Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to Stewart B. McKinney 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 Stewart B. McKinney 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:

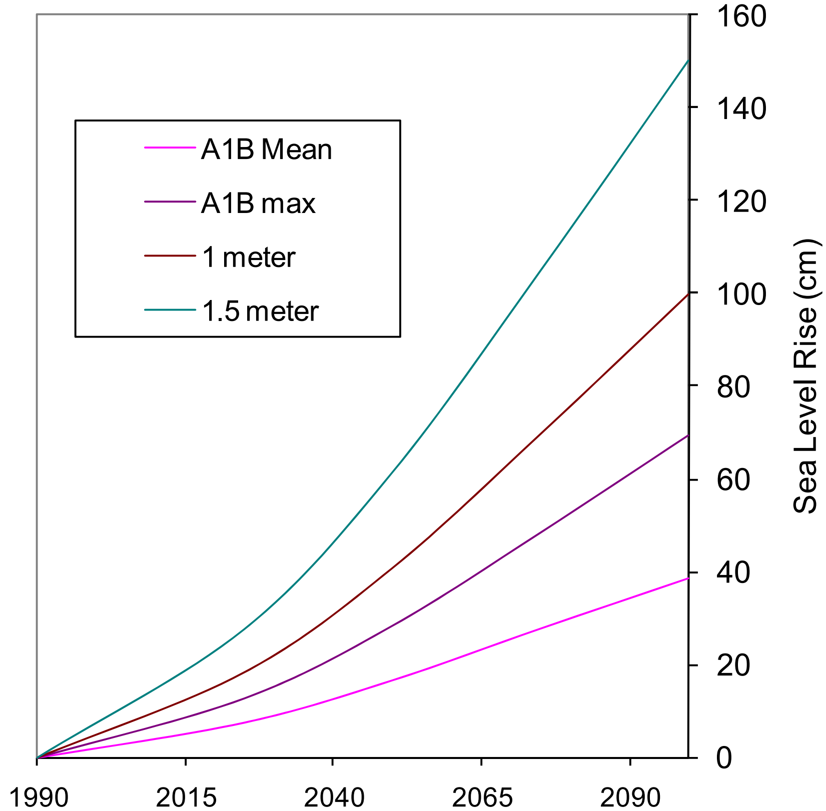
Scenario	Eustatic SLR by 2025 (cm)	Eustatic SLR by 2050 (cm)	Eustatic SLR by 2075 (cm)	Eustatic SLR by 2100 (cm)
A1B Mean	8	17	28	39
A1B Max	14	30	49	69
1 meter	13	28	48	100
1.5 meter	18	41	70	150

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. 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 sea level rises for the end of the 21st century are too low." (US Climate Change Science Program, 2008)

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

Elevation data used are based on a combination of LiDAR and the National Elevation Dataset (NED). The eastern portion of the study area was covered by LiDAR (Figure 2b).

For the portion of the refuge that lies outside of the LiDAR footprint, elevation data were based on several USGS surveys ranging from 1958 to 1970. An example map is illustrated below (Fig. 2a). The contour interval for these USGS maps was ten feet indicating considerable uncertainty between the shoreline and the first contour. For this reason, wetlands elevations in non LiDAR areas were estimated as a function of tidal range.

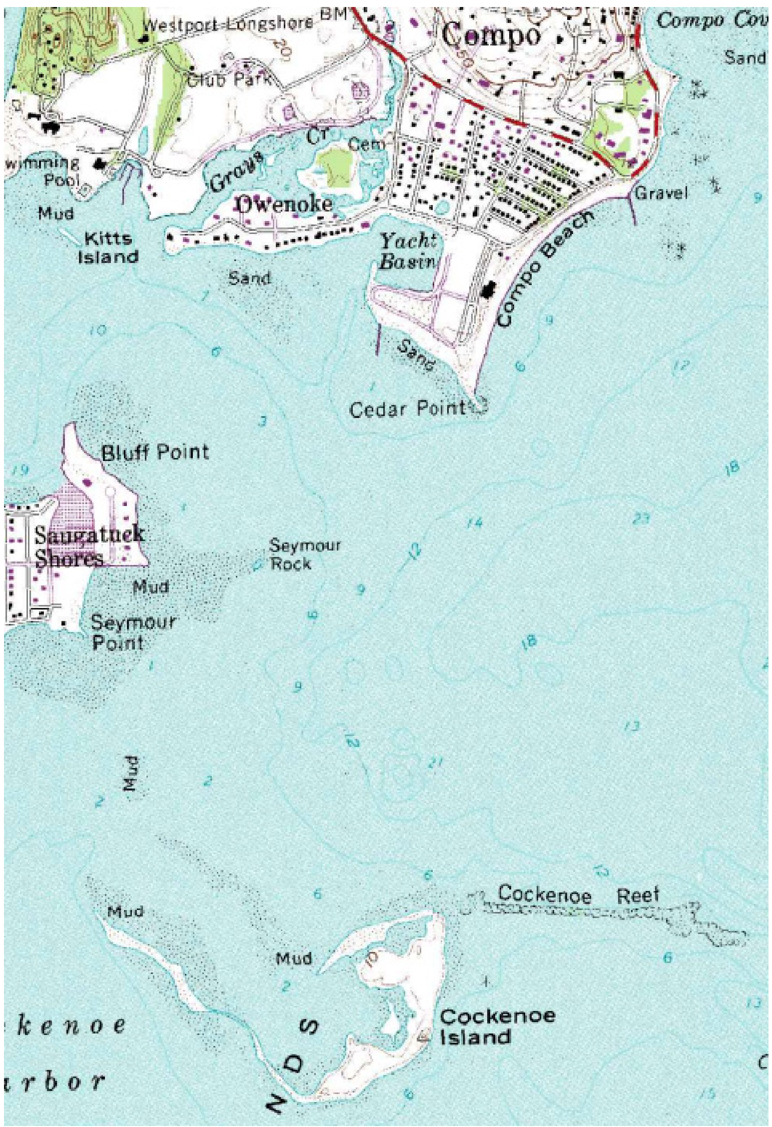


Figure 2a: Stewart B. McKinney Excerpt from USGS Map.

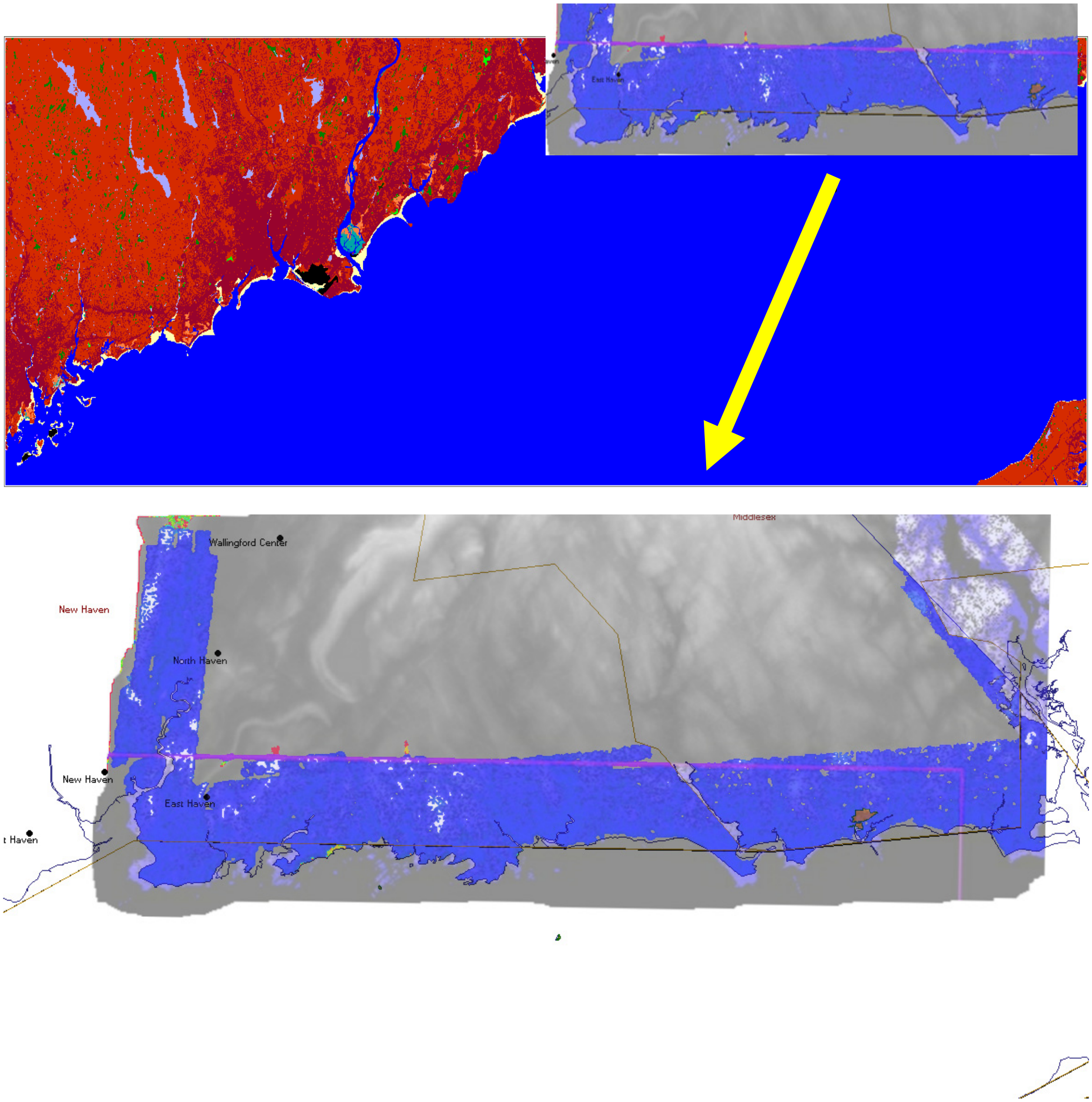


Figure 2b: LiDAR coverage (blue) within simulation context above and close-up below including relevant approved acquisition boundary (brown).

The National Wetlands Inventory for Stewart B. McKinney is based on a photo date of 1980. An examination of the NWI map overlaid on recent satellite photos indicates, in some areas, a potential dry land shift/inland water shift of about 20 meters (Figure 3).

Figure 3: Land- and water-cover shift of nearly 20 meters indicated by lines.

The National Wetland Inventory data do not cover Outer Island or Faulkner Island. LiDAR elevation data are available for Outer Island and it appears (based on photos of the site) to be composed primarily of the "Rocky Intertidal" and "Dry Land" SLAMM categories. Therefore, land-cover categories for this island were estimated using the elevation data. Cells with elevations that suggest that they are subject to regular inundation were assigned as "rocky intertidal" and non inundated cells were assigned as "dry land." This estimation technique increases uncertainty for model results for this island, but does enable it to be included in this analysis. For Faulkner Island neither elevation data nor NWI data were available, so this island was not included in this modeling analysis.

Converting the NWI survey into 30 meter cells indicates that the roughly eleven hundred acre refuge (approved acquisition boundary including water) is primarily composed of the categories as shown below:

Dry Land	37.7%
Brackish Marsh	30.8%
Estuarine Beach	12.2%
Saltmarsh	10.8%
Estuarine Open Water	4.0%
Dev. Dry Land	3.5%

Based on the NWI coverage, there are no dikes or impounded wetlands within Stewart B. McKinney NWR.

The historic trend for sea level rise was estimated at 2.49 mm/year using the average value from the three closest stations (8461490, New London, CT; 8510560, Montauk, New York; 8514560, Port Jefferson, New York). This measured rate is slightly higher than the global average for the last 100 years (approximately 1.5-2.0 mm/year). Note that any effects of isostatic rebound that have affected this region for the last 100 years are measured within that historic trend and that same rate of isostatic rebound is projected forward into the next 100 years.

The tide range for the western portion of this site was estimated at 2.04 meters using the average of the eight closest NOAA oceanic gages (8468448, South Norwalk, CT; 8468609, Rowayton, Fivemile River, CT; 8468799, Long Neck Point, Long Island Sound, CT; 8467373, Black Rock Harbor; 8467726, Southport, Southport Harbor, CT; 8466375, Gulf Beach, CT; 8465233, Branford, Branford River, CT; 8461467, Yale Boathouse, Thames River, CT). The tide range within the eastern portion of the site (LiDAR coverage) was estimated at 1.65 meters using the two closest gages (8464445, Guildford, Guildford Harbor, CT; 8463701, Clinton, Clinton Harbor, CT).

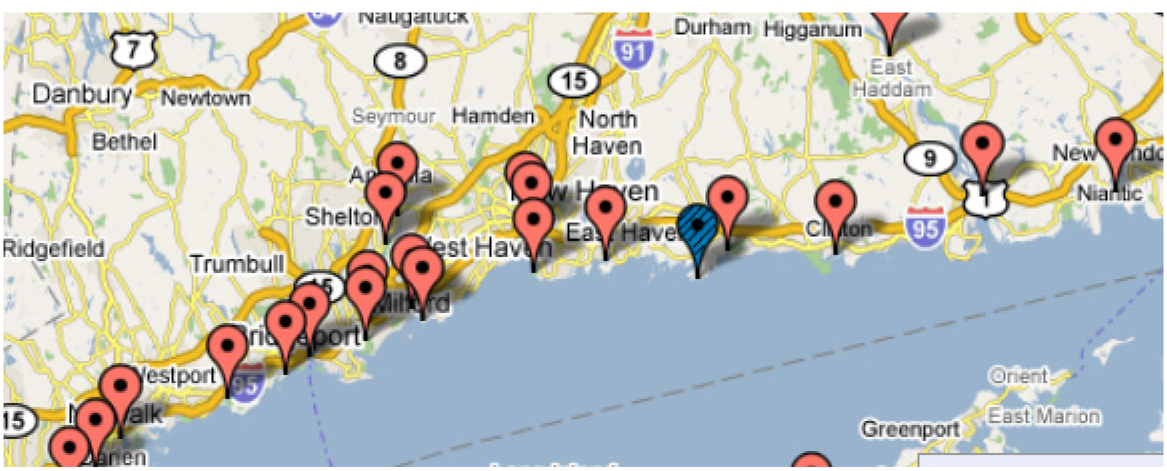


Figure 4: NOAA Gages Relevant to the Study Area.

Accretion rates in salt and brackish marshes were set to 2.275 mm/year, and the rates in tidal fresh marshes to 5.9 mm/year based on measurements from Barn Island, CT. (R.A. Orson, 1998).

Modeled U.S. Fish and Wildlife Service refuge boundaries 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 meter by 30 meter cells. (Note that since the LiDAR data produce a more accurate DEM, only the elevations of wetlands classes lying outside of the LiDAR data in Stewart B. McKinney were overwritten as a function of the local tidal range using the SLAMM elevation pre-processor.)

SUMMARY OF SLAMM INPUT PARAMETERS FOR STEWART B. MCKINNEY

Description	Stewart B McKinney	Stewart B McKinney LiDAR
DEM Source Date (yyyy)	1964	2004
NWI_photo_date (yyyy)	1980	1980
Direction_OffShore (N|S|E|W)	S	S
Historic_trend (mm/yr)	2.49	2.49
NAVD88_correction (MTL-NAVD88 in meters)	-0.066	-0.085
Water Depth (m below MLW- N/A)	2	3
TideRangeOcean (meters: MHHW-MLLW)	2.04	1.65
TideRangeInland (meters)	2.04	1.65
Mean High Water Spring (m above MTL)	1.357	1.097
MHSW Inland (m above MTL)	1.357	1.097
Marsh Erosion (horz meters/year)	1.8	1.8
Swamp Erosion (horz meters/year)	1	1
TFlat Erosion (horz meters/year) [from 0.5]	0.5	0.5
Salt marsh vertical accretion (mm/yr) Final	2.275	2.275
Brackish March vert. accretion (mm/yr) Final	2.275	2.275
Tidal Fresh vertical accretion (mm/yr) Final	5.9	5.9
Beach/T.Flat Sedimentation Rate (mm/yr)	0.5	0.5
Frequency of Large Storms (yr/washover)	50	50
Use Elevation Preprocessor for Wetlands	TRUE	FALSE

Results

This modeling exercise predicts that Stewart B. McKinney National Wildlife Refuge will show effects from sea level rise, regardless of the SLR scenario run. Across all scenarios, between one quarter and one third of the dry land (which comprises roughly 40% of the refuge) is predicted to be lost by 2100. Between 30% and 99% of the refuge's brackish marsh (irregularly flooded marsh) -- which comprises nearly one third of the refuge -- is expected to be lost (or converted to regularly flooded marsh) by 2100. Overall loss of salt marsh (regularly flooded marsh) is only predicted to occur in the most severe sea level rise scenario.

SLR by 2100 (m)	0.39	0.69	1	1.5
Dry Land	25%	27%	29%	33%
Brackish Marsh	30%	69%	98%	99%
Saltmarsh	-73%	-200%	-153%	27%
Estuarine Beach	39%	55%	76%	100%
Dev. Dry Land	60%	63%	66%	71%

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

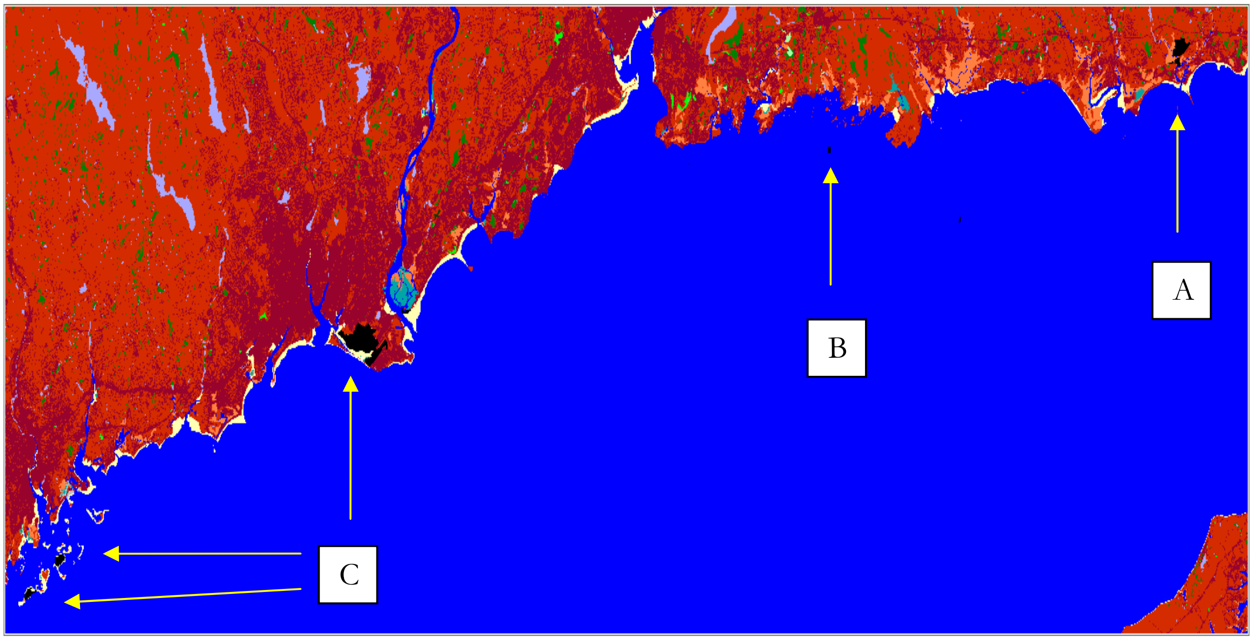
Maps of SLAMM input and output to follow will use the following legend:

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

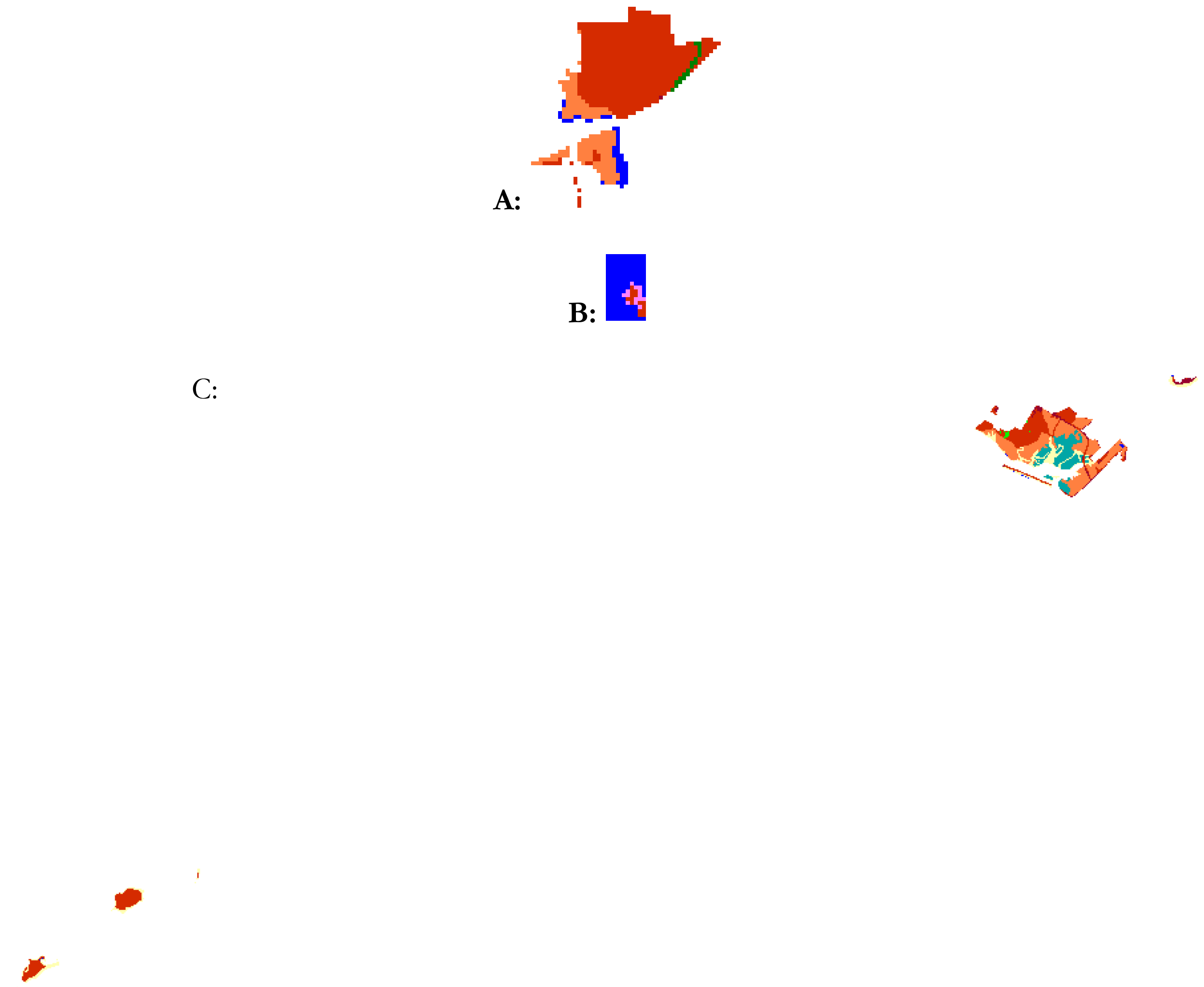
Results in Acres

	Initial	2025	2050	2075	2100
Dry Land	427.4	388.9	364.1	338.8	320.2
Brackish Marsh	348.7	330.0	310.4	279.0	244.9
Saltmarsh	121.9	145.0	177.0	184.1	211.0
Estuarine Beach	137.9	125.8	112.4	97.5	83.9
Estuarine Open Water	45.8	61.6	81.2	106.8	129.6
Trans. Salt Marsh	0.0	42.5	42.9	66.4	83.5
Dev. Dry Land	39.8	17.8	17.4	16.7	16.0
Tidal Flat	0.0	10.0	16.2	32.6	33.0
Inland Fresh Marsh	4.4	4.4	4.4	4.4	4.4
Swamp	4.0	4.0	4.0	4.0	4.0
Rocky Intertidal	3.1	3.1	3.0	2.8	2.5
Total (incl. water)	**1133.1**	**1133.1**	**1133.1**	**1133.1**	**1133.1**

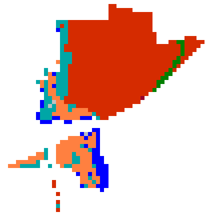
Within this report, in order to produce results maps in which model predictions are visible, result images have been split into three parts in each time-step: A) the northeast end of the refuge near Grove Beach, B) Outer Island and C) the southwest portion of the refuge between Stratford and East Haven.



Location of Stewart B. McKinney National Wildlife Refuge (black polygons) within simulation context



Stewart B. McKinney, Initial Condition



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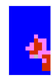

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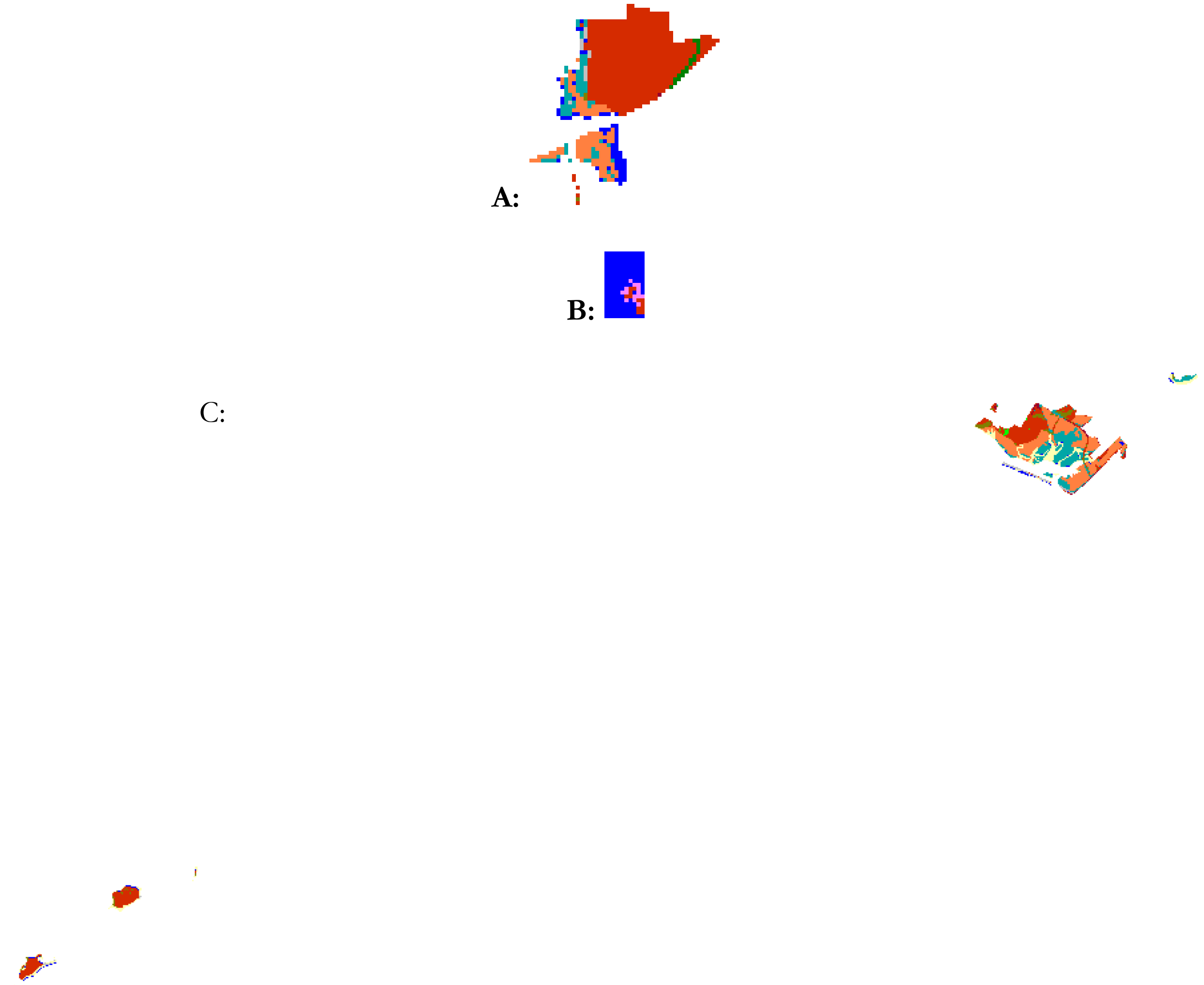
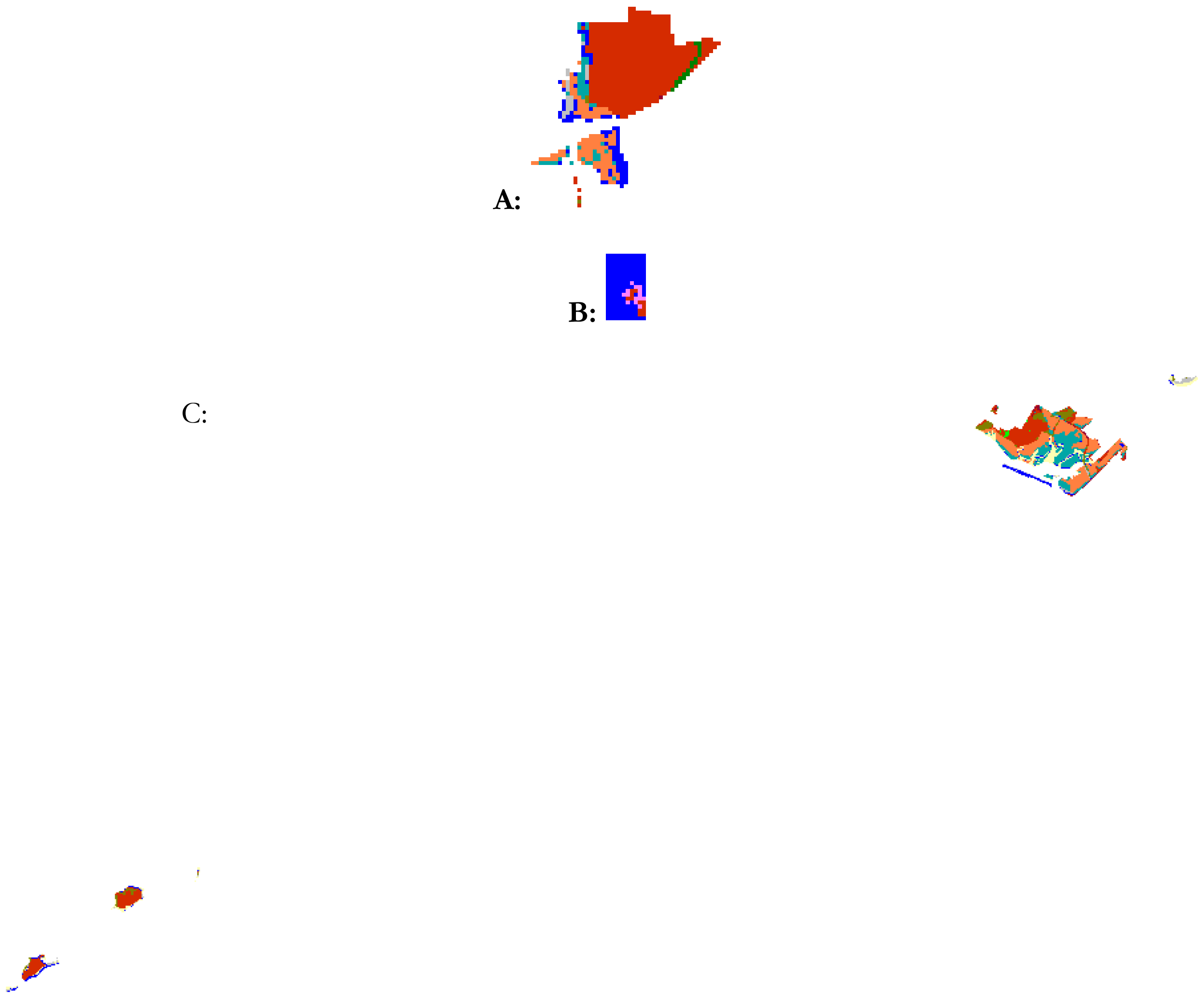
Stewart B. McKinney, 2025, Scenario A1B Mean



Stewart B. McKinney, 2050, Scenario A1B Mean



Stewart B. McKinney, 2075, Scenario A1B Mean

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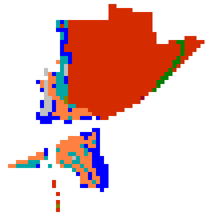

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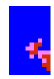


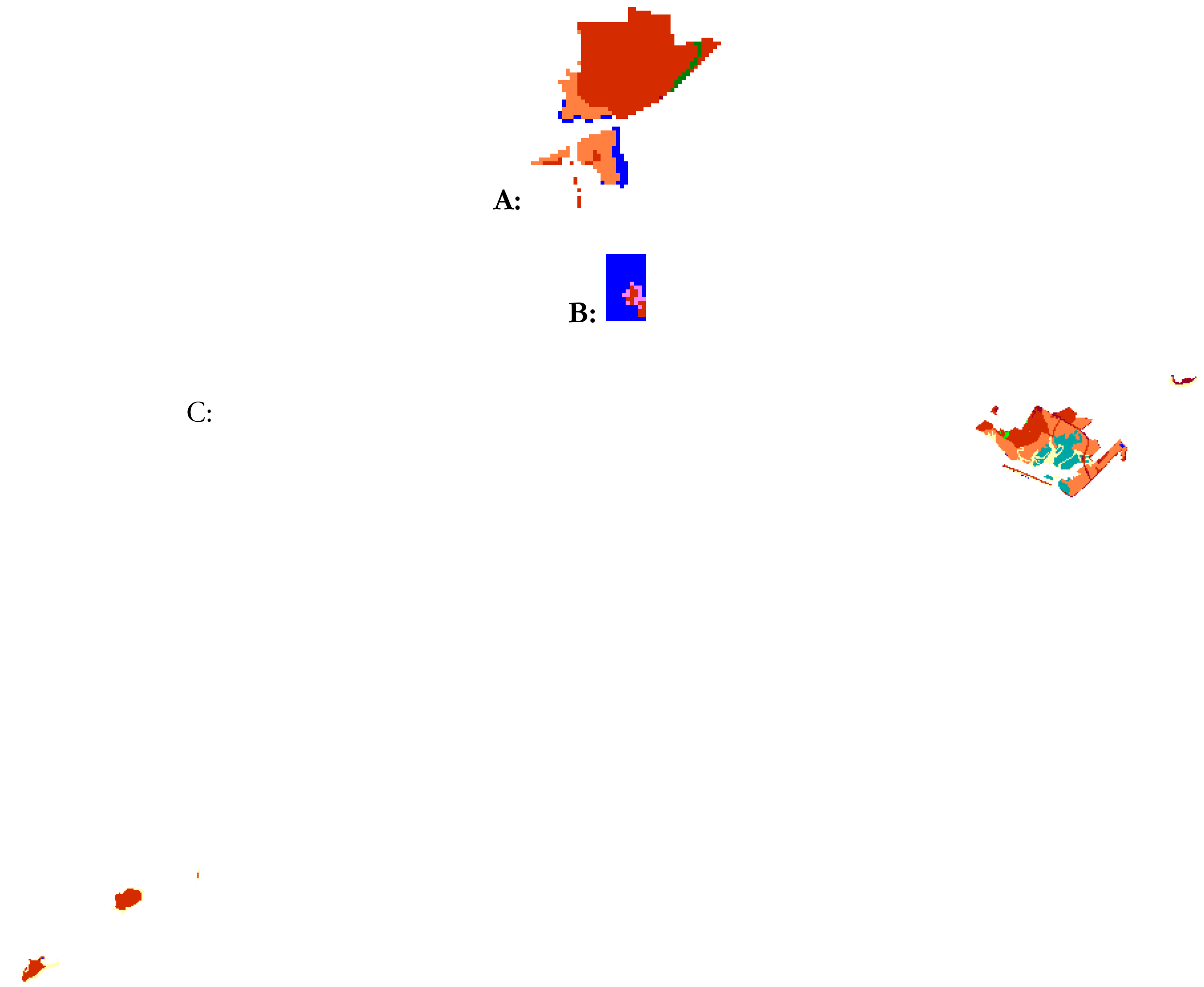
C:

Stewart B. McKinney, 2100, Scenario A1B Mean

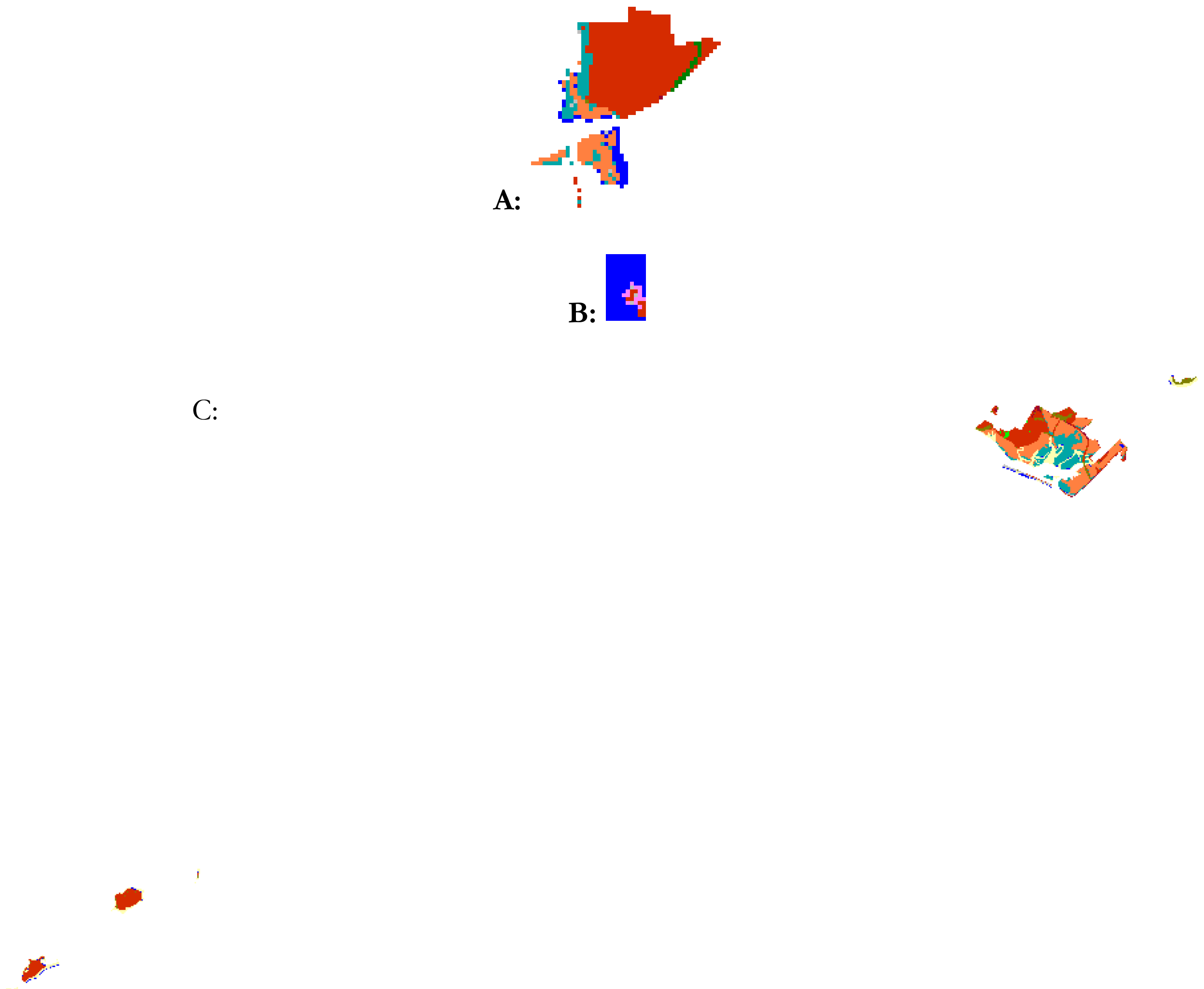
Combined NWR
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

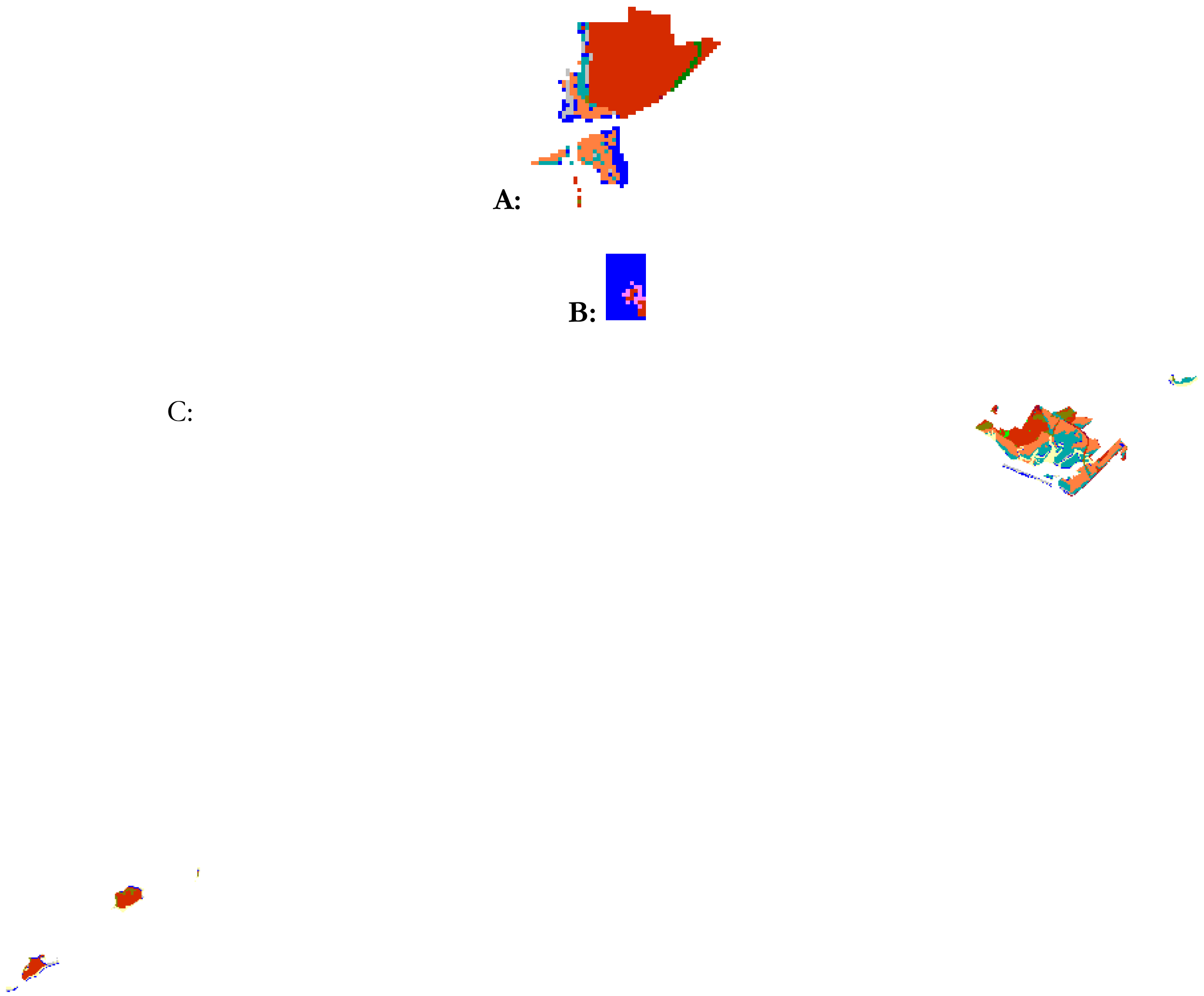
	Initial	2025	2050	2075	2100
Dry Land	427.4	378.2	342.4	318.2	311.0
Brackish Marsh	348.7	312.9	263.0	182.0	106.5
Saltmarsh	121.9	158.1	210.8	278.7	366.0
Estuarine Beach	137.9	120.9	101.5	79.5	62.6
Estuarine Open Water	45.8	68.7	93.3	123.5	159.9
Trans. Salt Marsh	0.0	51.3	63.0	65.2	27.4
Dev. Dry Land	39.8	17.6	16.8	15.6	14.7
Tidal Flat	0.0	13.8	31.1	59.6	74.7
Inland Fresh Marsh	4.4	4.4	4.4	4.4	4.4
Swamp	4.0	4.0	4.0	4.0	4.0
Rocky Intertidal	3.1	3.1	2.8	2.3	1.9
Total (incl. water)	**1133.1**	**1133.1**	**1133.1**	**1133.1**	**1133.1**



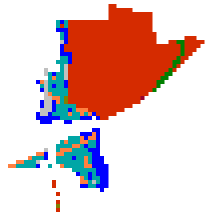
Stewart B. McKinney, Initial Condition



Stewart B. McKinney, 2025, Scenario A1B Maximum



Stewart B. McKinney, 2050, Scenario A1B Maximum



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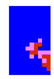

B:

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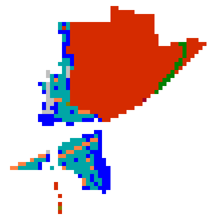
Stewart B. McKinney, 2075, Scenario A1B Maximum

A:



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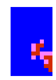

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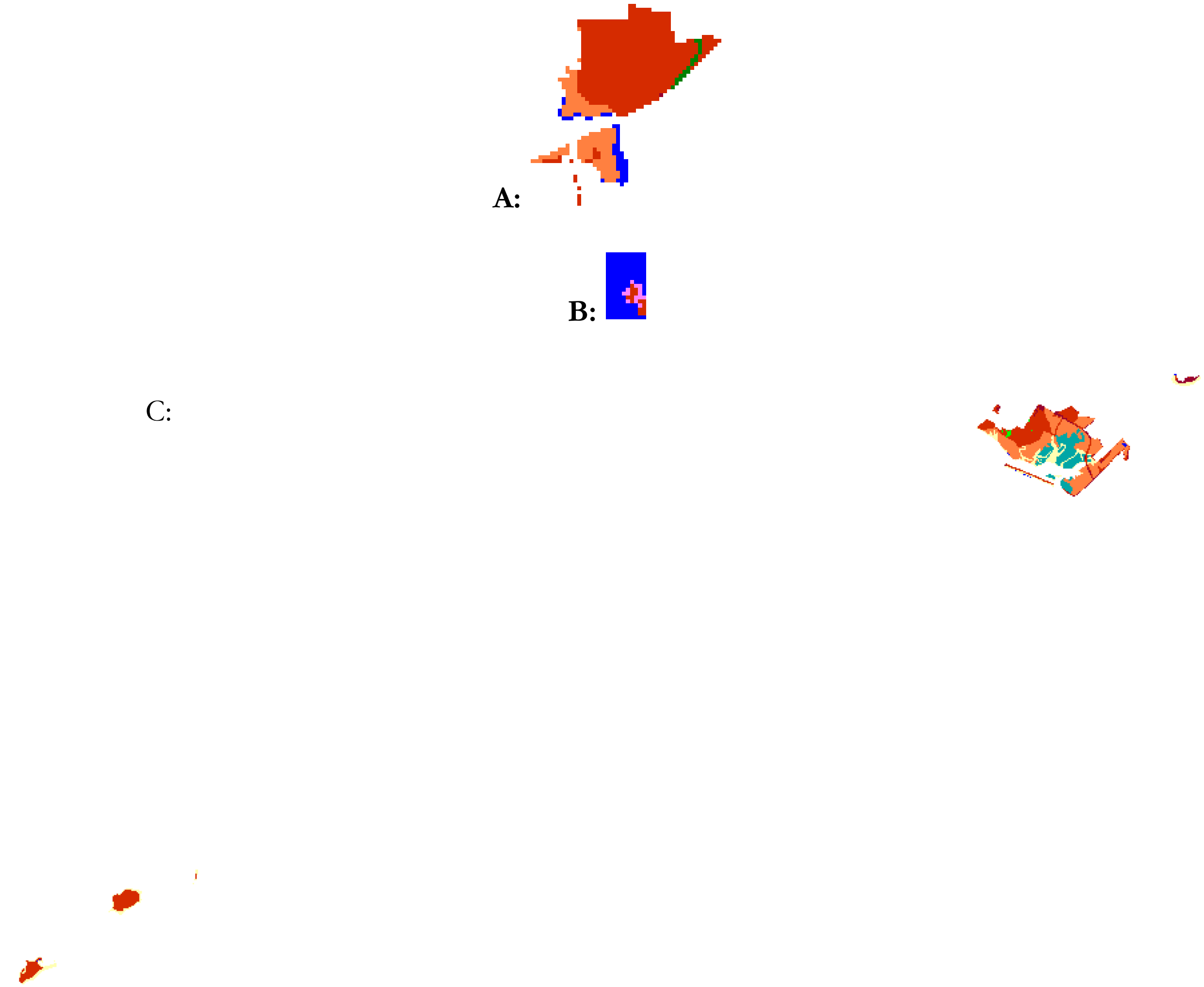
Stewart B. McKinney, 2100, Scenario A1B Maximum

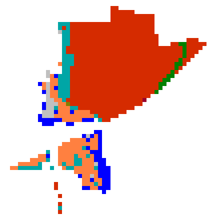
Combined NWR
1 Meter Eustatic SLR by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Dry Land	427.4	365.8	321.9	311.8	303.4
Brackish Marsh	348.7	291.0	201.2	91.3	5.8
Saltmarsh	121.9	172.8	270.6	363.3	308.0
Estuarine Beach	137.9	114.4	89.0	64.2	33.1
Estuarine Open Water	45.8	75.0	102.7	146.1	199.0
Trans. Salt Marsh	0.0	62.0	69.8	26.4	13.1
Dev. Dry Land	39.8	17.4	16.1	14.8	13.4
Tidal Flat	0.0	23.1	50.8	104.9	247.4
Inland Fresh Marsh	4.4	4.4	4.4	4.4	4.4
Swamp	4.0	4.0	4.0	4.0	4.0
Rocky Intertidal	3.1	3.0	2.5	1.9	1.5
Total (incl. water)	**1133.1**	**1133.1**	**1133.1**	**1133.1**	**1133.1**



Stewart B. McKinney, Initial Condition



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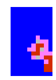

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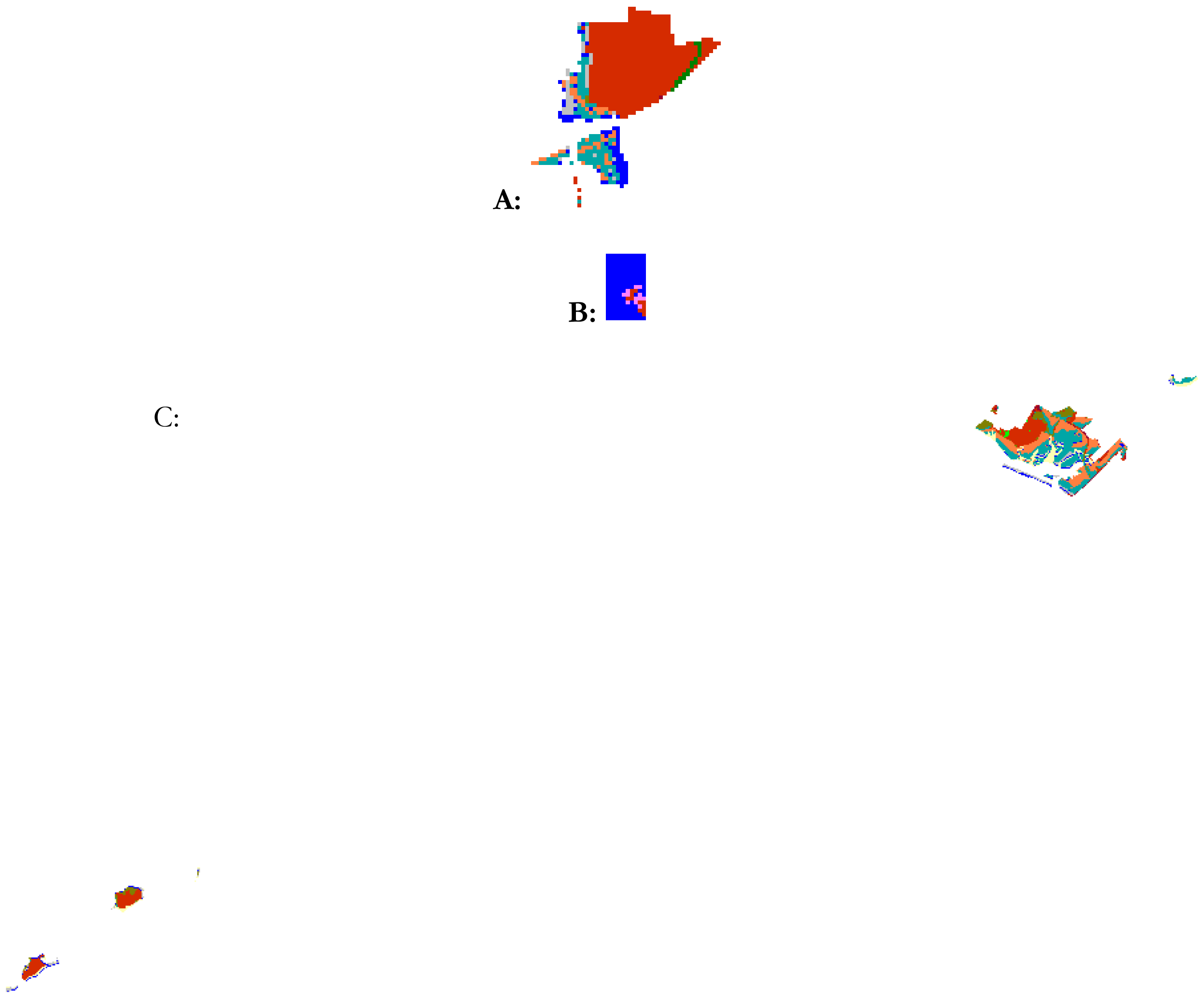
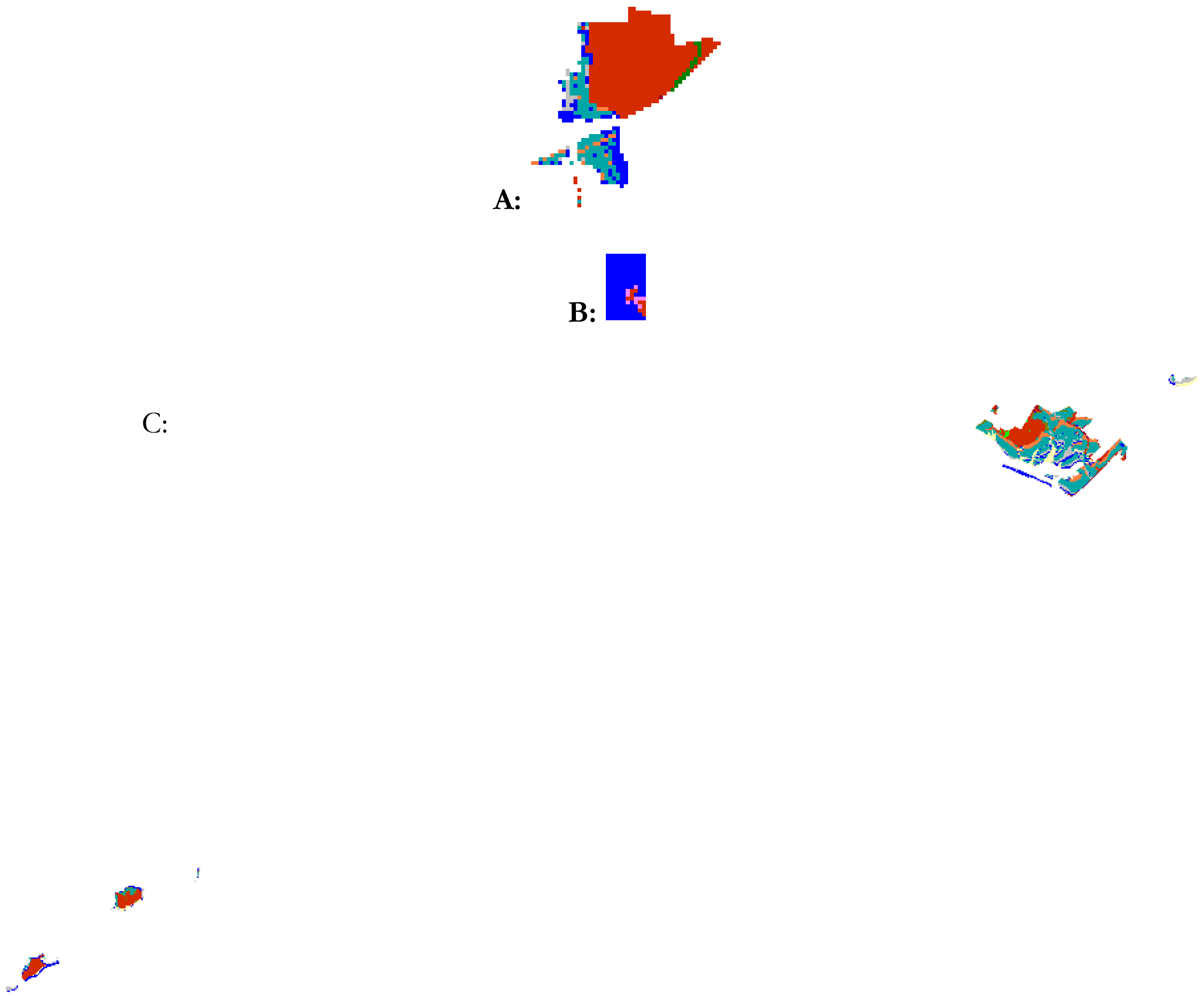
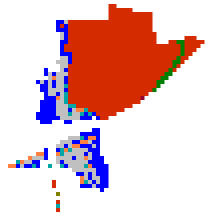
Stewart B. McKinney, 2025, 1 Meter



Stewart B. McKinney, 2050, 1 Meter



Stewart B. McKinney, 2075, 1 Meter



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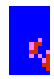

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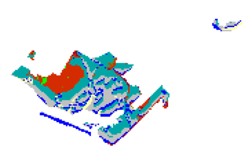
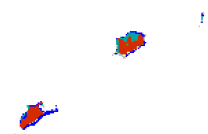


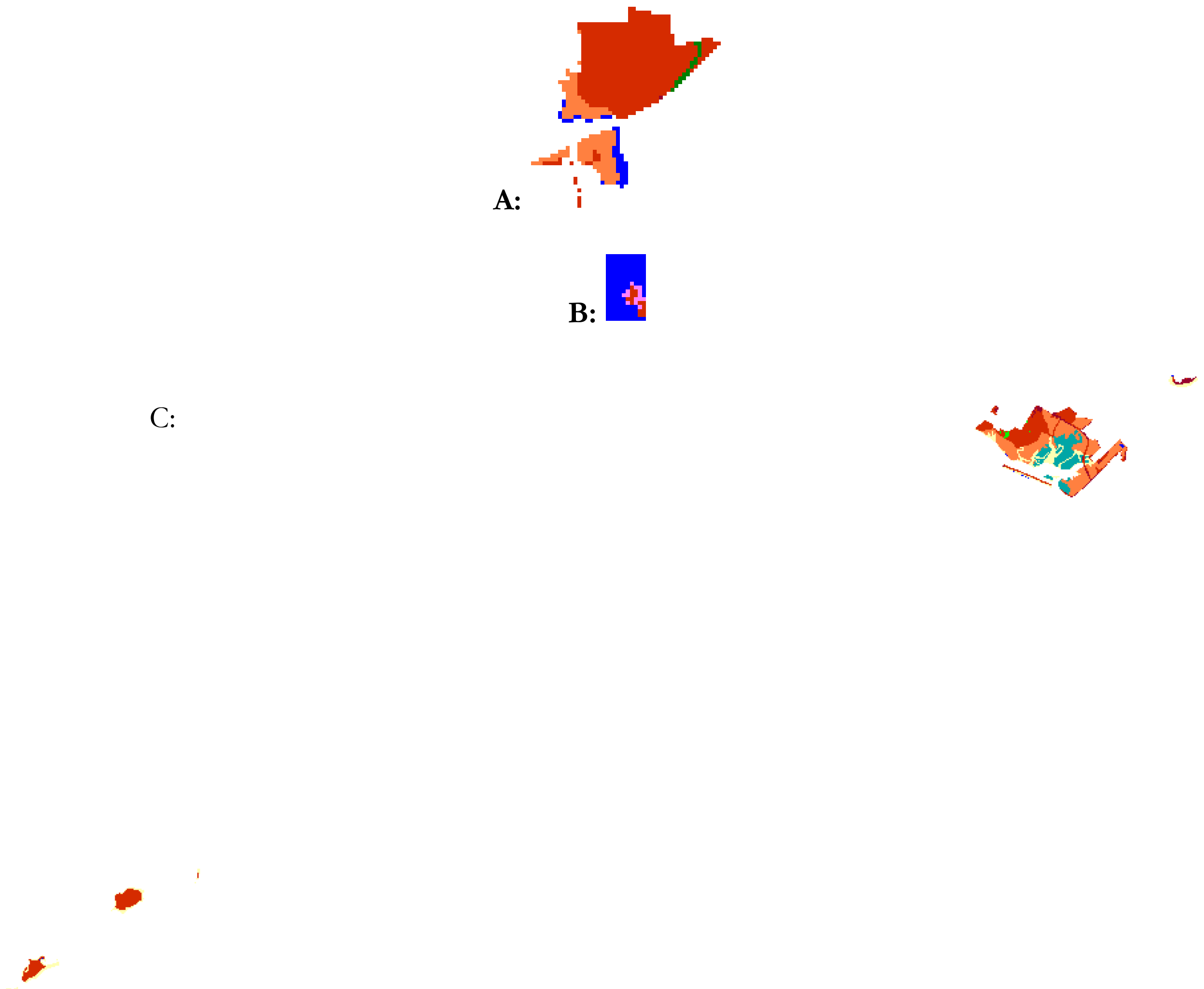


Stewart B. McKinney, 2100, 1 Meter

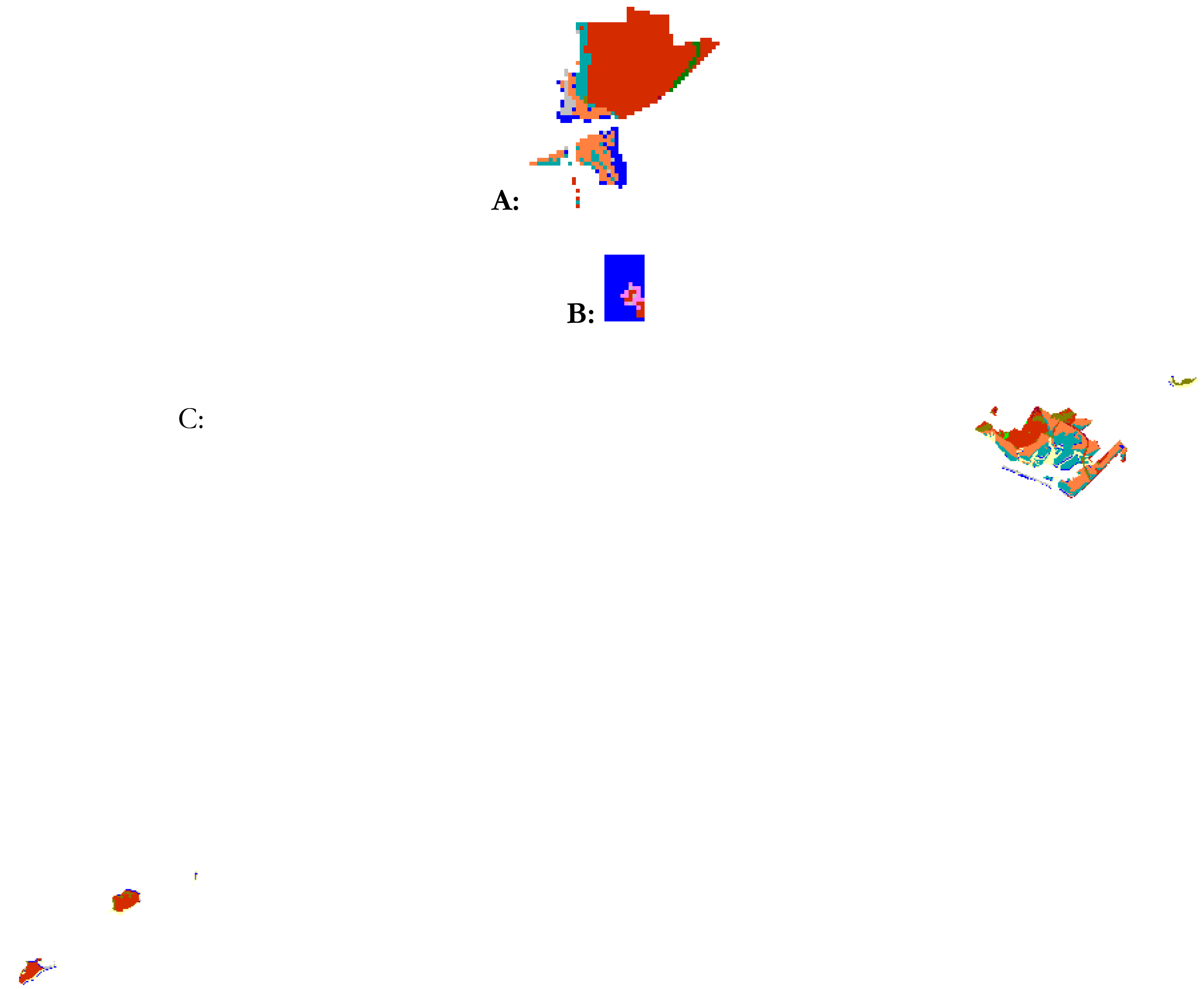
Combined NWR
1.5 Meters Eustatic SLR by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Dry Land	427.4	348.1	314.8	302.7	287.1
Brackish Marsh	348.7	251.6	113.1	5.2	3.5
Saltmarsh	121.9	201.9	364.5	266.2	88.5
Estuarine Beach	137.9	105.1	73.4	29.1	0.2
Estuarine Open Water	45.8	81.2	117.4	184.3	293.7
Trans. Salt Marsh	0.0	78.7	40.6	13.5	16.7
Dev. Dry Land	39.8	17.0	15.2	13.3	11.5
Tidal Flat	0.0	38.2	83.4	308.8	422.4
Inland Fresh Marsh	4.4	4.4	4.4	4.4	4.4
Swamp	4.0	4.0	4.0	4.0	4.0
Rocky Intertidal	3.1	2.9	2.1	1.5	1.0
Total (incl. water)	**1133.1**	**1133.1**	**1133.1**	**1133.1**	**1133.1**

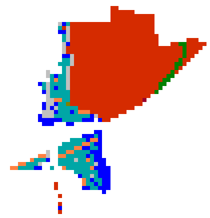


Stewart B. McKinney, Initial Condition



Stewart B. McKinney, 2025, 1.5 Meter

A:



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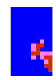
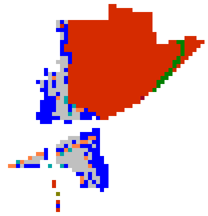


C:

Stewart B. McKinney, 2050, 1.5 Meter

A:



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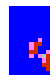
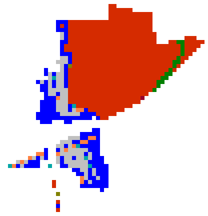


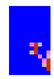
C:

Stewart B. McKinney, 2075, 1.5 Meter

A:



B:



C:

Stewart B. McKinney, 2100, 1.5 Meter

Discussion:

Model results for Stewart B. McKinney indicate that it is somewhat vulnerable to the effects of sea level rise under all scenarios. The majority of brackish marsh is predicted to be lost in all scenarios above 0.39 meters of sea level rise. Because of increased frequency of inundation, most of this lost brackish marsh converts to salt marsh resulting in a gain in refuge salt marsh. However, in the 1.5 meter scenario roughly one-quarter of salt marsh and nearly all of brackish marsh is converted to tidal flats or open water.

Regarding particular sites, site A in the eastern portion of the refuge is expected to lose the majority of its brackish marsh to salt marsh and, in higher scenarios, tidal flats.

Site B, Outer Island, is predicted to lose between 24% and 55% of its dry land to tidal flats across all scenarios.

Site C, the western portion of the refuge, is predicted to lose 28% to 100% of its brackish marsh to salt marsh, and 33% to 44% of its dry land to tidal flats. However, this portion of the refuge is subject to the largest uncertainty as elevation data are based on low-resolution NED data.

Model results are based on high-quality LiDAR elevation data for the eastern portion of this site (Sites A & B, see figure 2b). This reduces uncertainty in model results in this particular zone. The rest of the site is subject to significant uncertainty as cell elevations are based on the National Elevation Data set, derived from ten foot contours. The nearly 30-year old NWI coverage also increases uncertainty in model results, though extensive land-cover shifting does not seem to have occurred (figure 3.)

Note that there were no NWI data for either Faulkner Island or Outer Island. For Outer Island Google Earth and elevation data were used to estimate land-cover types but this increases uncertainty in model results. Faulkner Island was not simulated due to lack of both elevation and land-cover data.

The SLAMM model does account for the local effects of isostatic rebound by taking into account the historical sea level rise for each site. The historical rate of land movement is predicted to continue through the year 2100 (i.e. the rate of isostatic rebound is assumed to remain constant).

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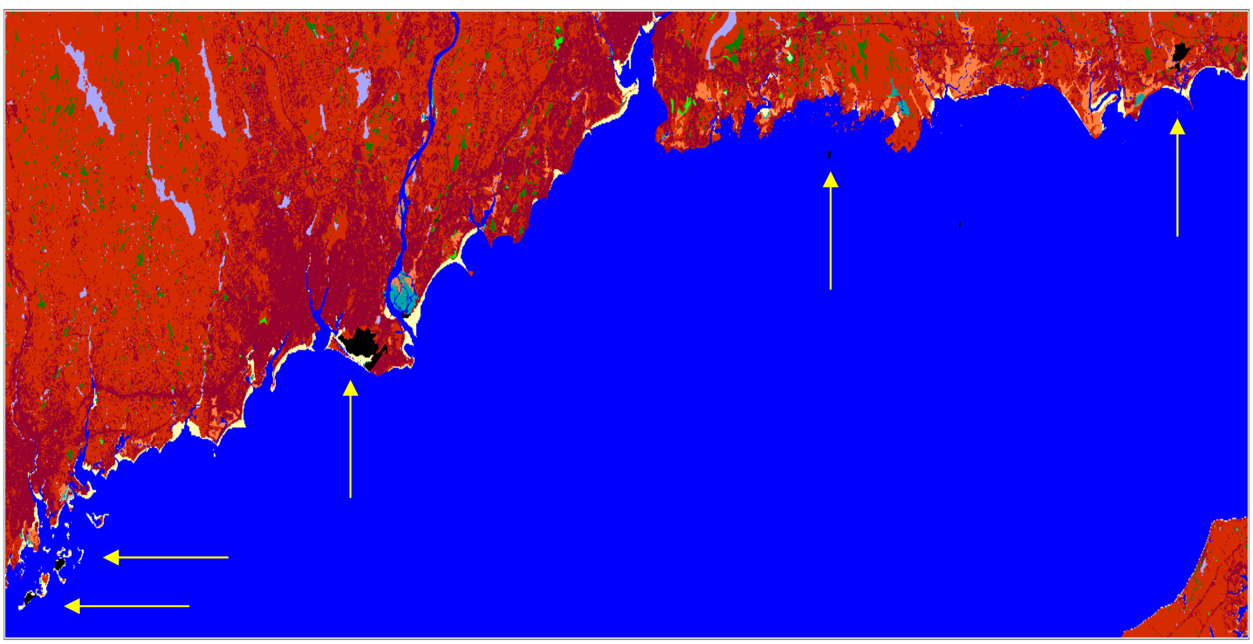
Appendix A: Contextual Results

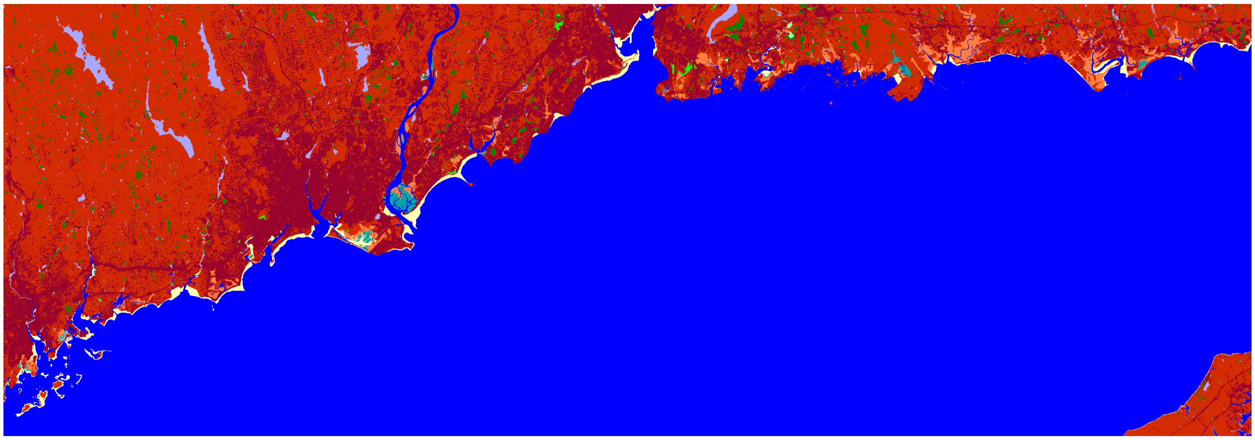
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

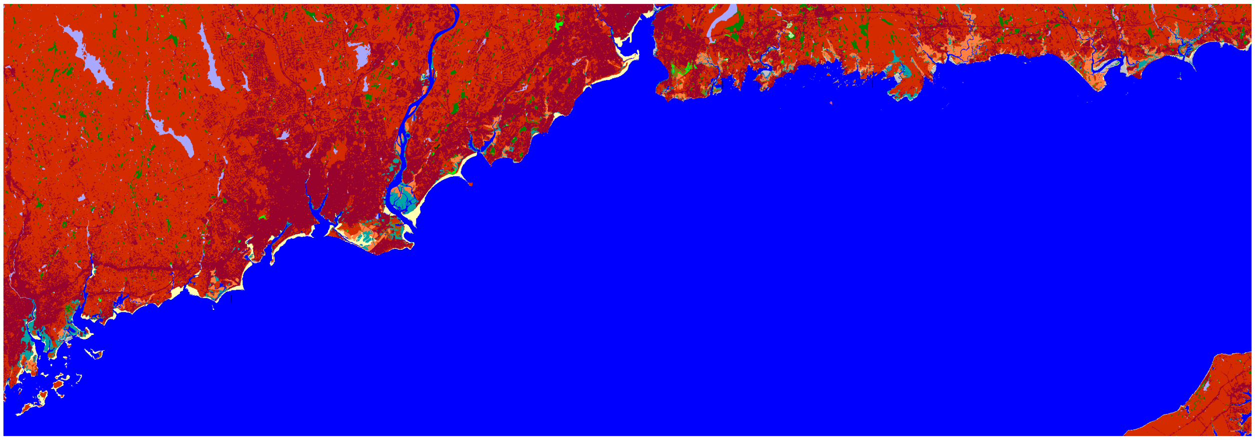
For this reason, an area larger than the boundaries of the USFWS refuge was modeled. These results maps are presented here with the following caveats:

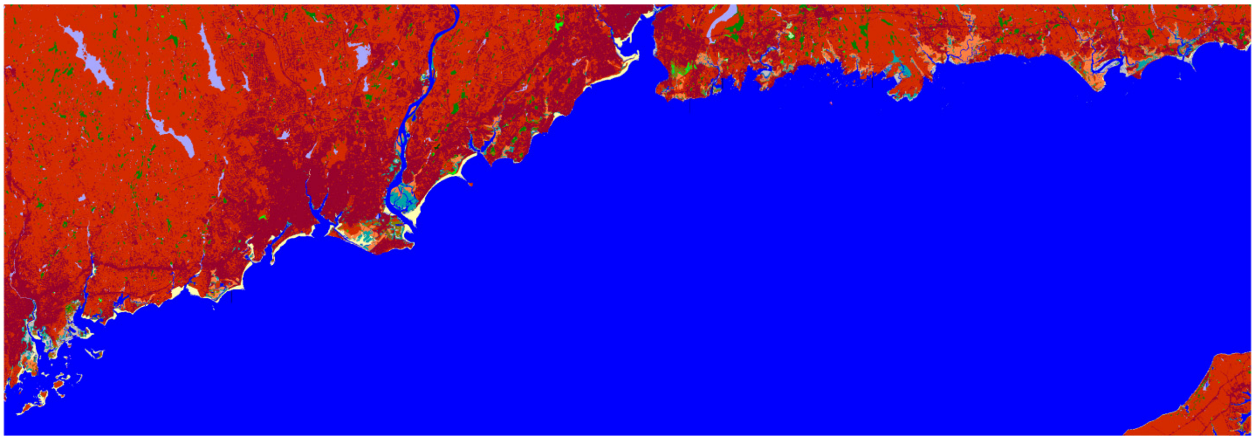
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort 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 Stewart B. McKinney National Wildlife Refuge (black) within simulation context (stretched vertically for clarity).


Stewart B. McKinney Context, Initial Condition


Stewart B. McKinney Context, 2025, Scenario A1B Mean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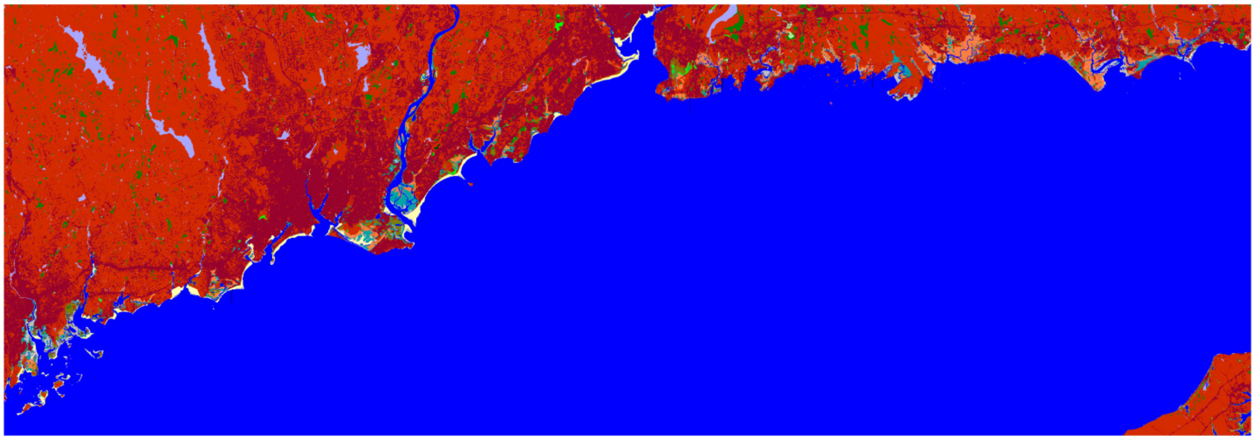
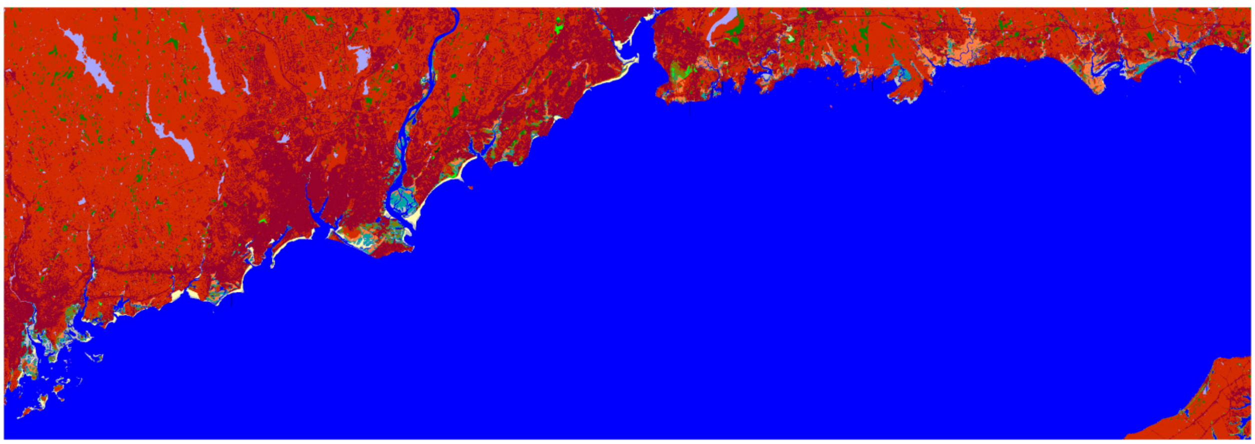
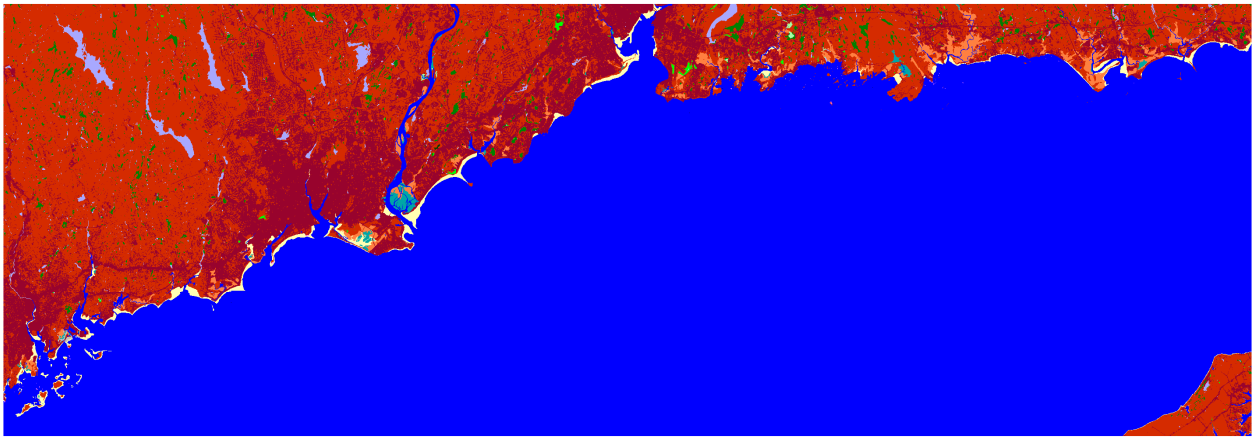
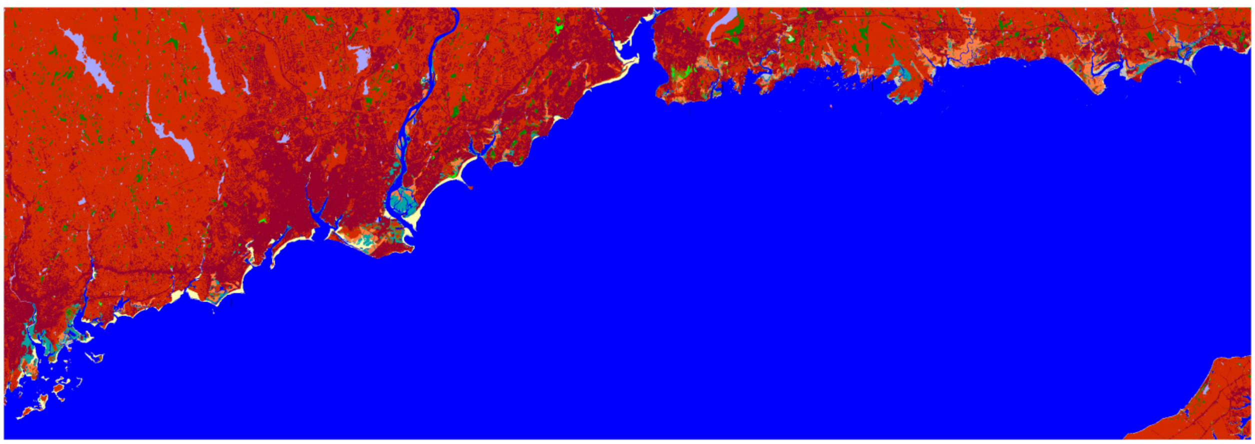

Stewart B. McKinney Context, 2075, Scenario A1B Mean

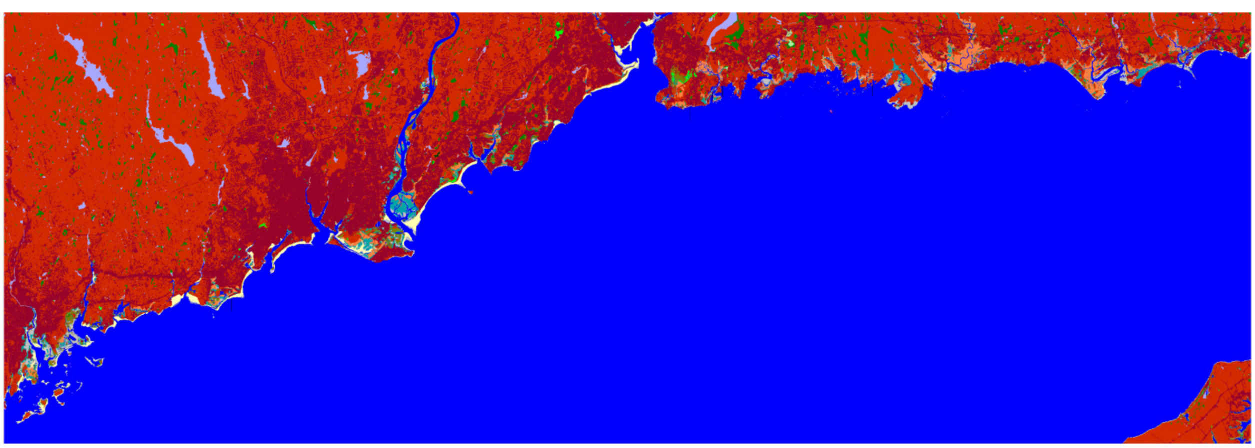

Stewart B. McKinney Context, 2100, Scenario A1B Mean



Stewart B. McKinney Context, Initial Condition



Stewart B. McKinney Context, 2025, Scenario A1B Maximum



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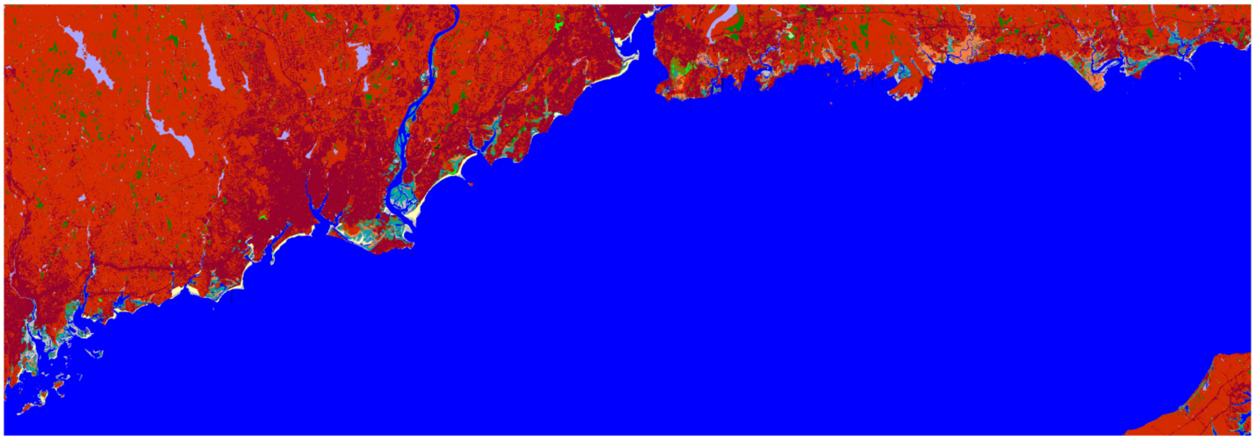

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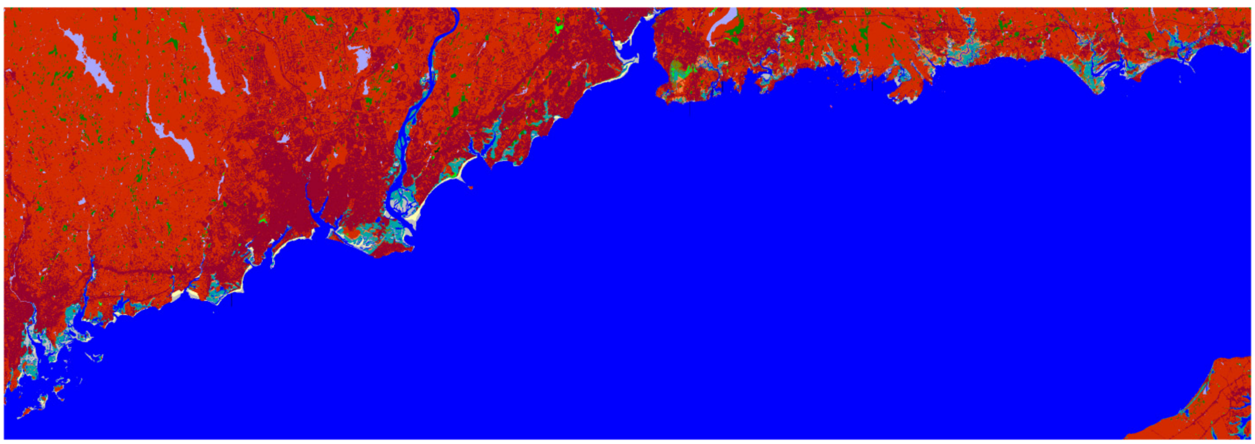

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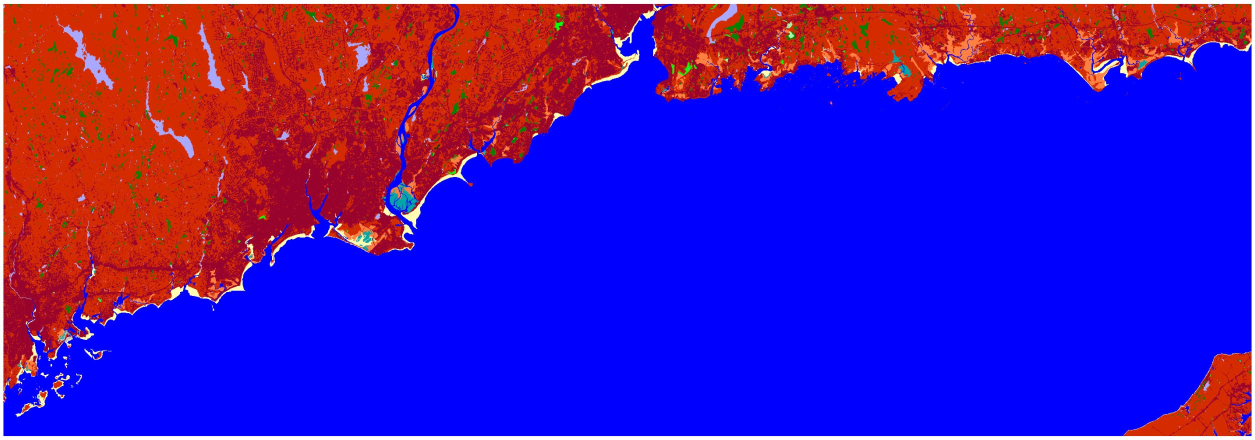

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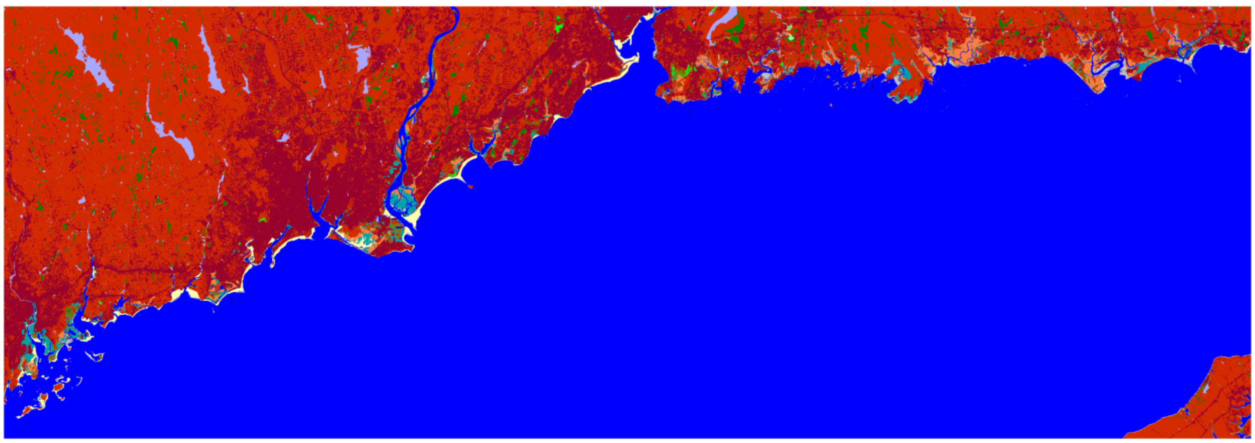
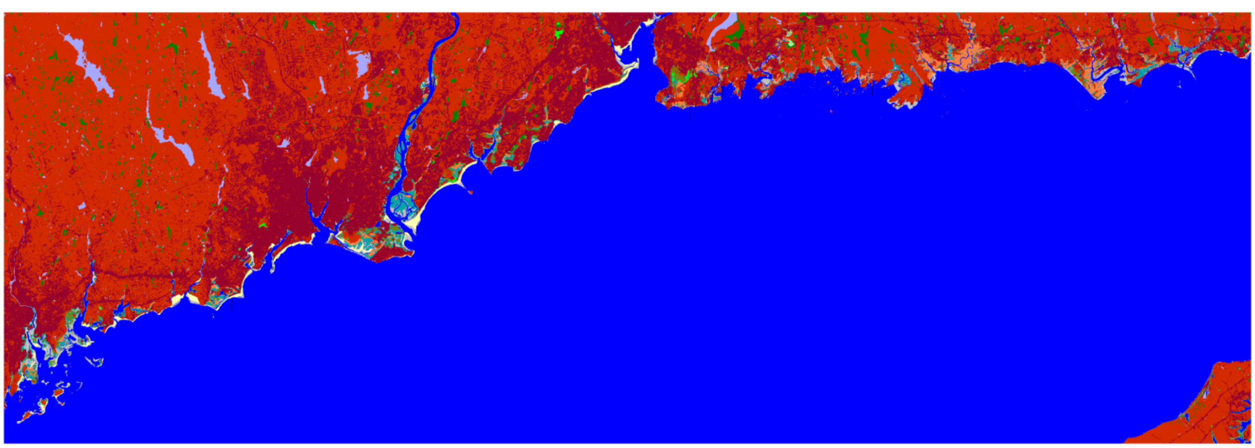


Stewart B. McKinney Context, 2025, 1 meter



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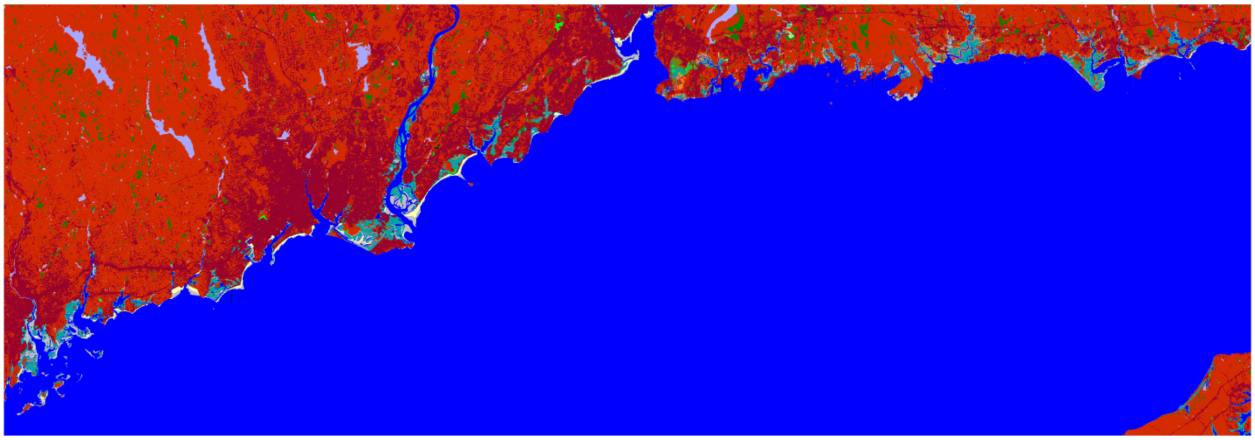
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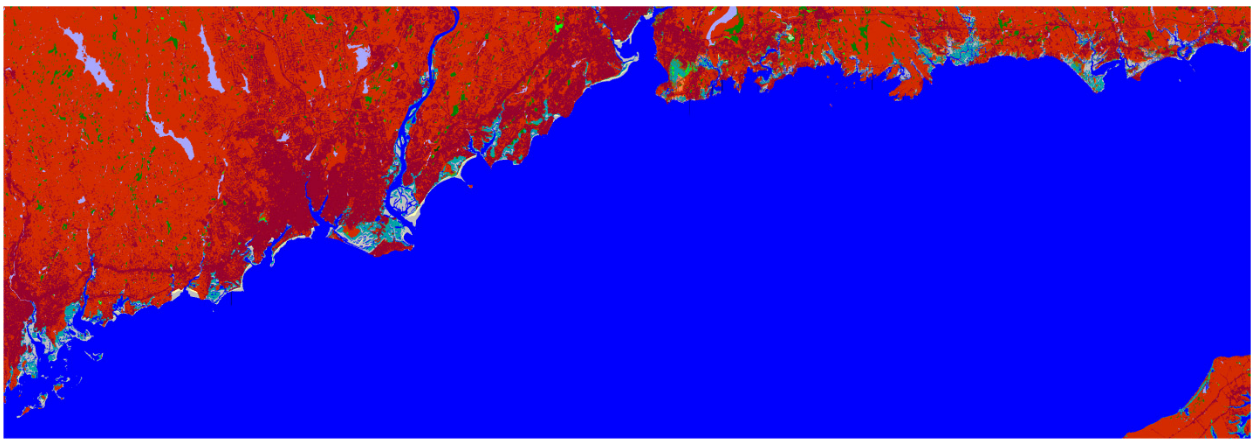
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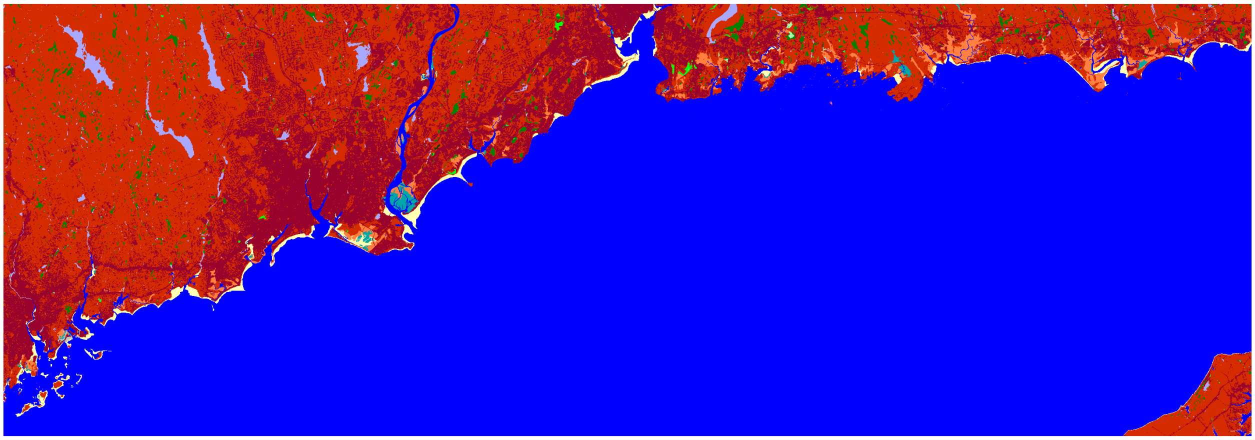
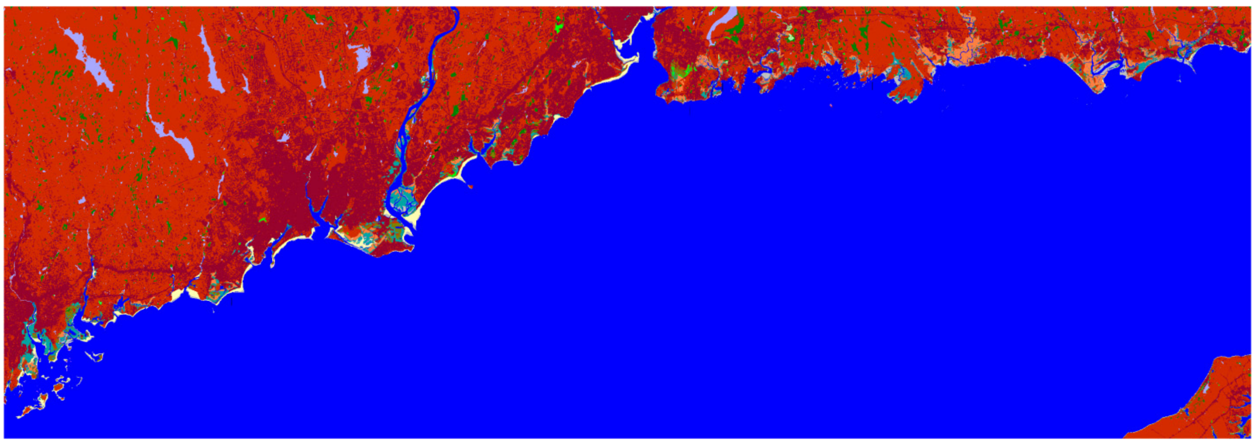
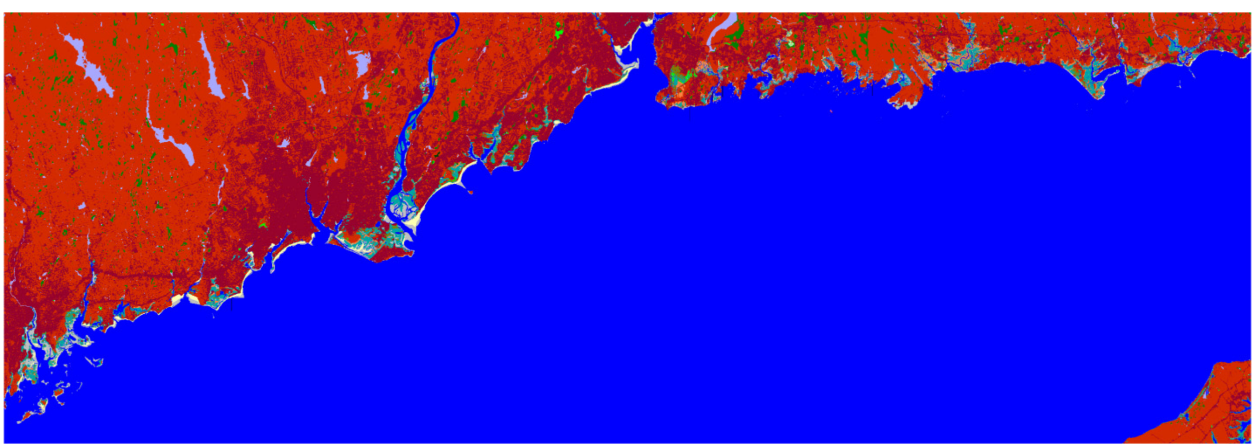


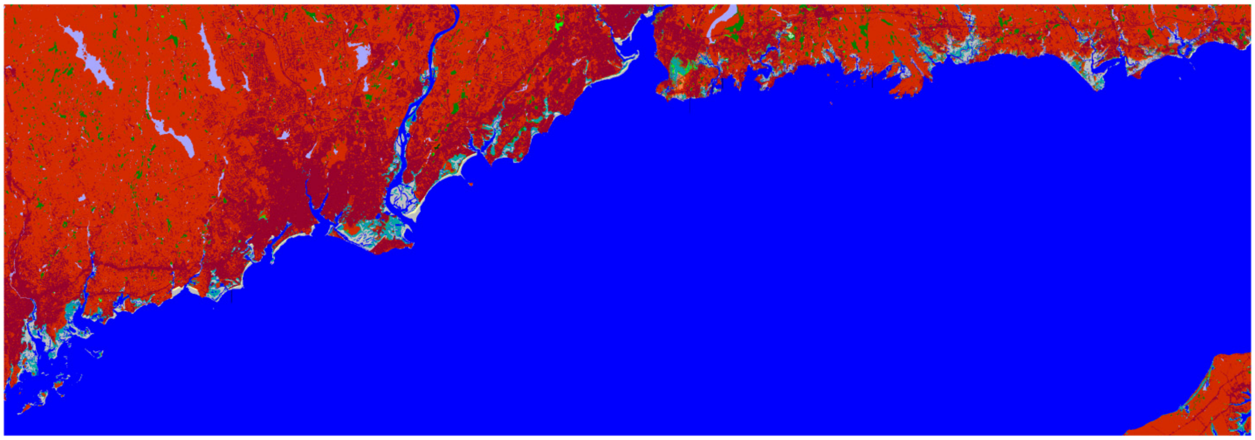
Stewart B. McKinney Context, Initial Condition



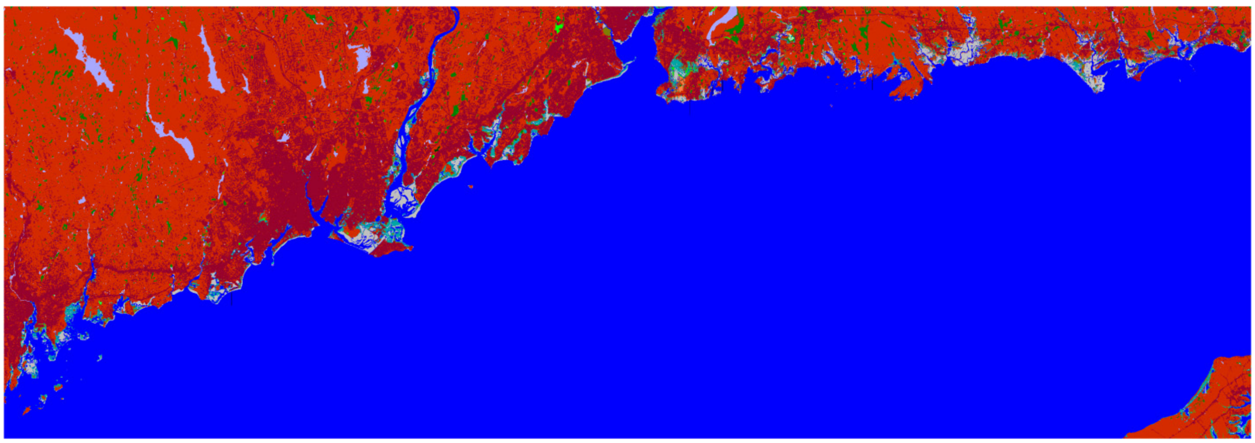
Stewart B. McKinney Context, 2025, 1.5 meter



Stewart B. McKinney Context, 2050, 1.5 meter



Stewart B. McKinney Context, 2075, 1.5 meter



Stewart B. McKinney Context, 2100, 1.5 meter