Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to Pea Island National Wildlife Refuge

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). Sea level is predicted to increase by 30 cm to 100 cm by 2100 based on the International Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) (Meehl et al. 2007). 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. A CCP is a document that provides a framework for guiding refuge management decisions. All refuges are required by law to complete a CCP by 2012.

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 Pea Island.

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

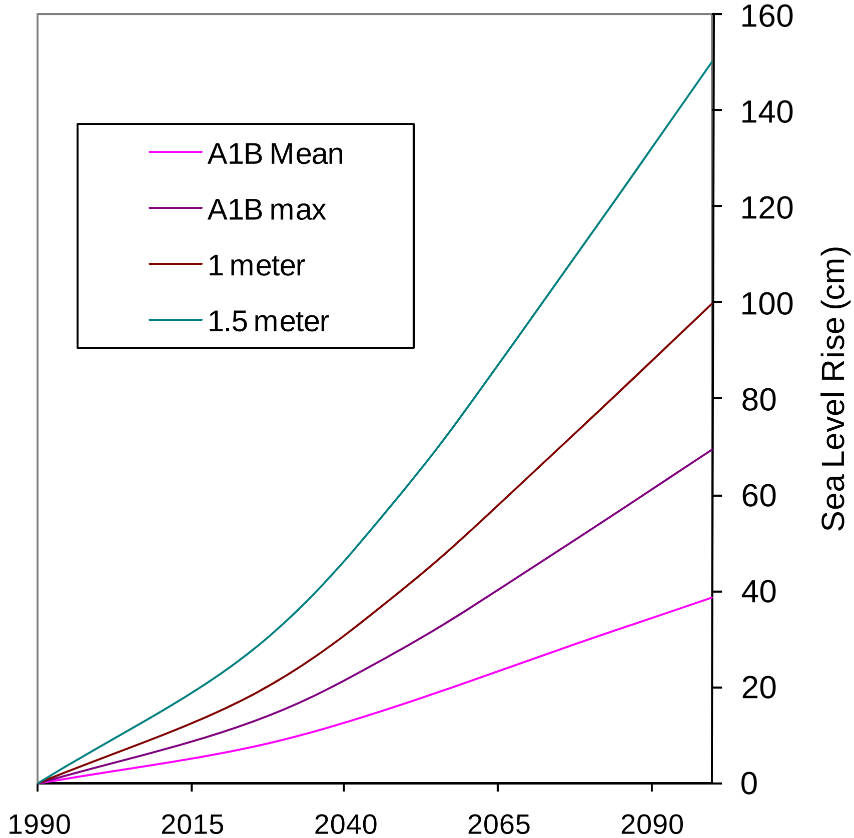
Sea-Level Rise Scenarios

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 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 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

High-resolution LIDAR data are available for Pea Island NWR as for all of coastal North Carolina. These elevation data are available through the National Elevation Dataset (NED), which was updated in 2008 to reflect these high-quality data. The error in vertical resolution for LIDAR data may be as low as 5-10 cm.

The National Wetlands Inventory for Pea Island is based on a photo date of 1983. This survey, when converted to 30 meter cells, suggests that on that date, the approximately five thousand acre refuge (approved acquisition boundary) was composed of a combination of brackish marsh, dry land, and salt marshes as shown below:

Brackish Marsh	25%
Dry Land	25%
Inland Open Water	16%
Trans. Salt Marsh	14%
Saltmarsh	6%
Estuarine Open Water	4%
Tidal Fresh Marsh	4%
Swamp	3%
Ocean Beach	2%

The historic trend for sea level rise was estimated at 3 mm/year using the approximate average of the long term trends measured at Wilmington, North Carolina (NOAA station 8658120) and Beaufort, North Carolina (8656483).

The oceanic tide range for this site was estimated at 1.056 meters based on the gage at Cape Hatteras Fishing Pier (8654400). This site was also used to relate the NED vertical datum of NAVD88 was to mean tide level.

Accretion rates for salt-marsh were set to 3.85 mm/year based on a study of vertical accretion in Cedar Island NC (Cahoon, Reed, and Day, 1995).

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.

A conversation with Michael Bryant, the U.S. Fish and Wildlife Service refuge manager for Pea Island occurred in July of 2008. He stated that when Pea Island was acquired it was 5900 acres. A survey based in 2000 found a loss of roughly 1000 acres. Additionally, Pea Island has a highway on it which reduces the potential for natural migration of a barrier island. Sands that move up onto the road surface during storms are pushed back into the high energy front end of the island, a management technique that has the potential to increase overall erosion rates.

For this analysis, the overwash process was turned off within SLAMM as, based on the conversation above, such overwash and barrier-island migration is not permitted to occur. This probably results in a conservative analysis in that it does not take into account the effects of large storm events. Furthermore, within SLAMM, erosion rates for ocean beaches are generally estimated using the Bruun rule. This means that site-specific erosion rates are not a relevant parameter for this analysis without additional reprogramming. Again, this suggests the model simulation may be overly conservative with respect to beach loss given the historically very high rates of erosion measured on the island.

SUMMARY OF SLAMM INPUT PARAMETERS FOR PEA ISLAND

Site		**Pea Island**
NED Source Date (yyyy)	,	2000
NWI_photo_date (yyyy)	,	1983
Direction_OffShore (N|S|E|W)	,	E
Historic_trend (mm/yr)	,	3
NAVD88_correction (MTL-NAVD88 in meters)	,	-0.136
Water Depth (m below MLW- N/A)	,	2
TideRangeOcean (meters: MHHW-MLLW)	,	1.056
TideRangeInland (meters)	,	1.056
Mean High Water Spring (m above MTL)	,	0.702
MHSW Inland (m above MTL)	,	0.702
Marsh Erosion (horz meters/year)	,	1.8
Swamp Erosion (horz meters/year)	,	1
TFlat Erosion (horz meters/year) [from 0.5]	,	1
Salt marsh vertical accretion (mm/yr) Final	,	3.85
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)	,	120
Use Elevation Preprocessor for Wetlands	,	FALSE

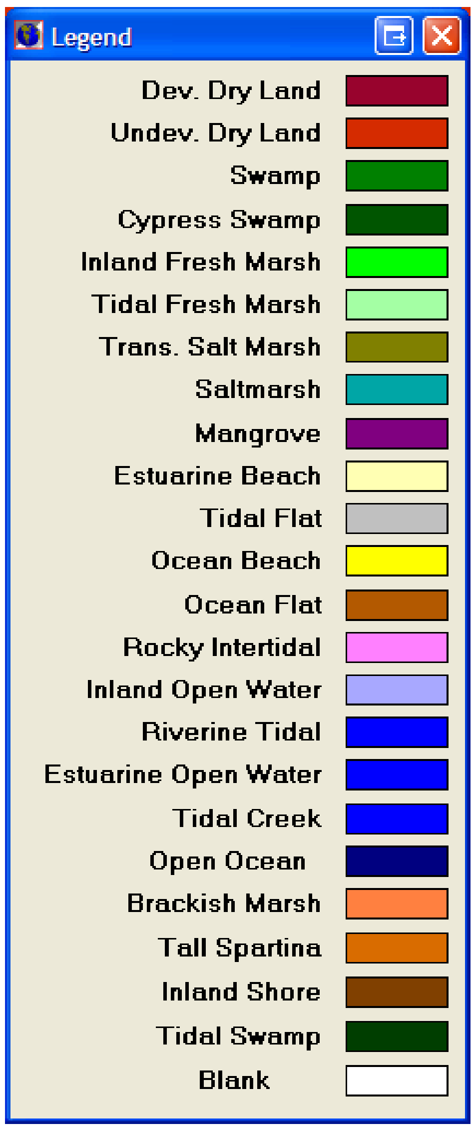
Results

Brackish marsh at this site is predicted to suffer from saline inundation and conversion to salt marsh (or tidal flats and open water under more extreme scenarios). Under the lowest simulated rate of SLR, over 50% loss of brackish marsh is predicted; under the highest rate essentially all brackish marsh is lost. Dry land at this site is also predicted to be vulnerable with losses from 47-76%.

SLR by 2100 (m)	0.39	0.69	1	1.5
Brackish Marsh	55%	84%	96%	100%
Dry Land	47%	58%	66%	76%

Loss rates of Top Two Land Categories as a Function of Eustatic Sea Level Rise

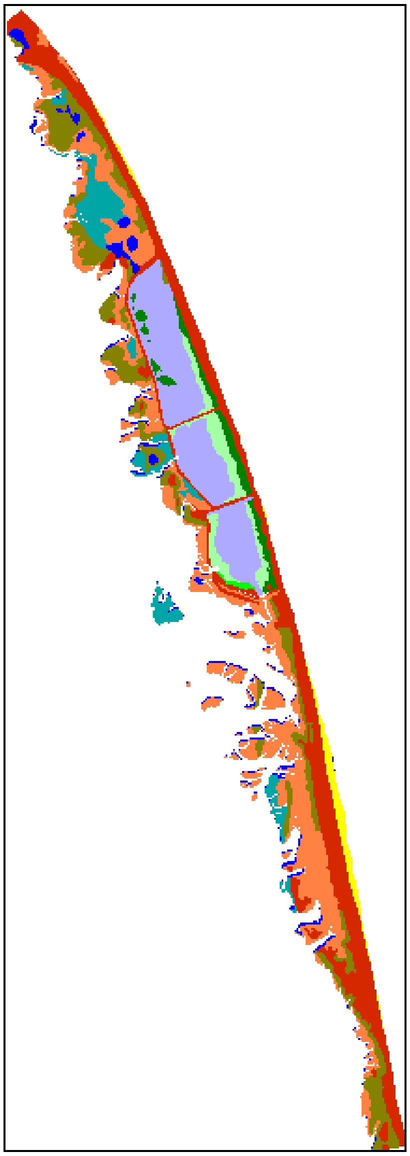
Maps of SLAMM input and output to follow will use the following legend:



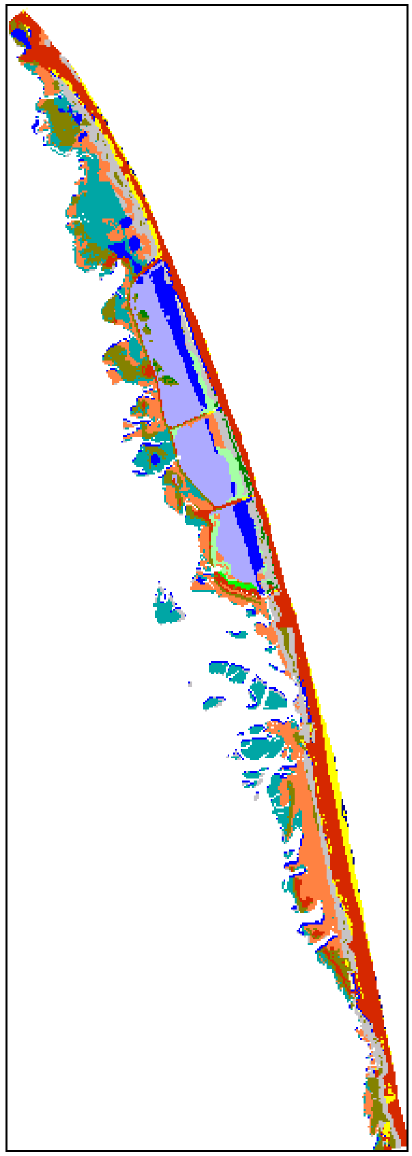
Pea Island
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

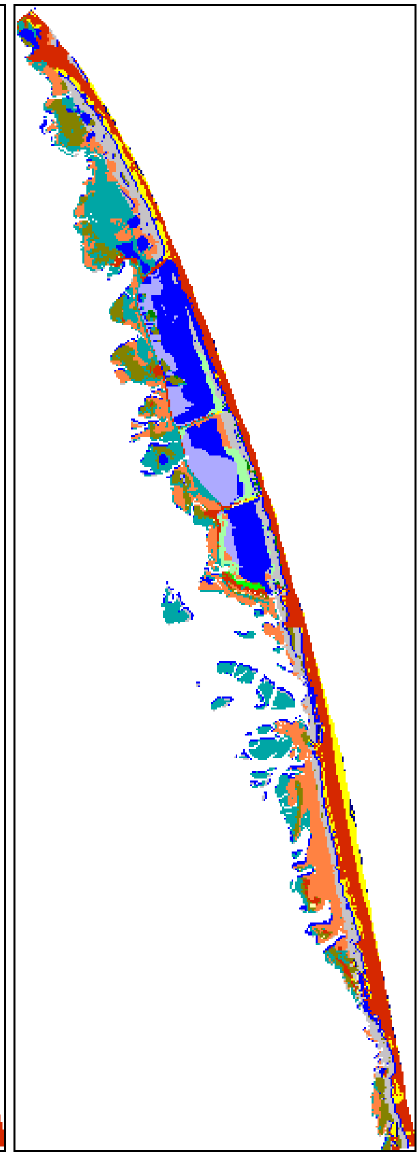
	Initial	2025	2050	2075	2100
Brackish Marsh	1174.5	766.0	678.8	598.1	526.3
Dry Land	1158.0	892.9	799.4	693.3	612.1
Inland Open Water	751.2	570.8	252.4	232.8	219.3
Trans. Salt Marsh	659.8	453.4	349.5	310.8	272.5
Saltmarsh	300.9	693.9	759.9	768.7	752.5
Estuarine Open Water	179.9	404.8	897.8	1112.8	1313.1
Tidal Fresh Marsh	175.7	91.6	91.6	91.5	91.5
Swamp	129.7	36.7	16.6	6.7	4.2
Ocean Beach	108.1	203.7	236.2	236.7	234.9
Inland Fresh Marsh	10.9	9.7	9.0	8.7	8.7
Open Ocean	0.9	11.9	26.5	49.0	69.7
Estuarine Beach	0.4	10.7	14.5	39.2	54.1
Tidal Flat	0.0	504.0	517.8	501.6	491.1
Total (incl. water)	**4650.0**	**4650.0**	**4650.0**	**4650.0**	**4650.0**



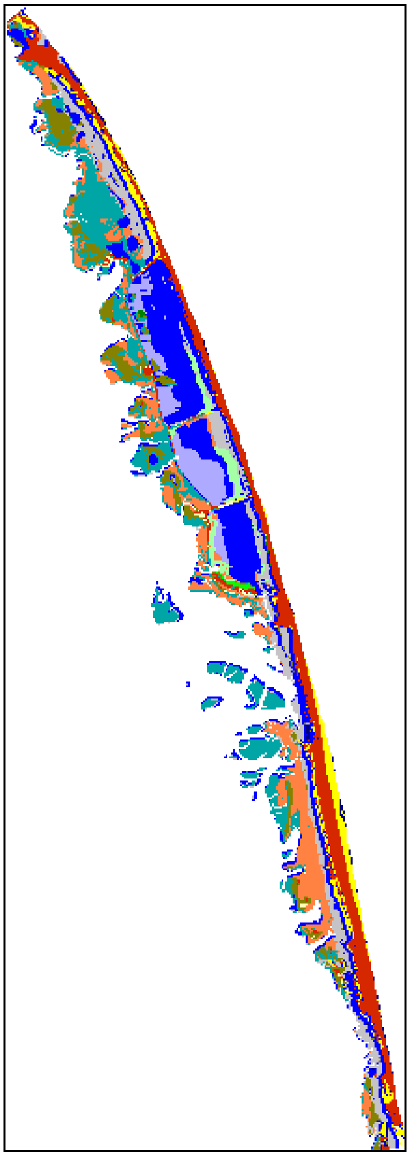
Pea Island
Initial Condition



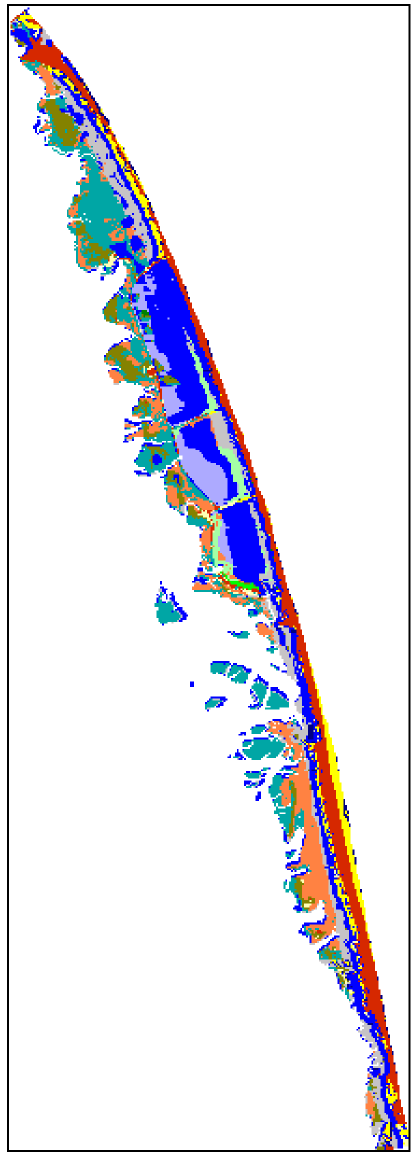
Pea Island
2025, A1B Mean



Pea Island
2050, A1B-Mean



Pea Island
2075, A1B Mean

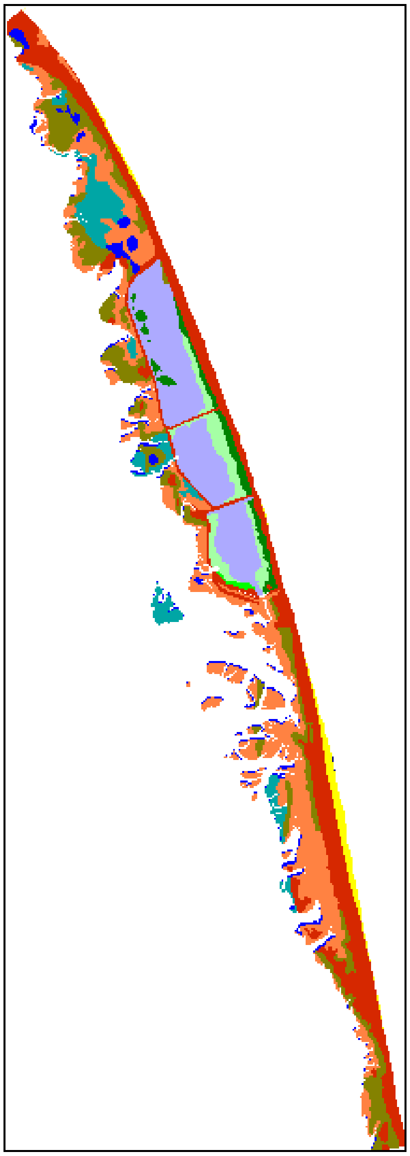


Pea Island
2100, A1B-Mean

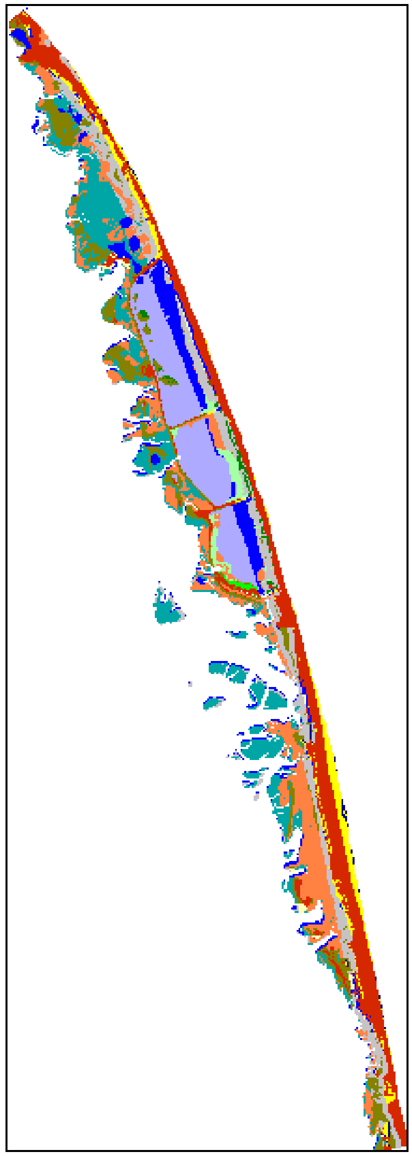
Pea Island
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

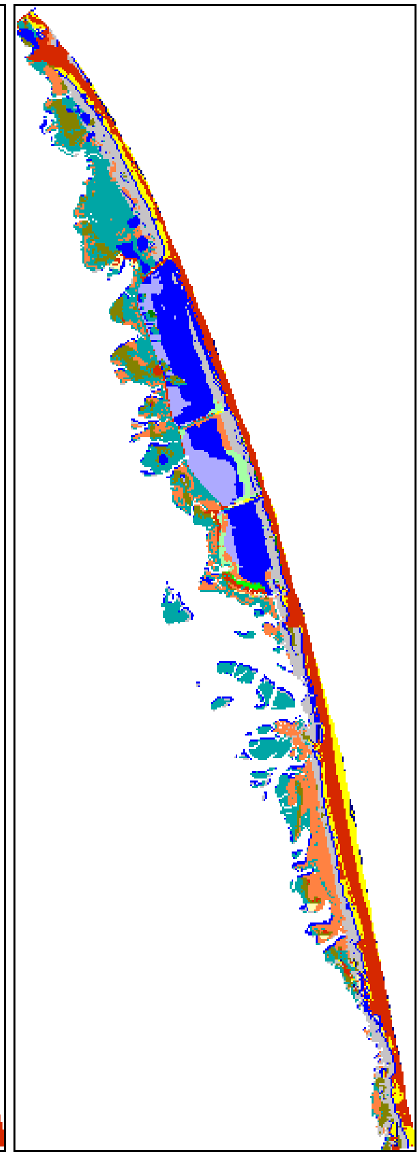
	Initial	2025	2050	2075	2100
Brackish Marsh	1174.5	721.8	530.1	335.5	182.7
Dry Land	1158.0	854.7	713.6	586.3	489.3
Inland Open Water	751.2	566.0	224.8	195.3	168.8
Trans. Salt Marsh	659.8	430.7	277.4	174.8	105.8
Saltmarsh	300.9	763.0	923.0	617.5	491.6
Estuarine Open Water	179.9	415.3	957.9	1318.4	1672.9
Tidal Fresh Marsh	175.7	68.9	60.2	46.4	34.1
Swamp	129.7	31.8	9.5	4.1	1.7
Ocean Beach	108.1	218.1	268.9	259.9	246.5
Inland Fresh Marsh	10.9	9.2	8.3	7.6	6.9
Open Ocean	0.9	15.6	40.0	80.0	125.6
Estuarine Beach	0.4	28.9	35.9	61.4	68.9
Tidal Flat	0.0	526.1	600.5	962.8	1055.2
Total (incl. water)	**4650.0**	**4650.0**	**4650.0**	**4650.0**	**4650.0**



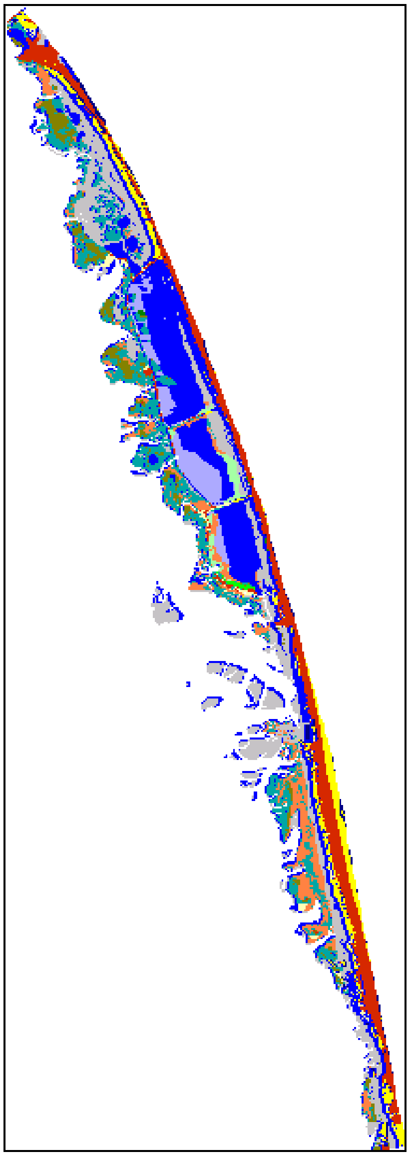
Pea Island
Initial Condition



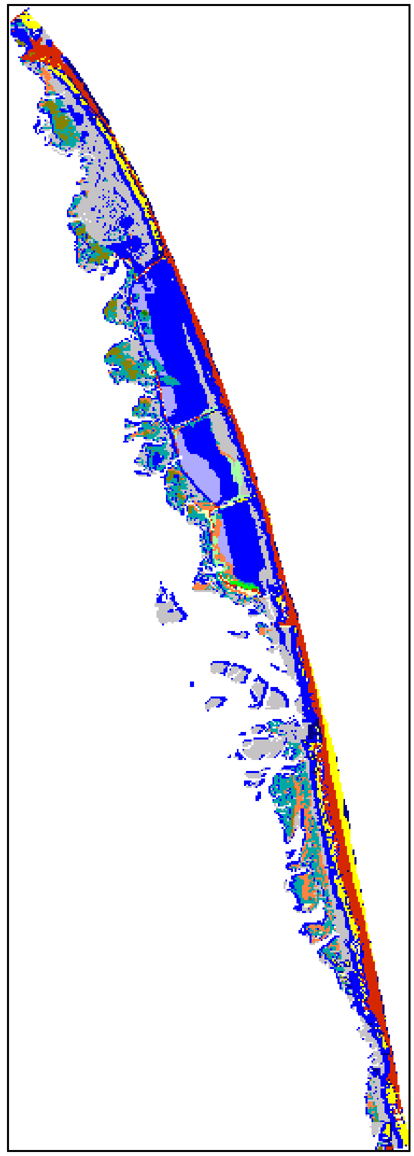
Pea Island
2025, A1B Max.



Pea Island
2050, A1B-Max.



Pea Island
2075, A1B Max.

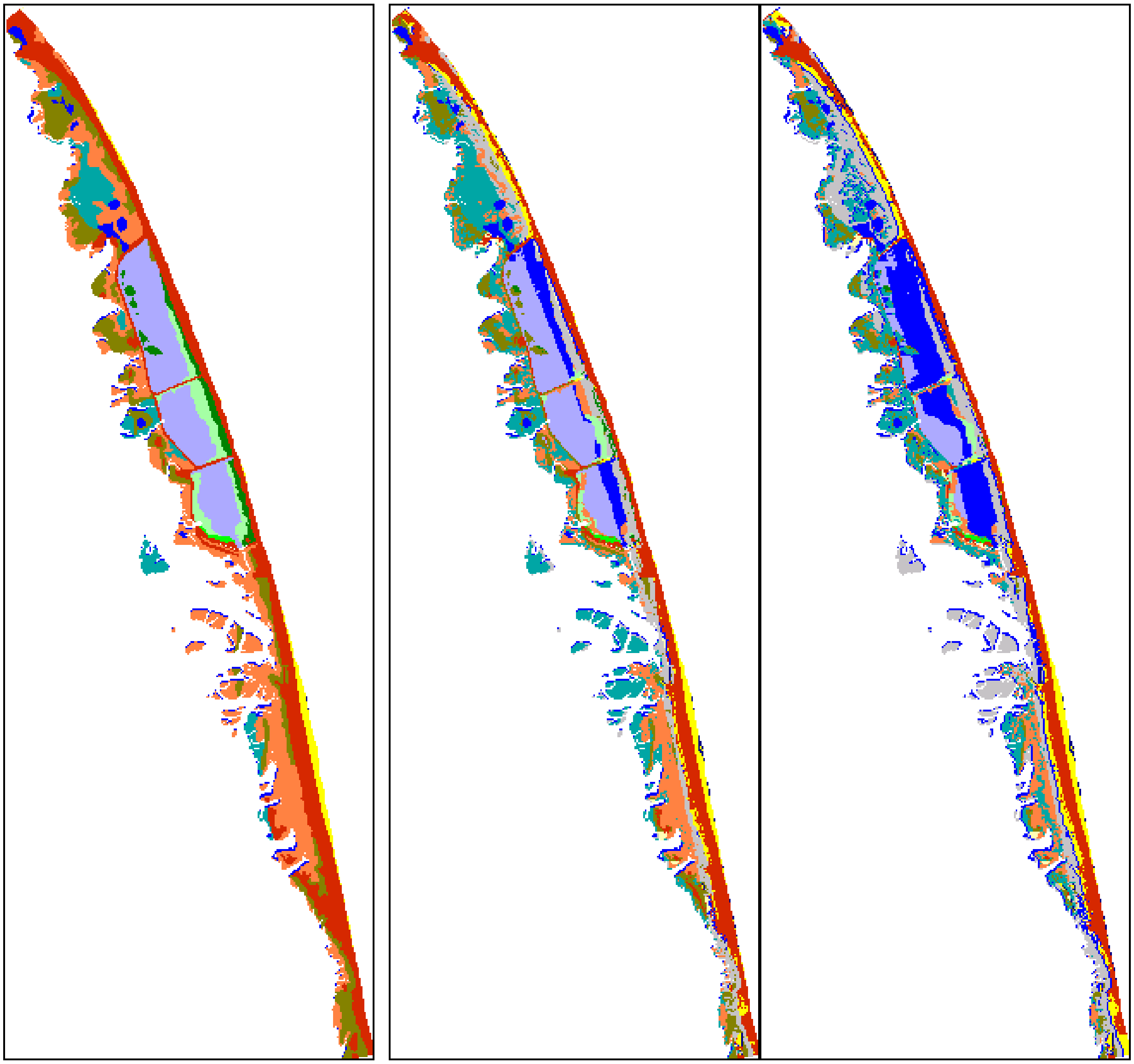


Pea Island
2100, A1B-Max.

Pea Island
1 Meter Eustatic SLR by 2100

Results in Acres

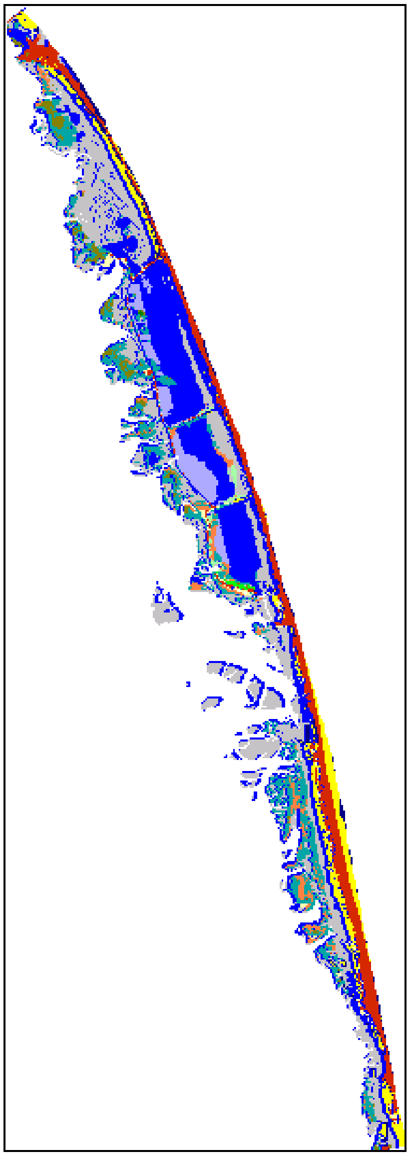
	Initial	2025	2050	2075	2100
Brackish Marsh	1174.5	642.4	356.5	133.8	42.8
Dry Land	1158.0	814.8	638.8	501.9	389.6
Inland Open Water	751.2	560.4	205.0	169.0	141.0
Trans. Salt Marsh	659.8	415.1	201.8	82.8	27.2
Saltmarsh	300.9	863.1	710.0	511.4	259.4
Estuarine Open Water	179.9	424.6	1078.9	1483.8	2397.4
Tidal Fresh Marsh	175.7	58.4	42.1	22.4	13.4
Swamp	129.7	26.1	6.5	2.0	0.4
Ocean Beach	108.1	236.4	295.6	253.7	11.3
Inland Fresh Marsh	10.9	8.7	7.4	6.2	4.6
Open Ocean	0.9	18.7	55.3	136.5	440.1
Estuarine Beach	0.4	33.9	44.3	62.4	56.2
Tidal Flat	0.0	547.5	1007.9	1284.1	866.5
Total (incl. water)	**4650.0**	**4650.0**	**4650.0**	**4650.0**	**4650.0**



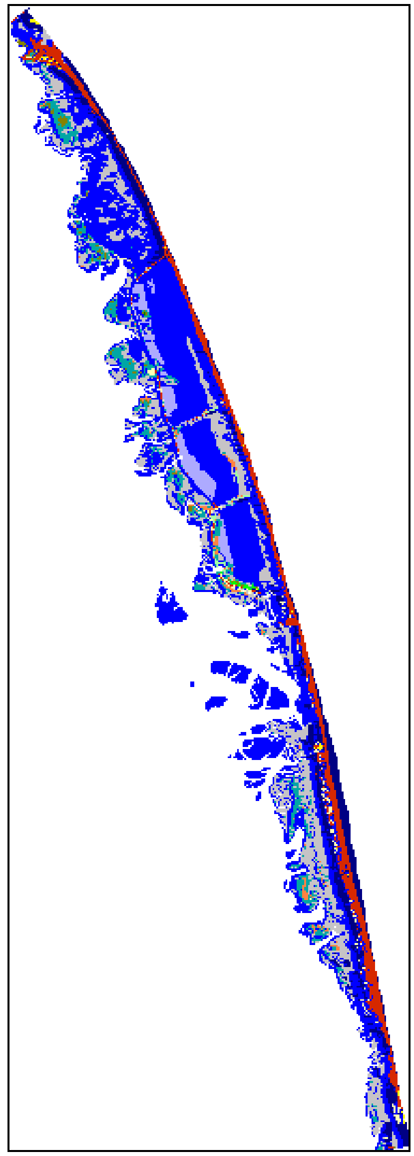
Pea Island
Initial Condition

Pea Island
2025, 1 Meter

Pea Island
2050, 1 Meter



Pea Island
2075, 1 Meter

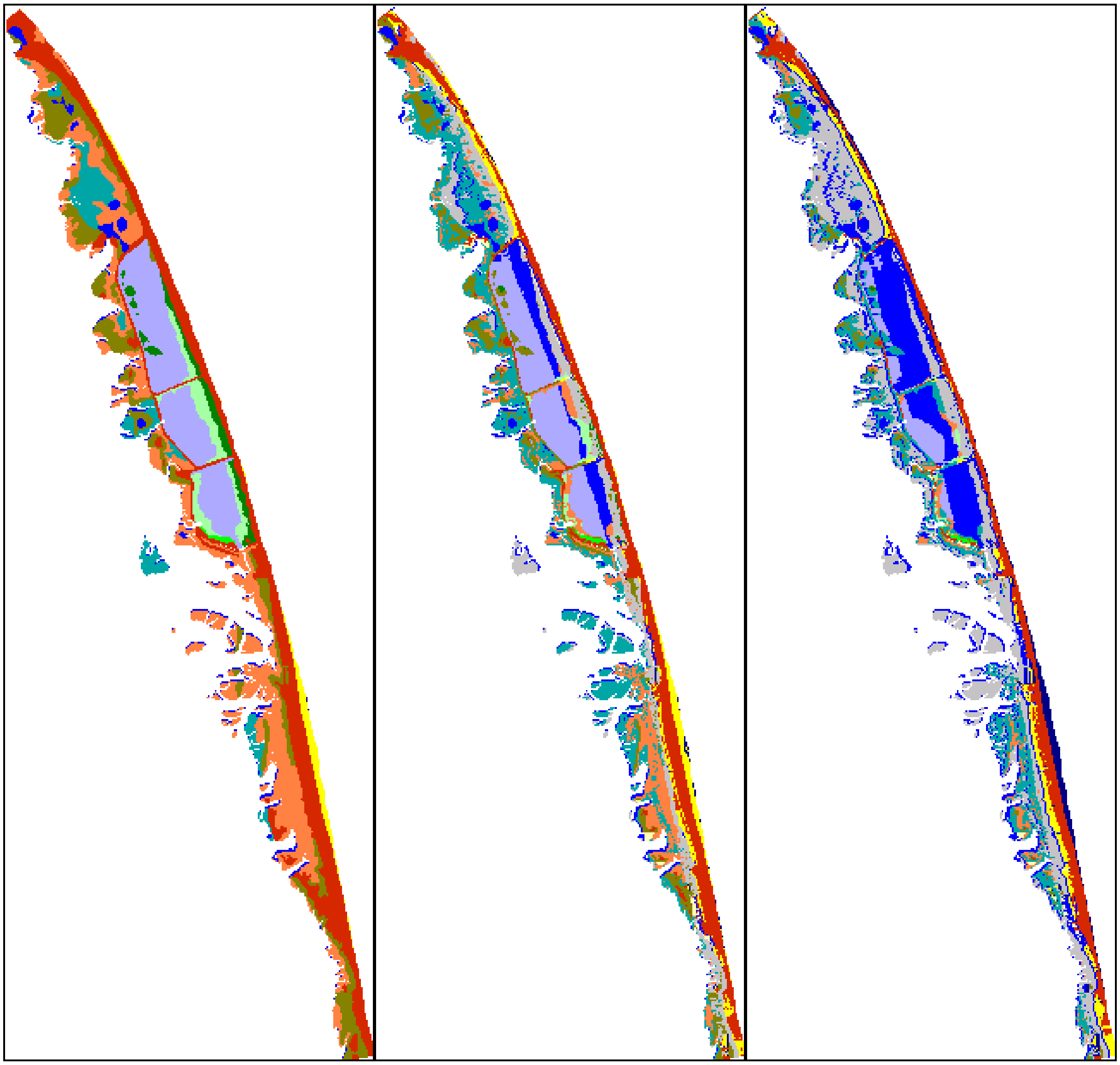


Pea Island
2100, 1 Meter

Pea Island
1.5 Meters Eustatic SLR by 2100

Results in Acres

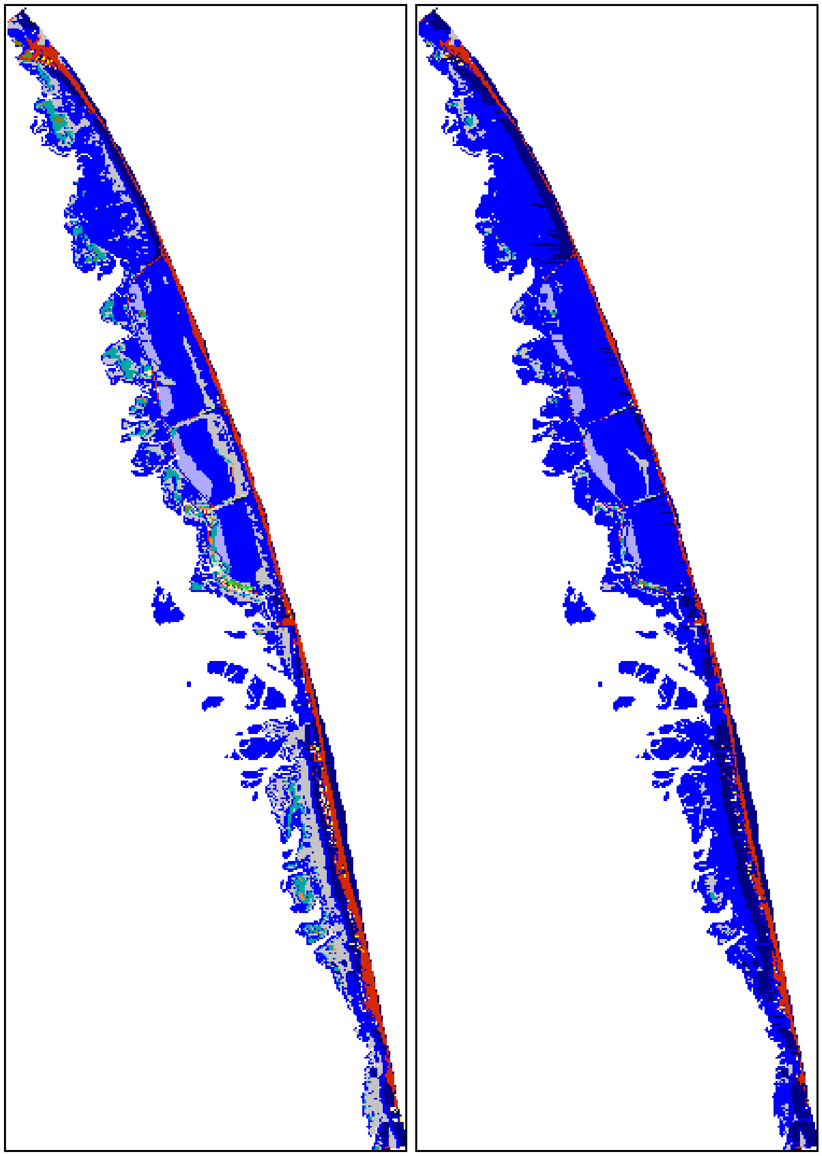
	Initial	2025	2050	2075	2100
Brackish Marsh	1174.5	500.2	151.2	23.1	5.4
Dry Land	1158.0	745.9	550.2	387.0	281.4
Inland Open Water	751.2	552.5	181.4	139.7	122.7
Trans. Salt Marsh	659.8	388.3	106.4	19.9	3.5
Saltmarsh	300.9	938.8	653.0	245.0	34.1
Estuarine Open Water	179.9	483.4	1217.4	2445.7	3210.6
Tidal Fresh Marsh	175.7	44.9	20.5	9.6	7.0
Swamp	129.7	16.6	3.3	0.4	0.0
Ocean Beach	108.1	252.2	186.4	40.1	9.3
Inland Fresh Marsh	10.9	7.9	6.2	3.7	1.7
Open Ocean	0.9	40.1	219.0	445.6	731.1
Estuarine Beach	0.4	44.2	47.3	43.8	24.4
Tidal Flat	0.0	635.0	1307.9	846.4	218.8
Total (incl. water)	**4650.0**	**4650.0**	**4650.0**	**4650.0**	**4650.0**



Pea Island
Initial Condition

Pea Island
2025, 1.5 Meter

Pea Island
2050, 1.5 Meter



Pea Island
2075, 1.5 Meter

Pea Island
2100, 1.5 Meter

Discussion:

The Pea Island National Wildlife Refuge is subject to a variety of pressures including overwash, the effects of large storms, potential loss of sediments due to nearby dredging, and rapid beach erosion rates. The SLAMM model does not capture all of these pressures but still predicts fairly dramatic changes under scenarios of sea level rise.

Under the A1B-Mean Scenario, or 0.39 meters of SLR by 2100, the most significant predictions appear to be the salt intrusion of brackish marsh and conversion to salt marsh. Significant dry land is also lost in this scenario.

Under the A1B-Max Scenario, or 0.69 meters of SLR by 2100, much of the salt marsh is also predicted to be lost.

Under the 1 and 1.5 meter scenarios, most of the refuge has converted to open water and tidal flats with only a thin strip of dry land remaining.

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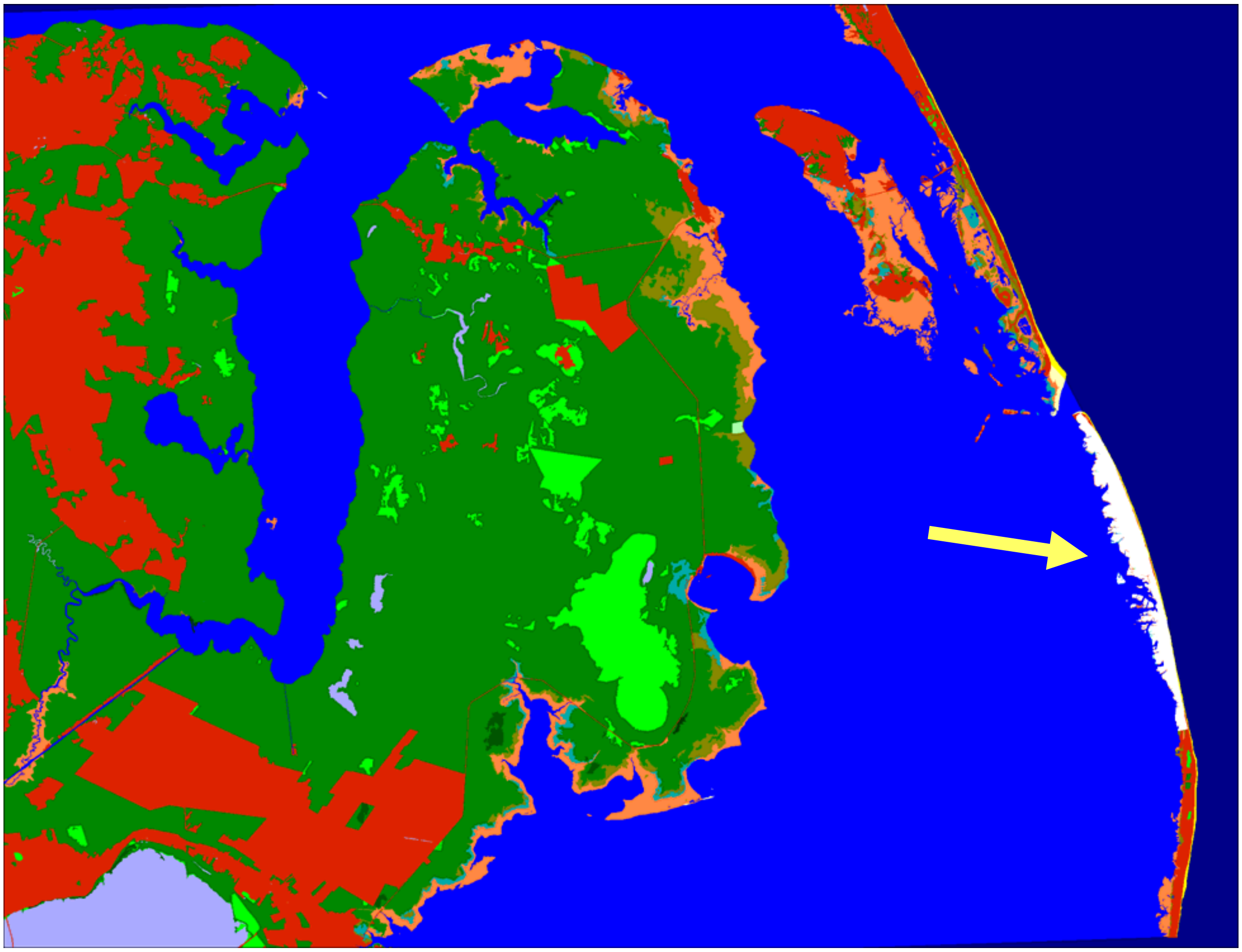
Appendix A: Contextual Results

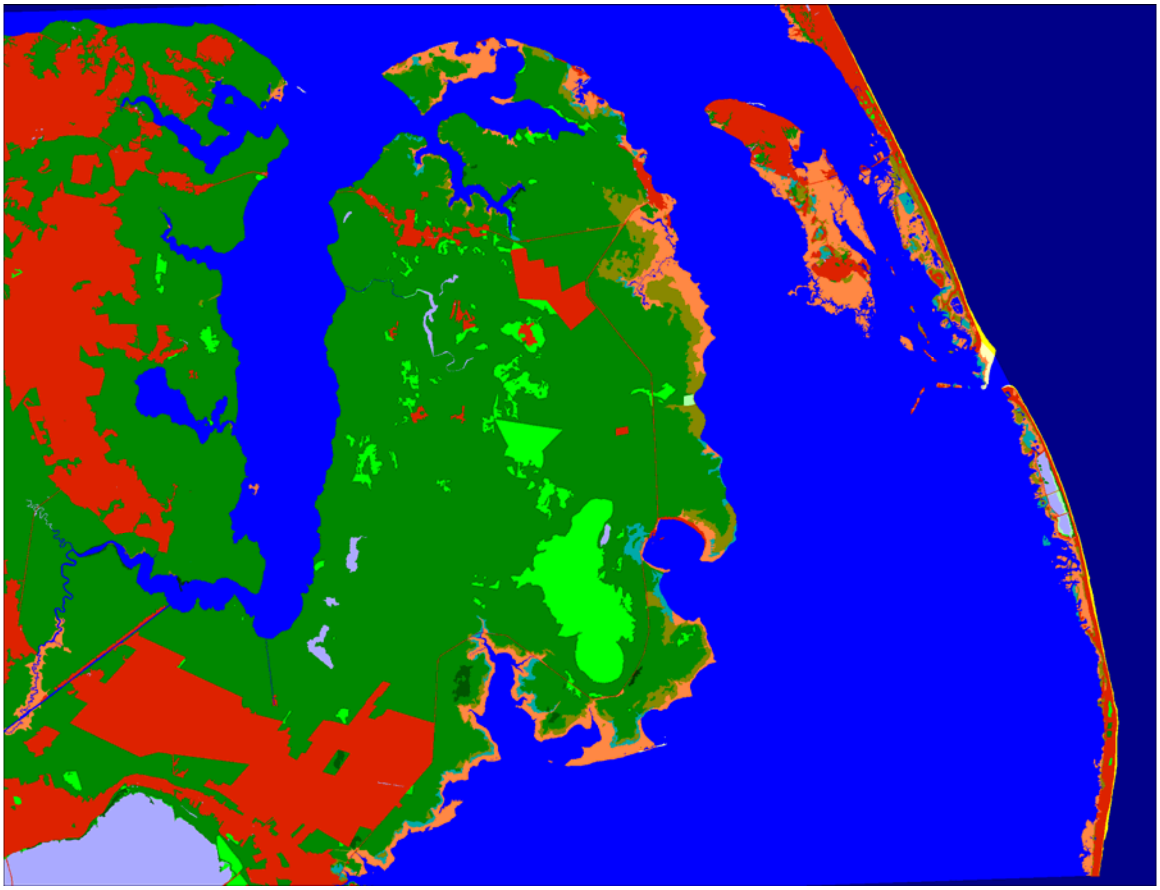
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

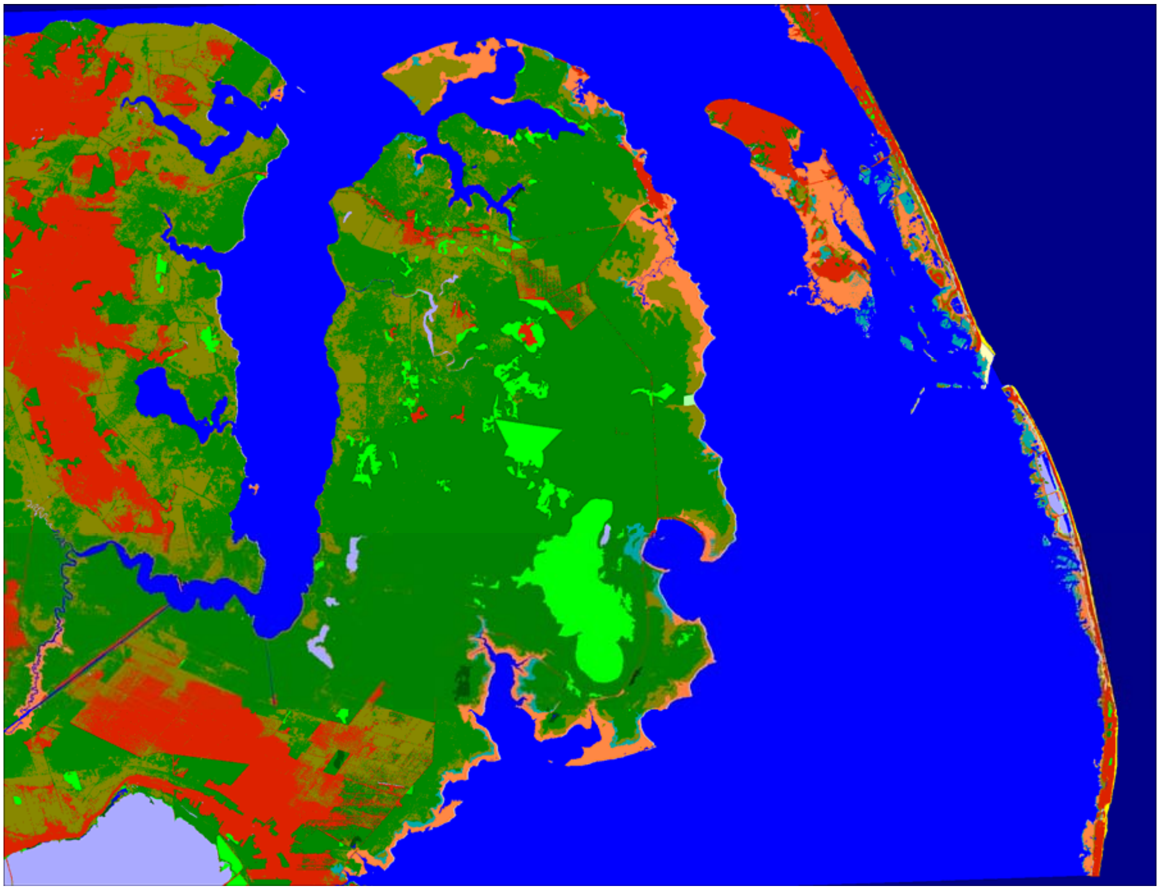
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



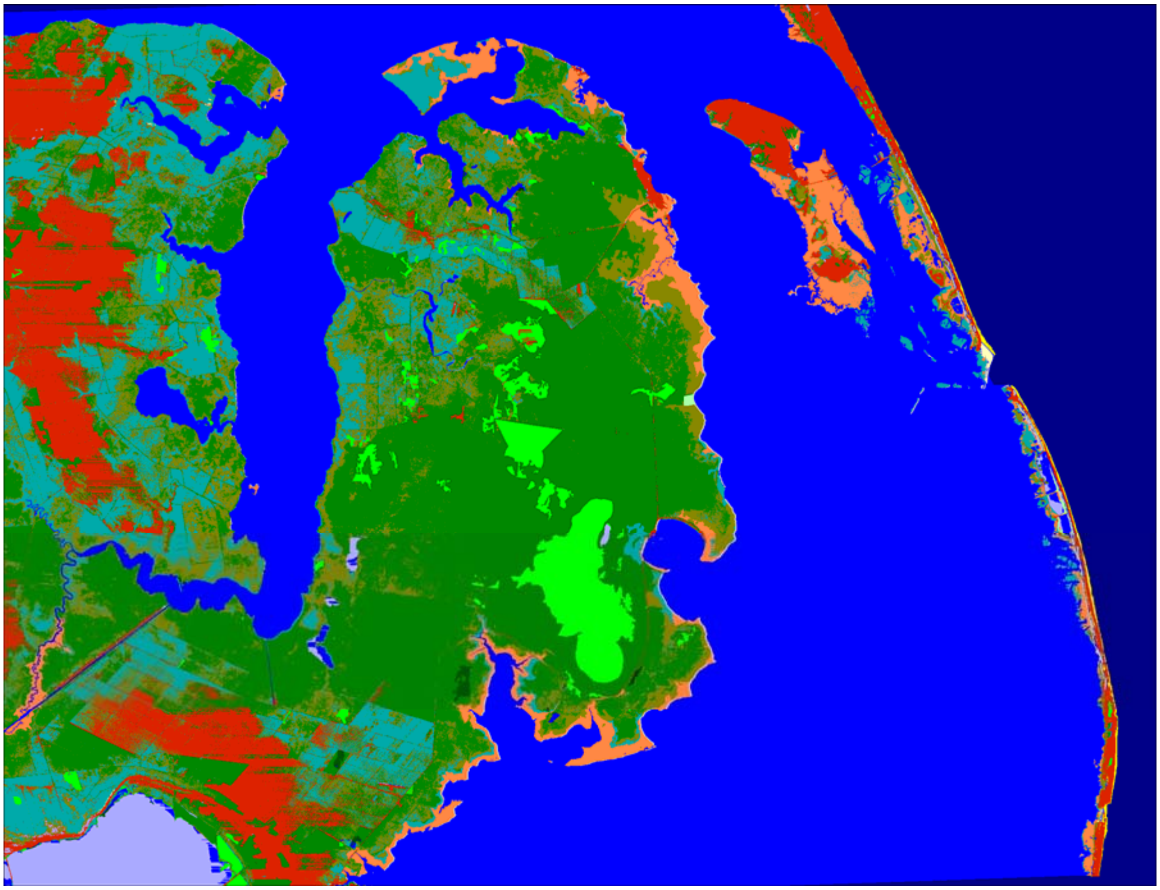
Location of Pea Island National Wildlife Refuge (white region) within North Carolina simulation context



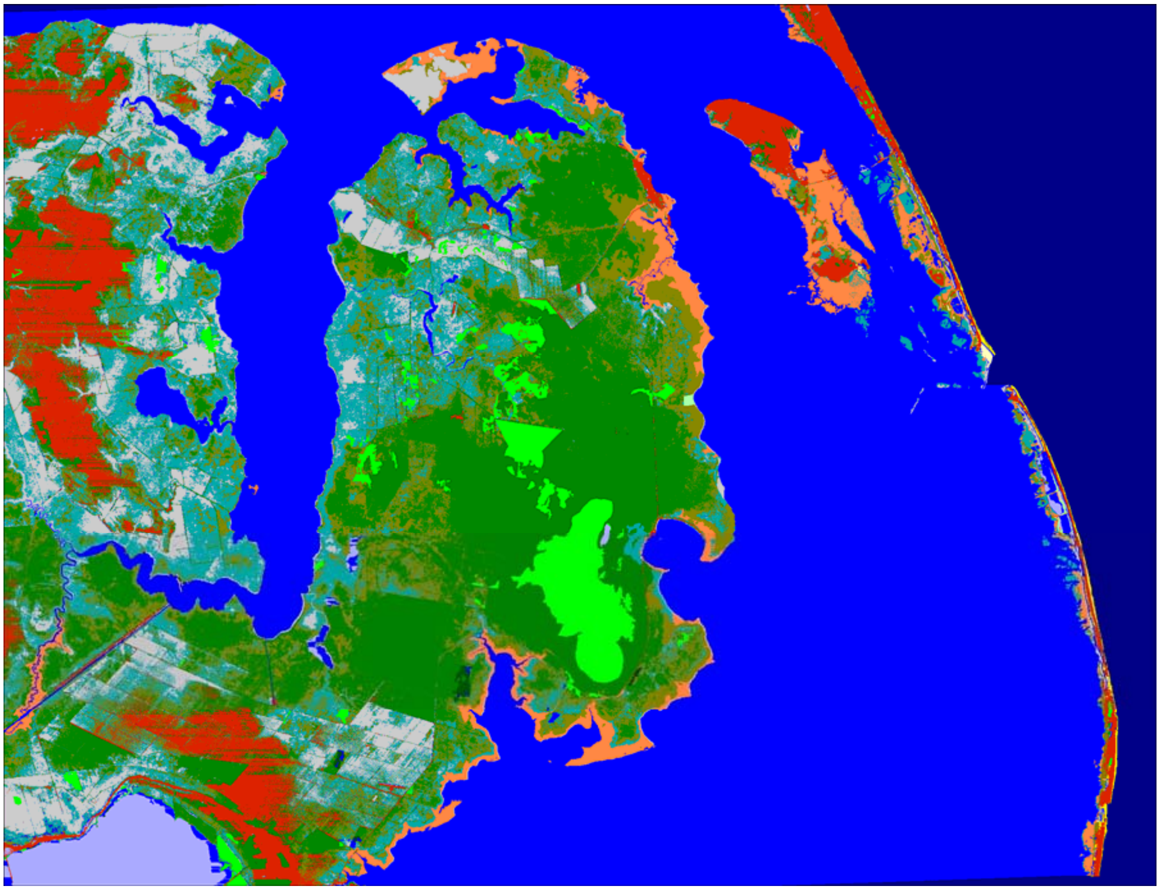
North Carolina Initial Condition



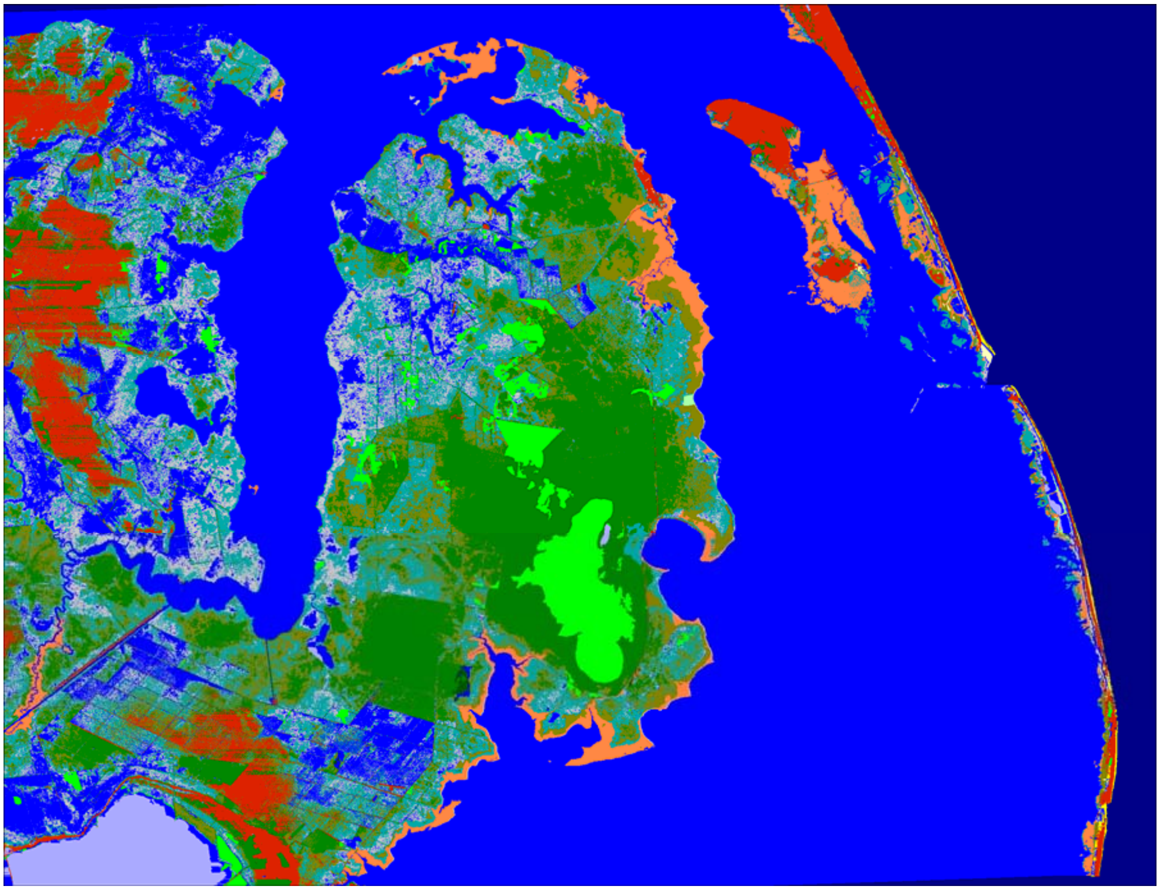
North Carolina 2025 IPCC Scenario A1B-Mean



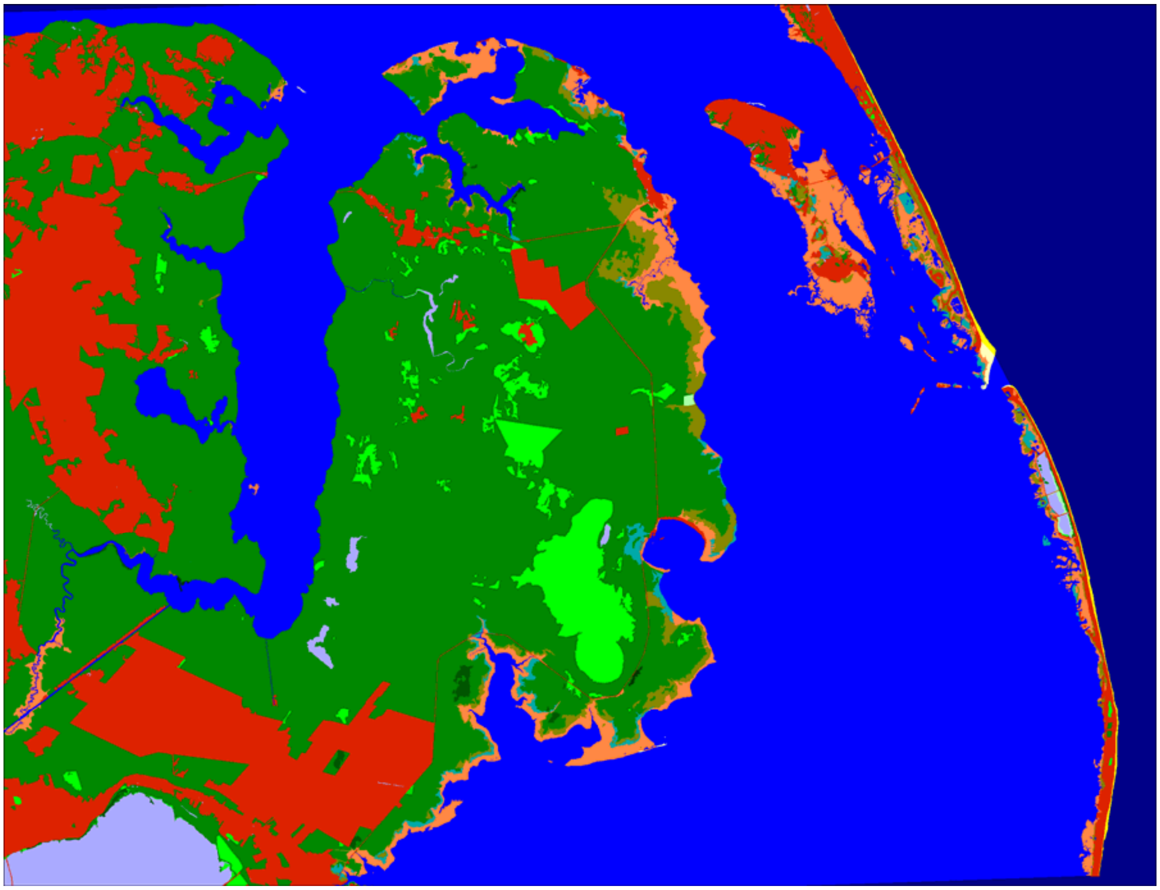
North Carolina 2050 IPCC Scenario A1B-Mean



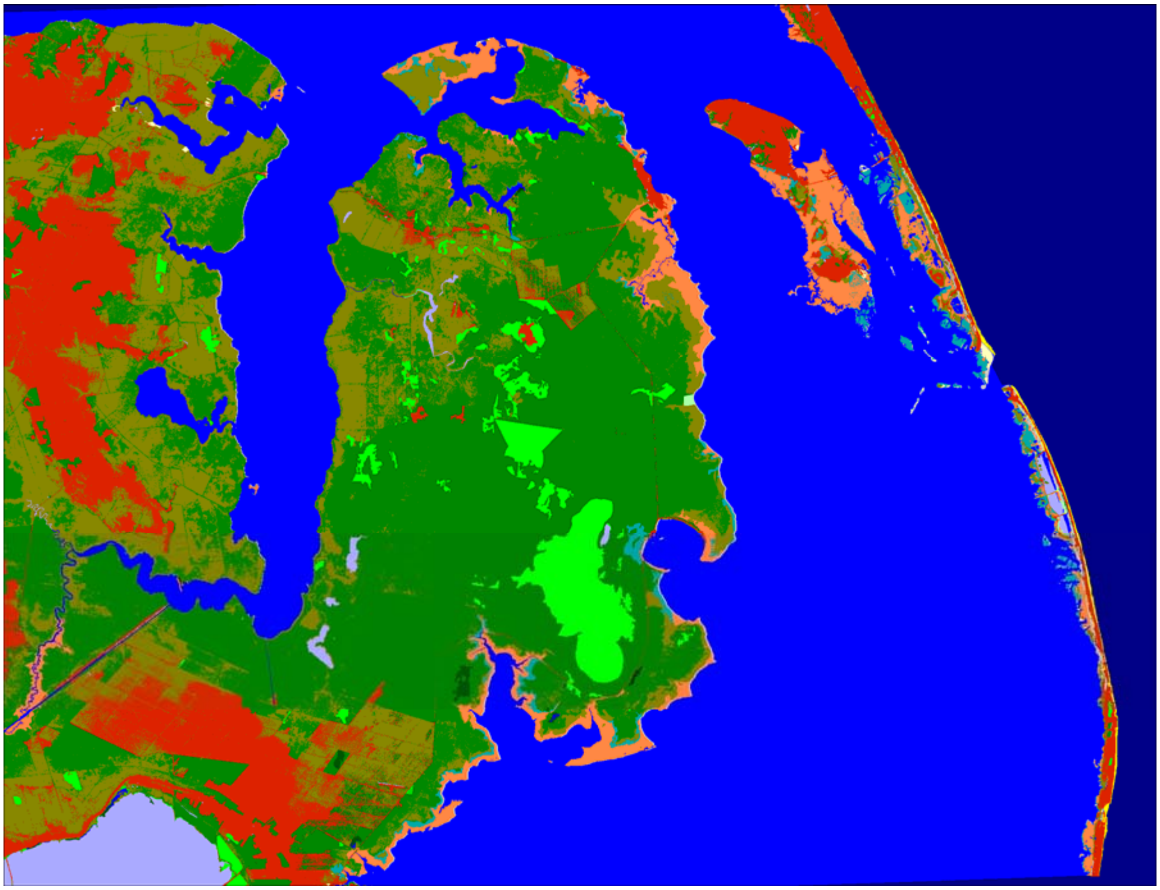
North Carolina 2075 IPCC Scenario A1B-Mean



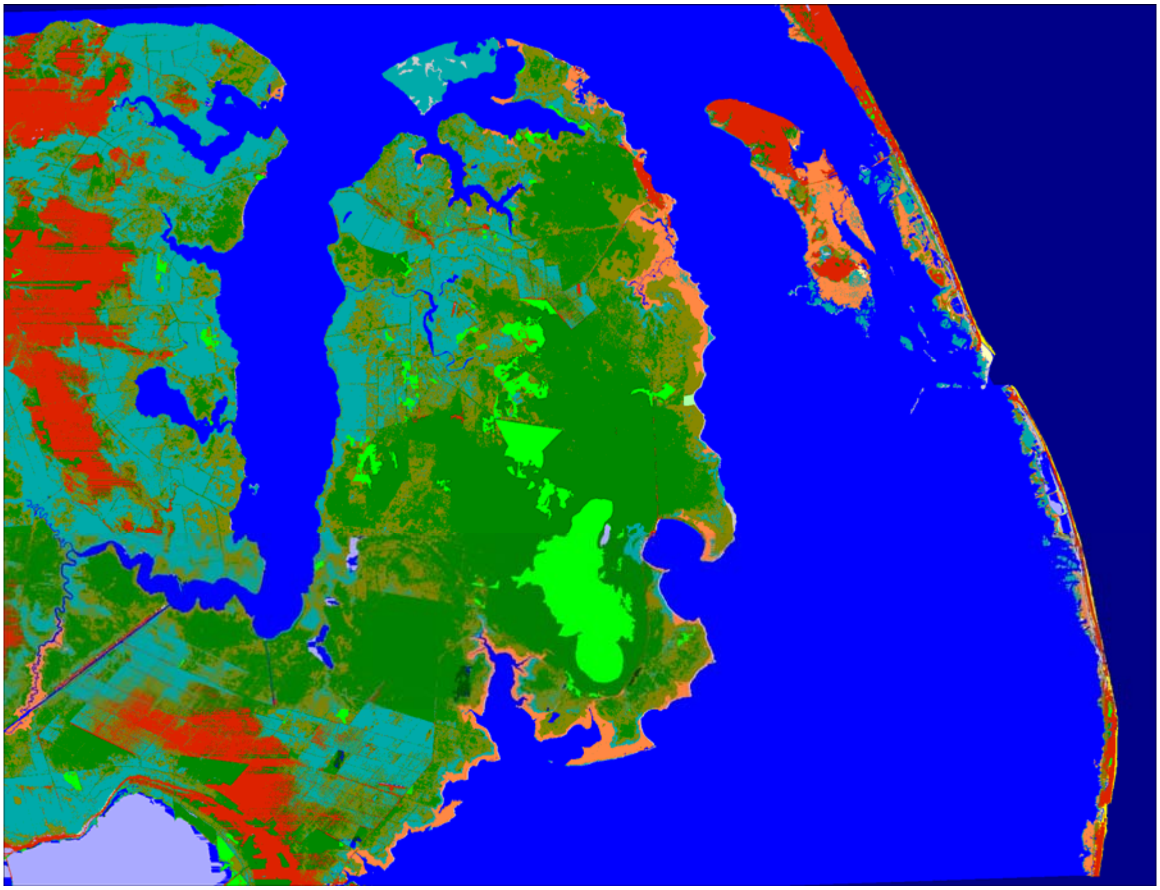
North Carolina 2100 IPCC Scenario A1B-Mean



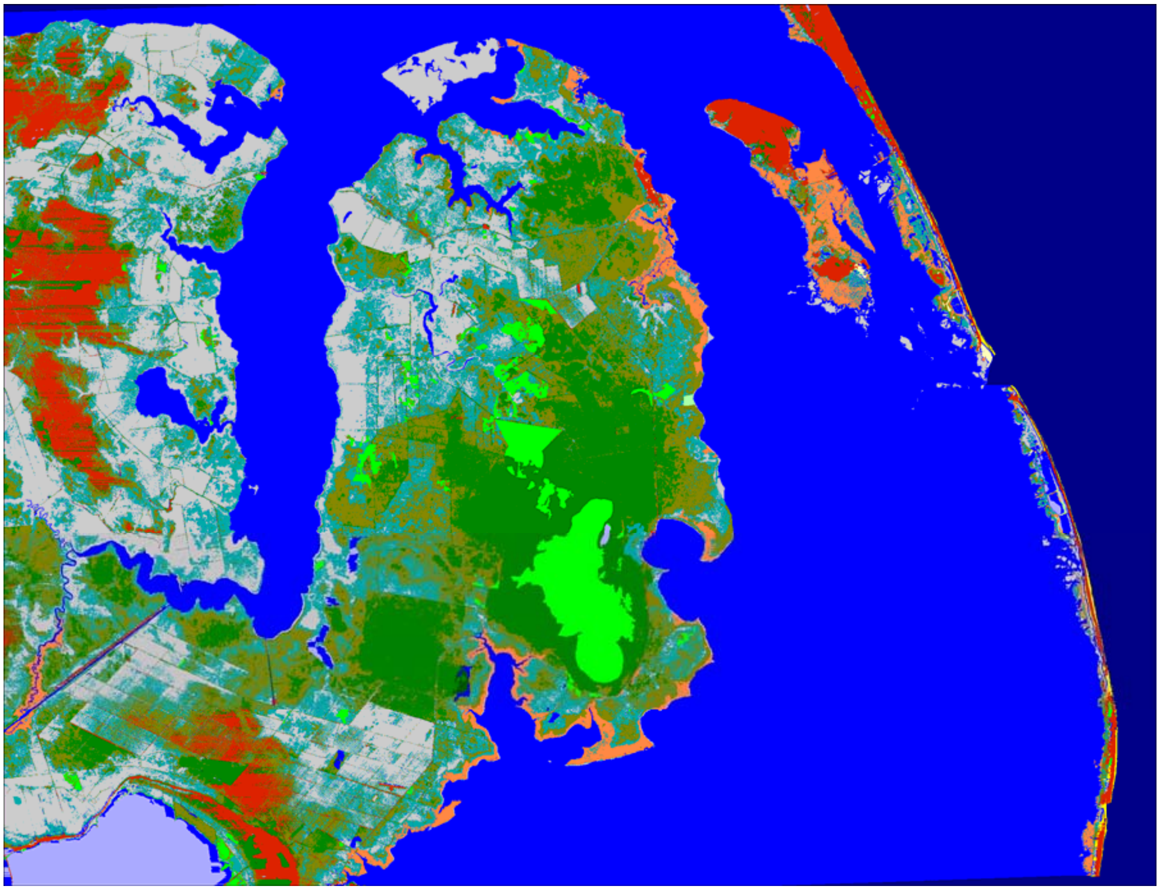
North Carolina Initial Condition



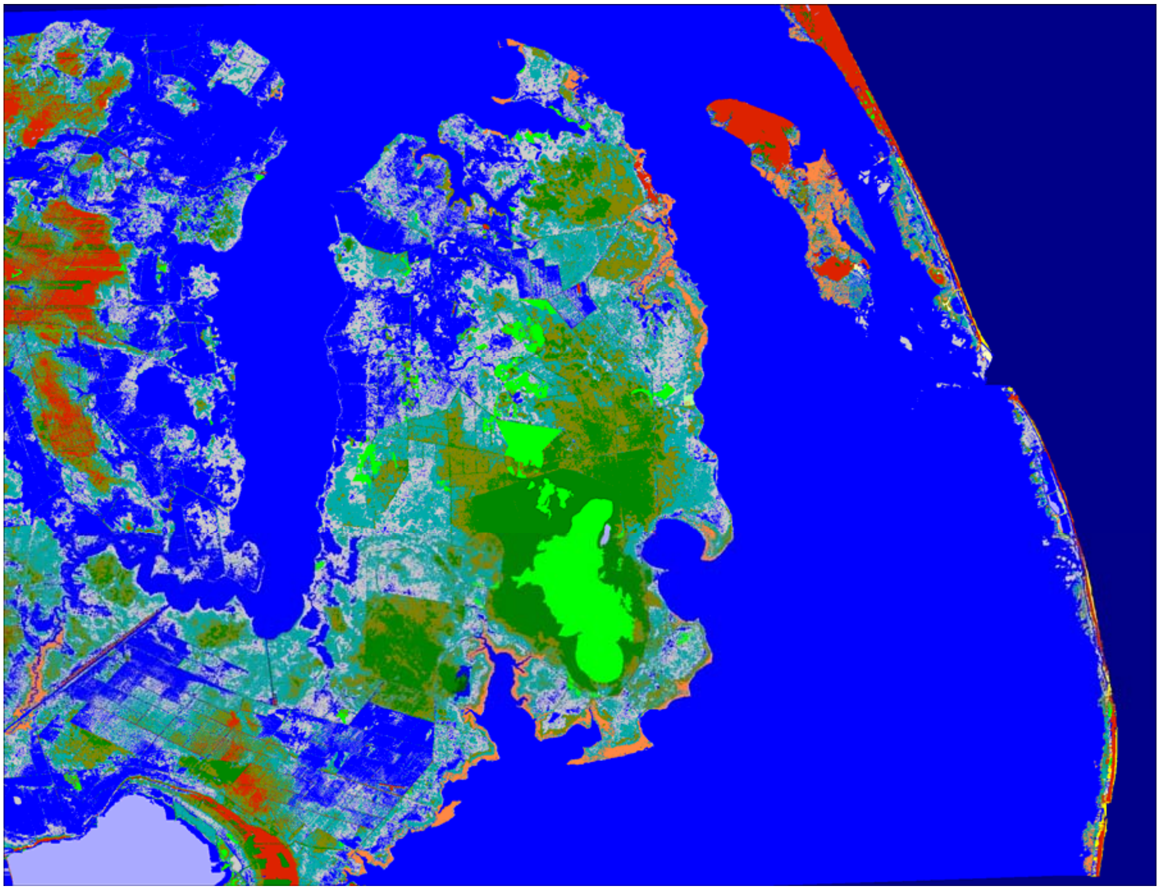
North Carolina 2025 IPCC Scenario A1B-Maximum



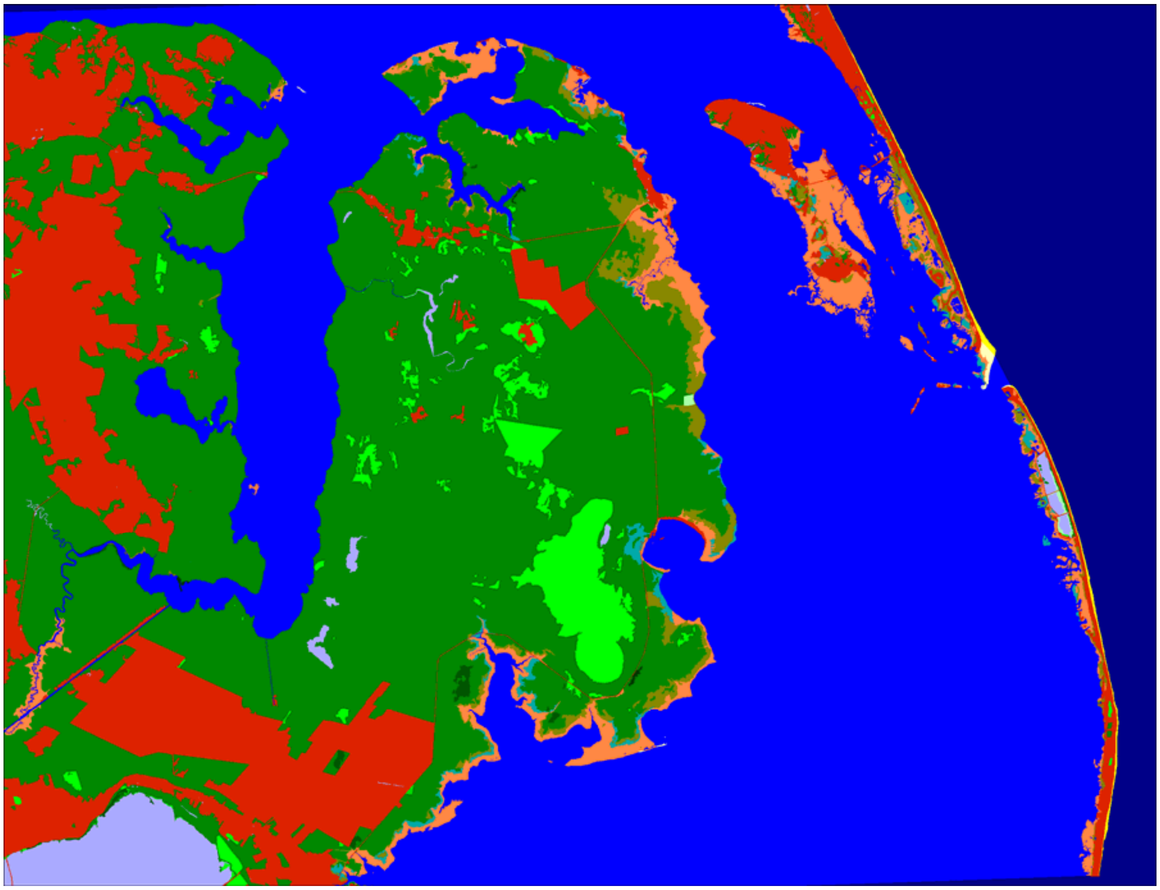
North Carolina 2050 IPCC Scenario A1B-Maximum



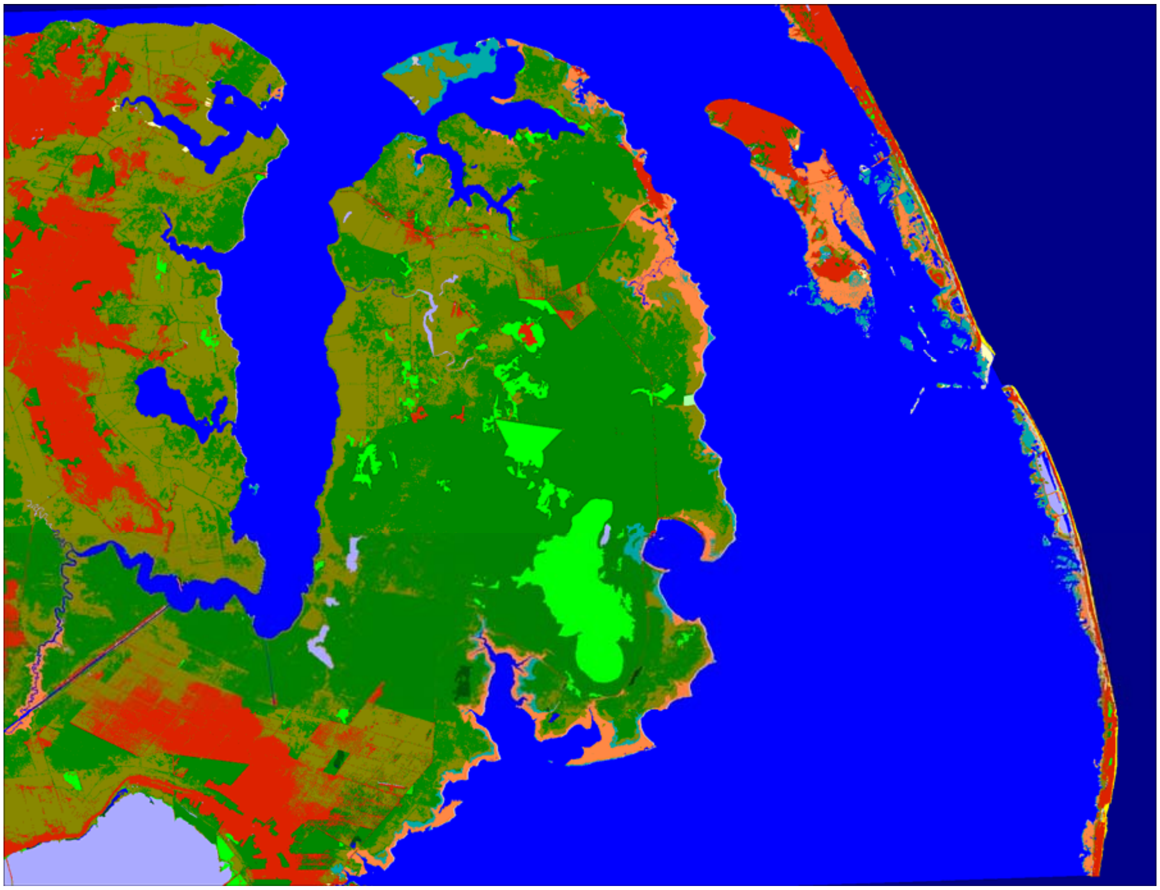
North Carolina 2075 IPCC Scenario A1B-Maximum



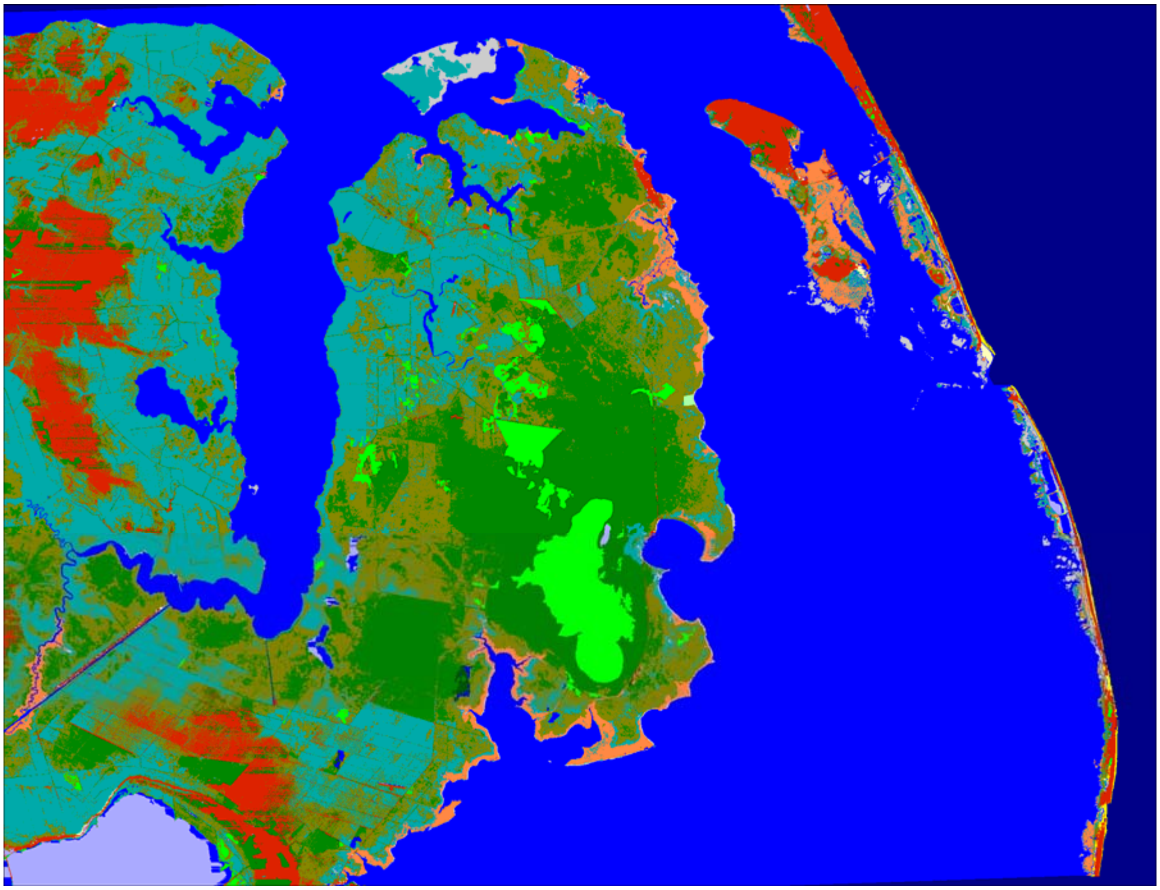
North Carolina 2100 IPCC Scenario A1B-Maximum



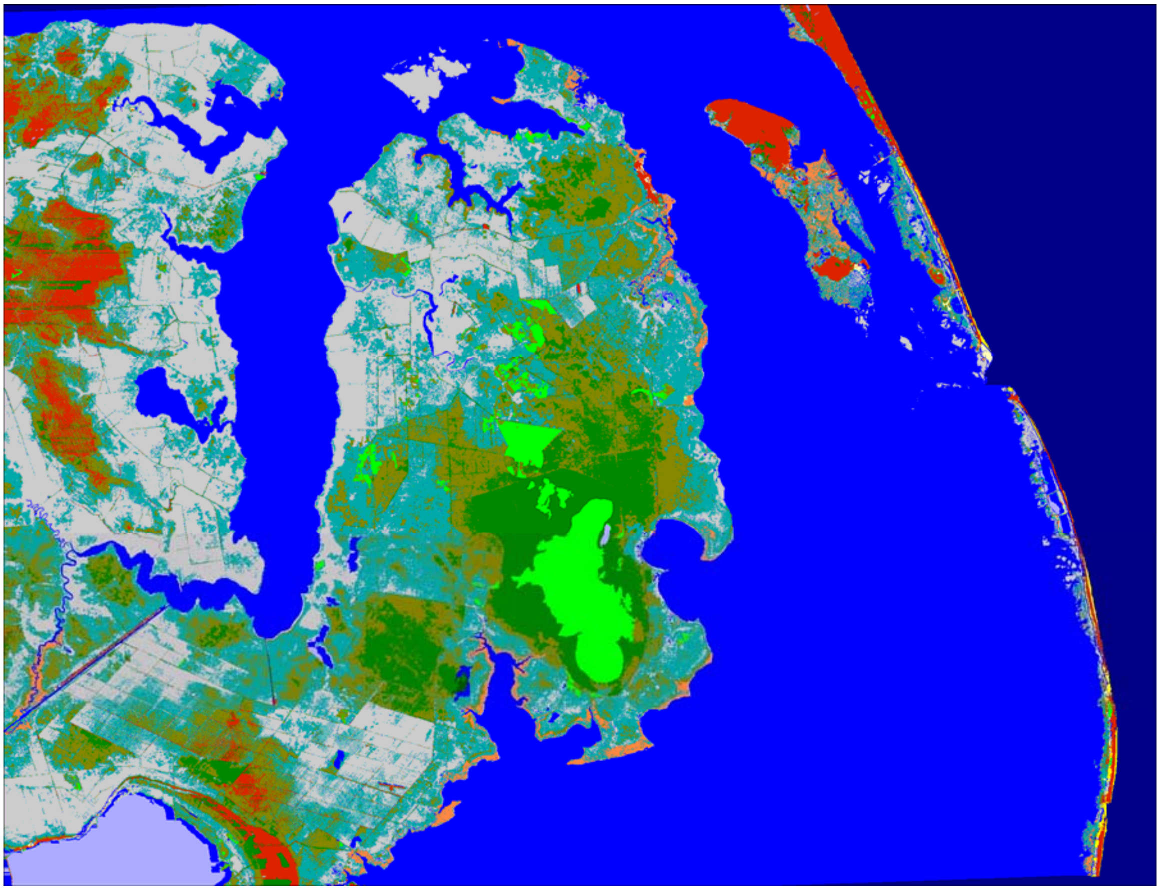
North Carolina Initial Condition



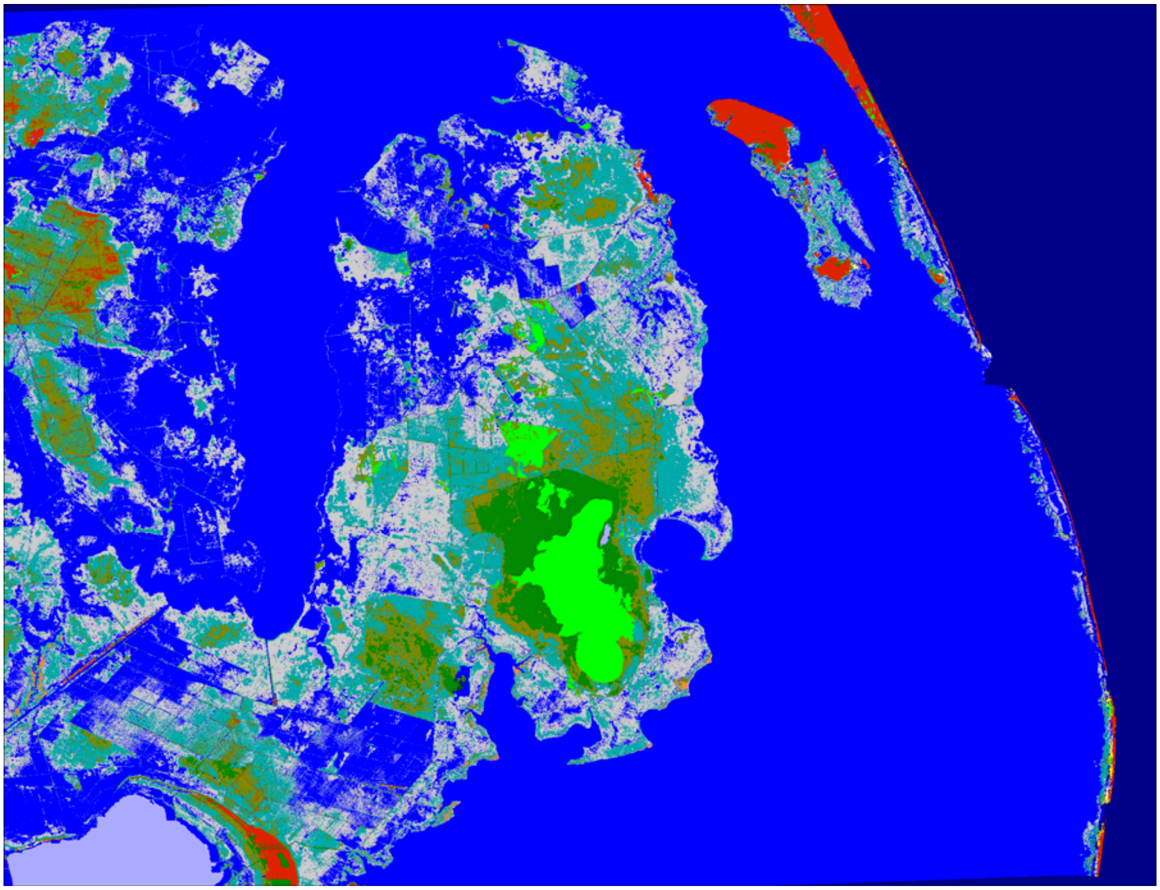
North Carolina 2025, 1 meter Eustatic by 2100



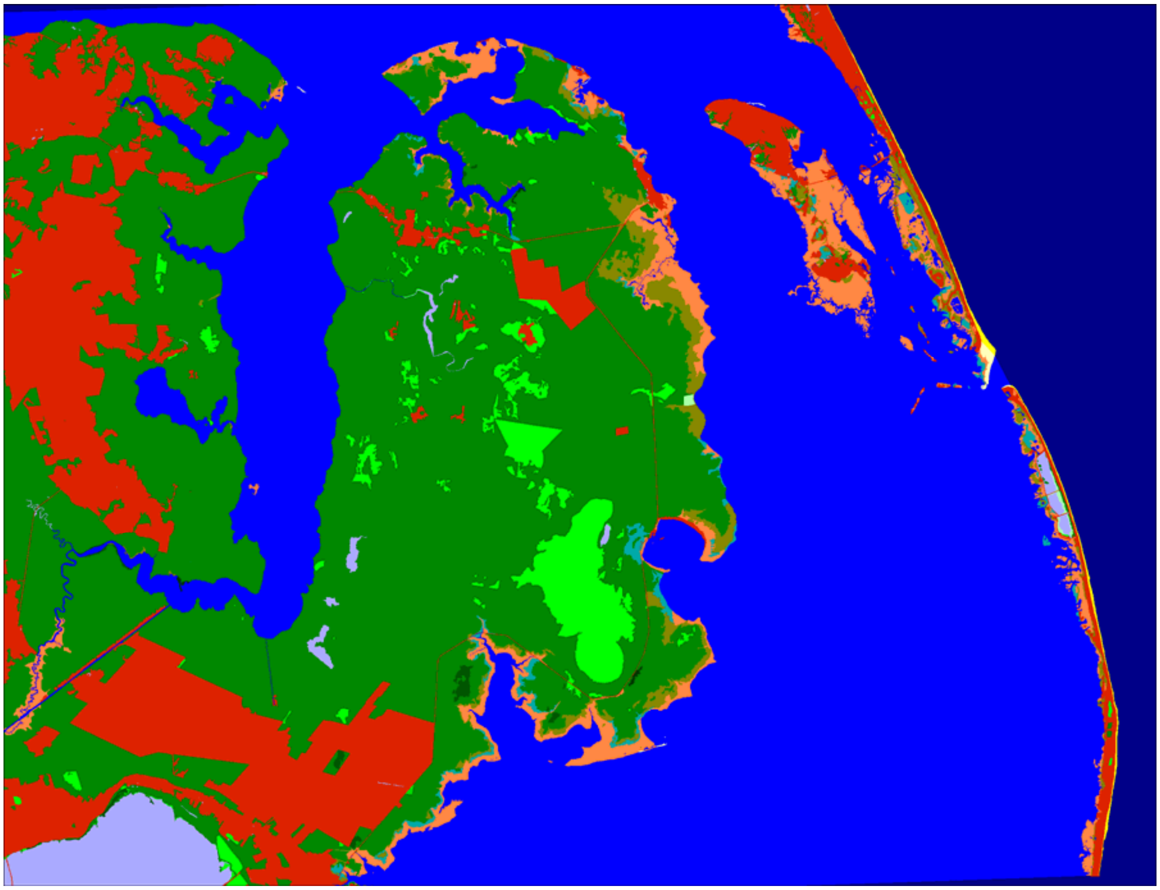
North Carolina 2050, 1 meter Eustatic by 2100



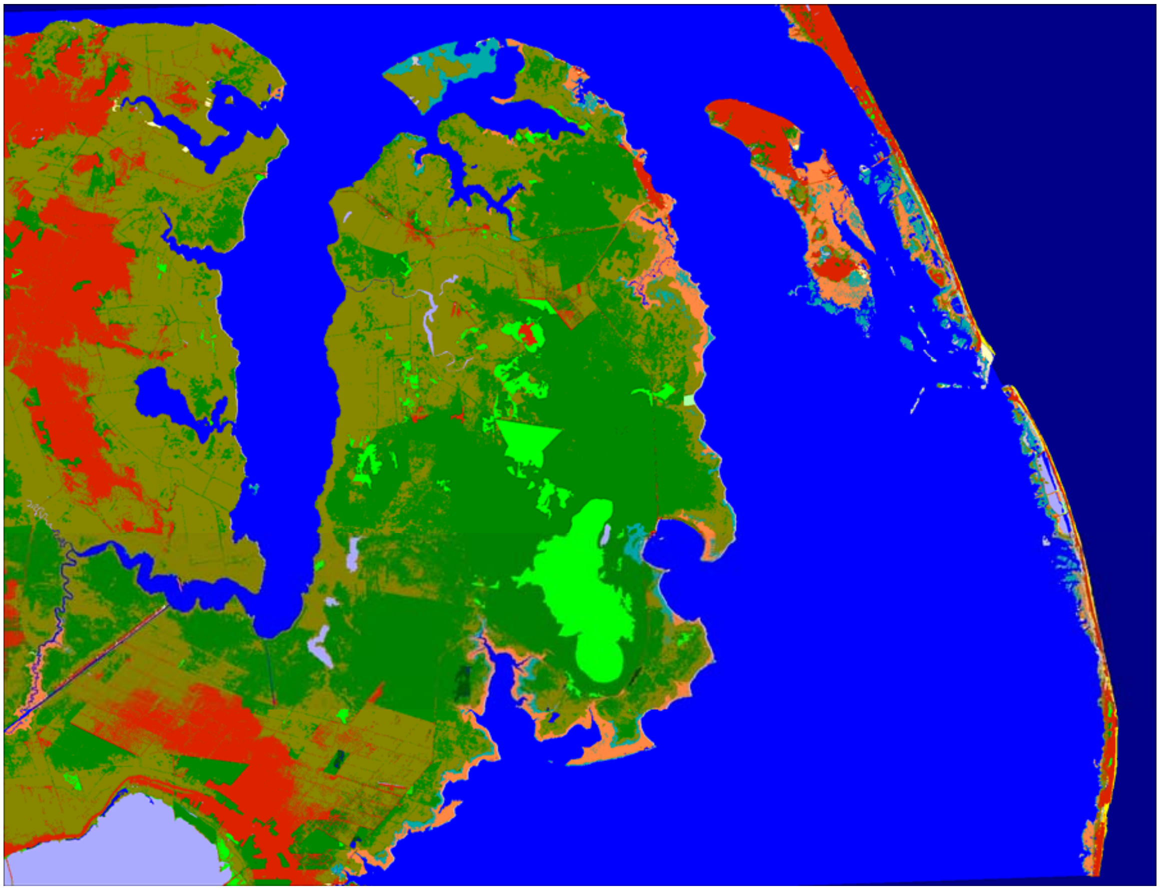
North Carolina 2075, 1 meter Eustatic by 2100



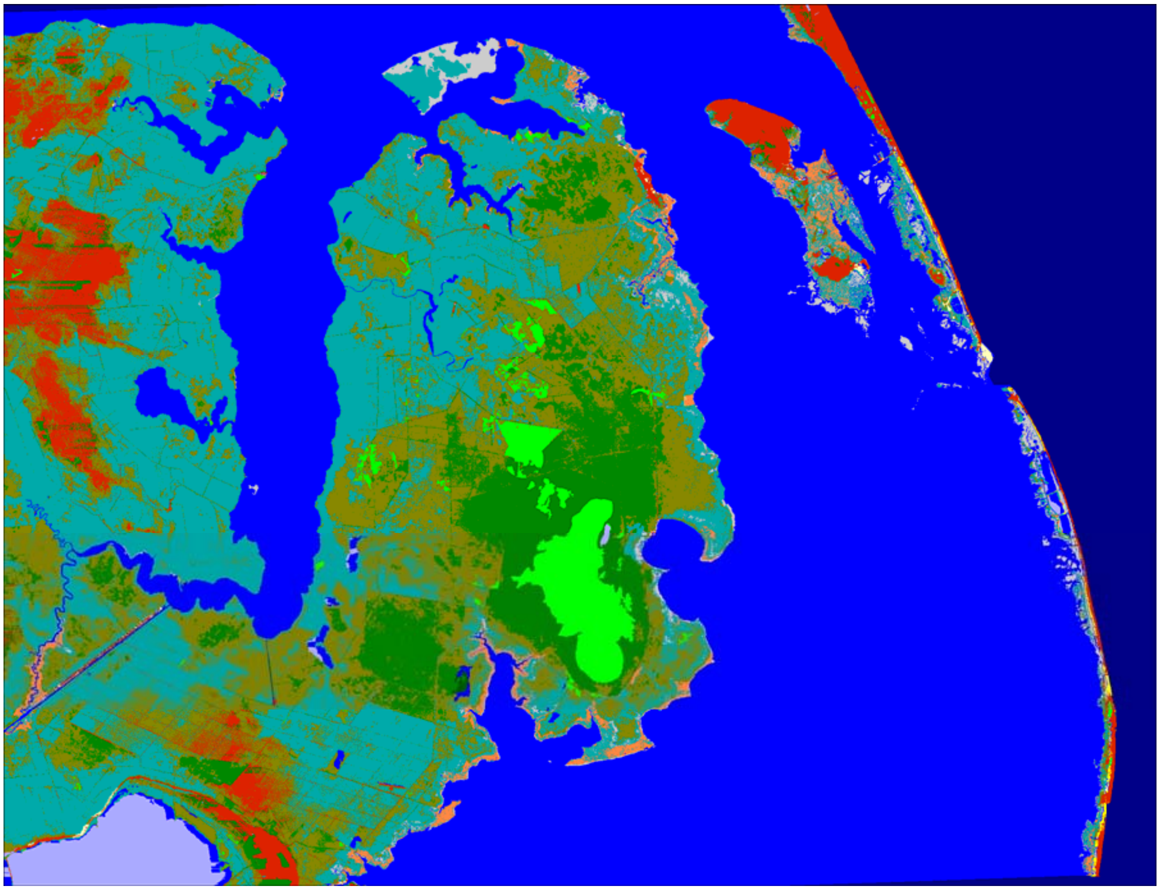
North Carolina 2100, 1 meter Eustatic by 2100



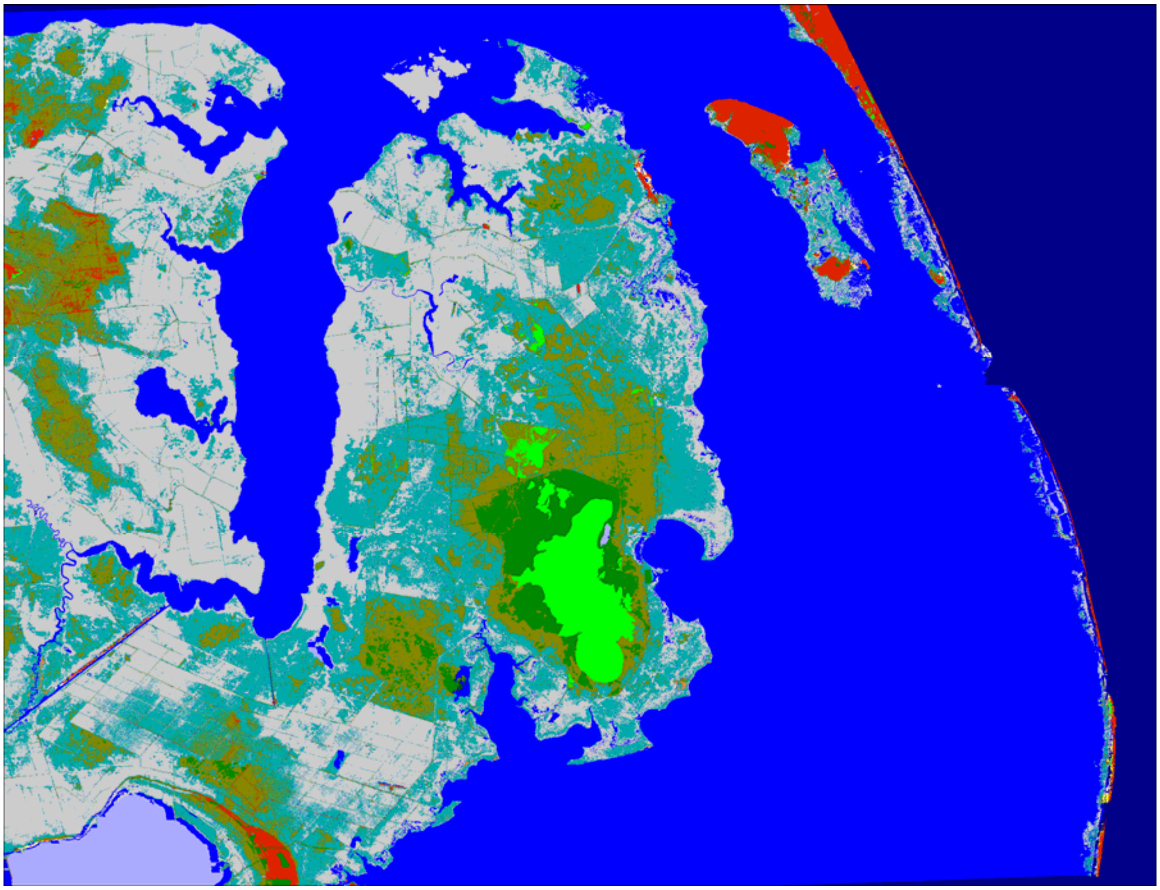
North Carolina Initial Condition



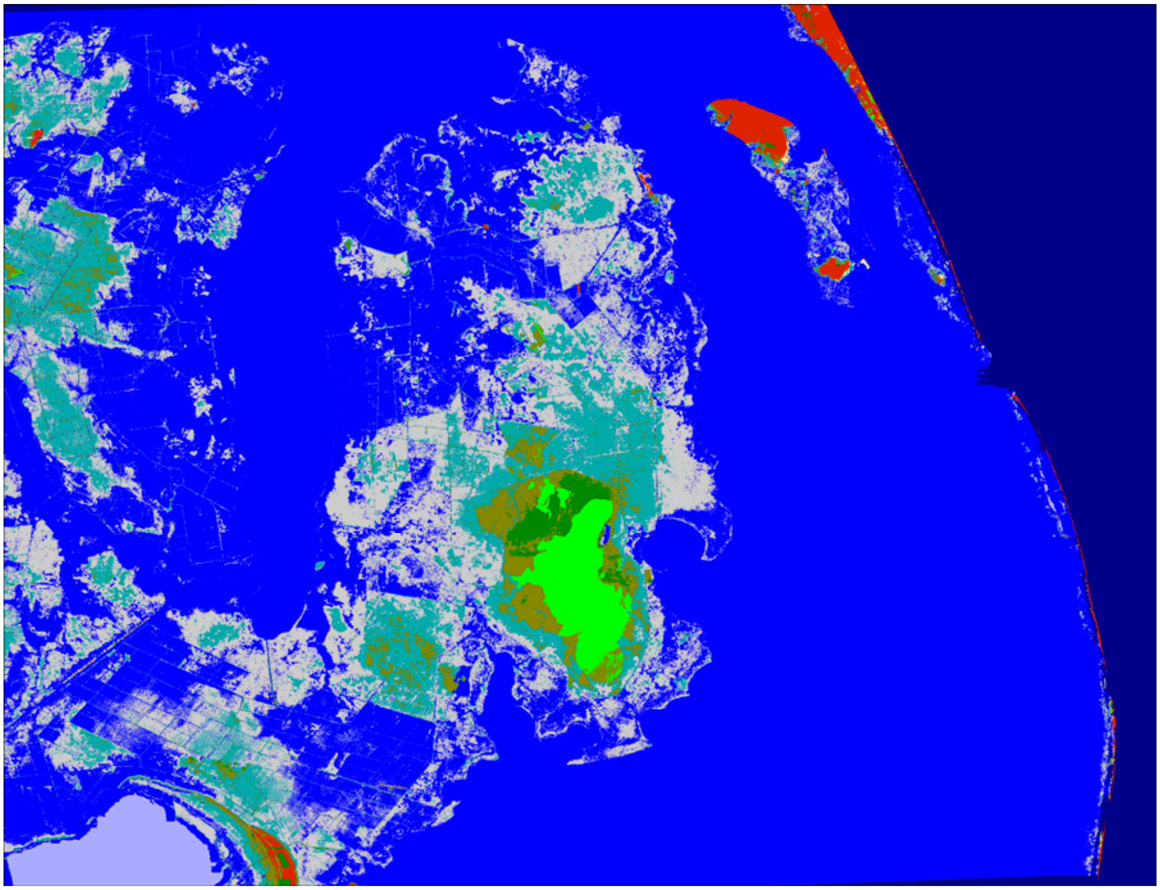
North Carolina 2025, 1.5 meter Eustatic by 2100



North Carolina 2050, 1.5 meter Eustatic by 2100



North Carolina 2075, 1.5 meter Eustatic by 2100



North Carolina 2100, 1.5 meter Eustatic by 2100