamaw NWR
2 m eustatic SLR by 2100

Results in Acres

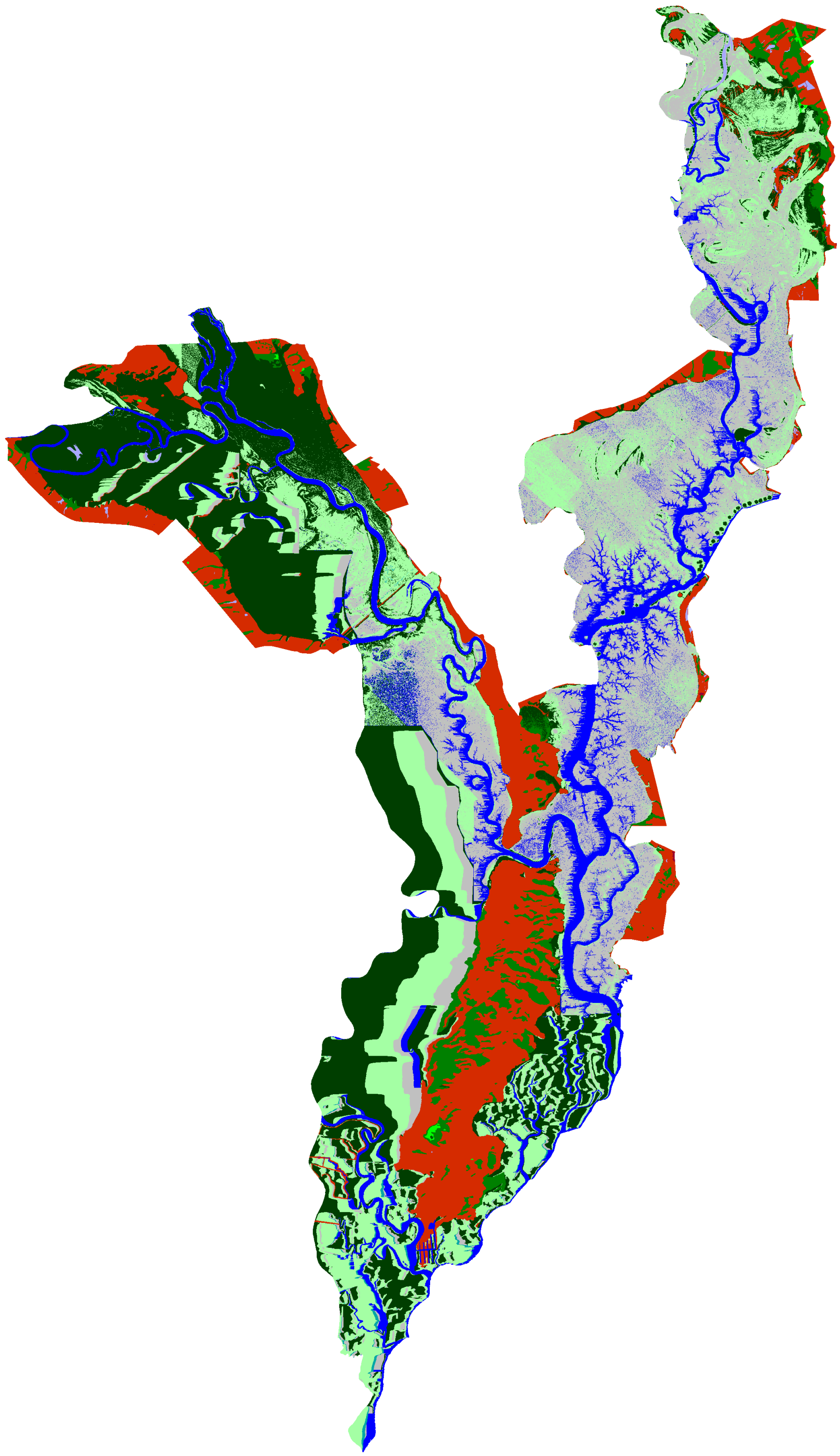
		Initial	2025	2050	2075	2100
	Tidal Swamp	38115	23412	13913	6439	3495
	Undeveloped Dry Land	9168	8997	8714	8356	8049
	Swamp	4313	2717	2042	1715	1558
	Riverine Tidal	3179	3156	1394	1157	749
	Tidal-fresh marsh	2756	17166	12509	9487	4170
	Inland Open Water	155	155	142	89	85
	Inland Fresh Marsh	107	67	48	41	36
	Developed Dry Land	11	11	11	11	10
	Cypress Swamp	4	4	4	4	4
	Tidal Flat	0	1766	13831	10213	7957
	Estuarine Open Water	0	184	5036	20139	31623
	Regularly Flooded Marsh	0	172	163	156	72
	Total (incl. water)	**57808**	**57808**	**57808**	**57808**	**57808**



Waccamaw NWR, SLAMM 2006.



Waccamaw NWR, 2025, 2 m SLR by 2100.



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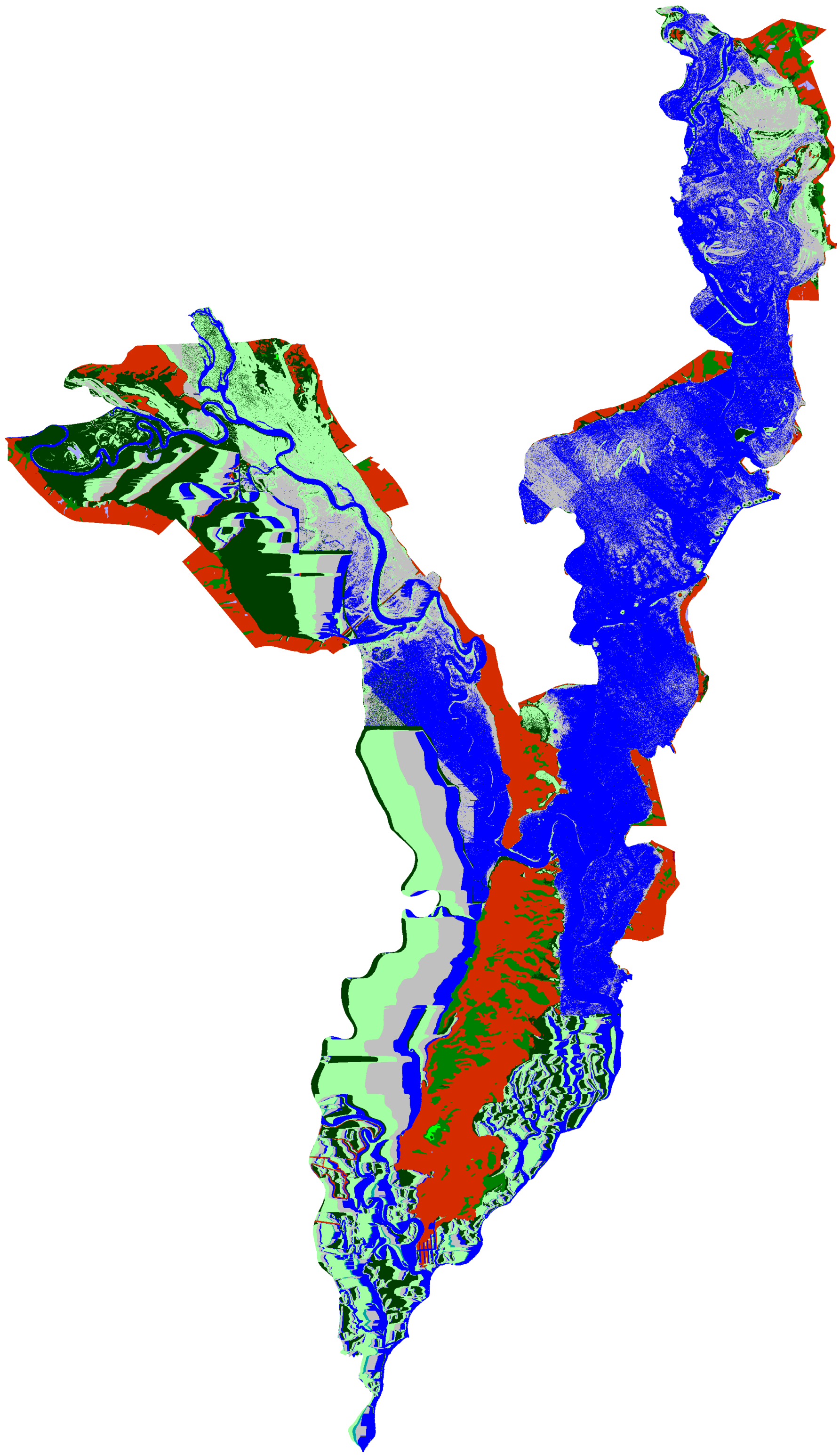
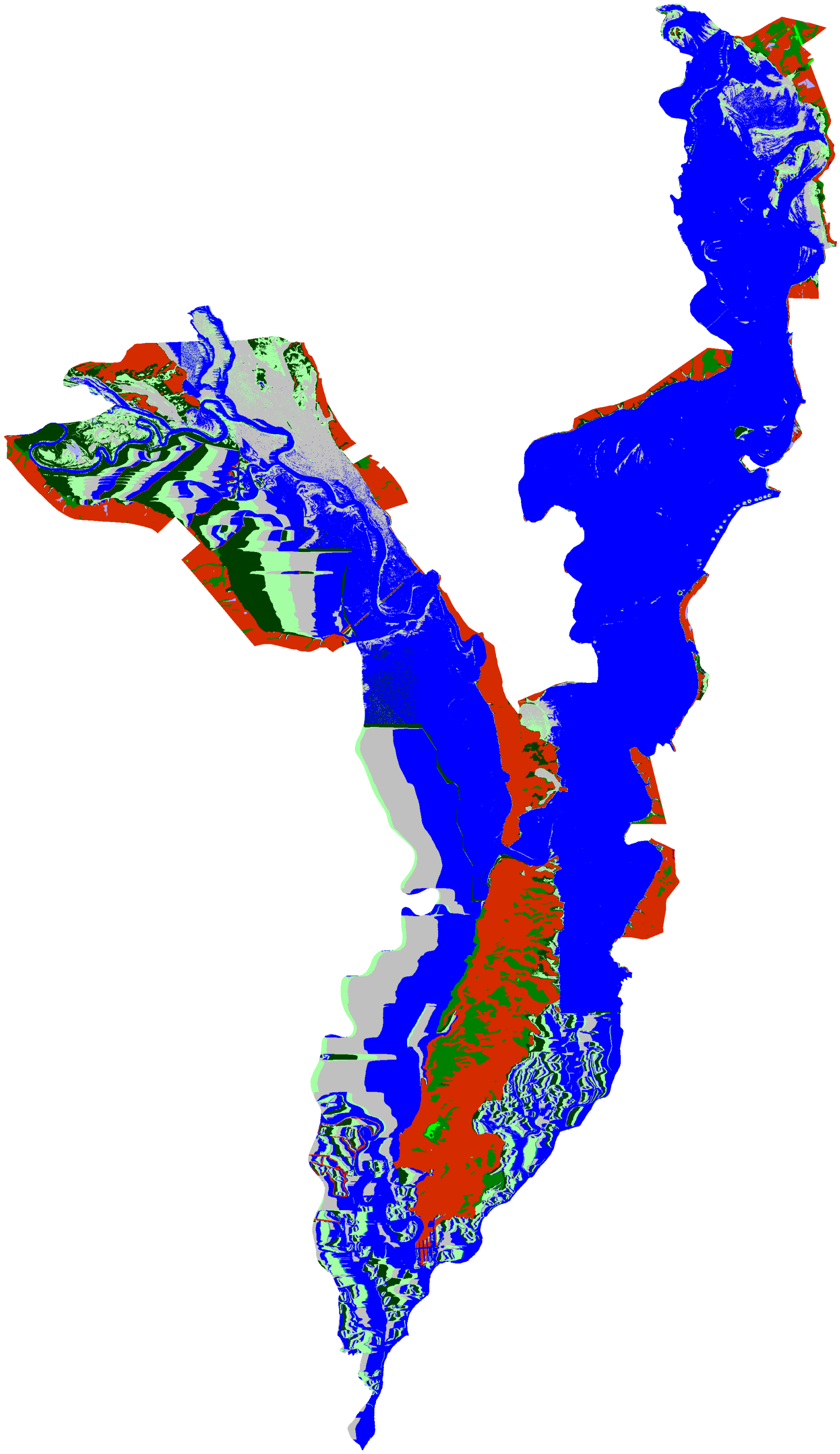


Waccamaw NWR, 2075, 2 m SLR by 2100.



Waccamaw NWR, 2100, 2 m SLR by 2100.

Discussion

SLAMM predictions suggest Waccamaw NWR will be vulnerable to accelerated SLR. The refuge is primarily composed of tidal swamp, which is predicted to be lost at increasing rates as predicted rates of accelerated SLR increase. Even under the lowest SLR scenario examined, SLAMM predicts a potential loss of the wetland-habitat richness currently covering the refuge.

Although elevation data quality has improved, the entire refuge still lacks LiDAR-derived elevation data. This lack of high-resolution data increases the uncertainty in model predictions, not only for those areas not covered by LiDAR, but also affects predictions in adjacent wetlands due to potentially mischaracterized hydraulic conductivity. Compared to the previous SLAMM analysis of the refuge conducted in 2008, overall wetlands appear less resilient to accelerated SLR than previously estimated.

These simulations suggest that tidal swamps and tidal-fresh marshes will be subject to more frequent inundation as a function of ocean levels rising. This is assumed to cause an increase in marsh and swamp pore water salinity which will ultimately drive habitat succession. A more precise estimate of tidal-swamp salinity under increasing SLR would require hydrodynamic salinity modeling including projected SLR increases and also an accounting for differences in projected fresh-water flows over the next 90 years. Such an analysis was beyond the scope of the current modeling project.

While data-layer updates have considerably improved the SLAMM projections reported here, input layers, parameter inputs (as mentioned above), and the conceptual model continue to have uncertainties that should be kept in mind when interpreting these results. Perhaps most importantly, the extent of future sea-level rise is unknown, as are the drivers of climate change used by scientists when projecting SLR rates. Future levels of economic activity, fuel type (e.g., fossil or renewable, etc.), fuel consumption, and greenhouse gas emissions are unknown and estimates of these driving variables are speculative. To account for these uncertainties, results presented here investigated effects for a wide range of possible sea level rise scenarios, from a more conservative rise (0.39 m by 2100) to a more accelerated process (2 m by 2100). To better support managers and decision-makers, the results presented here could be studied as a function of input-data uncertainty to provide a range of possible outcomes and their likelihood.

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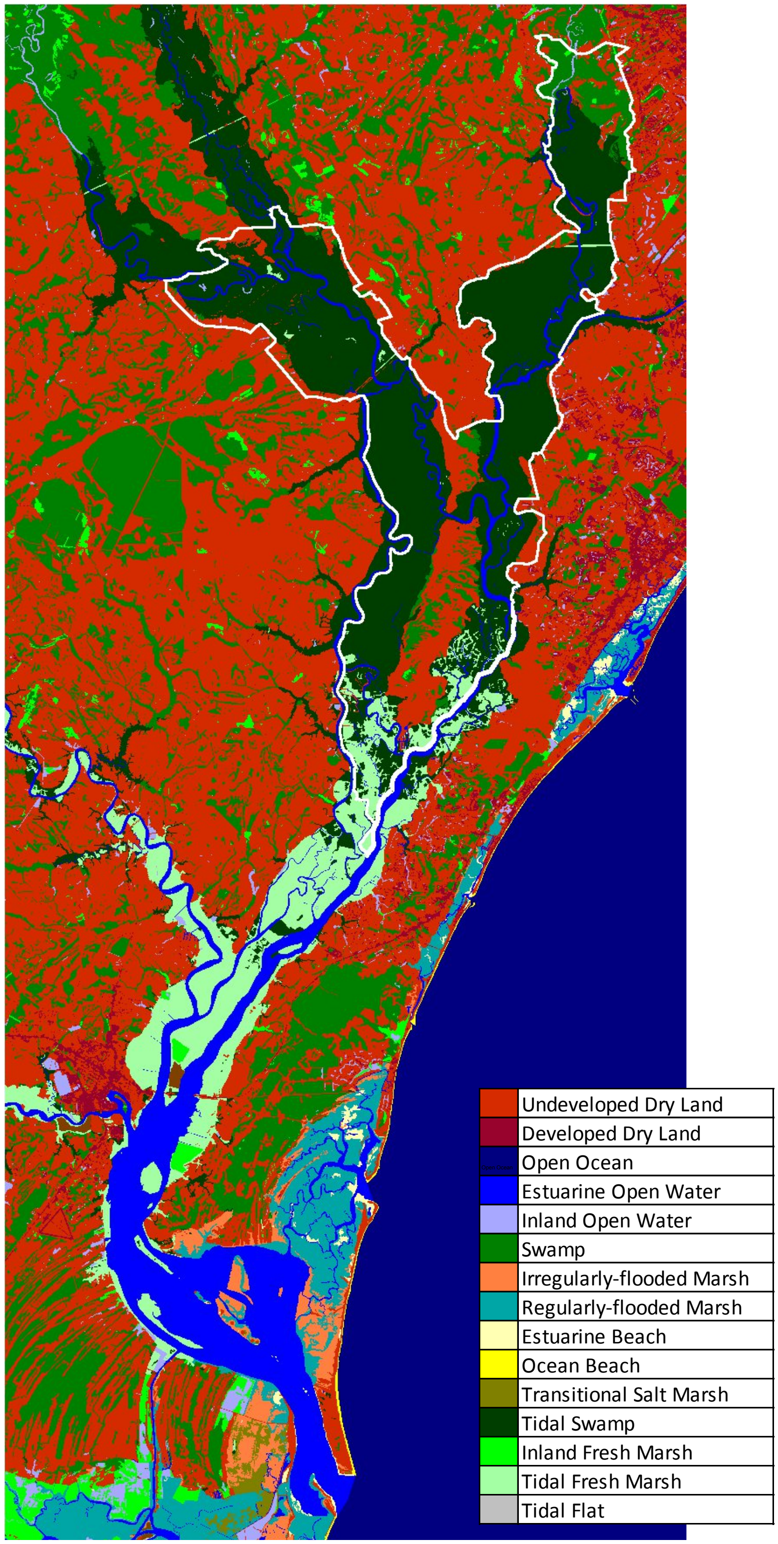
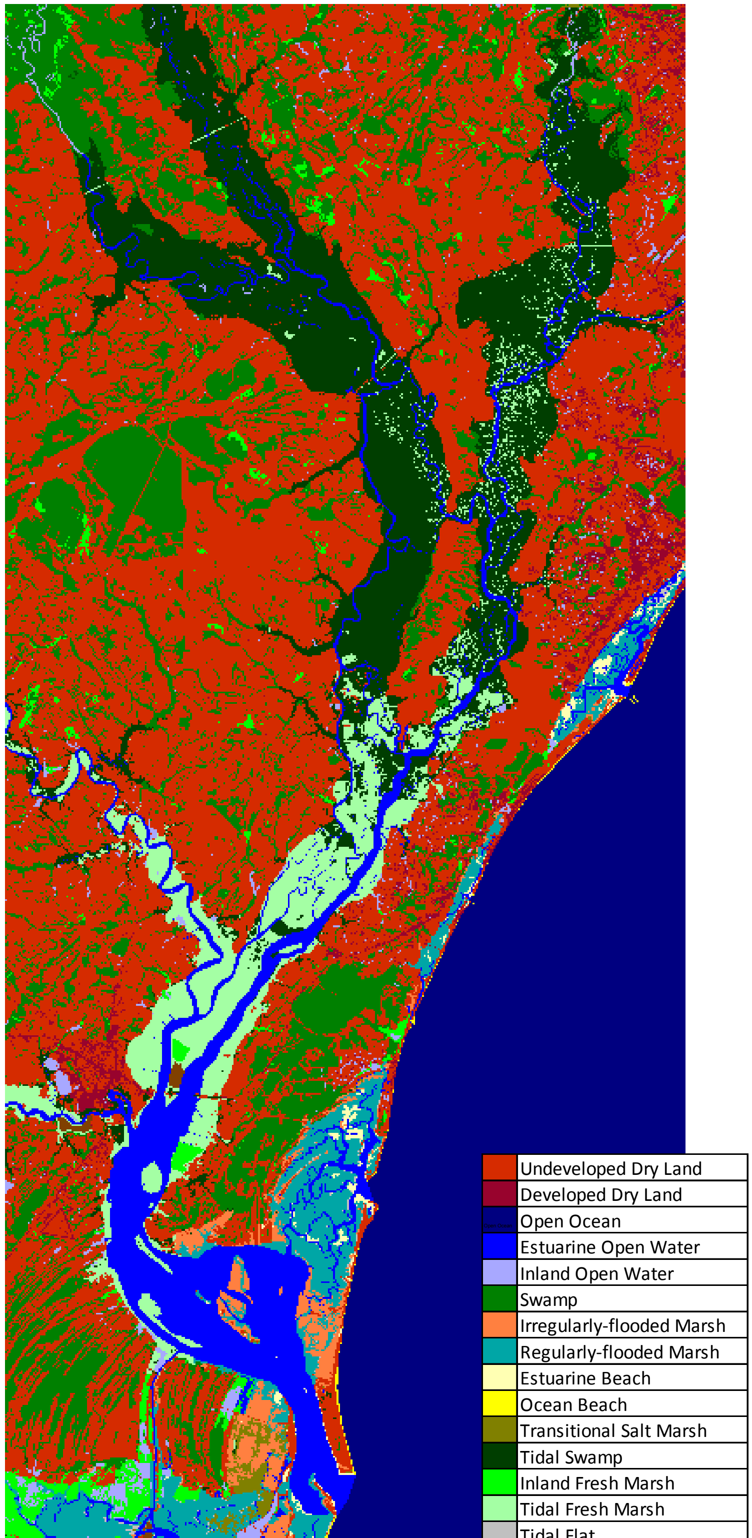
Appendix A: Contextual Results

The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated dry lands will convert to marshes or ocean beach depending on their proximity to open ocean. Therefore, an area larger than the boundaries of the USFWS refuge was modeled. Maps of these results are presented here with the following caveats:

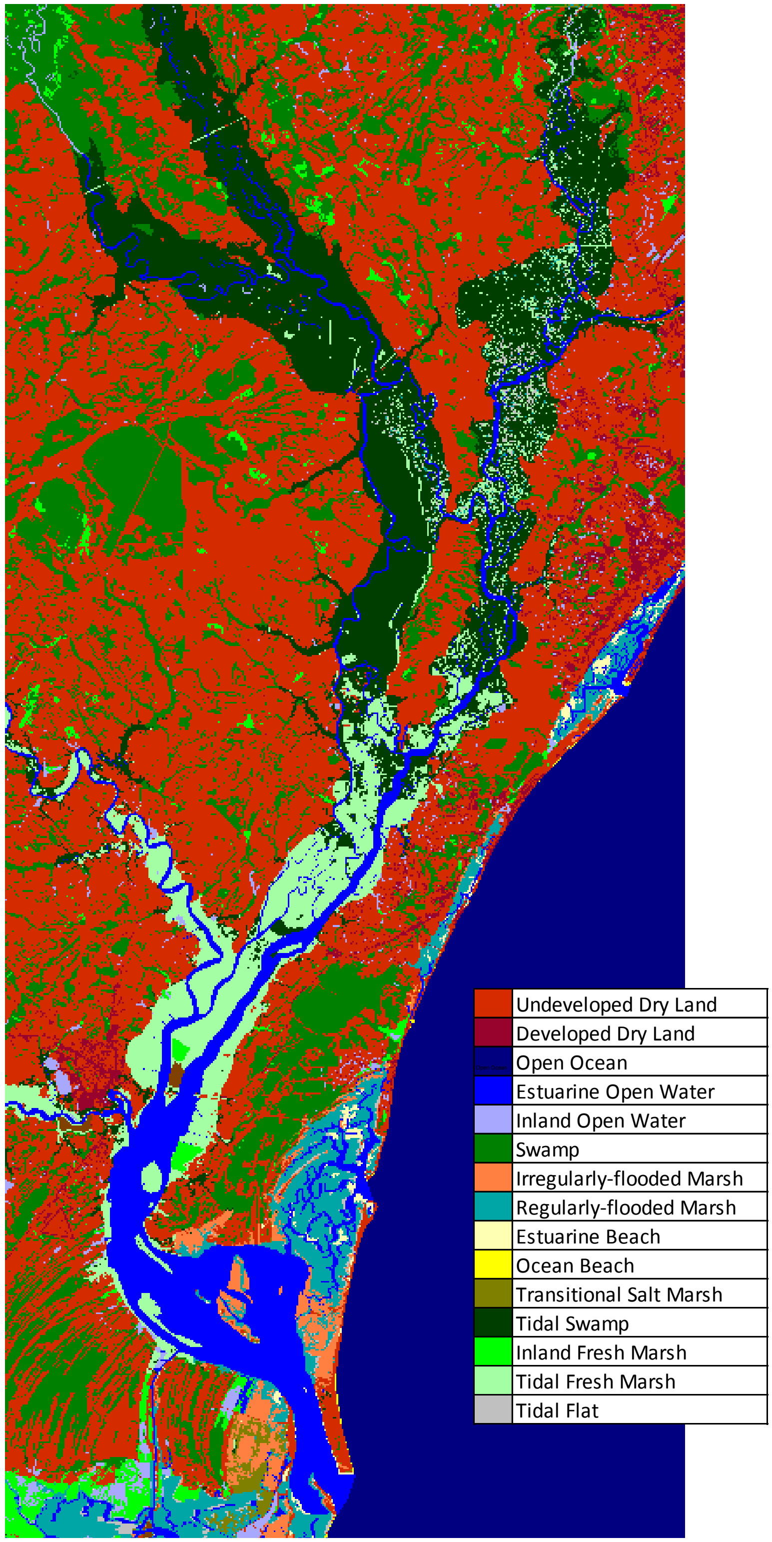
- Results were critically examined within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort was made to assess the probable location and effects of dikes for USFWS refuges, but this effort was not made for surrounding areas.



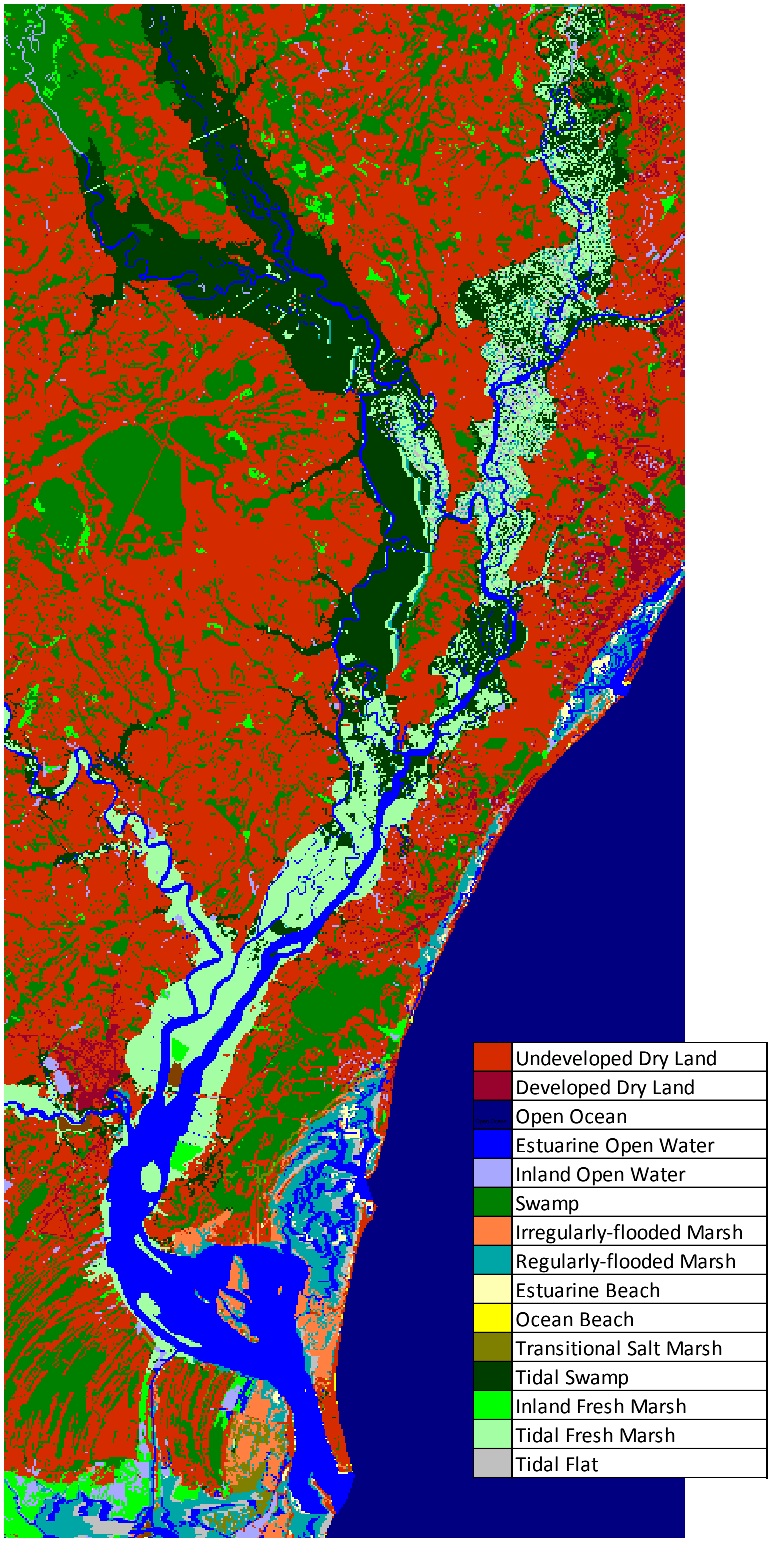
Waccamaw National Wildlife Refuge within simulation context (white).



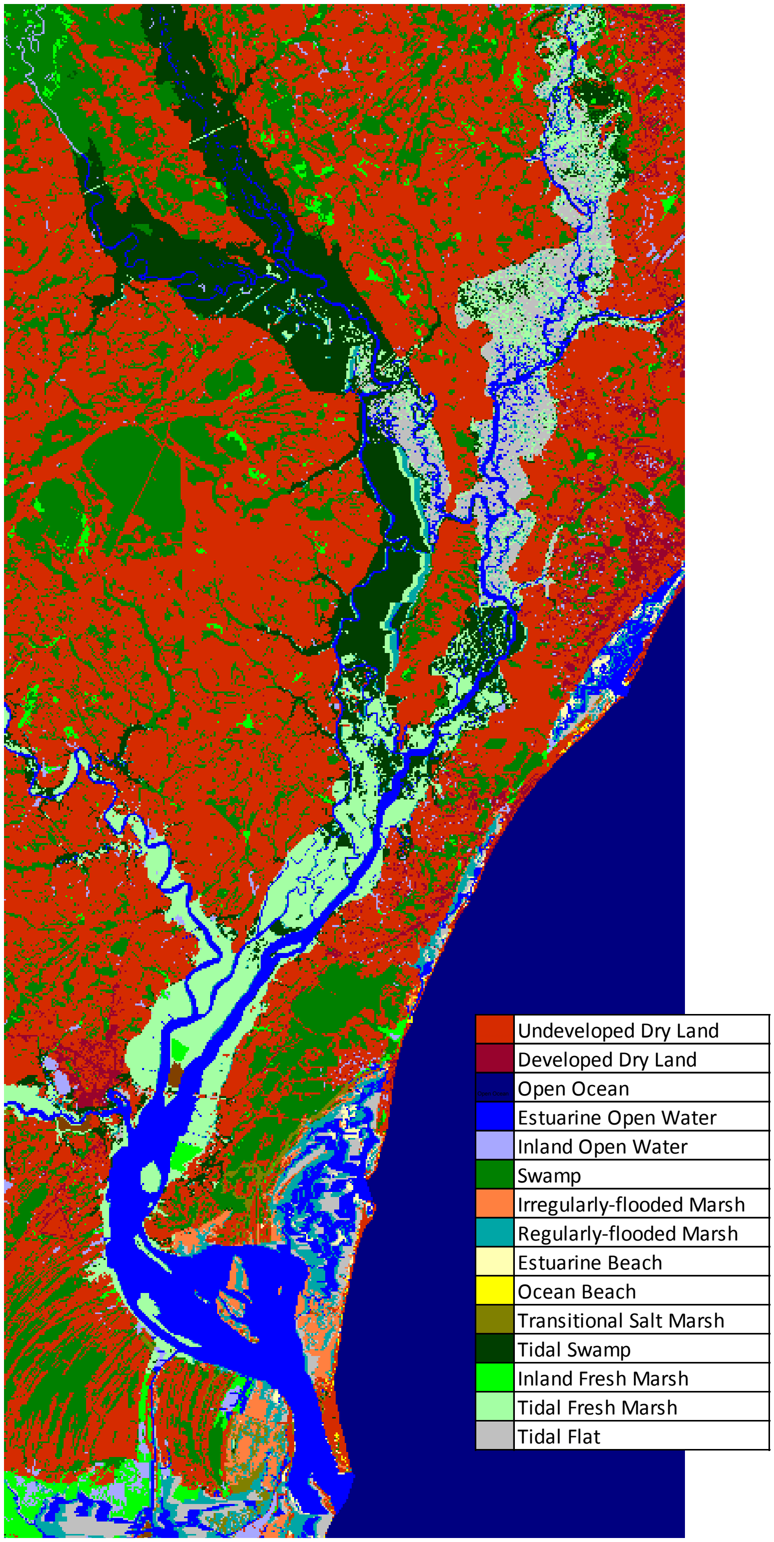
Waccamaw NWR, SLAMM 2006.



Waccamaw NWR, 2025, Scenario A1B Mean, 0.39 m SLR by 2100.



Waccamaw NWR, 2050, Scenario A1B Mean, 0.39 m SLR by 2100.



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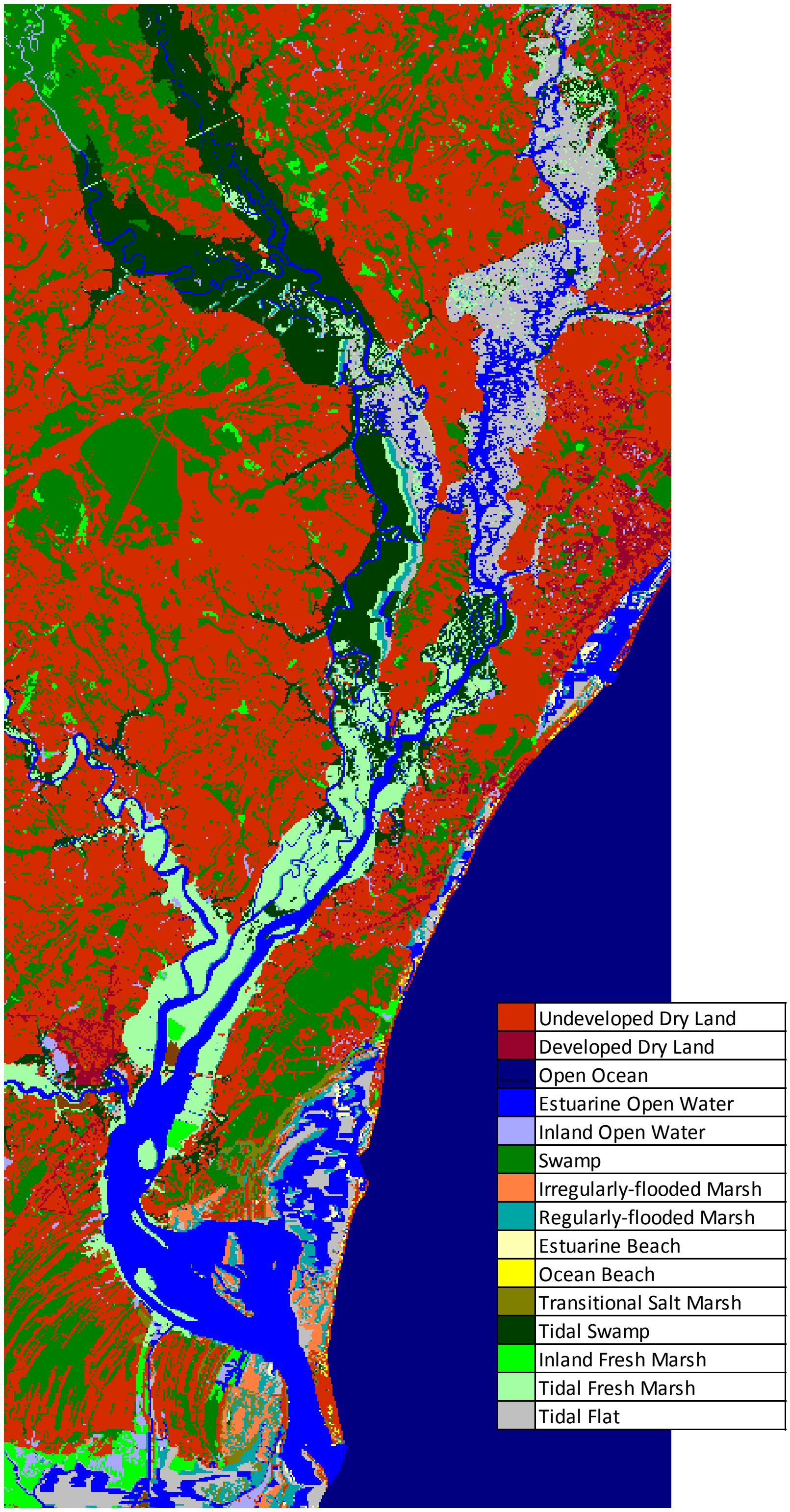
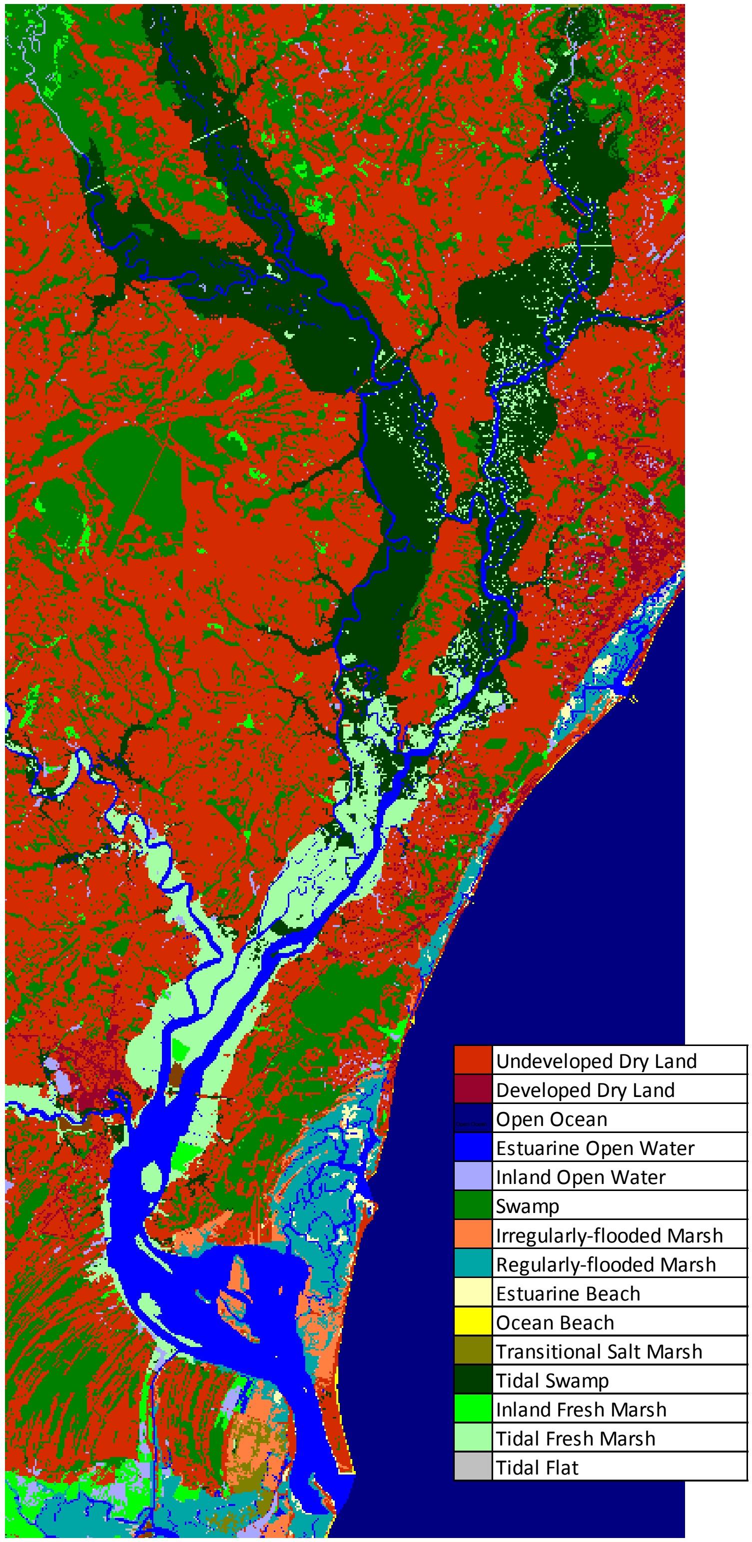
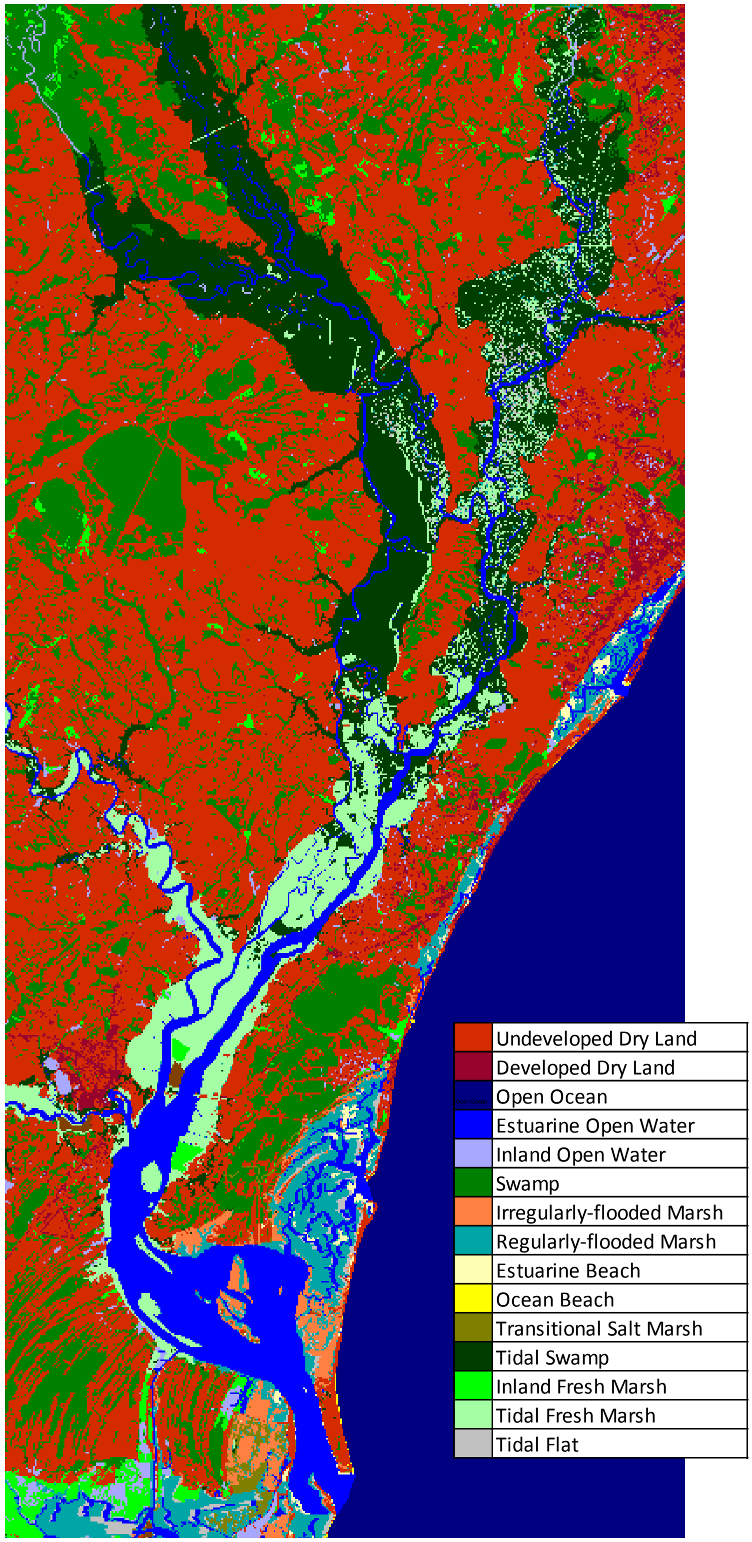


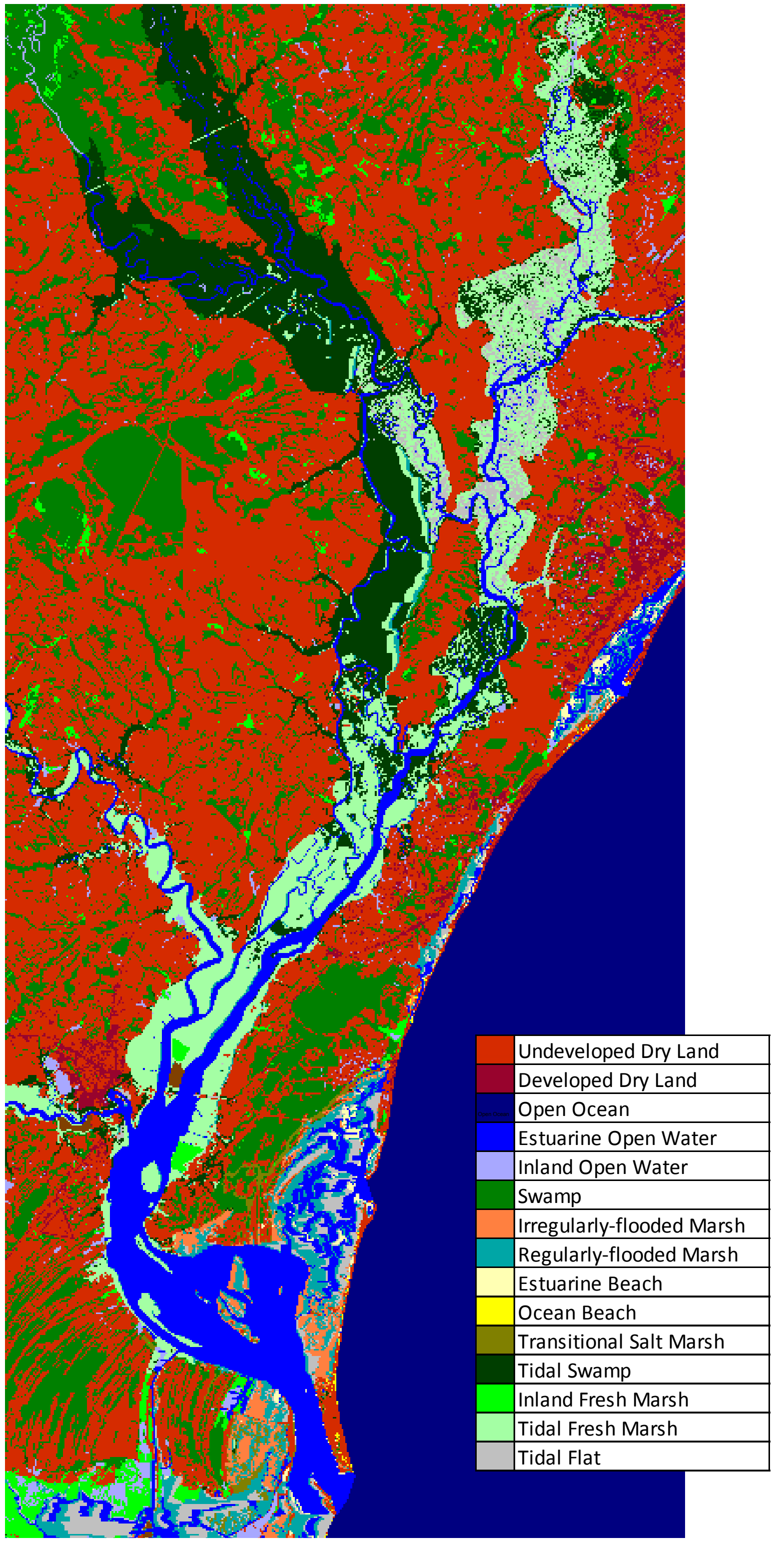
Waccamaw NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.



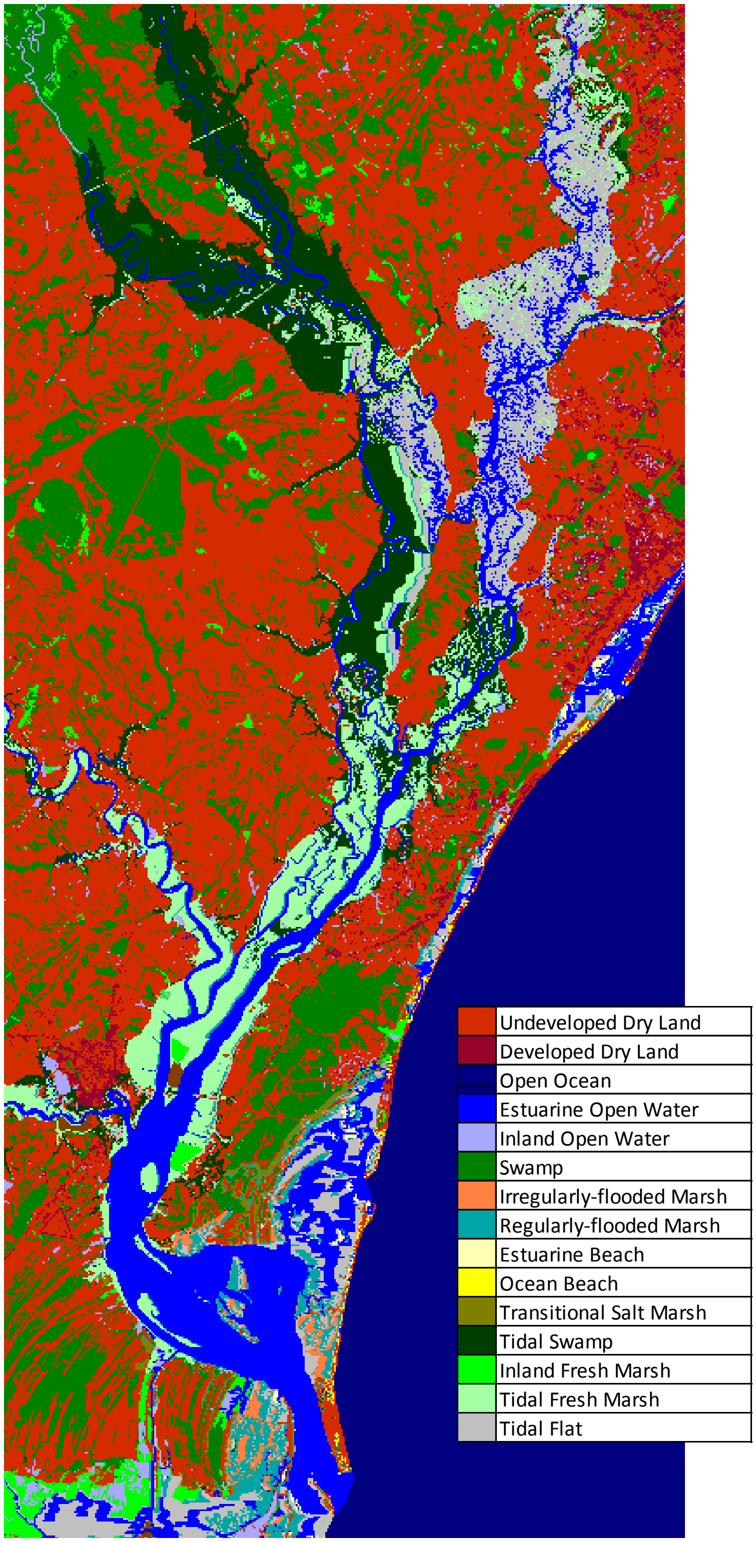
Waccamaw NWR, SLAMM 2006.



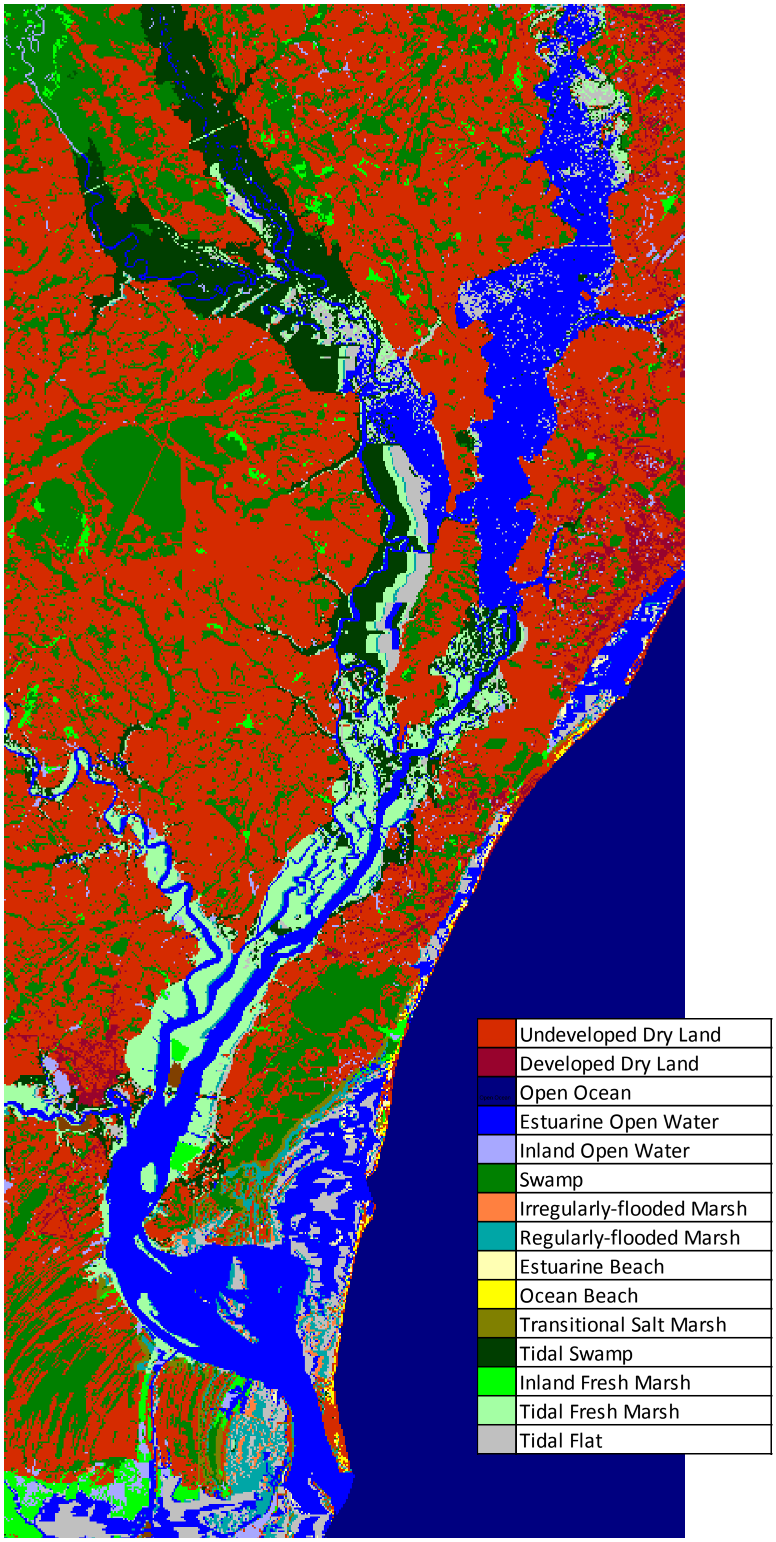
Waccamaw NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



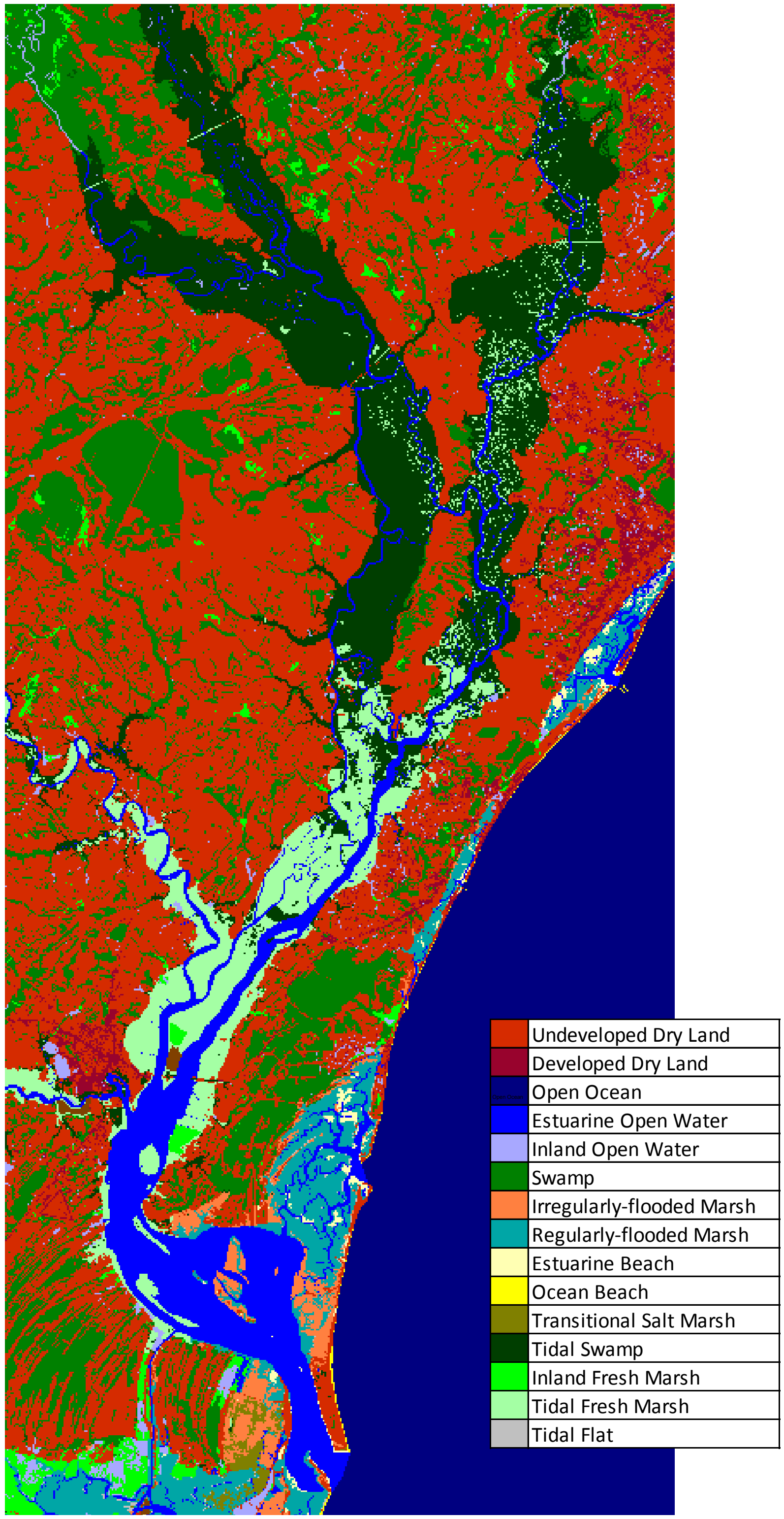
Waccamaw NWR, 2050, Scenario A1B Maximum, 0.69 m SLR by 2100.



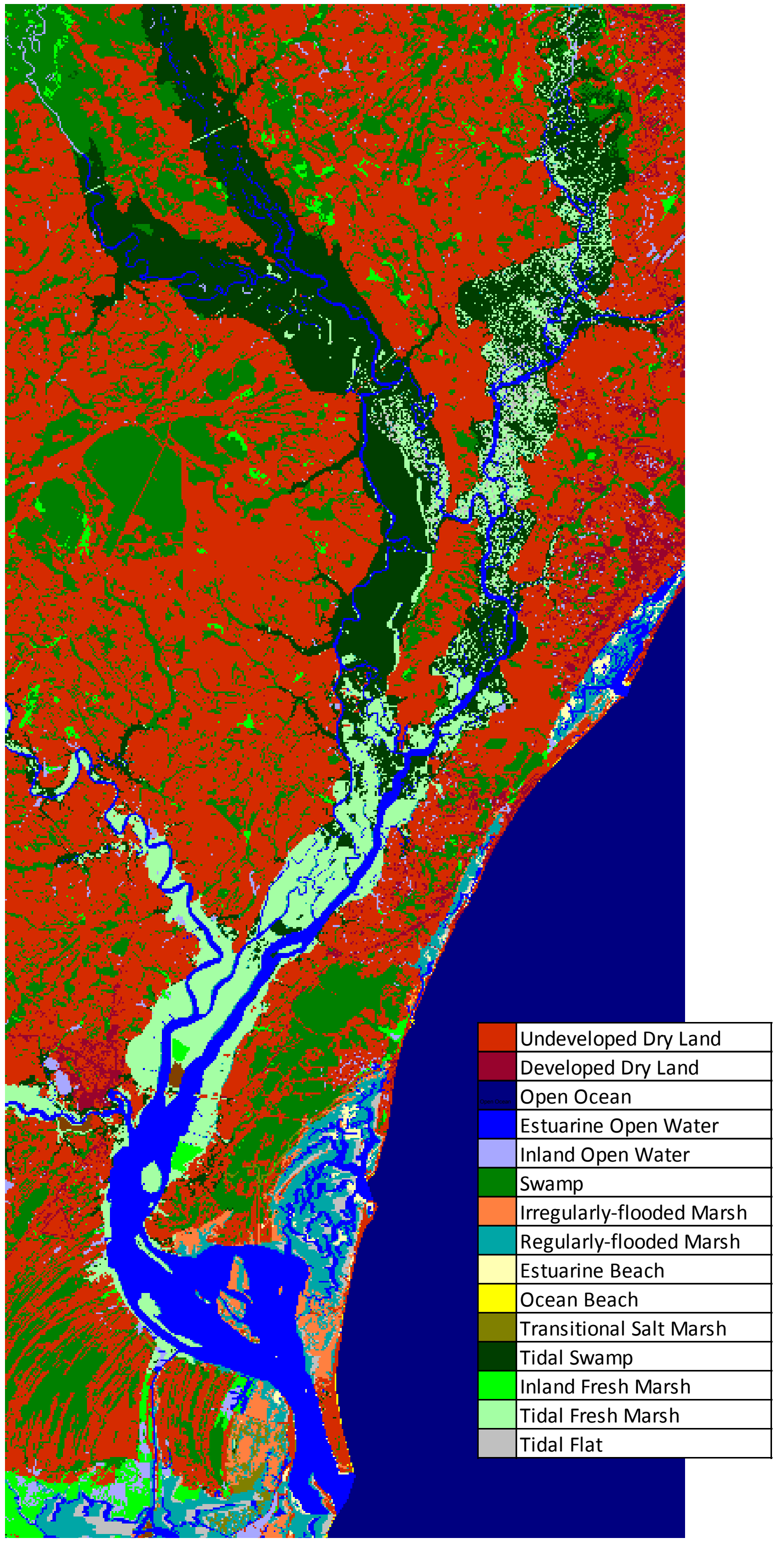
Waccamaw NWR, 2075, Scenario A1B Maximum 0.69 m SLR by 2100.



Waccamaw NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.



Waccamaw NWR, SLAMM 2006.



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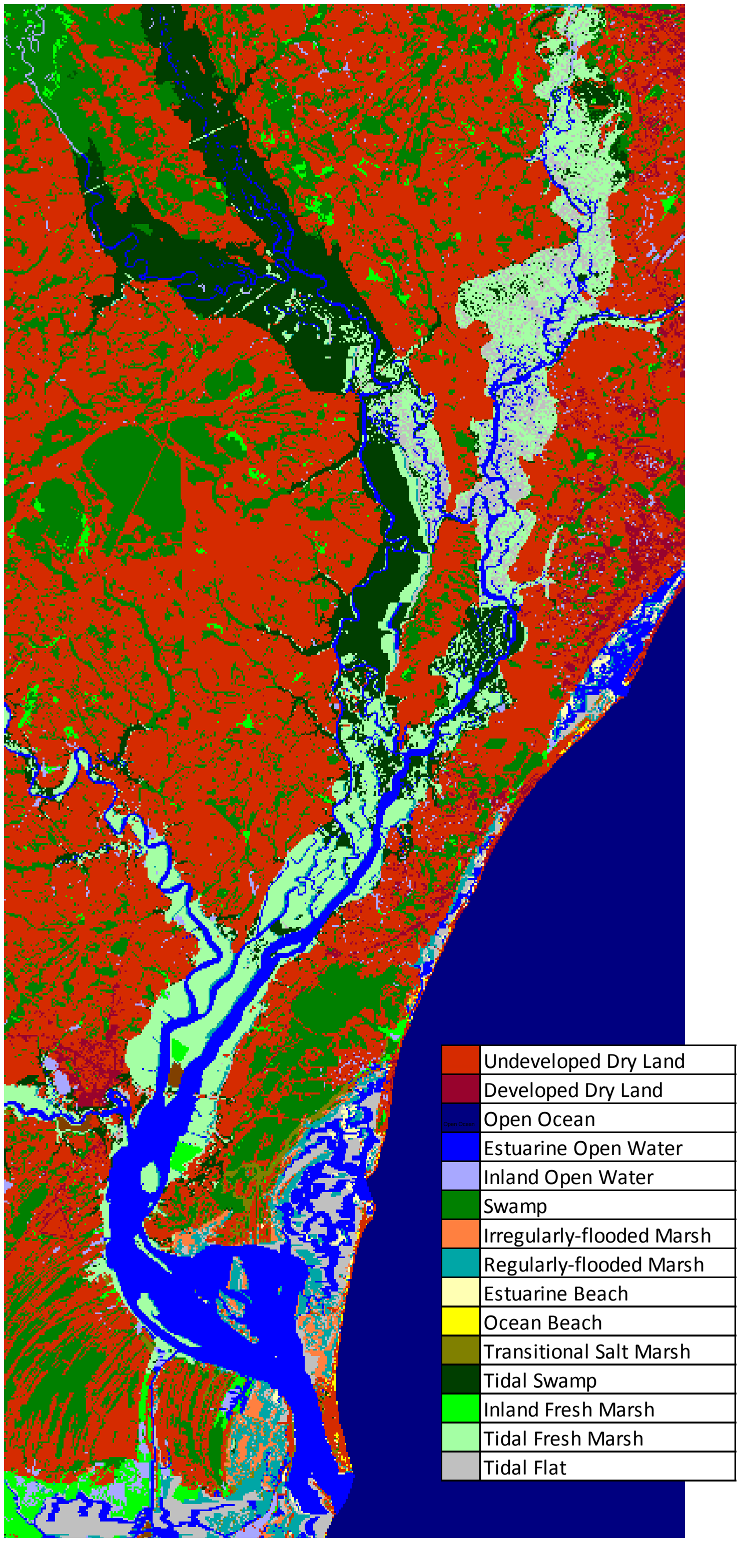

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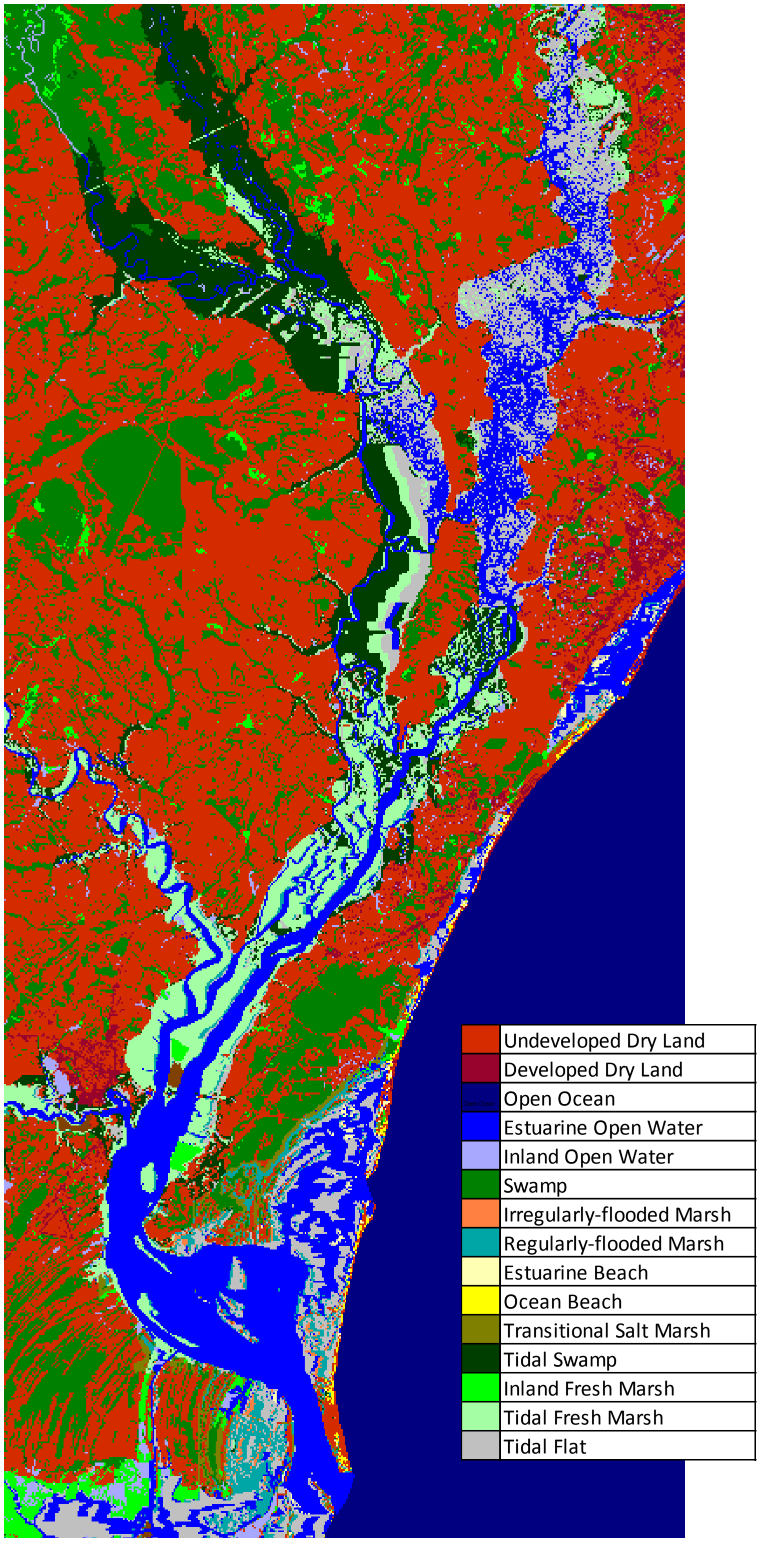

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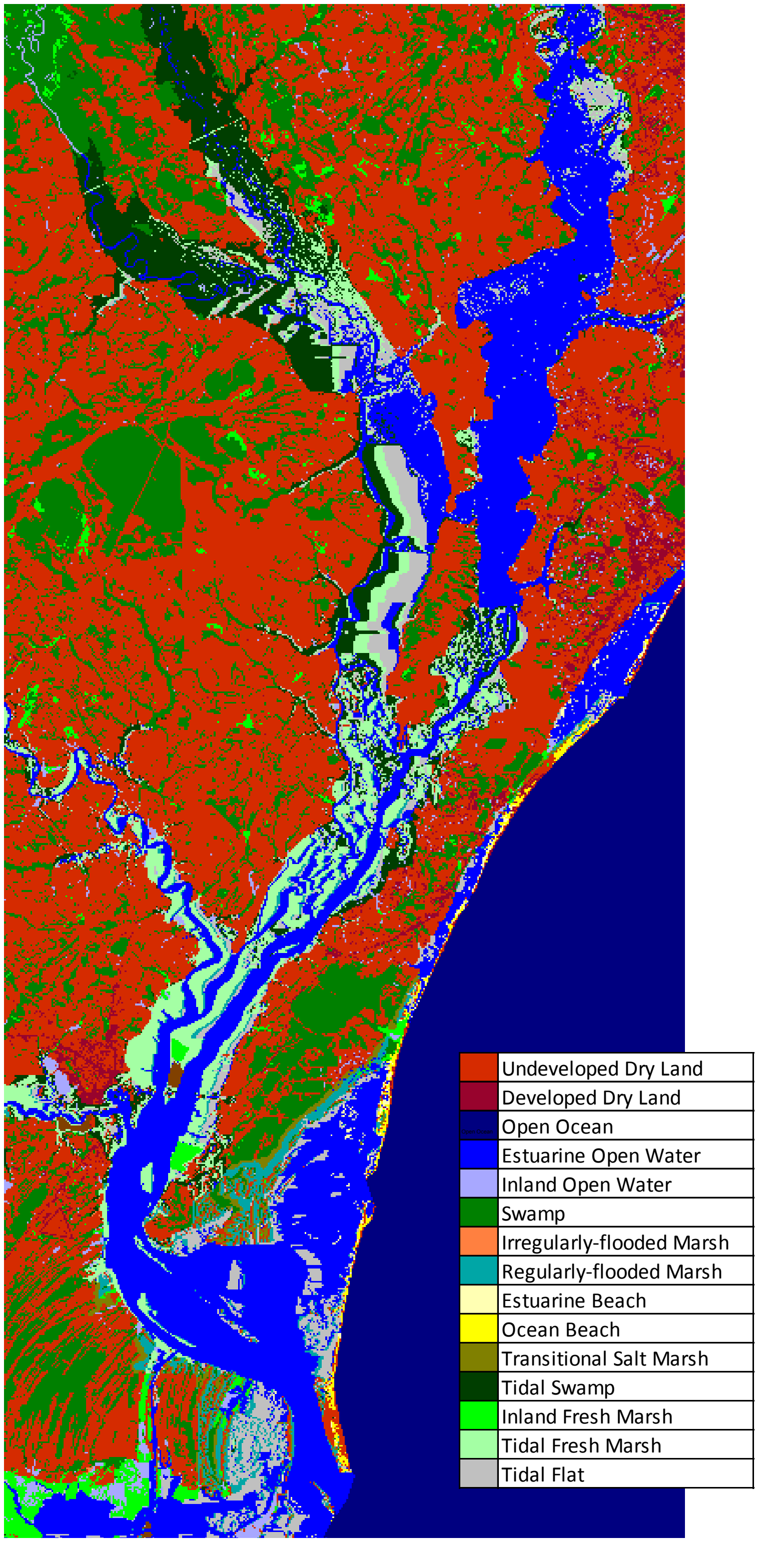

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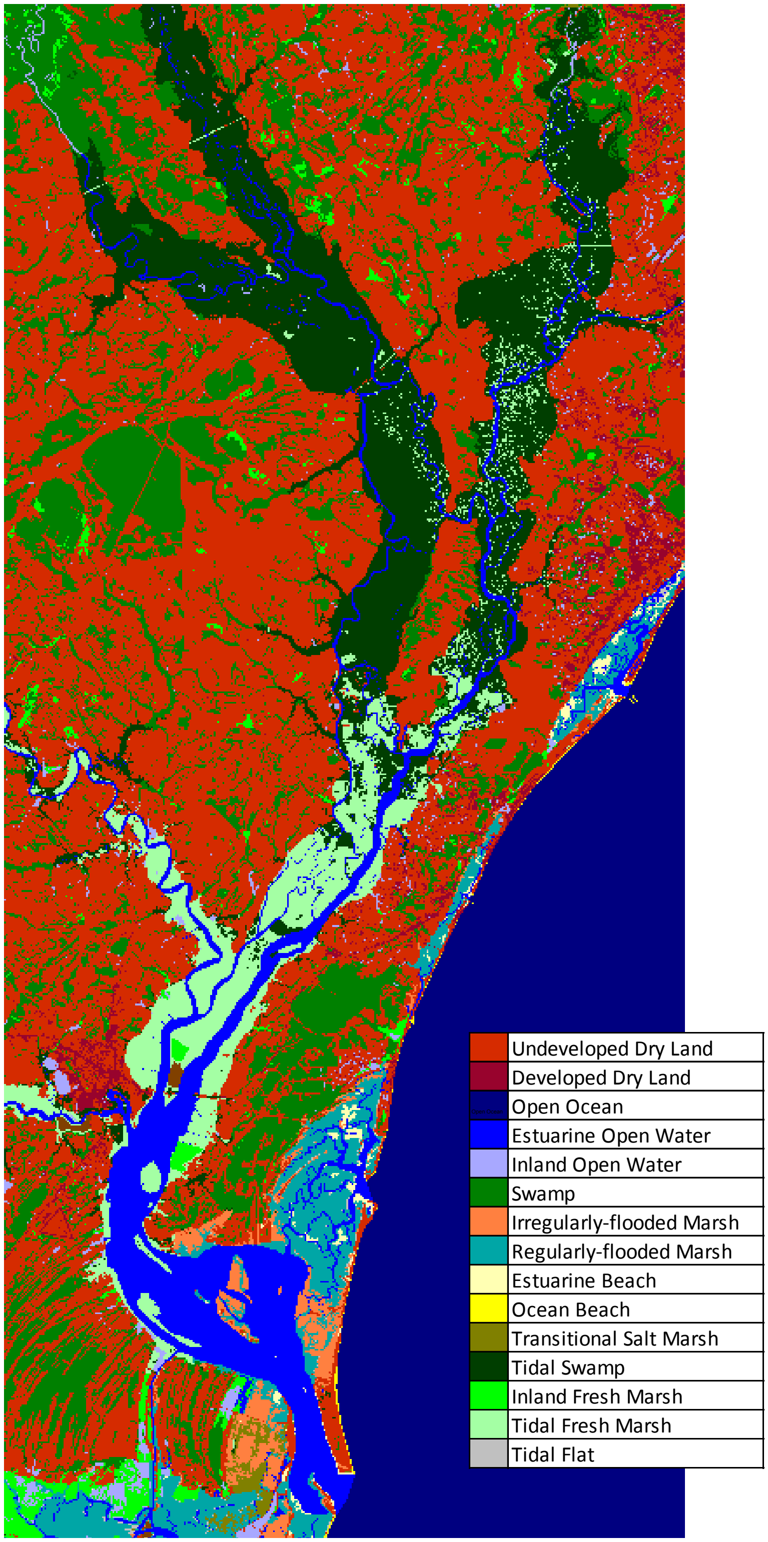
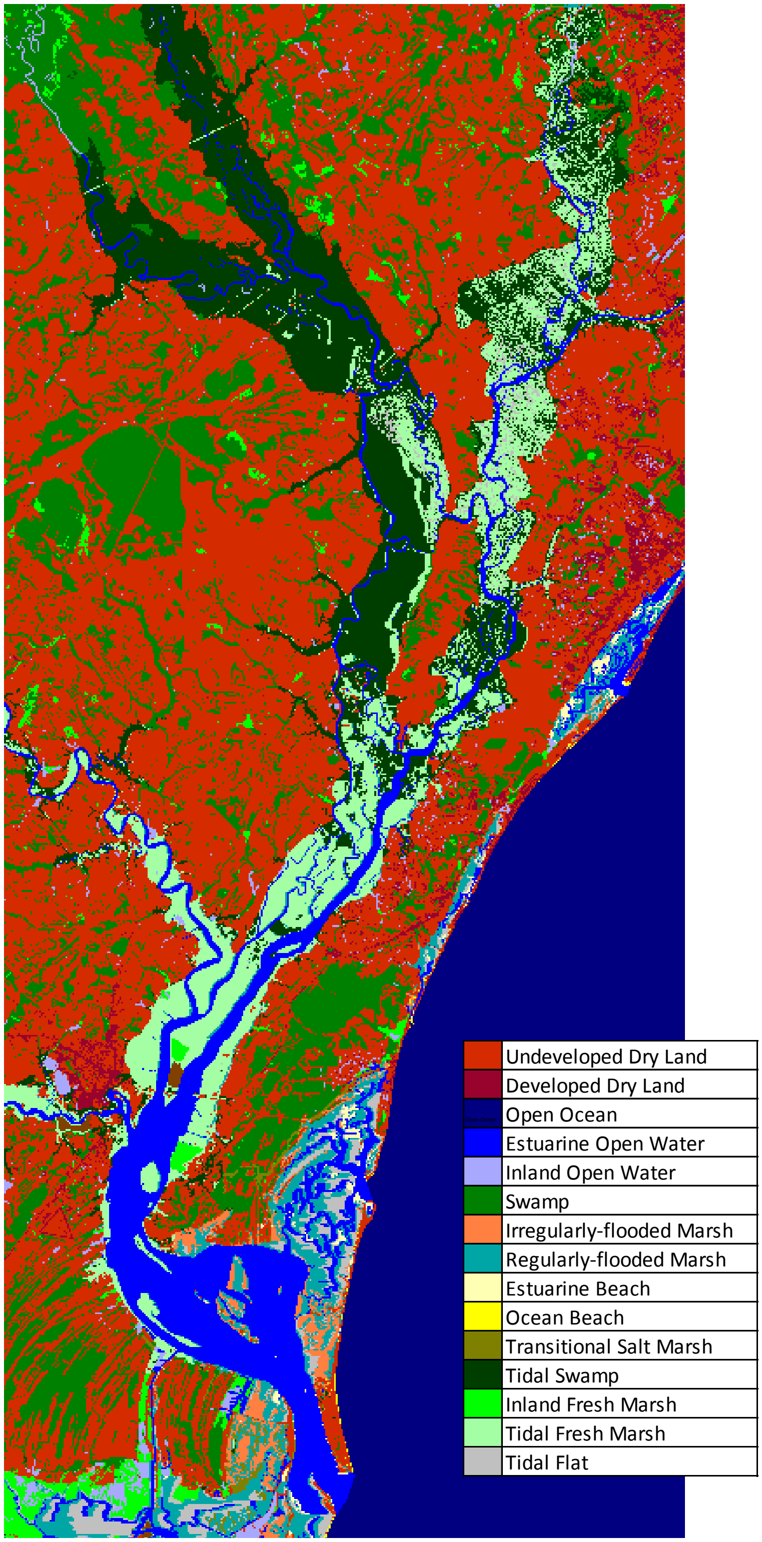
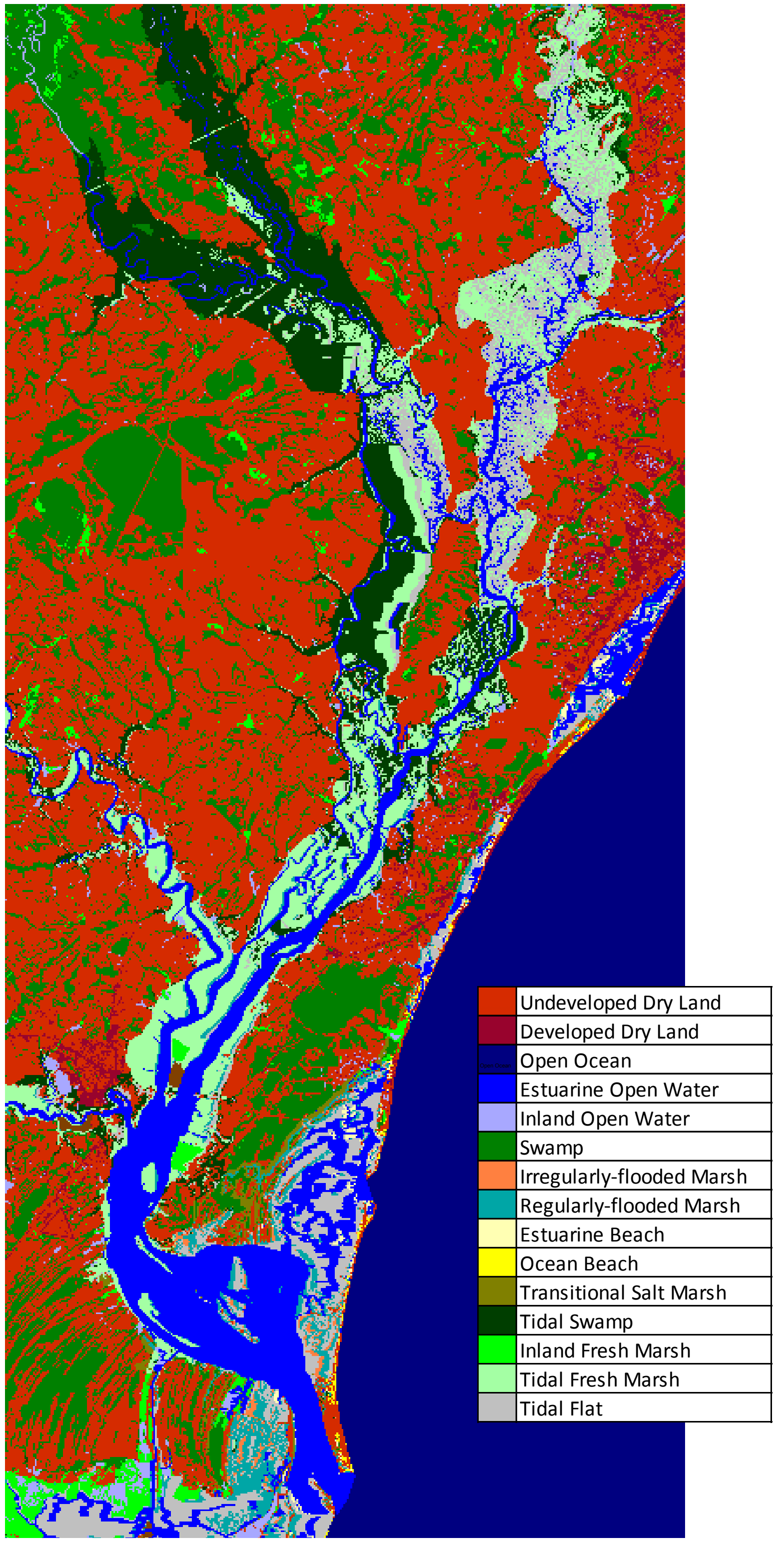


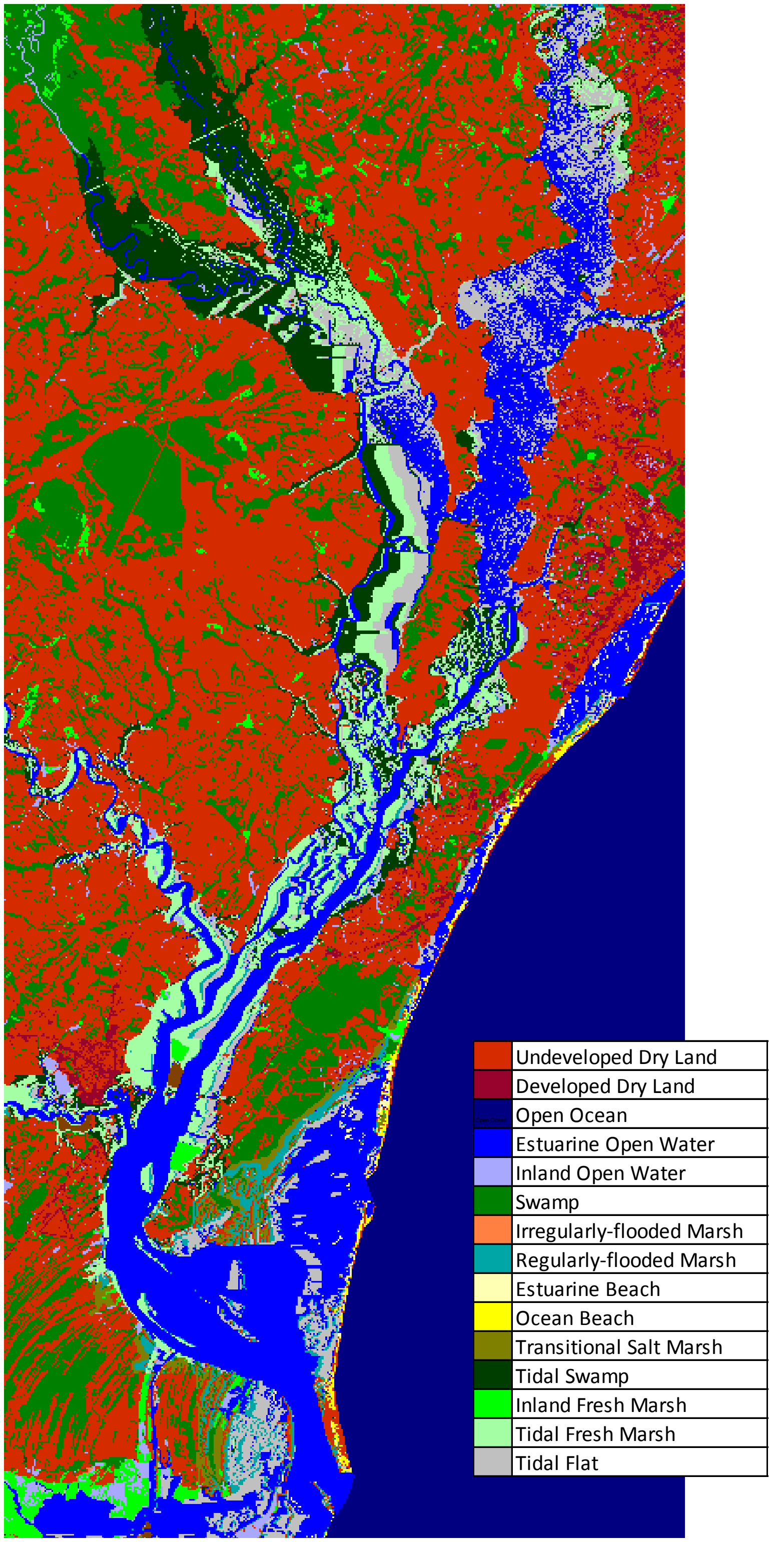
Waccamaw NWR, SLAMM 2006.



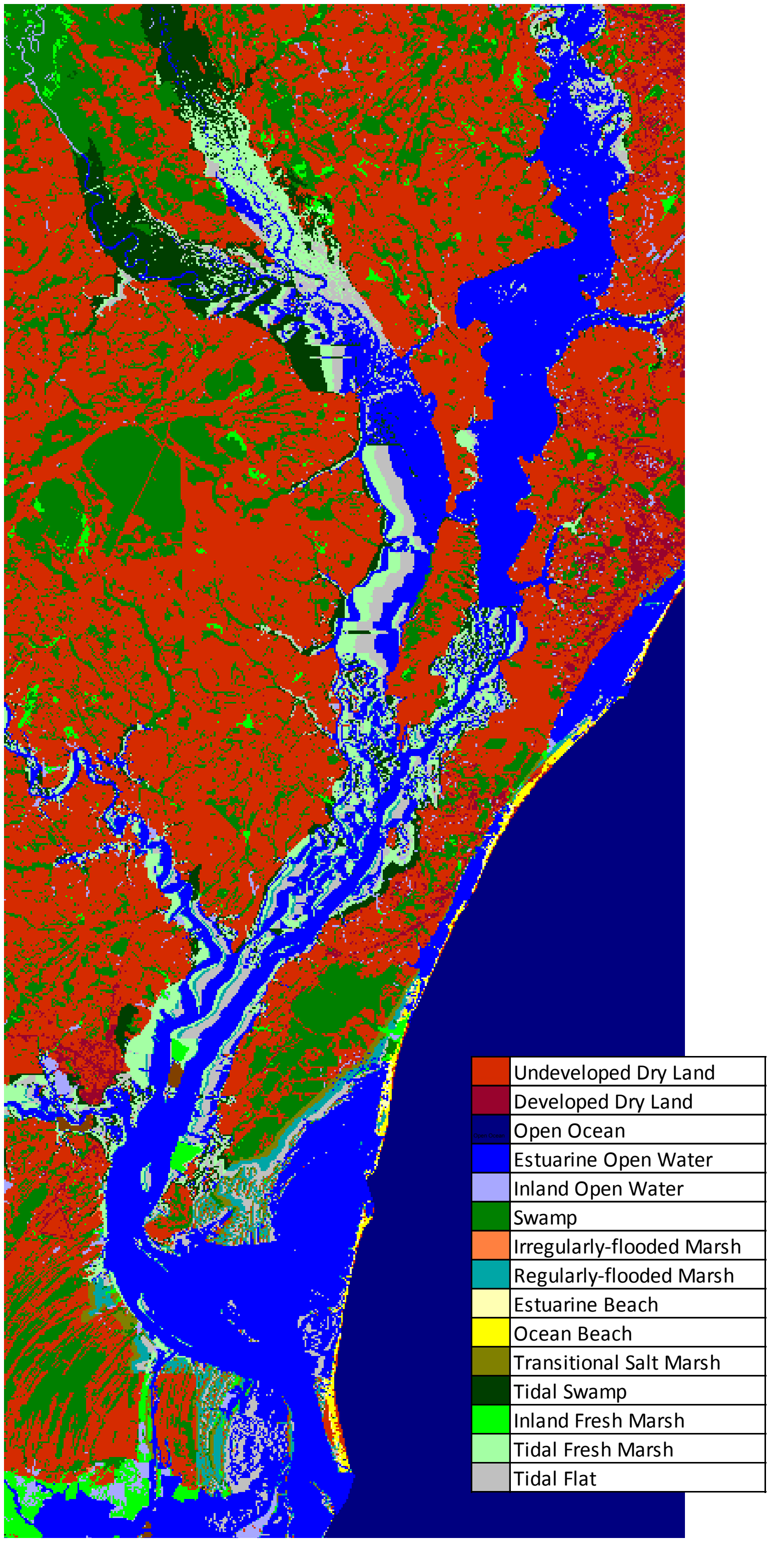
Waccamaw NWR, 2025, 1.5 m SLR by 2100.



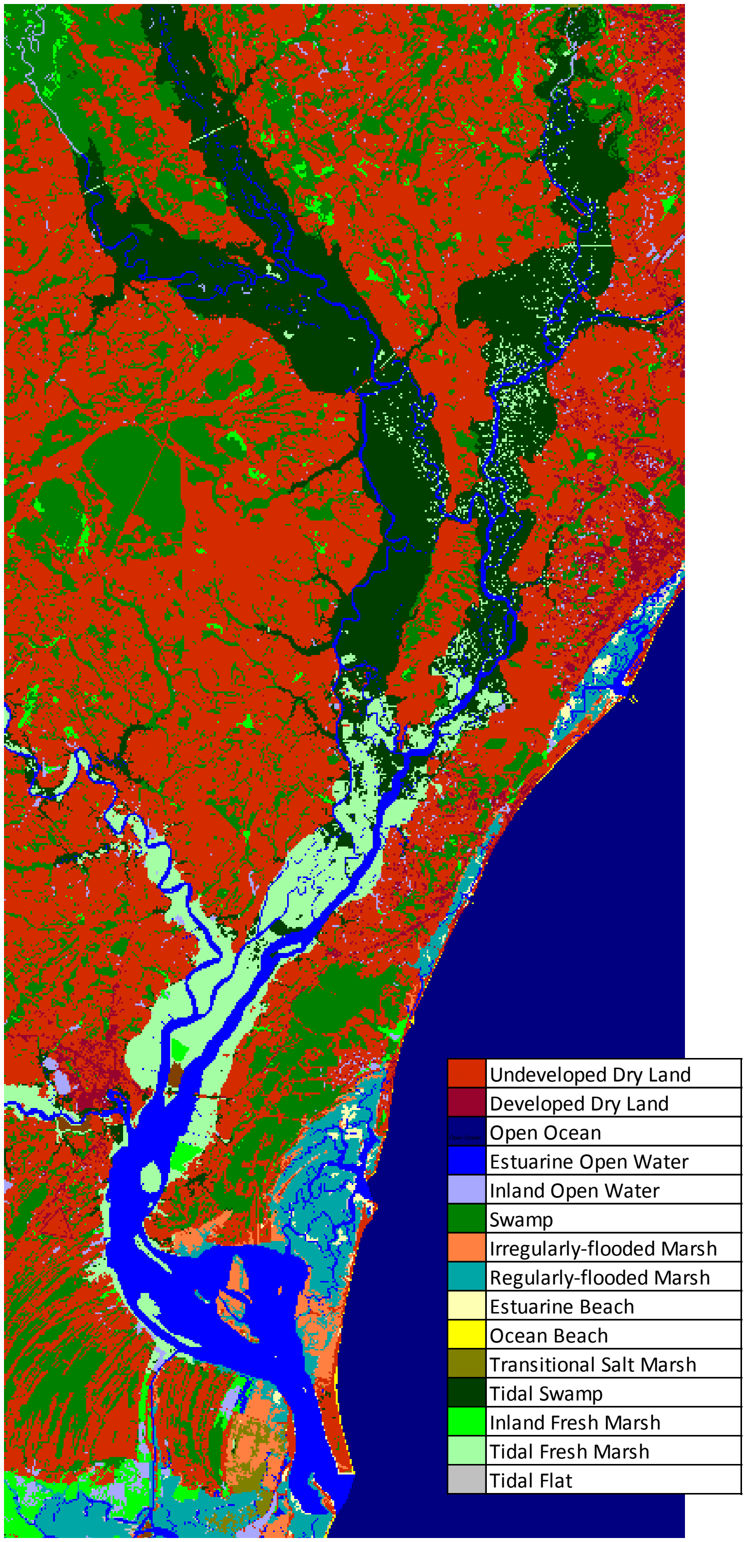
Waccamaw NWR, 2050, 1.5 m SLR by 2100.



Waccamaw NWR, 2075, 1.5 m SLR by 2100.



Waccamaw NWR, 2100, 1.5 m SLR by 2100.



Waccamaw NWR, SLAMM 2006.

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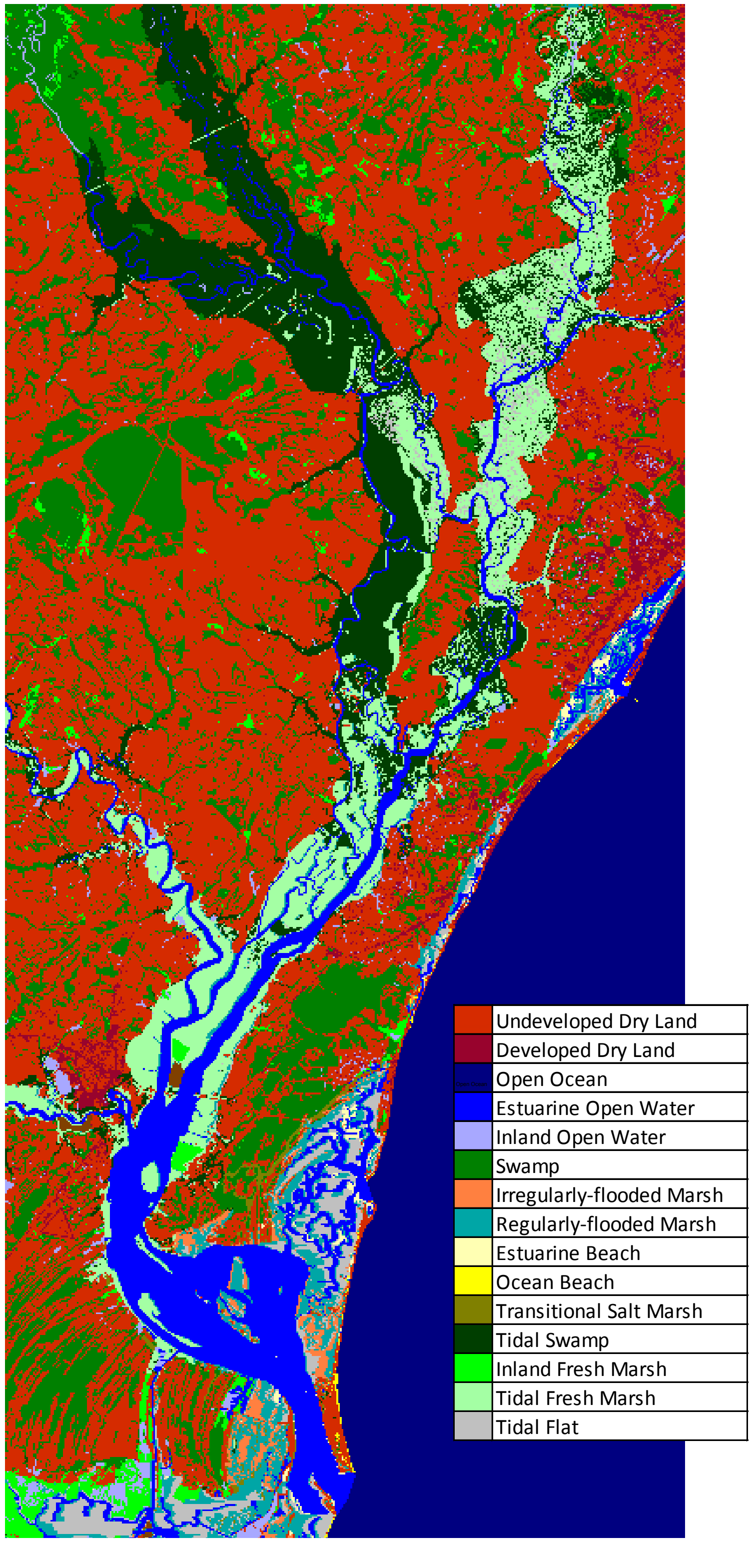
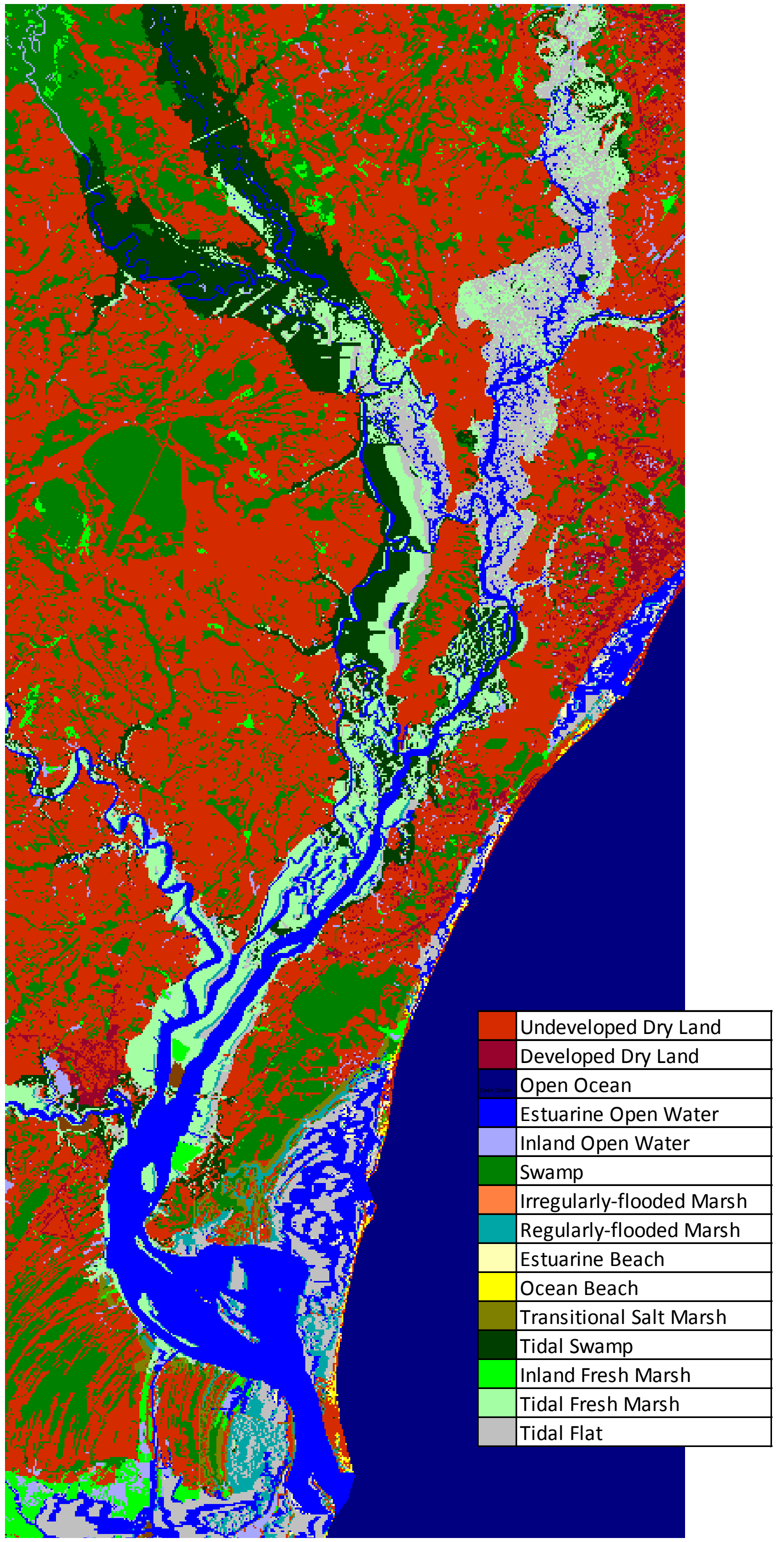
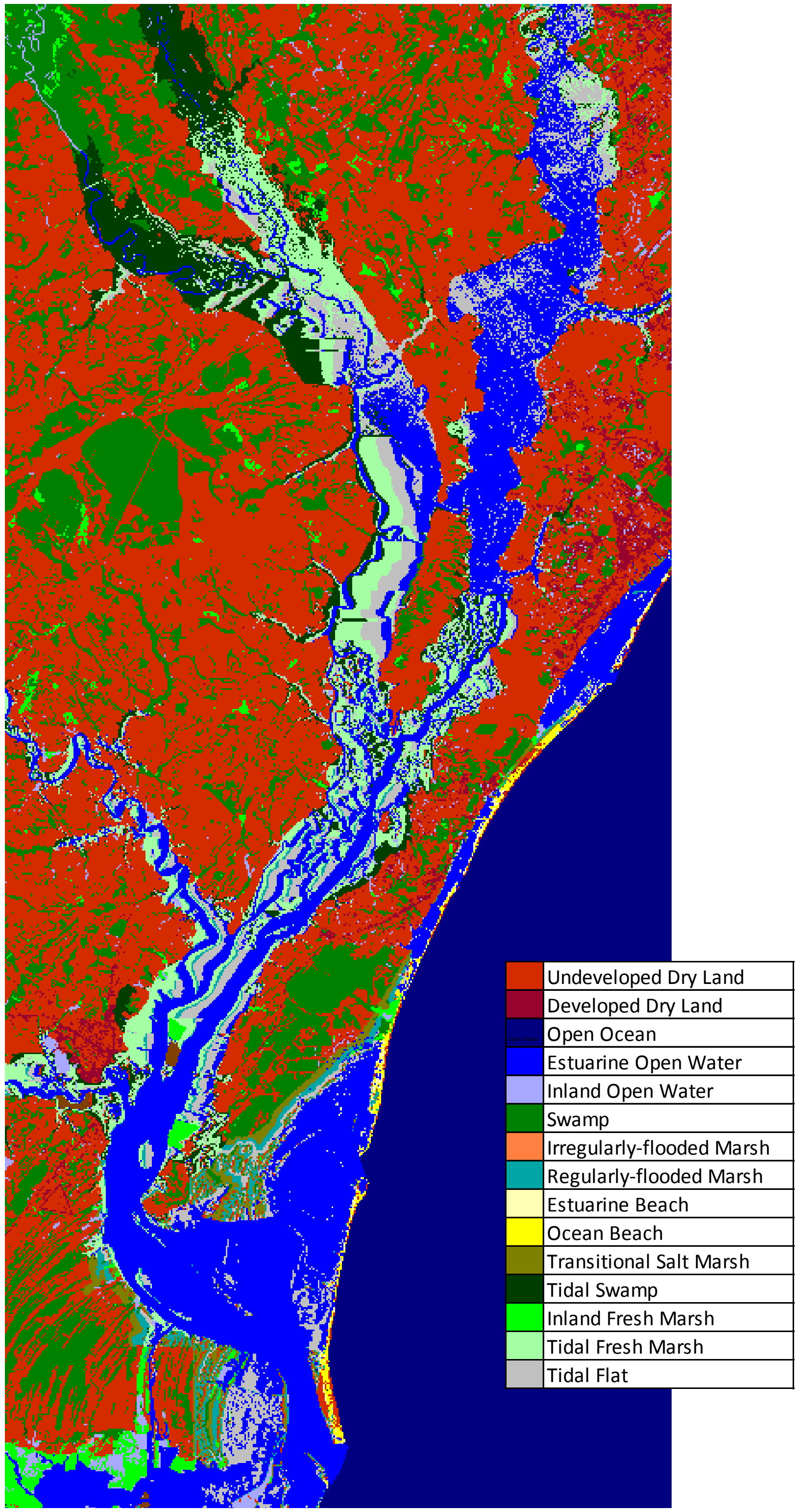


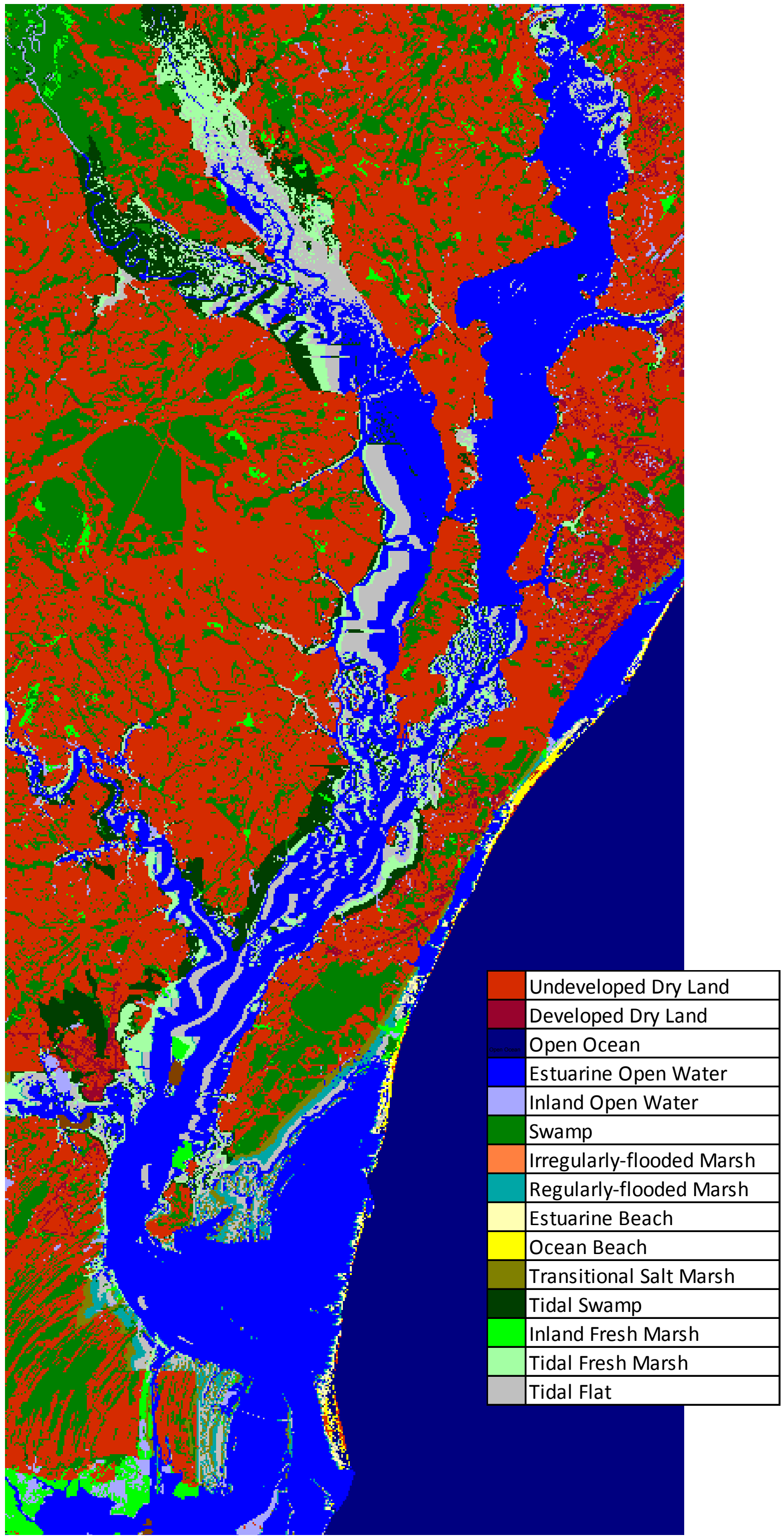
Waccamaw NWR, 2025, 2 m SLR by 2100.



Waccamaw NWR, 2050, 2 m SLR by 2100.



Waccamaw NWR, 2075, 2 m SLR by 2100.



Waccamaw NWR, 2100, 2 m SLR by 2100.