Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to Crystal River NWR

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). The International 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 could be 50 to 140 cm. Pfeffer et al. (2008) suggests that 200 cm by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. Rising sea level may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat migration as salt marshes transgress landward and replace tidal freshwater and brackish marsh (Park et al. 1991).

In an effort to address the potential effects of sea level rise on United States national wildlife refuges, the U. S. Fish and Wildlife Service contracted the application of the SLAMM model for most Region 4 refuges. This analysis is designed to assist in the production of comprehensive conservation plans (CCPs) for each refuge along with other long-term management plans.

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 5.0) 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, J.K., R.A. Park, and P.W. Mausel. 1992; Park, R.A., J.K. Lee, and D. Canning 1993; Galbraith, H., R. Jones, R.A. Park, J.S. Clough, S. Herrod-Julius, B. Harrington, and G. Page. 2002; National Wildlife Federation et al., 2006; Glick, Clough, 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 width are assumed to undergo overwash during each 25-year time-step due to 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.

SLAMM Version 5.0 is the latest version of the SLAMM Model, developed in 2006/2007 and based on SLAMM 4.0. SLAMM 5.0 provides the following refinements:

- The capability to simulate fixed levels of sea-level rise by 2100 in case IPCC estimates of sea-level rise prove to be too conservative;
- Additional model categories such as "Inland Shore," "Irregularly Flooded (Brackish) Marsh," and "Tidal Swamp."
- *Optional.* In a defined estuary, salt marsh, brackish marsh, and tidal fresh marsh can migrate based on changes in salinity, using a simple though geographically-realistic salt wedge model. This optional model was not used when creating results for Crystal River NWR.

Model results presented in this report were produced using SLAMM version 5.0.1 which was released in early 2008 based on only minor refinements to the original SLAMM 5.0 model. Specifically, the accretion rates for swamps were modified based on additional literature review. For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 5.0.1 technical documentation (Clough and Park, 2008).   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 (CREM 2008).

Sea-Level Rise Scenarios

The primary set of eustatic (global) sea level rise scenarios used within SLAMM was derived from the work of the Intergovernmental Panel on Climate Change (IPCC 2001).   SLAMM 5 was run using the following IPCC and fixed-rate scenarios:

Scenario	Eustatic SLR by 2025 (cm)	Eustatic SLR by 2050 (cm)	Eustatic SLR by 2075 (cm)	Eustatic SLR by 2100 (cm)
A1B Mean	8	17	28	39
A1B Max	14	30	49	69
1 meter	13	28	48	100
1.5 meter	18	41	70	150

Recent 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 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 might be 50 to 140 cm. To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 meter, 1½ meters of eustatic sea-level rise 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
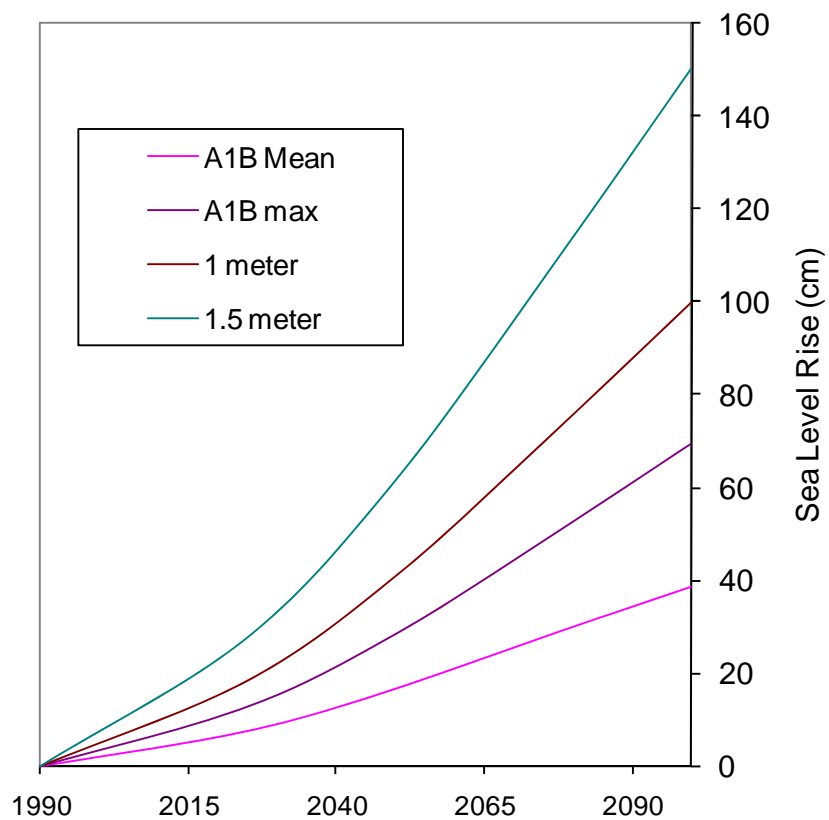
Methods and Data Sources

No LIDAR data were found for Crystal River NWR so elevation data are based on the National Elevation Dataset (NED). (LIDAR data are currently being gathered for all of coastal Florida through the Florida Division of Emergency Management but at this time, this remains a work in progress.)

An examination of the metadata for the NED indicates that these data were derived from a 1954 survey illustrated within USGS topographic map shown below. The contour intervals that resulted from this survey are five feet. The process of creating a digital elevation map (DEM) from a contour map does attempt to interpolate between contour lines but there is considerable uncertainty in this process. There are few (if any) 5 foot contour lines within the geographic footprint of this refuge meaning both that elevations are quite low and the elevation data are subject to considerable uncertainty. For this reason, elevations of wetlands classes within this refuge were overwritten as a function of the local tidal range using the SLAMM elevation pre-processor.
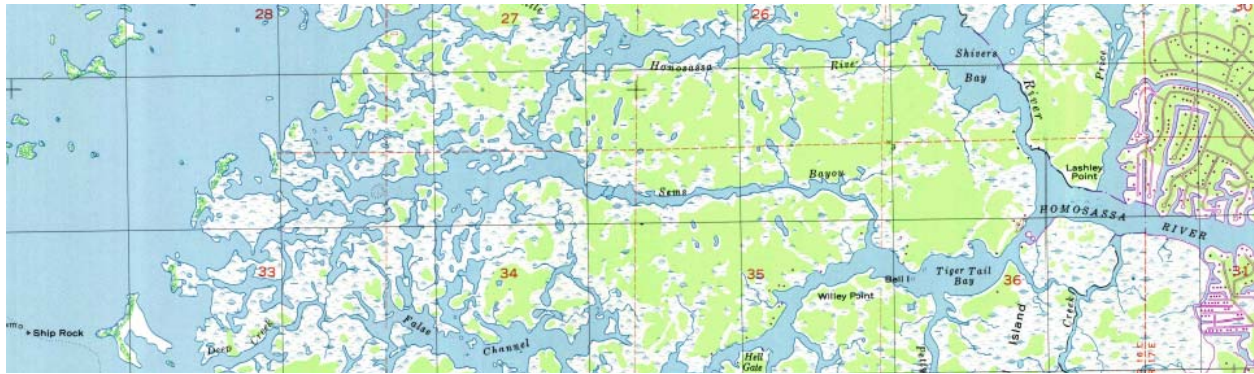
Figure 2: Crystal River Excerpt from USGS Map.

The National Wetlands Inventory for Crystal River is based on a photo date of 1984. This survey, when converted to 30 meter cells, suggests that on that date, the approximately eight thousand acre refuge (approved acquisition boundary including water) was composed of the categories as shown below:

Estuarine Open Water	52.0%
Brackish Marsh	25.2%
Trans. Salt Marsh	16.7%
Mangrove	2.4%
Dry Land	1.3%
Swamp	1.0%
Inland Open Water	0.7%
Tidal Swamp	0.4%
Tidal Fresh Marsh	0.2%

There are no dikes in the region of the Crystal River NWR according to the National Wetlands Inventory.

The historic trend for sea level rise was estimated at 2.12 mm/year using the average of the two closest stations (8727520, Cedar Key Florida; and 8726724, Clearwater Beach Florida). This measured rate is similar to the global average for the last 100 years (approximately 1.5 mm/year).

The tide range at this site was estimated at 0.573 meters using the average of the three closest NOAA oceanic gages (8727277, Tuckers Island Homosassa River, FL; 8727274, Mason Creek Homosassa Bay FL; and 8727235, Johns Island Chassahowitzka Bay). The USGS topographical map for this region suggests an approximate tidal range of two feet (0.61 meters).
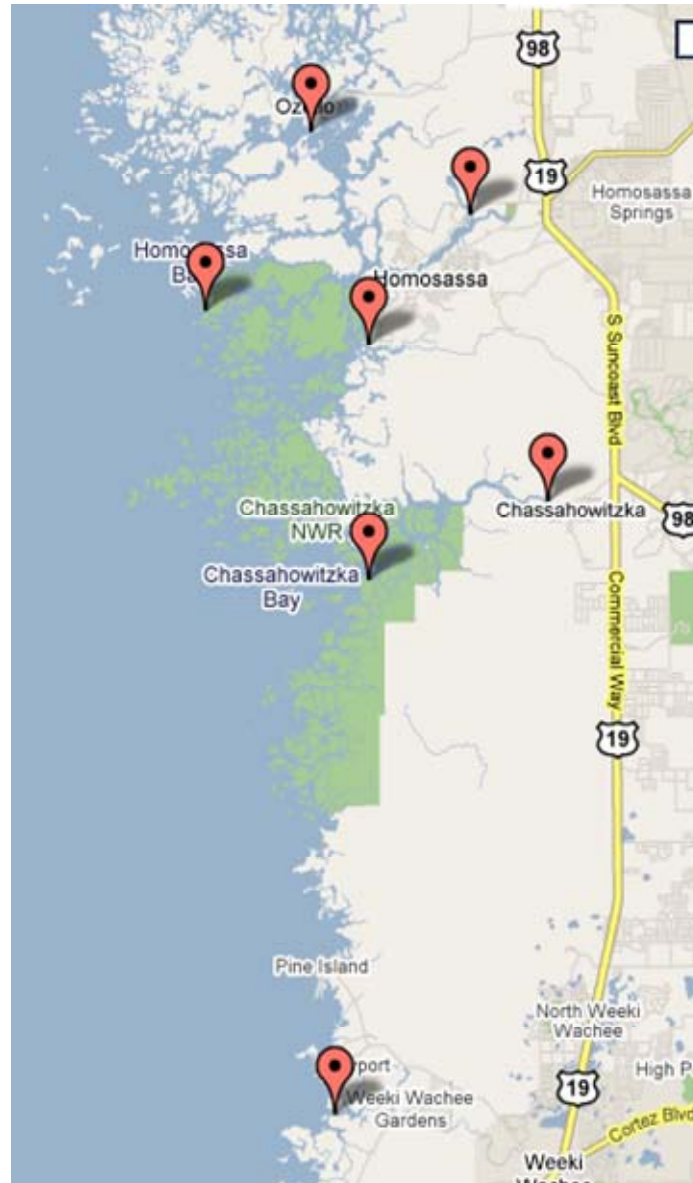
Figure 3: NOAA Gages Relevant to the Study Area.

Accretion rates in salt marshes were set to 4.0 mm/year. This value is the mean of two studies measuring accretion rates in the marshes of St. Marks, FL. (Cahoon et. al. 1995, and Hendrickson, J.C. 1997) The mean of two accretion rate observations taken from nearby Ochlockonee River, FL is similar (4.05 mm/year, Hendrickson, J.C. 1997)

Modeled U.S. Fish and Wildlife Service refuge boundaries are based on Approved Acquisition Boundaries as received from Kimberly Eldridge, lead cartographer with U.S. Fish and Wildlife Service, and are current as of June 2008.

The cell-size used for this analysis was 30 meter by 30 meter cells. However, the SLAMM model does track partial conversion of cells based on elevation and slope.

SUMMARY OF SLAMM INPUT PARAMETERS FOR CRYSTAL RIVER

Site	Crystal River
NED Source Date (yyyy)	1954
NWI_photo_date (yyyy)	1984
Direction_OffShore (N|S|E|W)	W
Historic_trend (mm/yr)	2.12
NAVD88_correction (MTL-NAVD88 in meters)	0.004
Water Depth (m below MLW- N/A)	2
TideRangeOcean (meters: MHHW-MLLW)	0.573
TideRangeInland (meters)	0.573
Mean High Water Spring (m above MTL)	0.381
MHSW Inland (m above MTL)	0.381
Marsh Erosion (horz meters/year)	1.8
Swamp Erosion (horz meters/year)	1
TFlat Erosion (horz meters/year) [from 0.5]	0.5
Salt marsh vertical accretion (mm/yr) Final	4.0
Brackish March vert. accretion (mm/yr) Final	4.7
Tidal Fresh vertical accretion (mm/yr) Final	5.9
Beach/T.Flat Sedimentation Rate (mm/yr)	0.5
Frequency of Large Storms (yr/washover)	25
Use Elevation Preprocessor for Wetlands	TRUE

Results

Crystal River National Wildlife Refuge is predicted to be vulnerable to Sea Level Rise, especially under more accelerated scenarios.

SLR by 2100 (m)	0.39	0.69	1	1.5
Brackish Marsh	0%	99%	100%	100%
Trans. Salt Marsh	0%	100%	100%	100%
Mangrove	-80%	-1833%	-1850%	76%
Dry Land	55%	67%	76%	95%
Swamp	97%	100%	100%	100%
Tidal Swamp	84%	100%	100%	100%
Tidal Fresh Marsh	0%	16%	90%	100%

**Predicted Loss Rates of Land Categories by 2100 Given Simulated
Scenarios of Eustatic Sea Level Rise**

Maps of SLAMM input and output to follow will use the following legend:
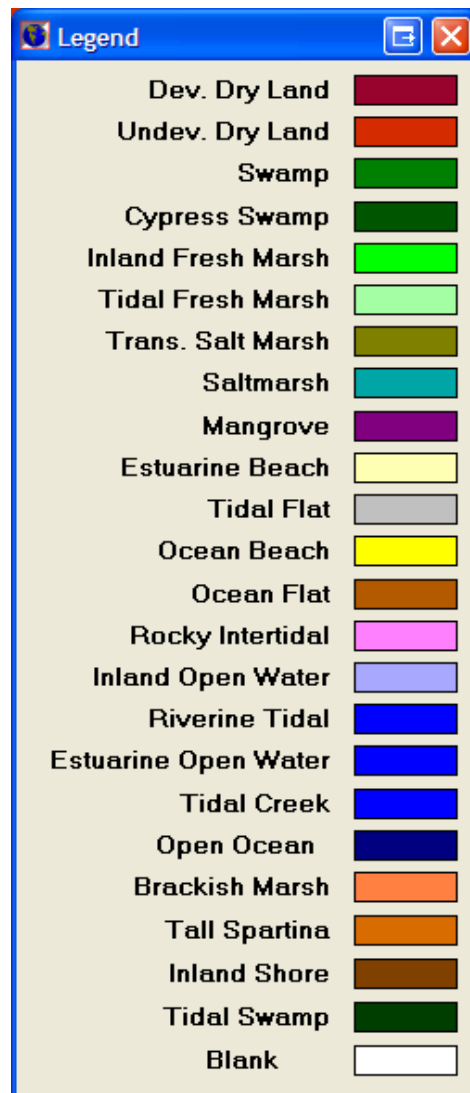
Crystal River

IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

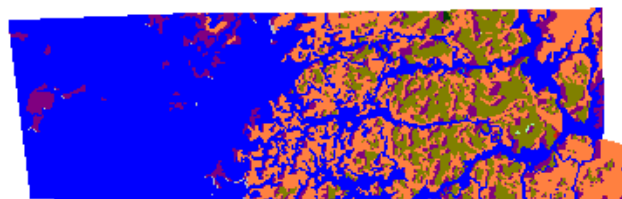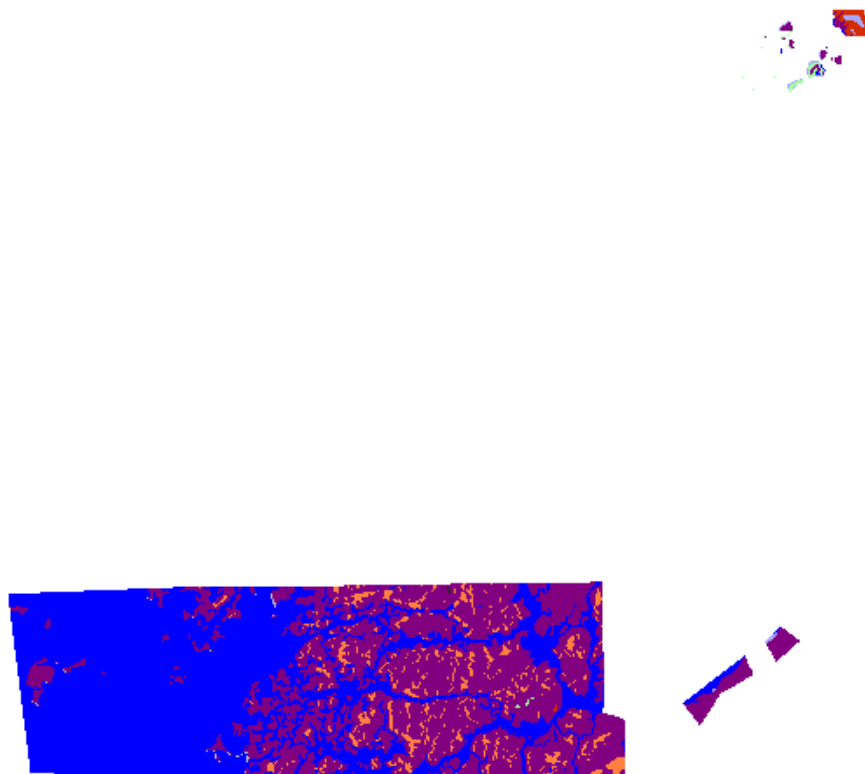|	Initial	2025	2050	2075	2100
Estuarine Open Water	4363.4	4363.6	4392.8	4403.5	4411.3
Brackish Marsh	2113.6	2110.1	2106.2	2105.3	2105.3
Trans. Salt Marsh	1400.9	1400.9	1400.9	1400.9	1400.9
Mangrove	200.4	253.2	307.0	340.7	360.0
Dry Land	110.1	85.1	66.4	56.5	50.1
Swamp	87.4	58.7	29.2	11.9	2.6
Inland Open Water	57.6	57.6	33.1	27.4	22.7
Tidal Swamp	32.9	26.9	19.2	10.7	5.3
Tidal Fresh Marsh	18.2	18.2	18.2	18.2	18.2
Riverine Tidal	2.0	2.0	2.0	1.6	0.7
Estuarine Beach	0.9	0.7	0.5	0.2	0.0
Saltmarsh	0.4	0.4	0.4	0.4	0.4
Tidal Flat	0.0	10.4	11.9	10.5	10.4
Total (incl. water)	**8387.8**	**8387.8**	**8387.8**	**8387.8**	**8387.8**
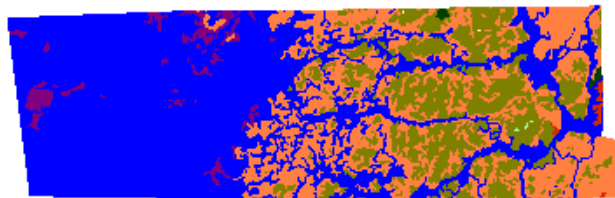
Crystal River, Initial Condition
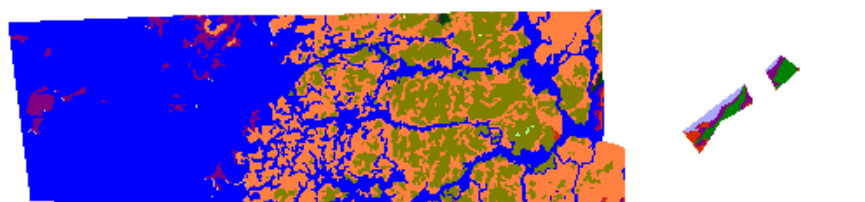
Crystal River, 2025, Scenario A1B Mean
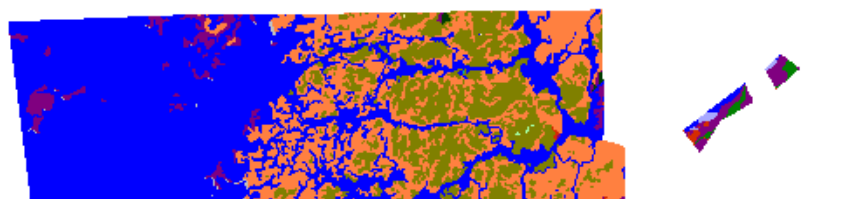
Crystal River, 2050, Scenario A1B Mean
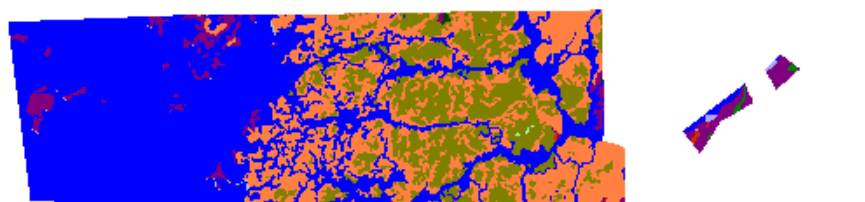
Crystal River, 2075, Scenario A1B Mean
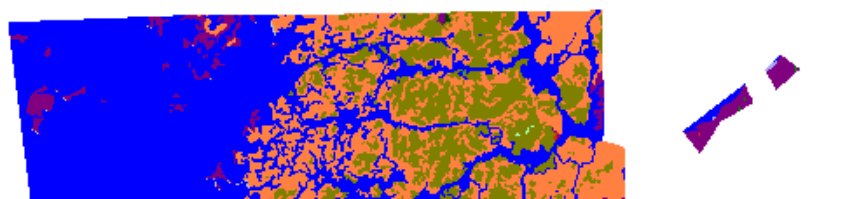
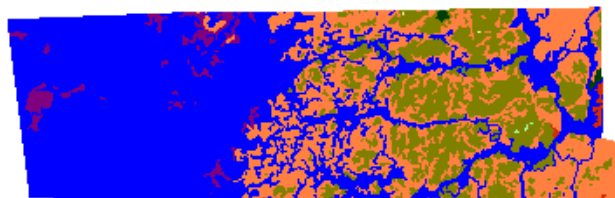Crystal River, 2100, Scenario A1B Mean

Crystal River

IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Estuarine Open Water	4363.4	4363.7	4395.8	4410.1	4421.2
Brackish Marsh	2113.6	2110.1	1848.6	414.3	19.0
Trans. Salt Marsh	1400.9	1400.9	1030.7	0.2	0.0
Mangrove	200.4	284.7	971.2	3467.7	3873.4
Dry Land	110.1	75.6	57.0	43.2	36.1
Swamp	87.4	41.8	12.2	0.0	0.0
Inland Open Water	57.6	57.6	30.9	22.7	18.9
Tidal Swamp	32.9	21.8	9.6	1.3	0.0
Tidal Fresh Marsh	18.2	18.2	18.2	17.9	15.3
Riverine Tidal	2.0	2.0	1.6	0.2	0.2
Estuarine Beach	0.9	0.6	0.2	0.0	0.0
Saltmarsh	0.4	0.4	0.4	0.2	0.0
Tidal Flat	0.0	10.5	11.5	10.0	3.8
Total (incl. water)	**8387.8**	**8387.8**	**8387.8**	**8387.8**	**8387.8**
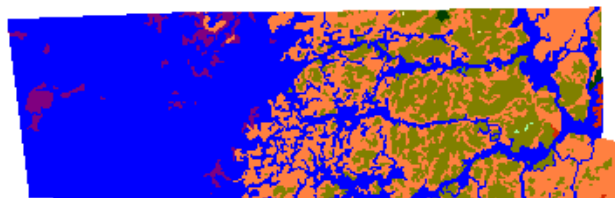
Crystal River, Initial Condition
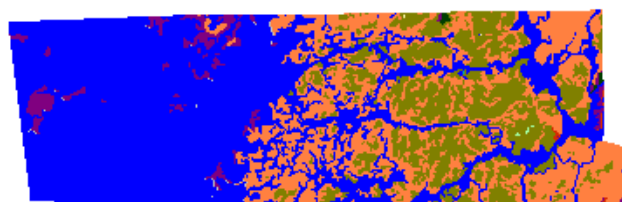
Crystal River, 2025, Scenario A1B Maximum

Crystal River, 2050, Scenario A1B Maximum

Crystal River, 2075, Scenario A1B Maximum
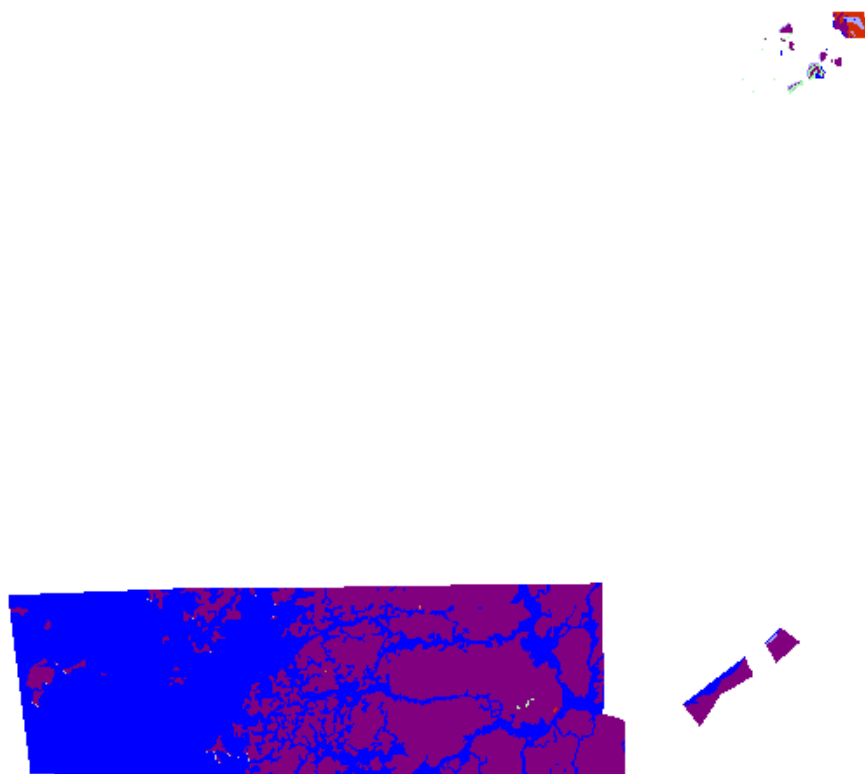
Crystal River, 2100, Scenario A1B Maximum

Crystal River

1 Meter Eustatic SLR by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Estuarine Open Water	4363.4	4363.9	4400.4	4421.6	4434.4
Brackish Marsh	2113.6	1819.1	274.2	0.0	0.0
Trans. Salt Marsh	1400.9	986.8	0.0	0.0	0.0
Mangrove	200.4	1018.2	3601.5	3899.1	3907.8
Dry Land	110.1	66.2	50.6	36.3	26.3
Swamp	87.4	27.2	2.2	0.0	0.0
Inland Open Water	57.6	57.6	27.4	17.6	9.6
Tidal Swamp	32.9	16.2	3.5	0.0	0.0
Tidal Fresh Marsh	18.2	18.2	16.0	8.5	1.8
Riverine Tidal	2.0	2.0	0.9	0.2	0.0
Estuarine Beach	0.9	0.4	0.0	0.0	0.0
Saltmarsh	0.4	0.4	0.2	0.0	0.0
Tidal Flat	0.0	11.7	10.9	4.5	8.0
Total (incl. water)	**8387.8**	**8387.8**	**8387.8**	**8387.8**	**8387.8**

Crystal River, Initial Condition
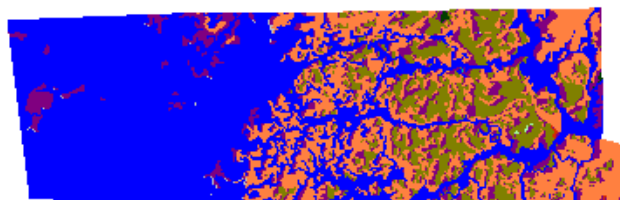
Crystal River, 2025, 1 meter eustatic SLR by 2100
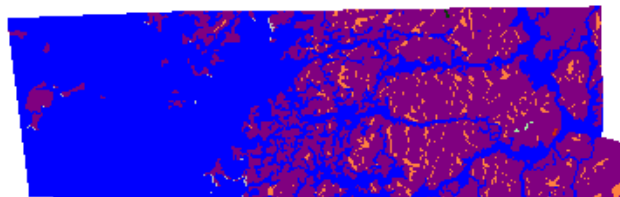
Crystal River, 2050, 1 meter eustatic SLR by 2100
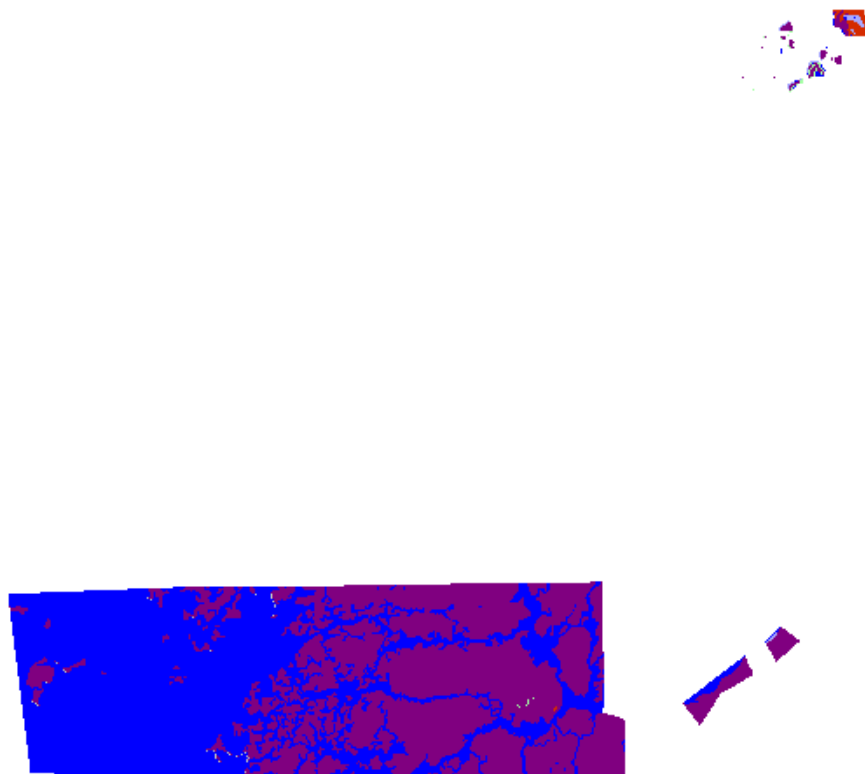
Crystal River, 2075, 1 meter eustatic SLR by 2100
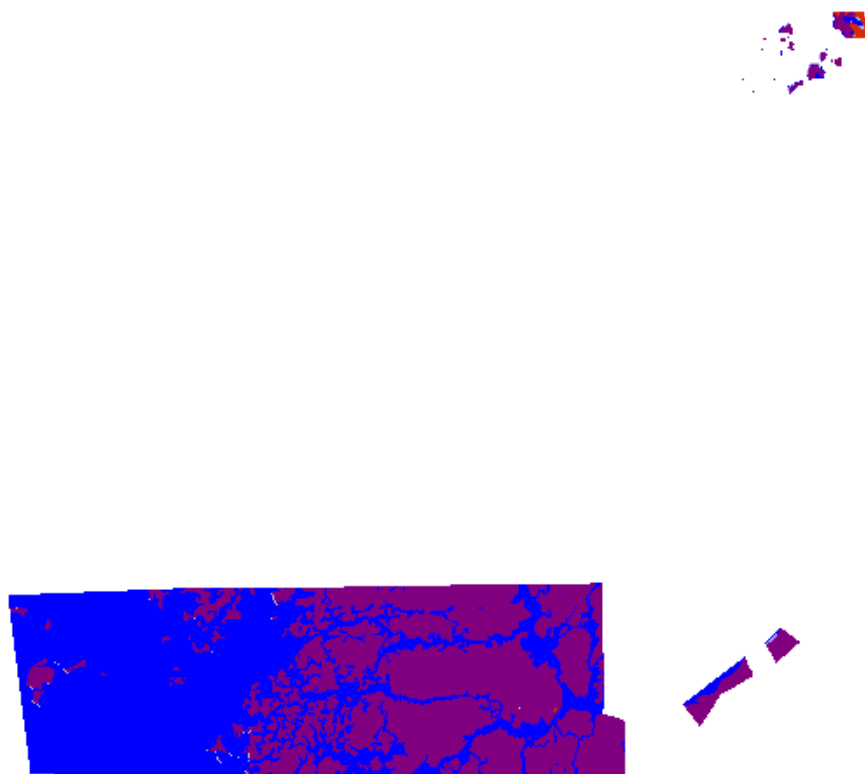
Crystal River, 2100, 1 meter eustatic SLR by 2100

Crystal River
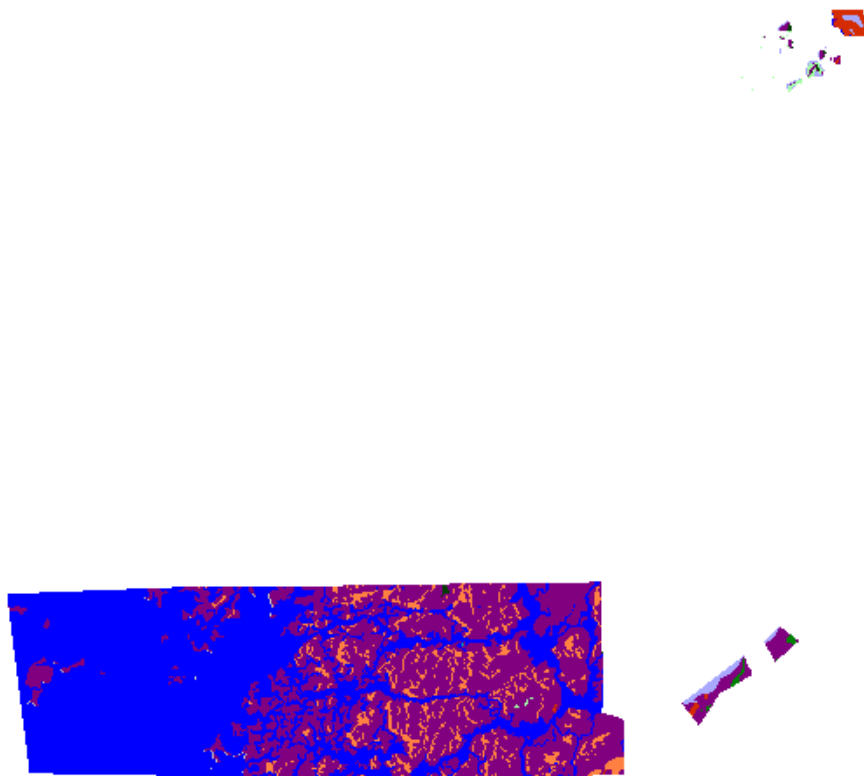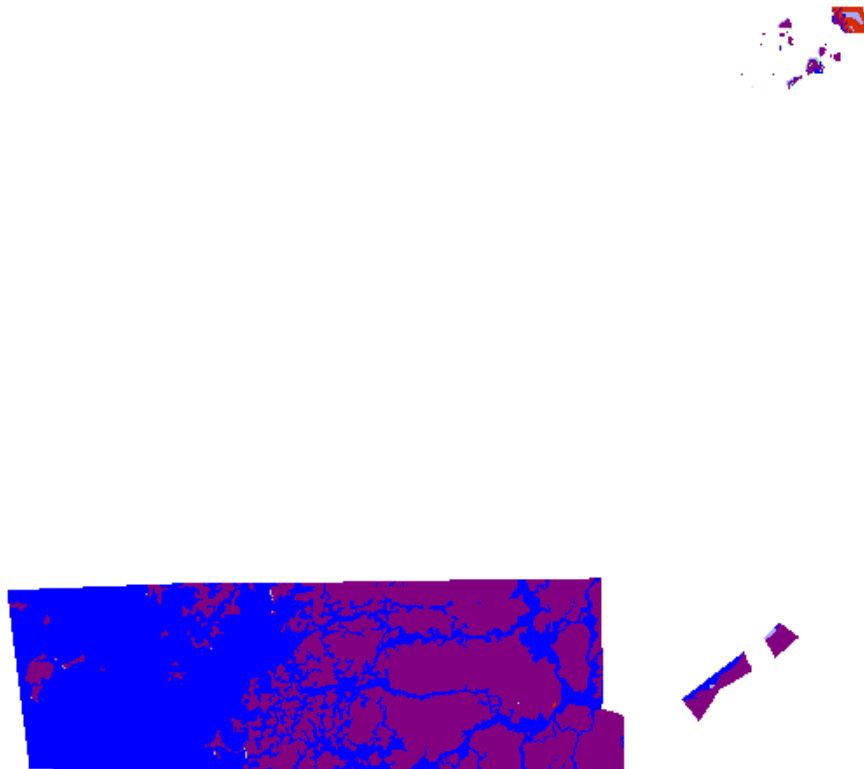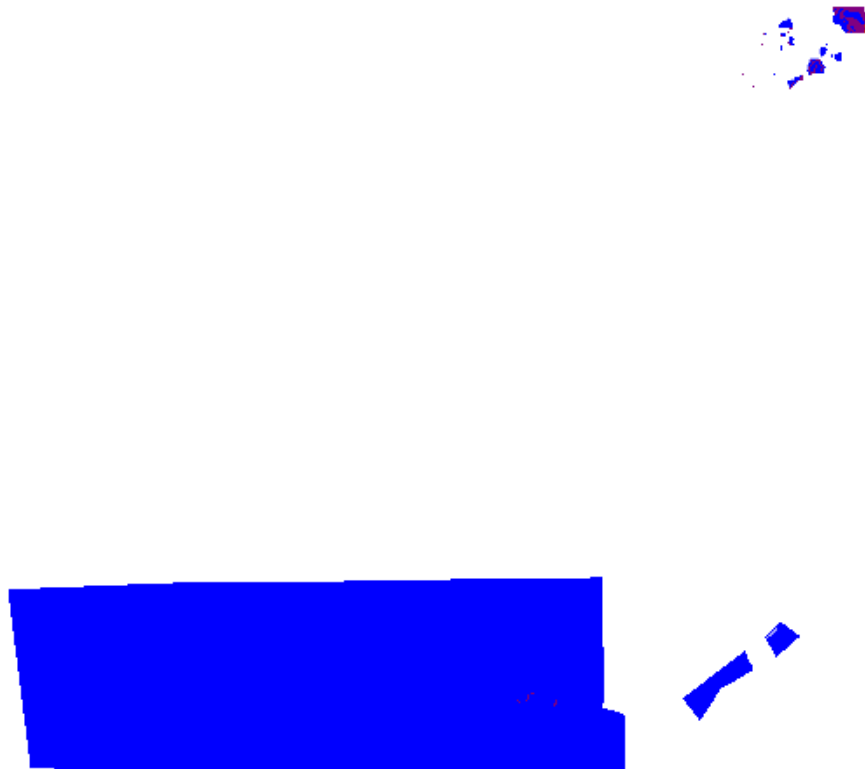
1.5 Meters Eustatic SLR by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Estuarine Open Water	4363.4	4364.2	4413.0	6651.8	8328.8
Brackish Marsh	2113.6	439.5	0.0	0.0	0.0
Trans. Salt Marsh	1400.9	0.4	0.0	0.0	0.0
Mangrove	200.4	3416.0	3903.4	1701.2	47.6
Dry Land	110.1	58.2	38.6	25.1	5.0
Swamp	87.4	13.9	0.0	0.0	0.0
Inland Open Water	57.6	57.6	20.2	9.3	6.4
Tidal Swamp	32.9	9.3	0.0	0.0	0.0
Tidal Fresh Marsh	18.2	16.0	6.1	0.1	0.0
Riverine Tidal	2.0	2.0	0.2	0.0	0.0
Estuarine Beach	0.9	0.2	0.0	0.0	0.0
Saltmarsh	0.4	0.2	0.0	0.0	0.0
Tidal Flat	0.0	10.3	6.3	0.3	0.0
Total (incl. water)	**8387.8**	**8387.8**	**8387.8**	**8387.8**	**8387.8**
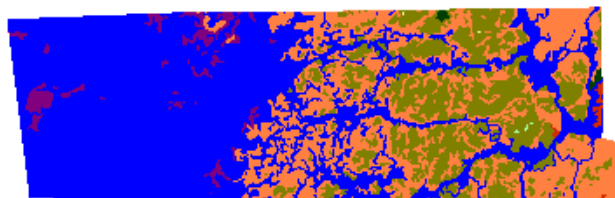
Crystal River, Initial Condition

Crystal River, 2025, 1.5 meter eustatic SLR by 2100

Crystal River, 2050, 1.5 meter eustatic SLR by 2100

Crystal River, 2075, 1.5 meter eustatic SLR by 2100

Crystal River, 2100, 1.5 meter eustatic SLR by 2100

Discussion:

The predicted progression of sea level rise effects on Crystal River NWR is as follows:

- Under lower rates of sea level rise, small portions of irregularly flooded marsh (herein referred to as "brackish marsh") are subject to more frequent inundation making them prone to inhabitation by mangroves.
- Under moderate rates of sea level rise, the loss of brackish marsh is extreme and mangroves are predicted to dominate the entire ecosystem.
- Under the highest rates of sea level rise, even the mangroves are predicted to be lost as their accretion rate cannot keep pace with Sea Level Rise.

As noted above, the elevation data at this site are subject to considerable uncertainty, as they are based on a map with five foot contours and few if any contours showing on the source map. A reexamination of these results may be warranted when high resolution LiDAR data becomes available over the next few years.

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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. These results maps 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.
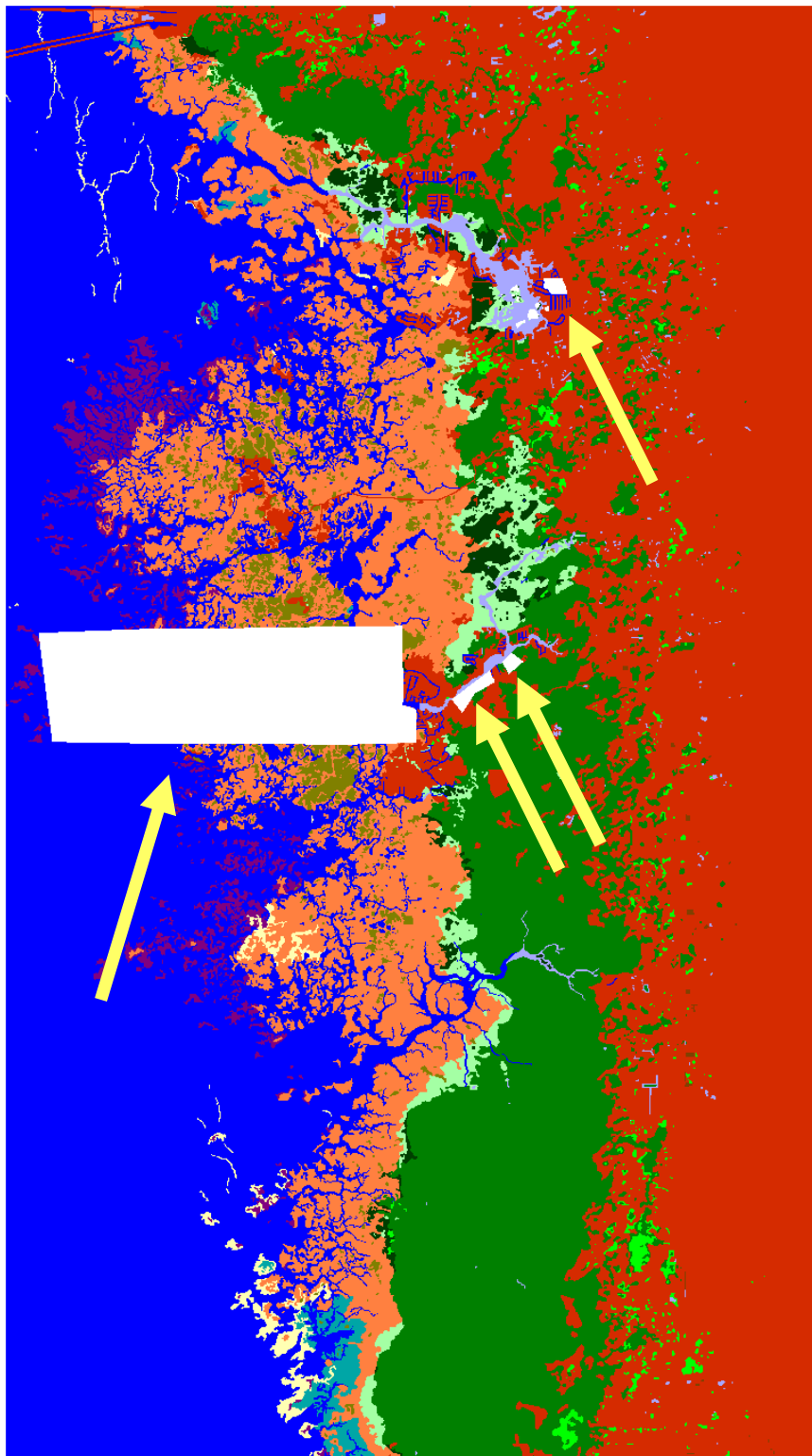
Location of Crystal River National Wildlife Refuge (white areas) within simulation context
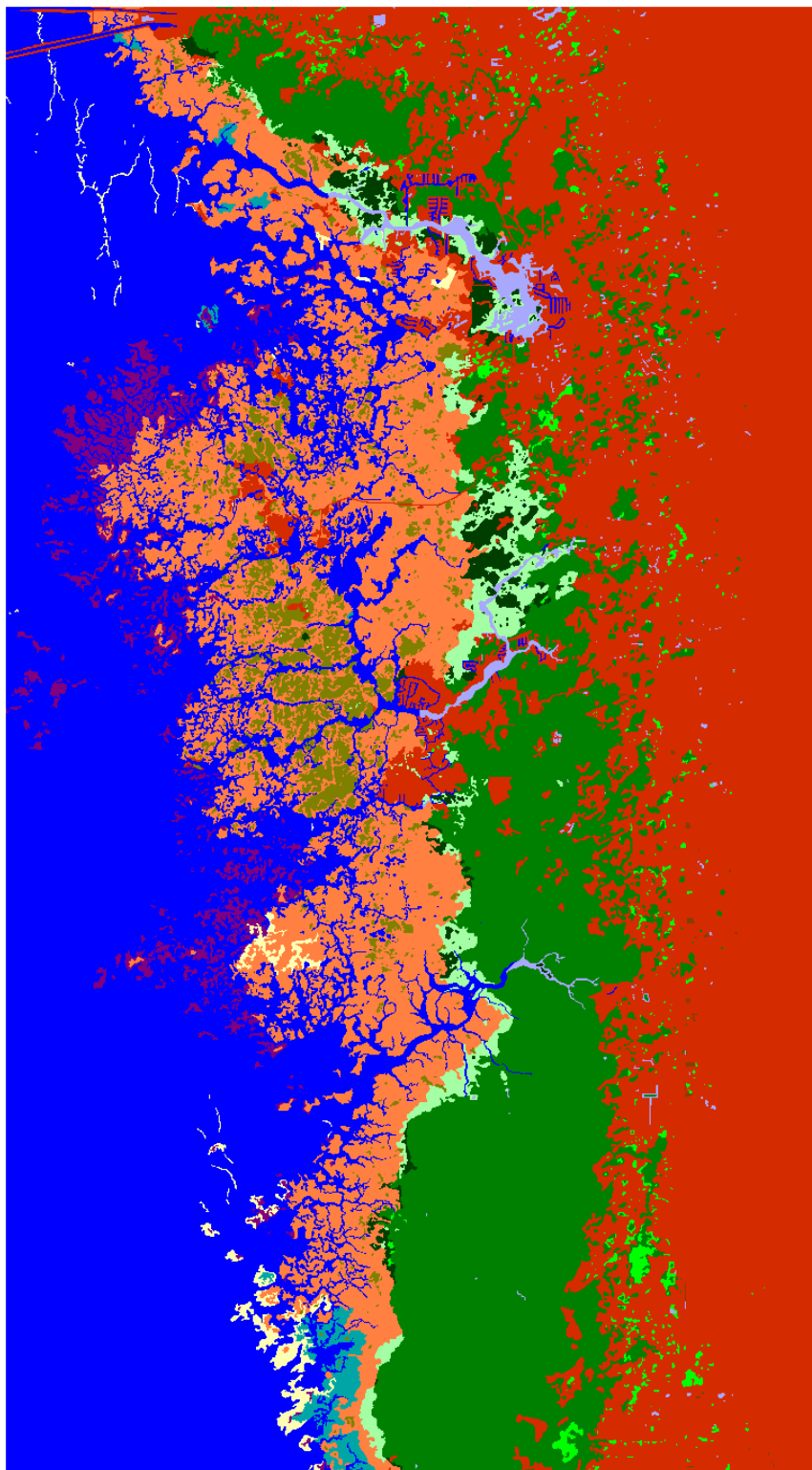
Crystal River Context, Initial Condition
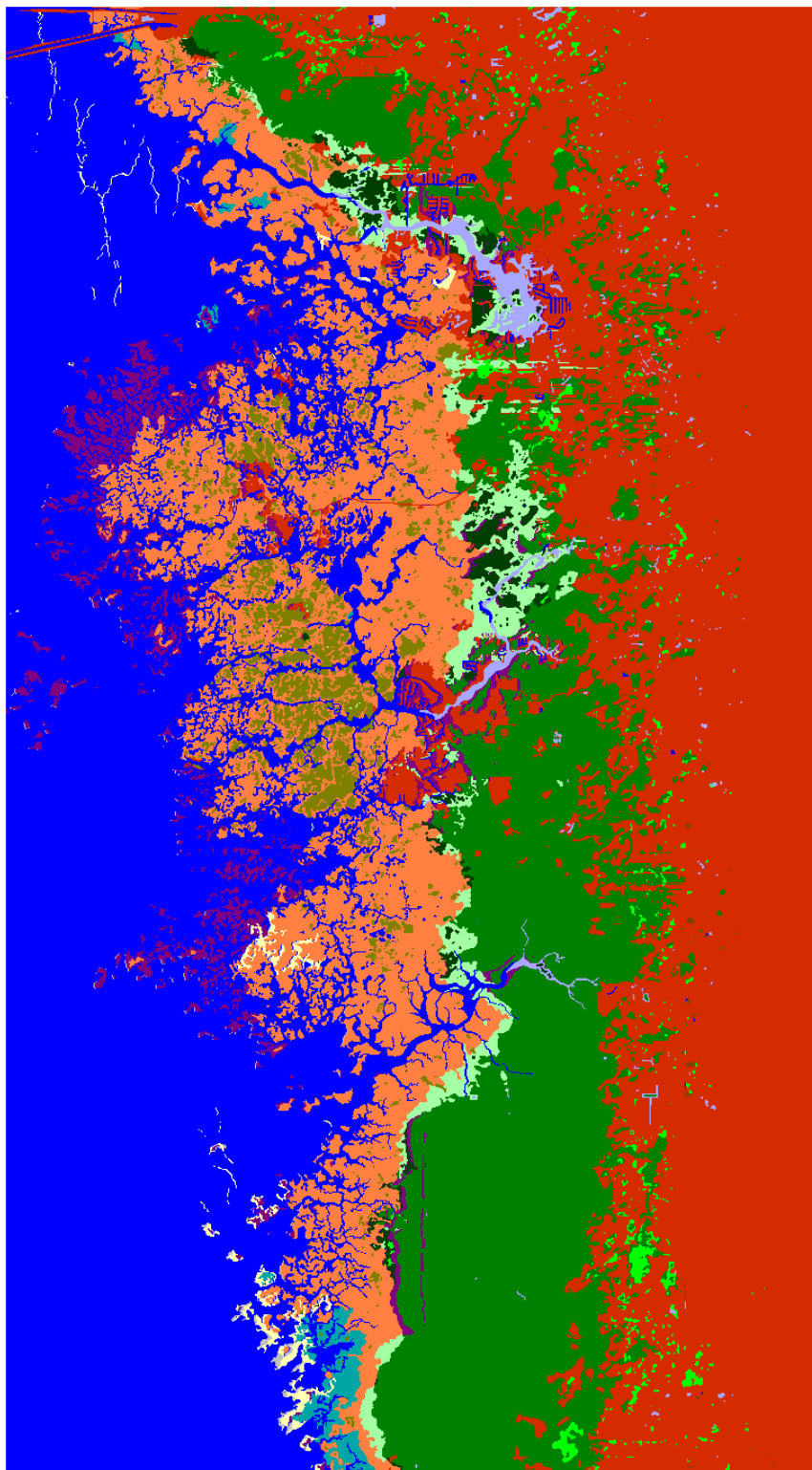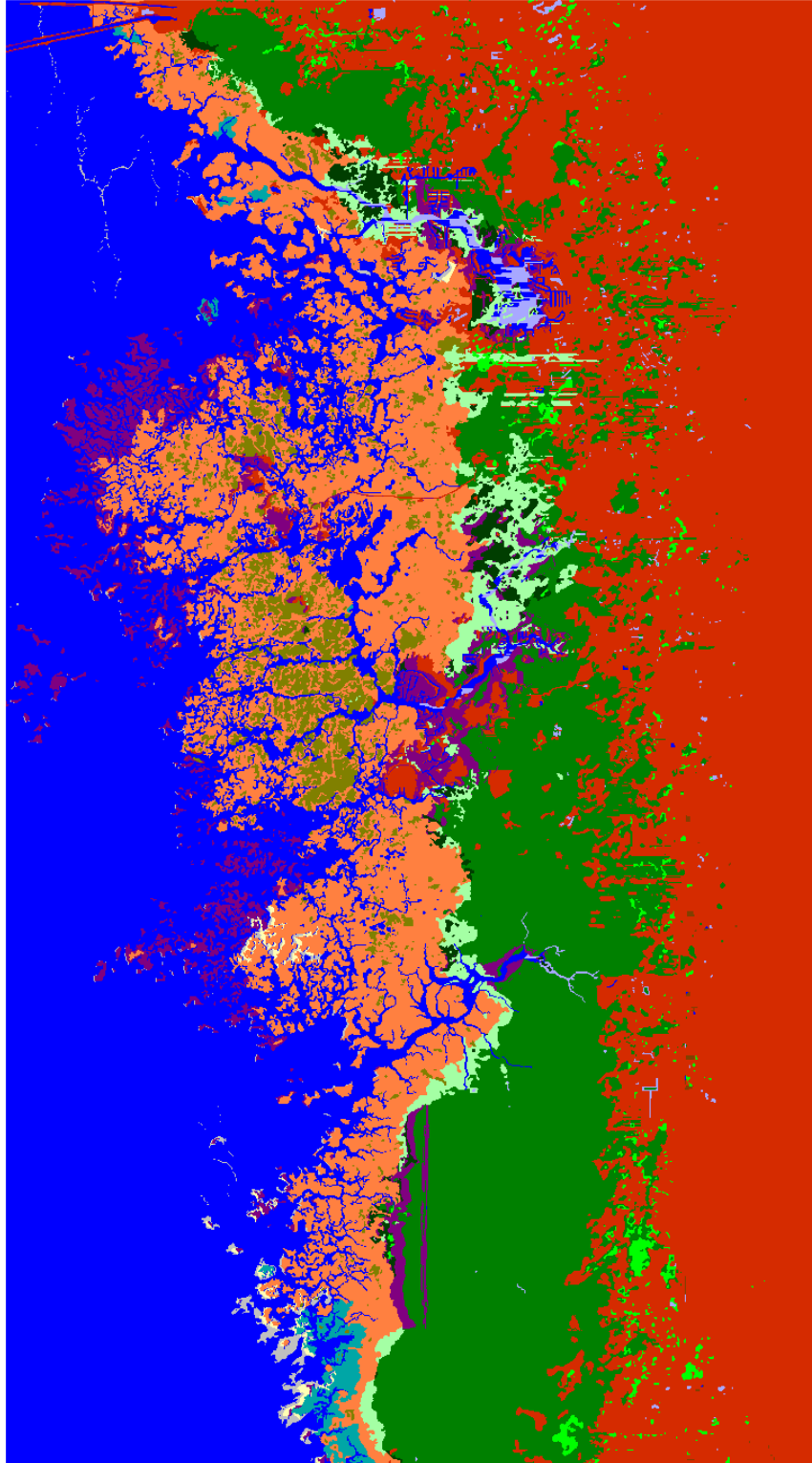
Crystal River Context, 2025, Scenario A1B Mean

Crystal River Context, 2050, Scenario A1B Mean

Crystal River Context, 2075, Scenario A1B Mean
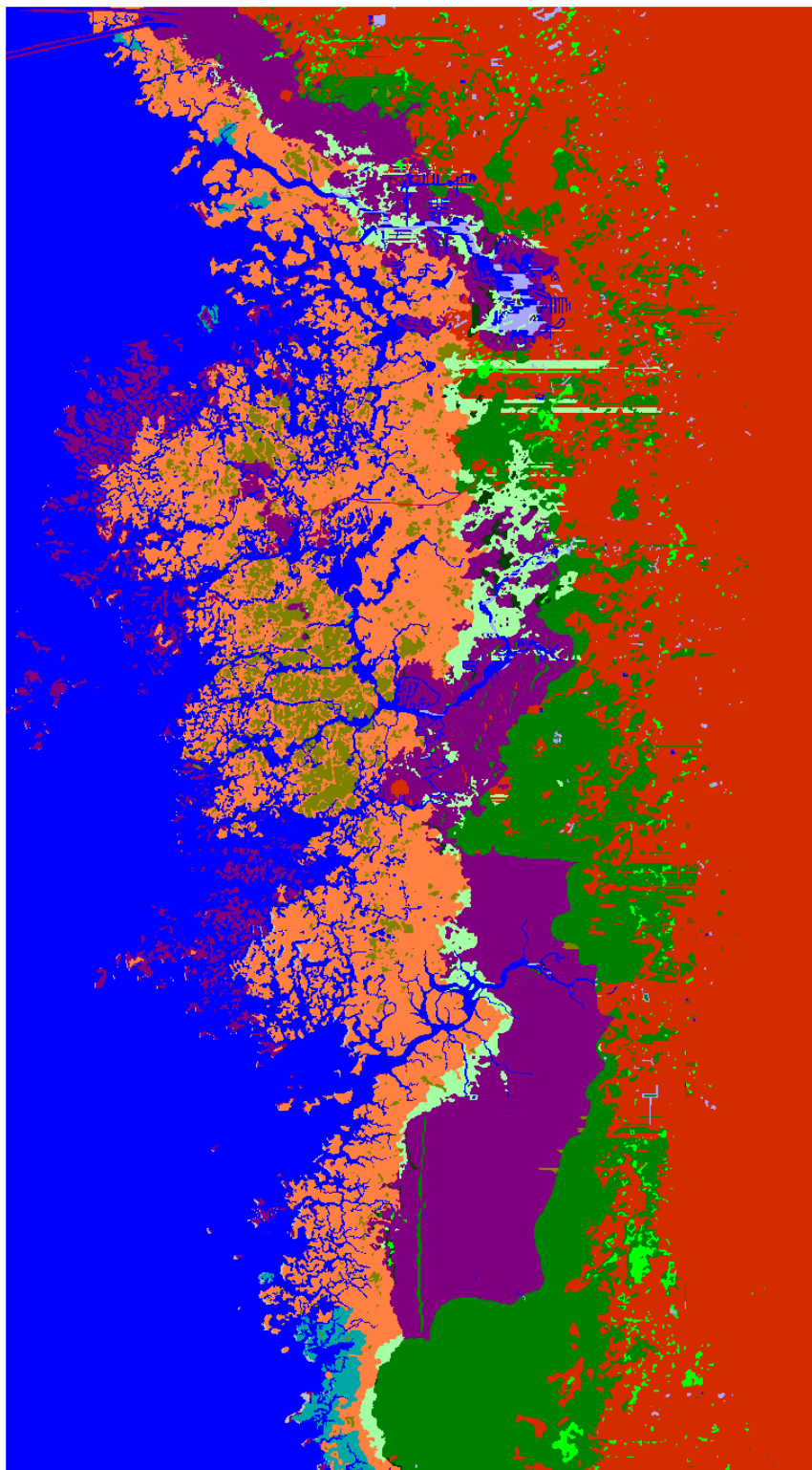
Crystal River Context, 2100, Scenario A1B Mean
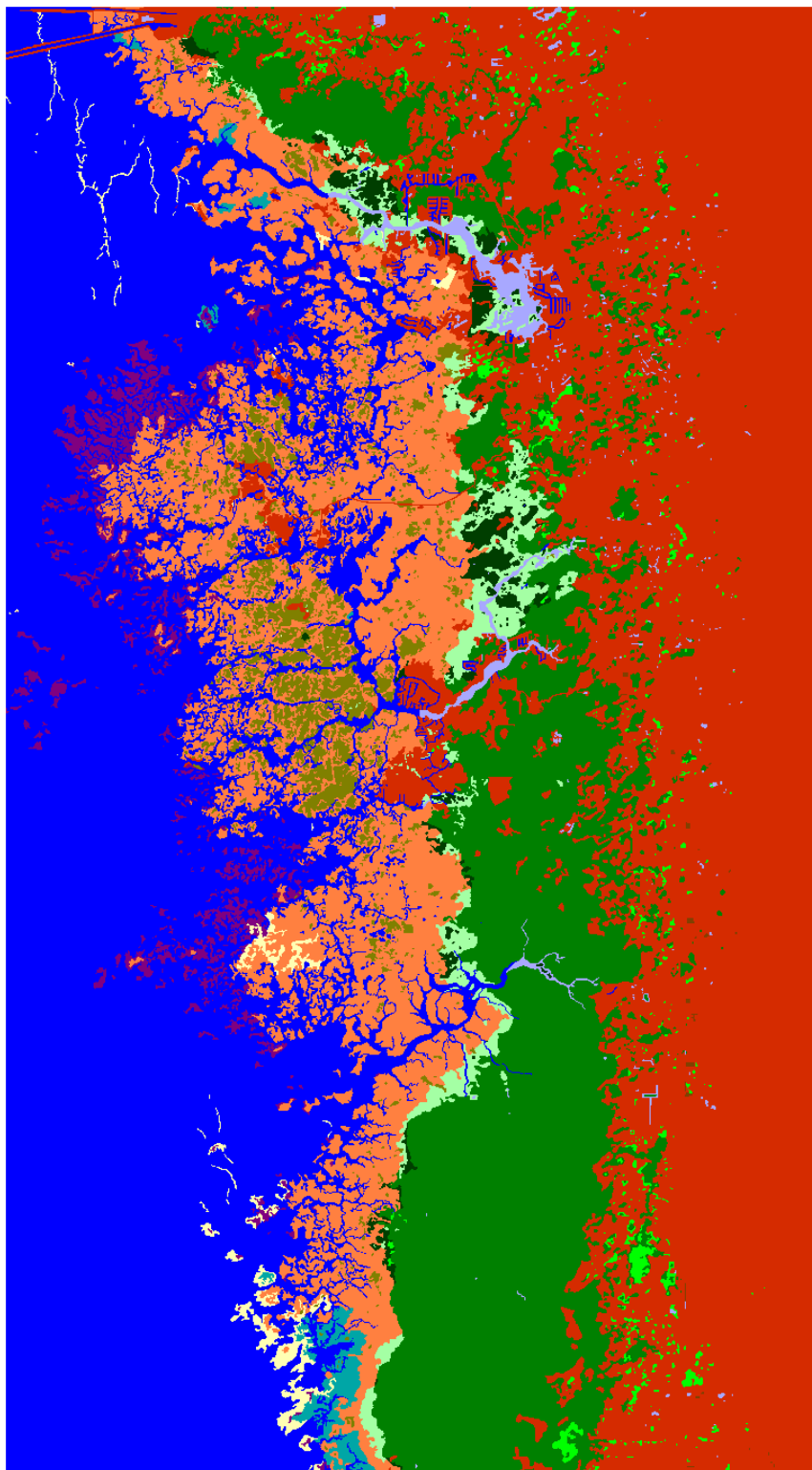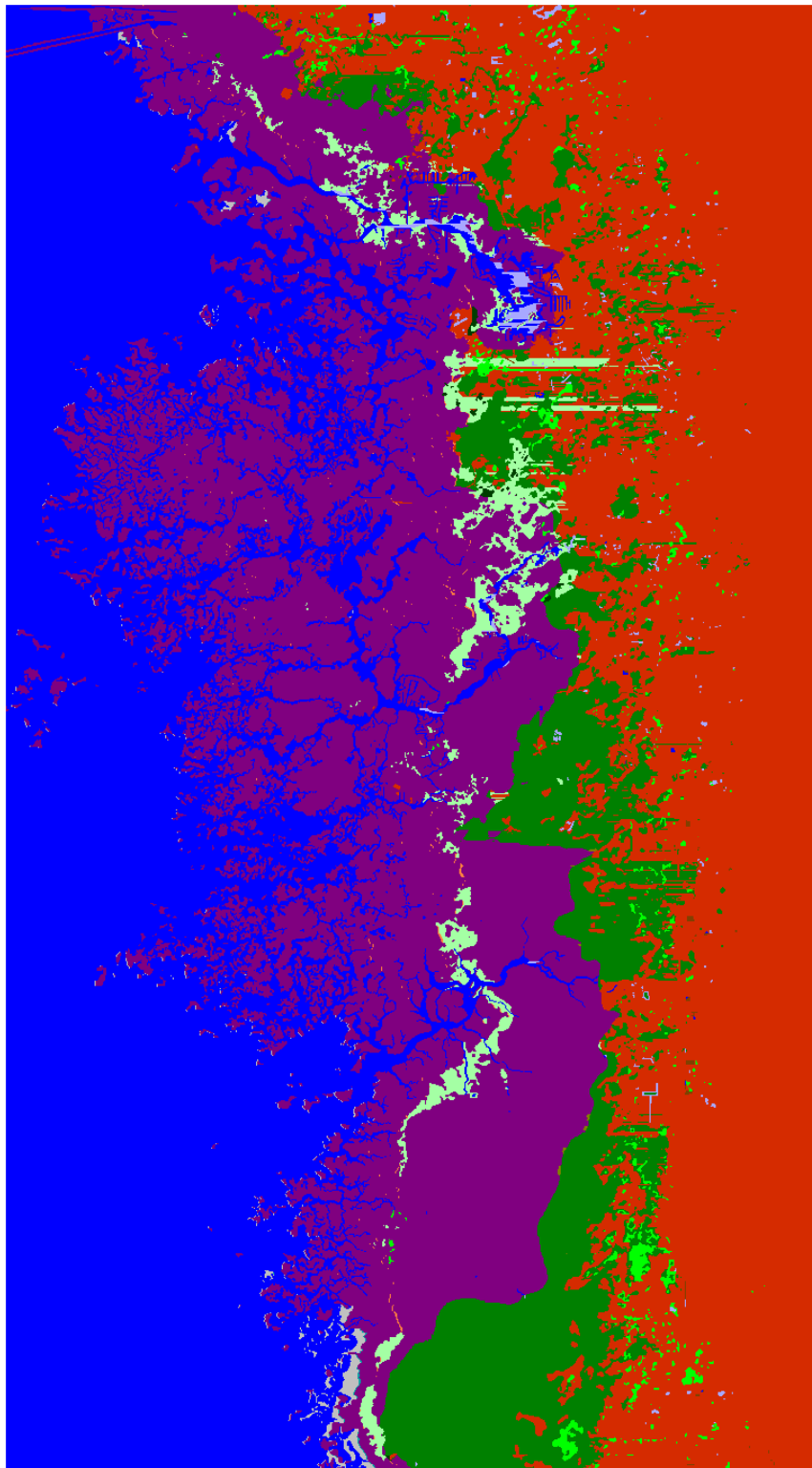
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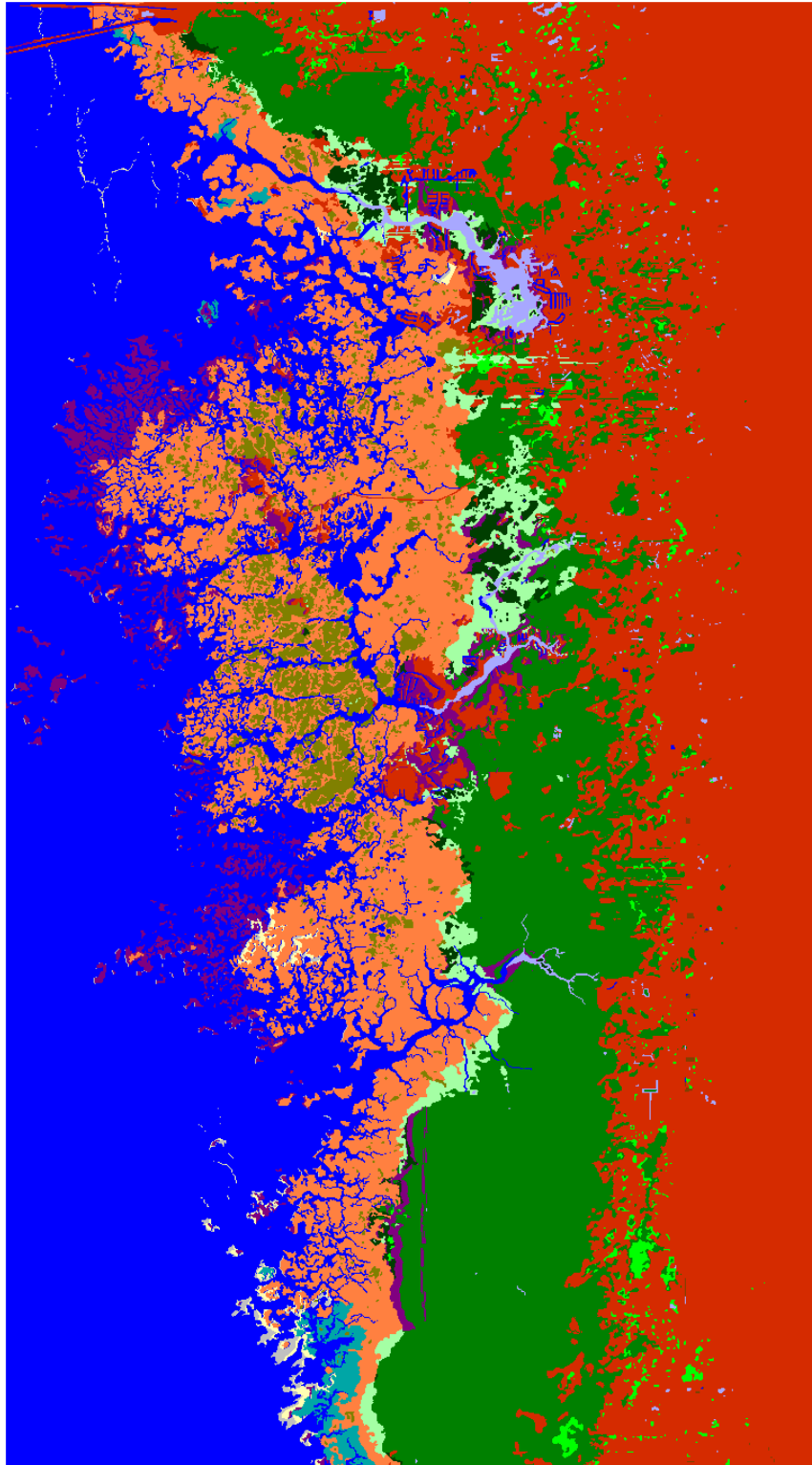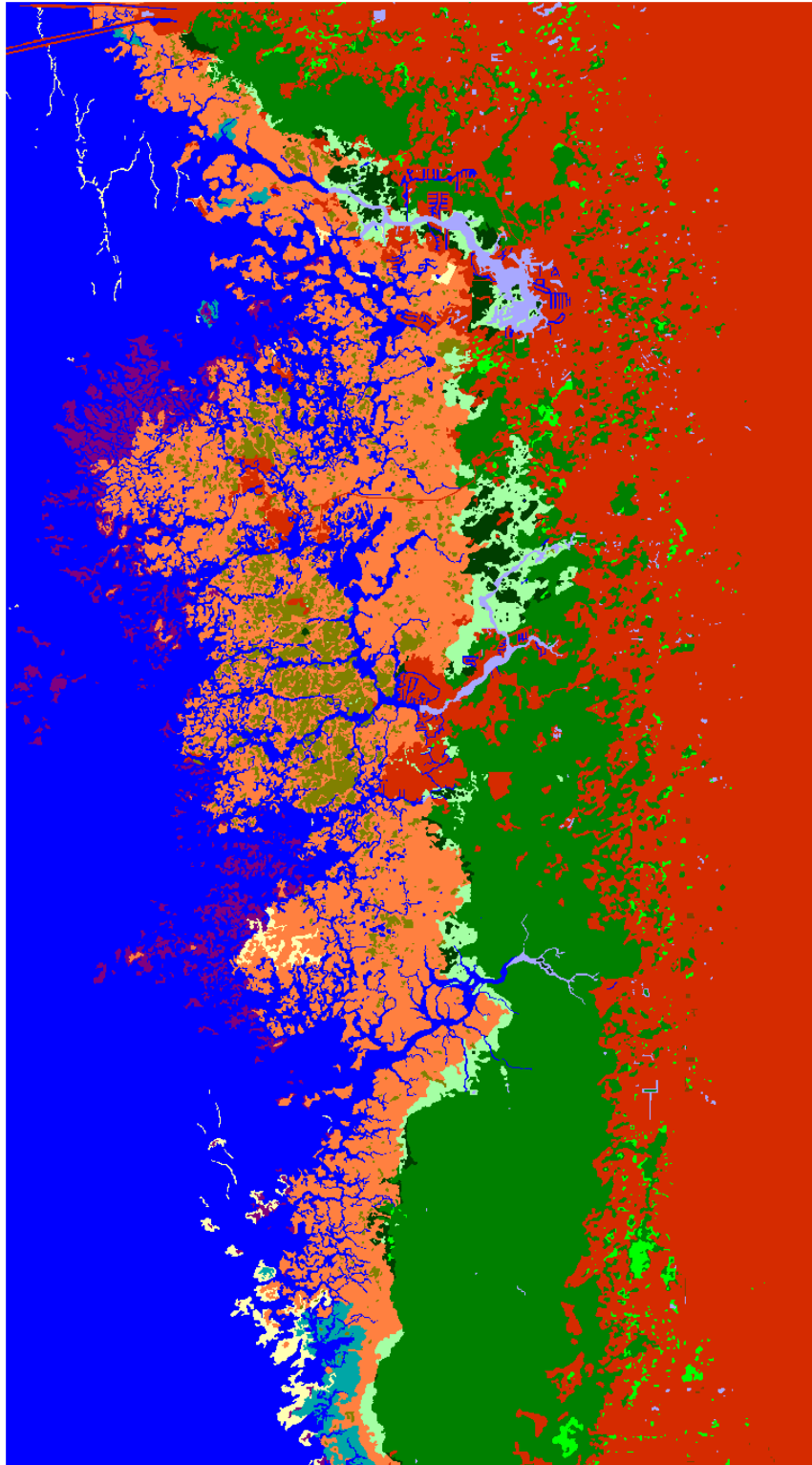
Crystal River Context, 2025, Scenario A1B Maximum
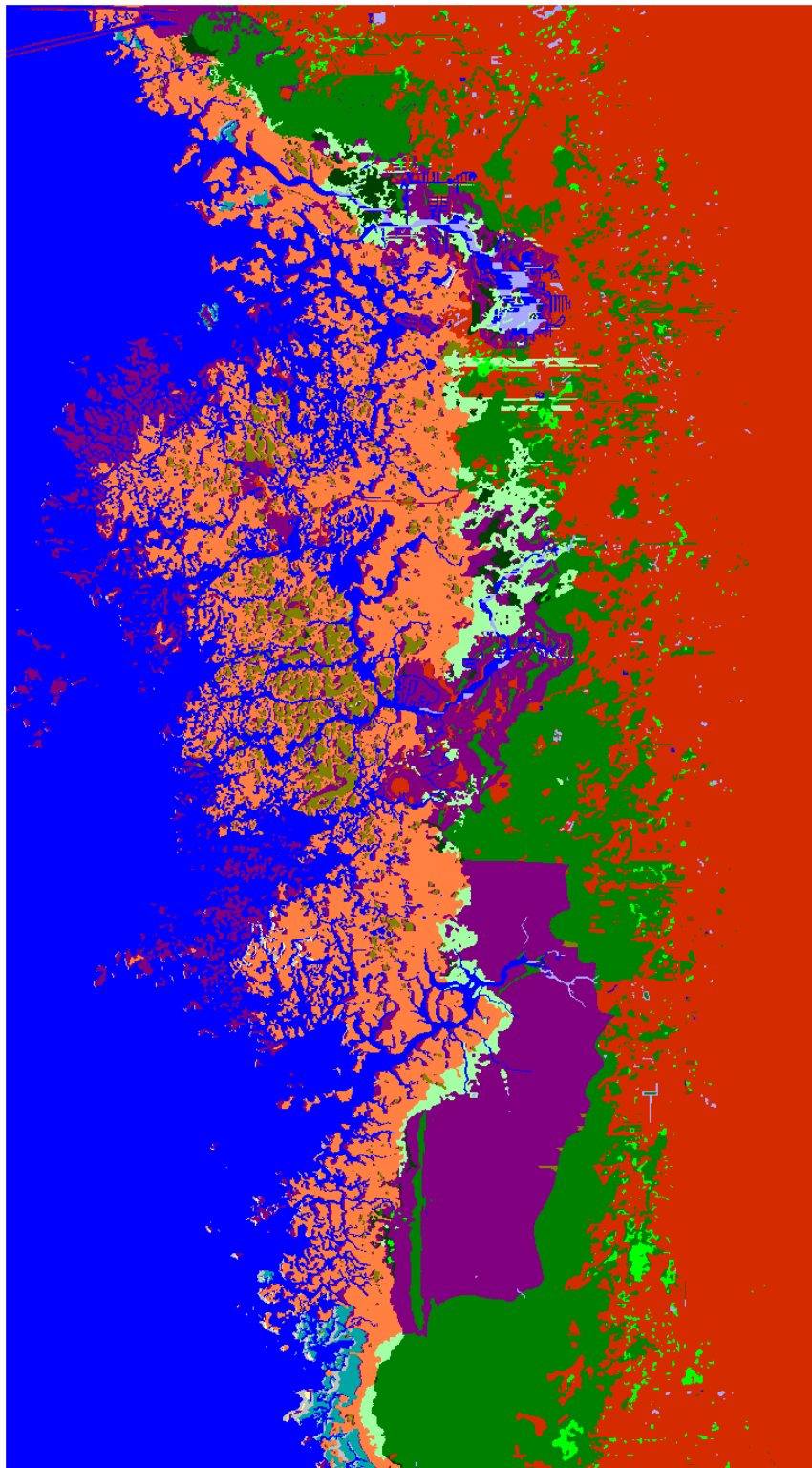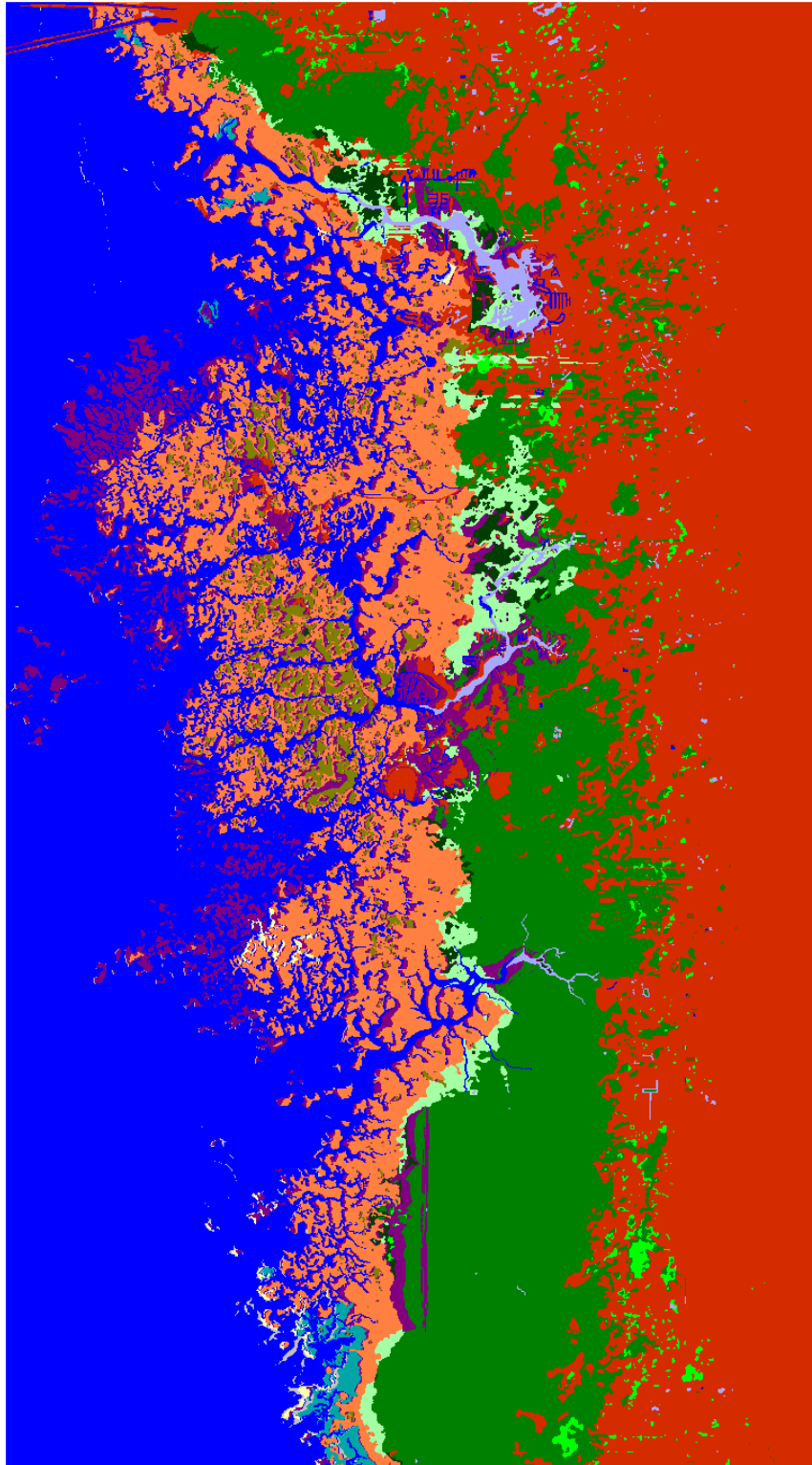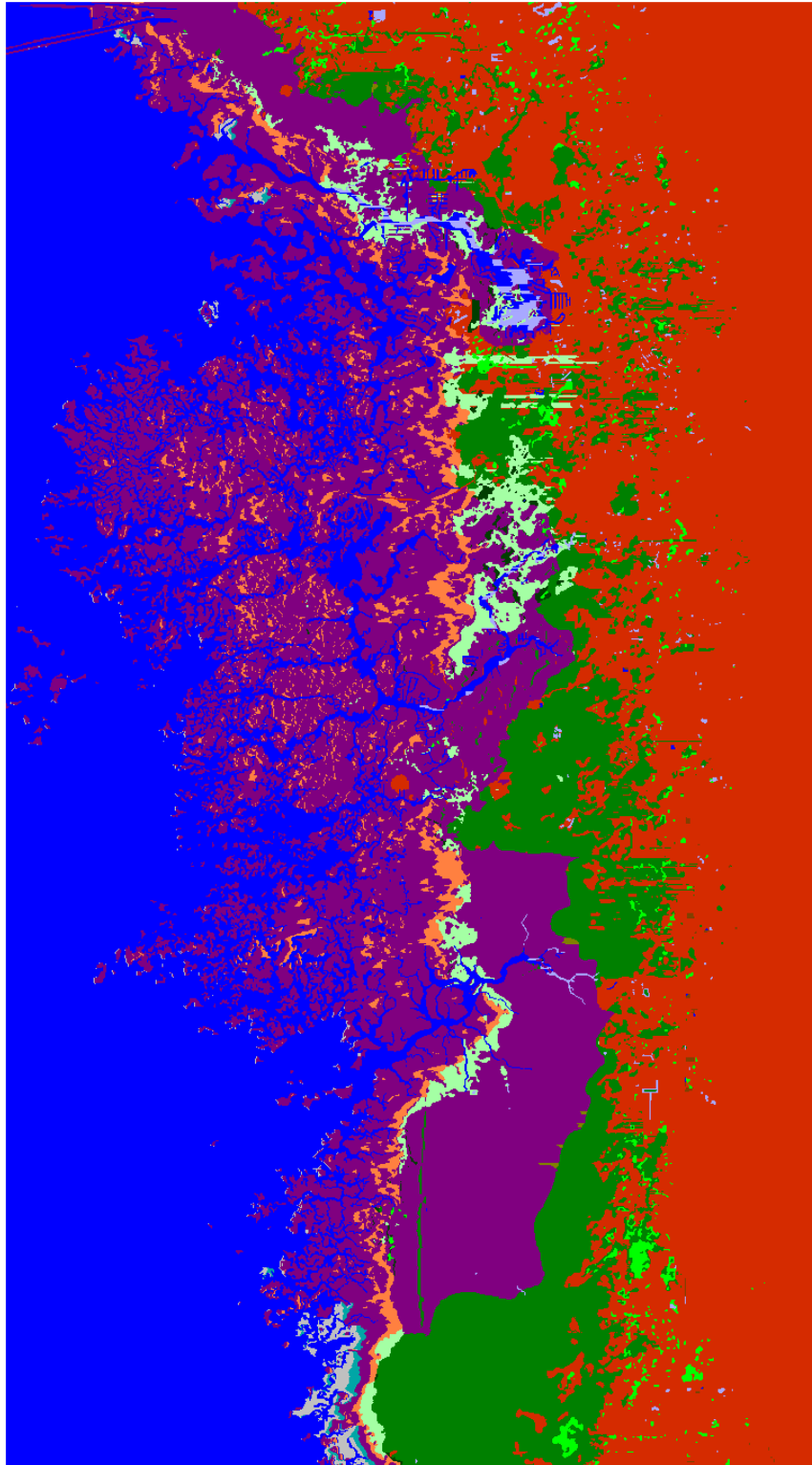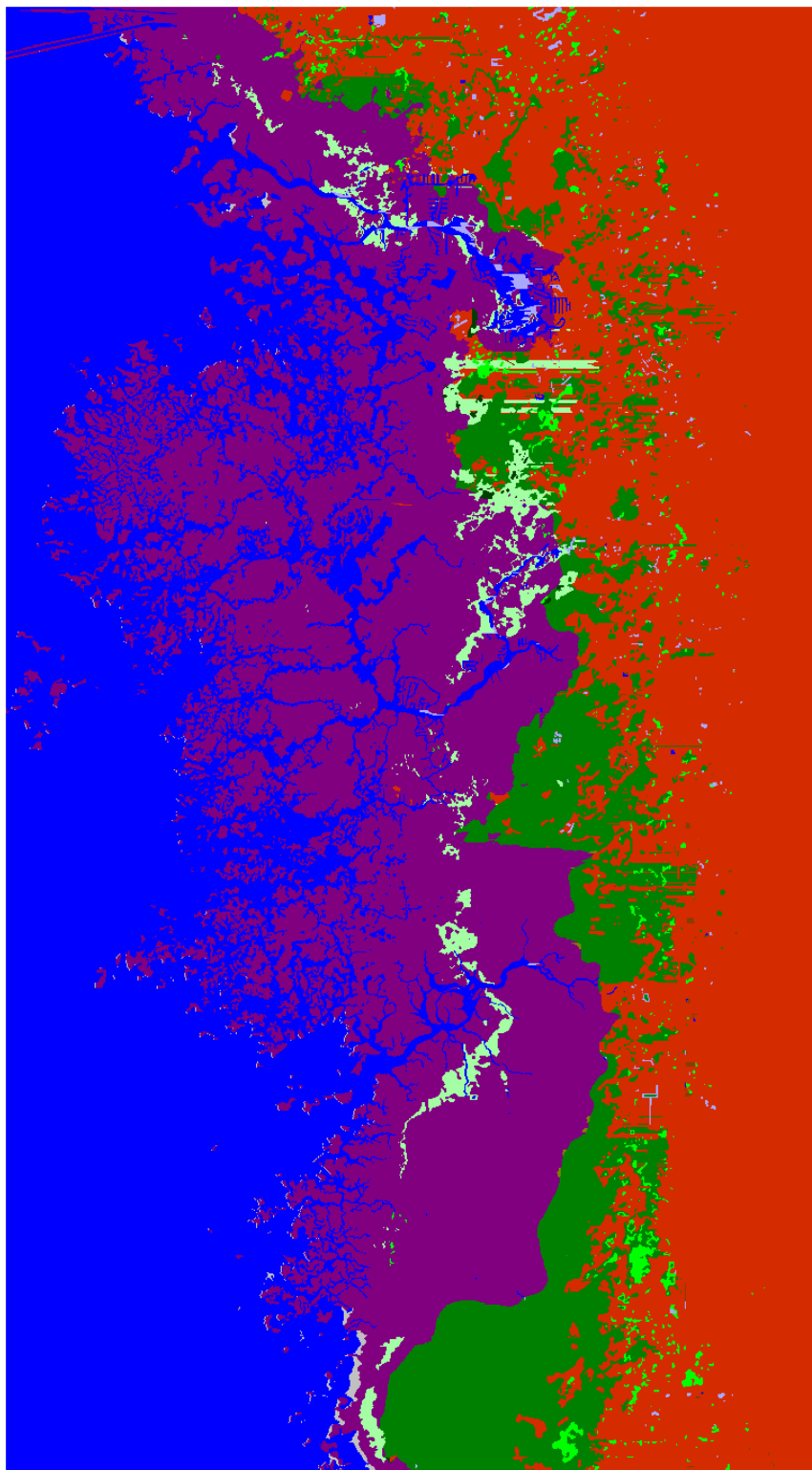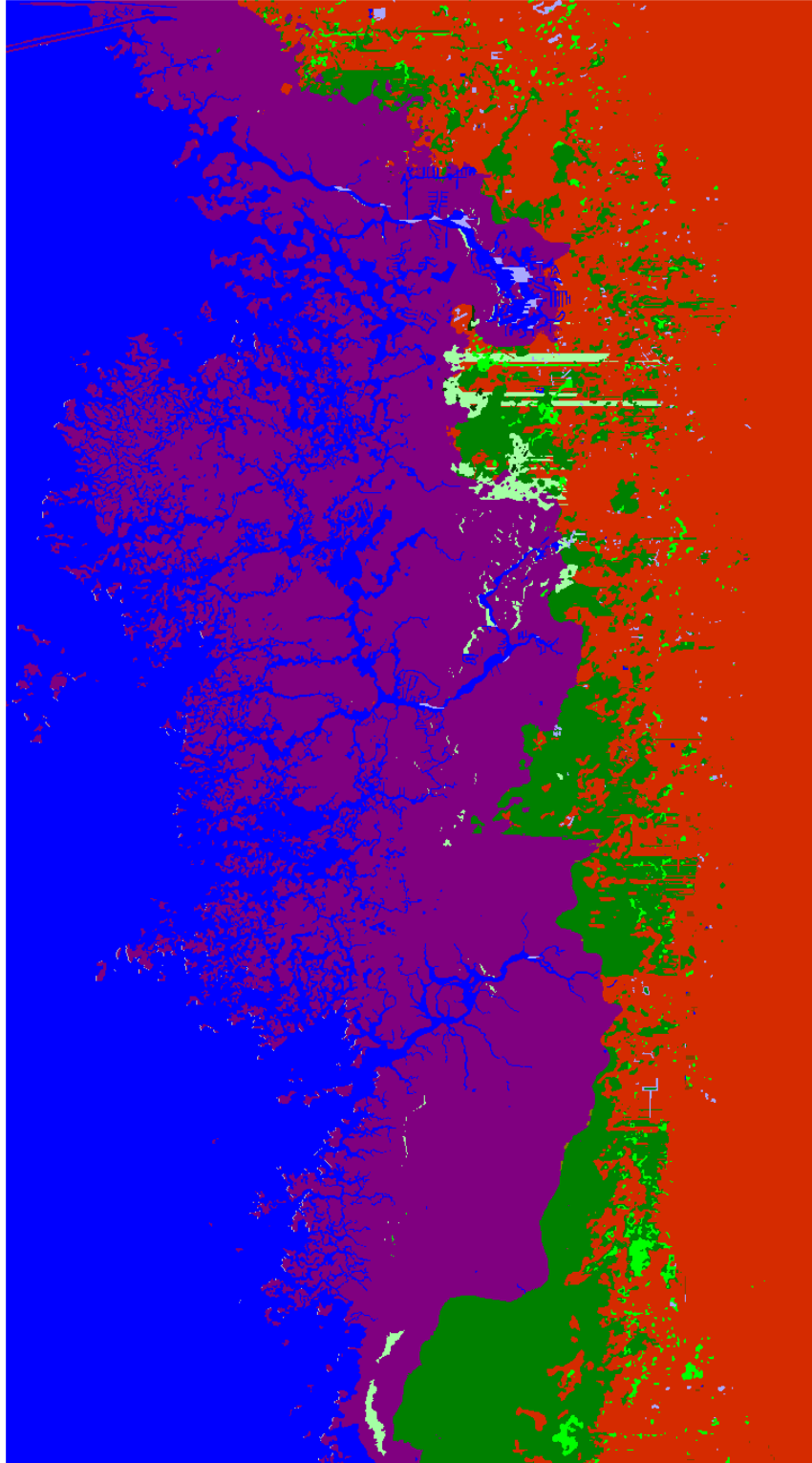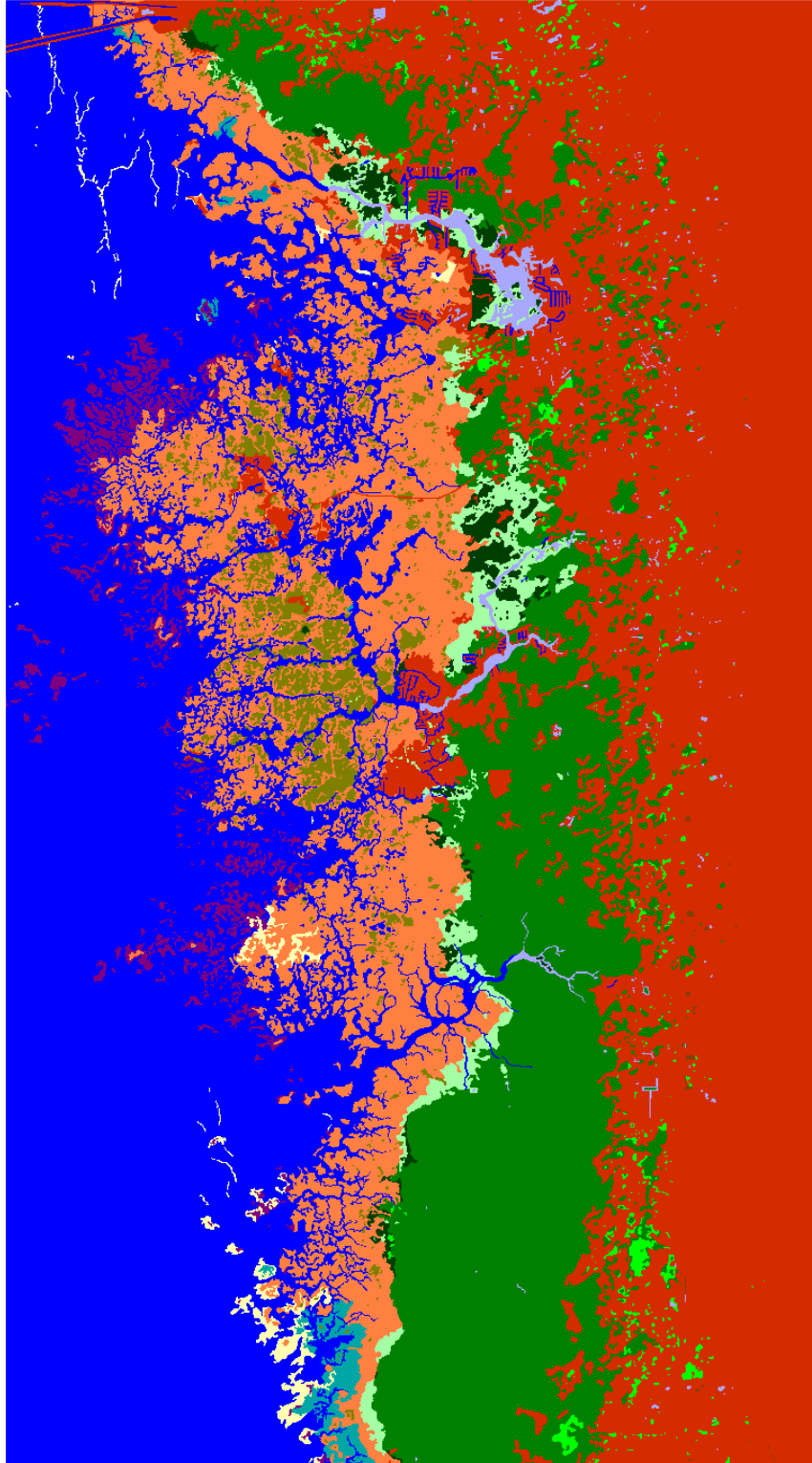
Crystal River Context, 2050, Scenario A1B Maximum
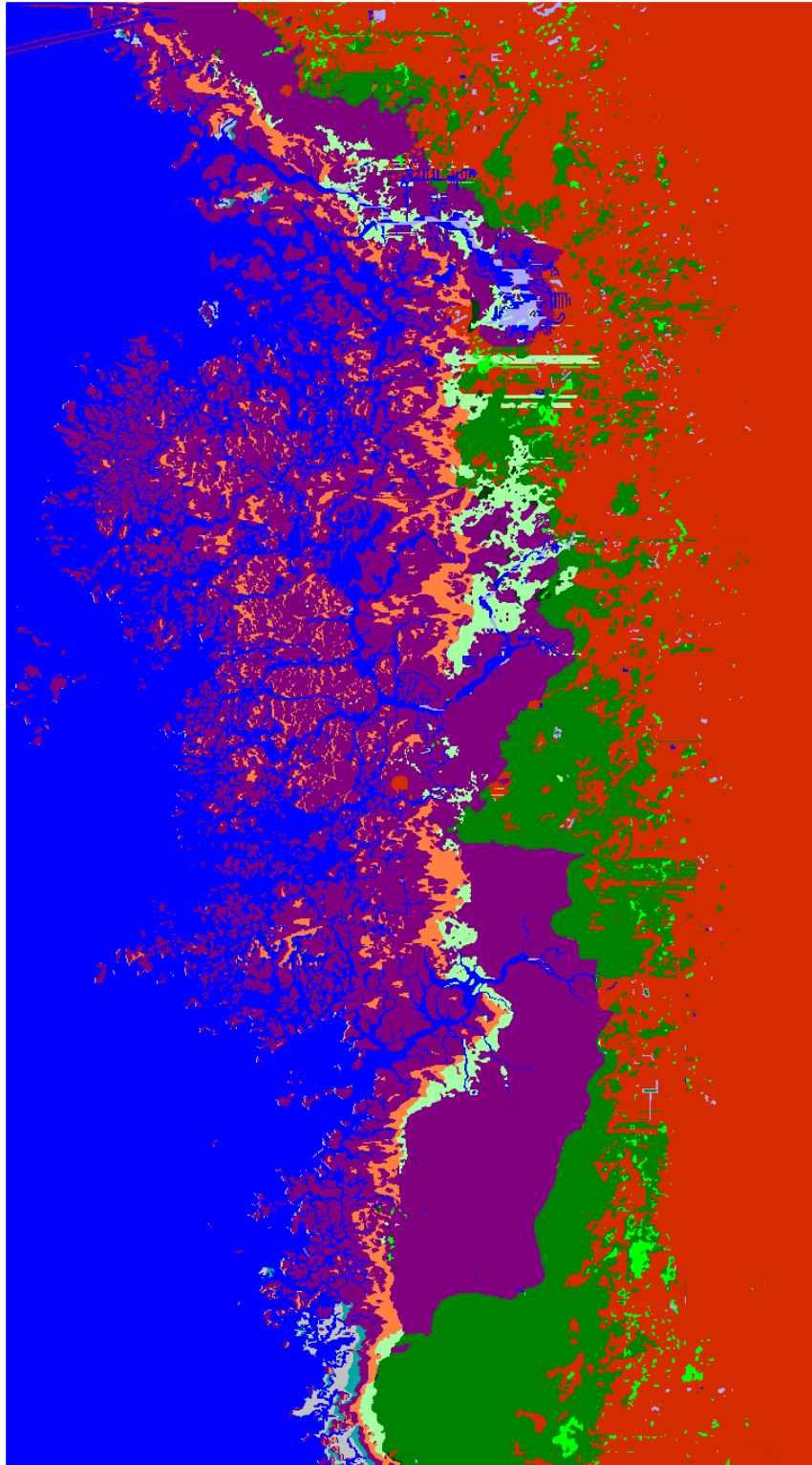
Crystal River Context, 2075, Scenario A1B Maximum

Crystal River Context, 2100, Scenario A1B Maximum

Crystal River Context, Initial Condition

Crystal River Context, 2025, 1 meter eustatic SLR by 2100
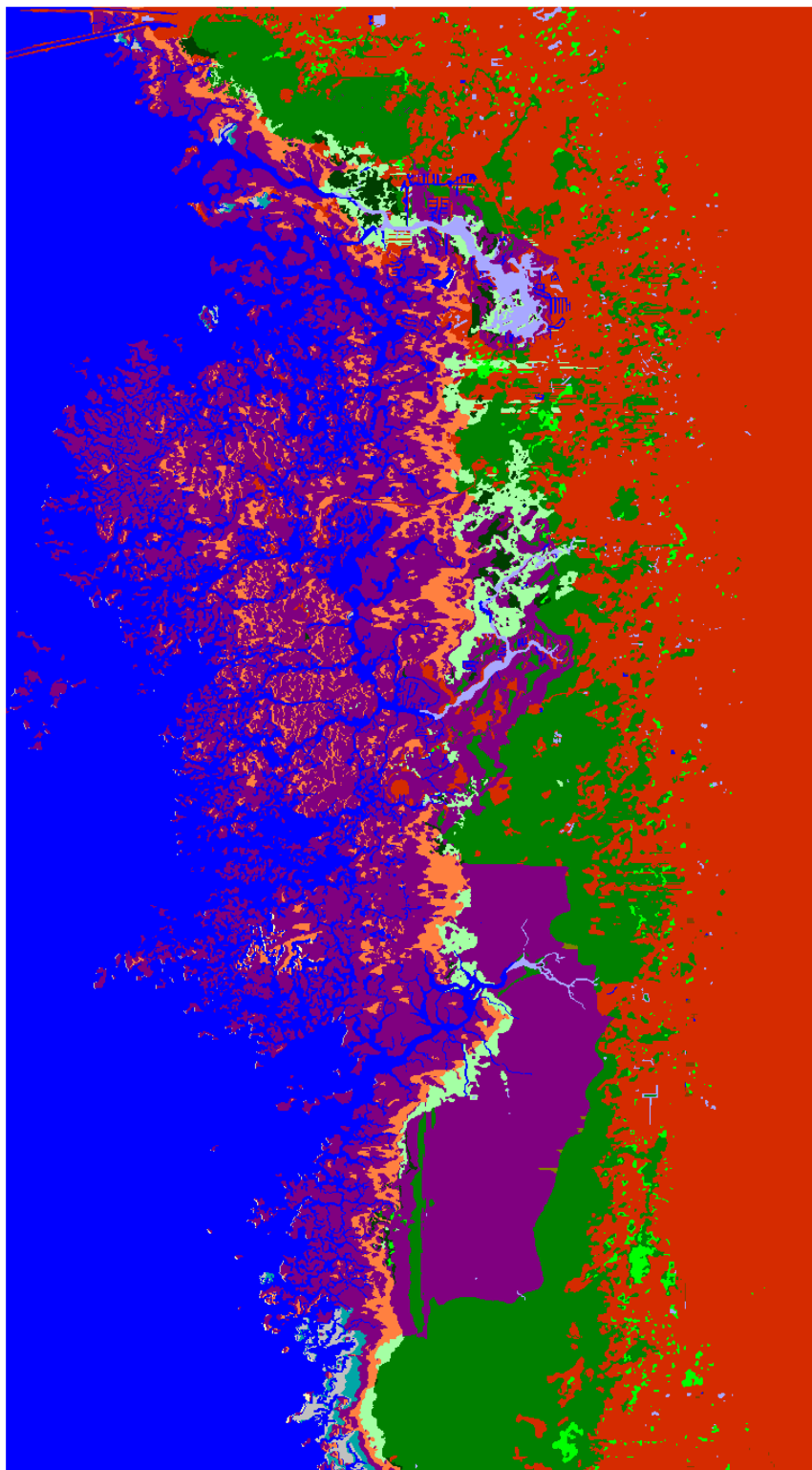
Crystal River Context, 2050, 1 meter eustatic SLR by 2100

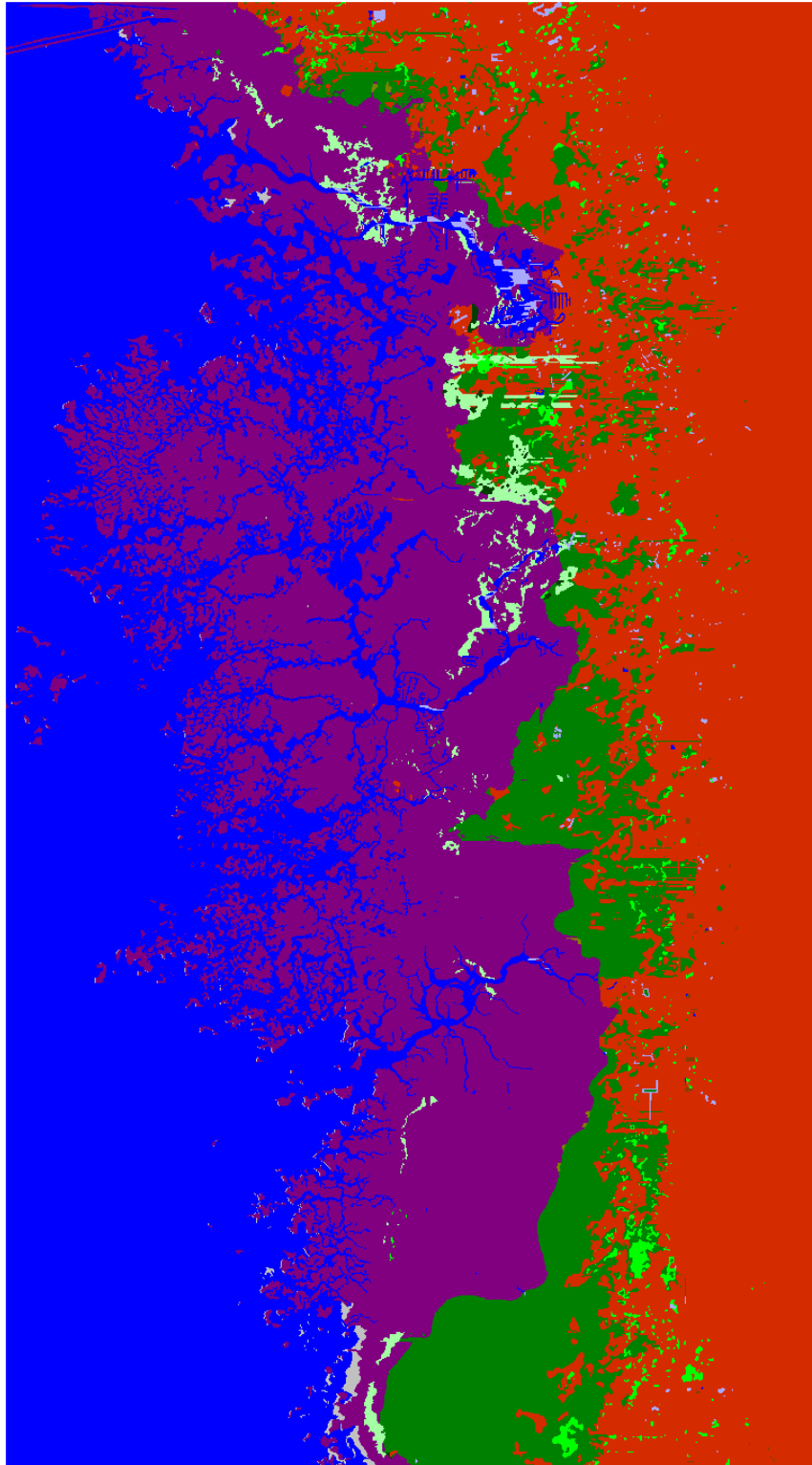Crystal River Context, 2075, 1 meter eustatic SLR by 2100

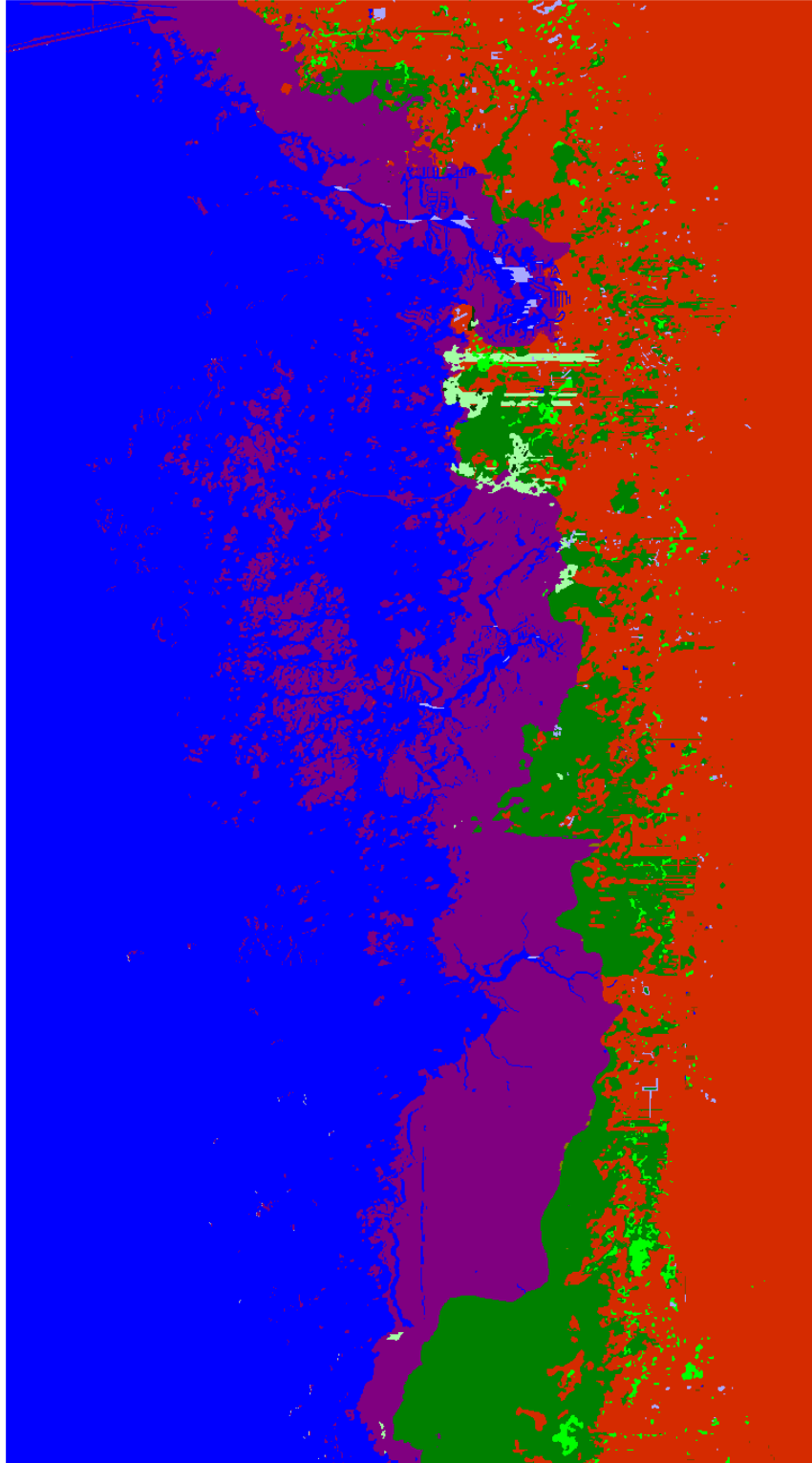Crystal River Context, 2100, 1 meter eustatic SLR by 2100
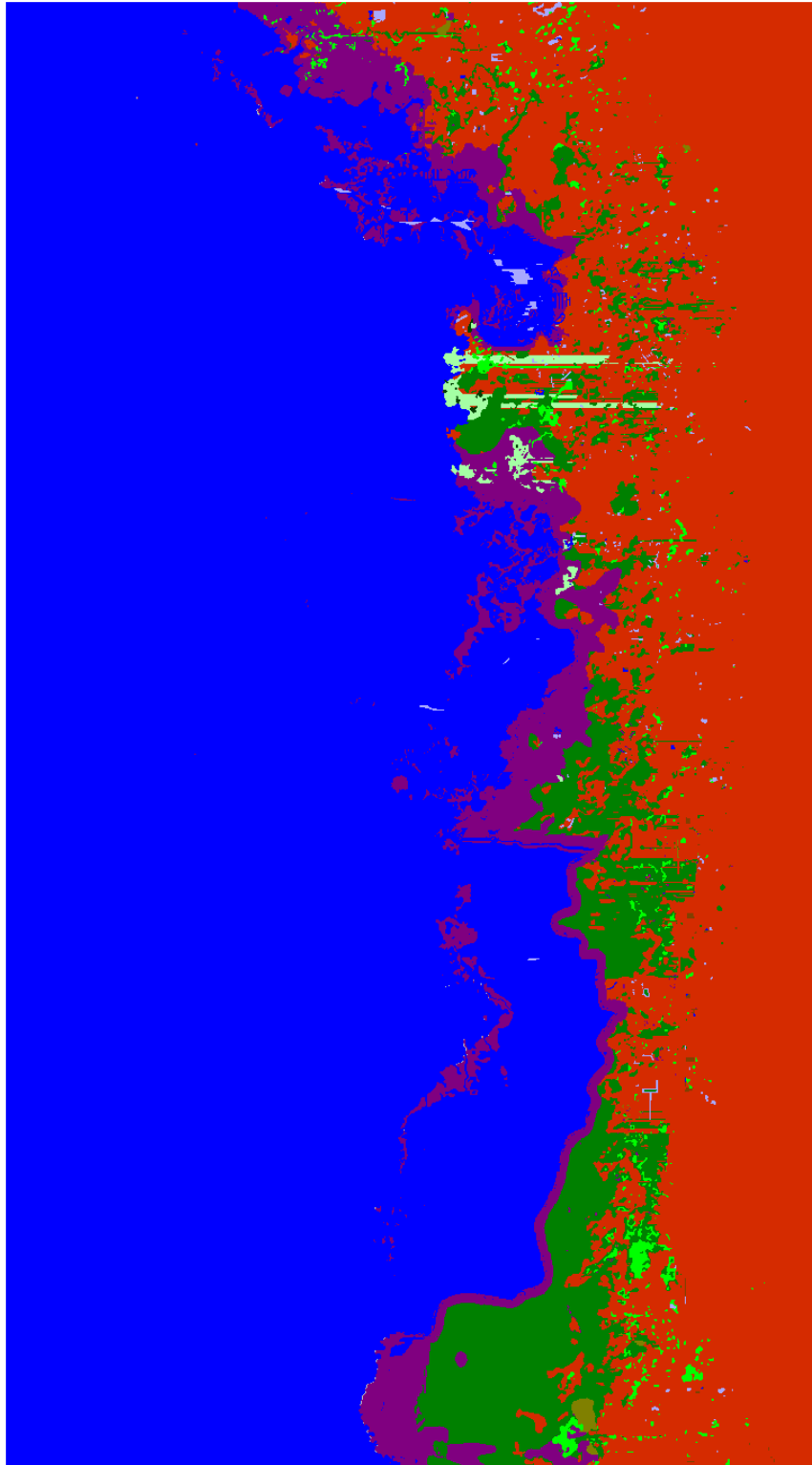
Crystal River Context, Initial Condition

Crystal River Context, 2025, 1.5 meter eustatic SLR by 2100

Crystal River Context, 2050, 1.5 meter eustatic SLR by 2100

Crystal River Context, 2075, 1.5 meter eustatic SLR by 2100

Crystal River Context, 2100, 1.5 meter eustatic SLR by 2100