Application of the Sea-Level Affecting Marshes Model (SLAMM 5.1) to Plum Tree Island NWR

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December 18, 2009

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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 Irregularly Flooded 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 5 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 was developed in 2006/2007 and is 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 (Irregularly Flooded) Marsh," and "Tidal Swamp."
- *Optional.* In a defined estuary, salt marsh, Irregularly Flooded 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 in this model application.

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).

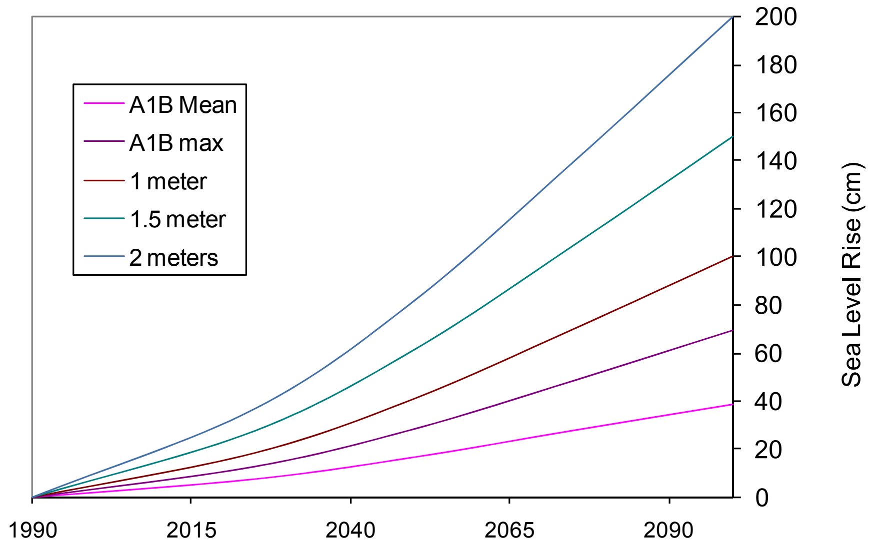
Sea Level Rise Scenarios

SLAMM 5 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 scenario assumes that the future world includes very 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 (IPC, 2007) suggests a likely range of 0.21 to 0.48 meters of sea level rise 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 0.40 meters of global sea level rise 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 might be 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 meters 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 sea level rises for the end of the 21st century are too low." (US Climate Change Science Program, 2008) 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, with low probability of the rise being within Intergovernmental Panel on Climate Change (IPCC) confidence limits."

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 meter, 1½ meters, and 2 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



Additional information on the development of the SLAMM model is available in the technical documentation, which may be downloaded from the SLAMM website (Clough and Park, 2008).

Methods and Data Sources

The digital elevation map (DEM) used in this model simulation was derived from the National Elevation Dataset (NED). NED metadata indicate that these data were derived from USGS maps dated 1963, with 5 foot contour intervals (Figure 1). No high resolution elevation data (e.g. LiDAR data) were located for this refuge simulation.

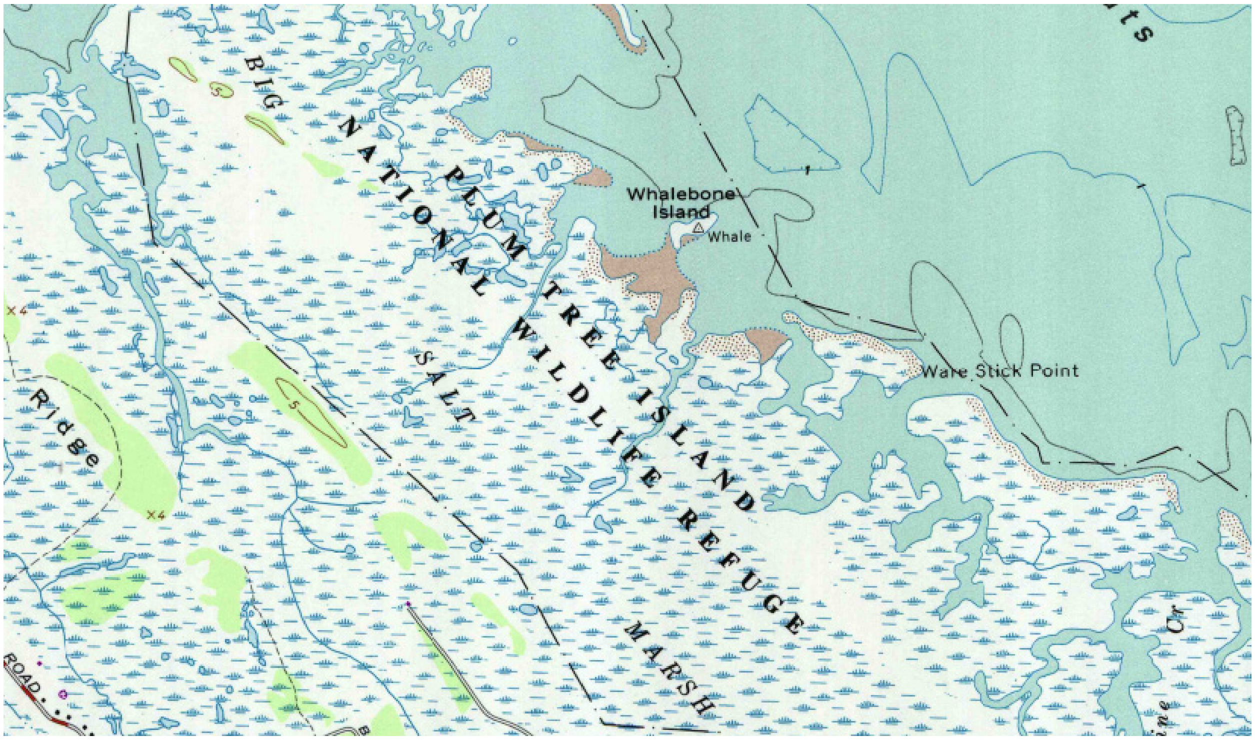


Figure 1: USGS topographical map of Plum Tree Island NWR.

The National Wetlands Inventory (NWI) for Plum Tree Island is based on a photo date of 2000. A examination of the NWI layer against current Google Earth satellite imagery reveals erosion of slightly more than 30 meters (one cells width) in northern refuge estuarine beach (Figure 2). This erosion can reach as much as 60 meters in other parts of the refuge. This difference primarily reflects shoreline changes that have occurred in the last nine years, though it may also be partially a function of horizontal uncertainty in the NWI coverage.

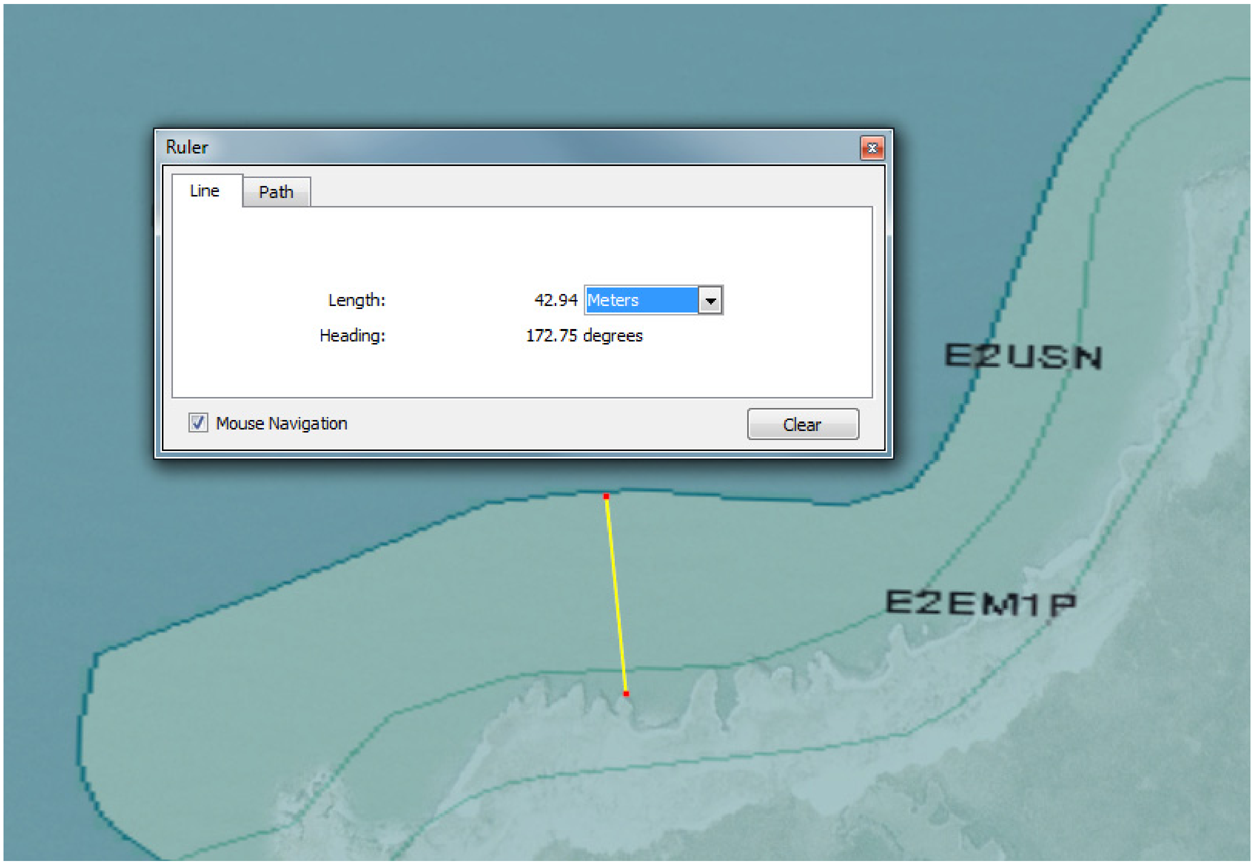


Figure 2: NWI layer over satellite imagery.

Converting the NWI survey into 30 meter cells indicates that the approximately five thousand acre refuge (approved acquisition boundary including water) is composed of the categories as shown below:

Saltmarsh	42.9%
Brackish Marsh	33.1%
Estuarine Open Water	12.7%
Tidal Swamp	4.8%
Estuarine Beach	3.5%
Trans. Salt Marsh	2.3%

According to the National Wetlands Inventory there are no diked or impounded regions within this refuge.

The historic trend for sea level rise was estimated 4.125 mm/year using the mean of the two nearest NOAA gages (8637624, Gloucestor Point, VA; 8638610, Sewells Point, VA). This historical rate of sea level rise is more than twice the global average for the last 100 years (approximately 1.7 mm/year).

The tidal range for the Plum Tree Island NWR of 0.792 meters was determined using the nearest NOAA gage (8637689, Yorktown USCG Training Center, VA) (Figure 4).

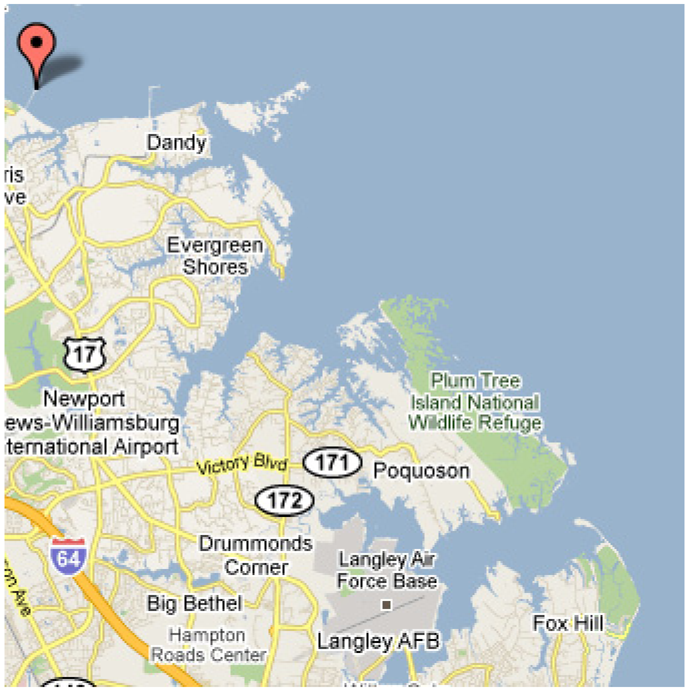


Figure 3: NOAA Gage Relevant to the Study Area.

No site-specific marsh accretion data were located for this refuge. The marsh accretion values used were based on three different estimates:

- Based on a large analysis of accretion studies within mid-Atlantic region (Reed et al. 2008), the average Virginia marsh accretion value was calculated at 4.02 mm/yr (n=5);
- From this same study, the average salt marsh accretion rates in Chesapeake Bay was 4.04 mm/year (n=12, Reed et al. 2008);
- The average accretion rate of fresh marshes in Chesapeake Bay was somewhat higher (n=8) so a value of 5 mm/yr was used for this marsh type (Reed et al. 2008).

The MTL to NAVD88 correction was derived using the NOAA VDATUM modeling product. The correction was determined to be -0.085 meters.

Contact with USFWS refuge manager of Nansemond NWR did not result in additional refinement of data. The refuge manager did attempt to seek out LiDAR from nearby Langley Airforce Base but it seemed that LiDAR data outside the base's boundaries are not available.

Modeled U.S. Fish and Wildlife Service refuge boundaries for Virginia 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. Additionally, the SLAMM model will track partial conversion of cells based on elevation and slope.

SUMMARY OF SLAMM INPUT PARAMETERS FOR PLUM TREE ISLAND NWR

Parameter	Global	SubSite 1
Description	VA	Plum Tree Island
NWI Photo Date (YYYY)	1989	2000
DEM Date (YYYY)	1975	1963
Direction Offshore [n,s,e,w]	East	East
Historic Trend (mm/yr)	3.9	4.125
MTL-NAVD88 (m)	-0.06	-0.0854
GT Great Diurnal Tide Range (m)	0.9	0.792
Salt Elev. (m above MTL)	0.6	0.527
Marsh Erosion (horz. M /yr)	1.5	3
Swamp Erosion (horz. M /yr)	1.5	3
T.Flat Erosion (horz. M /yr)	3	5
Reg. Flood Marsh Accr (mm/yr)	4	4
Irreg. Flood Marsh Accr (mm/yr)	4	4
Tidal Fresh Marsh Accr (mm/yr)	1	5
Beach Sed. Rate (mm/yr)	0.5	0.5
Freq. Overwash (years)	25	25
Use Elev Pre-processor [True,False]	TRUE	TRUE

Results

SLAMM predicts Plum Tree Island NWR to be considerably susceptible to the effects of sea level rise. Salt marsh (regularly flooded marsh), which makes up almost half of the refuge, is predicted to be resilient to SLR of up to 0.4 meters by 2100 at which point the vast majority is lost. In scenarios of over 0.4 meters of eustatic SLR by 2100, the refuge is predicted to lose between 74% and 99% of its regularly flooded (salt marsh) acreage. The refuge's irregularly flooded marsh (brackish marsh) – one third of the NWR – does not show much resilience to SLR, and is predicted to lose between 62% and 99% of its initial land coverage across all SLR scenarios. Tidal swamp loses between 67% and 83% of its initial acreage in scenarios of over 0.4 meters.

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Saltmarsh	1%	74%	99%	91%	91%
Brackish Marsh	62%	90%	90%	99%	99%
Tidal Swamp	0%	67%	73%	79%	83%
Estuarine Beach	74%	91%	100%	100%	100%

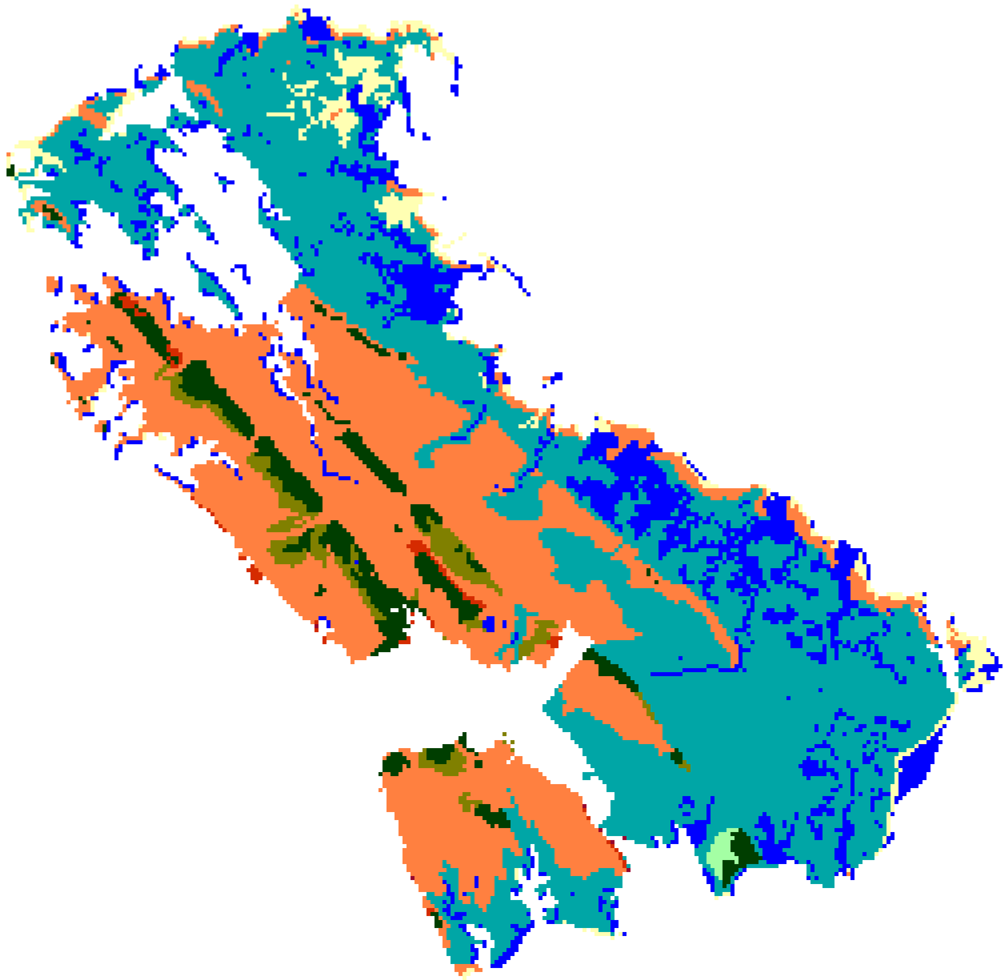
Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

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

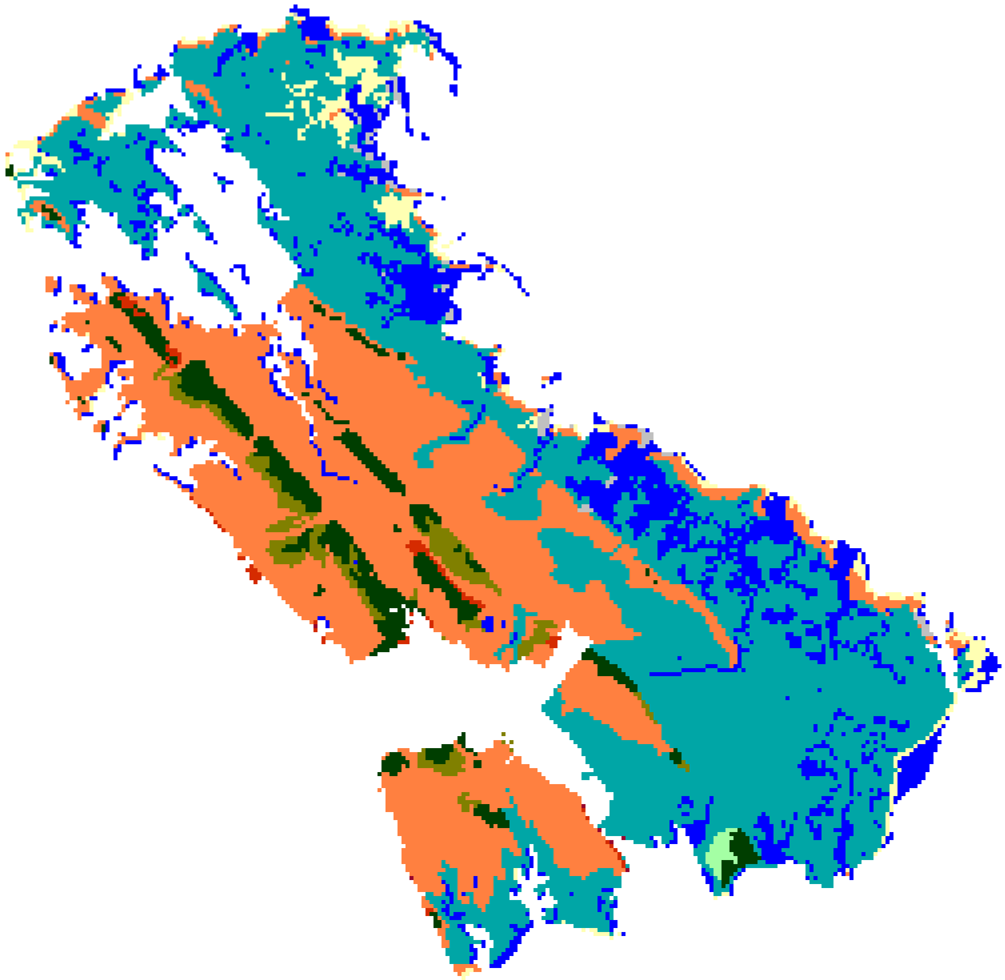
Plum Tree Island NWR
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

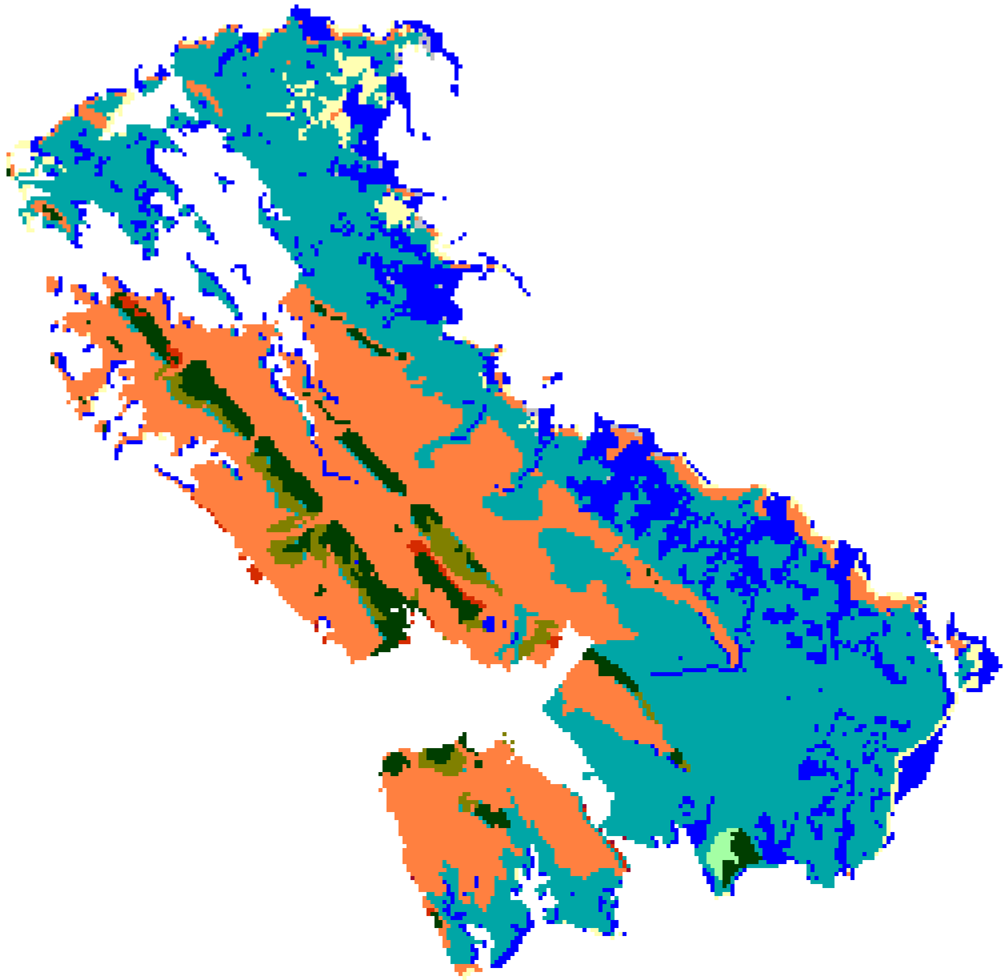
	Initial	2025	2050	2075	2100
Saltmarsh	2129.4	2110.7	2128.1	2191.0	2098.3
Brackish Marsh	1642.6	1629.9	1561.8	1084.4	632.3
Estuarine Open Water	630.0	655.4	765.7	1230.4	1780.6
Tidal Swamp	238.4	238.4	237.7	237.6	237.5
Estuarine Beach	175.0	149.7	118.2	79.1	45.7
Trans. Salt Marsh	114.8	114.8	106.2	31.5	0.1
Undev. Dry Land	25.4	25.4	25.4	25.4	25.4
Tidal Fresh Marsh	11.8	11.8	11.8	11.8	11.8
Dev. Dry Land	1.6	1.6	1.6	1.6	1.6
Tidal Flat	0.0	31.4	12.5	76.2	135.7
Total (incl. water)	**4968.9**	**4968.9**	**4968.9**	**4968.9**	**4968.9**



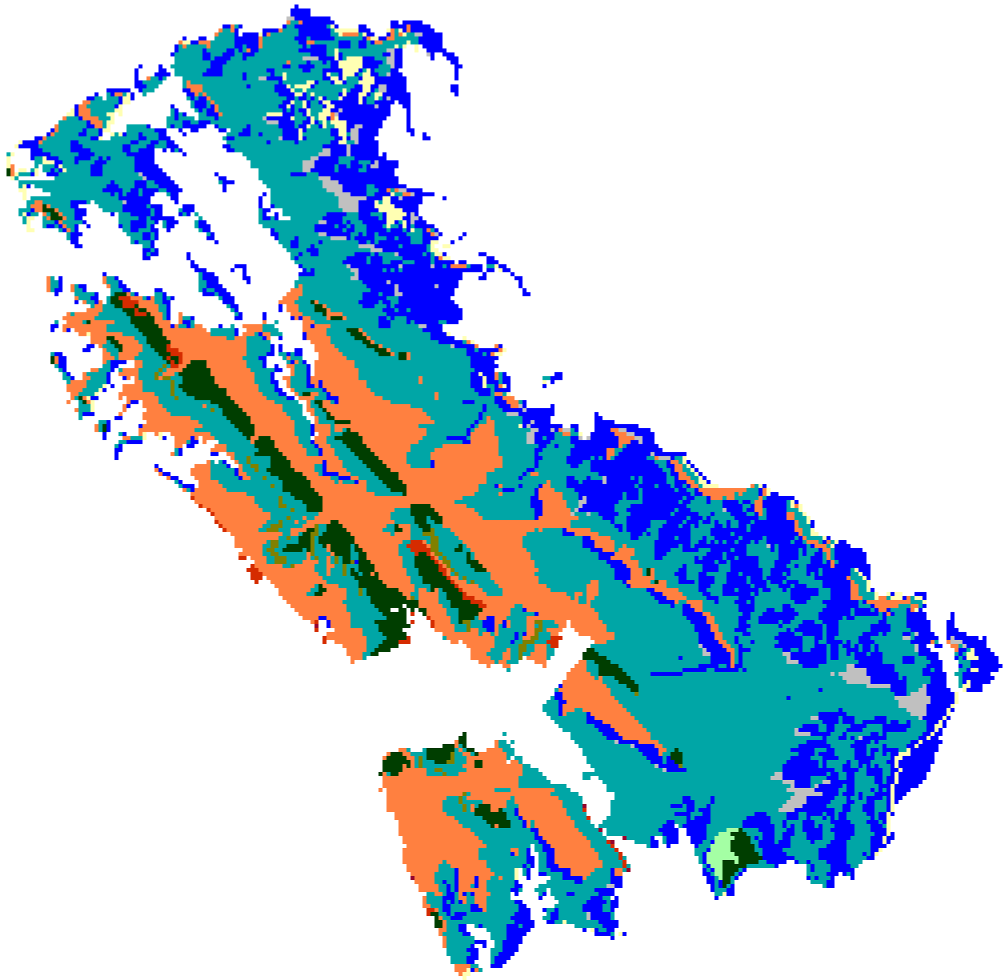
Plum Tree Island NWR, Initial Condition



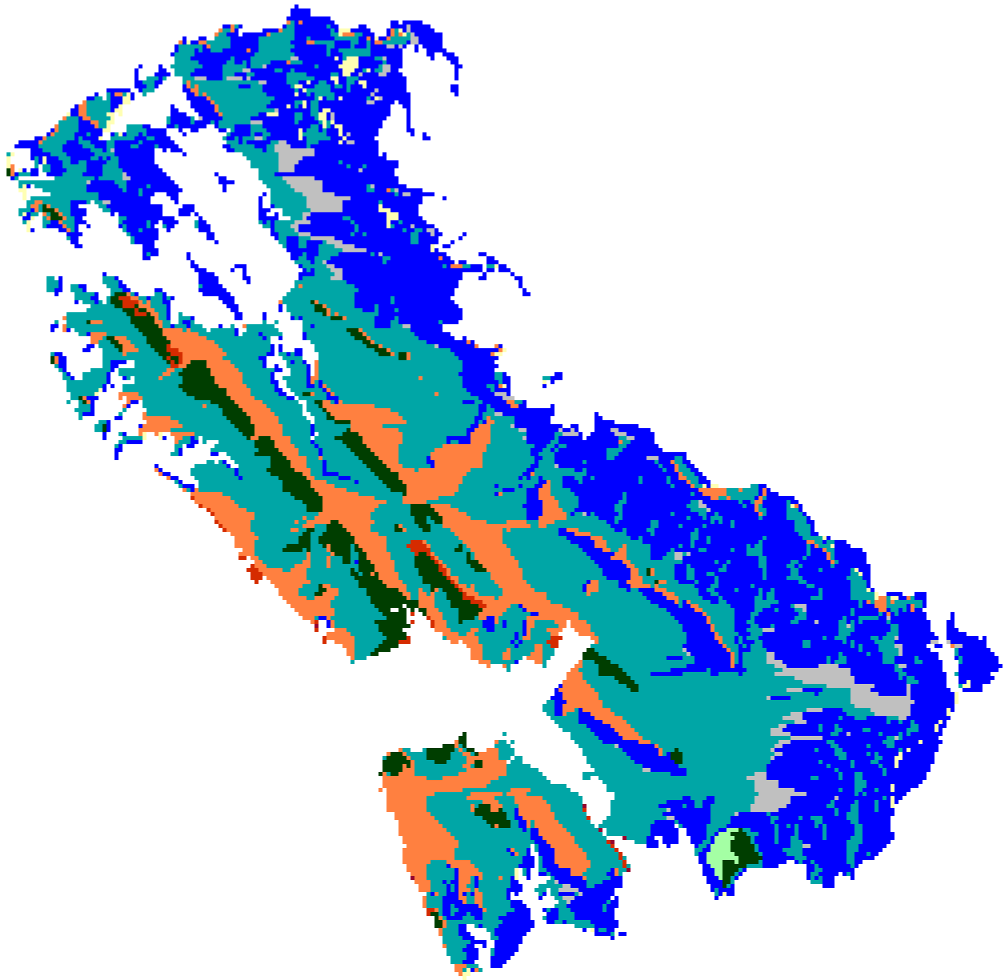
Plum Tree Island NWR, 2025, Scenario A1B Mean



Plum Tree Island NWR, 2050, Scenario A1B Mean



Plum Tree Island NWR, 2075, Scenario A1B Mean

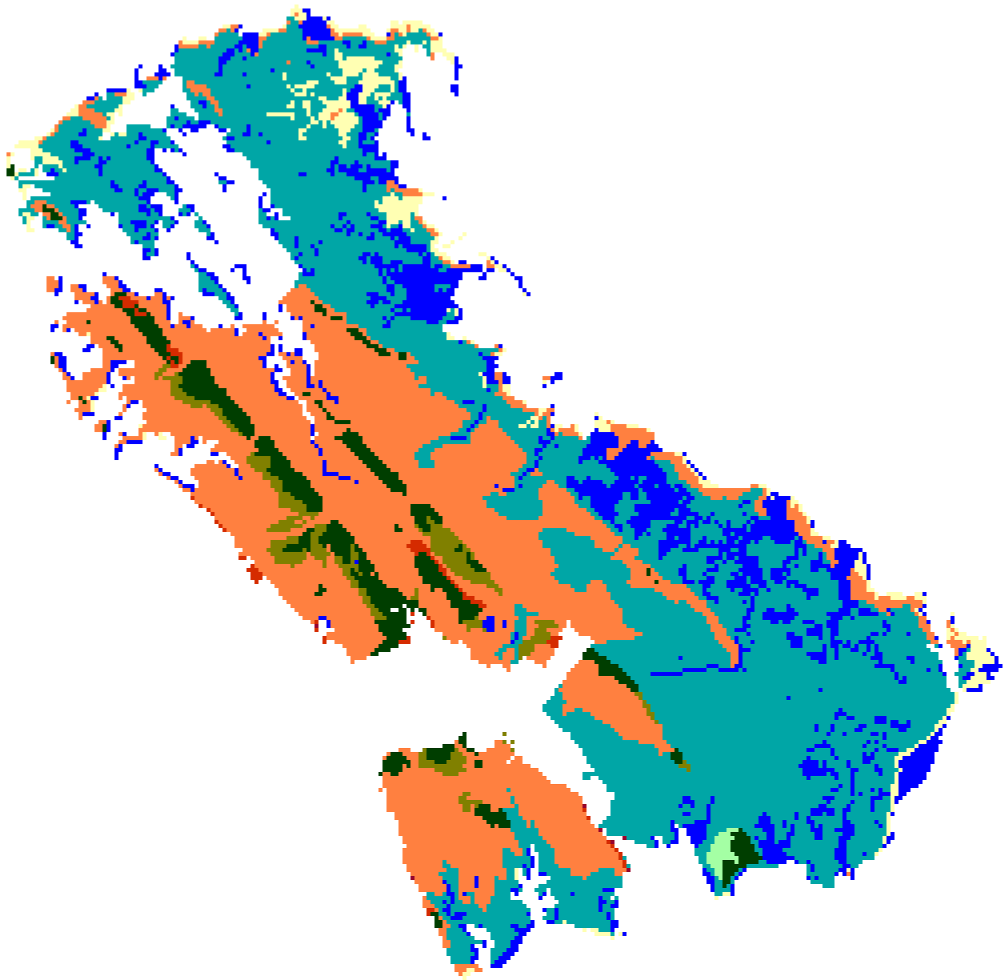


Plum Tree Island NWR, 2100, Scenario A1B Mean

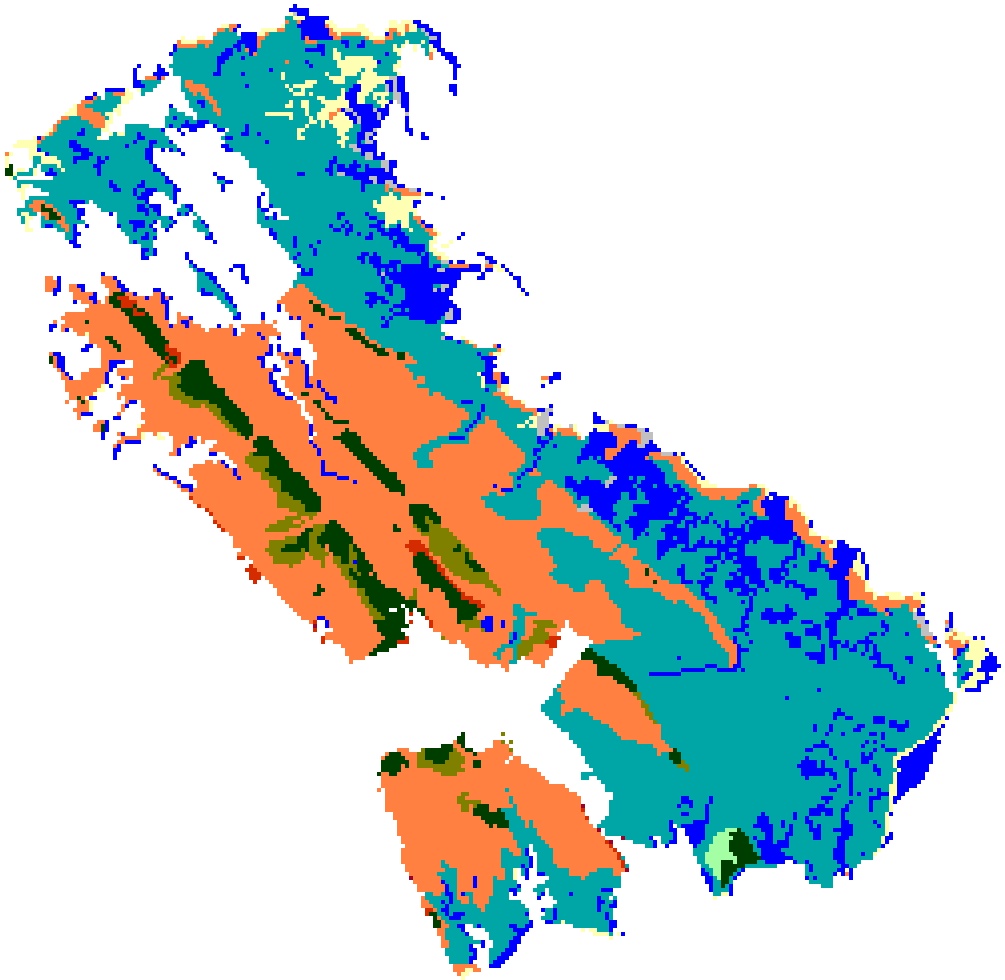
Plum Tree Island NWR
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

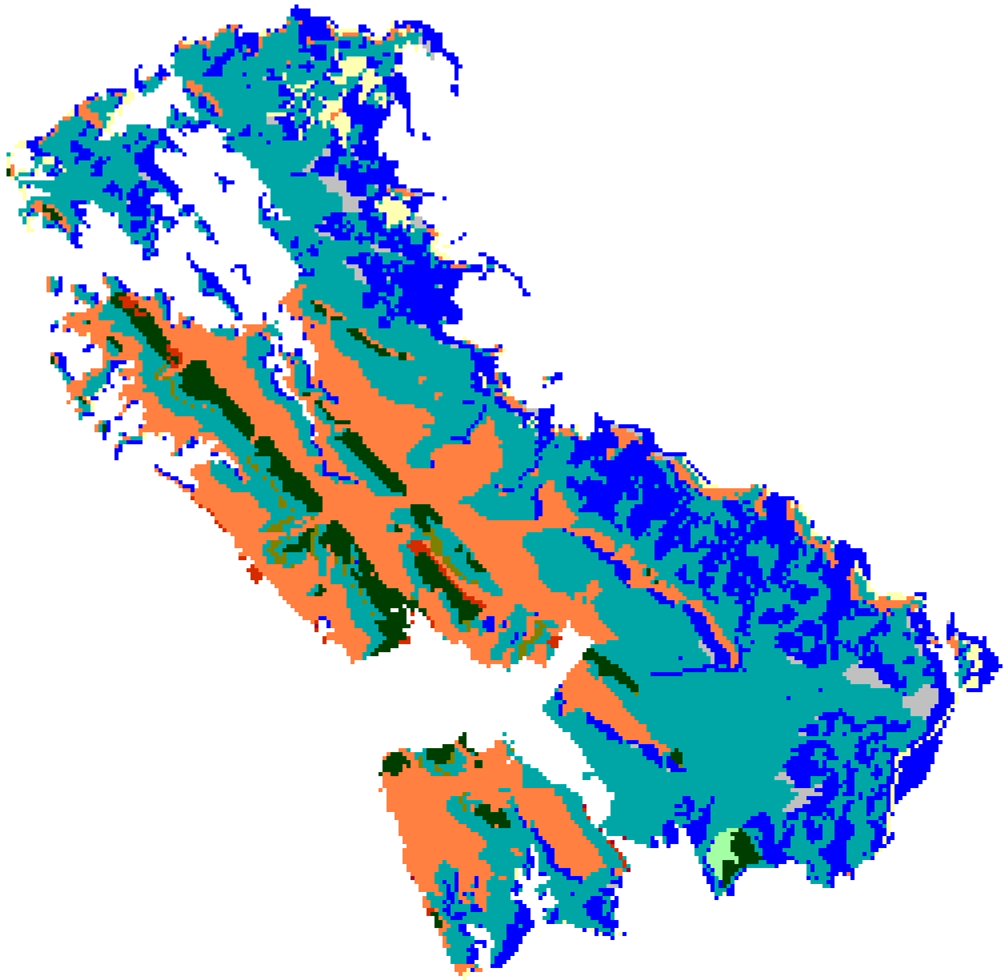
	Initial	2025	2050	2075	2100
Saltmarsh	2129.4	2110.7	2211.2	1732.6	556.6
Brackish Marsh	1642.6	1629.9	1137.3	250.3	160.0
Estuarine Open Water	630.0	655.4	1132.0	2162.8	3214.2
Tidal Swamp	238.4	238.4	237.7	237.5	77.9
Estuarine Beach	175.0	149.7	108.1	54.2	16.5
Trans. Salt Marsh	114.8	114.8	38.8	0.0	17.3
Undev. Dry Land	25.4	25.4	25.4	25.4	8.1
Tidal Fresh Marsh	11.8	11.8	11.8	11.7	11.7
Dev. Dry Land	1.6	1.6	1.6	1.6	1.6
Tidal Flat	0.0	31.4	65.1	492.9	905.1
Total (incl. water)	**4968.9**	**4968.9**	**4968.9**	**4968.9**	**4968.9**



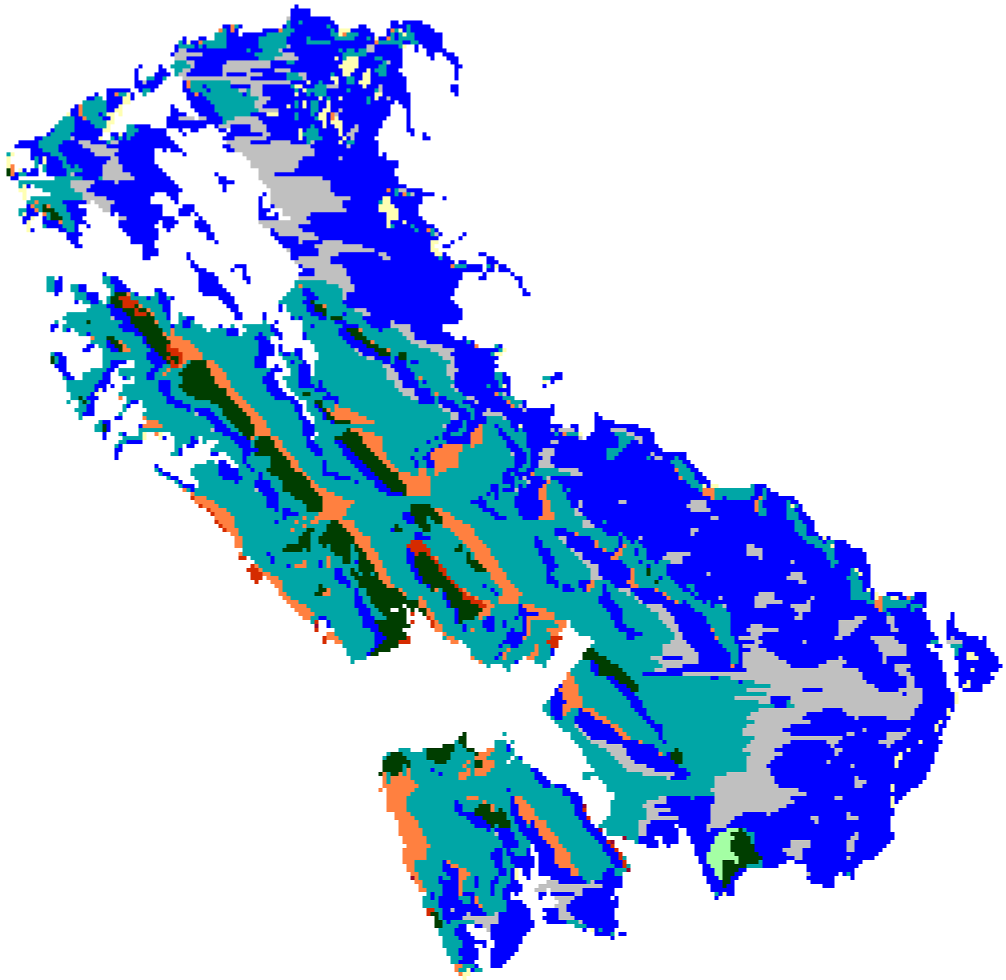
Plum Tree Island NWR, Initial Condition



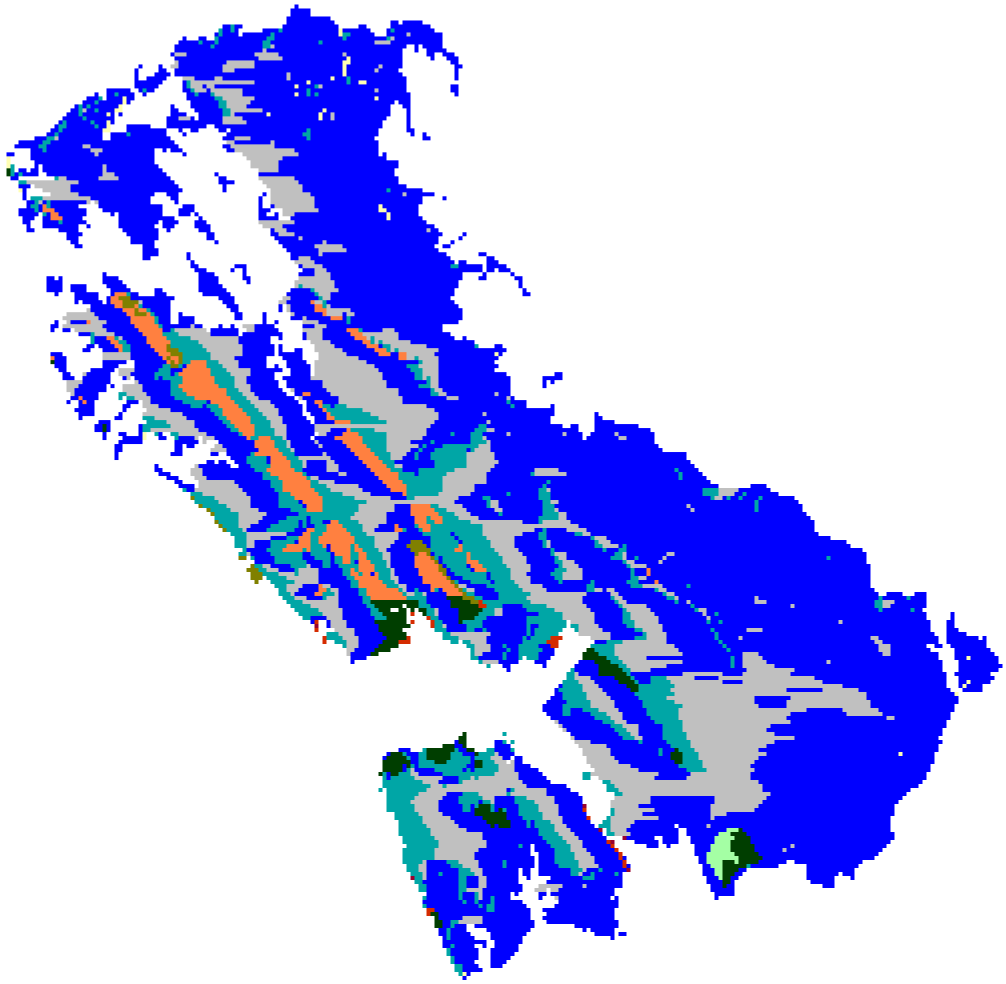
Plum Tree Island NWR, 2025, Scenario A1B Maximum



Plum Tree Island NWR, 2050, Scenario A1B Maximum



Plum Tree Island NWR, 2075, Scenario A1B Maximum

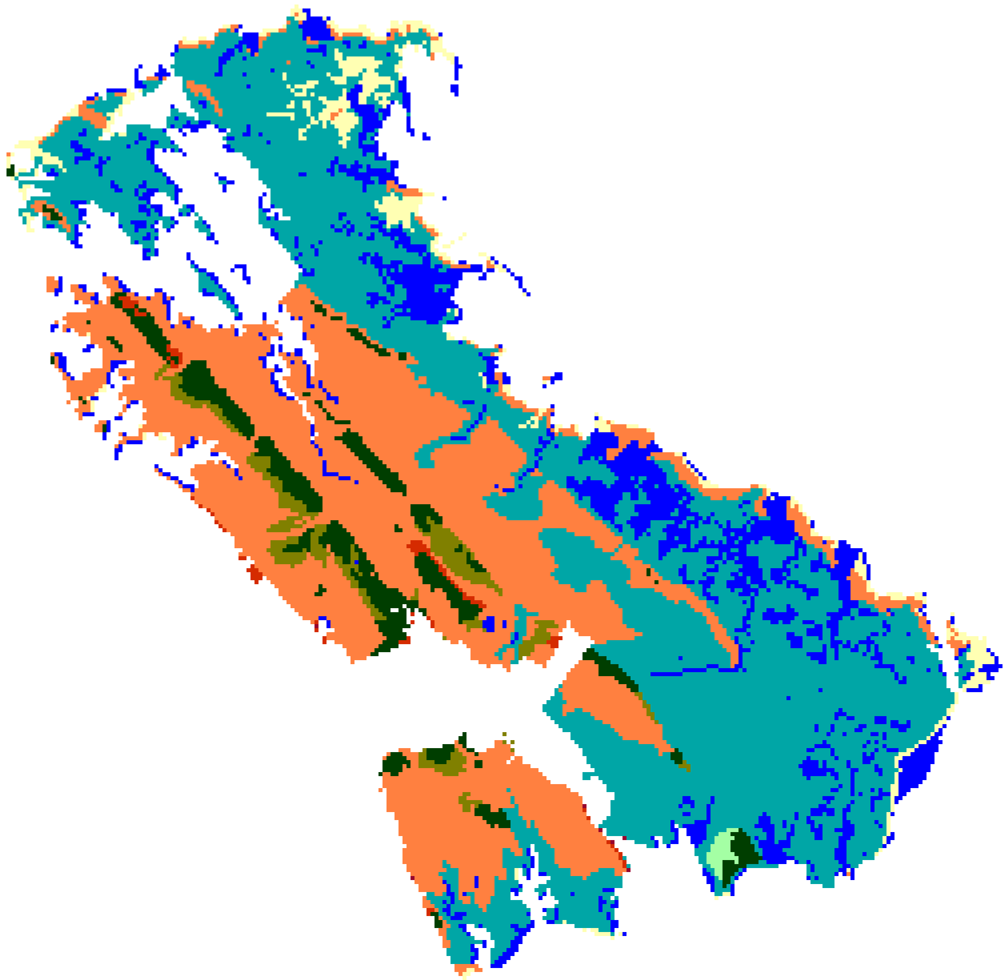


Plum Tree Island NWR, 2100, Scenario A1B Maximum

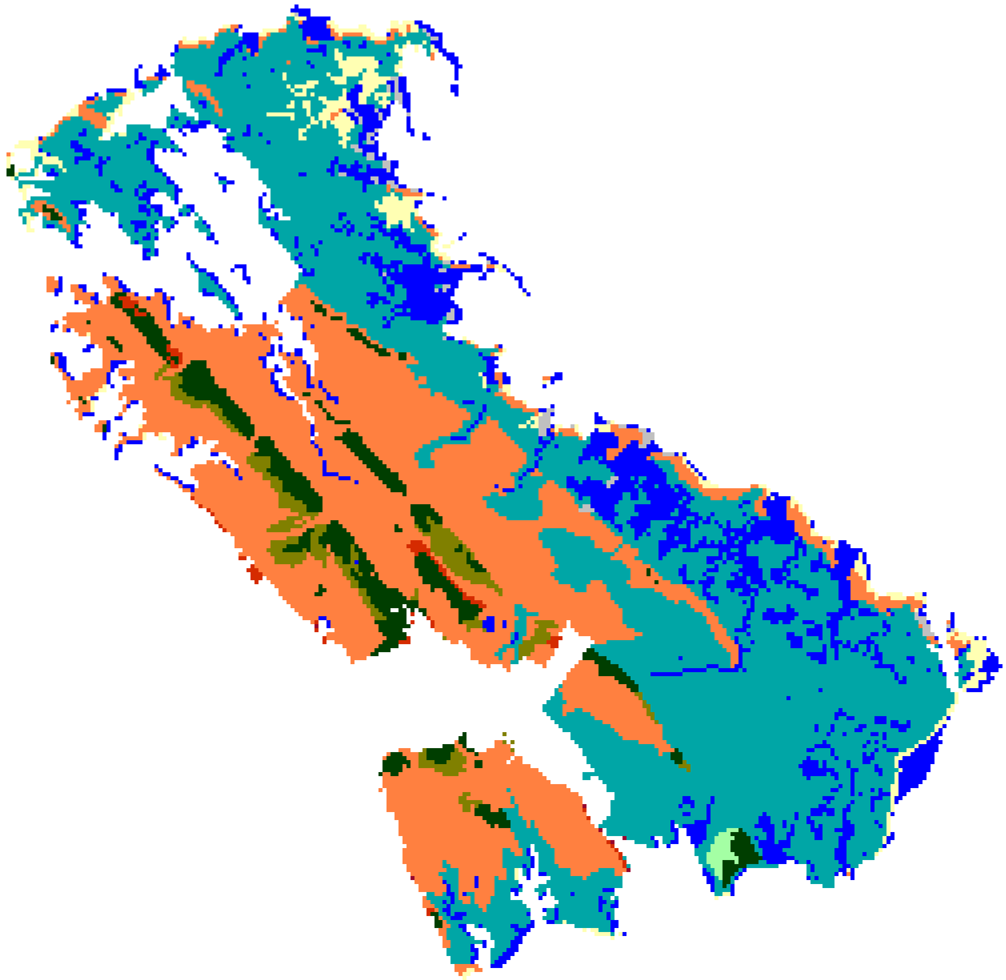
Plum Tree Island NWR
1 Meter Eustatic SLR by 2100

Results in Acres

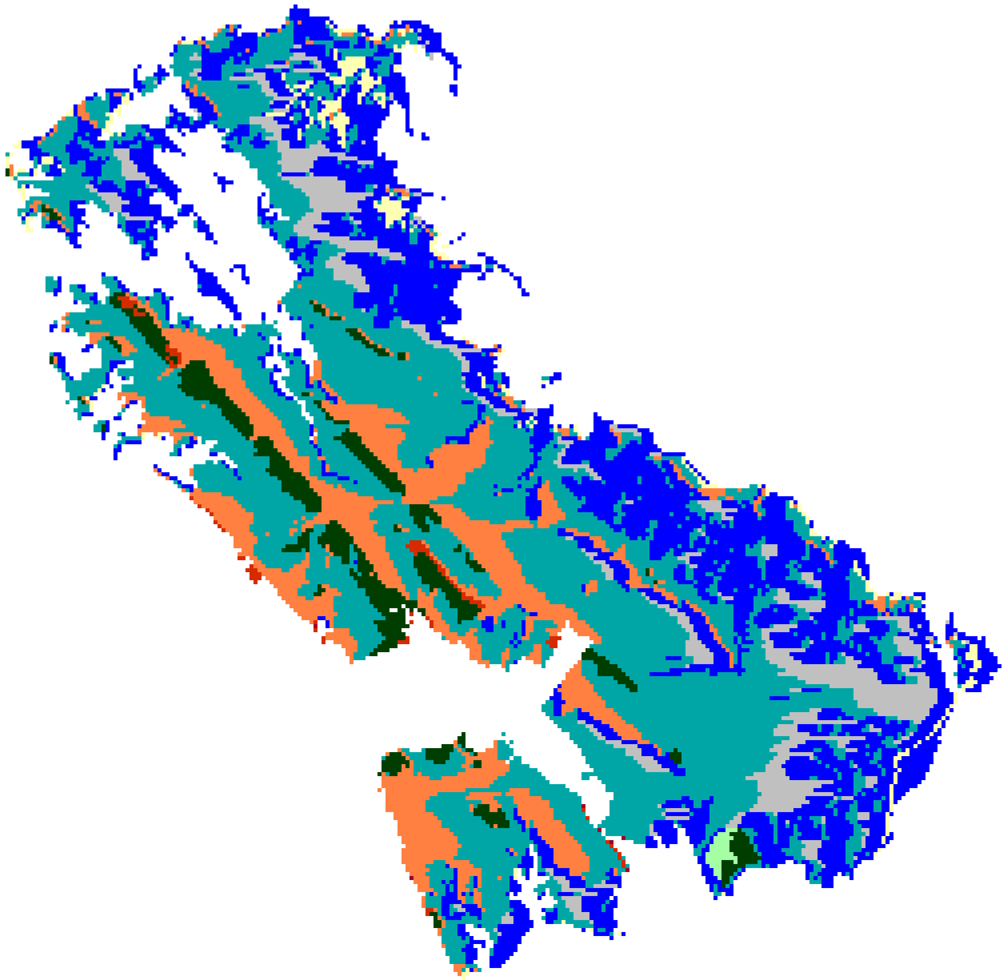
	Initial	2025	2050	2075	2100
Saltmarsh	2129.4	2110.7	2139.4	906.7	17.2
Brackish Marsh	1642.6	1629.9	680.1	1.3	172.0
Estuarine Open Water	630.0	655.4	1407.4	2720.5	4305.2
Tidal Swamp	238.4	238.4	237.6	236.8	65.1
Estuarine Beach	175.0	149.7	96.7	32.5	0.6
Trans. Salt Marsh	114.8	114.8	0.1	16.2	2.9
Undev. Dry Land	25.4	25.4	25.4	9.1	6.2
Tidal Fresh Marsh	11.8	11.8	11.8	11.7	11.6
Dev. Dry Land	1.6	1.6	1.6	1.6	1.6
Tidal Flat	0.0	31.4	369.0	1032.6	386.6
Total (incl. water)	**4968.9**	**4968.9**	**4968.9**	**4968.9**	**4968.9**



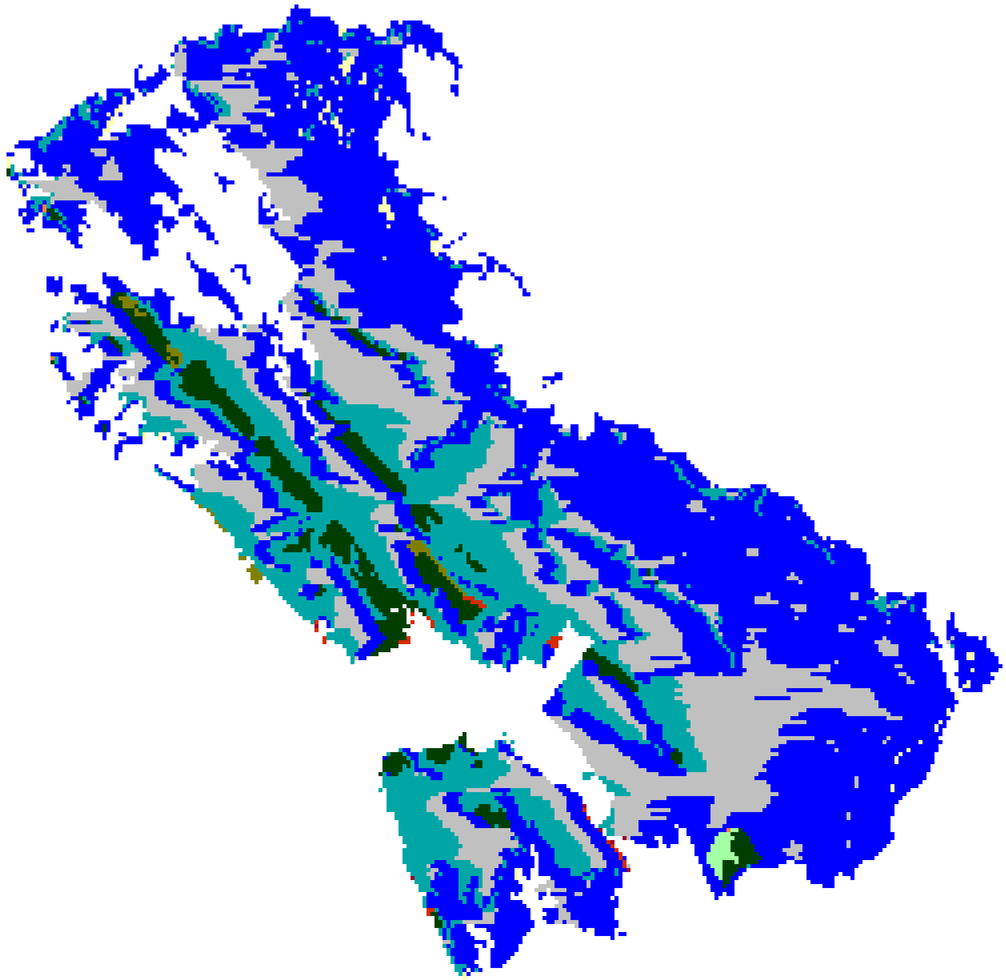
Plum Tree Island NWR, Initial Condition



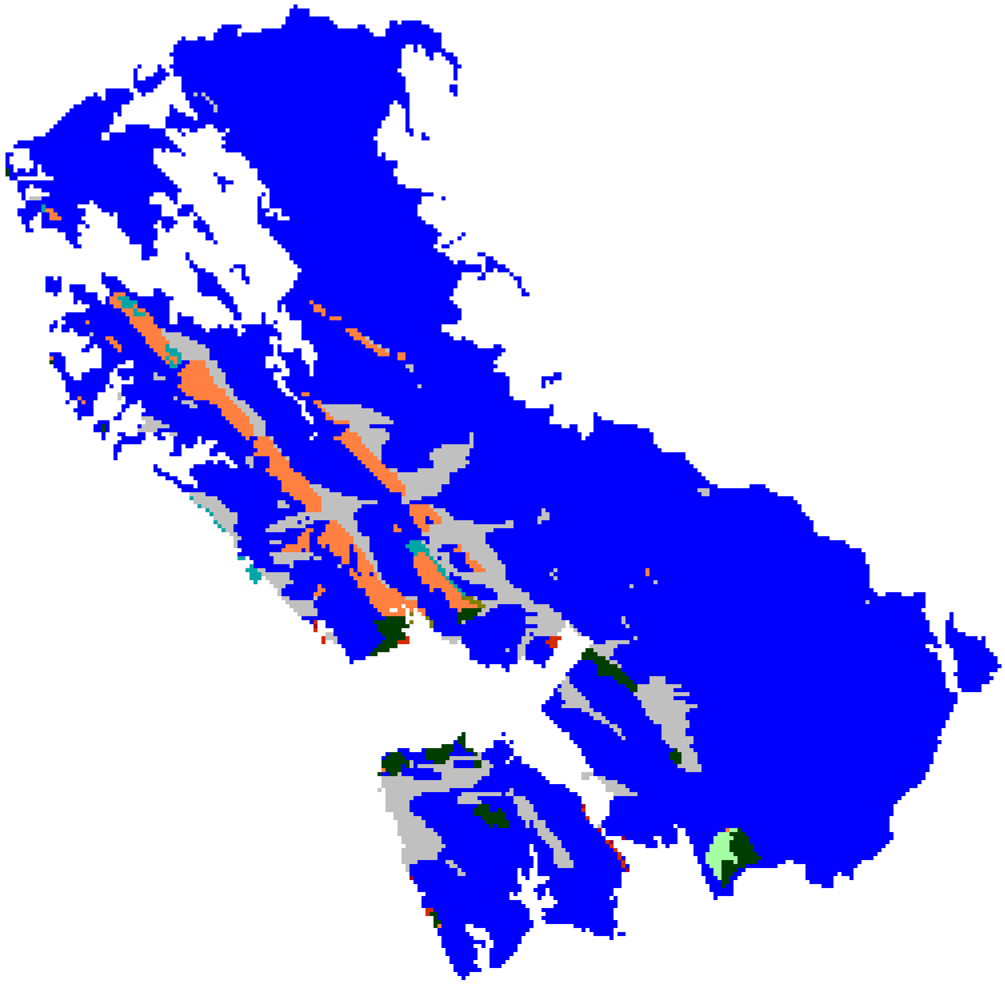
Plum Tree Island NWR, 2025, 1 meter



Plum Tree Island NWR, 2050, 1 meter



Plum Tree Island NWR, 2075, 1 meter

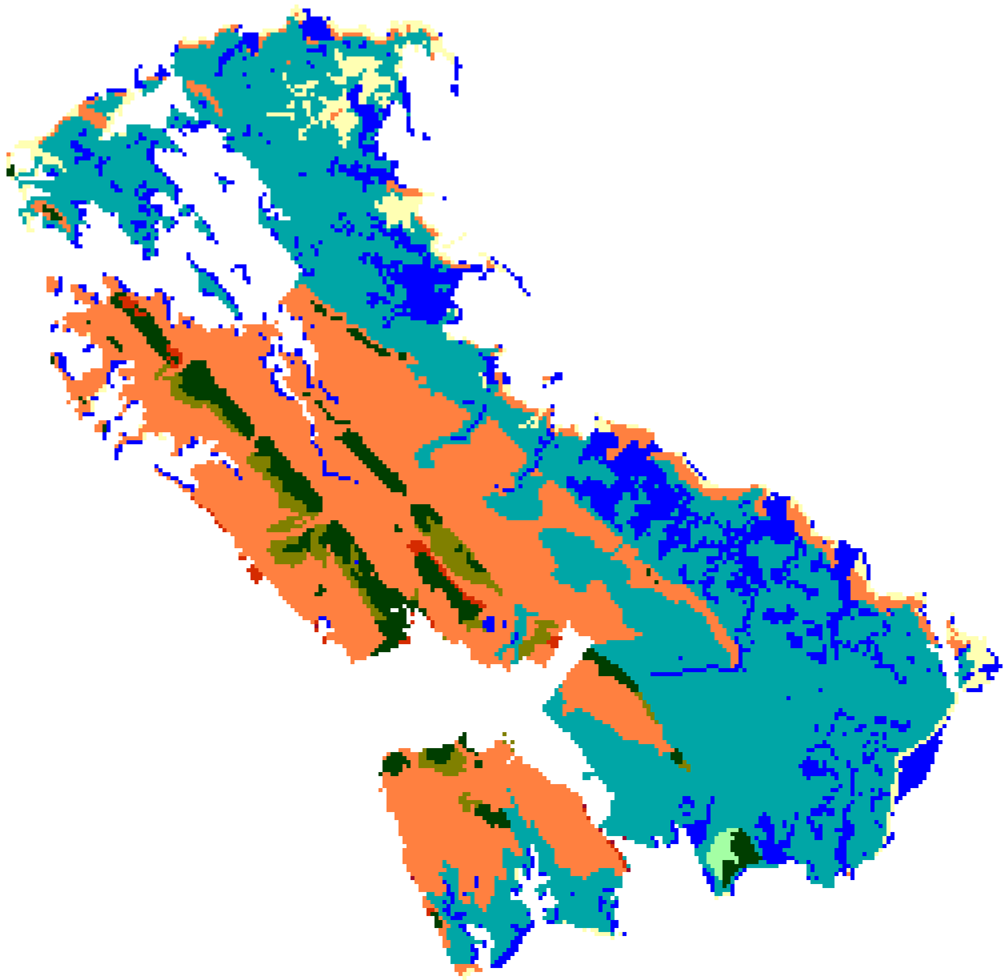


Plum Tree Island NWR, 2100, 1 meter

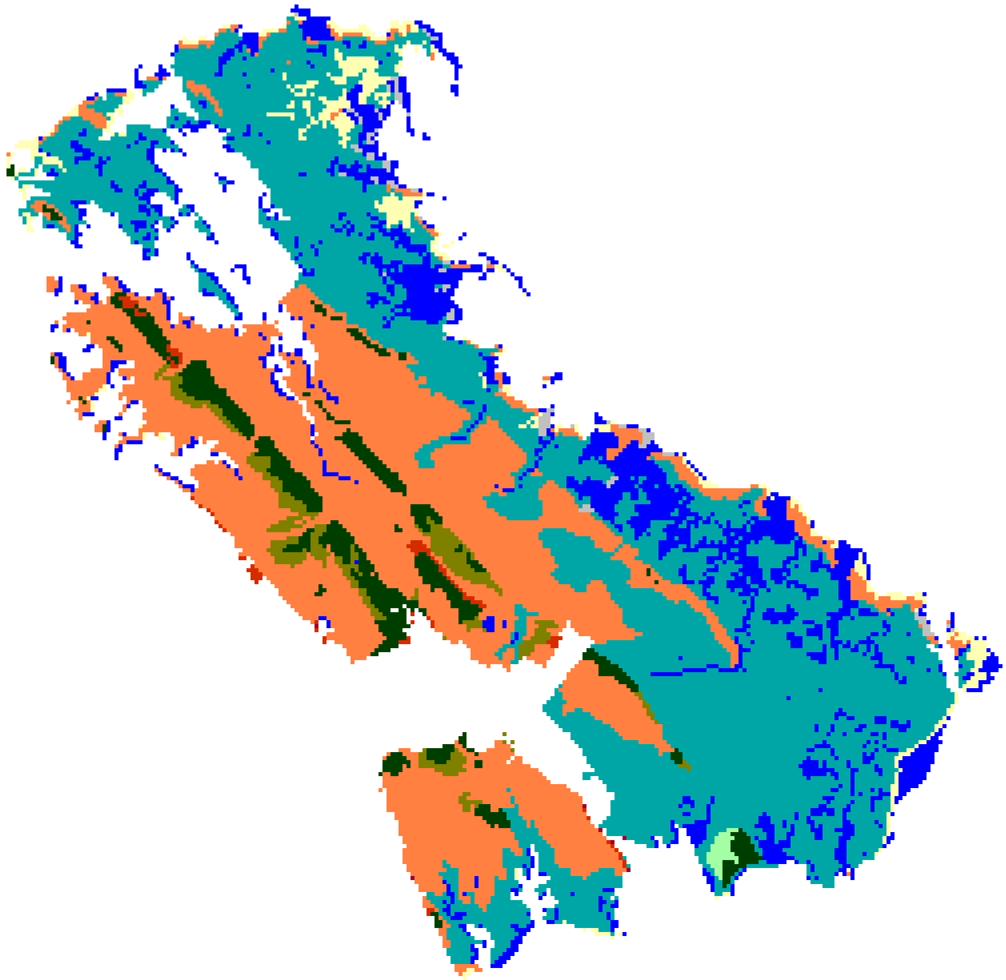
Plum Tree Island NWR
1.5 Meters Eustatic SLR by 2100

Results in Acres

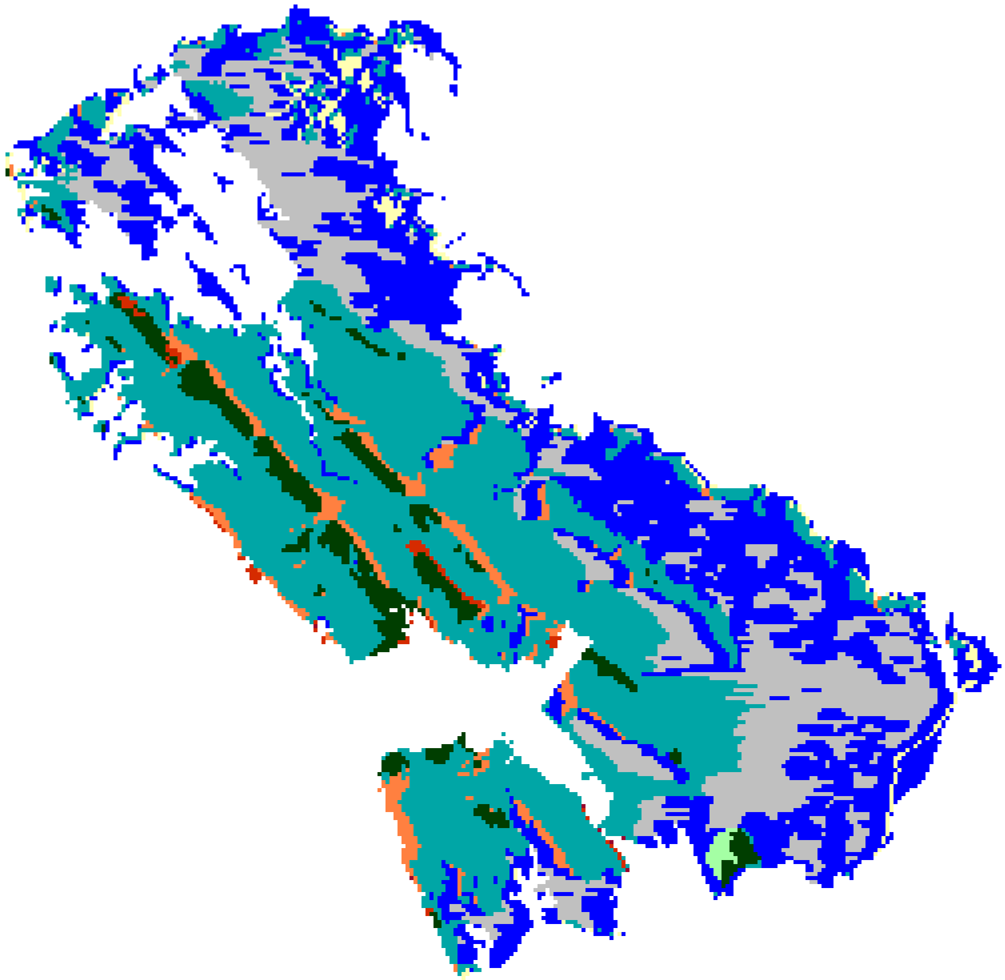
	Initial	2025	2050	2075	2100
Saltmarsh	2129.4	2110.7	2003.7	176.1	181.1
Brackish Marsh	1642.6	1629.7	177.2	169.0	16.7
Estuarine Open Water	630.0	655.4	1578.3	3279.6	4686.3
Tidal Swamp	238.4	238.4	237.6	68.7	50.4
Estuarine Beach	175.0	149.7	75.5	1.9	0.0
Trans. Salt Marsh	114.8	114.8	0.0	18.3	2.9
Undev. Dry Land	25.4	25.4	25.4	7.0	4.4
Tidal Fresh Marsh	11.8	11.8	11.7	11.5	11.5
Dev. Dry Land	1.6	1.6	1.6	1.6	1.3
Tidal Flat	0.0	31.6	858.0	1235.1	14.4
Total (incl. water)	**4968.9**	**4968.9**	**4968.9**	**4968.9**	**4968.9**



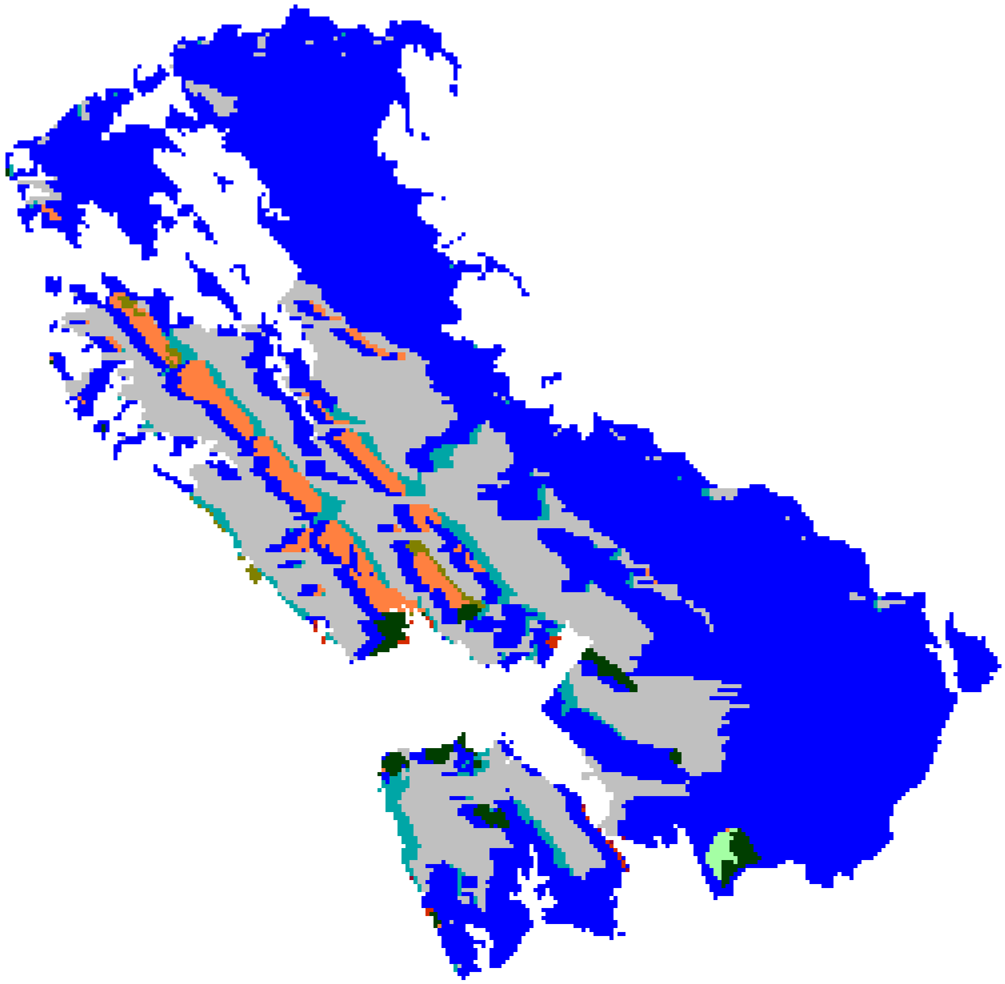
Plum Tree Island NWR, Initial Condition



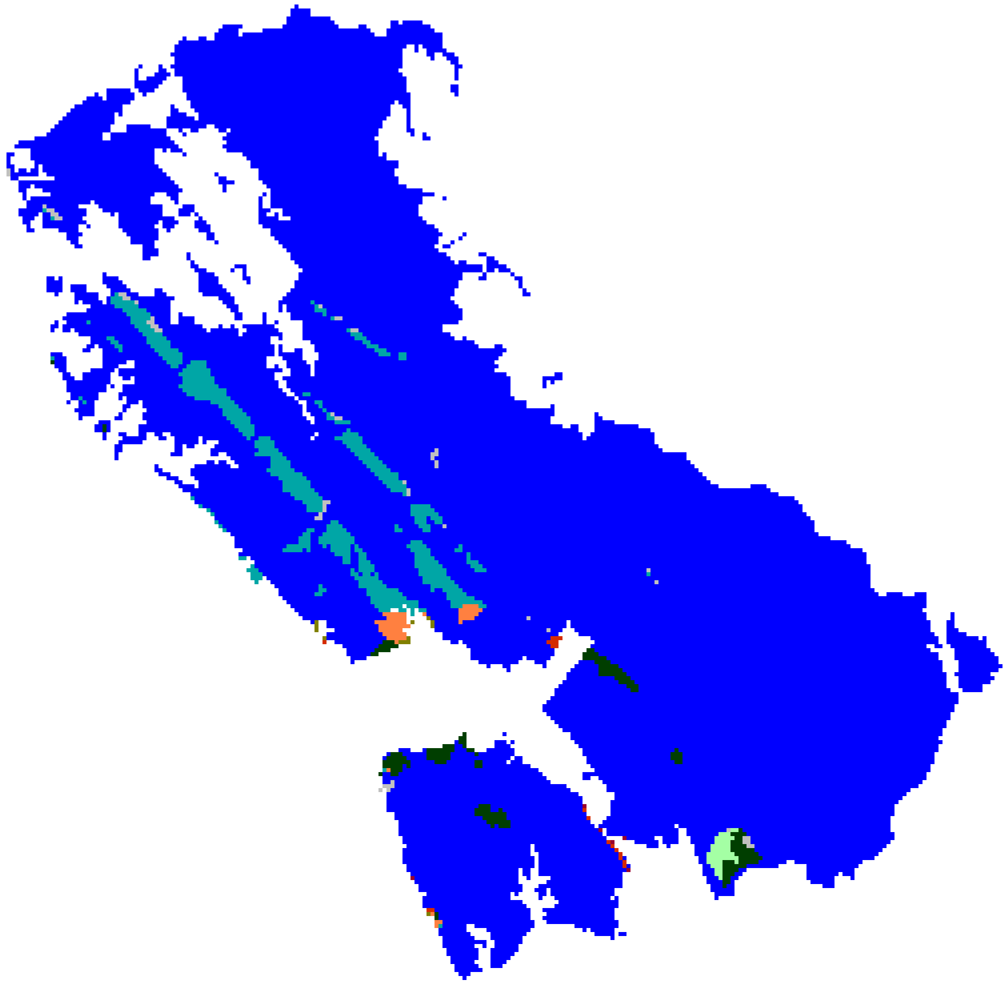
Plum Tree Island NWR, 2025, 1.5 meter



Plum Tree Island NWR, 2050, 1.5 meter



Plum Tree Island NWR, 2075, 1.5 meter

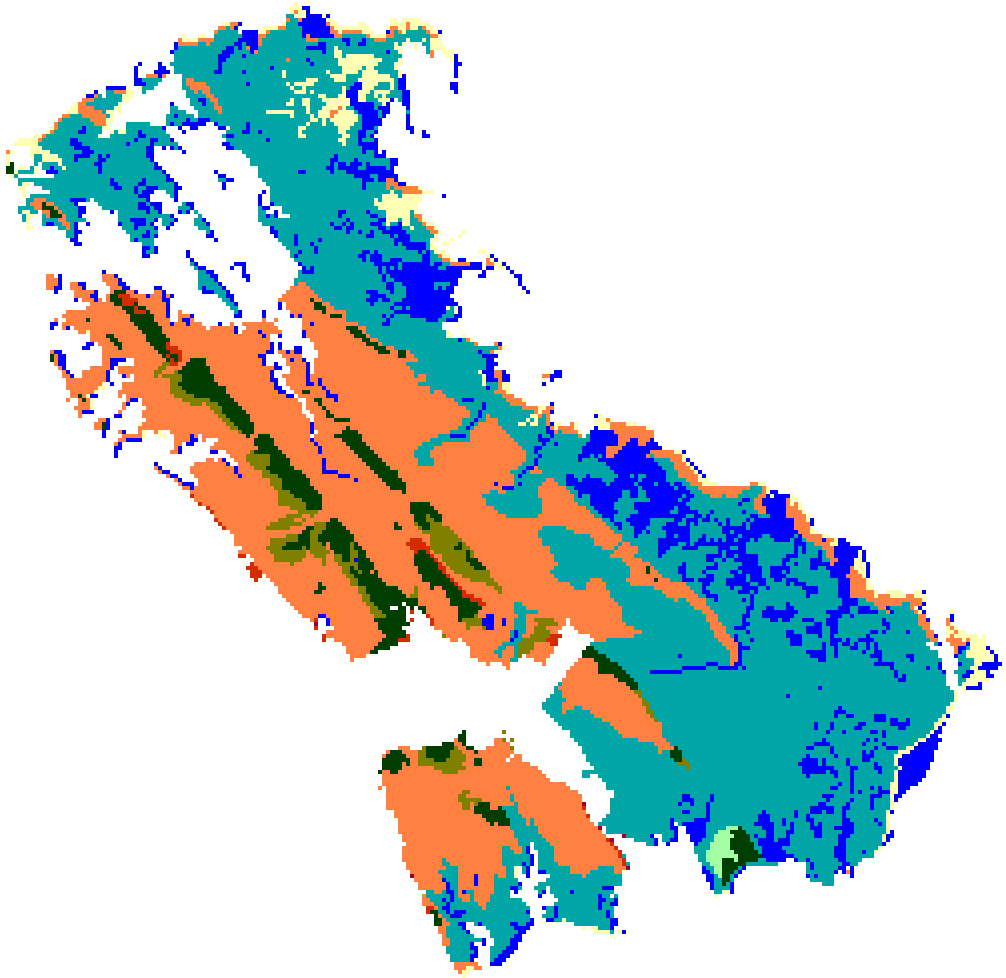


Plum Tree Island NWR, 2100, 1.5 meter

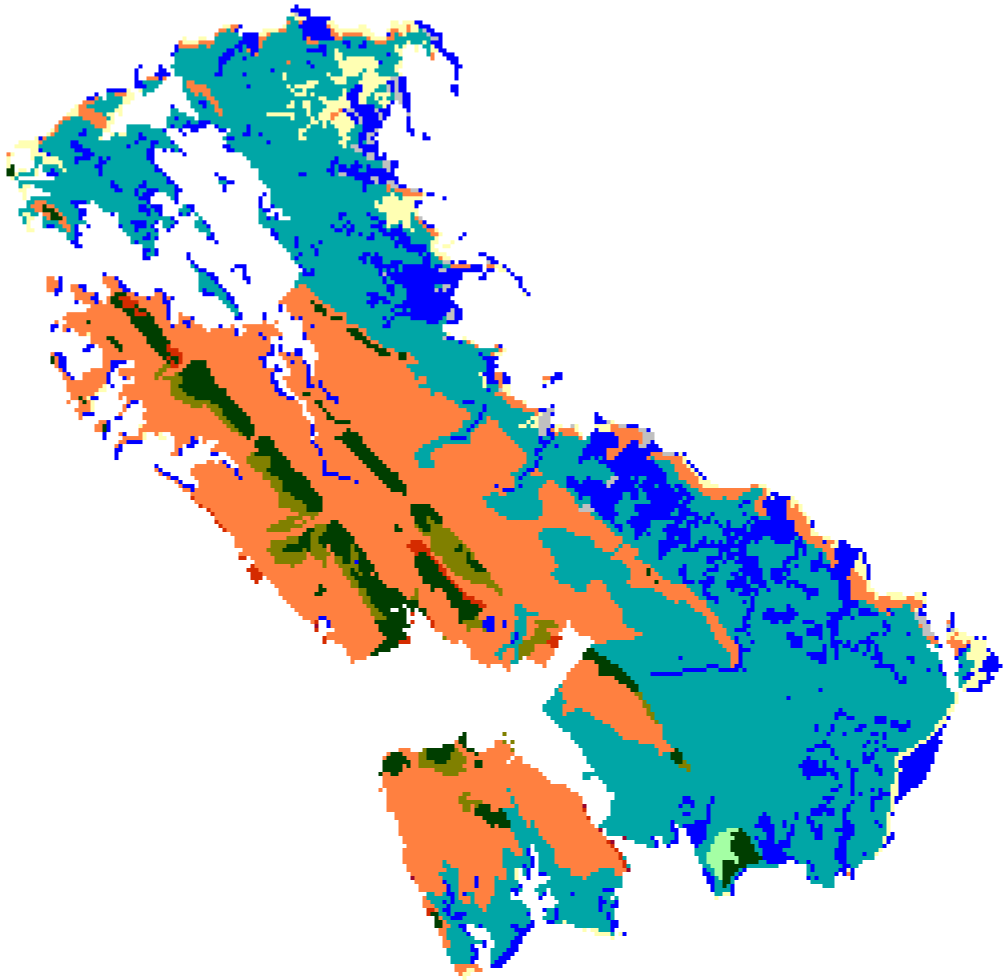
Plum Tree Island NWR
2 Meters Eustatic SLR by 2100

Results in Acres

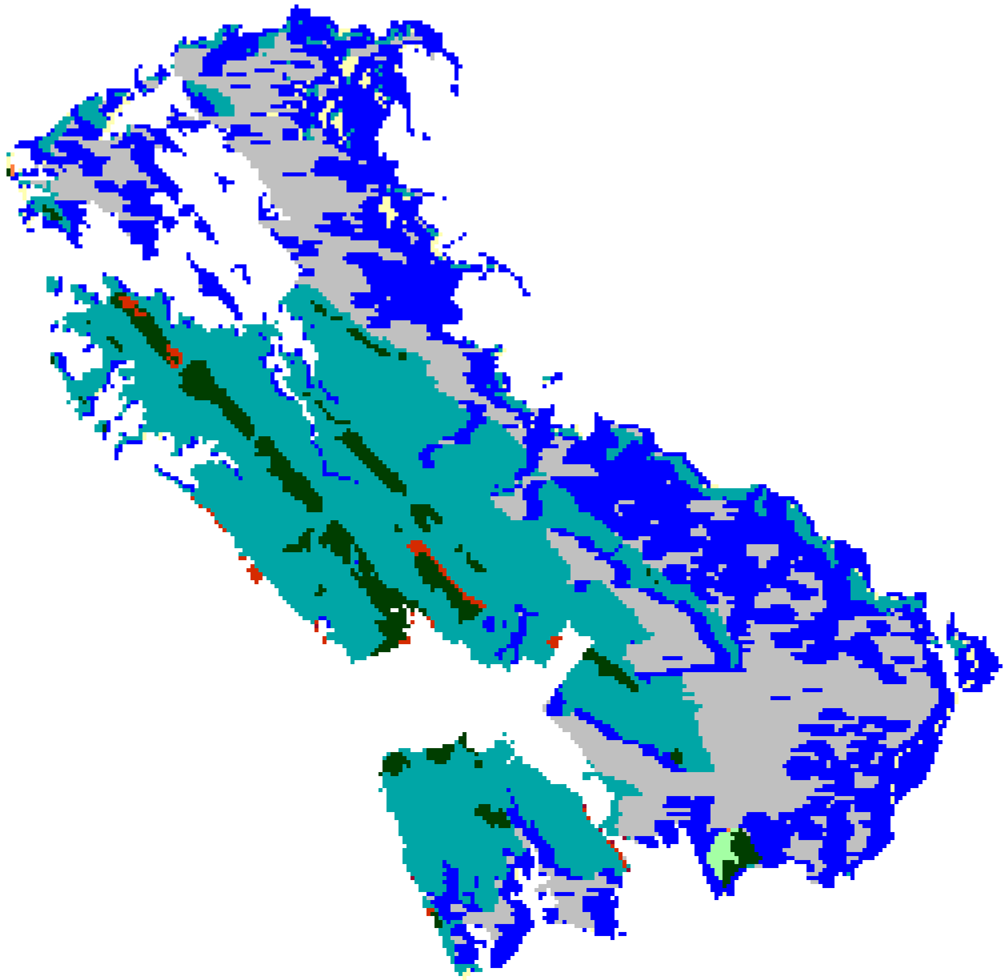
	Initial	2025	2050	2075	2100
Saltmarsh	2129.4	2110.7	1904.5	1.7	187.0
Brackish Marsh	1642.6	1629.7	1.8	179.8	9.6
Estuarine Open Water	630.0	655.4	1629.9	3464.1	4692.8
Tidal Swamp	238.4	238.4	237.4	57.8	41.4
Estuarine Beach	175.0	149.7	54.8	0.1	0.0
Trans. Salt Marsh	114.8	114.8	0.0	19.8	2.9
Undev. Dry Land	25.4	25.4	25.4	5.7	2.9
Tidal Fresh Marsh	11.8	11.8	11.7	11.5	11.3
Dev. Dry Land	1.6	1.6	1.6	1.3	1.3
Tidal Flat	0.0	31.6	1102.0	1227.0	19.9
Total (incl. water)	**4968.9**	**4968.9**	**4968.9**	**4968.9**	**4968.9**



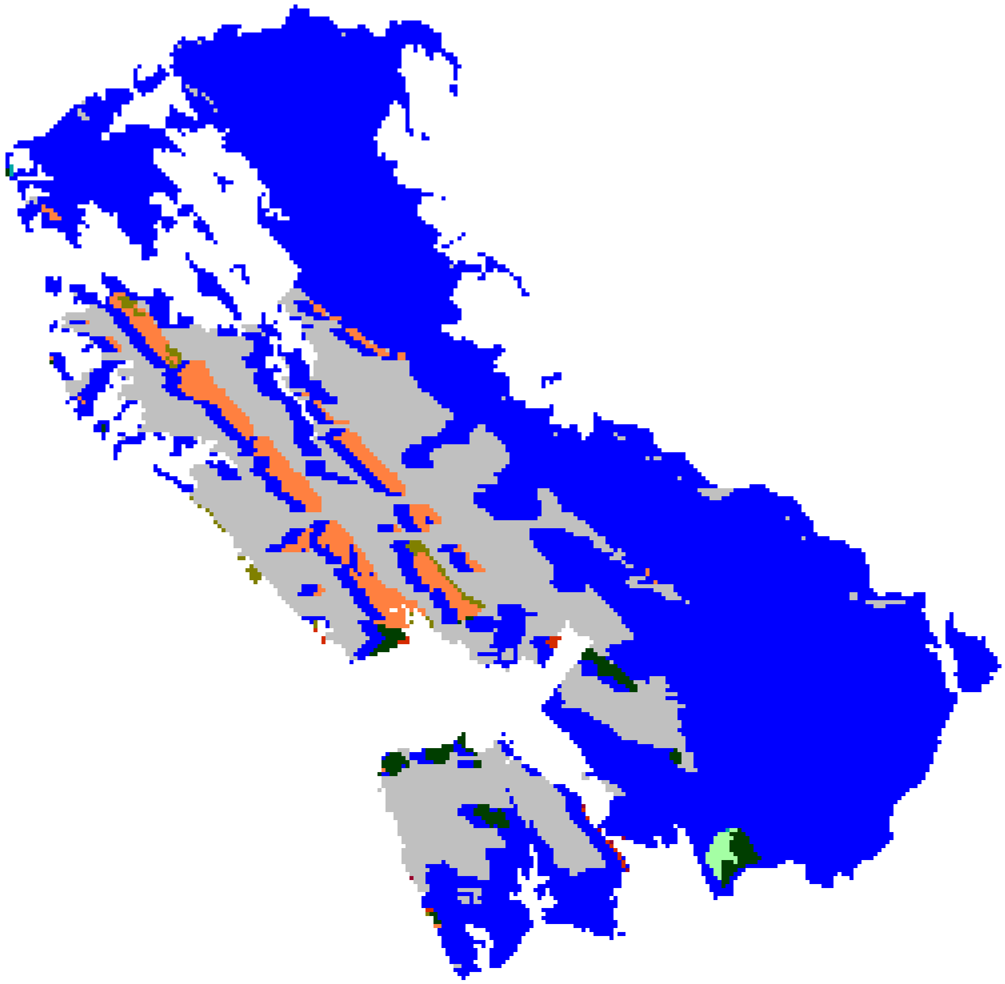
Plum Tree Island NWR, Initial Condition



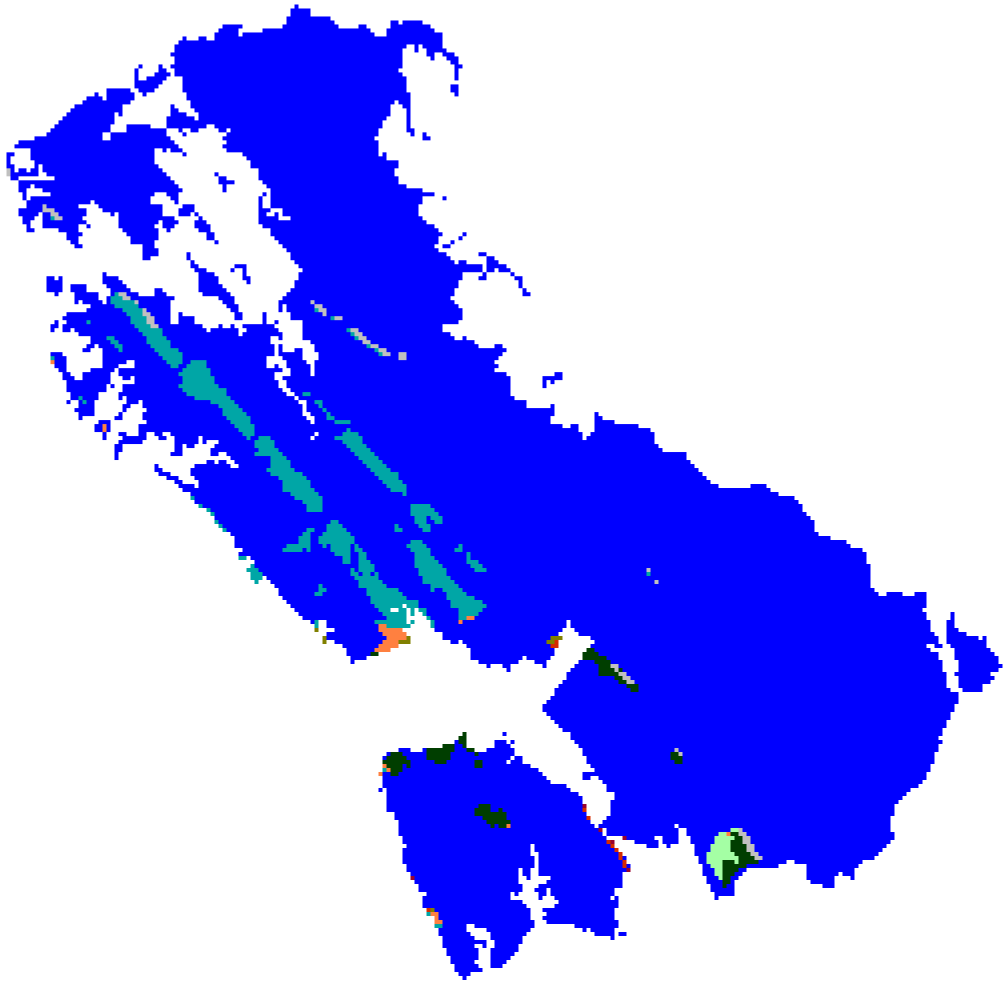
Plum Tree Island NWR, 2025, 2 meters



Plum Tree Island NWR, 2050, 2 meters



Plum Tree Island NWR, 2075, 2 meters



Plum Tree Island NWR, 2100, 2 meters

Discussion

The combination of a relatively low tidal elevation range and a high rate of historical sea level rise (SLR) make Plum Tree Island NWR especially susceptible to global sea level rise. Under all scenarios utilized, large quantities of the refuge are predicted to convert to open water. Under scenarios of one meter eustatic SLR and above, only small marsh fringes are predicted to persist by 2100.

Historical sea level rise at this site has been higher than global trends. This difference has been maintained in model projections, resulting in a higher predicted local SLR than will be experienced globally. This difference is likely a combination of land subsidence and other local effects. For example, a study performed by Dr. Victoria Coles of University of Maryland (Coles 2009) suggests that sea level rise in Chesapeake Bay will increase faster than eustatic trends due to regional heating, freshwater effects, and other mass adjustments.

The best available elevation data for this site were derived from five foot USGS contours created in 1963. Interpolation between contours and estimates of land elevations below the five foot contour are quite uncertain. The SLAMM pre-processor was utilized to estimate elevation ranges for all of the wetlands at this site as a function of tide range and known relationships between wetland types and tide ranges. However, wetland elevations were assumed to be uniformly distributed over their feasible vertical elevation ranges or "tidal frames"—an assumption that may not reflect reality. If wetlands elevations are actually clustered high in the tidal frame they would be less vulnerable to SLR. If wetlands are towards the bottom, they would be more vulnerable. LiDAR data for the site would assist in reducing model uncertainty in this manner. However, given the short height of the tidal frame (low tidal elevation range), wetlands are likely to be overwhelmed by most scenarios of eustatic SLR regardless of their initial condition elevations.

Perhaps the most significant source of model uncertainty is whether a higher frequency of inundation will allow refuge marshes to sequester additional sediment and thus vertically accrete at a higher rate. Such a feedback would provide some additional resilience to SLR. However this feedback mechanism is unlikely to provide perfect protection from SLR, given the fact that significant shoreline erosion and marsh conversion has already occurred under conditions of sea level rise much less severe than those predicted for the future. (Reed et. al, 2008, section 3.1 ". . .Plum Tree Island Marsh . . . and adjacent areas east of the city are already experiencing loss to erosion and rising sea levels.")

Overall, SLAMM model results tend to agree with the expert assessment of *Climate Change Science Program Synthesis and Assessment Product 4.1:* (Reed et. al 2008) "There are some coastal wetlands, however, that cannot keep pace with current rates and are being lost. Specific areas are at . . . Plum Tree Island National Wildlife Refuge on the western shore. . . These SF marshes are not sustainable and will certainly be lost under even midrange estimates of future sea level rise."

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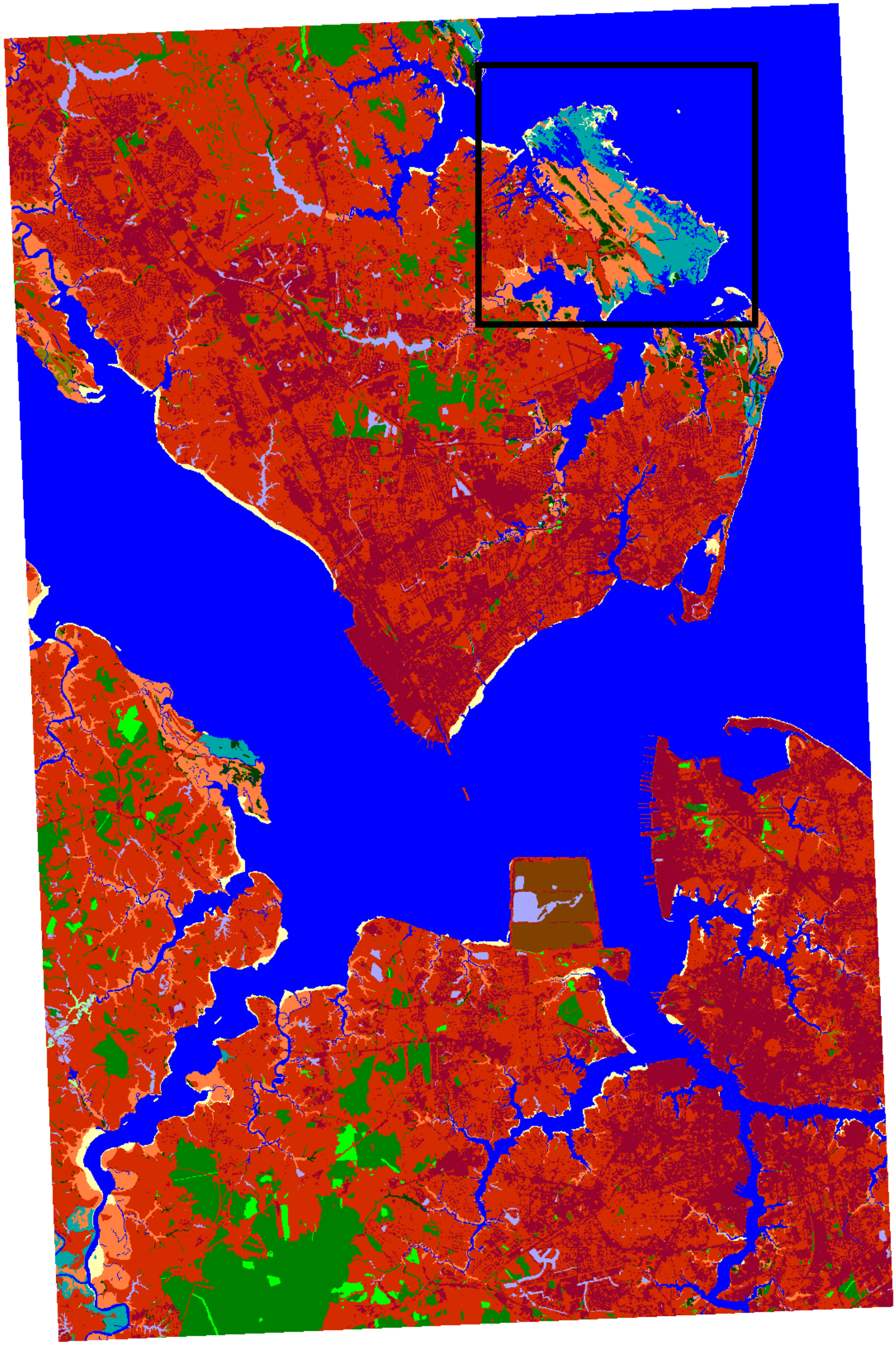
Appendix A: Contextual Results

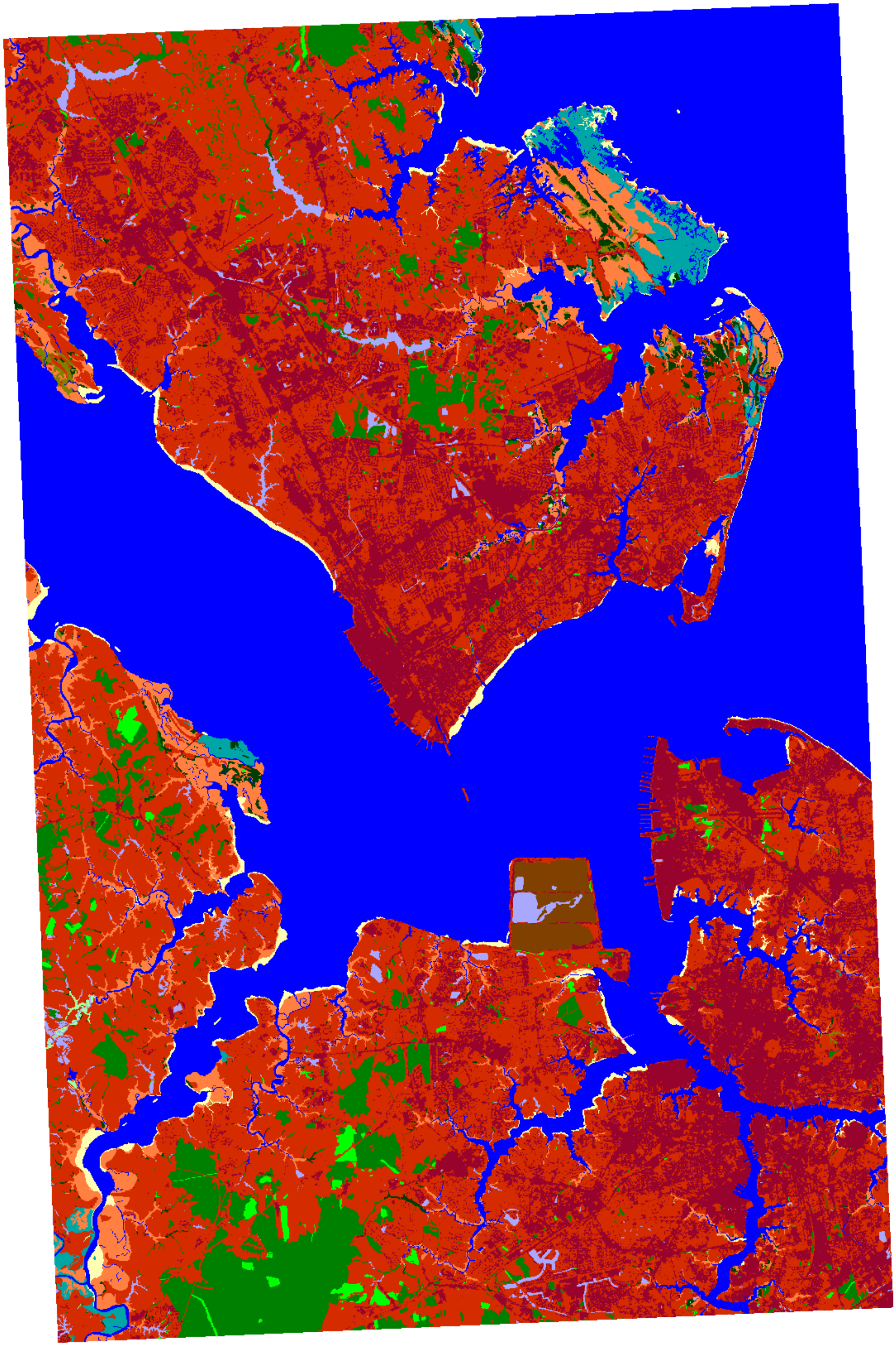
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

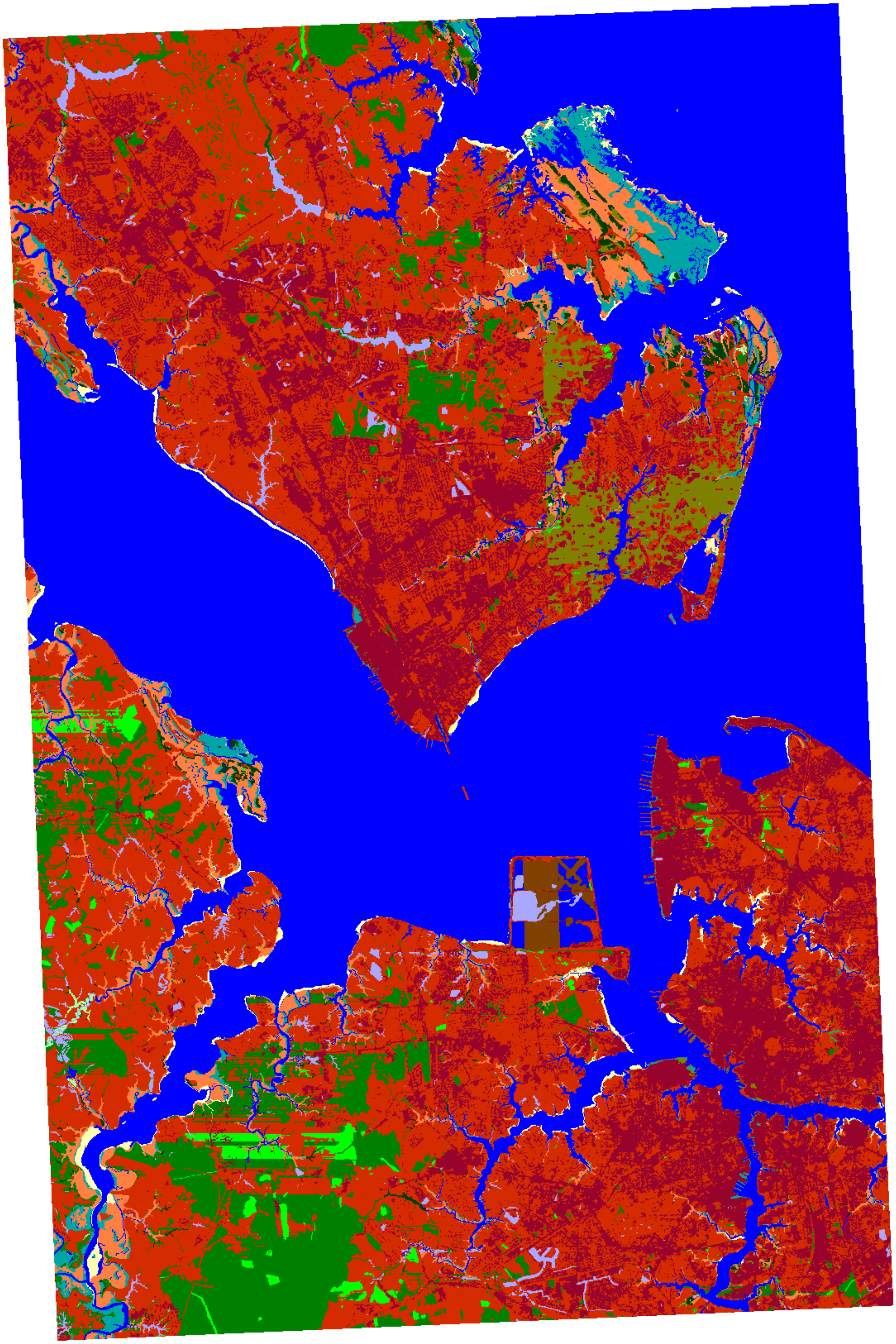
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



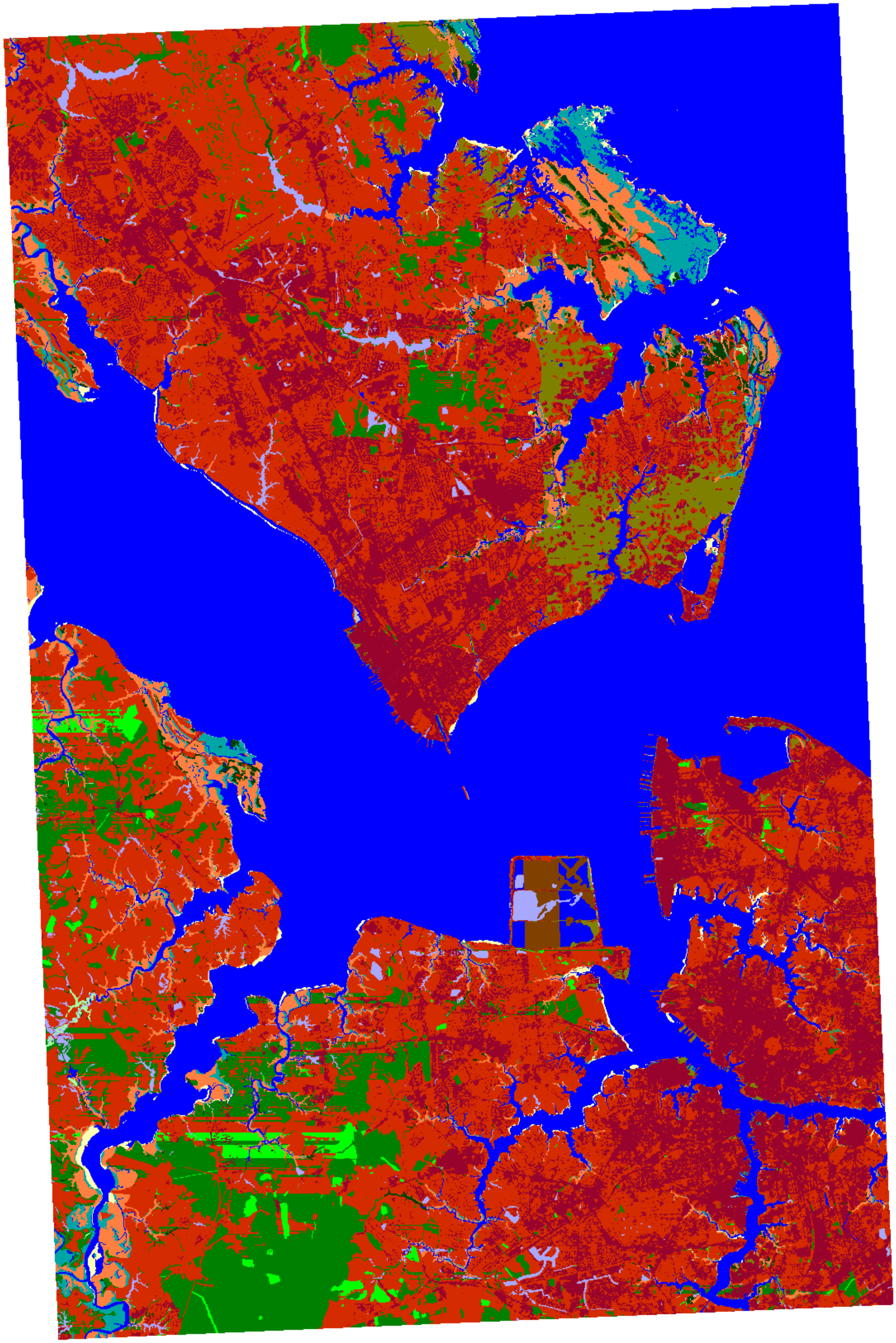
Location of Plum Tree Island National Wildlife Refuge (in rectangle) within simulation context



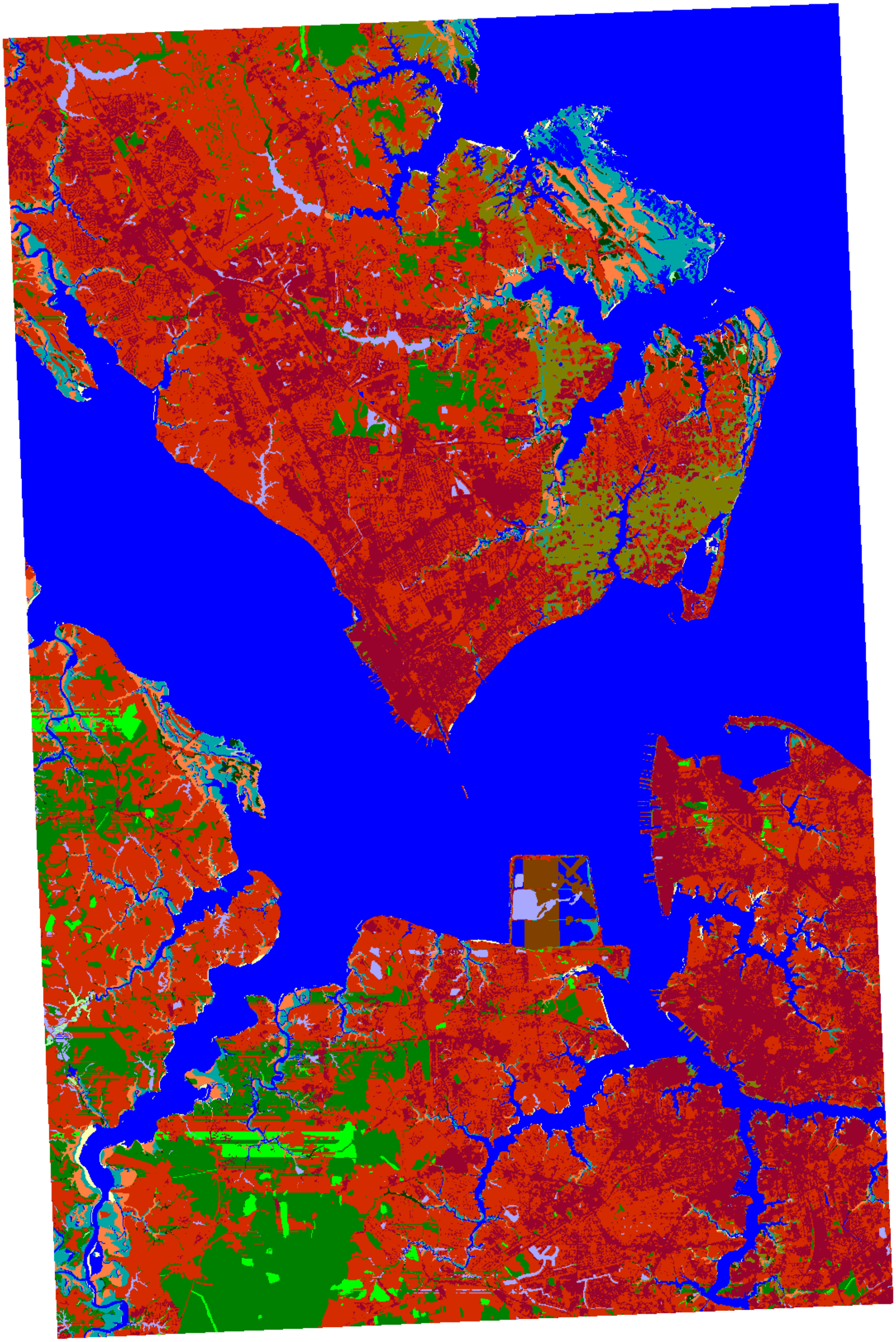
Plum Tree Island NWR, Initial Condition



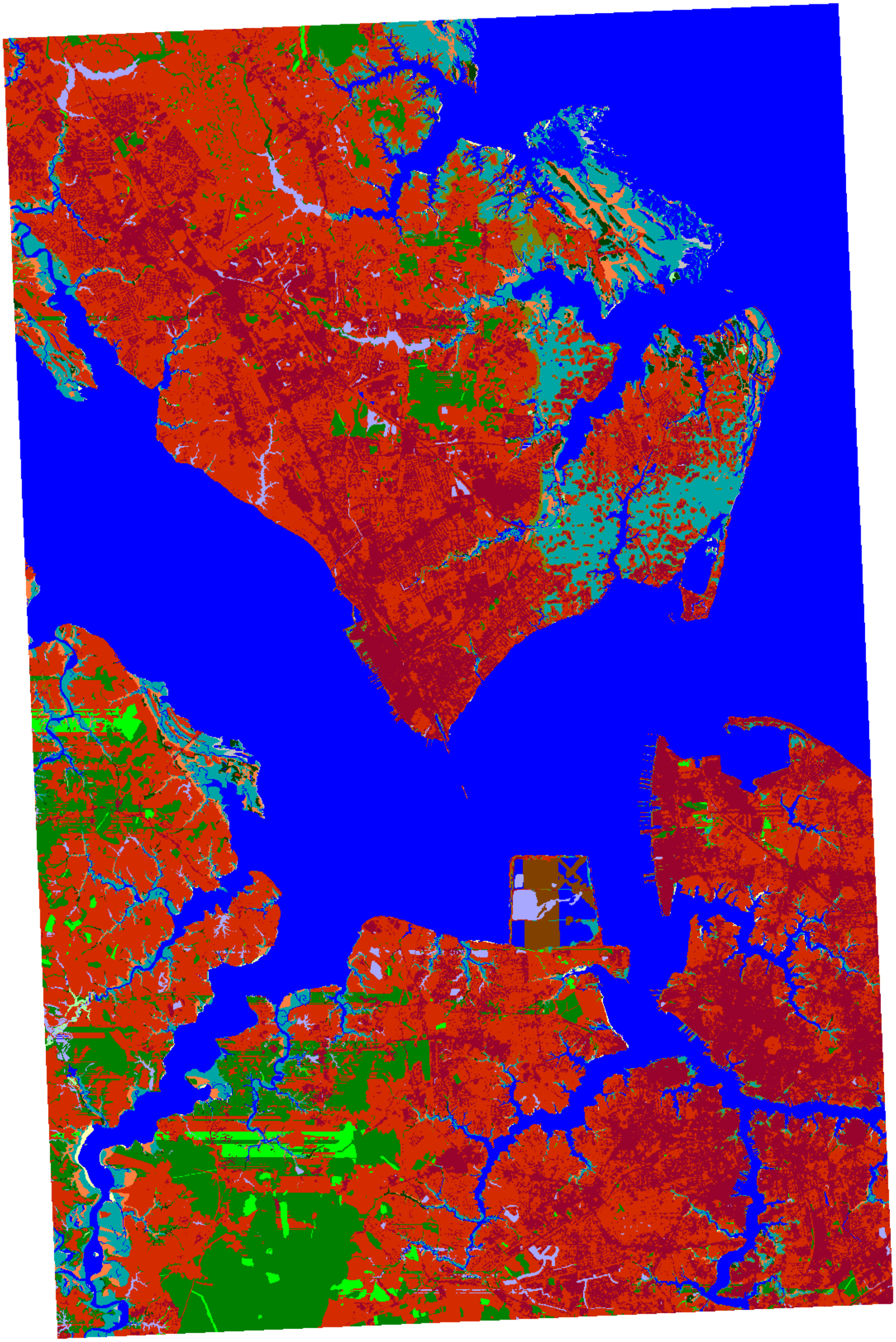
Plum Tree Island NWR, 2025, Scenario A1B Mean



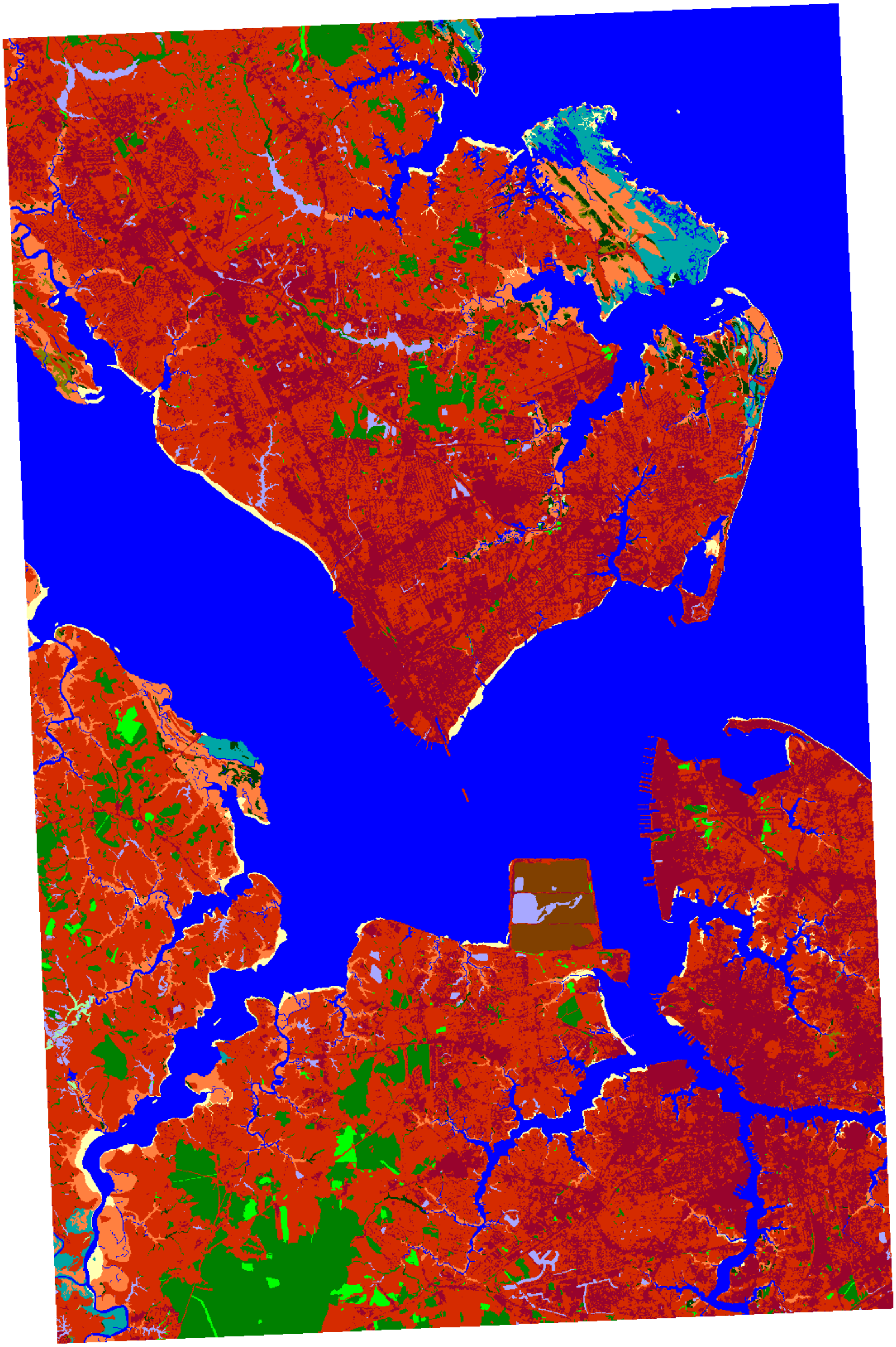
Plum Tree Island NWR, 2050, Scenario A1B Mean



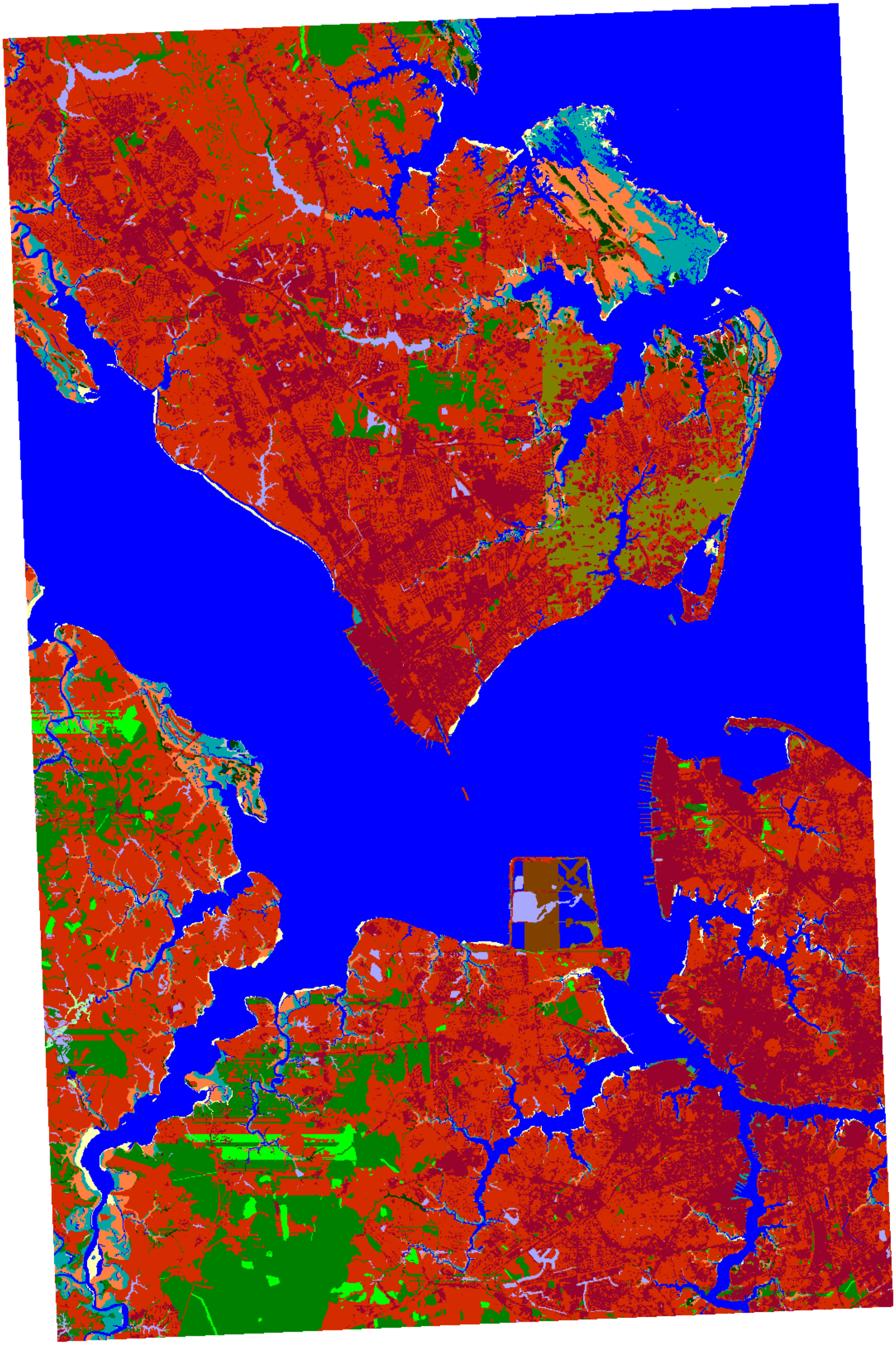
Plum Tree Island NWR, 2075, Scenario A1B Mean



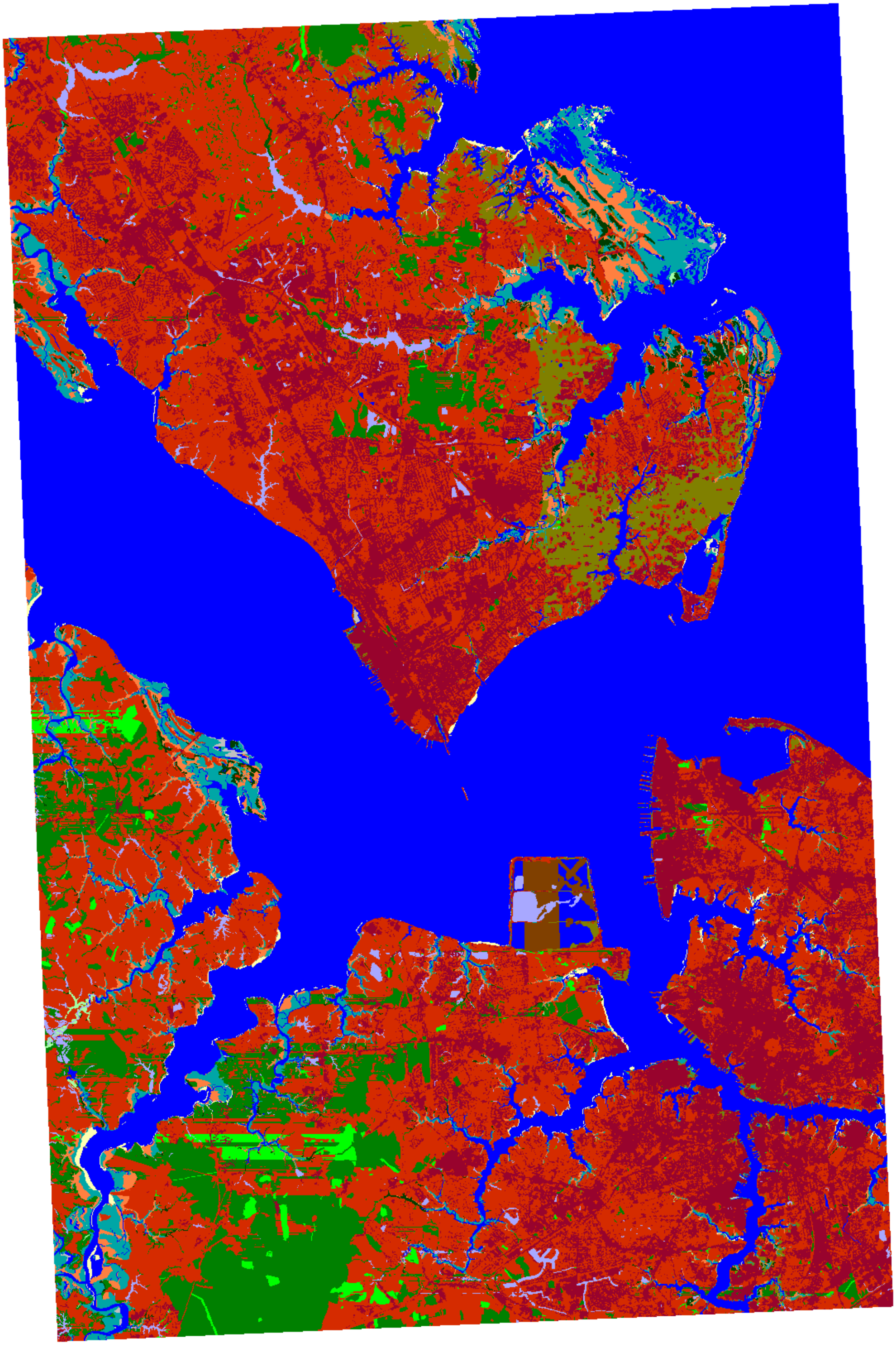
Plum Tree Island NWR, 2100, Scenario A1B Mean



Plum Tree Island NWR, Initial Condition



Plum Tree Island NWR, 2025, Scenario A1B Maximum



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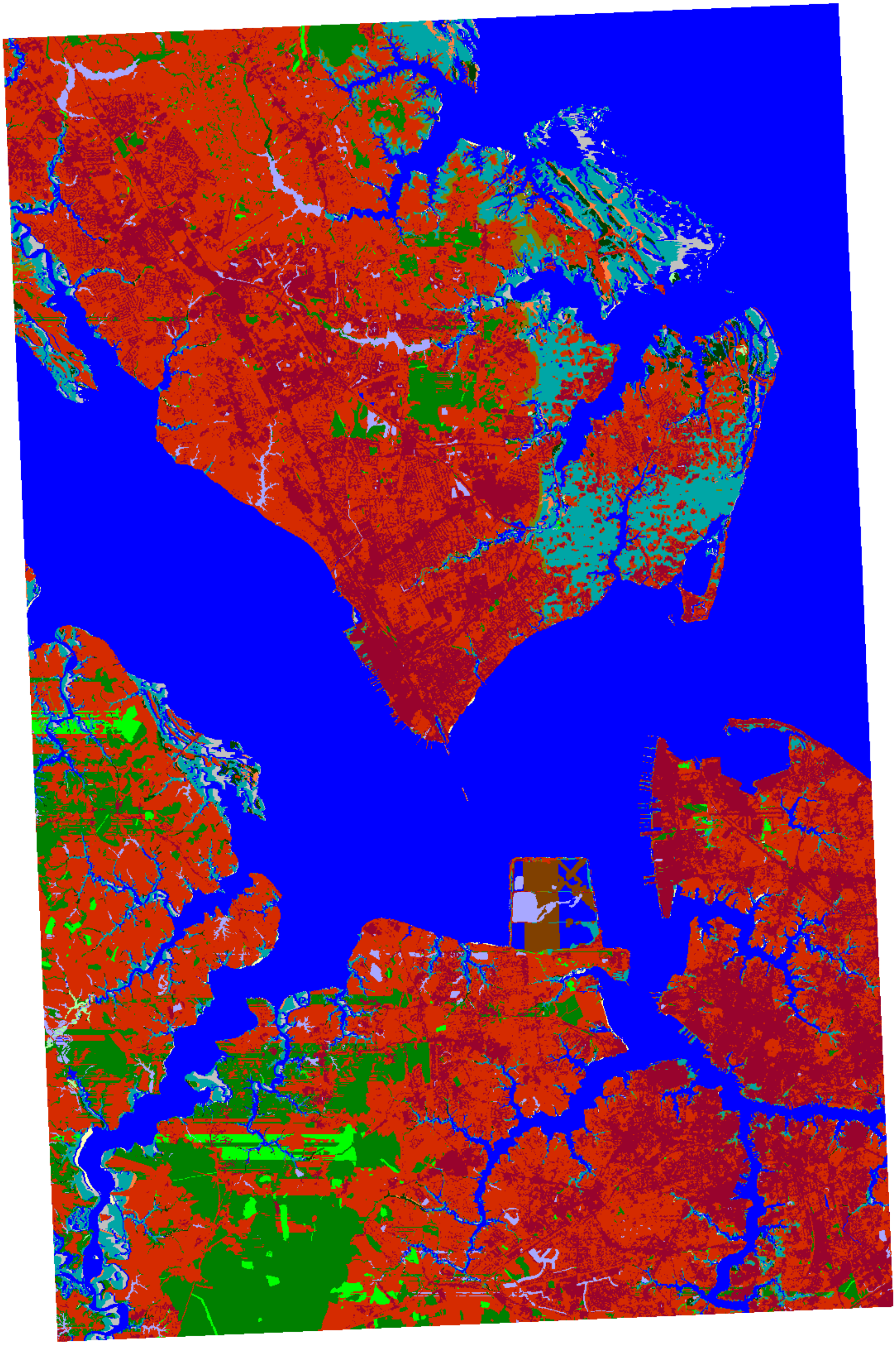

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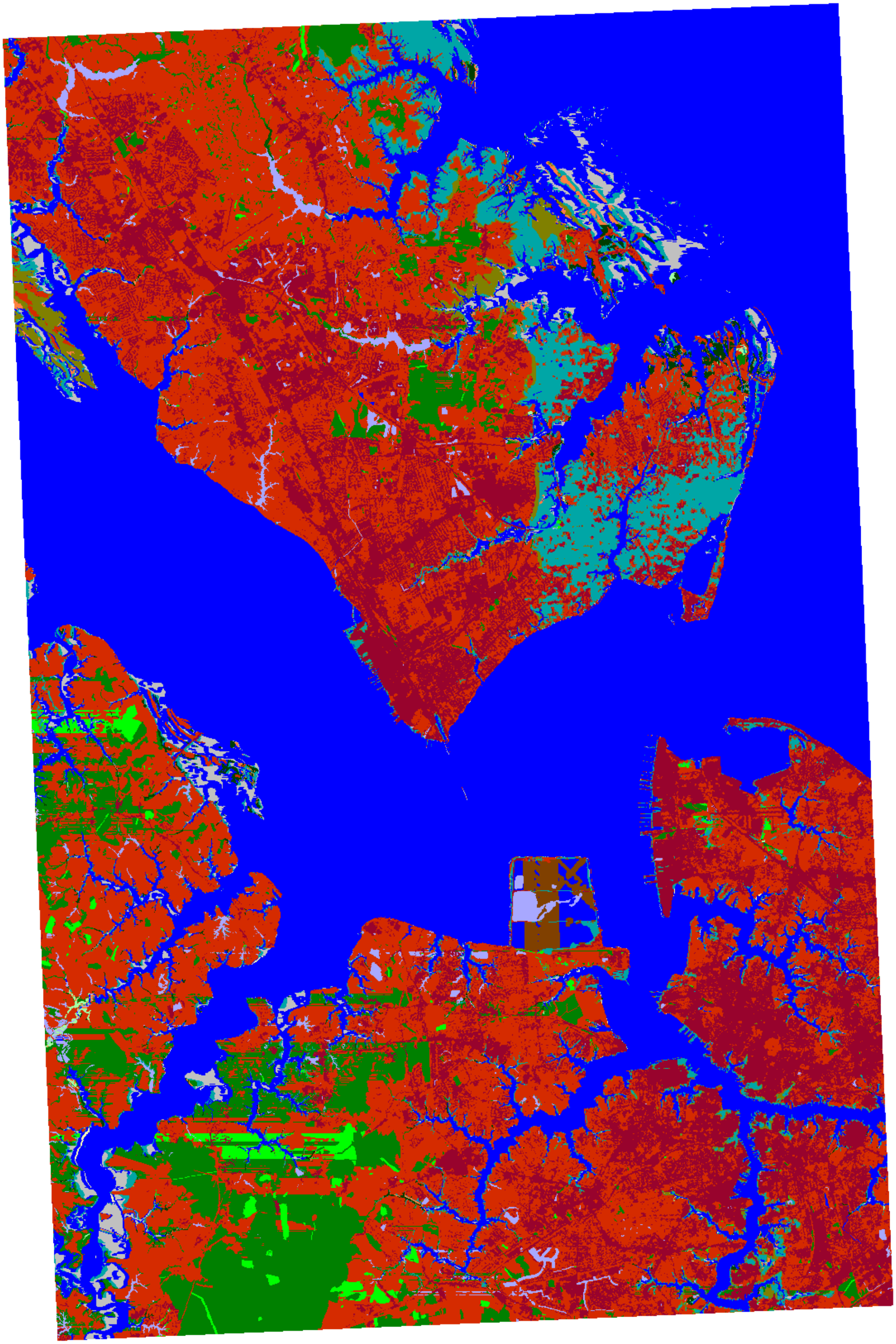

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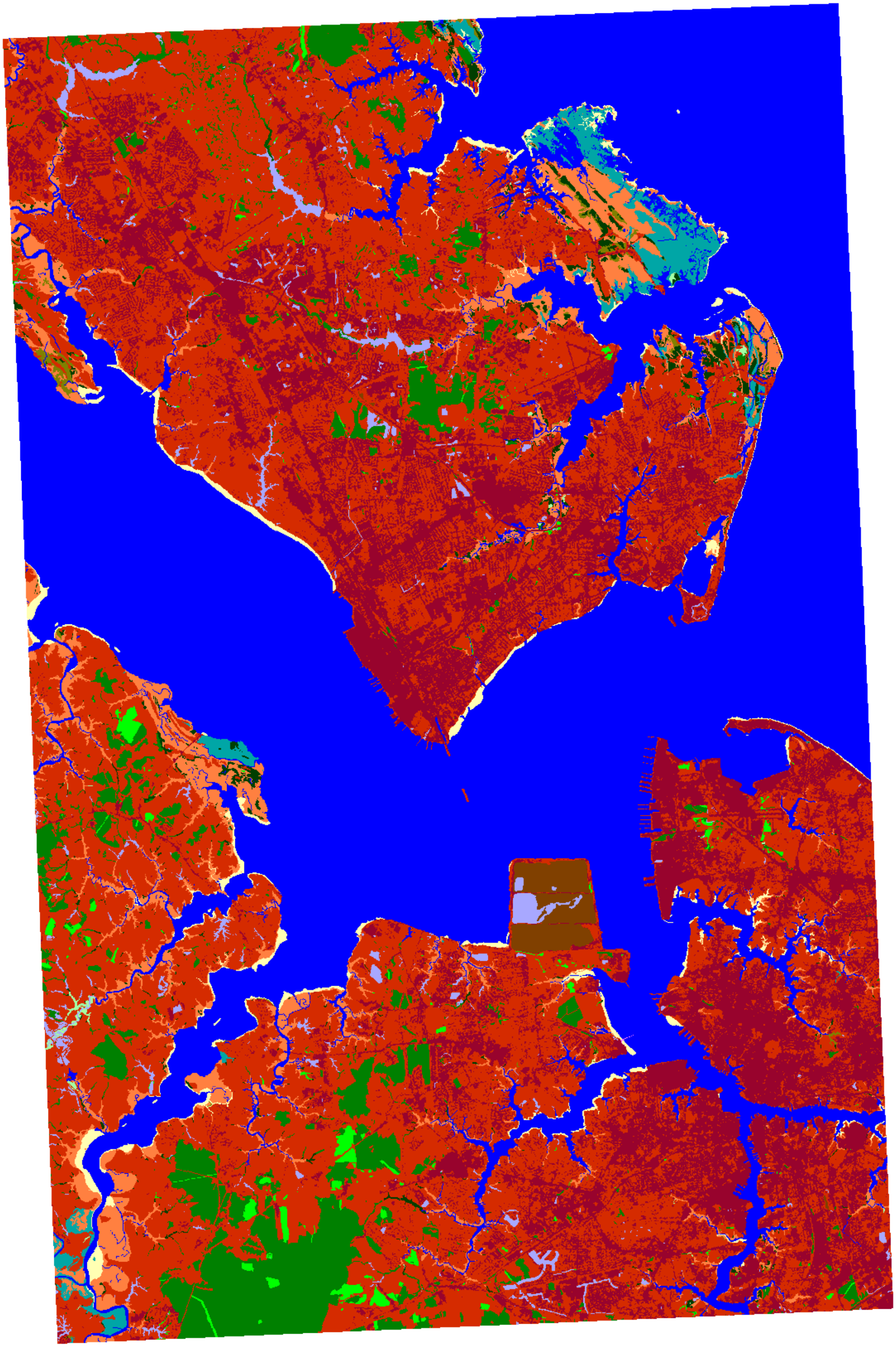
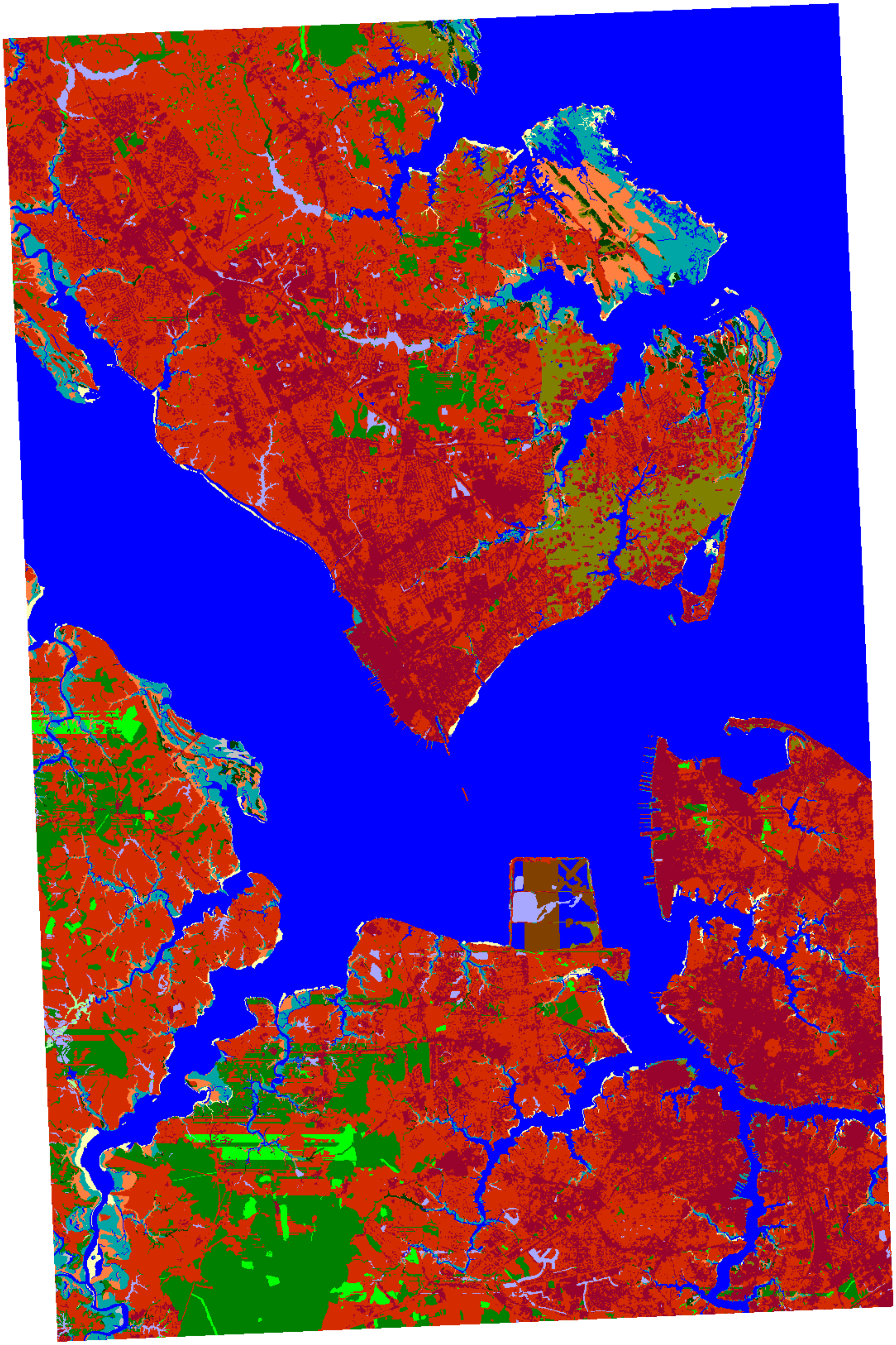
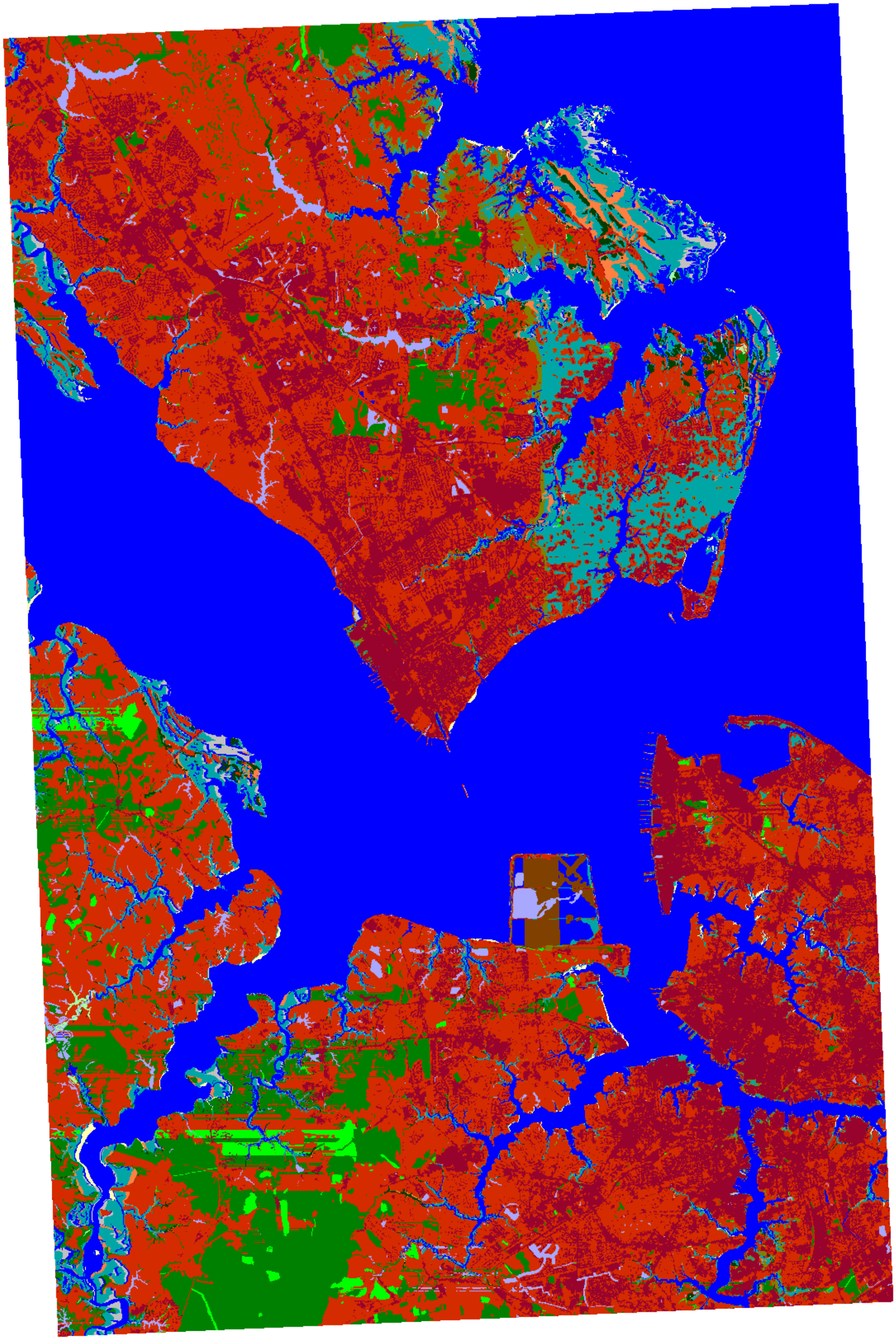


Plum Tree Island NWR, Initial Condition



Plum Tree Island NWR, 2025, 1 meter



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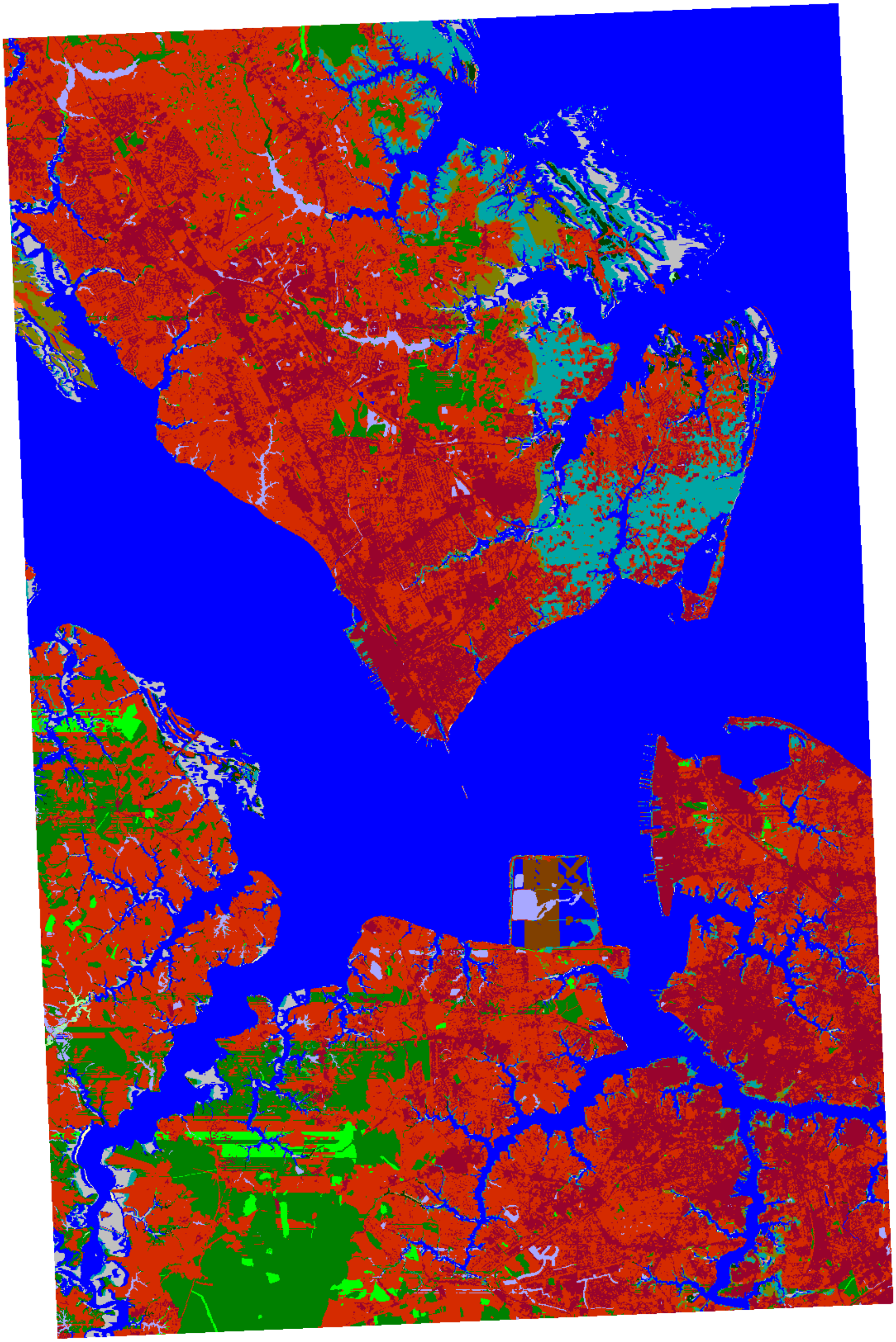

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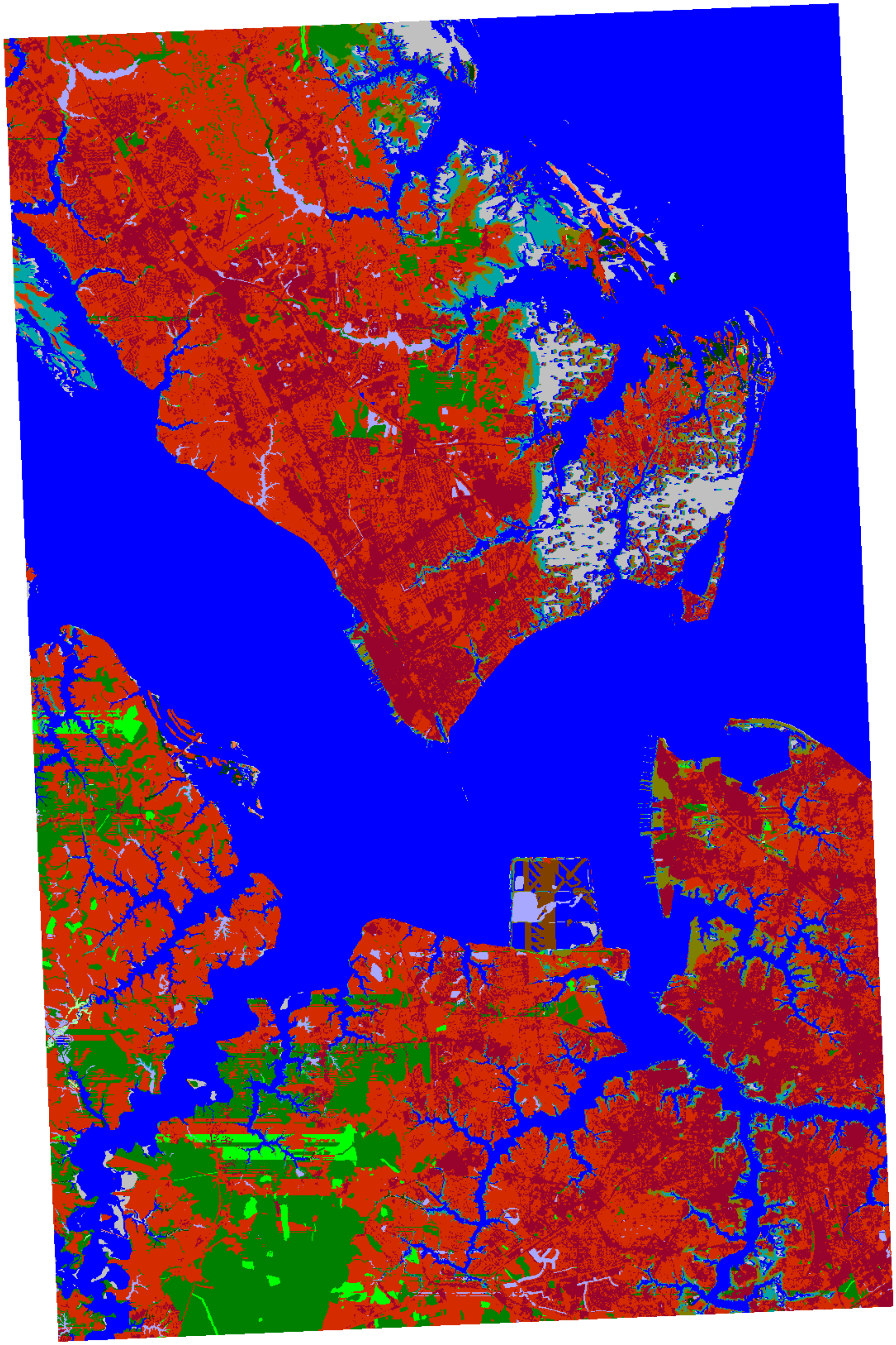

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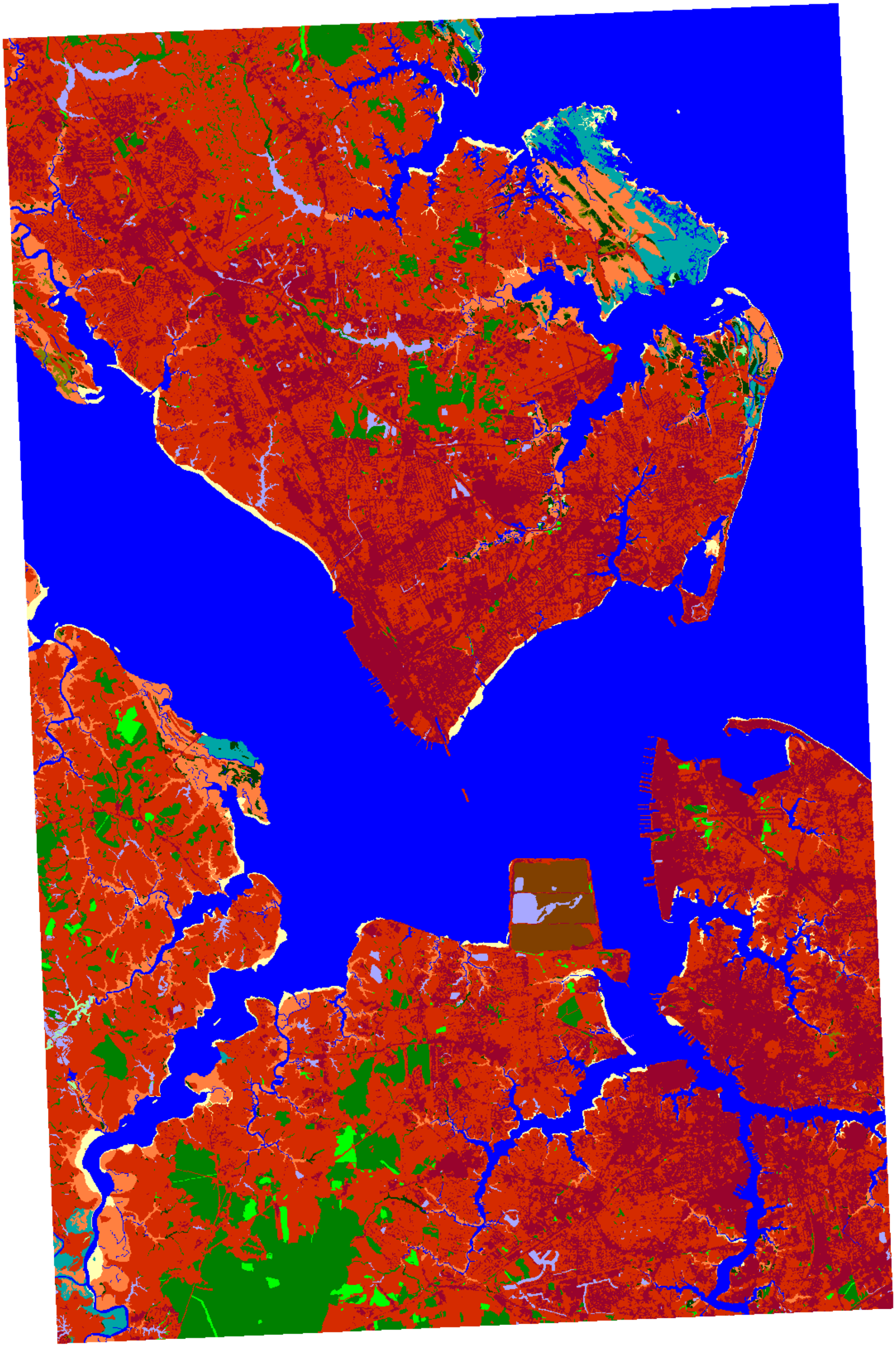

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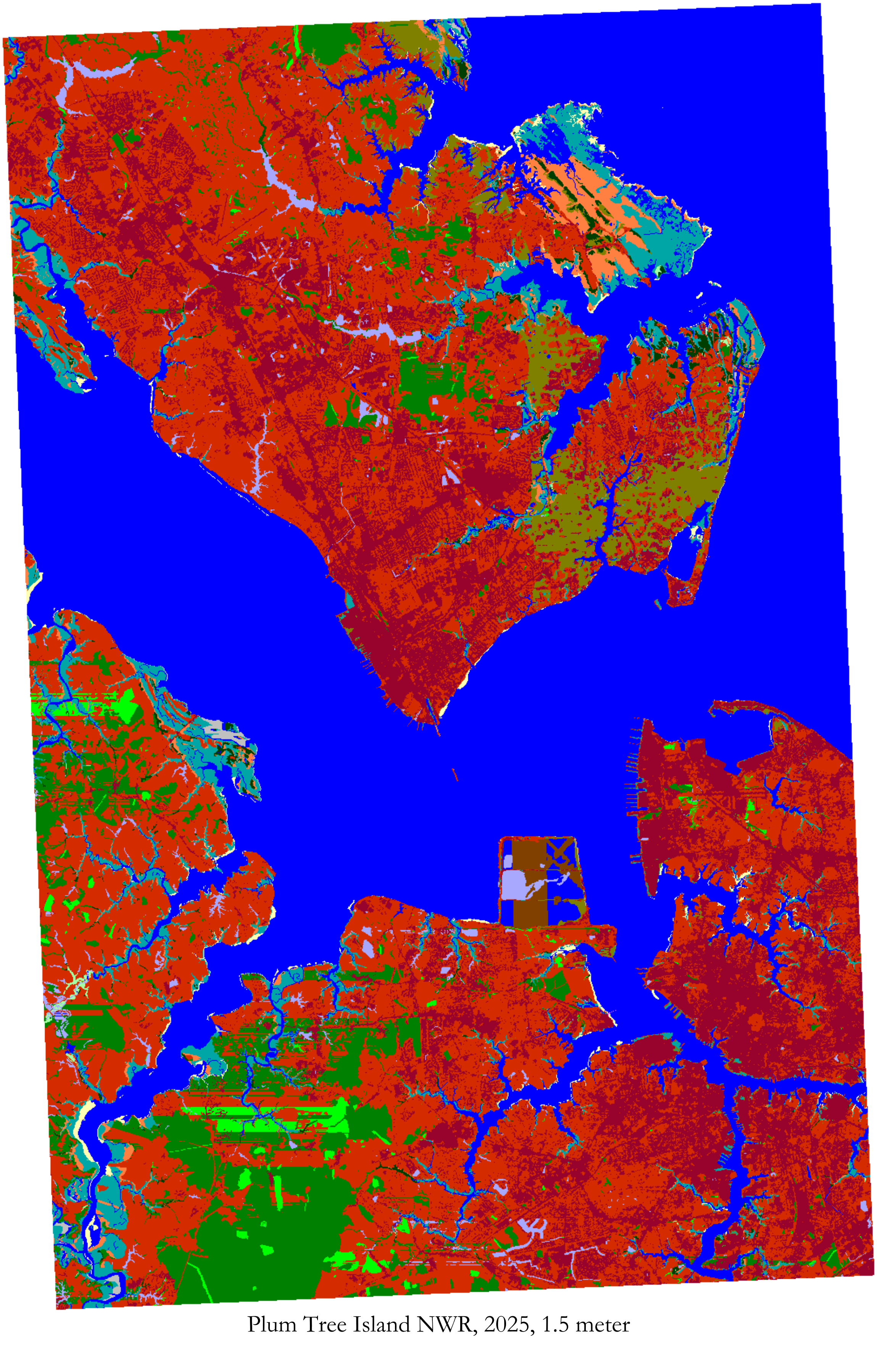
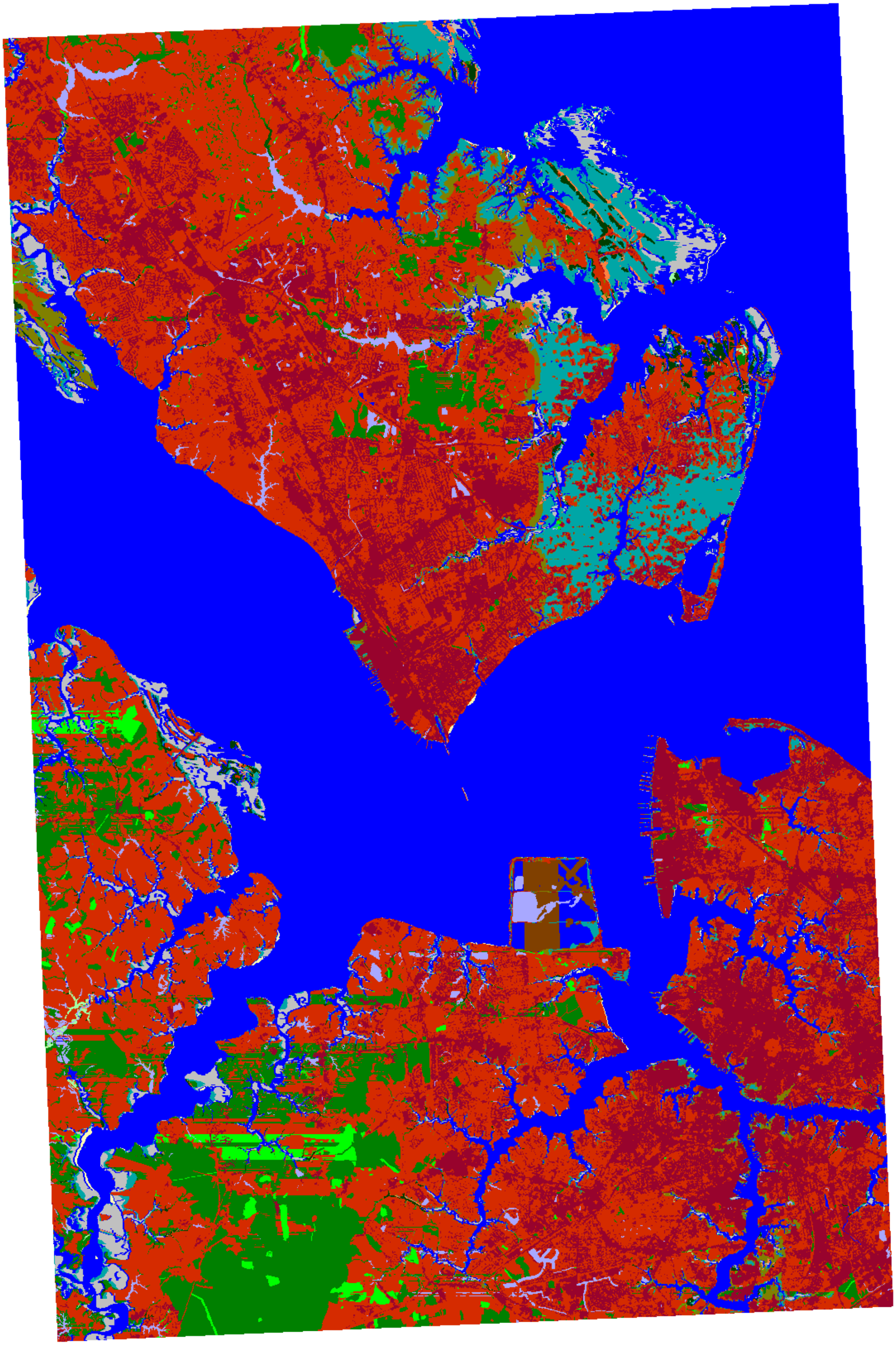
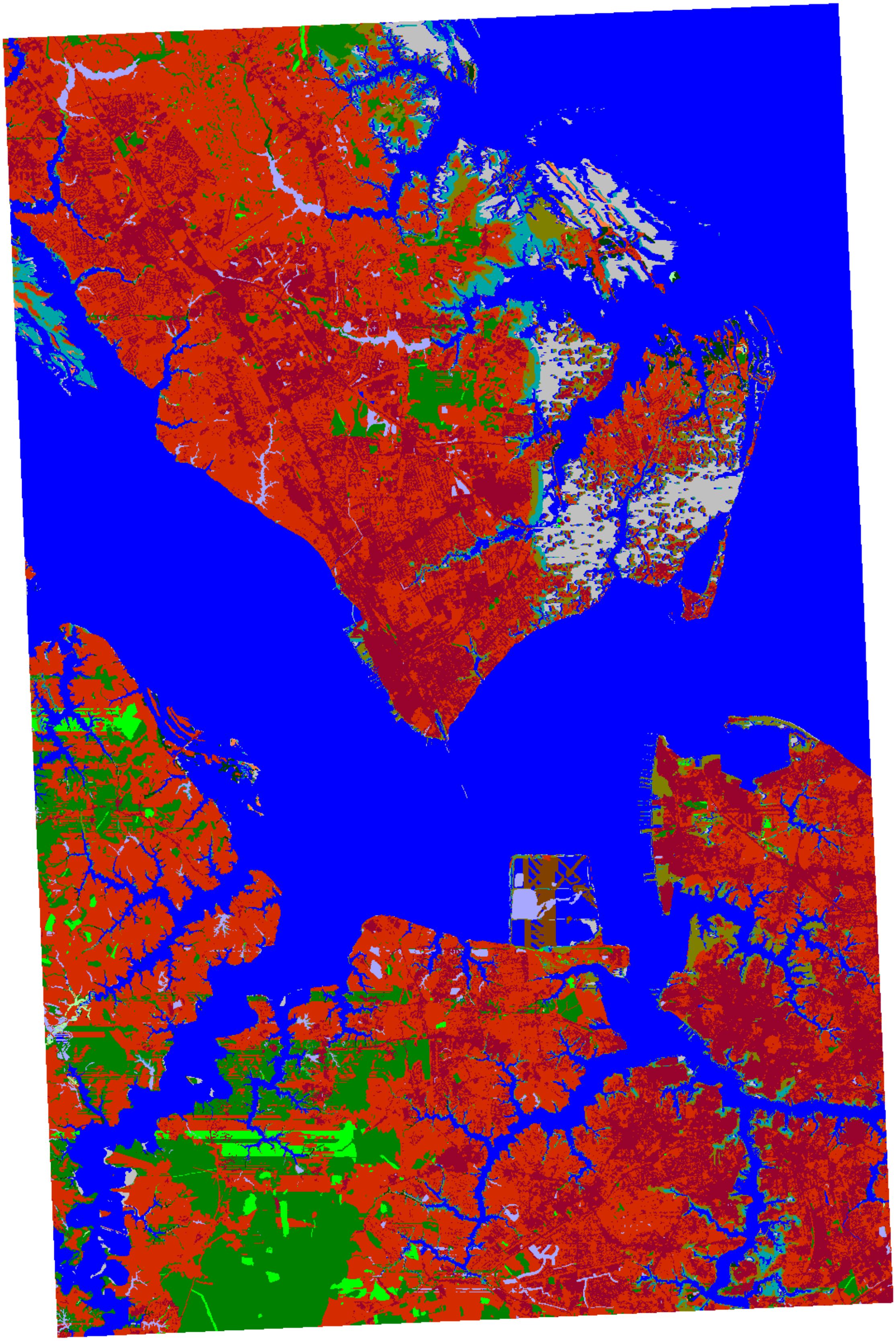


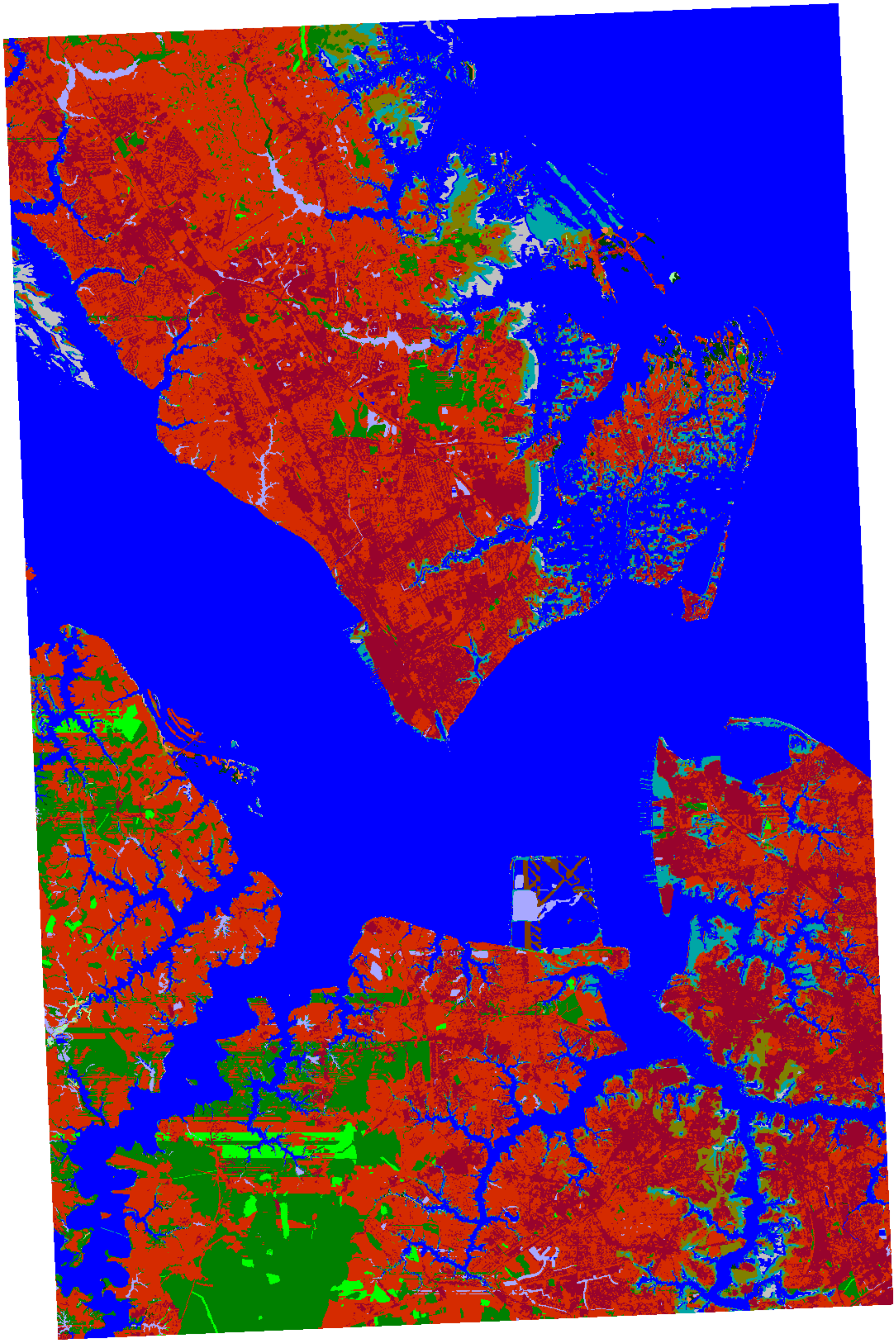
Plum Tree Island NWR, 2025, 1.5 meter



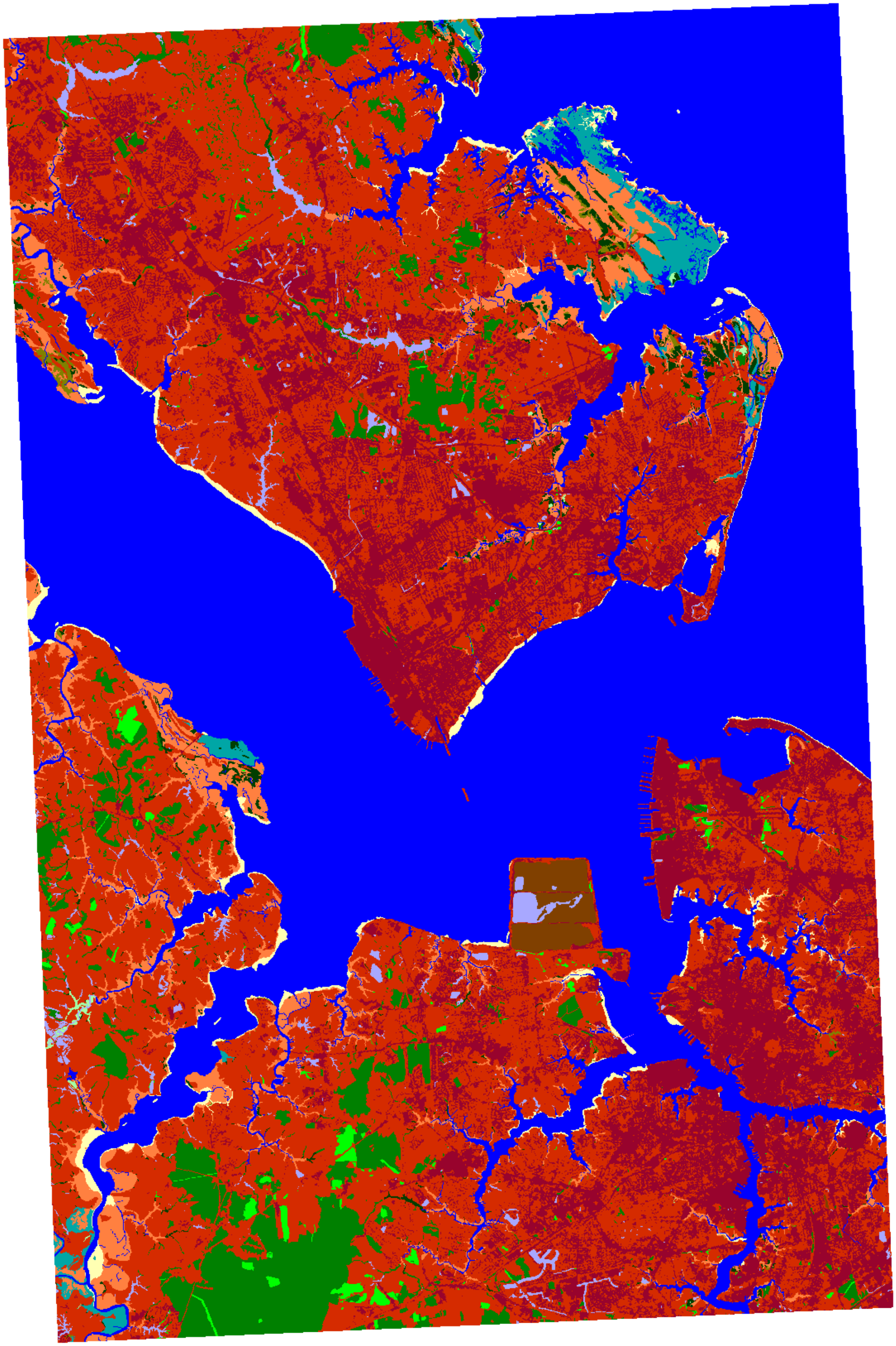
Plum Tree Island NWR, 2050, 1.5 meter



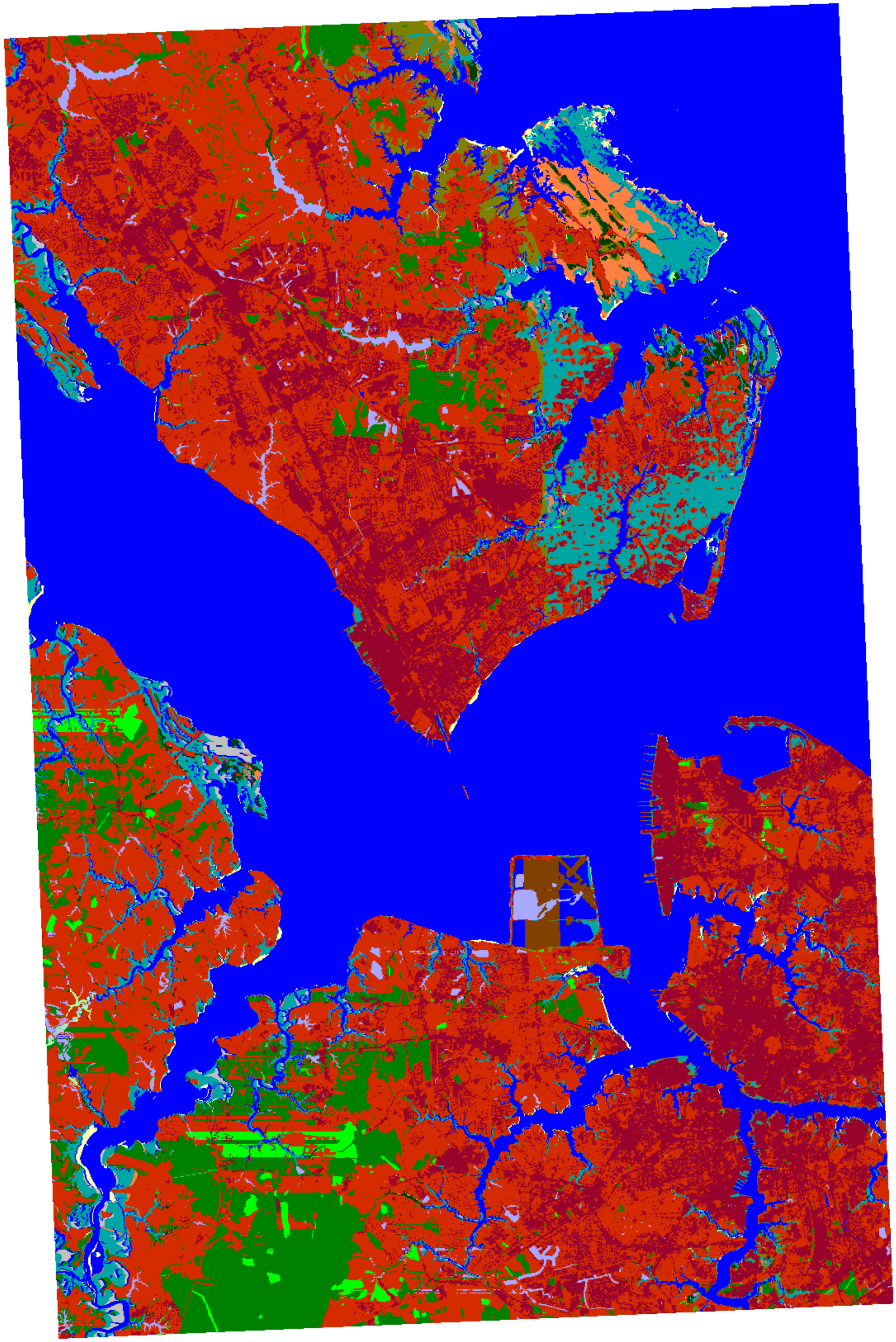
Plum Tree Island NWR, 2075, 1.5 meter



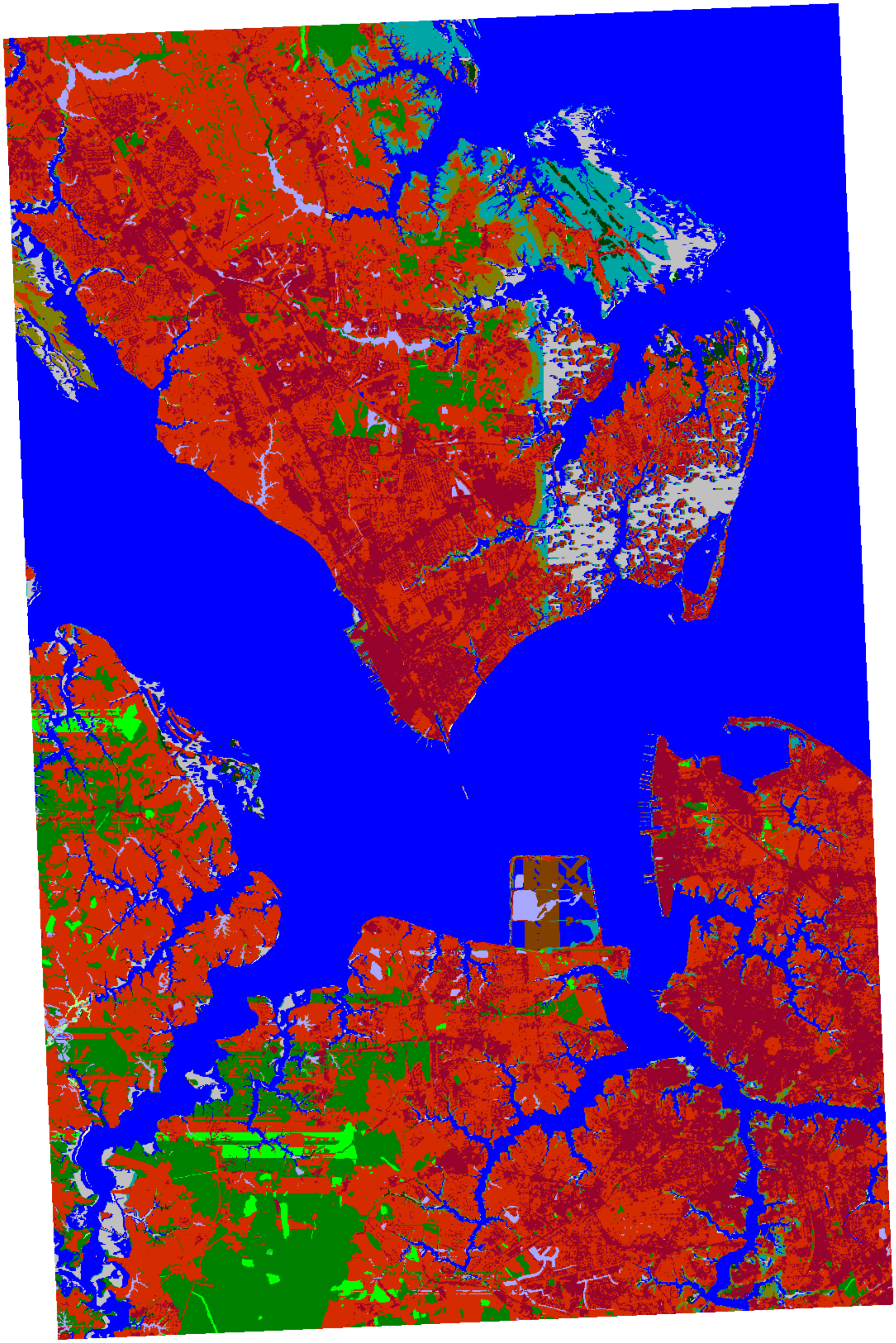
Plum Tree Island NWR, 2100, 1.5 meter



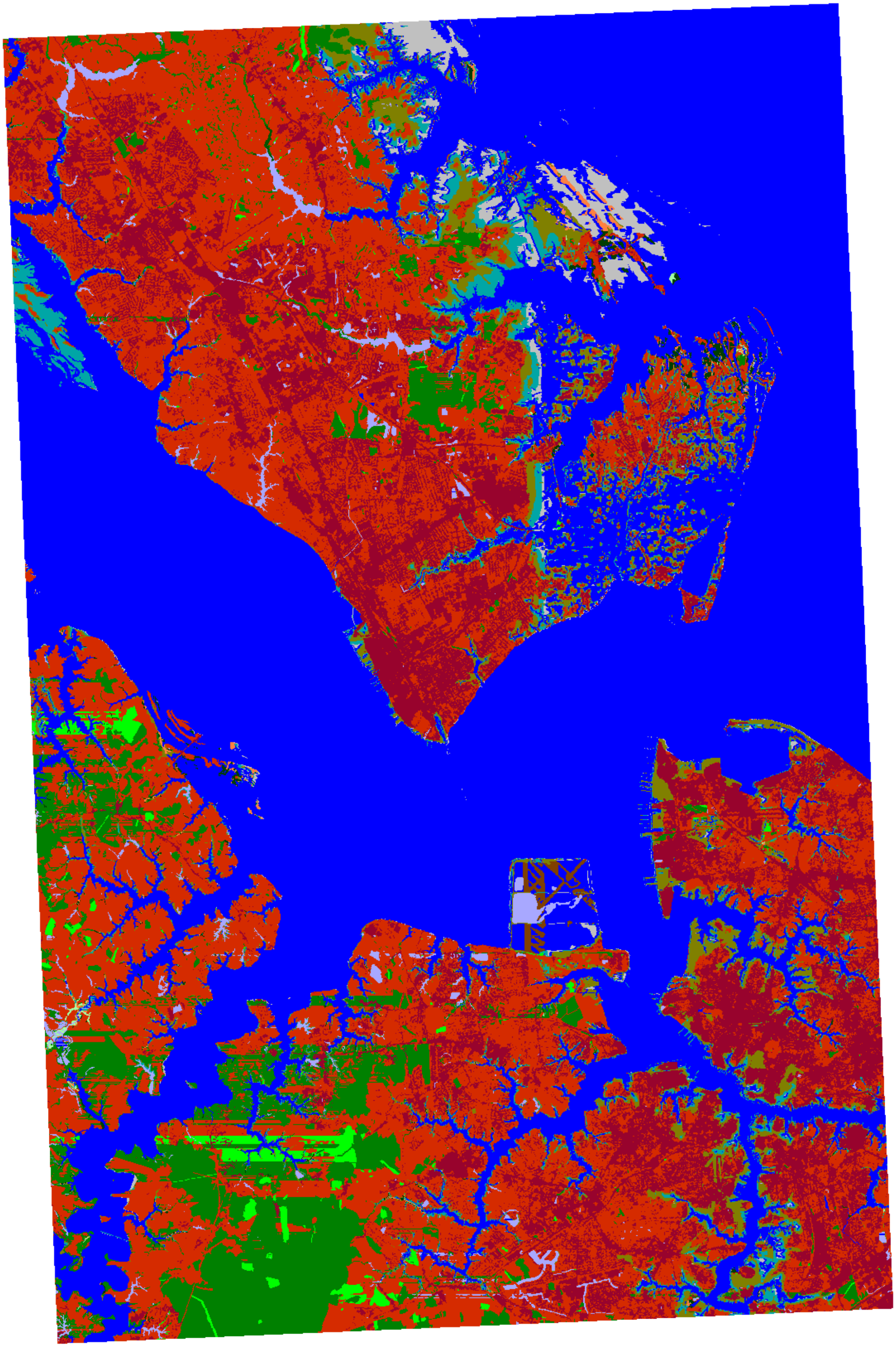
Plum Tree Island NWR, Initial Condition



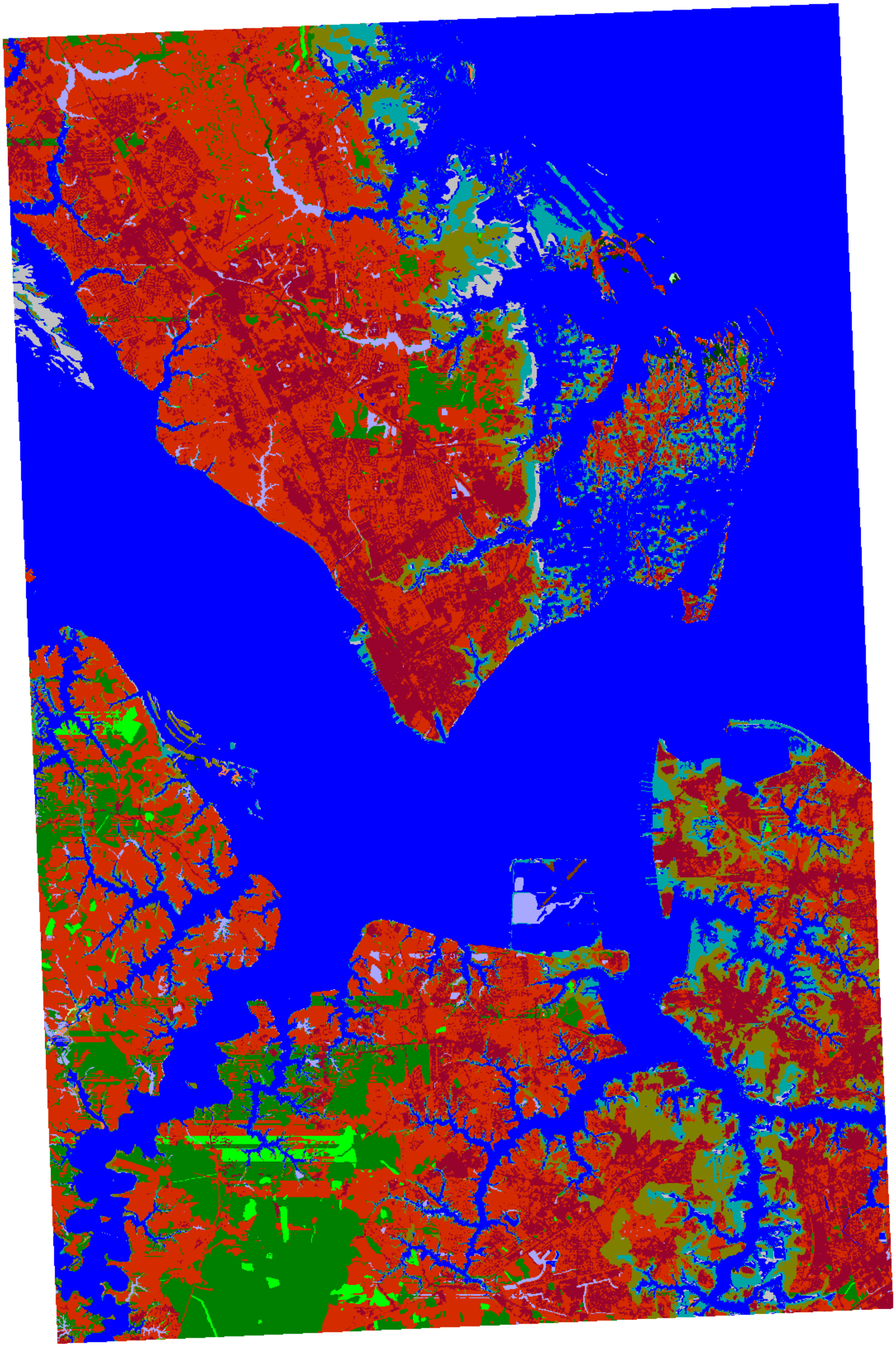
Plum Tree Island NWR, 2025, 2 meter



Plum Tree Island NWR, 2050, 2 meter



Plum Tree Island NWR, 2075, 2 meter



Plum Tree Island NWR, 2100, 2 meter