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

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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 (R. A. Park et al. 1991).

In 2010, the Gulf of Mexico Alliance Habitat Conservation and Restoration Team (HCRT), in assistance to the USFWS effort through a contract with the Gulf of Mexico Foundation, funded additional model application to six coastal refuges in the Gulf of Mexico, including the Lower Suwannee NWR. This study is part of a larger effort that the HCRT is undertaking with the Florida and Texas chapters of TNC to understand the Gulf-wide vulnerability of coastal natural communities to SLR and thus to identify appropriate conservation and restoration strategies and actions. Cedar Keys NWR was included in the "contextual area" for the final report on Lower Suwannee River and these results were therefore parsed out of that document.

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).

SLAMM predictions are generally obtained by two consecutive steps: (1) calibration of the model using available historical wetland and SLR data, referred to as the "hindcast;" (2) starting from the most recent available wetland and elevation data, the calibrated model is run to predict wetland changes in response to estimated future SLR.

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 will be used in USFWS simulations, but only 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.
- 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

SLAMM 6 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. 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. In particular, the A1B scenario assumes that energy sources will be balanced across all sources. Under the A1B scenario, the IPCC WGI Fourth Assessment Report (IPCC 2007) suggests a likely range of 0.21 to 0.48 m of SLR by 2090-2099 "excluding future rapid dynamical changes in ice flow." The 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.

The latest literature (Chen et al. 2006; Monaghan et al. 2006) indicates that the eustatic rise in sea levels is progressing more rapidly than was previously assumed, perhaps due to the dynamic changes in ice flow omitted within the IPCC report's calculations. A recent paper in the journal *Science* (Rahmstorf 2007) suggests that, taking into account possible model error, a feasible range by 2100 of 50 to 140 cm. 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.

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 m, 1.5 m, and 2 m of eustatic SLR by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 1).

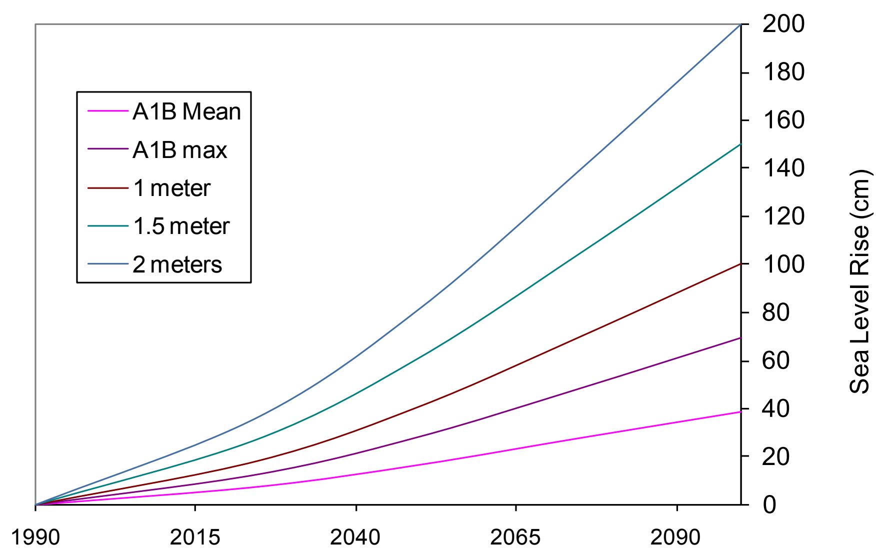


Figure 1. Summary of SLR scenarios utilized

Data Sources and Methods

Wetland layer. Figure 2 shows the most recent available wetlands layer obtained from a National Wetlands Inventory (NWI) photo with dates ranging 2007-2010. Converting the NWI survey into 30 m cells indicated that the approximately 800 acre Cedar Keys NWR (approved acquisition boundary including water) is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Mangrove	330	40
	Regularly Flooded Marsh	261	32
	Beach	116	14
	Open Water	104	13
	Irregularly Flooded Marsh	9	1
	Undeveloped Dry Land	2	< 1
	Tidal Flat	0.4	< 1
	Total (incl. water)	**822**	**100**

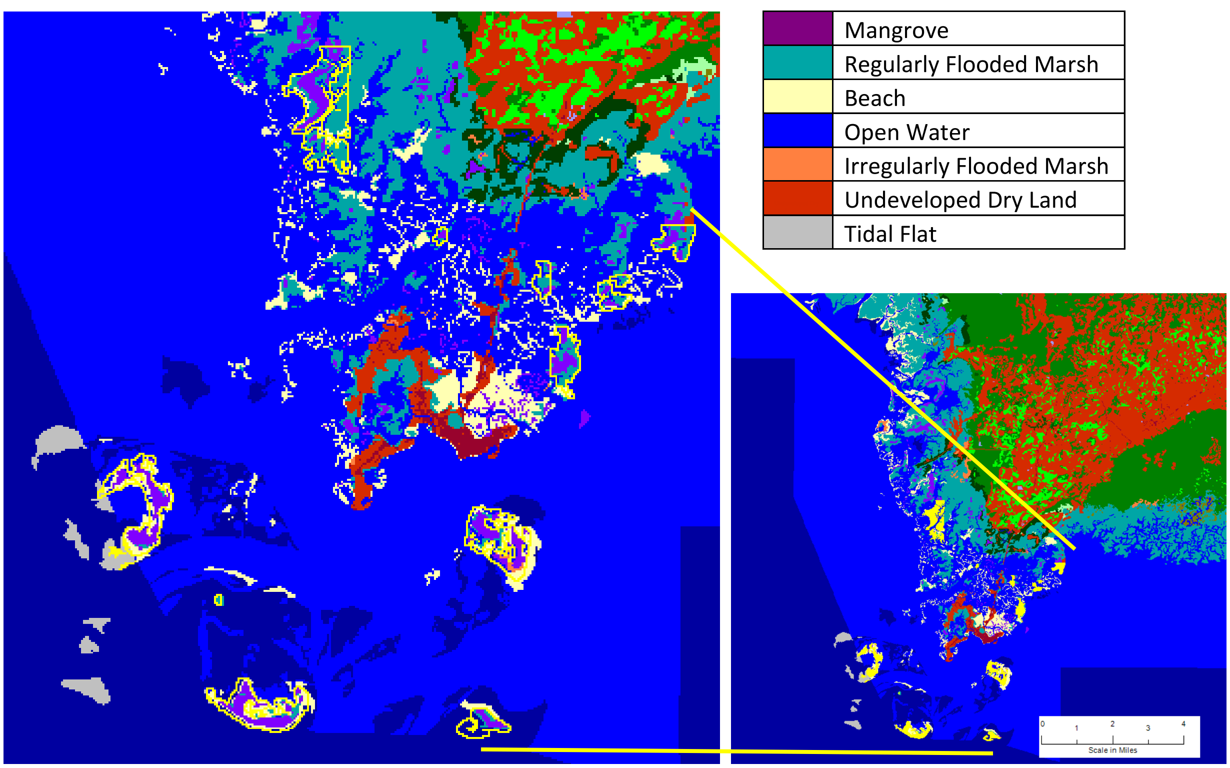


Figure 2. Wetland coverage of the study area. Islands in Cedar Keys NWR are outlined in yellow

Elevation Data. The digital elevation map used in this simulation was derived from a combination of LiDAR data of the Florida Division of Emergency Management (FDEM) with a timestamp of 2007 and an older contour map from the USGS National Elevation Dataset (NED). In particular, all the keys offshore do not have any LiDAR coverage, as shown in Figure 3. Therefore, the elevation pre-processor module of SLAMM was used to assign elevations for wetlands as a function of the local tide range. For a more in-depth description of the elevation preprocessor, see the SLAMM 6 technical documentation (Clough et al. 2010). This process causes additional uncertainty in model results as covered in the *Discussion* section below.

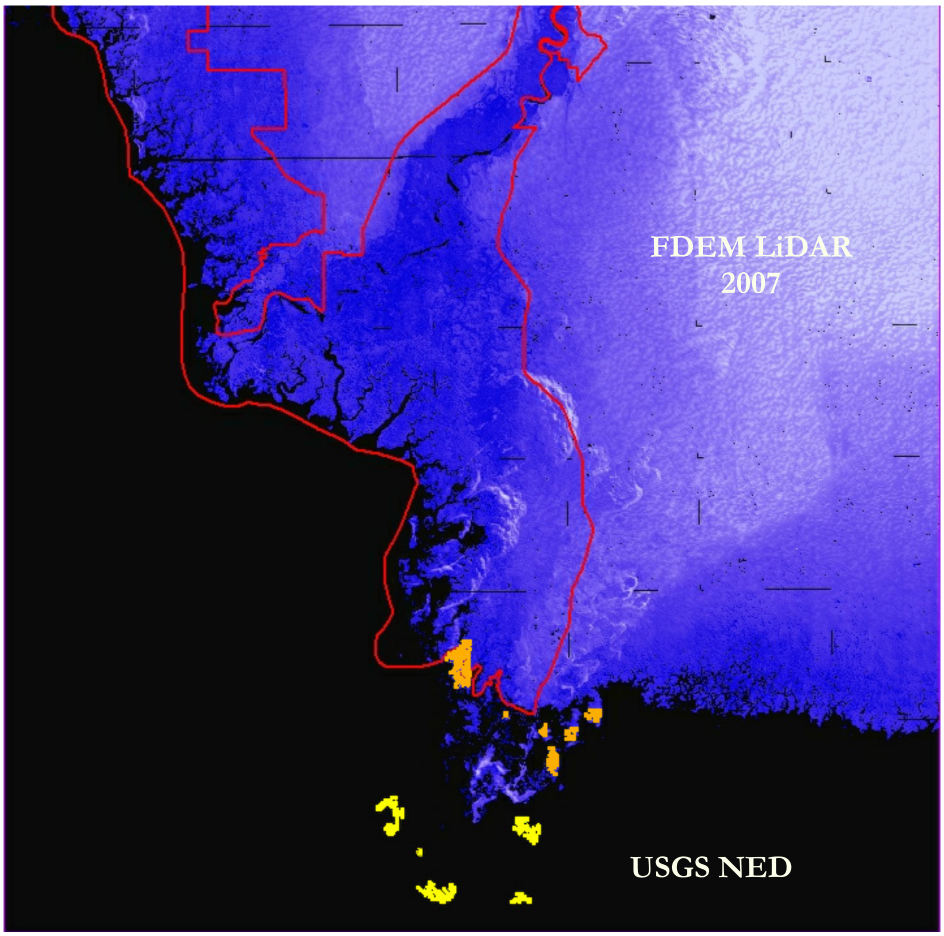


Figure 3. Elevation coverage for the study area. In orange the keys of the Cedar Keys NWR covered by LiDAR; in yellow the ones covered by NED. The red contour is the nearby Lower Suwannee NWR

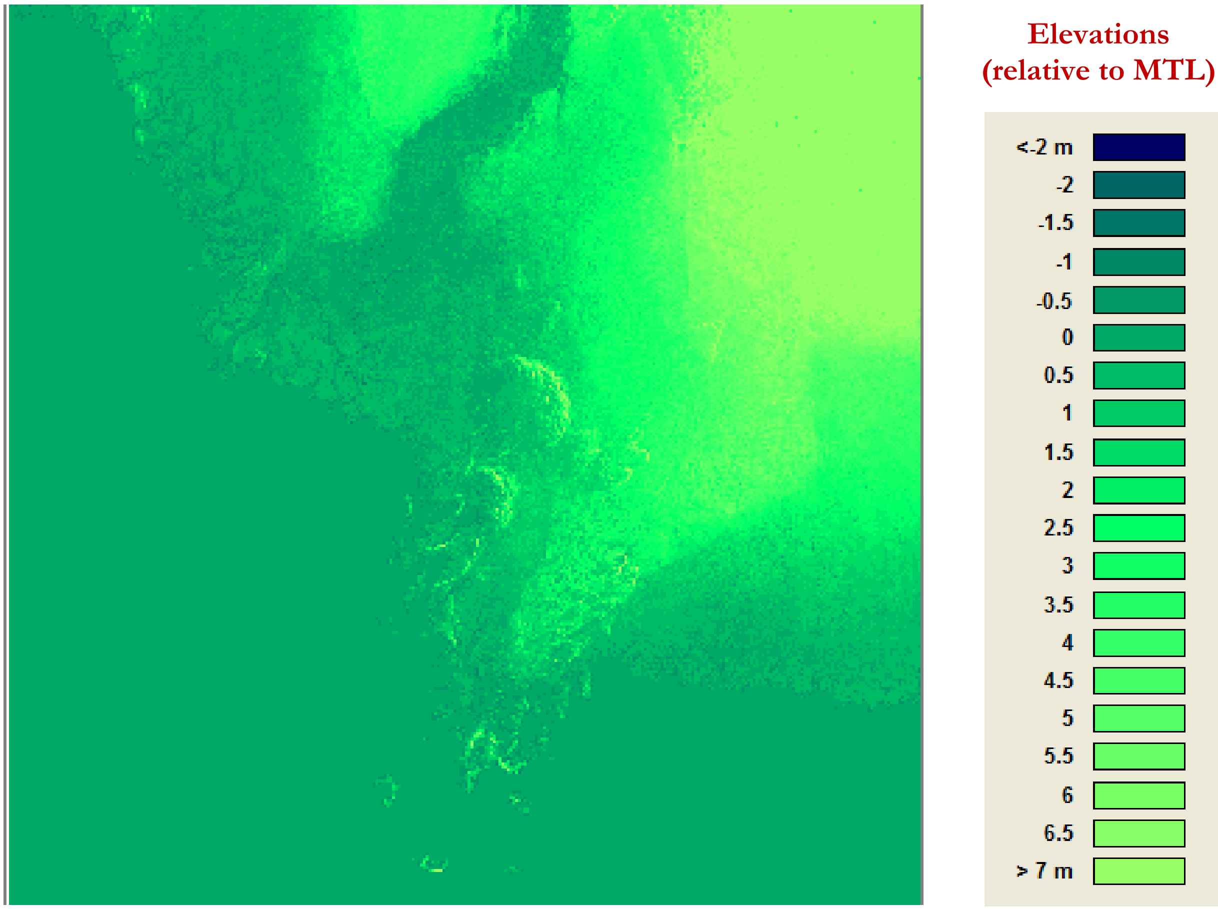


Figure 4. Shade-relief elevation map of the study area.

Model Timesteps. Data were output from the model at years 2025, 2050, 2075 and 2100 with the initial condition date set to 2008 (the average date of the most recent layer).

Dikes and Impoundments. According to the NWI, there are no impounded or diked areas within Cedar Keys NWR.

Historic sea level rise rates. The historic SLR rate was assigned to 1.8 mm/year based on the value recorded at the NOAA Tide Datum located at Cedar Key, FL (gauge #8727520). The rate of SLR for this refuge has been similar to the estimated global average for the last 100 years (approximately 1.7 mm/year, IPCC 2007).

Tide Ranges. The great diurnal tide range for the entire refuge was set to 1.16 m, the value observed at Cedar Key, FL gauge station.

Salt elevation. This parameter within SLAMM designates the boundary between wet lands and dry lands or saline wetlands and fresh water wetlands. As such, this value may be best derived by examining historical tide gauge data. For this application, the salt boundary was defined as the elevation above which inundation is predicted less than once per 30 days using data from the tide gauge station at Cedar Key, FL. Based on the frequency of inundation analysis of the period 11/2006-11/2009, this salt elevation is estimated to be approximately 0.92 m above MTL, equivalent to an elevation of 1.7 Half Tide Units (HTU), as shown in Figure 4.

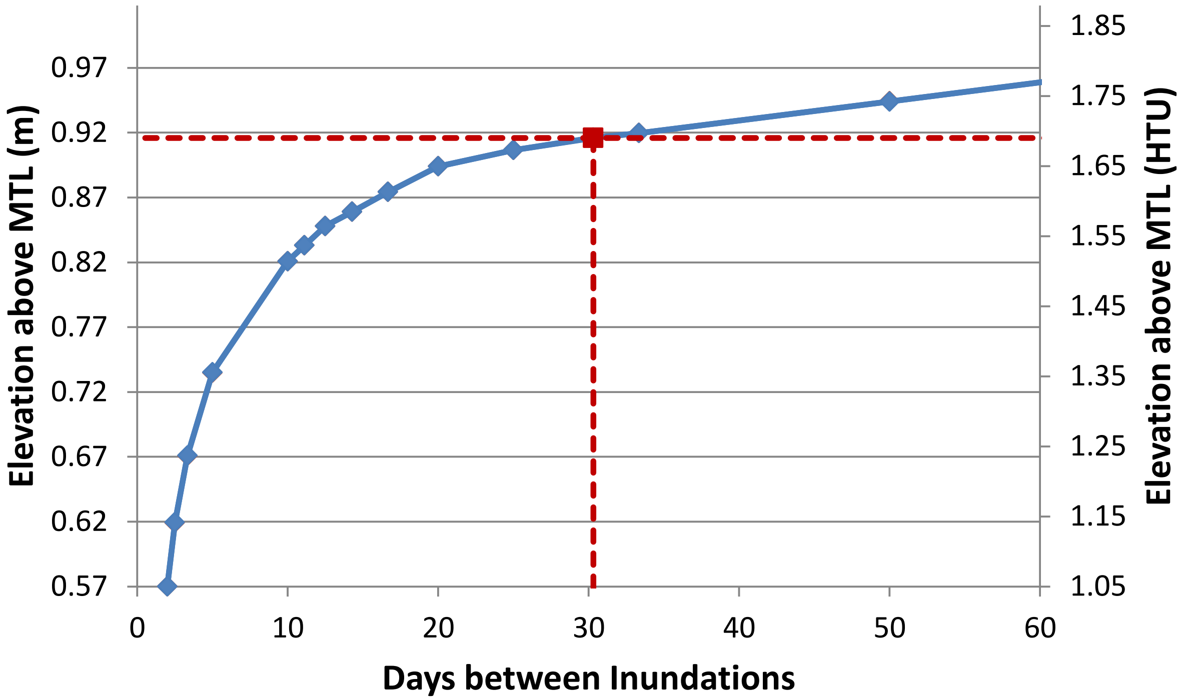


Figure 5. Frequency of inundation based on 3 years of data at Cedar Key, FL

Elevation corrections. The MTL to NAVD88 correction was derived using NOAA's VDATUM software. A raster of MTL to NAVD88 correction values was created for the study area using VDATUM software. The resulting correction in the refuge area is approximately -0.063 m, a very similar value to that derived from data collected at the Cedar Key gauge station.

Refuge boundaries. Modeled USFWS refuge boundaries for Florida are based on Approved Acquisition Boundaries as published on the FWS National Wildlife Refuge Data and Metadata website. The cell-size used for this analysis was 30 m by 30 m. Note that the SLAMM model will track also partial conversion of cells based on elevation and slope.

Parameter summary. Table 1 summarizes all SLAMM input parameters for the refuge. Values for parameters with no specific local information were kept at their default value.

Table 1. Summary of SLAMM input parameters for Cedar Keys NWR

Description	Cedar Key
NWI Photo Date (YYYY)	2008
DEM Date (YYYY)	2007
Direction Offshore [n,s,e,w]	South
Historic Trend (mm/yr)	1.8
MTL-NAVD88 (m)	([1])
GT Great Diurnal Tide Range (m)	1.1582
Salt Elev. (m above MTL)	0.9393
Marsh Erosion (horz. m /yr)	1.8
Swamp Erosion (horz. m /yr)	1
T.Flat Erosion (horz. m /yr)	0.5
Reg.-Flood Marsh Accr (mm/yr)	3.9
Irreg.-Flood Marsh Accr (mm/yr)	4.7
Tidal-Fresh Marsh Accr (mm/yr)	5.9
Inland-Fresh Marsh Accr (mm/yr)	5.9
Mangrove Accr (mm/yr)	7
Tidal Swamp Accr (mm/yr)	1.1
Swamp Accretion (mm/yr)	0.3
Beach Sed. Rate (mm/yr)	0.5
Freq. Overwash (years)	100
Use Elev Pre-processor [True,False]	FALSE/TRUE([2])

([1]) Spatially variable raster map used in place of fixed values.

([2]) Pre-processor set to TRUE for the keys with NED elevation data

Results

SLAMM predicts that Cedar Keys NWR wetlands will be significantly affected by each of the five SLR scenarios examined. Table 2 presents the predicted loss of the major wetland categories by 2100 under each SLR scenario.

Table 2. Predicted loss rates of land categories by 2100 given simulated scenarios of eustatic SLR at Cedar Keys NWR

Land cover category	Initial coverage (acres)	Land cover loss by 2100 for different SLR scenarios				
		0.39 m	0.69 m	1 m	1.5 m	2 m
Mangrove	330	5%	5%	25%	64%	78%
Regularly Flooded Marsh	261	8%	17%	45%	84%	95%
Beach	116	38%	59%	75%	93%	100%
Irregularly Flooded Marsh	9	15%	55%	92%	100%	100%
Undeveloped Dry Land	2	32%	44%	52%	59%	82%

Approximately 10% to 76% of the overall refuge area is predicted to be converted into open water or tidal flat by 2100 depending on the SLR scenario considered.

Mangroves, which today cover approximately 40% of the refuge, are predicted to be the most resilient wetland category with losses ranging from 5% to 78%. Marshes appear to be more affected by SLR. For scenarios lower than 1 m predicted losses are limited, while for scenarios of 1 m and above losses are 45% or higher for regularly-flooded marsh while irregularly flooded marsh is pretty much wiped out. Similarly, beach is predicted to be increasingly lost as sea level continues to rise, with losses ranging 38% to 100%.

For the 1 m SLR scenario, a scenario that researchers consider quite plausible (see section *Sea Level Rise Scenarios* above), open water or tidal flat is predicted to cover 49% of the refuge area (versus 13% today) with mangroves reduced by 25%, irregularly flooded marshes and regularly flooded marshes reduced by approximately 92% and 45% respectively and beach reduced by over 75%.

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

Results in Acres

		Initial	2025	2050	2075	2100
	Mangrove	330	326	322	322	312
	Regularly Flooded Marsh	261	248	248	248	241
	Estuarine Beach	113	106	93	80	69
	Estuarine Open Water	78	86	107	126	141
	Open Ocean	26	26	26	26	27
	Irregularly Flooded Marsh	9	8	8	8	8
	Ocean Beach	3	3	3	2	2
	Undeveloped Dry Land	2	2	2	2	1
	Tidal Flat	0	17	15	8	21
	Total (incl. water)	**822**	**822**	**822**	**822**	**822**

Cedar Keys NWR, Initial Condition

Cedar Keys NWR, 2025, Scenario A1B Mean, 0.39 m SLR

Cedar Keys NWR, 2050, Scenario A1B Mean, 0.39 m SLR

Cedar Keys NWR, 2075, Scenario A1B Mean, 0.39 m SLR

Cedar Keys NWR, 2100, Scenario A1B Mean, 0.39 m SLR

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

Results in Acres

		Initial	2025	2050	2075	2100
	Mangrove	330	326	322	321	312
	Regularly Flooded Marsh	261	248	243	233	217
	Estuarine Beach	113	104	85	65	45
	Estuarine Open Water	78	88	115	144	174
	Open Ocean	26	26	26	27	27
	Irregularly Flooded Marsh	9	8	7	6	4
	Ocean Beach	3	3	2	2	2
	Undeveloped Dry Land	2	2	2	1	1
	Tidal Flat	0	17	19	22	40
	Total (incl. water)	**822**	**822**	**822**	**822**	**822**

Cedar Keys NWR, Initial Condition

Cedar Keys NWR, 2025, Scenario A1B Maximum, 0.69 m SLR

Cedar Keys NWR, 2050, Scenario A1B Maximum, 0.69 m SLR

Cedar Keys NWR, 2075, Scenario A1B Maximum, 0.69 m SLR

Cedar Keys NWR, 2100, Scenario A1B Maximum, 0.69 m SLR

Cedar Keys NWR
1 m eustatic SLR by 2100

Results in Acres

		Initial	2025	2050	2075	2100
	Mangrove	330	326	317	290	248
	Regularly Flooded Marsh	261	246	235	210	144
	Estuarine Beach	113	102	77	50	28
	Estuarine Open Water	78	91	129	196	281
	Open Ocean	26	26	27	27	28
	Irregularly Flooded Marsh	9	8	6	3	1
	Ocean Beach	3	3	2	2	1
	Undeveloped Dry Land	2	2	1	1	1
	Tidal Flat	0	19	28	43	92
	Total (incl. water)	**822**	**822**	**822**	**822**	**822**

Cedar Keys NWR, Initial Condition

Cedar Keys NWR, 2025, 1 m SLR

Cedar Keys NWR, 2050, 1 m SLR

Cedar Keys NWR, 2075, 1 m SLR

Cedar Keys NWR, 2100, 1 m SLR

Cedar Keys NWR
1.5 m eustatic SLR by 2100

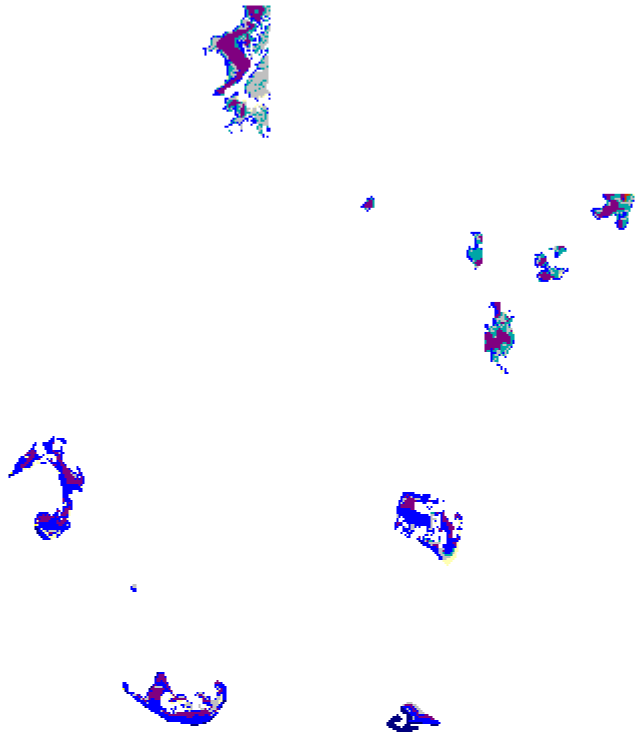
Results in Acres

		Initial	2025	2050	2075	2100
	Mangrove	330	323	282	201	119
	Regularly Flooded Marsh	261	242	217	107	41
	Estuarine Beach	113	98	62	29	8
	Estuarine Open Water	78	98	187	331	514
	Open Ocean	26	26	27	28	29
	Irregularly Flooded Marsh	9	7	3	0	0
	Ocean Beach	3	3	2	1	0
	Undeveloped Dry Land	2	2	1	1	1
	Tidal Flat	0	23	42	124	110
	Total (incl. water)	**822**	**822**	**822**	**822**	**822**

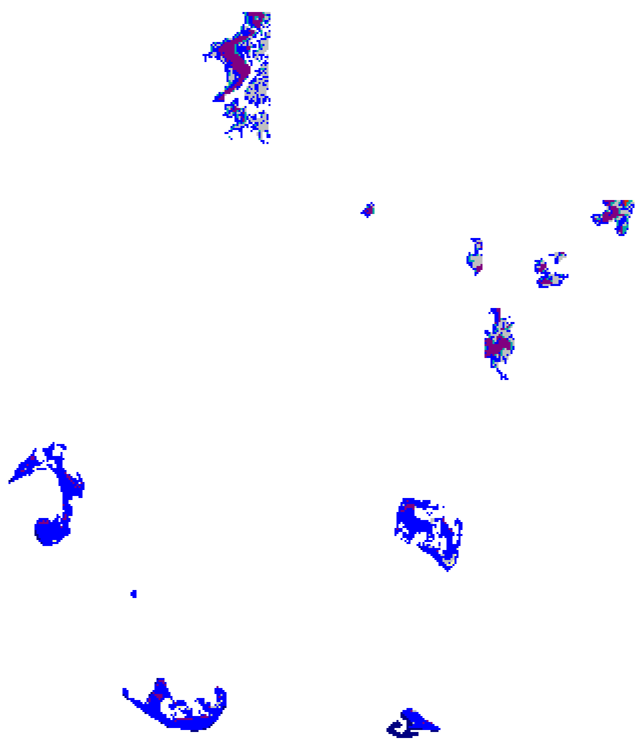
Cedar Keys NWR, Initial Condition

Cedar Keys NWR, 2025, 1.5 m SLR

Cedar Keys NWR, 2050, 1.5 m SLR



Cedar Keys NWR, 2075, 1.5 m SLR



Cedar Keys NWR, 2100, 1.5 m SLR

Cedar Keys NWR
2 m eustatic SLR by 2100

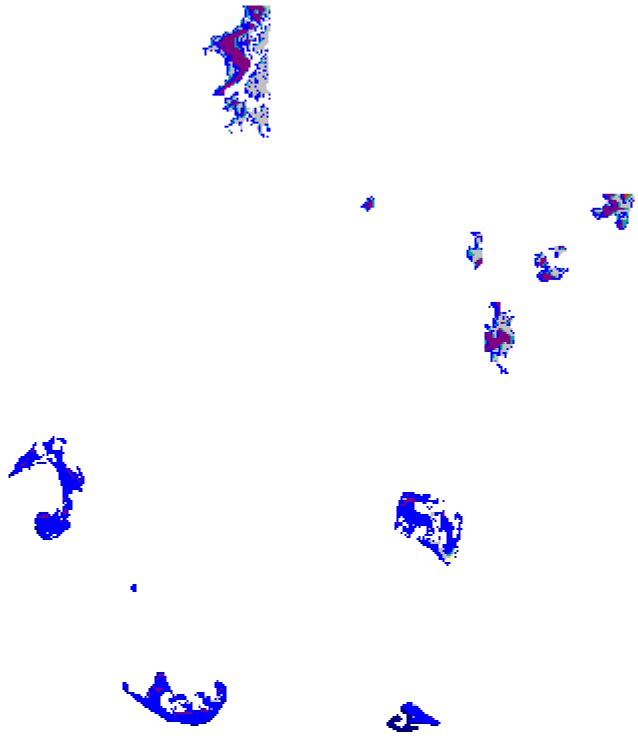
Results in Acres

		Initial	2025	2050	2075	2100
	Mangrove	330	314	236	118	74
	Regularly Flooded Marsh	261	238	181	47	14
	Estuarine Beach	113	95	49	14	0
	Estuarine Open Water	78	112	251	483	675
	Open Ocean	26	26	27	28	29
	Irregularly Flooded Marsh	9	6	1	0	0
	Ocean Beach	3	3	2	0	0
	Undeveloped Dry Land	2	2	1	1	0
	Tidal Flat	0	27	74	131	30
	Total (incl. water)	**822**	**822**	**822**	**822**	**822**

Cedar Keys NWR, Initial Condition

Cedar Keys NWR, 2025, 2 m SLR

Cedar Keys NWR, 2050, 2 m SLR



Cedar Keys NWR, 2075, 2 m SLR

Cedar Keys NWR, 2100, 2 m SLR

Discussion

Application of SLAMM to Cedar Keys NWR indicates the effects of SLR on this refuge will be severe, with 23% to 89% of the total land cover being open water or tidal flat by 2100 as compared to 13% today.

Mangroves, which currently cover approximately 40% of the refuge, are predicted to be the most resilient wetland category with losses ranging from 5% to 78%. In particular, for SLR scenarios of 0.69 m by 2100 and below, mangroves and regularly flooded marshes are predicted to be fairly resilient due to their elevation distribution. However, as sea level continues to rise, loss rates dramatically increase. Other wetlands types are predicted to have very significant losses for all SLR scenarios and more or less totally inundated for higher SLR scenarios. Their loss significantly reduces the wetland habitat richness in the refuge.

Although somewhat uncertain, model results shed some light on the potential timing of land loss in Cedar Keys NWR. In the 1 m SLR scenario, all wetlands are predicted to slowly lose coverage to open water at an average rate of 5% every 25 years until 2050. After this date the loss rate is predicted to accelerate to 10% for the final 25 years of simulation. For other SLR scenarios, although different quantitatively, results the overall trends are similar.

An important source of model uncertainty is from the accretion rates. Local accretion data were taken for the available literature and applied on the entire study area. However, more specific measurements of accretion rates within the refuge could provide better predictions of marsh losses in the future.

In addition, for the offshore keys no LiDAR elevation data were available; therefore additional uncertainty in characterizing these lower-elevation land covers is certainly present. In these regions, the SLAMM elevation pre-processor was utilized, that assumes wetland elevations to be uniformly distributed over their feasible vertical elevation ranges or "tidal frames." If wetlands elevations are actually clustered high in the tidal frame they would be less vulnerable to SLR. On the contrary, if in reality wetlands are towards the bottom, they are more vulnerable than what is predicted by the simulation results.

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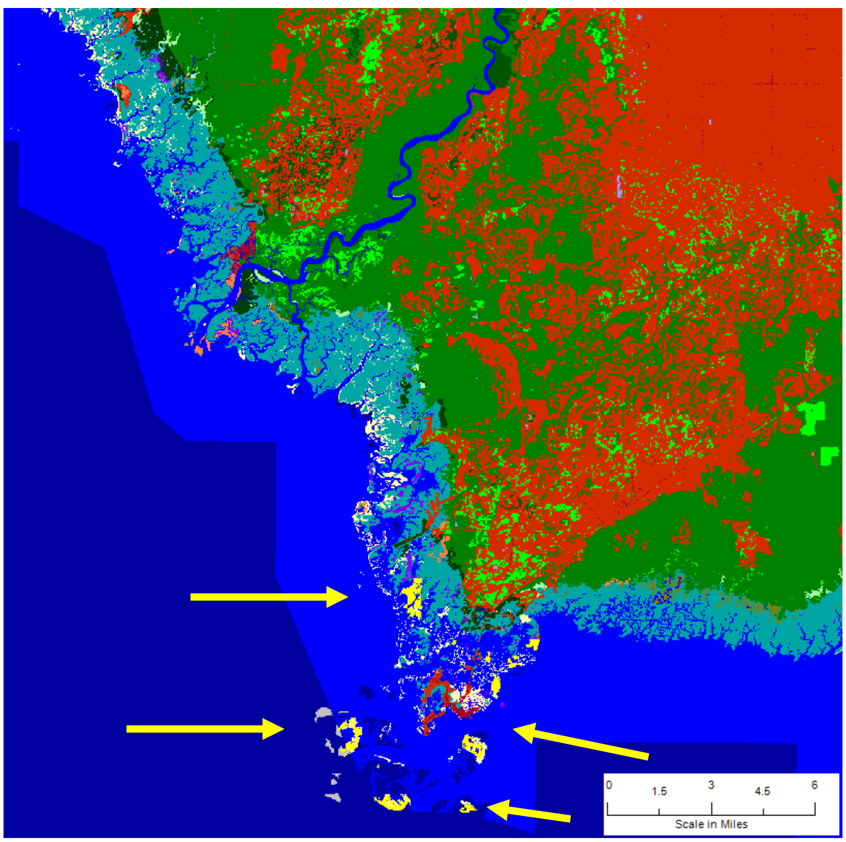
Appendix A: Contextual Results

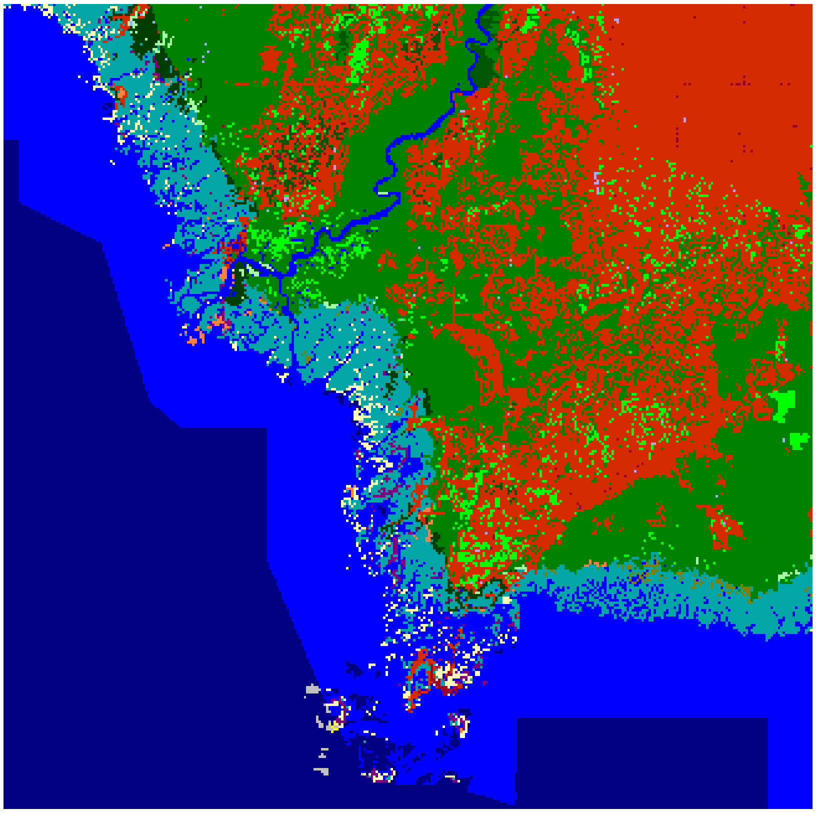
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated dry lands will convert to marshes or ocean beach depending on their proximity to open ocean.

For this reason, an area larger than the boundaries of the USFWS refuge was modeled. Maps of these results are presented here with the following caveats:

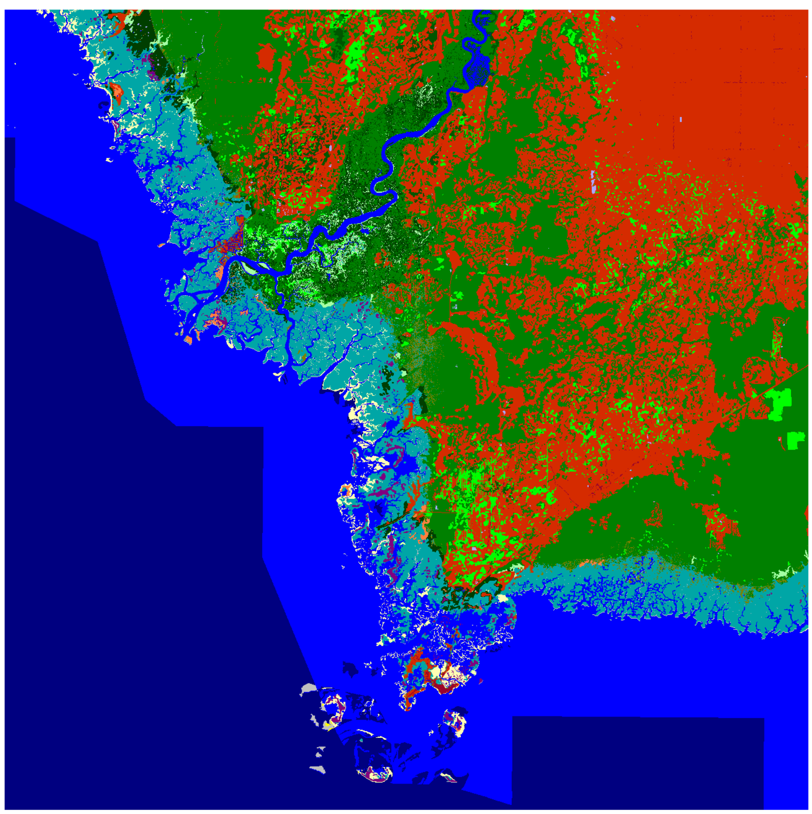
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



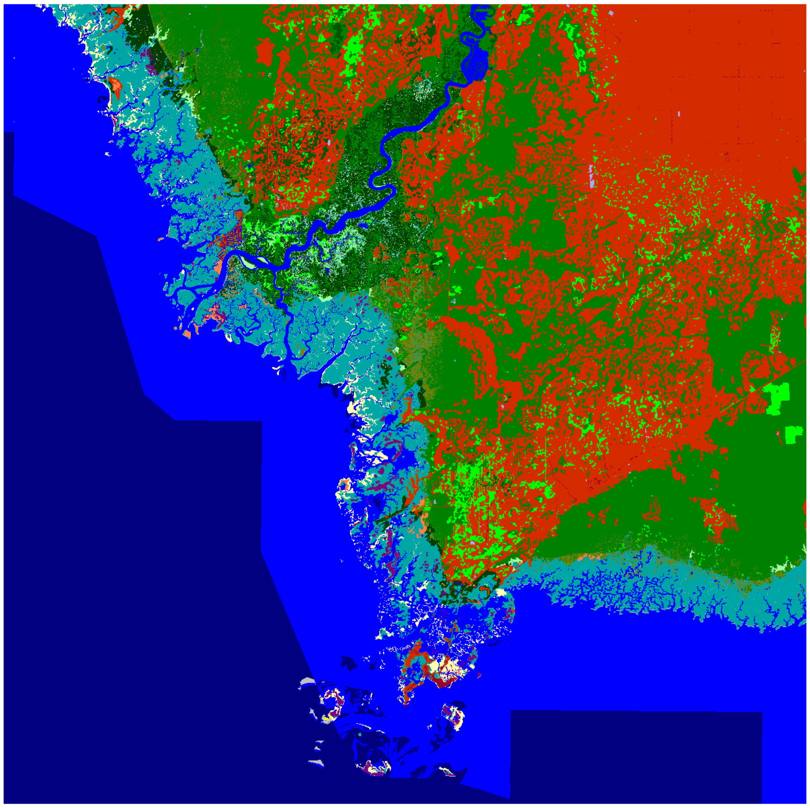
Cedar Keys National Wildlife Refuge (yellow areas) within simulation context



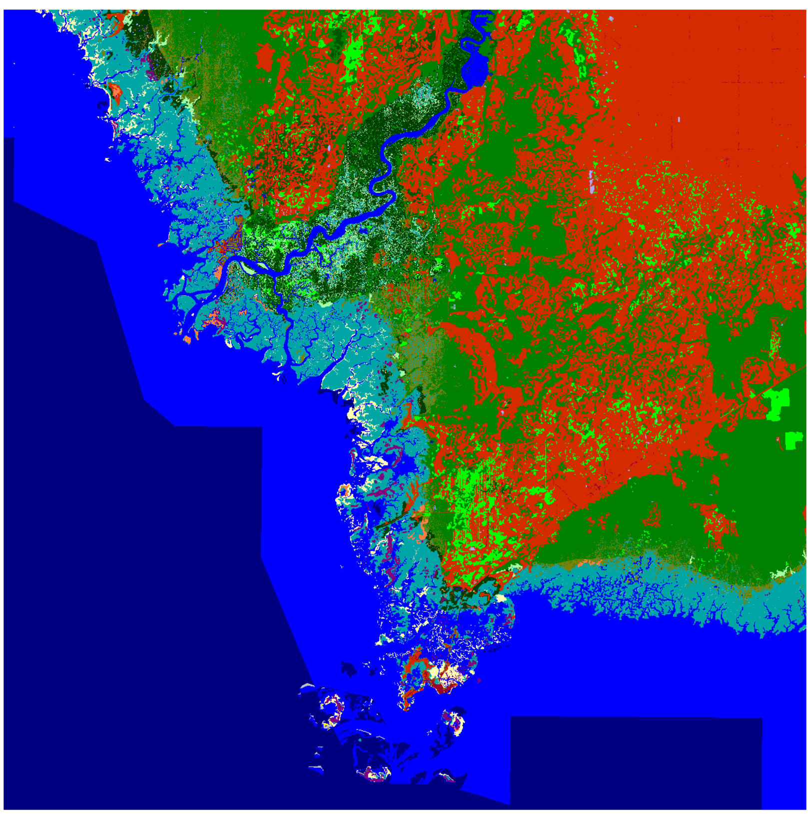
Cedar Keys NWR, Initial Condition



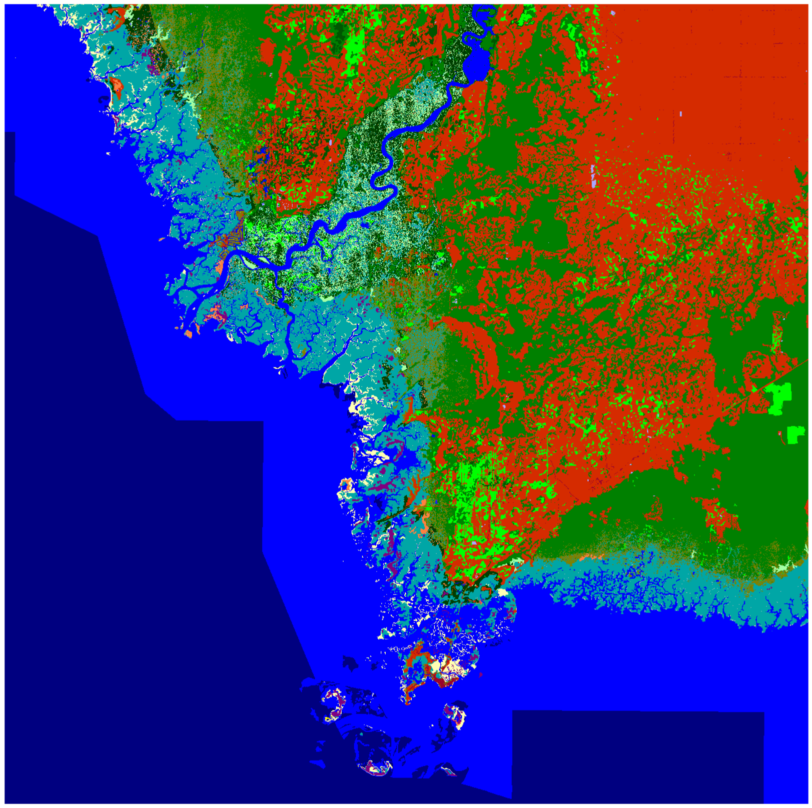
Cedar Keys NWR, 2025, Scenario A1B Mean, 0.39 m SLR



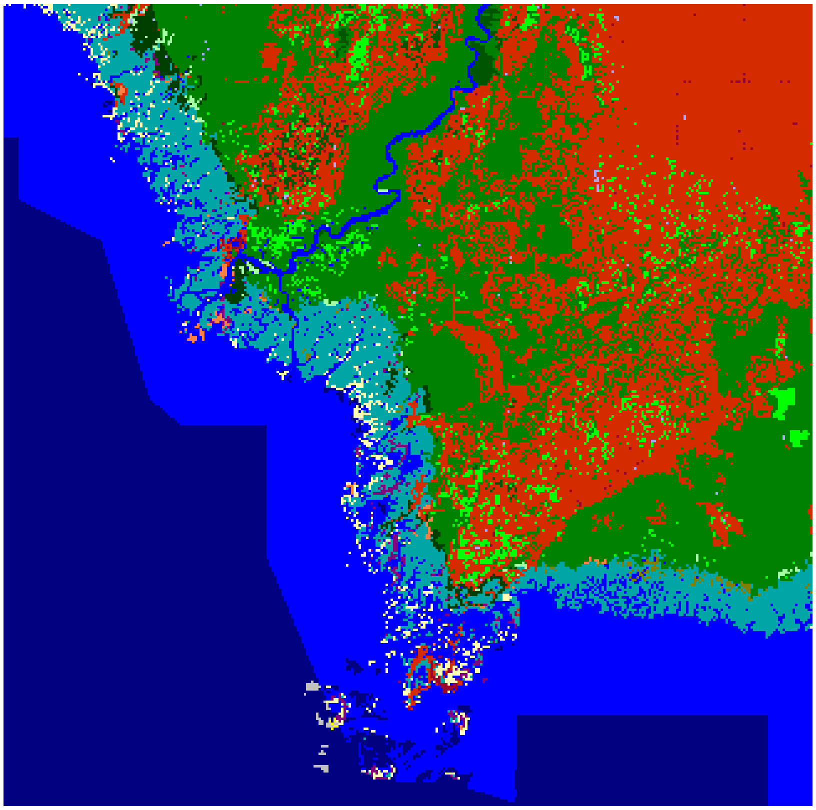
Cedar Keys NWR, 2050, Scenario A1B Mean, 0.39 m SLR



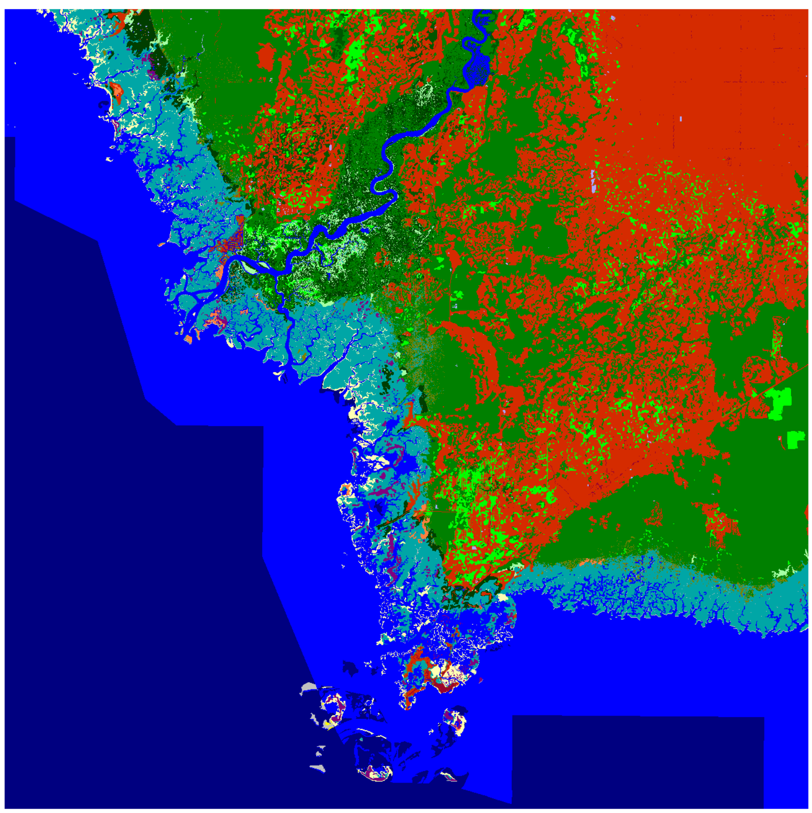
Cedar Keys NWR, 2075, Scenario A1B Mean, 0.39 m SLR



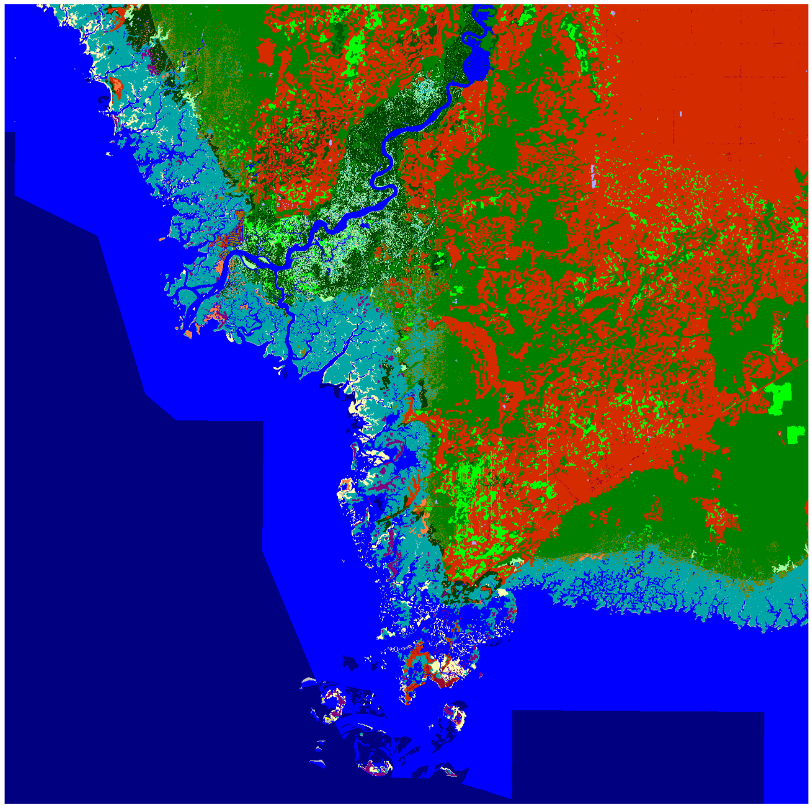
Cedar Keys NWR, 2100, Scenario A1B Mean, 0.39 m SLR



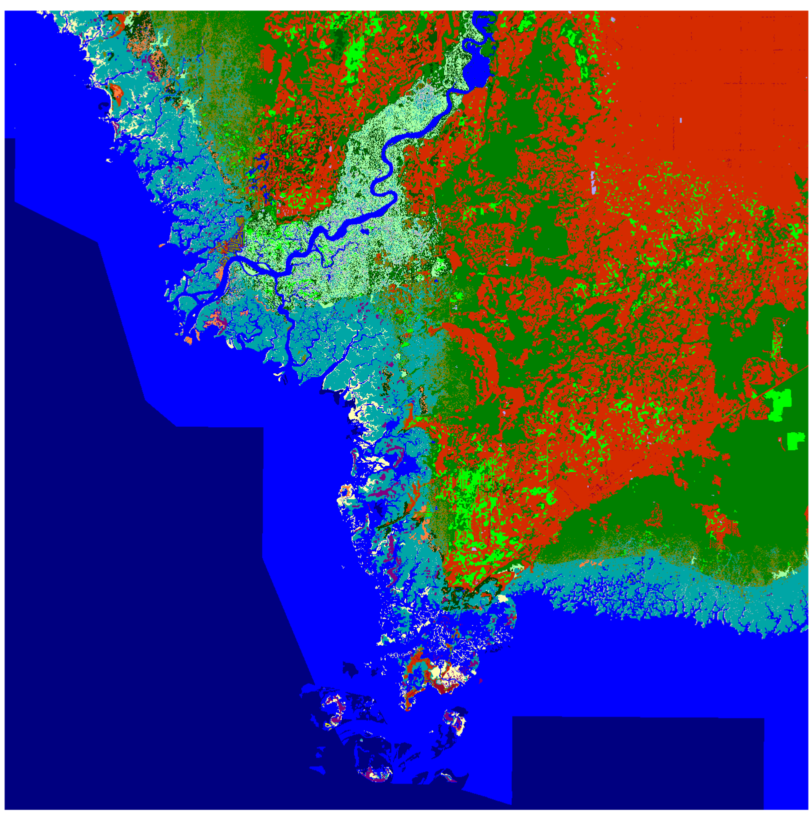
Cedar Keys NWR, Initial Condition



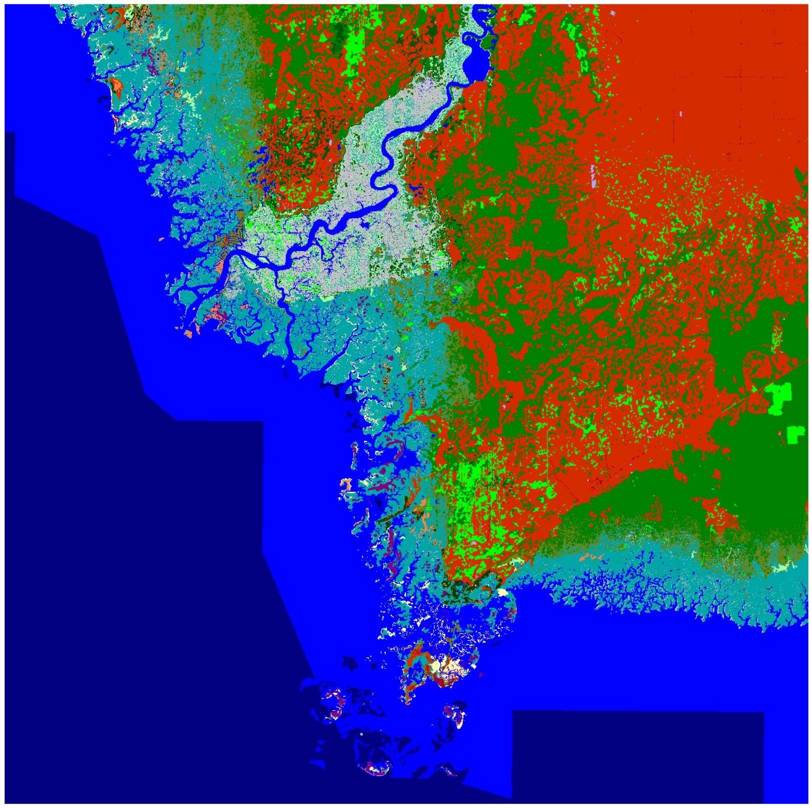
Cedar Keys NWR, 2025, Scenario A1B Maximum, 0.69 m SLR



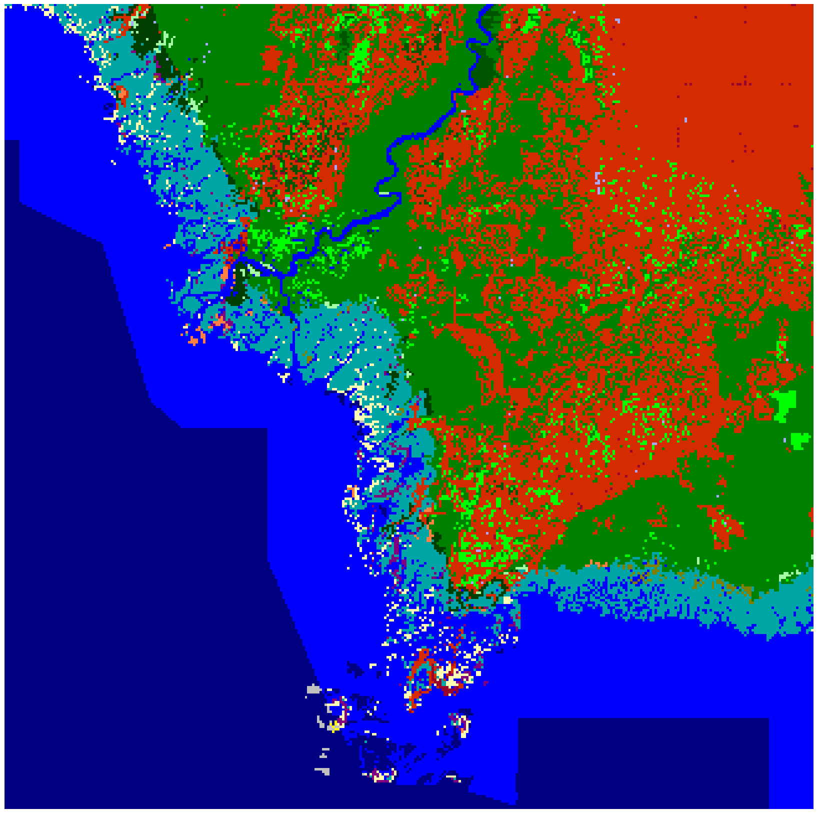
Cedar Keys NWR, 2050, Scenario A1B Maximum, 0.69 m SLR



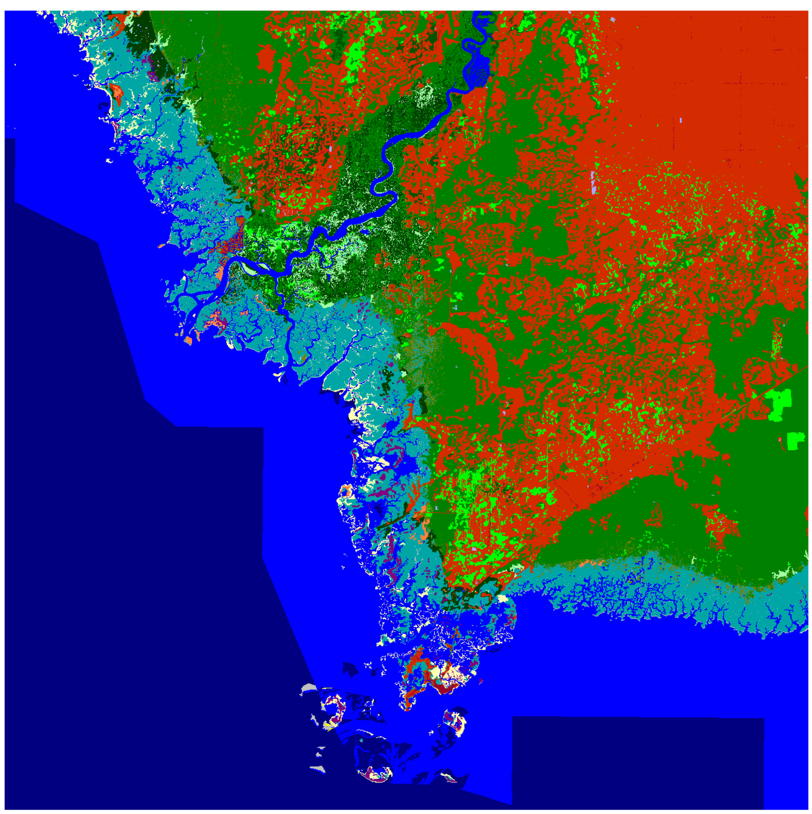
Cedar Keys NWR, 2075, Scenario A1B Maximum, 0.69 m SLR



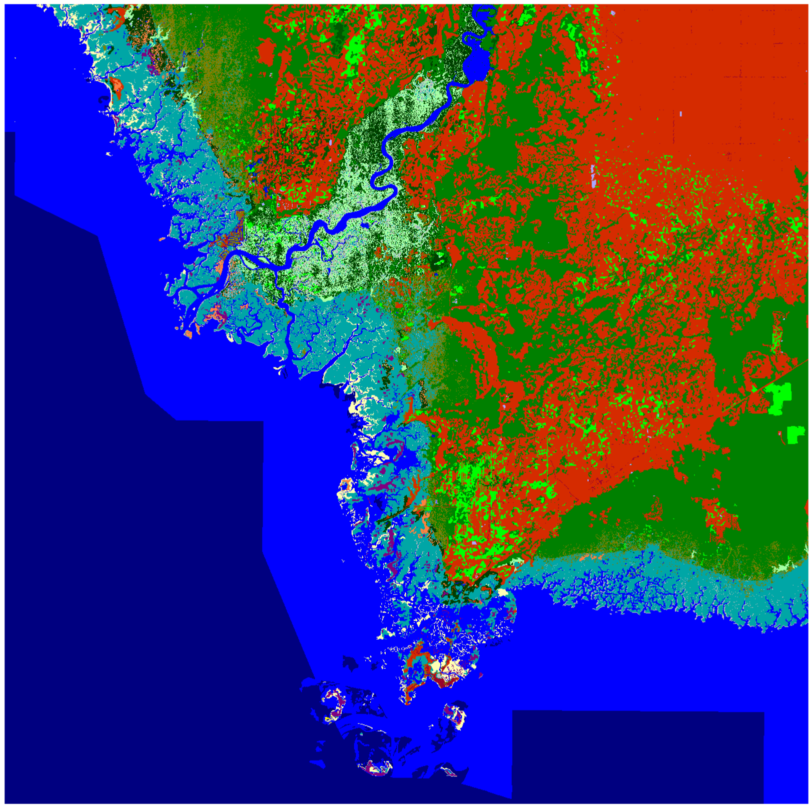
Cedar Keys NWR, 2100, Scenario A1B Maximum, 0.69 m SLR

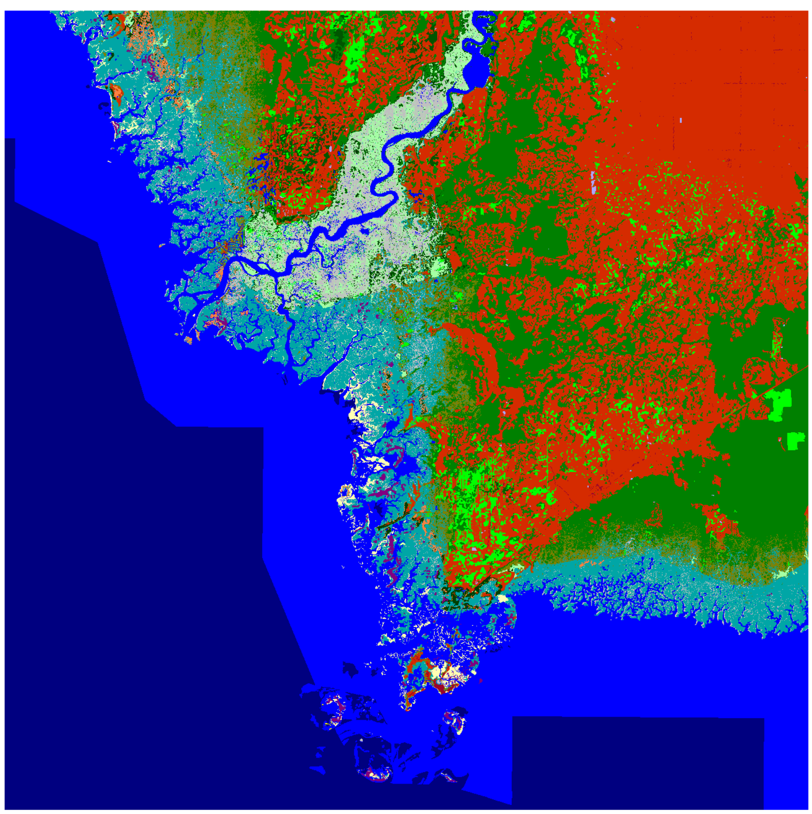


Cedar Keys NWR, Initial Condition



Cedar Keys NWR, 2025, 1 m SLR


Cedar Keys NWR, 2050, 1 m SLR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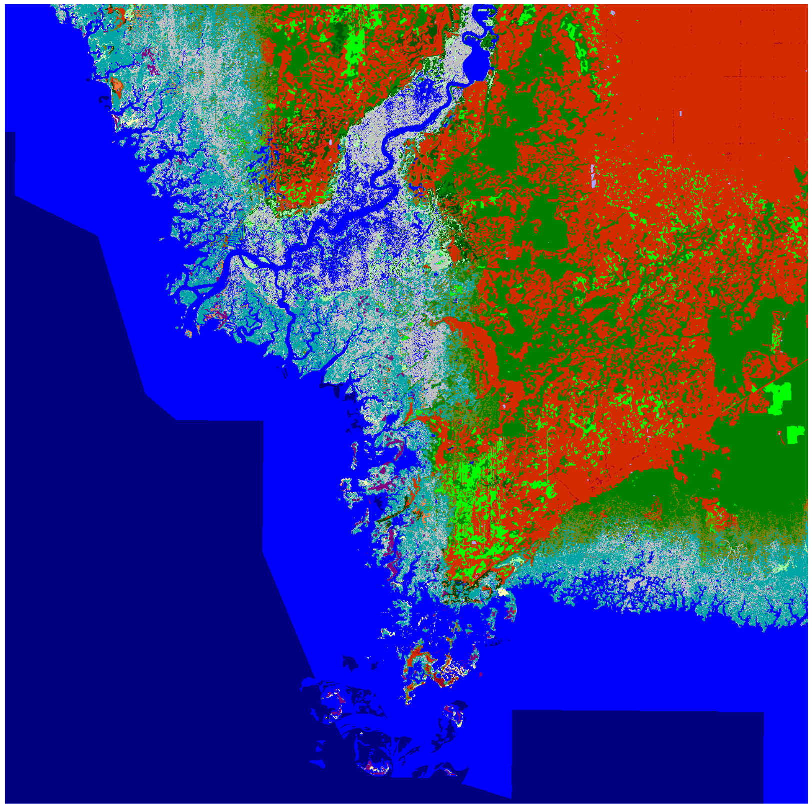
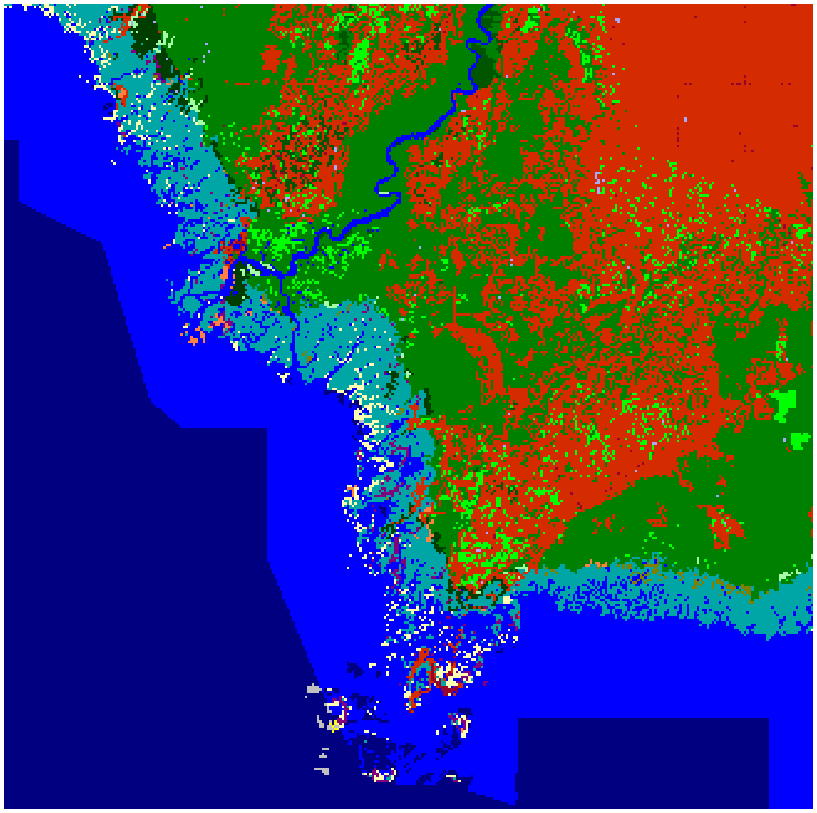
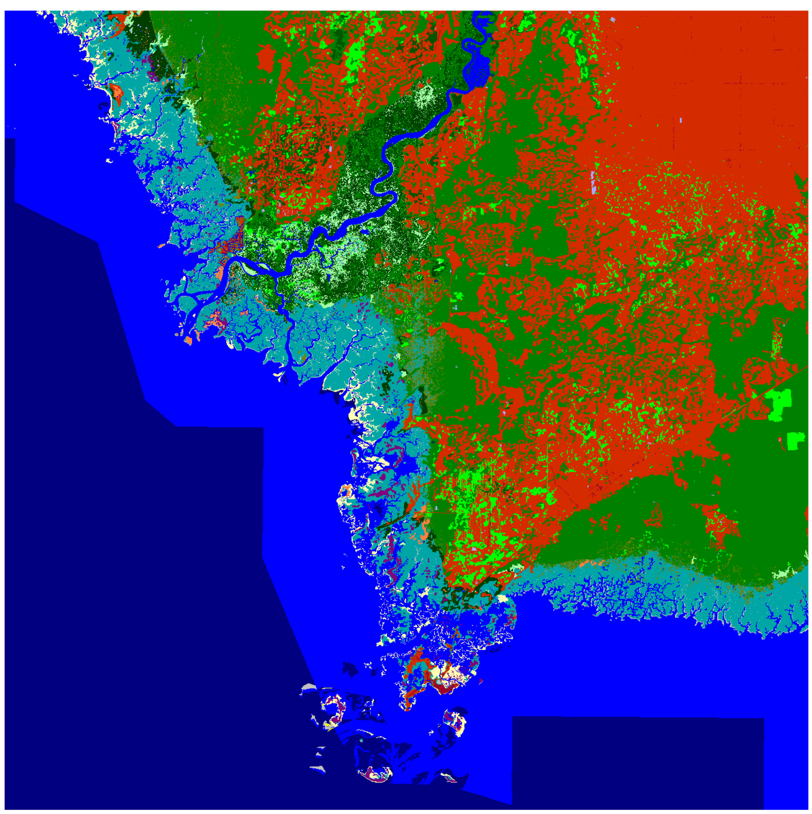
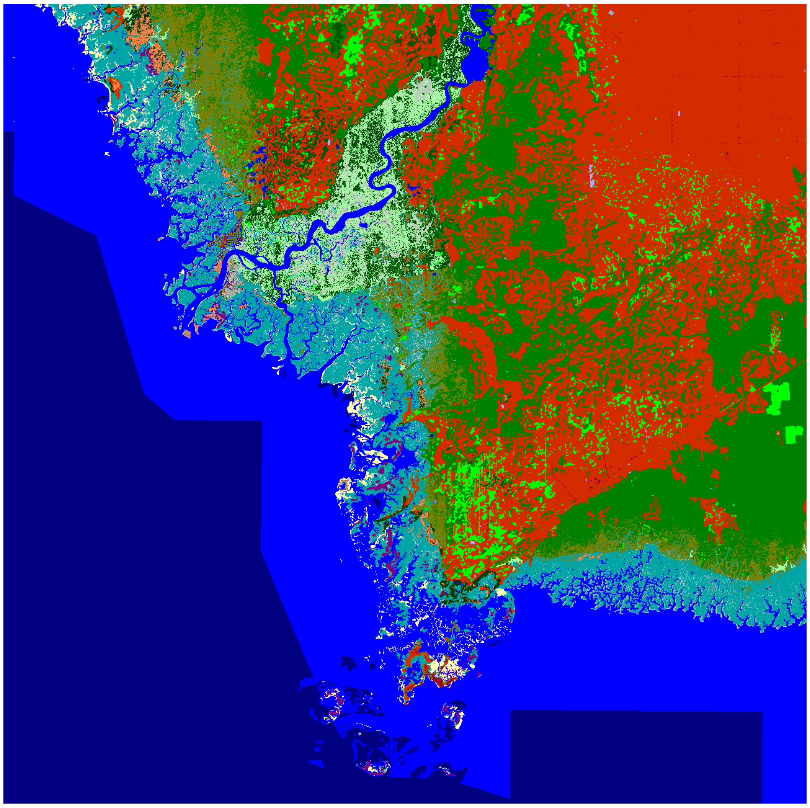


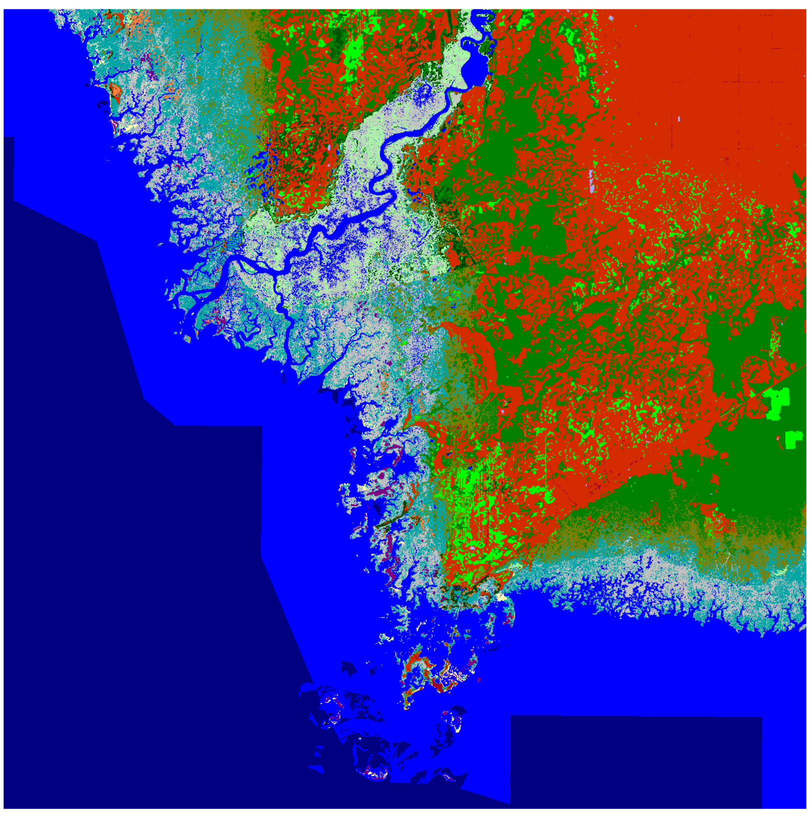
Cedar Keys NWR, 2100, 1 m SLR


Cedar Keys NWR, Initial Condition

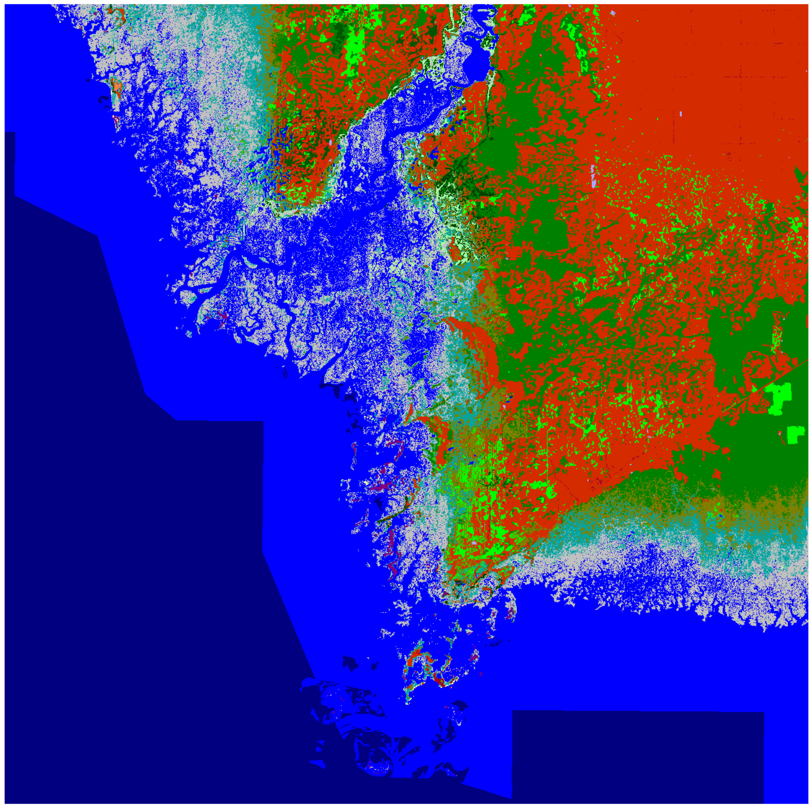

Cedar Keys NWR, 2025, 1.5 m SLR



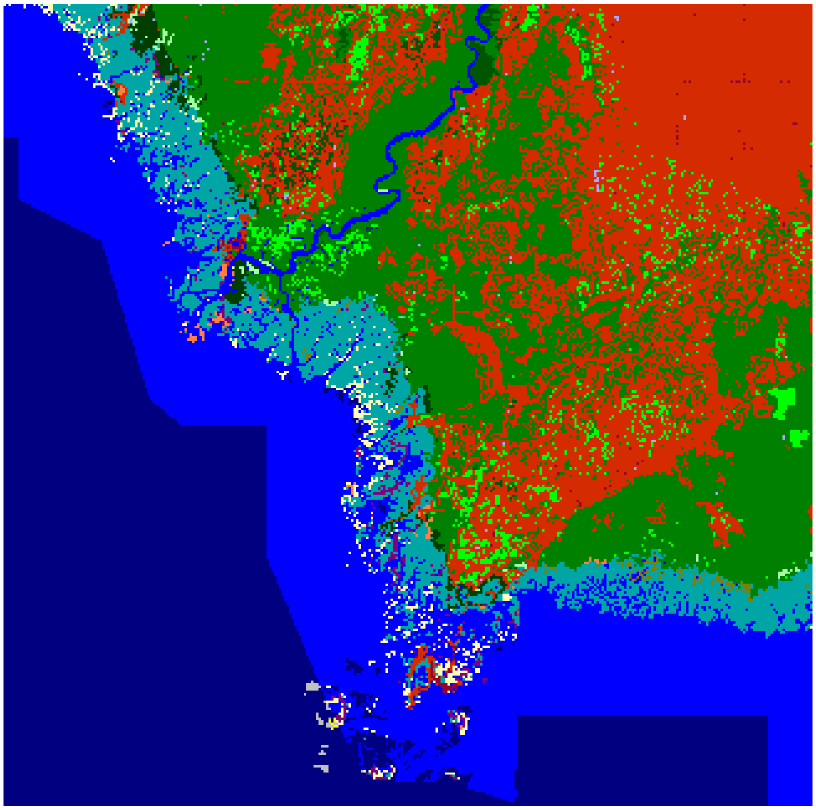
Cedar Keys NWR, 2050, 1.5 m SLR



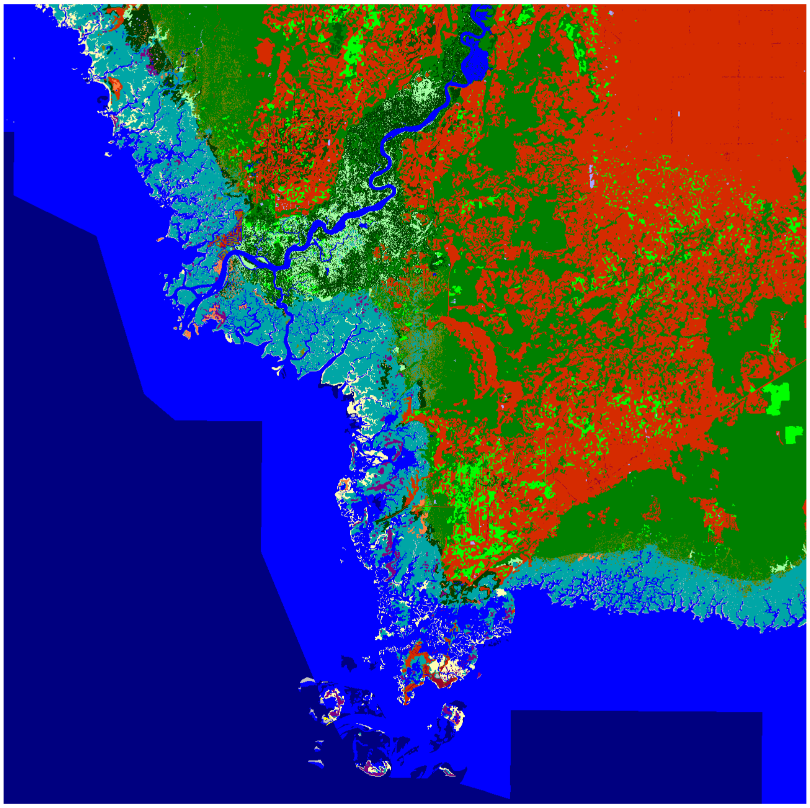
Cedar Keys NWR, 2075, 1.5 m SLR



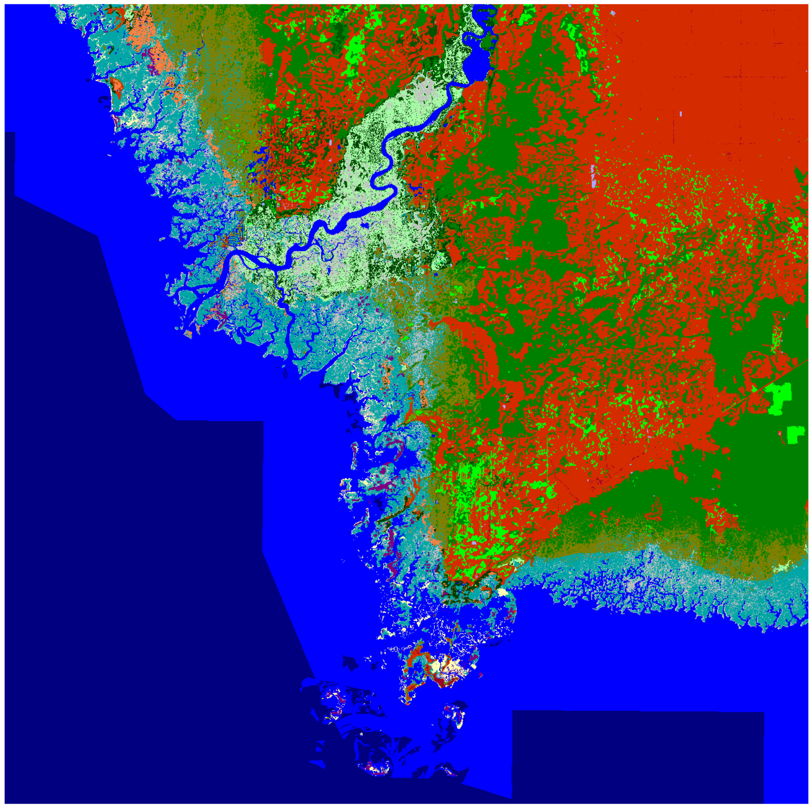
Cedar Keys NWR, 2100, 1.5 m SLR



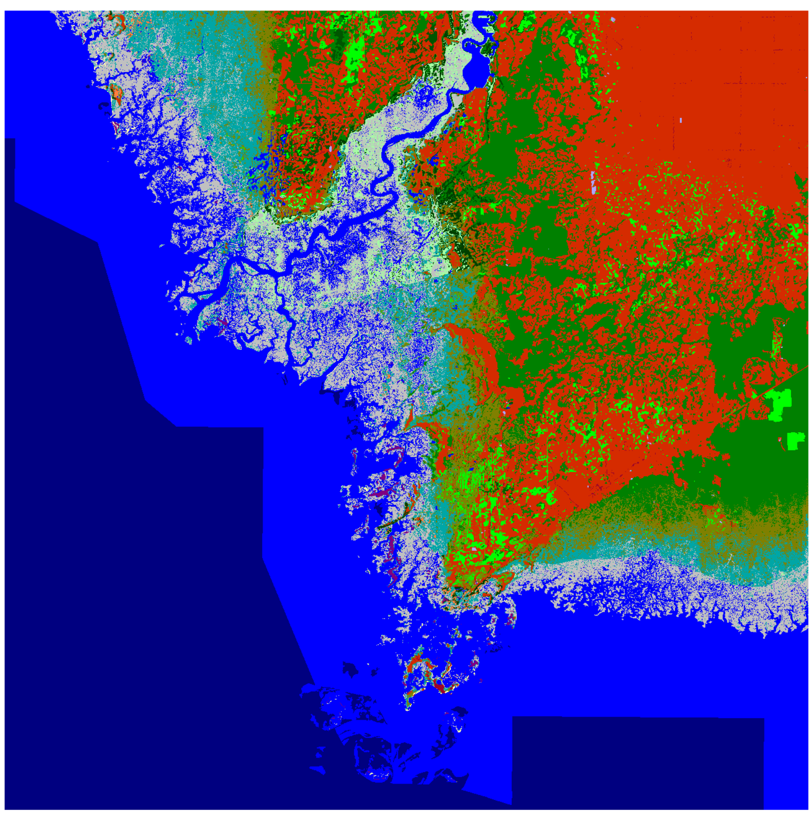
Cedar Keys NWR, Initial Condition



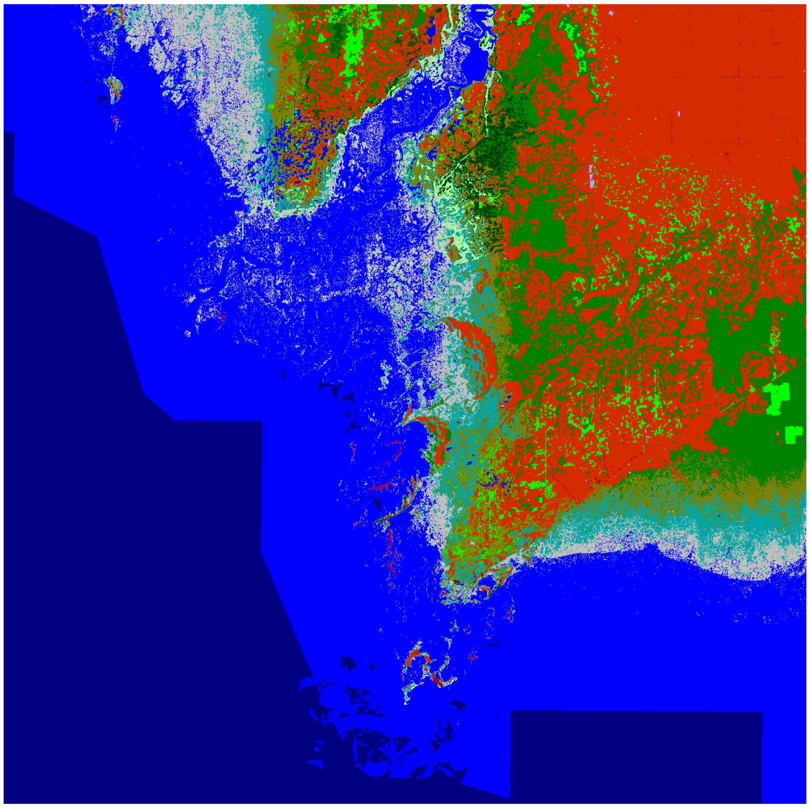
Cedar Keys NWR, 2025, 2 m SLR



Cedar Keys NWR, 2050, 2 m SLR



Cedar Keys NWR, 2075, 2 m SLR



Cedar Keys NWR, 2100, 2 m SLR