Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Petit Manan NWR

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) suggested that global sea level will increase by approximately 30 cm to 100 cm by 2100 (IPCC 2001). Rahmstorf (2007) suggests that this range may be too conservative and that the feasible range by 2100 is 50 to 140 cm. Rising sea levels may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat "migration" as salt marshes transgress landward and replace tidal freshwater and Irregularly Flooded marsh (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 1 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 6) that accounts for the dominant processes involved in wetland conversion and shoreline modifications during long-term sea level rise (Park et al. 1989; www.warrenpinnacle.com/prof/SLAMM).

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 specified interval for large storms. Beach migration and transport of sediments are calculated.
- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the fresh water table to rising sea level close to the coast.

- **Accretion:** Sea level rise is offset by sedimentation and vertical accretion using average or site-specific values for each wetland category. Accretion rates may be spatially variable within a given model domain or can be specified to respond to feedbacks such as frequency of flooding.

SLAMM Version 6.0 was developed in 2008/2009 and is based on SLAMM 5. SLAMM 6.0 provides backwards compatibility to SLAMM 5, that is, SLAMM 5 results can be replicated in SLAMM 6. However, SLAMM 6 also provides several optional capabilities.

- Accretion Feedback Component: Feedbacks based on wetland elevation, distance to channel, and salinity may be specified. This feedback will be used in USFWS simulations, but only where adequate data exist for parameterization.
- Salinity Model: Multiple time-variable freshwater flows may be specified. Salinity is estimated and mapped at MLLW, MHHW, and MTL. Habitat switching may be specified as a function of salinity. This optional sub-model is not utilized in USFWS simulations.
- Integrated Elevation Analysis: SLAMM will summarize site-specific categorized elevation ranges for wetlands as derived from LiDAR data or other high-resolution data sets. This functionality is used in USFWS simulations to test the SLAMM conceptual model at each site. The causes of any discrepancies are then tracked down and reported on within the model application report.
- Flexible Elevation Ranges for land categories: If site-specific data indicate that wetland elevation ranges are outside of SLAMM defaults, a different range may be specified within the interface. In USFWS simulations, the use of values outside of SLAMM defaults is rarely utilized. If such a change is made, the change and the reason for it are fully documented within the model application reports.
- Many other graphic user interface and memory management improvements are also part of the new version including an updated *Technical Documentation*, and context sensitive help files.

For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 6.0 *Technical Documentation* (Clough, Park, Fuller, 2010). This document is available at http://warrenpinnacle.com/prof/SLAMM

All model results are subject to uncertainty due to limitations in input data, incomplete knowledge about factors that control the behavior of the system being modeled, and simplifications of the system (CREM 2008). Site-specific factors that increase or decrease model uncertainty may be covered in the *Discussion* section of this report.

Sea Level Rise Scenarios

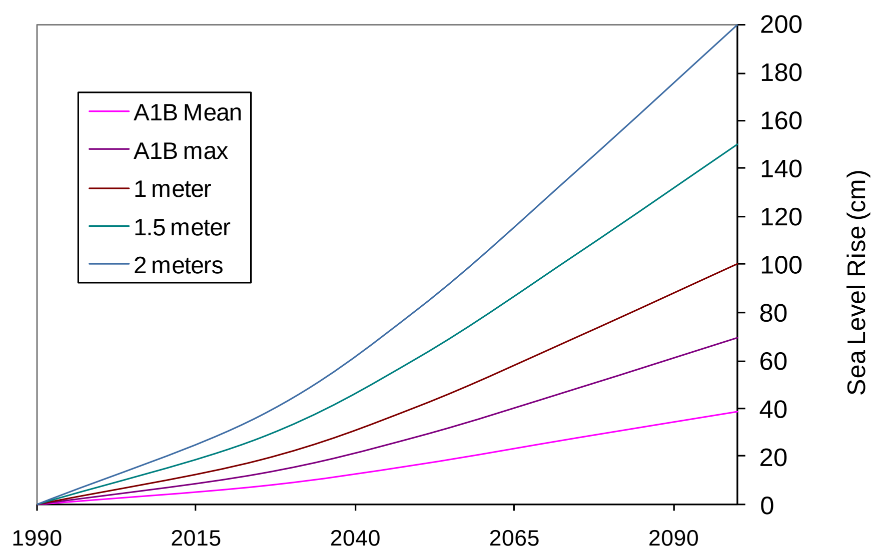
SLAMM 6 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 family of scenarios assumes that the future world includes rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. In particular, the A1B scenario assumes that energy sources will be balanced across all sources. Under the A1B scenario, the IPCC WGI Fourth Assessment Report (IPCC, 2007) suggests a likely range of 0.21 to 0.48 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 0.39

meters of global sea level rise by 2100. IPCC predictions for A1B-maximum are 0.69 meters of global SLR by 2100.

The latest literature (Chen et al., 2006, Monaghan et al., 2006) indicates that the eustatic rise in sea levels is progressing more rapidly than was previously assumed, perhaps due to the dynamic changes in ice flow omitted within the IPCC report's calculations. A recent paper in the journal *Science* (Rahmstorf, 2007) suggests that, taking into account possible model error, a feasible range by 2100 of 50 to 140 cm. This work was recently updated and the ranges were increased to 75 to 190 cm (Vermeer and Rahmstorf, 2009). Pfeffer et al. (2008) suggests that 2 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…" Grinsted also states that there is a "low probability" that SLR will match the lower IPCC estimates.

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 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



Methods and Data Sources

This SLAMM simulation for Petit Manan National Wildlife Refuge was divided into four parts, labeled Section A, Section B, Section C and Section D (Figure 2). The digital elevation maps used sections in A, B and D were derived from NED (National Elevation Dataset) contour data with photo dates ranging from 1943 to 1993. The digital elevation map used in Section C was comprised primarily of LiDAR data as supplied by NED with a timestamp of 2006, along with 2000, 2004, and 2007 NOAA LiDAR data (Figure 3). Sections A through D were divided into multiple subsites for SLAMM simulation, each parameterized and run independently of each other.

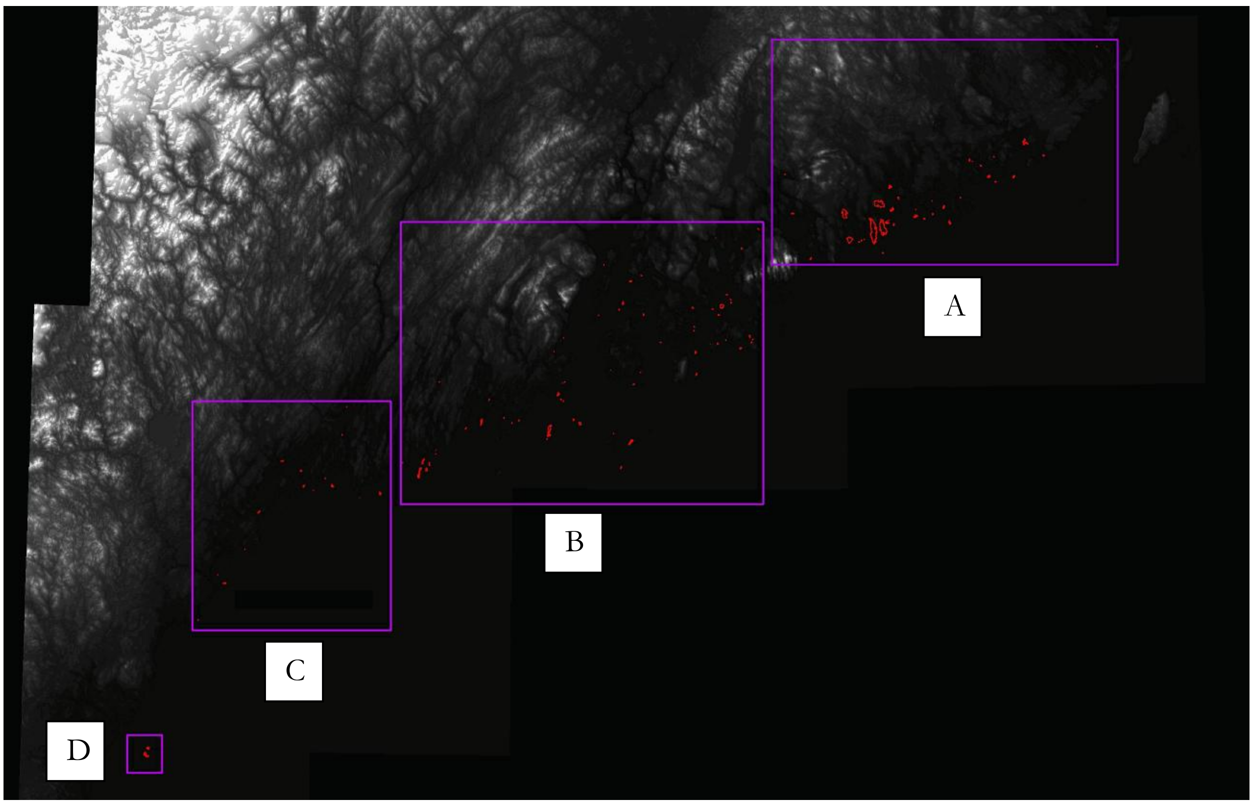


Figure 2: Shade-relief elevation map of refuge (red) divided into sections A through D.

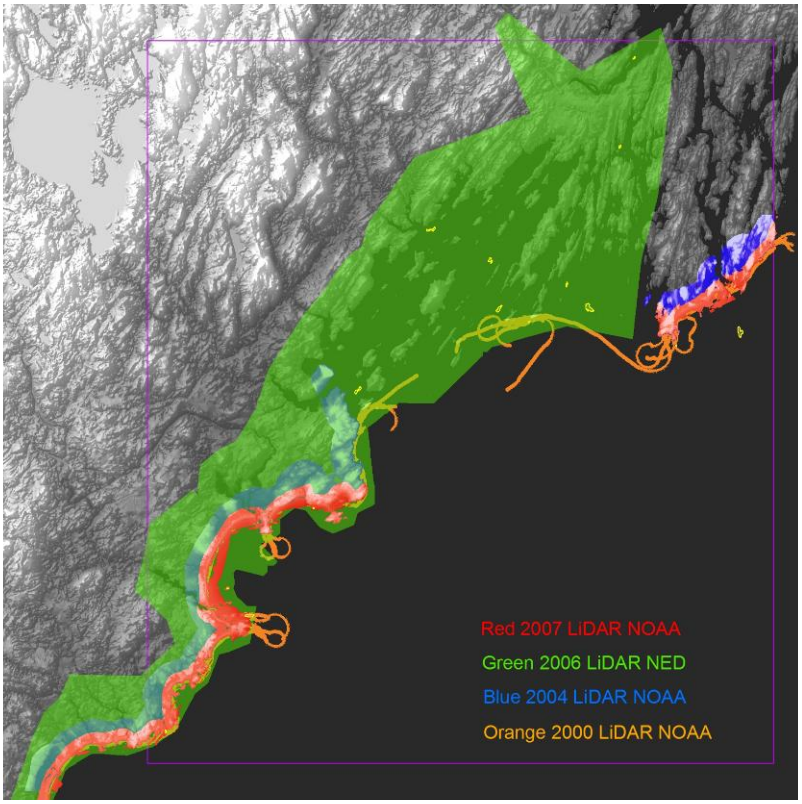


Figure 3: LiDAR coverage and dates for area C

The wetlands layer for the study area was produced by the National Wetlands Inventory and was based on photo dates ranging from 1983 to 2004. Converting the NWI survey into 30 meter cells indicates that the approximately 9,145 acre refuge (approved acquisition boundary including water) is composed of the following categories (see next page):

	Undeveloped Dry Land	65.2%
	Rocky Intertidal	10.8%
	Swamp	10.5%
	Tidal Flat	4.2%
	Open Ocean	1.8%
	Irregularly Flooded Marsh	1.5%
	Estuarine Open Water	1.5%
	Inland Fresh Marsh	0.9%
	Tidal Swamp	0.8%
	Developed Dry Land	0.7%
	Tidal Fresh Marsh	0.6%
	Ocean Flat	0.5%
	Inland Open Water	0.4%
	Ocean Beach	0.4%
	Needle-Leaved Swamp	0.3%
	Regularly Flooded Marsh	0.1%
	Estuarine Beach	0.1%

According to the National Wetland Inventory, there were few diked and impounded areas within the study area.

Table 1: Historic SLR, tide range and elevation correction (MTL-NAVD88) values listed by tide station/tide table and model section.

NOAA Station	Site Name	Model Section where applied	Historic SLR (mm/yr)	Tide Range (GT) (m)	MTL-NAVD88 (m)
8419870	Seavey Island	D	1.76		
8418606	Camp Ellis, Saco River, ME	C		0.942	
8418445	Pine Point, ME	C		2.9	-0.062
8418031	Portland Head Light Station, ME	C		2.943	
8418268	Fore River, Portland, ME	C		3.034	
8417997	Cushing Island, Casco Bay, ME	C		2.988	0.080
8418150	Portland, ME	C	1.82	3.019	-0.105
8417988	Great Diamon Is., Casco Bay, ME	C		3.006	
8418009	Cow Island, Casco Bay, ME	C		3.012	
8417941	Long Island, Casco Bay, ME	C		3.006	
8417881	Great Chebeague Island, ME	C		3.02	
8418015	Falmouth Foreside, ME	C		3.027	
8417948	Prince Point, Yarmouth, ME	C		3.031	
8416731	Walpole, Damariscotta River, ME	B		3.094	
8415709	Thomaston, ME	B		3	0.140
8415490	Rockland, ME	B		3.223	
8414888	Pulpit Harbor, Penobscot Bay, ME	B		3.245	
8415191	Belfast, Penobscot Bay, ME	B		3.362	-0.097
8414721	Fort Point, ME	B		3.397	
8413320	Bar Harbor, ME	A	2.04 (applied to Section B)	3.466	-0.095
8412581	Milbridge, ME	A		3.694	-0.068
8411250	Cutler Naval Base, ME	A		4.132	
	Isles of Shoals (tide table)	D		2.7	
8410140	Eastport, ME	A	2	5.874	-0.096
8410715	Garnet Point	A		6.142	

The historic trend for sea-level rise varies from across the four sections of the study area. In Section A, the historic sea level trend is 2 mm/year, the historic sea level trend in Section B is 2.04 mm/year, and the values for Section C and D are 1.82 mm/year and 1.76 mm/year, respectively. The rate of sea level rise for this refuge has been roughly equal to the global average for the last 100 years (approximately 1.7 mm/year, IPCC 2007a).

A number of tide gages were used to determine tide range for this SLAMM application (see Table 1). These values range from roughly 1 meter to more than 6 meters (see Figure 1).

The MTL to NAVD88 correction was derived using the NOAA gages. The correction values varied by study Section (Table 1) and by Section input sites (see Summary of SLAMM Input Parameters).

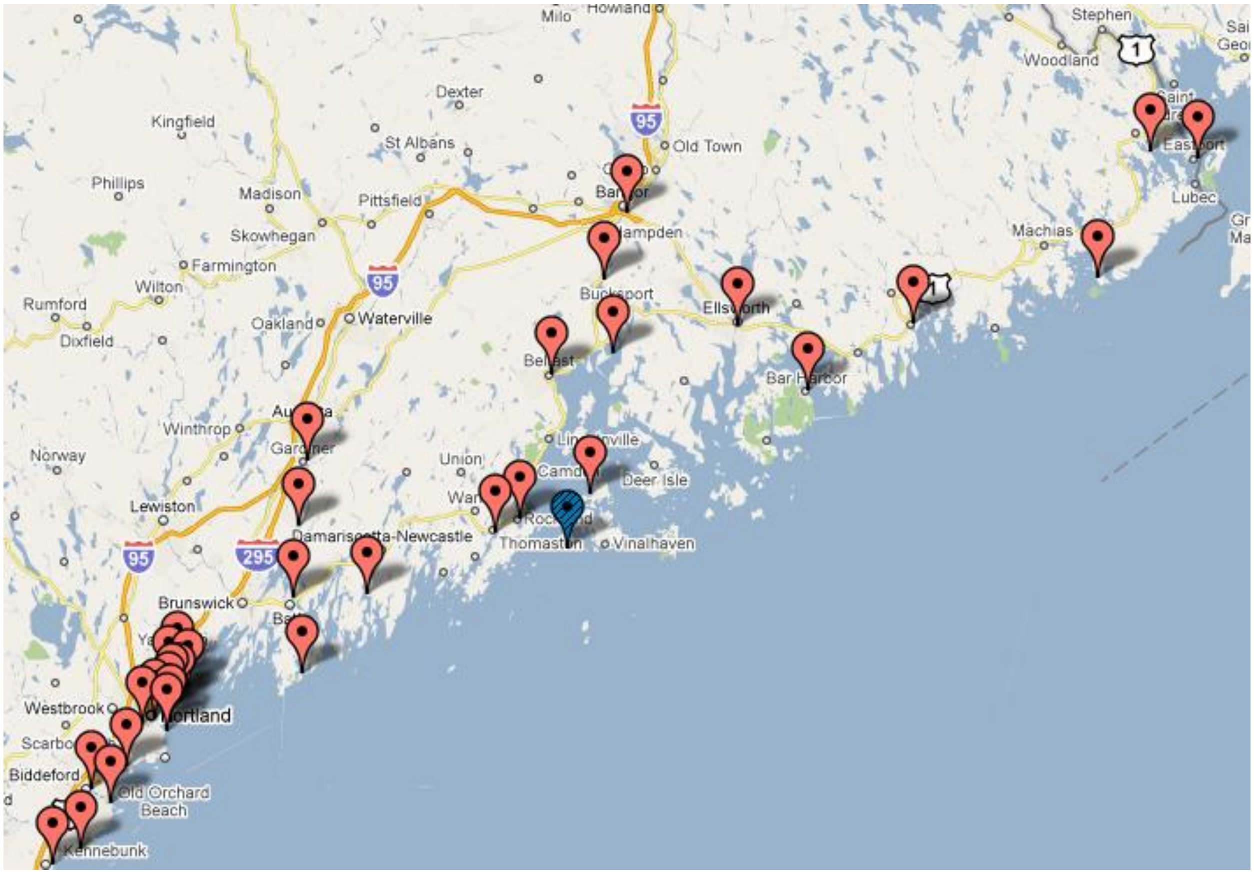


Figure 4: Location of NOAA tides gages used for Petit Manan NWR study area.

Martha Nielsen, a hydrologist for the USGS in Augusta, Maine, indicated the existence of an accretion study performed in Maine by Goodman. Goodman and coworkers measured accretion for 17years (1986 - 2003) along the coast of Maine (Figure 5) and observed rates ranging from 1.40 mm/year to 4.24 m/year. Accretion values for regularly flooded and irregularly flooded marshes were set to 2.7 mm/year based on the average of the most geographically relevant sites observed by Goodman et al. in their 2007 study (sites labeled SN, SC, LC, and HC in Figure 5) . Tidal fresh marsh accretion values were set to 5.9 mm/year based on a study of the Chesapeake Bay, Maryland (these habitats make up only 0.6% of the study area).

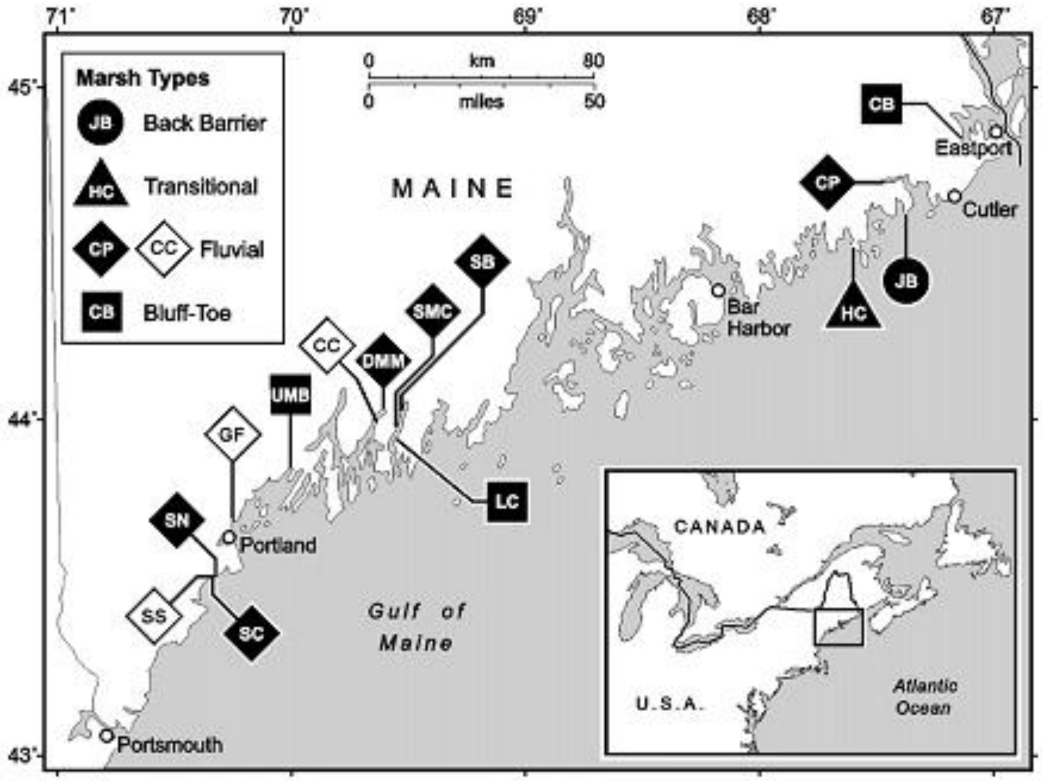


Figure 5: Location of accretion study (Goodman et al., 2007)

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

SUMMARY OF SLAMM INPUT PARAMETERS FOR PETIT MANAN NWR

Section A

Parameter	Global	SubSite 1	SubSite 2
Description		Spectacle Isl	Libby Isl
NWI Photo Date (YYYY)	2003	1983	2003
DEM Date (YYYY)	1945	1946	1993
Direction Offshore [n,s,e,w]	South	West	South
Historic Trend (mm/yr)	2	2	2
MTL-NAVD88 (m)	-0.0955	-0.0955	-0.0955
GT Great Diurnal Tide Range (m)	3.764	6.142	4.133
Salt Elev. (m above MTL)	2.5	4.08	2.75
Marsh Erosion (horz. m /yr)	1.8	1.8	1.8
Swamp Erosion (horz. m /yr)	1	1	1
T.Flat Erosion (horz. m /yr)	0.5	0.5	0.5
Reg. Flood Marsh Accr (mm/yr)	2.7	2.7	2.7
Irreg. Flood Marsh Accr (mm/yr)	2.7	2.7	2.7
Tidal Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5
Freq. Overwash (years)	12	12	12
Use Elev Pre-processor [True,False]	TRUE	TRUE	TRUE

Section A (continued)

Parameter	SubSite 3	SubSite 4	SubSite 5
Description	Petit Manan	Lobster Isl	Bean and Egg Isl.
NWI Photo Date (YYYY)	1983	2003	2003
DEM Date (YYYY)	1944	1976	1976
Direction Offshore [n,s,e,w]	East	South	South
Historic Trend (mm/yr)	2	2	2
MTL-NAVD88 (m)	-0.0955	-0.068	-0.0955
GT Great Diurnal Tide Range (m)	3.465	3.694	3.465
Salt Elev. (m above MTL)	2.3	2.46	2.3
Marsh Erosion (horz. m /yr)	1.8	1.8	1.8
Swamp Erosion (horz. m /yr)	1	1	1
T.Flat Erosion (horz. m /yr)	0.5	0.5	0.5
Reg. Flood Marsh Accr (mm/yr)	2.7	2.7	2.7
Irreg. Flood Marsh Accr (mm/yr)	2.7	2.7	2.7
Tidal Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5
Freq. Overwash (years)	12	12	12
Use Elev Pre-processor [True,False]	TRUE	TRUE	TRUE

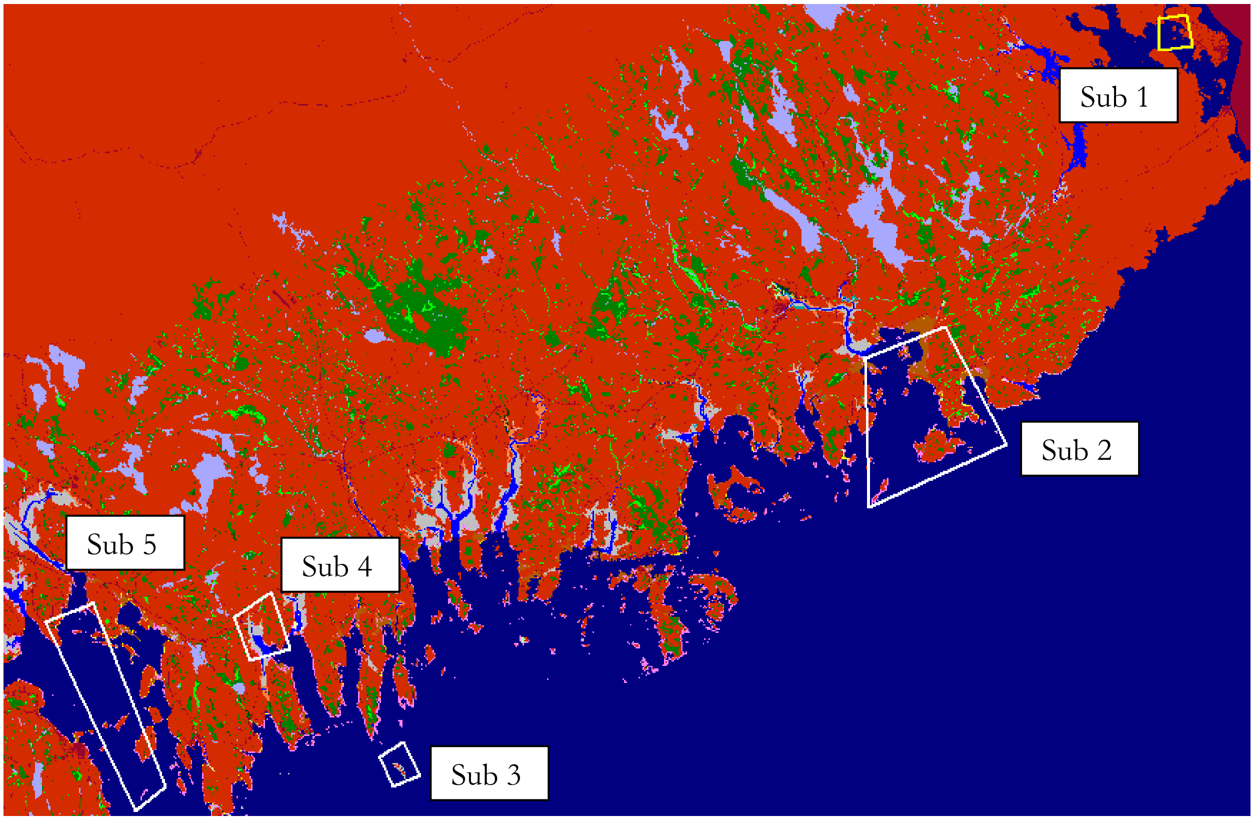


Figure 6: **Input subsites in Section A for model application.**

Section B

Parameter	Global	SubSite 1	SubSite 2	SubSite 3	SubSite 4
Description		Deer Island	2 Bush Island	Matinicus Island	Boothbay
NWI Photo Date (YYYY)	2004	2003	1983	1983	2004
DEM Date (YYYY)	1954	1973	1973	1952	1967
Direction Offshore [n,s,e,w]	East	East	East	East	East
Historic Trend (mm/yr)	2.04	2.04	2.04	2.04	2.04
MTL-NAVD88 (m)	0.14	-0.097	0.14	0.14	0.14
GT Great Diurnal Tide Range (m)	3.1	3.3	3.22	3.22	3
Salt Elev. (m above MTL)	2.07	2.21	2.14	2.14	2.05
Marsh Erosion (horz. m /yr)	1.8	1.8	1.8	1.8	1.8
Swamp Erosion (horz. m /yr)	1	1	1	1	1
T.Flat Erosion (horz. m /yr)	0.5	0.5	0.5	0.5	0.5
Reg. Flood Marsh Accr (mm/yr)	2.7	2.7	2.7	2.7	2.7
Irreg. Flood Marsh Accr (mm/yr)	2.7	2.7	2.7	2.7	2.7
Tidal Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9	5.9	5.9
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5	0.5	0.5
Freq. Overwash (years)	12	12	12	12	12
Use Elev Pre-processor [True,False]	TRUE	TRUE	TRUE	TRUE	TRUE

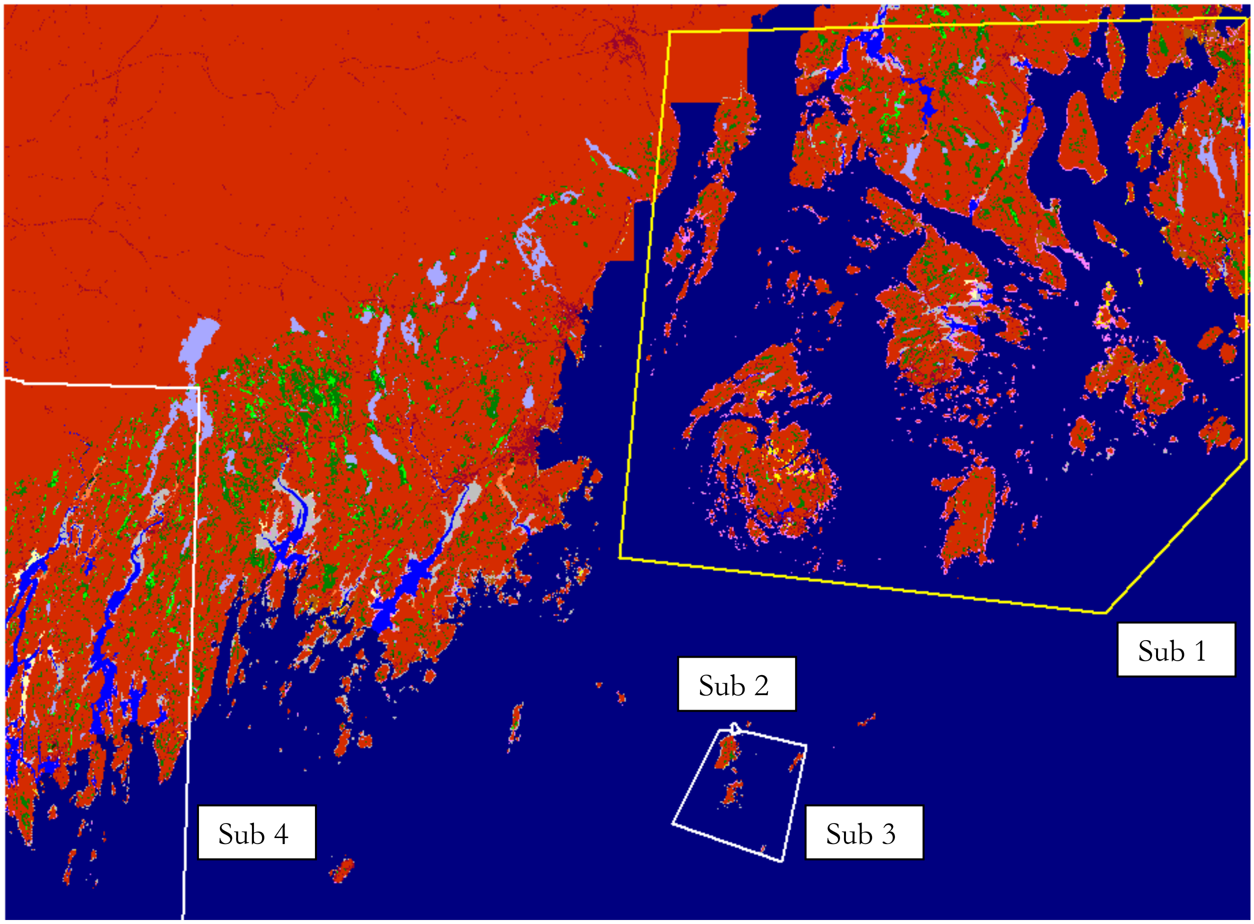


Figure 7: **Input subsites in Section B for model application.**

Section C

Parameter	Global
Description	
NWI Photo Date (YYYY)	2004
DEM Date (YYYY)	2006
Direction Offshore [n,s,e,w]	East
Historic Trend (mm/yr)	1.82
MTL-NAVD88 (m)	-0.105
GT Great Diurnal Tide Range (m)	3
Salt Elev. (m above MTL)	2
Marsh Erosion (horz. m /yr)	1.8
Swamp Erosion (horz. m /yr)	1
T.Flat Erosion (horz. m /yr)	0.5
Reg. Flood Marsh Accr (mm/yr)	2.7
Irreg. Flood Marsh Accr (mm/yr)	2.7
Tidal Fresh Marsh Accr (mm/yr)	5.9
Beach Sed. Rate (mm/yr)	0.5
Freq. Overwash (years)	12
Use Elev Pre-processor [True,False]	FALSE

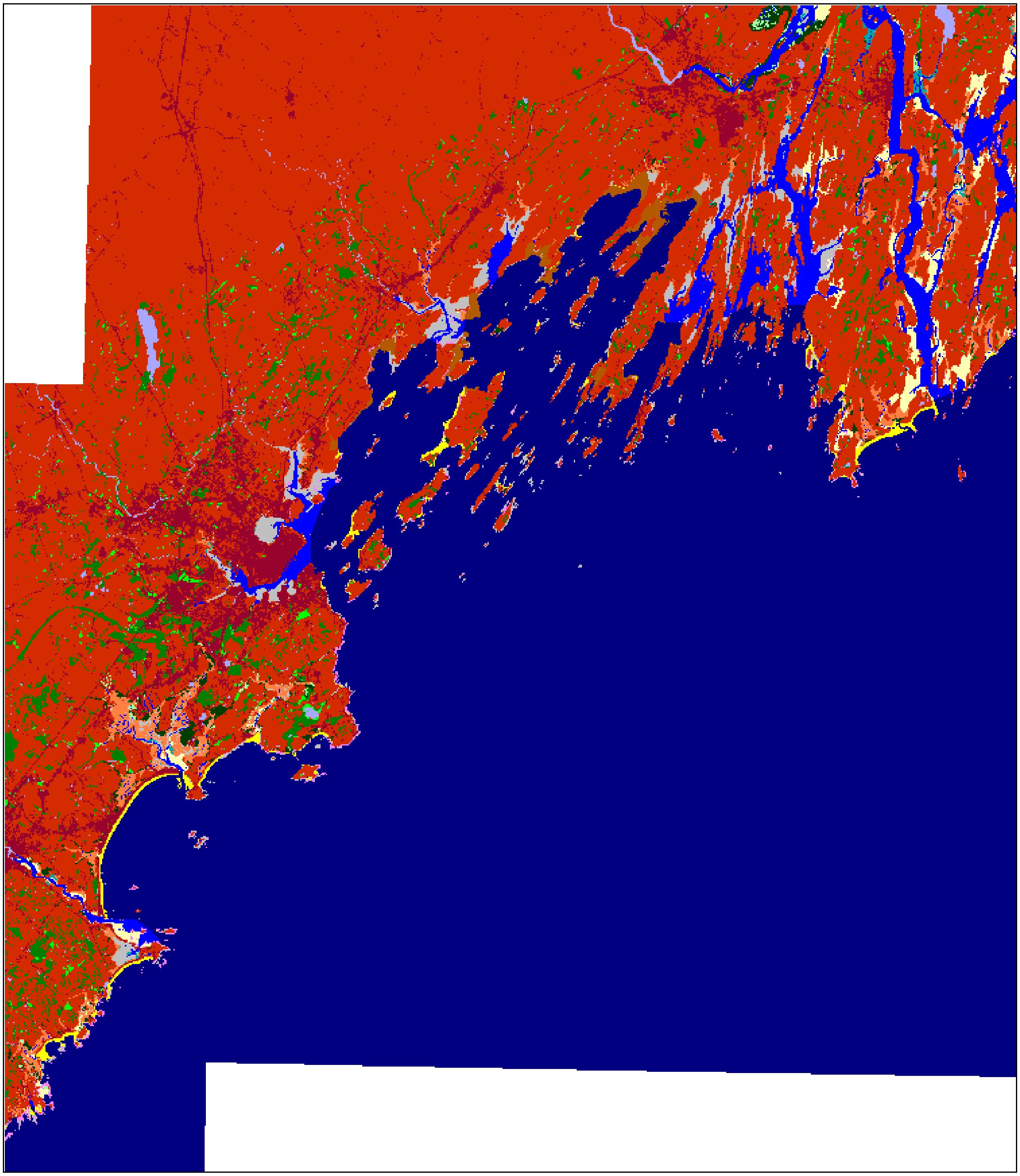


Figure 8: **Section C of study area.**

Section D

Parameter	Global	SubSite 1
Description		SubSite 1
NWI Photo Date (YYYY)	2004	1985
DEM Date (YYYY)	1943	1943
Direction Offshore [n,s,e,w]	East	East
Historic Trend (mm/yr)	1.76	1.76
MTL-NAVD88 (m)	-0.1	-0.1
GT Great Diurnal Tide Range (m)	2.7	2.7
Salt Elev. (m above MTL)	1.8	1.8
Marsh Erosion (horz. m /yr)	1.8	1.8
Swamp Erosion (horz. m /yr)	1	1
T.Flat Erosion (horz. m /yr)	0.5	0.5
Reg. Flood Marsh Accr (mm/yr)	2.7	2.7
Irreg. Flood Marsh Accr (mm/yr)	2.7	2.7
Tidal Fresh Marsh Accr (mm/yr)	5.9	5.9
Beach Sed. Rate (mm/yr)	0.5	0.5
Freq. Overwash (years)	12	12
Use Elev Pre-processor [True,False]	TRUE	TRUE

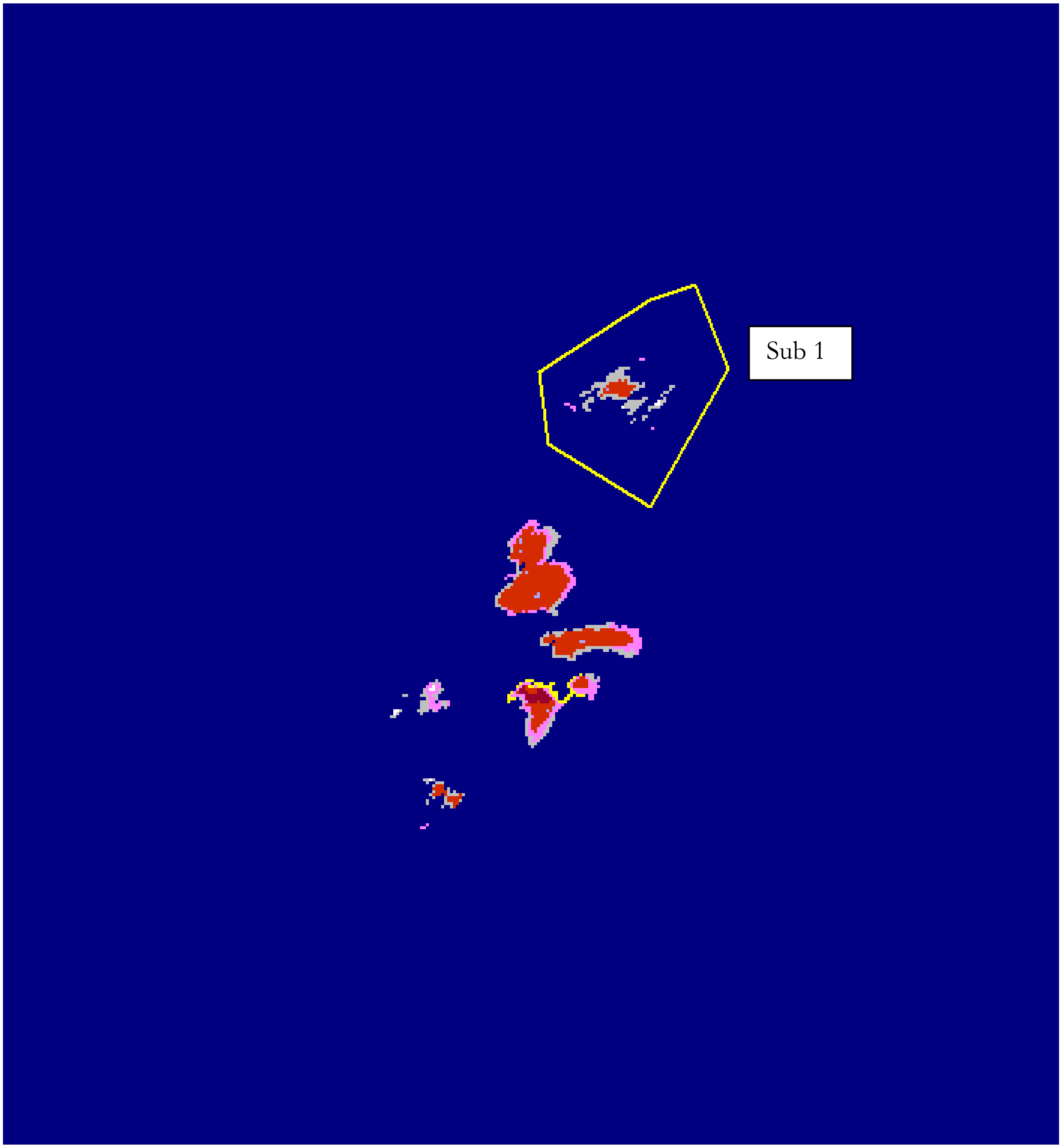


Figure 9: Input subsite for Isles of Shoals (Section D) portion of study area.

Results

SLAMM predicts that Petit Manan NWR will be moderately susceptible to inundation from sea level rise (SLR). The losses of the dominant land cover types (undeveloped dry land, rocky intertidal, swamp, and tidal flat) appeared to be proportional to SLR. For example, 8% of undeveloped dry land was lost in the 0.39 meter SLR scenario, while 16% was lost under the 2 meter scenario. Losses in rocky intertidal zones, which make up nearly 11% of the total study area, ranged from 9 to 57% and also increased with increasing sea level rise. Conversely, irregularly-flooded marsh habitat was predicted to increase in all scenarios below 2 meters SLR (represented by negative loss values).

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Undeveloped Dry Land	8%	11%	13%	15%	16%
Rocky Intertidal	9%	17%	27%	43%	57%
Swamp	6%	12%	14%	16%	18%
Tidal Flat	35%	52%	66%	81%	77%
Irregularly Flooded Marsh	-21%	-34%	-31%	-9%	19%

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

Due to the geographically dispersed nature of the study area, and the small size of the islands within the refuge, showing maps of output that exclusively contain refuge boundaries is impractical. Attempting to do this resulted in maps spread across the page with each relevant island comprising a pixel or less. Interpreting results from these maps was not possible.

Therefore, this *Results* section includes representative maps for portions of the Petit Manan NWR area. The full set of contextual results for sites A through D (Figure 2) may also be found starting on page 79 of this document.

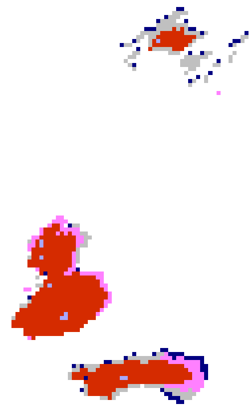
Maps of SLAMM input and output to follow will use the following legend:

Undeveloped Dry Land	
Inland Fresh Marsh	
Estuarine Open Water	
Regularly Flooded Marsh	
Open Ocean	
Irregularly Flooded Marsh	
Estuarine Beach	
Swamp	
Inland Open Water	
Ocean Beach	
Tidal Flat	
Developed Dry Land	
Inland Shore	
Mangrove	
Tidal Fresh Marsh	
Transitional Salt Marsh	

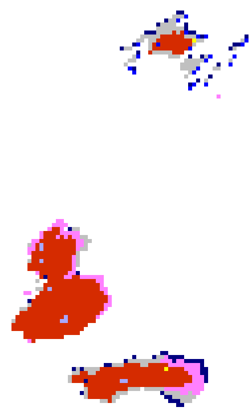
Petit Manan NWR
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

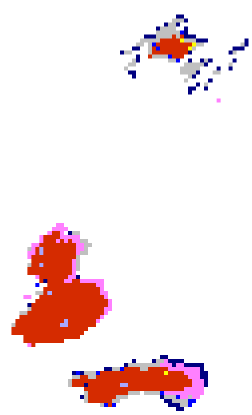
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	5959.4	5870.2	5774.6	5636.1	5505.0
	Rocky Intertidal	983.2	972.8	951.7	924.6	895.2
	Swamp	958.7	985.0	967.5	933.2	898.4
	Tidal Flat	386.9	363.4	330.7	291.7	249.7
	Open Ocean	160.6	177.2	211.3	257.3	309.7
	Irregularly Flooded Marsh	140.9	143.9	151.2	161.4	170.8
	Estuarine Open Water	133.4	157.4	186.6	219.7	253.0
	Inland Fresh Marsh	80.5	80.5	80.5	80.5	80.5
	Tidal Swamp	75.8	72.8	64.2	50.7	37.6
	Developed Dry Land	59.6	59.1	59.1	59.1	59.0
	Tidal Fresh Marsh	51.4	51.4	51.4	51.4	51.4
	Ocean Flat	41.6	40.6	38.5	36.2	33.4
	Inland Open Water	37.8	36.3	34.9	34.7	34.7
	Ocean Beach	34.2	64.0	121.5	203.5	272.2
	Needle-Leaved Swamp	23.8	23.8	23.8	23.8	23.8
	Regularly Flooded Marsh	9.3	9.4	14.4	16.6	20.3
	Estuarine Beach	6.9	15.3	23.2	36.5	52.0
	Riverine Tidal	0.3	0.3	0.1	0.1	0.1
	Transitional Salt Marsh	0.0	21.3	59.3	127.4	197.7
	Total (incl. water)	**9144.6**	**9144.6**	**9144.6**	**9144.6**	**9144.6**



Petit Manan NWR Section D (Isles of Shoals), Initial Condition

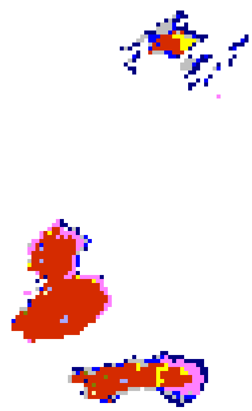


Petit Manan NWR Section D (Isles of Shoals), 2025, Scenario A1B Mean

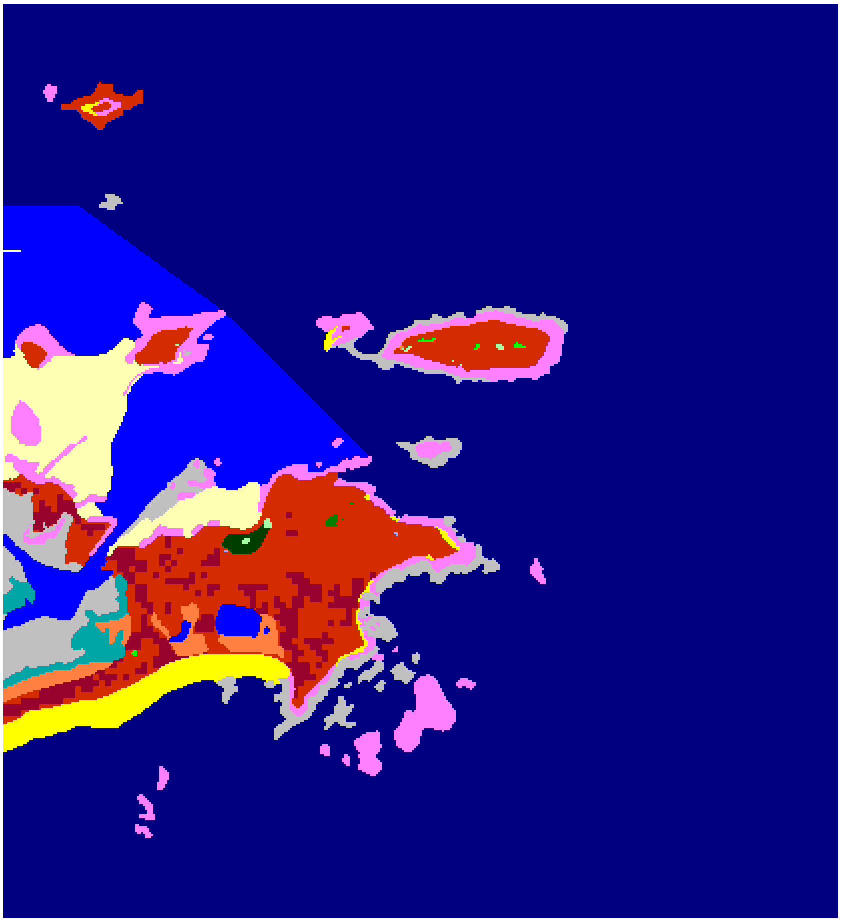


Petit Manan NWR Section D (Isles of Shoals), 2050, Scenario A1B Mean

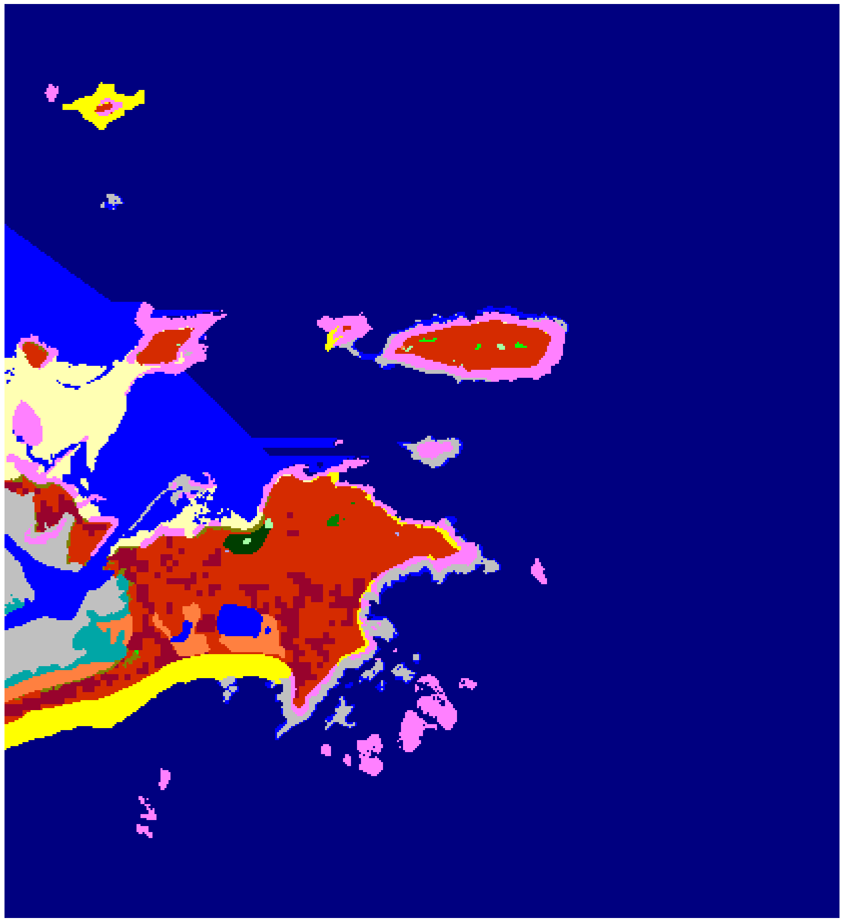
Petit Manan NWR Section D (Isles of Shoals), 2075, Scenario A1B Mean



Petit Manan NWR Section D (Isles of Shoals), 2100, Scenario A1B Mean



Petit Manan NWR Section C (Biddeford Pools), Initial Condition



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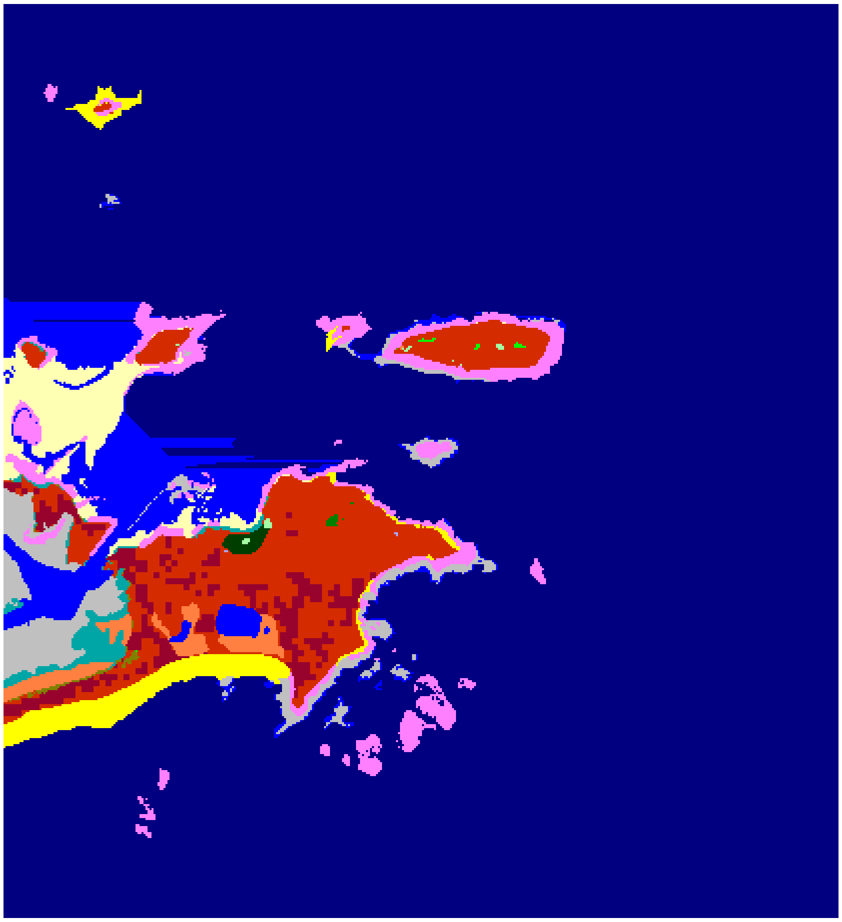
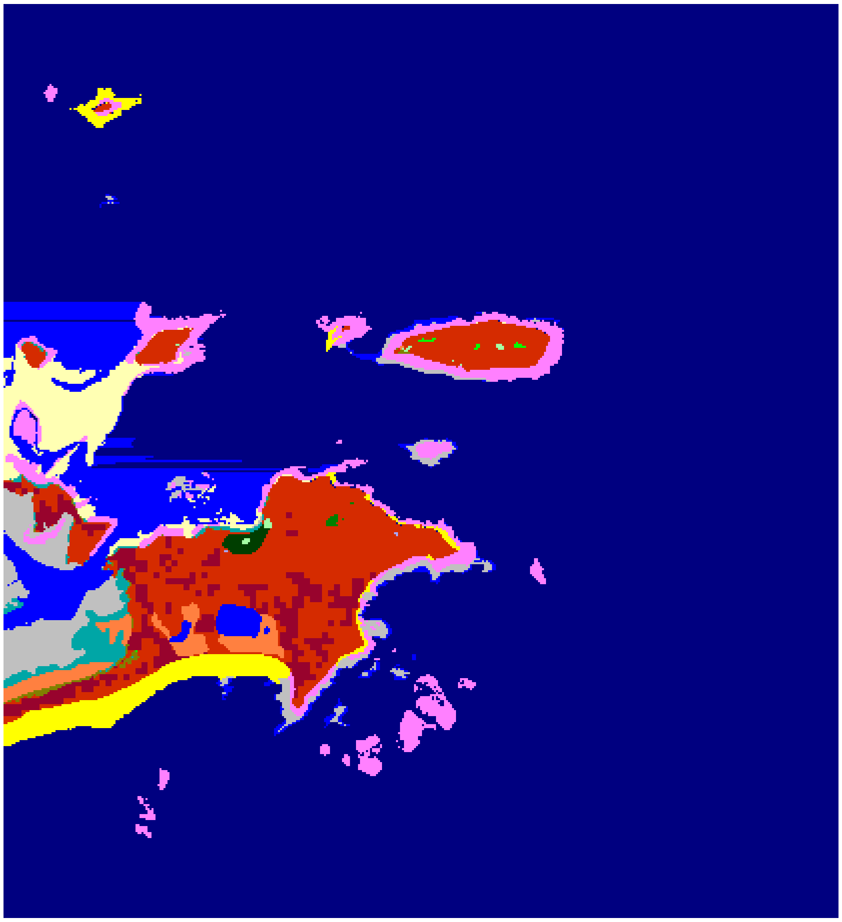


Petit Manan NWR Section C (Biddeford Pools), 2050, Scenario A1B Mean



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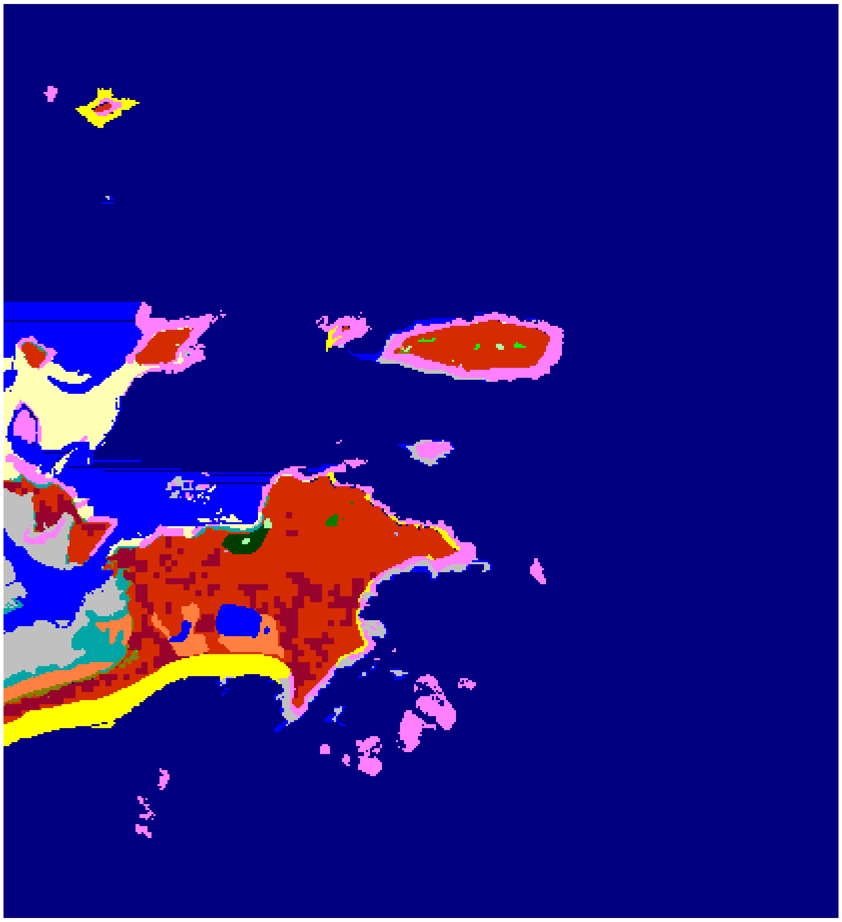
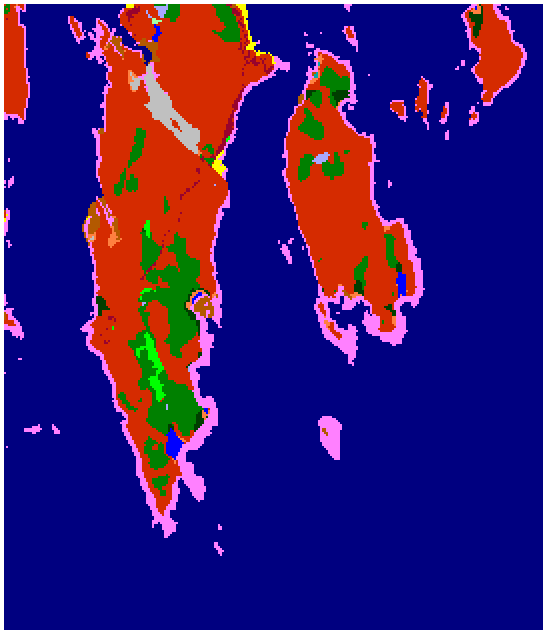
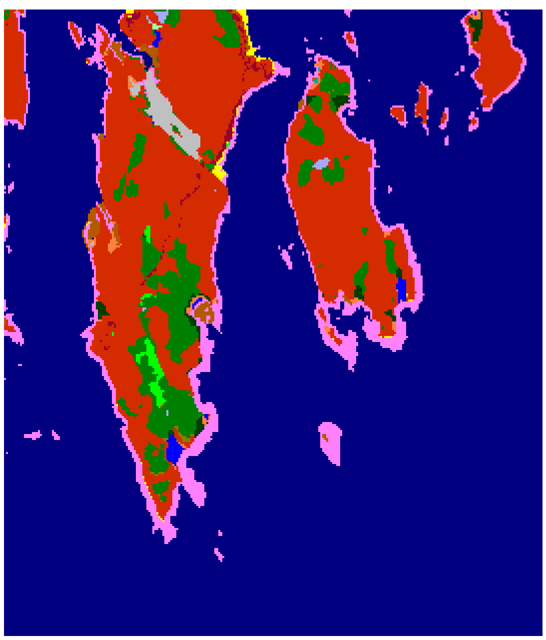


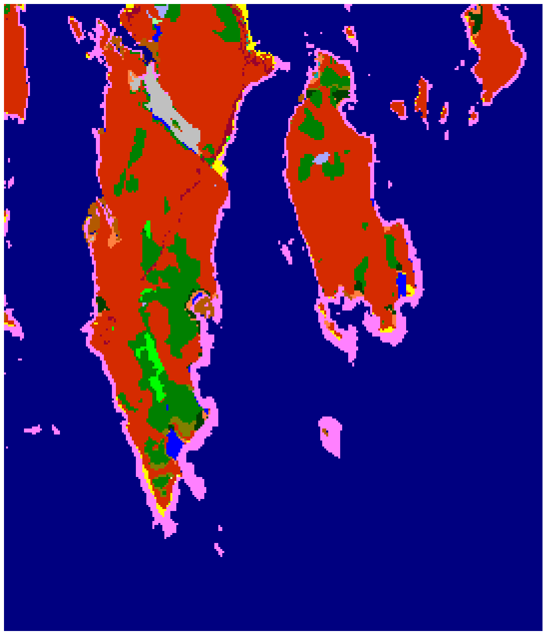
Petit Manan NWR Section C (Biddeford Pools), 2100, Scenario A1B Mean



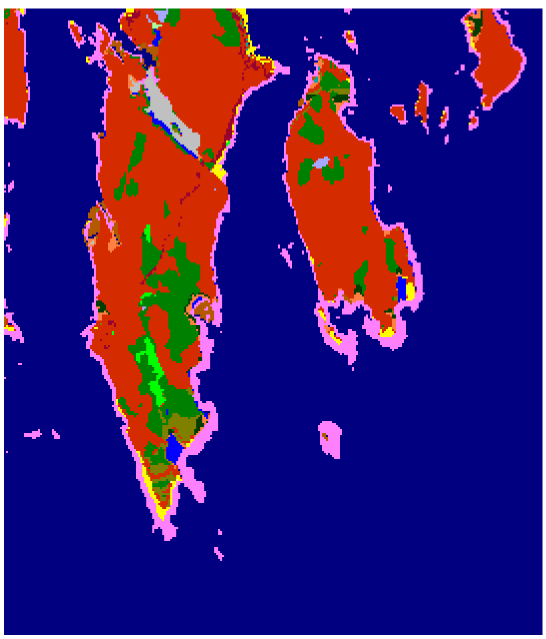
Petit Manan NWR Section A (Abbott/Bois Bubert Islands), Initial Condition



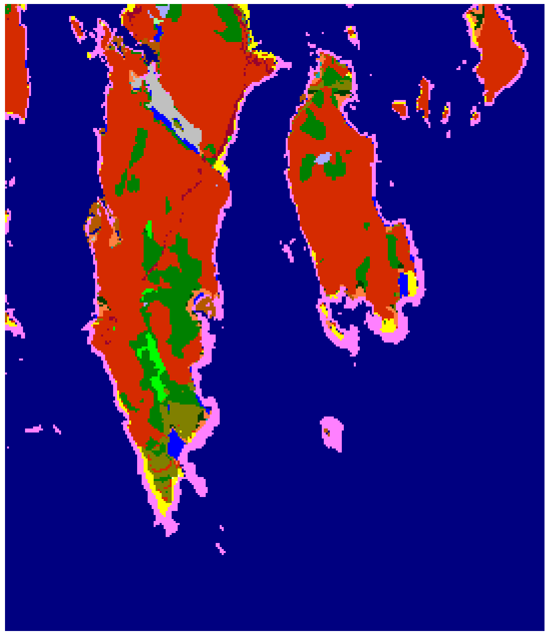
Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2025, Scenario A1B Mean



Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2050, Scenario A1B Mean



Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2075, Scenario A1B Mean

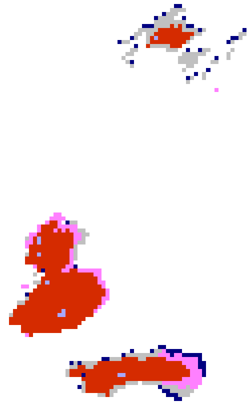


Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2100, Scenario A1B Mean

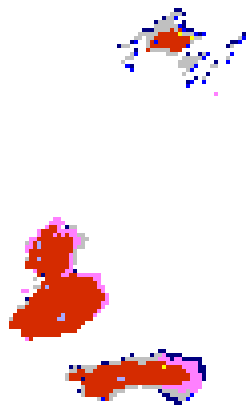
Petit Manan NWR
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

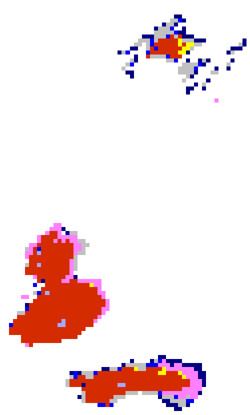
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	5959.4	5844.5	5662.5	5433.7	5287.3
	Rocky Intertidal	983.2	966.3	929.7	875.8	814.4
	Swamp	958.7	976.5	936.7	874.9	842.4
	Tidal Flat	386.9	356.1	305.6	244.6	184.7
	Open Ocean	160.6	185.2	246.2	334.4	439.0
	Irregularly Flooded Marsh	140.9	146.1	158.9	175.3	189.3
	Estuarine Open Water	133.4	166.4	216.6	275.0	329.6
	Inland Fresh Marsh	80.5	80.5	80.5	80.2	78.6
	Tidal Swamp	75.8	69.2	49.8	24.8	3.5
	Developed Dry Land	59.6	59.1	59.1	59.0	59.0
	Tidal Fresh Marsh	51.4	51.4	51.4	48.7	41.1
	Ocean Flat	41.6	39.8	36.5	31.1	26.0
	Inland Open Water	37.8	36.3	34.7	34.7	34.7
	Ocean Beach	34.2	79.8	176.8	281.0	328.1
	Needle-Leaved Swamp	23.8	23.8	23.8	23.8	23.8
	Regularly Flooded Marsh	9.3	10.7	21.2	31.3	46.0
	Estuarine Beach	6.9	18.3	38.0	71.9	106.5
	Riverine Tidal	0.3	0.3	0.1	0.1	0.1
	Transitional Salt Marsh	0.0	34.3	116.5	244.3	310.6
	Total (incl. water)	**9144.6**	**9144.6**	**9144.6**	**9144.6**	**9144.6**



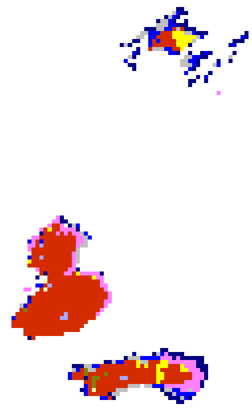
Petit Manan NWR Section D (Isles of Shoals), Initial Condition



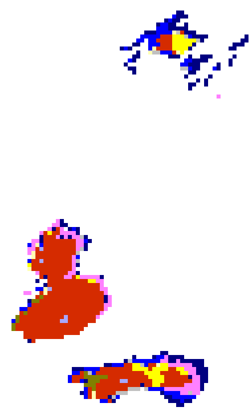
Petit Manan NWR Section D (Isles of Shoals), 2025, Scenario A1B Maximum



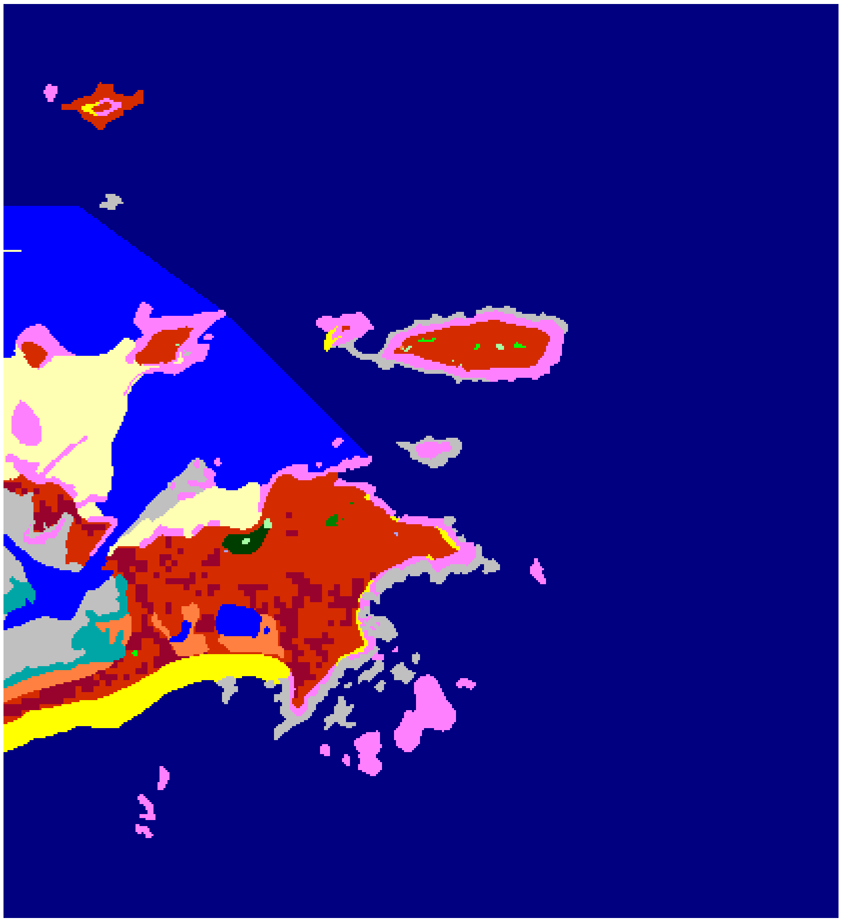
Petit Manan NWR Section D (Isles of Shoals), 2050, Scenario A1B Maximum



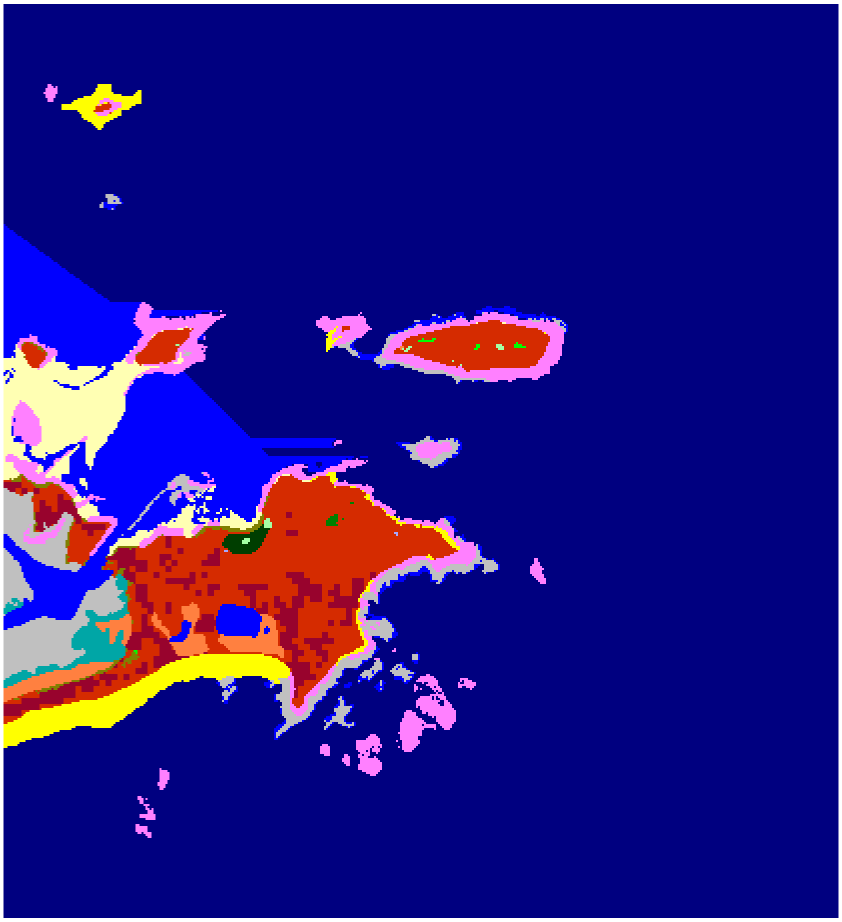
Petit Manan NWR Section D (Isles of Shoals), 2075, Scenario A1B Maximum



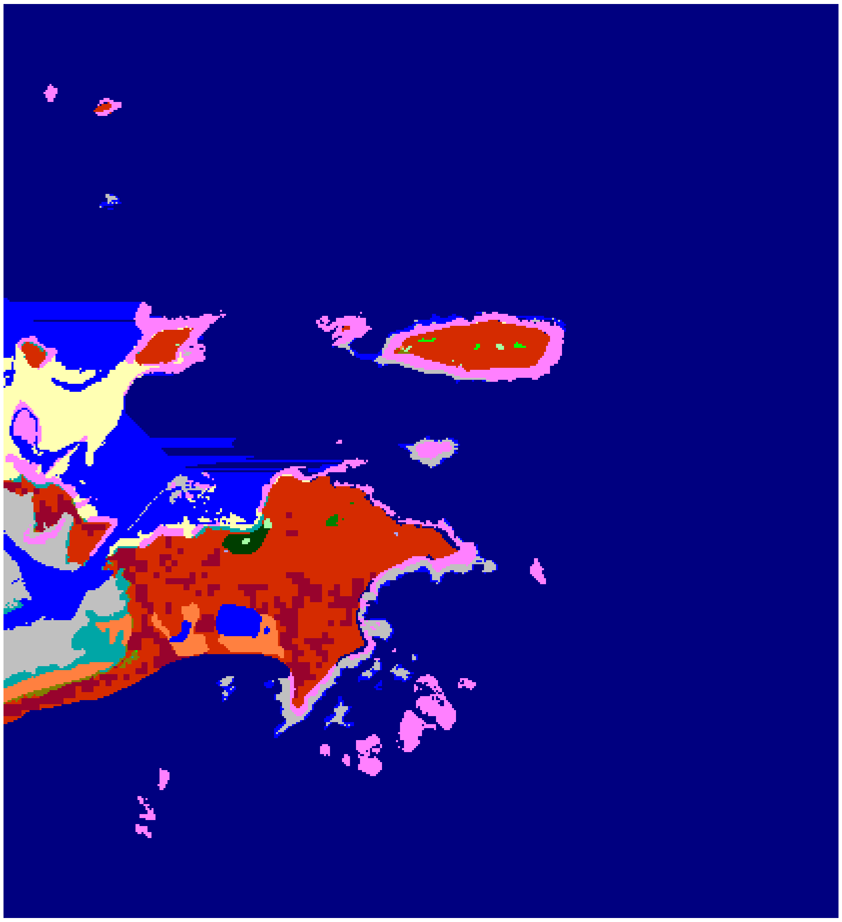
Petit Manan NWR Section D (Isles of Shoals), 2100, Scenario A1B Maximum



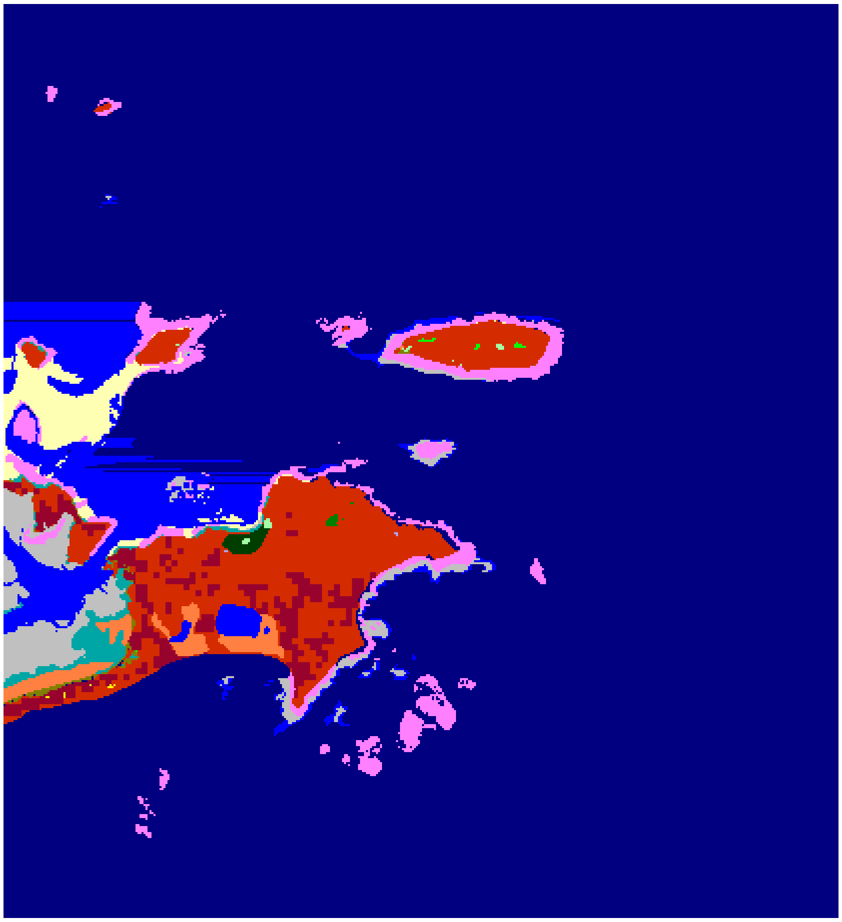
Petit Manan NWR Section C (Biddeford Pools), Initial Condition



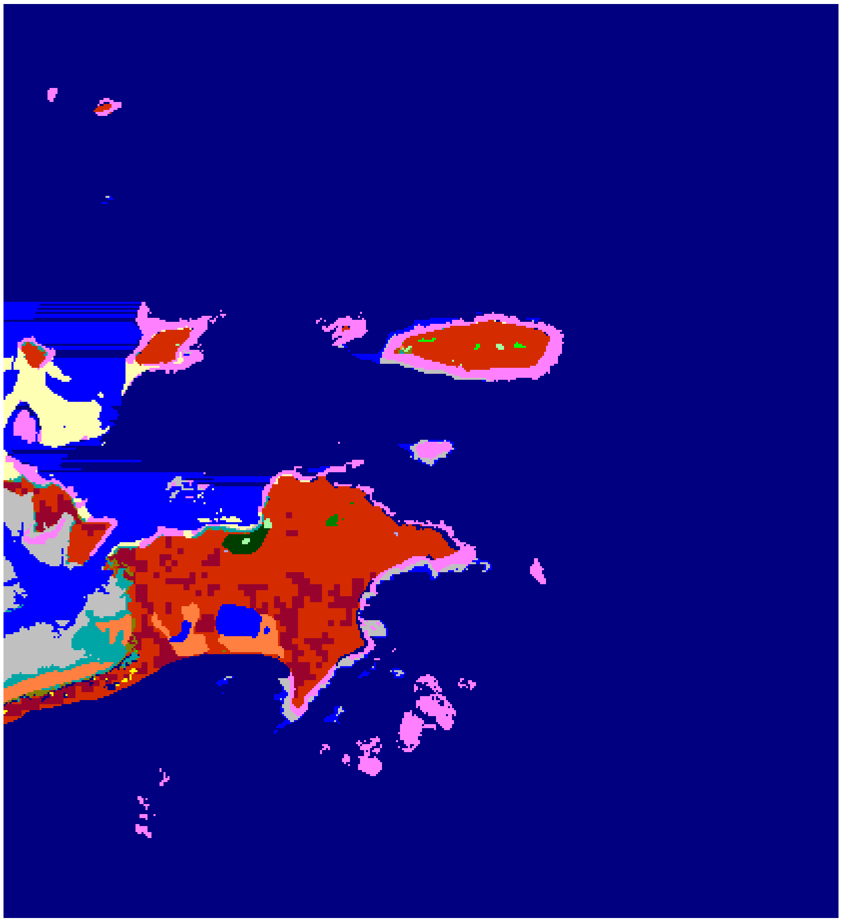
Petit Manan NWR Section C (Biddeford Pools), 2025, Scenario A1B Maximum



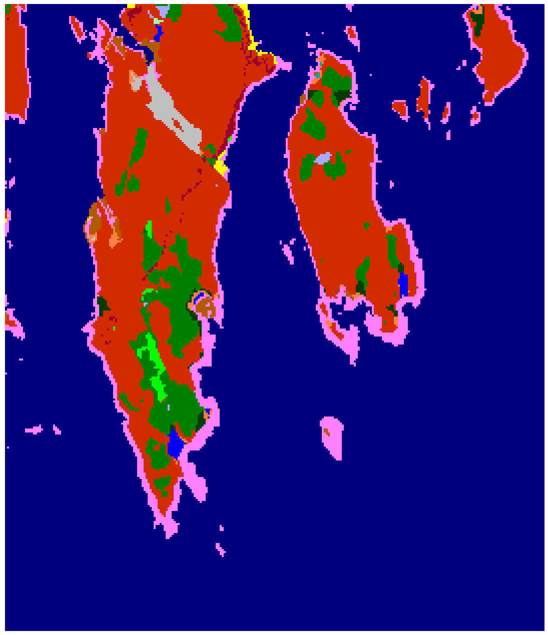
Petit Manan NWR Section C (Biddeford Pools), 2050, Scenario A1B Maximum



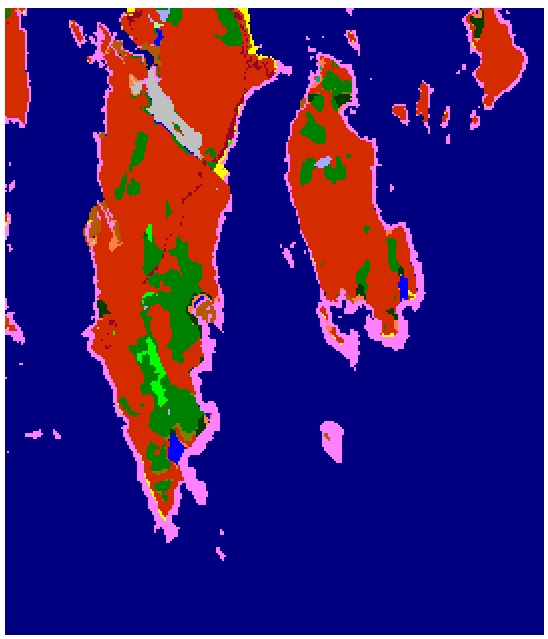
Petit Manan NWR Section C (Biddeford Pools), 2075, Scenario A1B Maximum



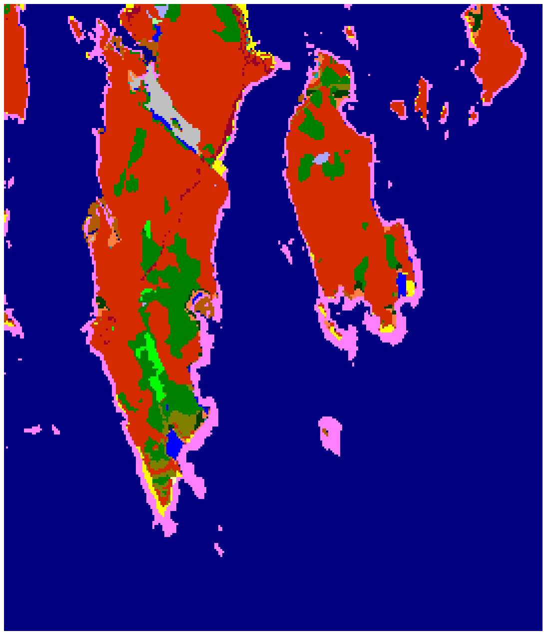
Petit Manan NWR Section C (Biddeford Pools), 2100, Scenario A1B Maximum



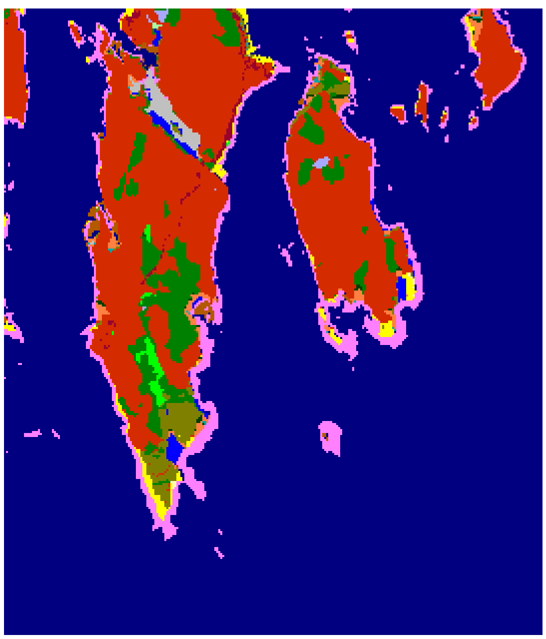
Petit Manan NWR Section A (Abbott/Bois Bubert Islands), Initial Condition



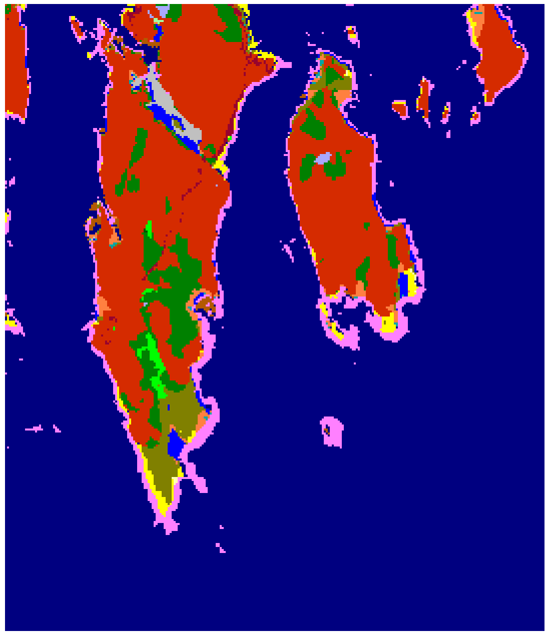
Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2025, Scenario A1B Maximum



Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2050, Scenario A1B Maximum



Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2075, Scenario A1B Maximum

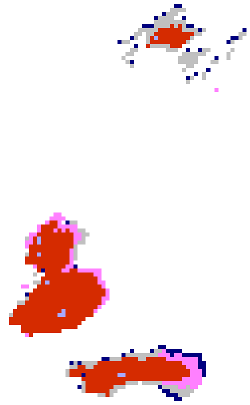


Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2100, Scenario A1B Maximum

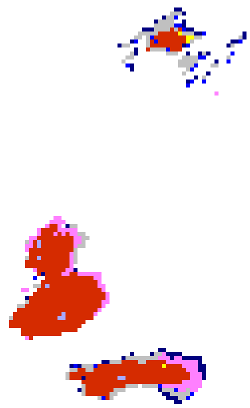
Petit Manan NWR
1 Meter Eustatic SLR by 2100

Results in Acres

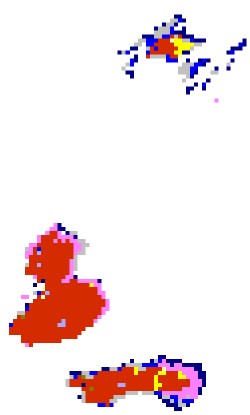
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	5959.4	5811.5	5539.6	5298.6	5171.0
	Rocky Intertidal	983.2	958.6	903.9	821.6	721.7
	Swamp	958.7	966.4	903.7	844.6	828.6
	Tidal Flat	386.9	347.5	277.1	197.8	133.1
	Open Ocean	160.6	194.5	286.8	434.3	622.3
	Irregularly Flooded Marsh	140.9	148.6	173.5	197.0	184.8
	Estuarine Open Water	133.4	177.0	250.2	329.1	387.3
	Inland Fresh Marsh	80.5	80.5	79.4	75.3	70.8
	Tidal Swamp	75.8	64.6	34.9	3.4	0.6
	Developed Dry Land	59.6	59.1	59.0	59.0	58.9
	Tidal Fresh Marsh	51.4	51.4	43.7	28.5	14.4
	Ocean Flat	41.6	38.9	33.7	26.2	18.3
	Inland Open Water	37.8	36.3	34.7	34.7	34.5
	Ocean Beach	34.2	99.7	227.0	301.4	296.1
	Needle-Leaved Swamp	23.8	23.8	23.8	23.8	23.8
	Regularly Flooded Marsh	9.3	12.8	29.4	51.0	162.7
	Estuarine Beach	6.9	22.7	59.4	107.8	148.4
	Riverine Tidal	0.3	0.3	0.1	0.1	0.0
	Transitional Salt Marsh	0.0	50.3	184.9	310.5	267.2
	Total (incl. water)	**9144.6**	**9144.6**	**9144.6**	**9144.6**	**9144.6**



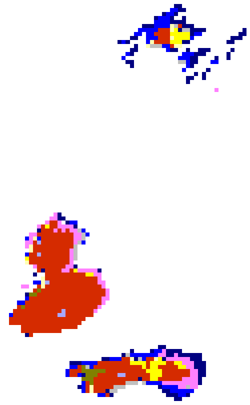
Petit Manan NWR Section D (Isles of Shoals), Initial Condition



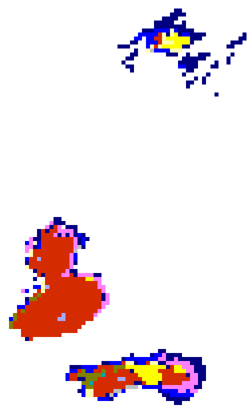
Petit Manan NWR Section D (Isles of Shoals), 2025, 1 Meter



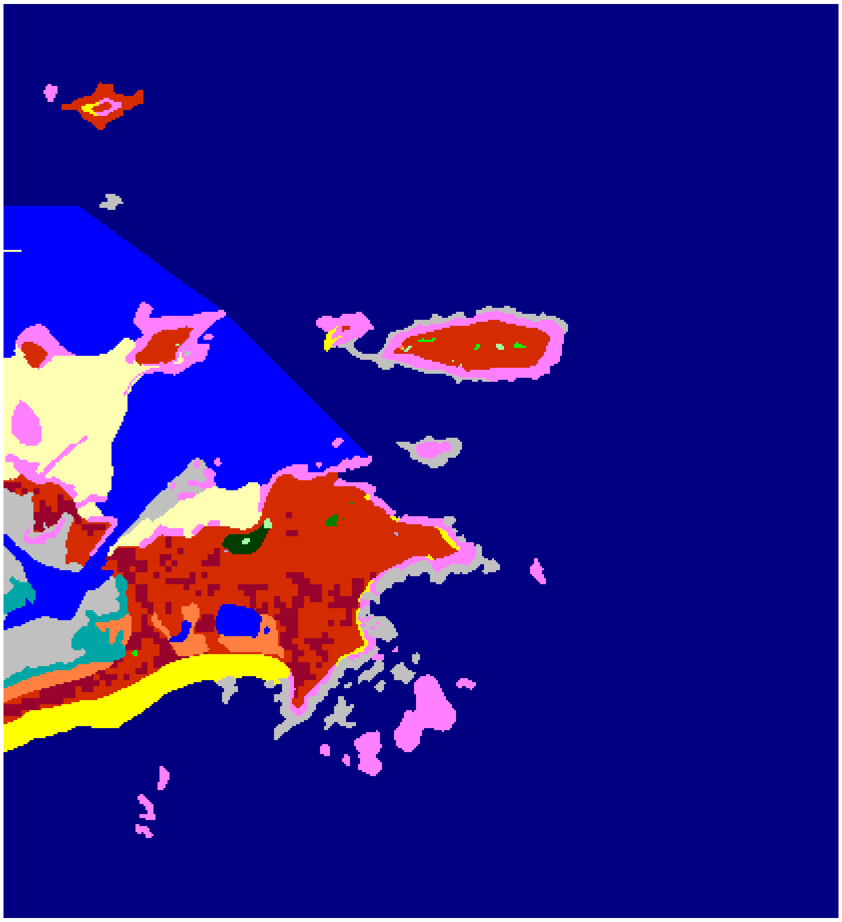
Petit Manan NWR Section D (Isles of Shoals), 2050, 1 Meter



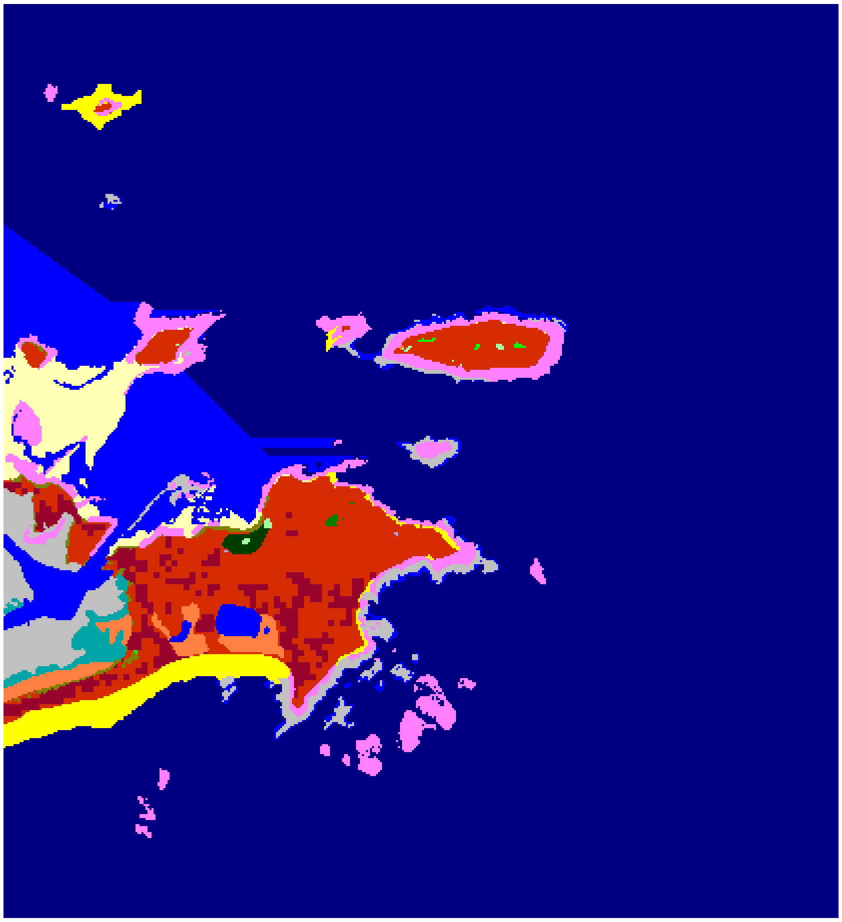
Petit Manan NWR Section D (Isles of Shoals), 2075, 1 Meter

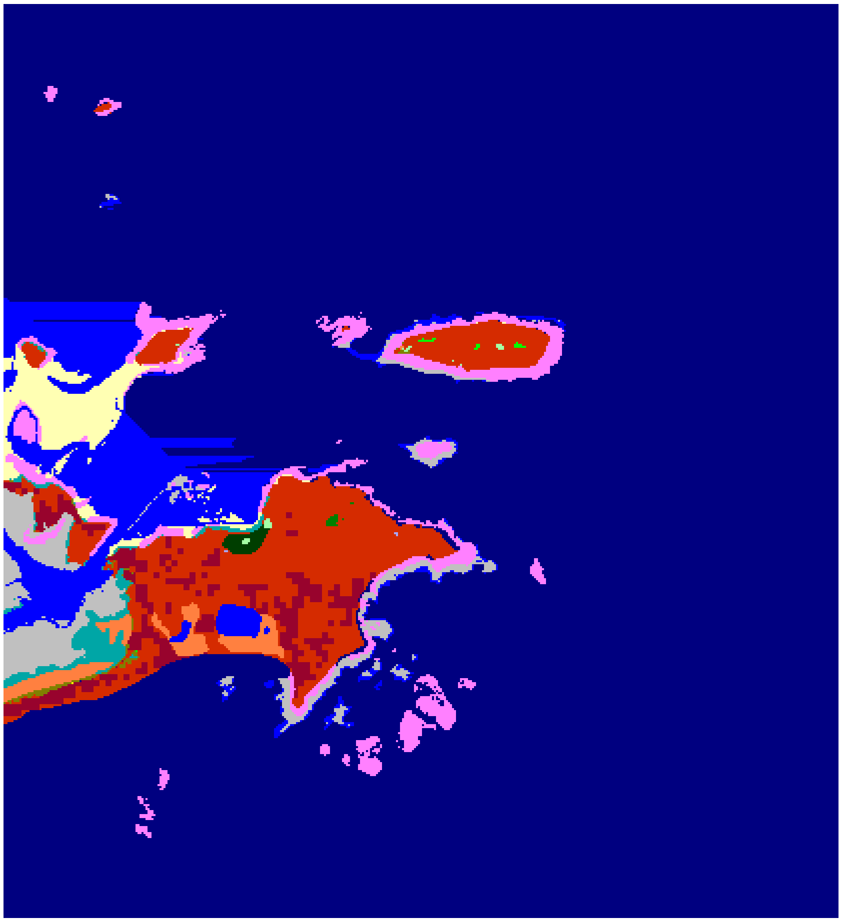


Petit Manan NWR Section D (Isles of Shoals), 2100, 1 Meter

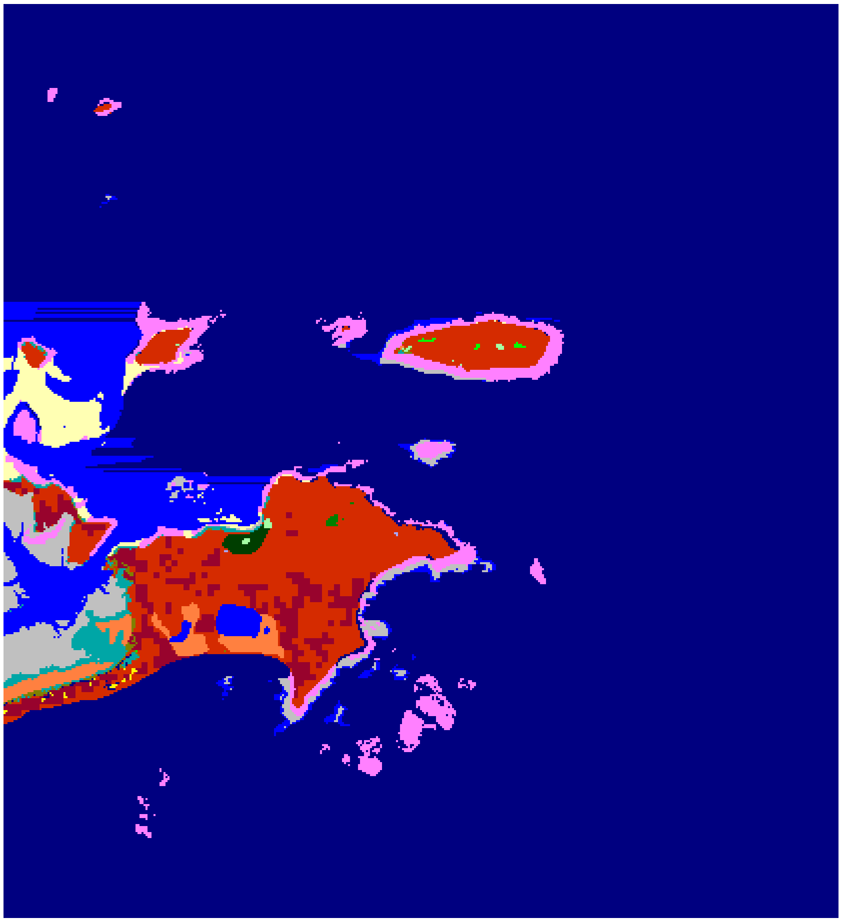


Petit Manan NWR Section C (Biddeford Pools), Initial Condition

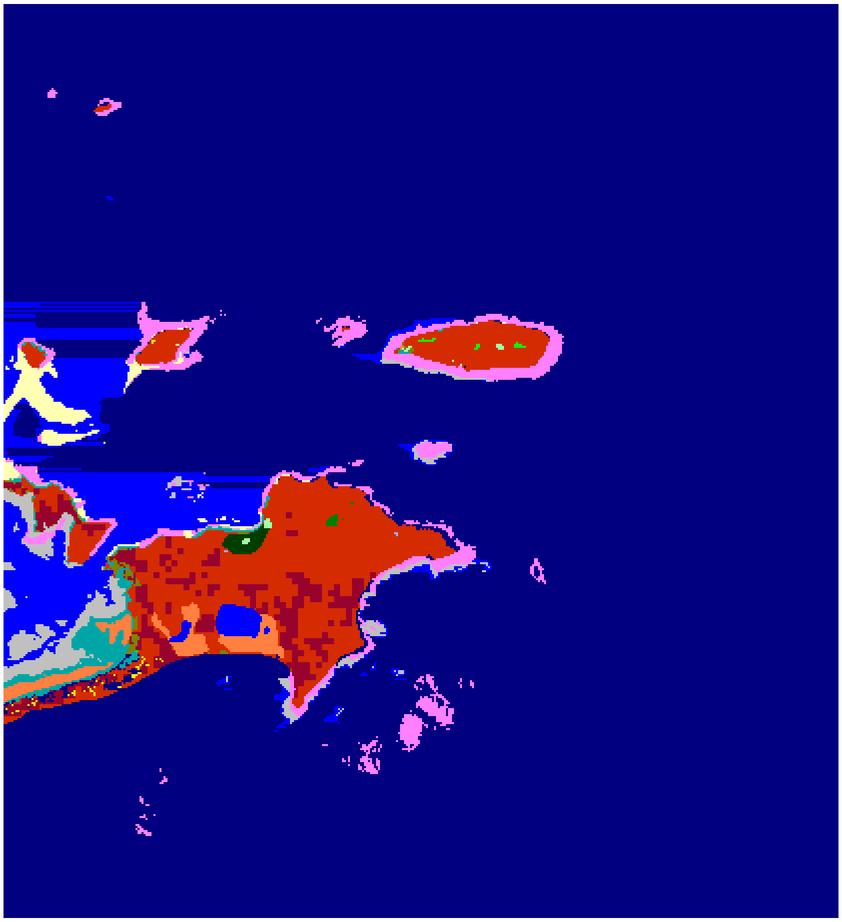

Petit Manan NWR Section C (Biddeford Pools), 2025, 1 Meter



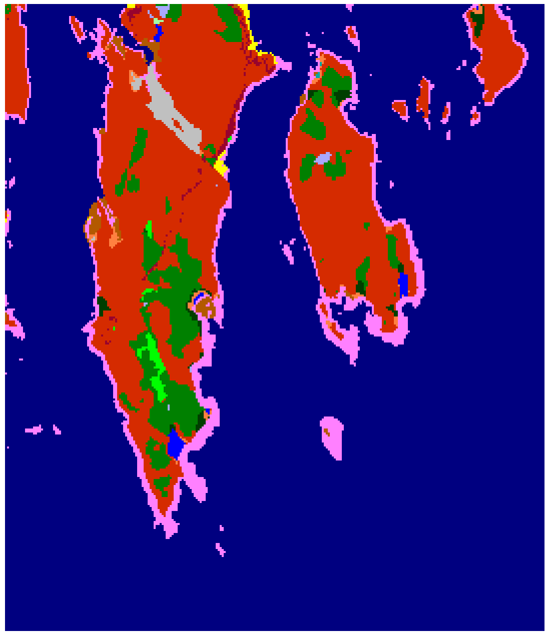
Petit Manan NWR Section C (Biddeford Pools), 2050, 1 Meter



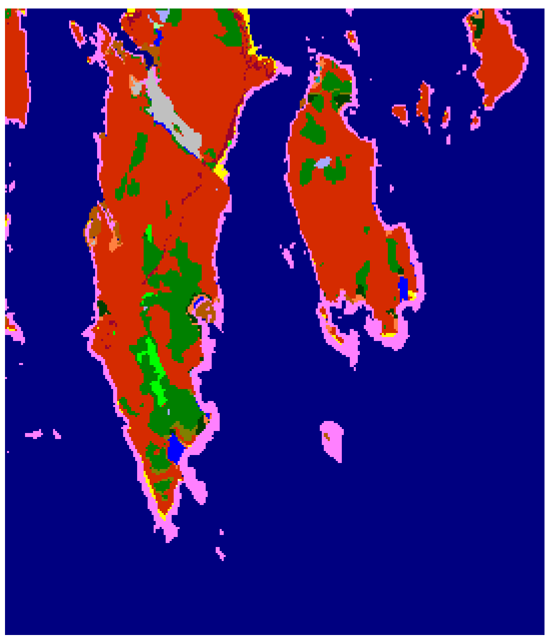
Petit Manan NWR Section C (Biddeford Pools), 2075, 1 Meter



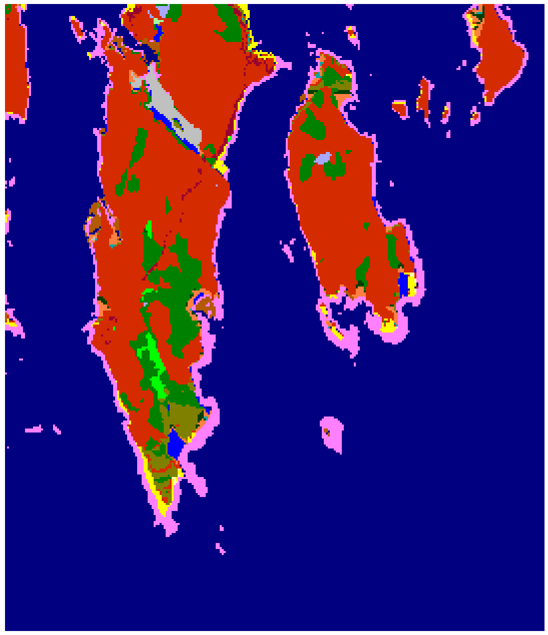
Petit Manan NWR Section C (Biddeford Pools), 2100, 1 Meter



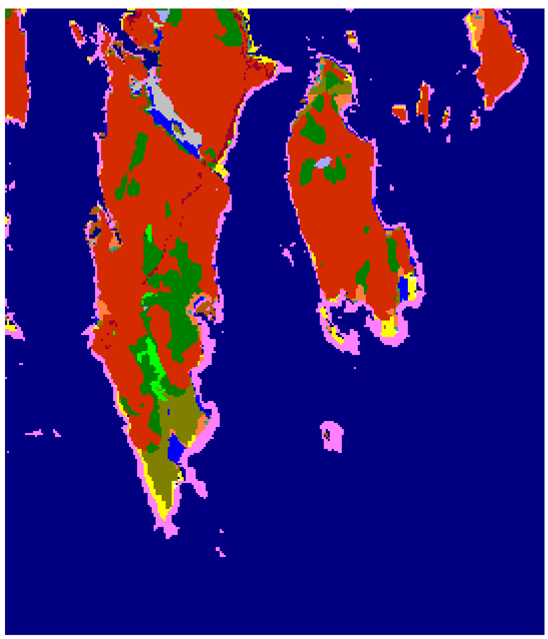
Petit Manan NWR Section A (Abbott/Bois Bubert Islands), Initial Condition



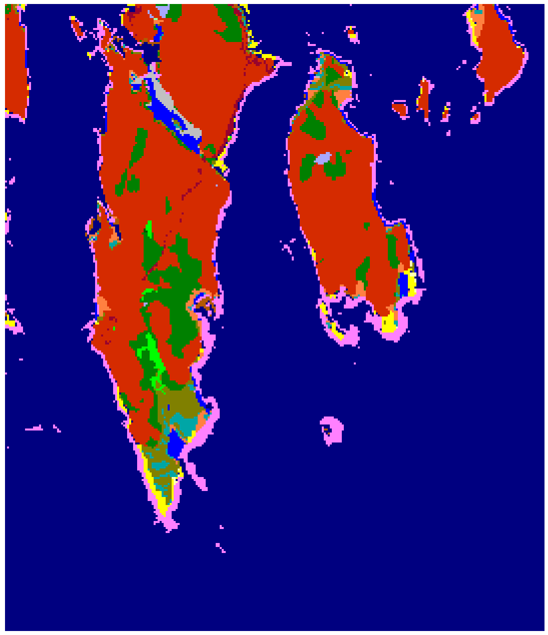
Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2025, 1 Meter



Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2050, 1 Meter



Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2075, 1 Meter

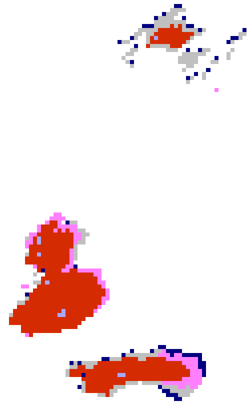


Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2100, 1 Meter

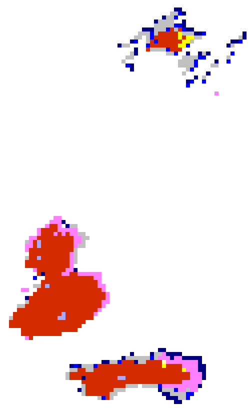
Petit Manan NWR
1.5 Meters Eustatic SLR by 2100

Results in Acres

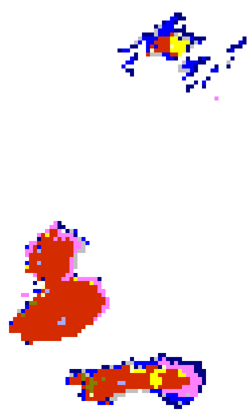
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	5959.4	5746.5	5375.7	5169.0	5074.1
	Rocky Intertidal	983.2	945.4	857.9	719.9	560.8
	Swamp	958.7	949.6	855.2	828.4	808.6
	Tidal Flat	386.9	332.8	231.7	136.1	73.9
	Open Ocean	160.6	211.1	389.7	787.4	1122.1
	Irregularly Flooded Marsh	140.9	157.6	196.6	188.5	153.8
	Estuarine Open Water	133.4	195.1	304.9	399.6	467.2
	Inland Fresh Marsh	80.5	79.9	74.9	67.9	62.5
	Tidal Swamp	75.8	56.0	12.6	0.5	0.0
	Developed Dry Land	59.6	59.1	59.0	58.9	58.9
	Tidal Fresh Marsh	51.4	46.7	26.5	2.6	1.0
	Ocean Flat	41.6	37.6	29.2	17.8	8.7
	Inland Open Water	37.8	36.3	34.7	34.5	34.5
	Ocean Beach	34.2	133.7	245.7	105.5	17.4
	Needle-Leaved Swamp	23.8	23.8	23.8	23.8	23.8
	Regularly Flooded Marsh	9.3	17.0	45.7	217.1	424.2
	Estuarine Beach	6.9	34.6	96.3	164.0	181.0
	Riverine Tidal	0.3	0.3	0.1	0.0	0.0
	Transitional Salt Marsh	0.0	81.6	284.5	223.0	72.1
	Total (incl. water)	**9144.6**	**9144.6**	**9144.6**	**9144.6**	**9144.6**



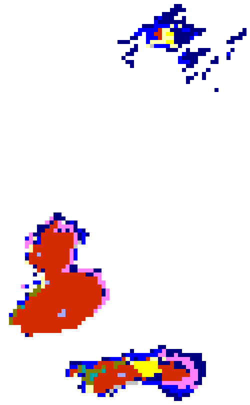
Petit Manan NWR Section D (Isles of Shoals), Initial Condition



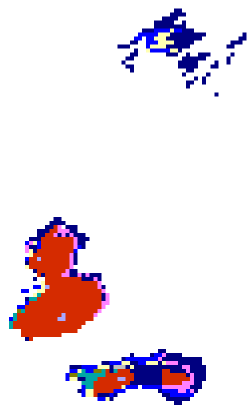
Petit Manan NWR Section D (Isles of Shoals), 2025, 1.5 Meters



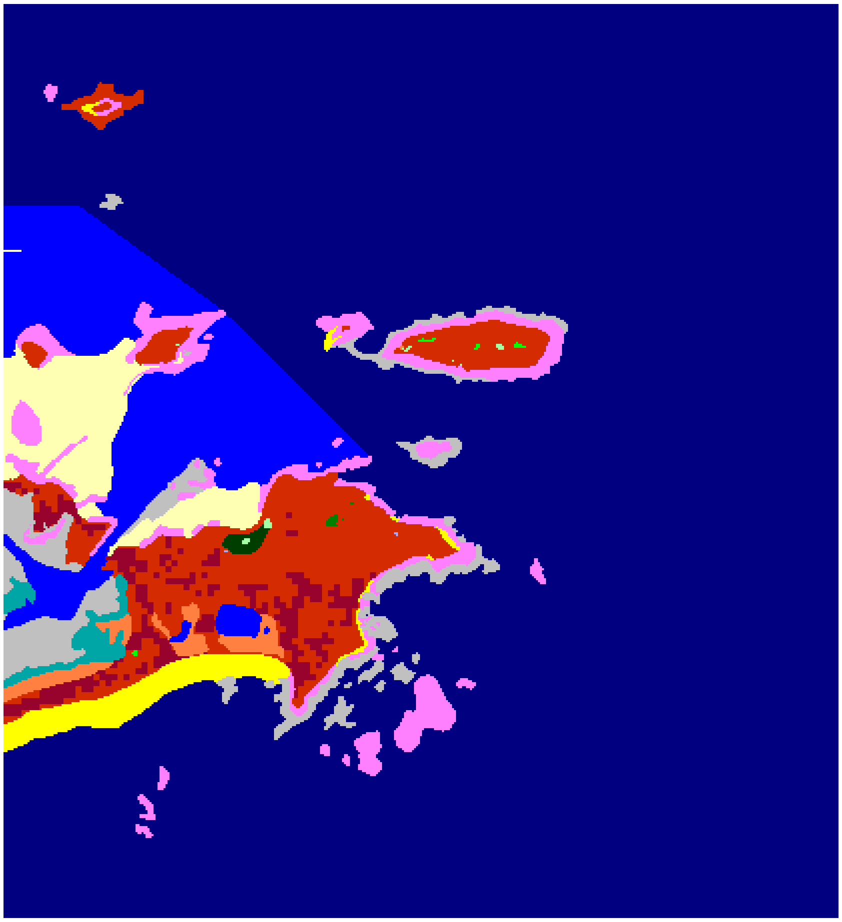
Petit Manan NWR Section D (Isles of Shoals), 2050, 1.5 Meters



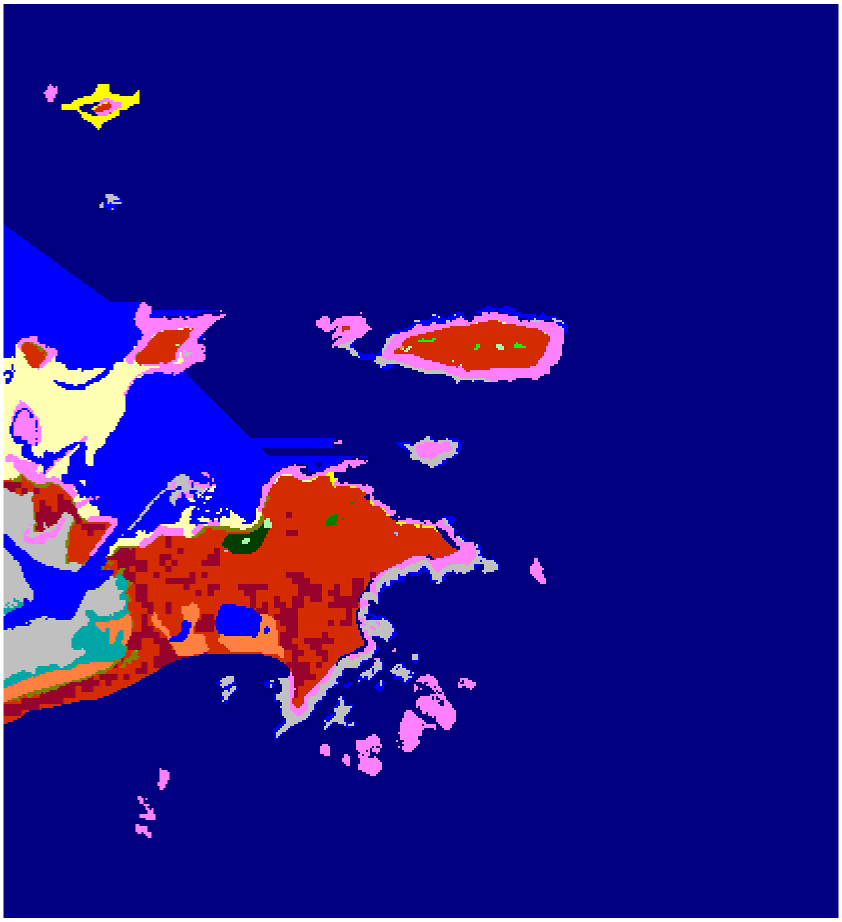
Petit Manan NWR Section D (Isles of Shoals), 2075, 1.5 Meters



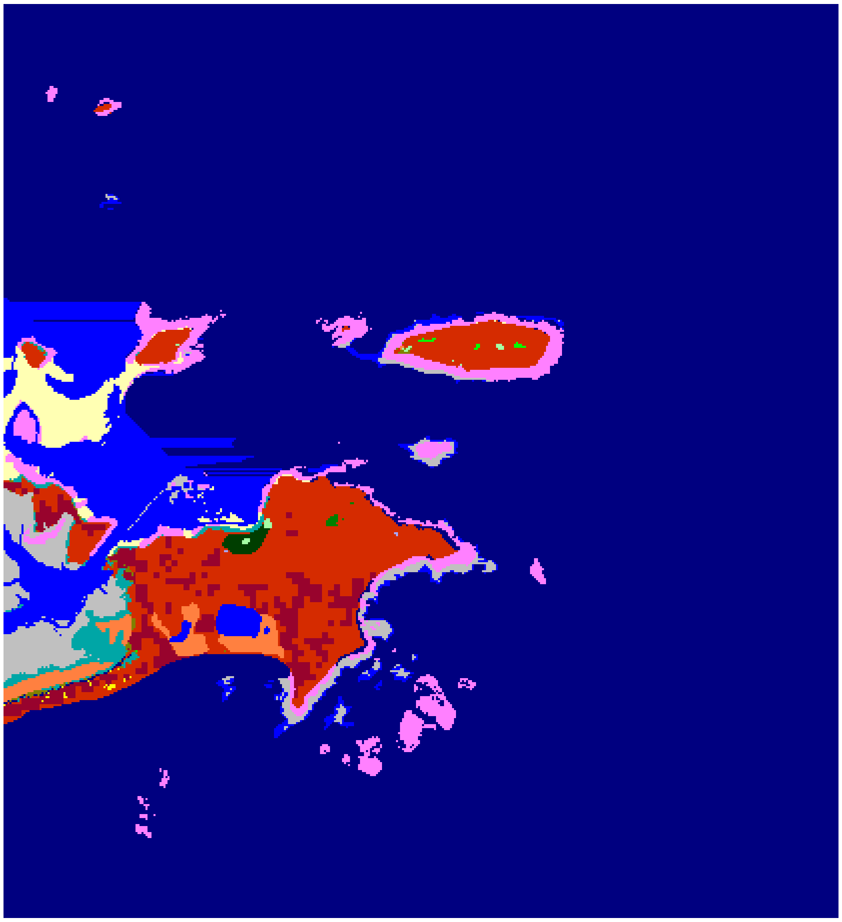
Petit Manan NWR Section D (Isles of Shoals), 2100, 1.5 Meters



Petit Manan NWR Section C (Biddeford Pools), Initial Condition



Petit Manan NWR Section C (Biddeford Pools), 2025, 1.5 Meters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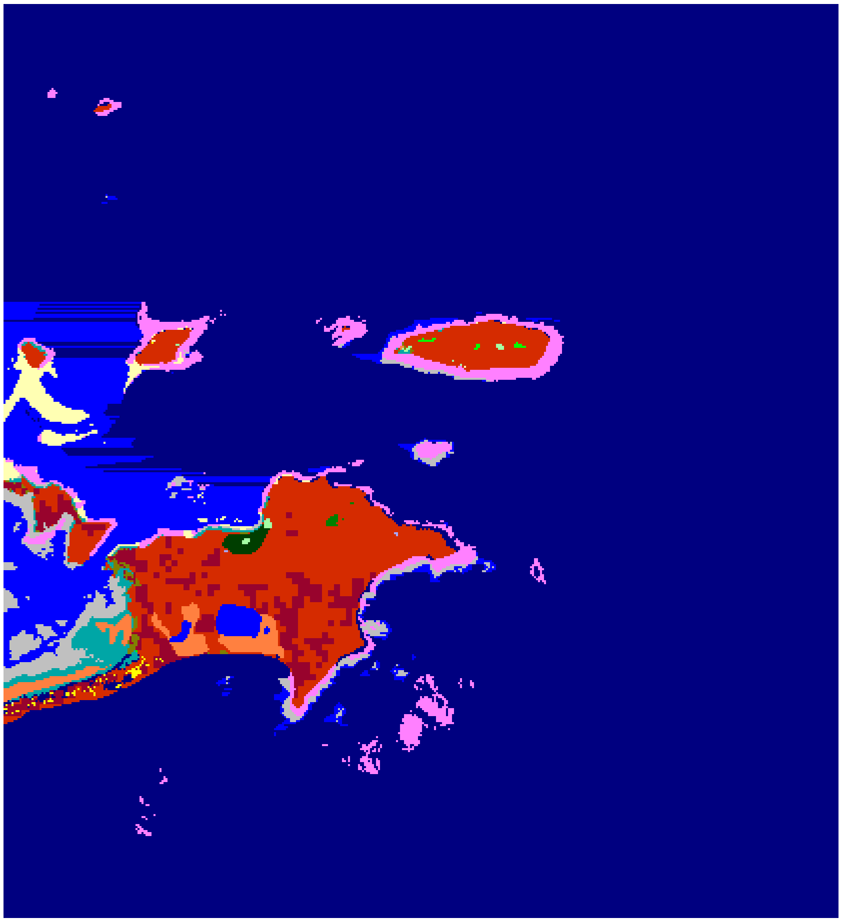

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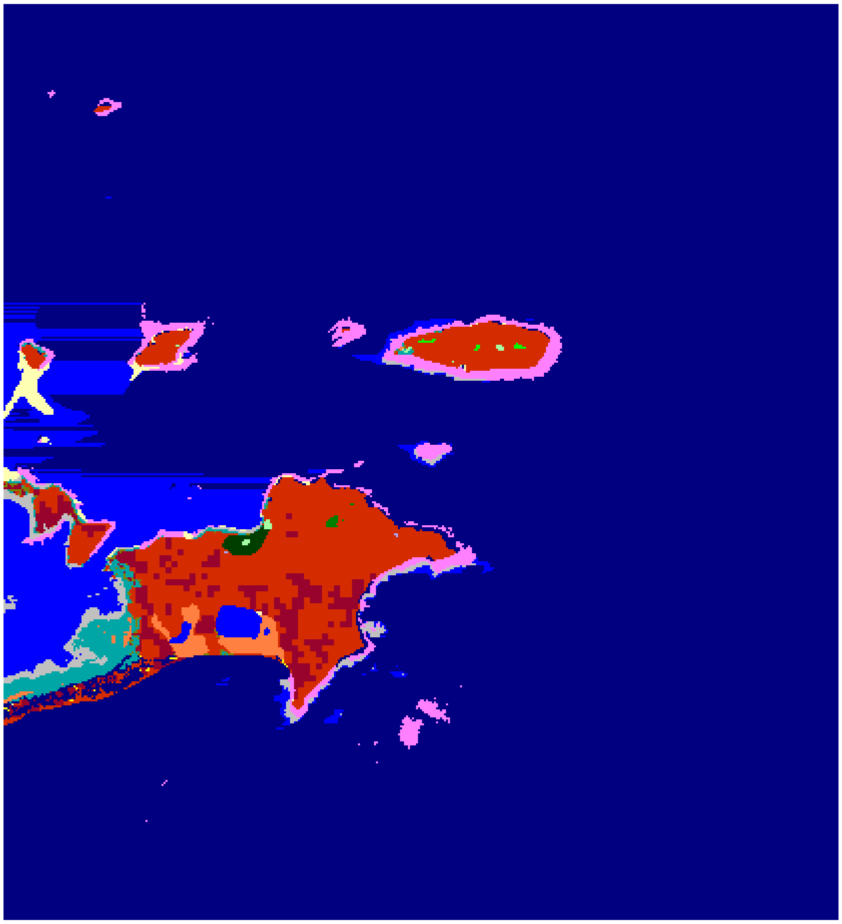

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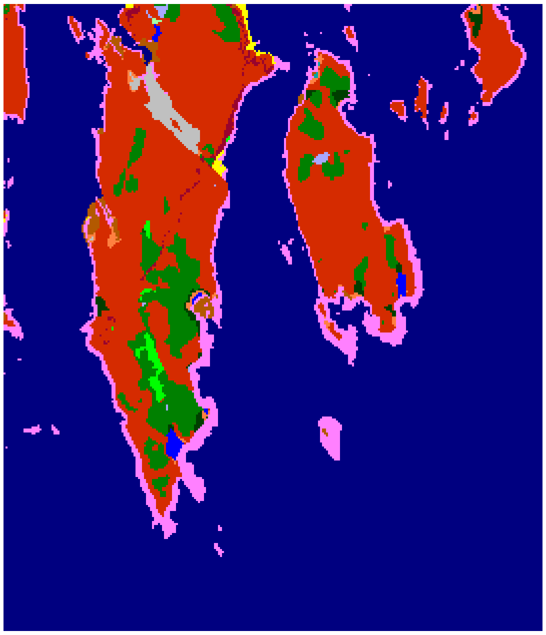
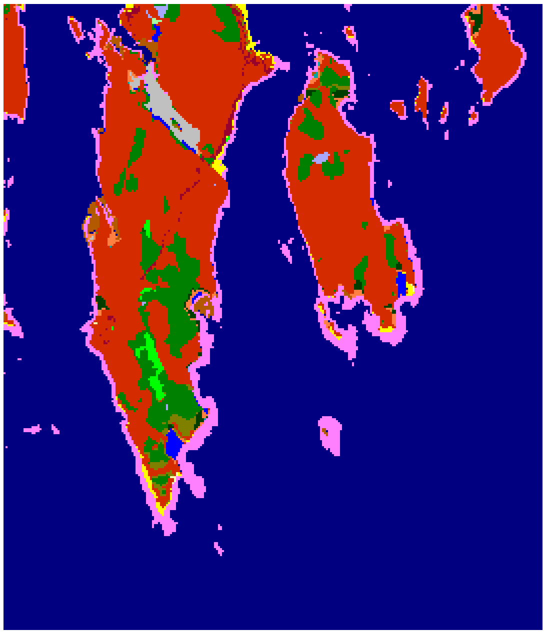


Petit Manan NWR Section A (Abbott/Bois Bubert Islands), Initial Condition



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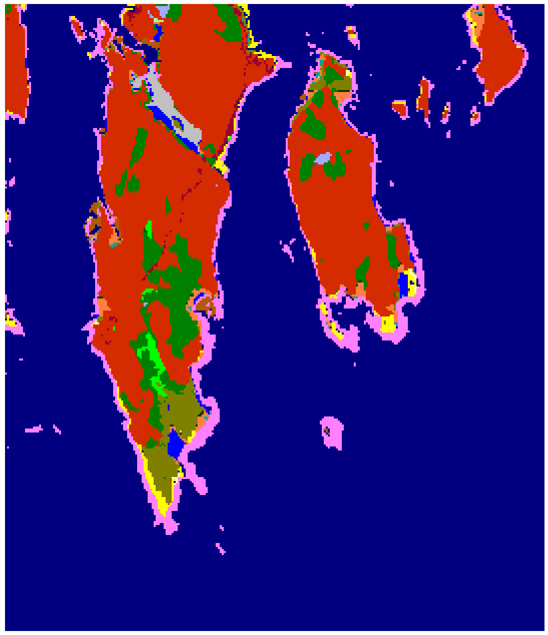

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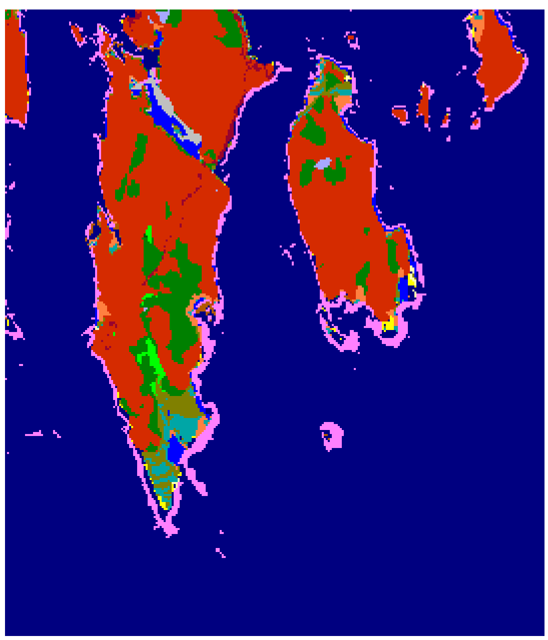
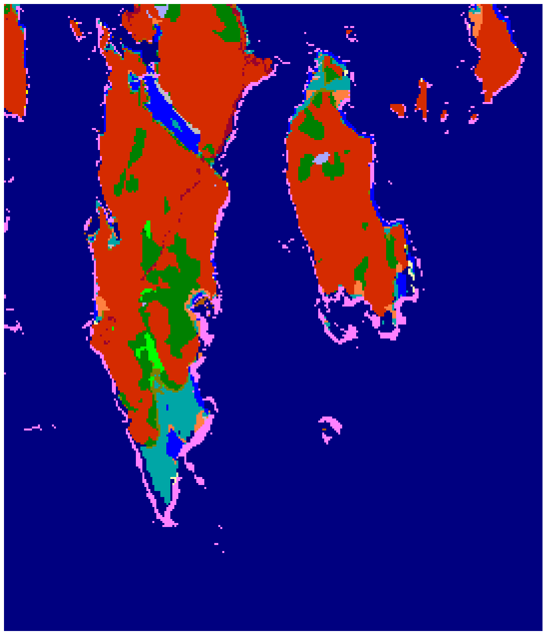


Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2075, 1.5 Meters

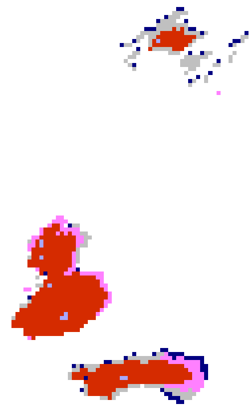


Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2100, 1.5 Meters

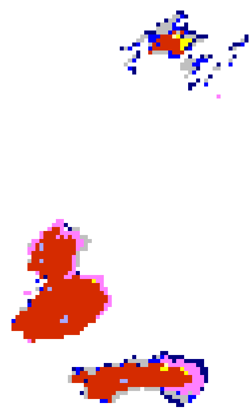
Petit Manan NWR
2 Meters Eustatic SLR by 2100

Results in Acres

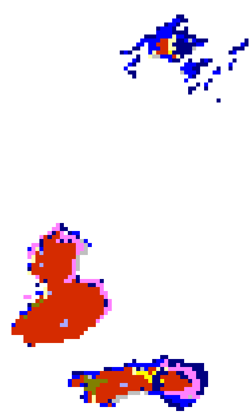
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	5959.4	5679.7	5275.1	5101.5	4984.7
	Rocky Intertidal	983.2	932.7	808.5	611.4	419.6
	Swamp	958.7	930.7	841.8	816.5	789.4
	Tidal Flat	386.9	316.3	195.8	94.0	89.7
	Open Ocean	160.6	228.3	553.4	1011.4	1325.5
	Irregularly Flooded Marsh	140.9	168.0	200.9	160.4	114.1
	Estuarine Open Water	133.4	214.5	349.5	467.1	512.5
	Inland Fresh Marsh	80.5	78.7	70.4	62.8	57.8
	Tidal Swamp	75.8	47.5	2.5	0.0	0.0
	Developed Dry Land	59.6	59.1	59.0	58.8	58.7
	Tidal Fresh Marsh	51.4	40.6	12.0	1.0	0.5
	Ocean Flat	41.6	36.4	24.8	11.0	1.7
	Inland Open Water	37.8	36.3	34.7	34.5	34.5
	Ocean Beach	34.2	163.9	169.7	17.2	11.2
	Needle-Leaved Swamp	23.8	23.8	23.8	23.8	23.8
	Regularly Flooded Marsh	9.3	21.2	69.8	411.4	458.6
	Estuarine Beach	6.9	49.1	132.5	186.5	197.9
	Riverine Tidal	0.3	0.3	0.1	0.0	0.0
	Transitional Salt Marsh	0.0	117.7	320.2	75.3	64.2
	Total (incl. water)	**9144.6**	**9144.6**	**9144.6**	**9144.6**	**9144.6**



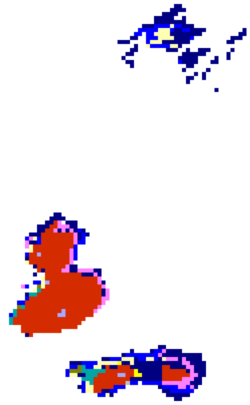
Petit Manan NWR Section D (Isles of Shoals), Initial Condition



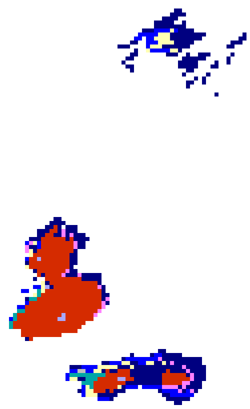
Petit Manan NWR Section D (Isles of Shoals), 2025, 2 Meters



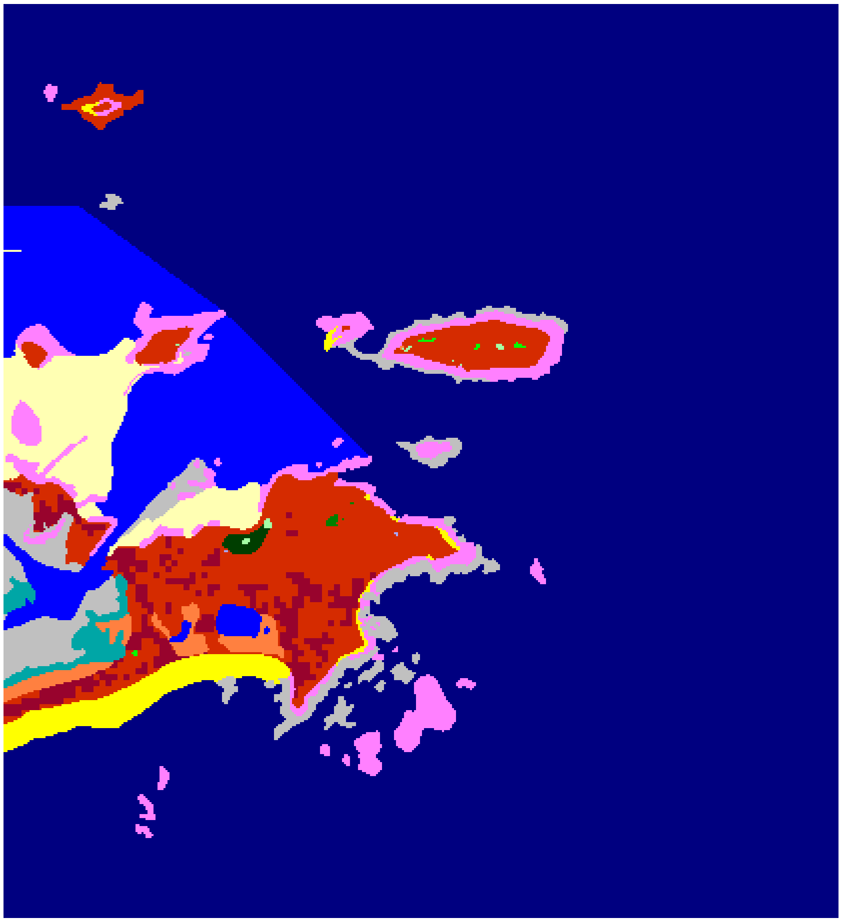
Petit Manan NWR Section D (Isles of Shoals), 2050, 2 Meters



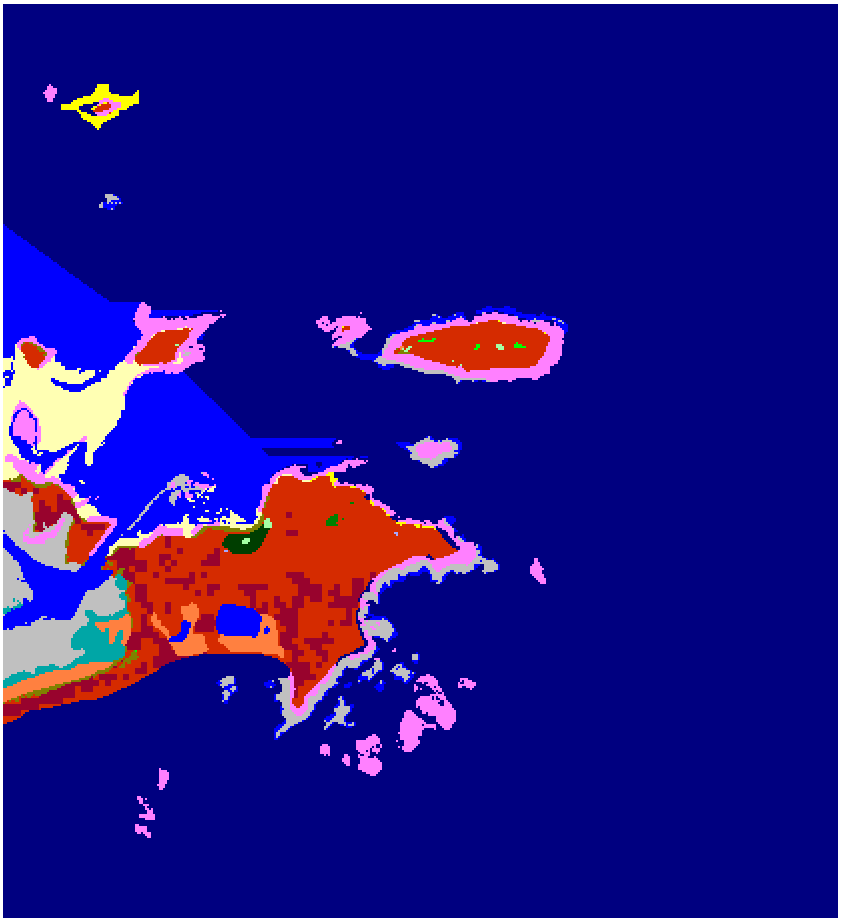
Petit Manan NWR Section D (Isles of Shoals), 2075, 2 Meters



Petit Manan NWR Section D (Isles of Shoals), 2100, 2 Meters



Petit Manan NWR Section C (Biddeford Pools), Initial Condition



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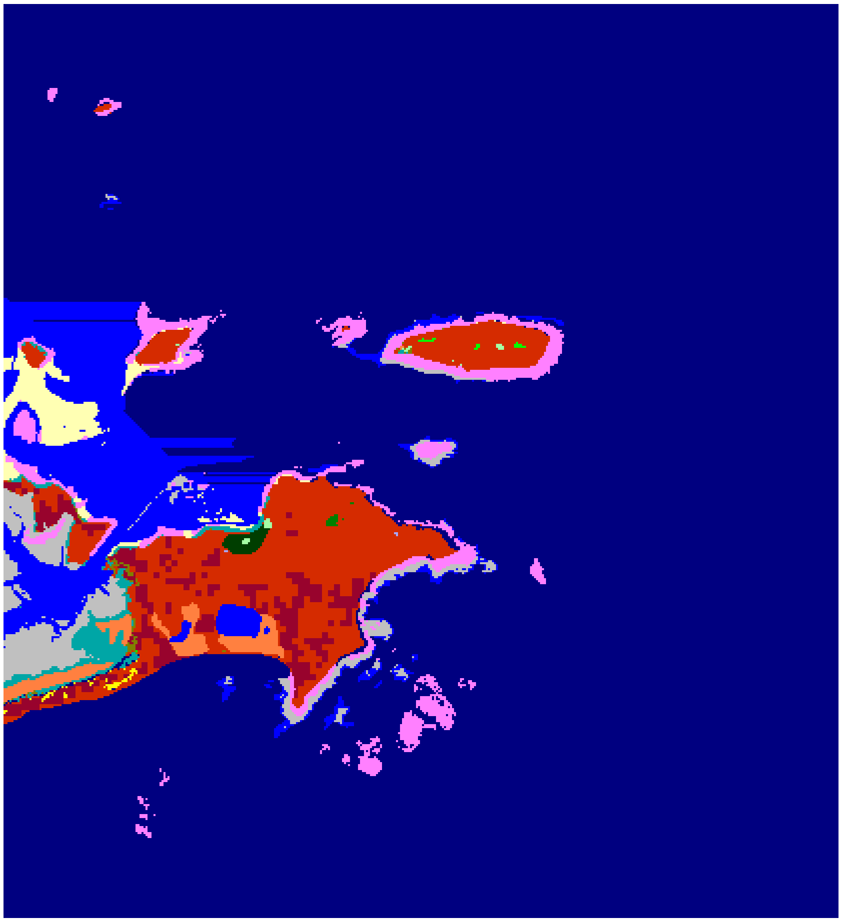

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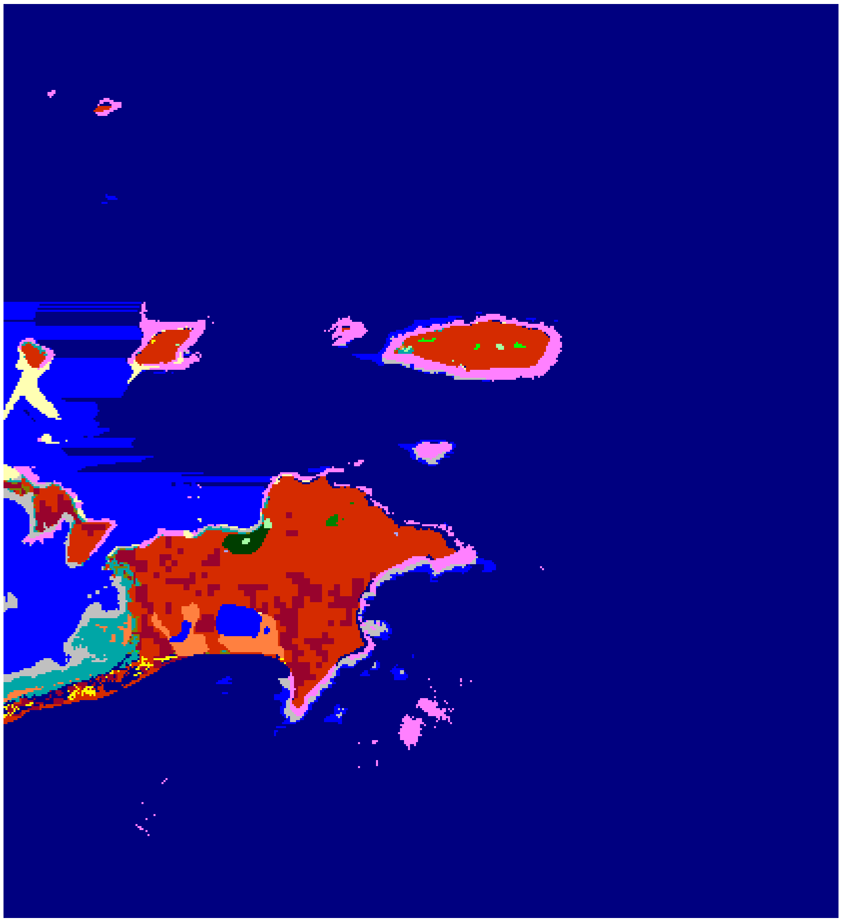
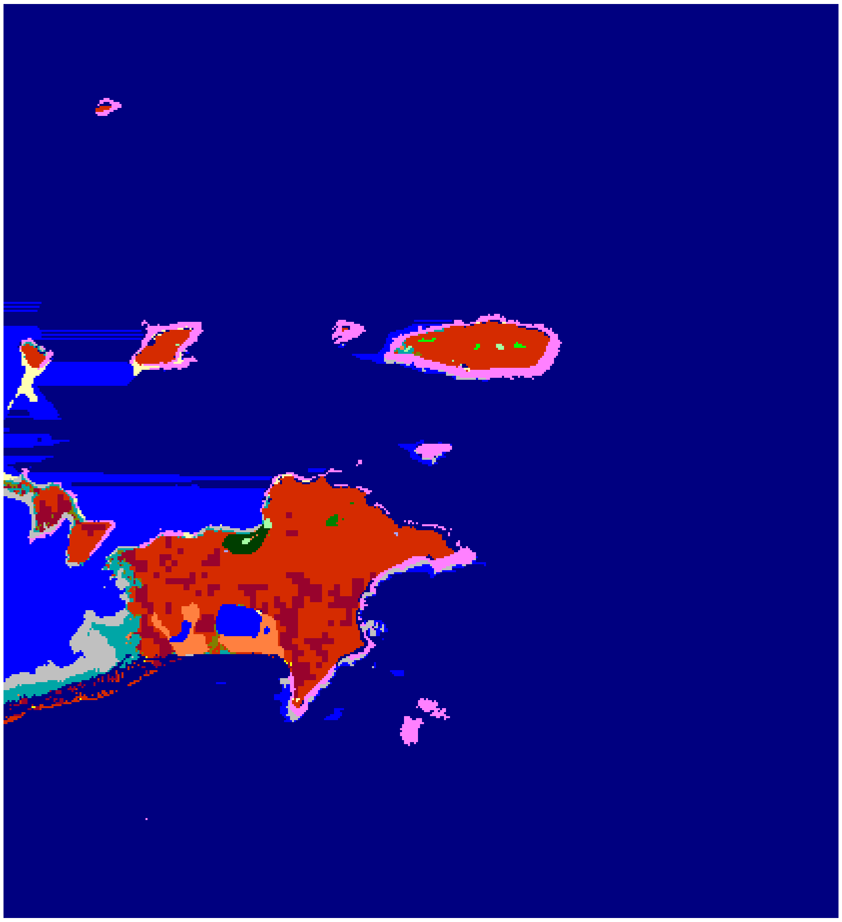
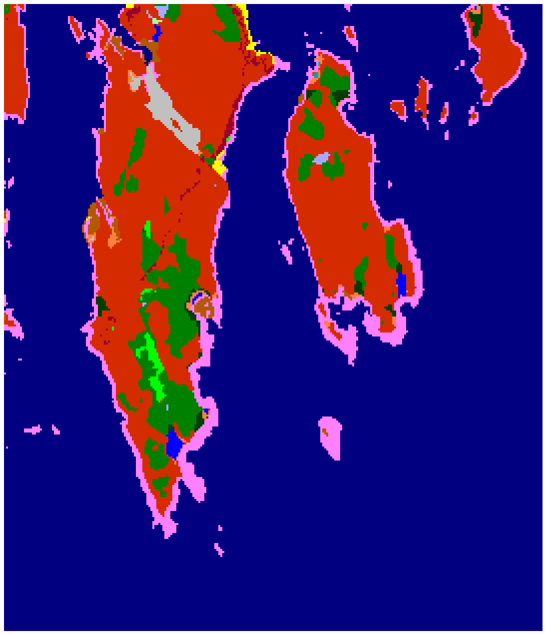


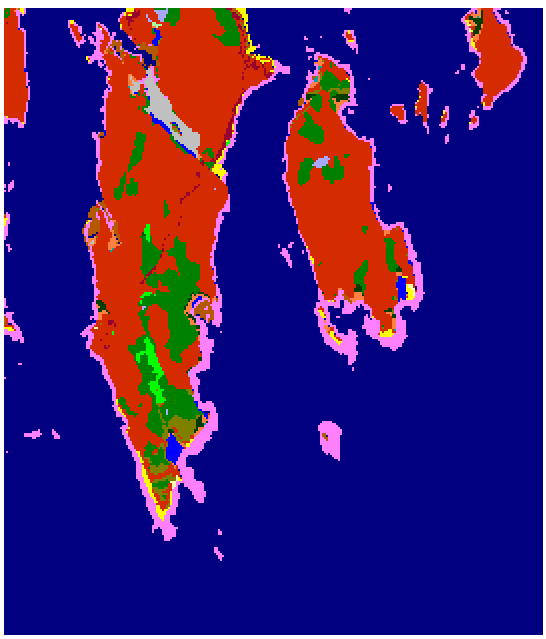
Petit Manan NWR Section C (Biddeford Pools), 2075, 2 Meters



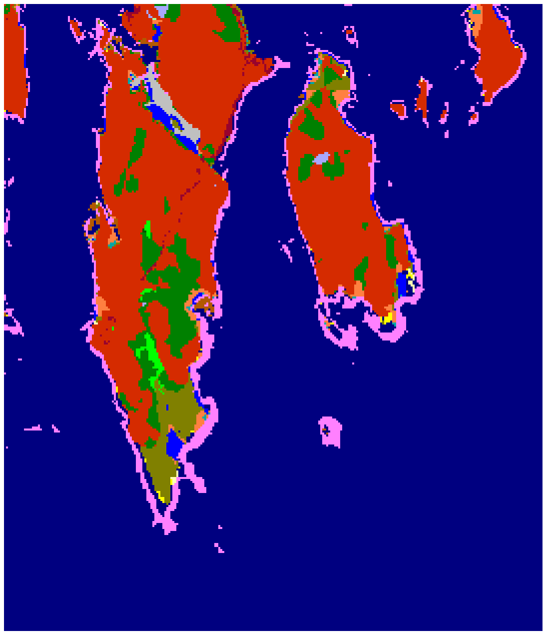
Petit Manan NWR Section C (Biddeford Pools), 2100, 2 Meters



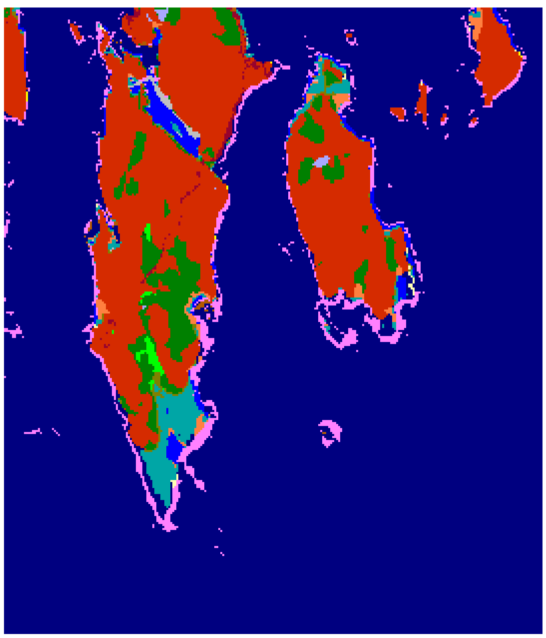
Petit Manan NWR Section A (Abbott/Bois Bubert Islands), Initial Condition



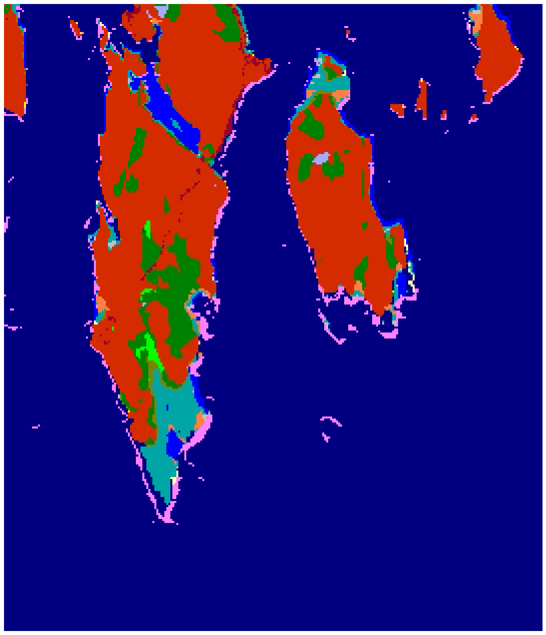
Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2025, 2 Meters



Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2050, 2 Meters



Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2075, 2 Meters



Petit Manan NWR Section A (Abbott/Bois Bubert Islands), 2100, 2 Meters

Discussion

The majority of Petit Manan NWR is characterized by high vertical relief and a relatively-high tide range. These features translate into predictions of resilience and even growth for most marsh categories, including irregularly flooded marsh, regularly flooded marsh, and transitional marsh. The resilience of swamp is due in part to high elevations as well as soil saturation, which can convert dry land into swamp as the water table rises.

Within this simulation beach acreages were observed to increase in scenarios up to 1.5 meters by 2100, primarily as a result of the inundation of dry lands. Ocean-beach fate predictions are subject to considerable uncertainty, however. Depending on the substrate, dry lands may instead convert to rocky-intertidal lands or directly to water. Additionally, within this model, the Bruun rule was employed to model beach erosion rates. The Bruun rule is commonly applied by scientists who model sea level rise because of its simplicity, but it has been criticized as a "one model fits all" approach that is unsuitable to for characterizing the complex spatial and temporal sedimentary processes occurring in coastal areas (Cooper and Pilkey, 2004).

The refuge is comprised primarily of small islands, many of which lack unique parameters like tide, accretion and erosion data. Although several sources of tidal, accretion/erosion and MTL-NAVD correction data were applied on an input subsite basis during model parameterization (Figure 6 to Figure 9), uncertainty is introduced into the results the farther from the data source a cell is located. For instance, results from oceanic islands modeled with tidal data collected at the coast have higher uncertainty than results from islands nearer to the relevant NOAA gage.

Several sources of tidal and accretion/erosion data were reviewed for inclusion in the model simulations. Accretion rates for marshes are assumed to remain constant over time, which is an additional source of model uncertainty.

In Sections A, B and D, elevation data were more than 60 years old with low vertical resolution (20 foot contours), increasing model uncertainty. Future analysis of Petit Manan NWR would benefit from higher quality elevation data. This would characterize land lost between the shoreline and the first contour more precisely. With LiDAR data available in Section C, model uncertainty is lower relative to non-LiDAR sections.

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Appendix A: Contextual Results

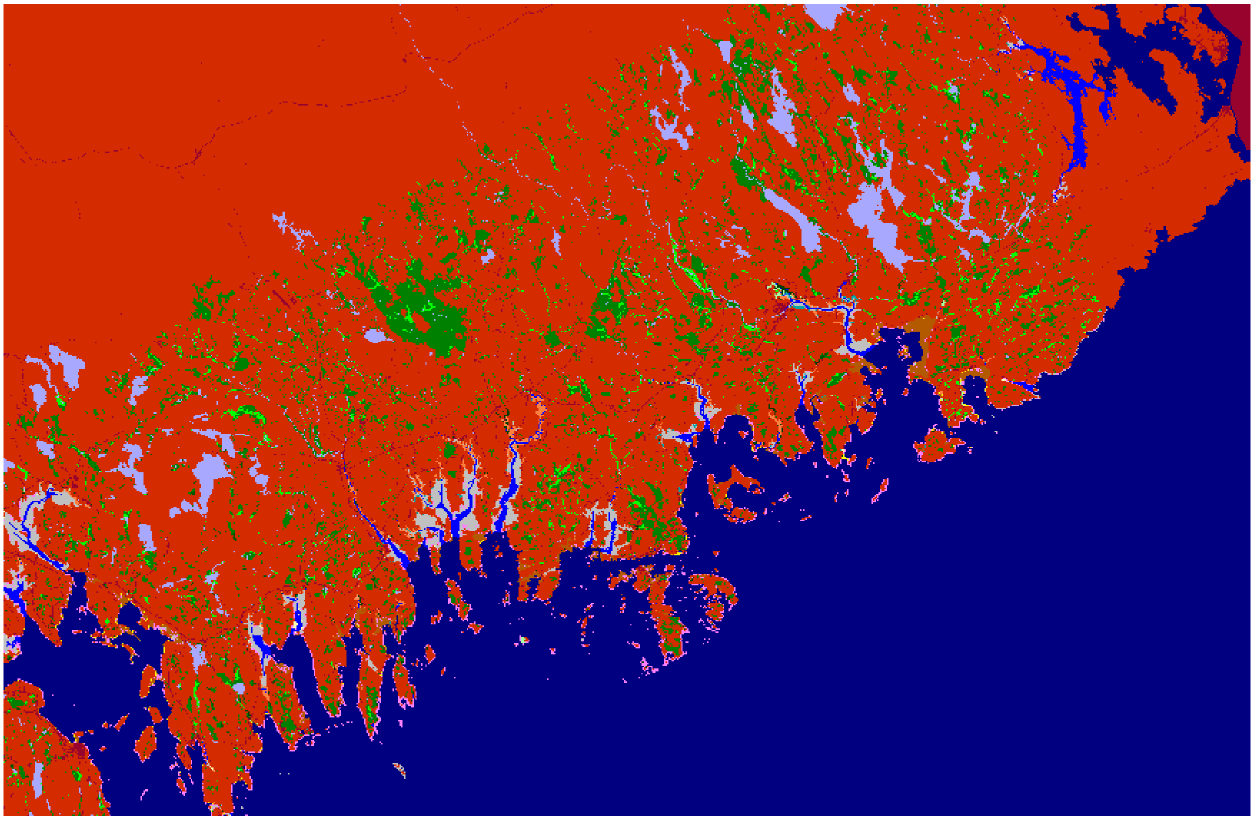
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

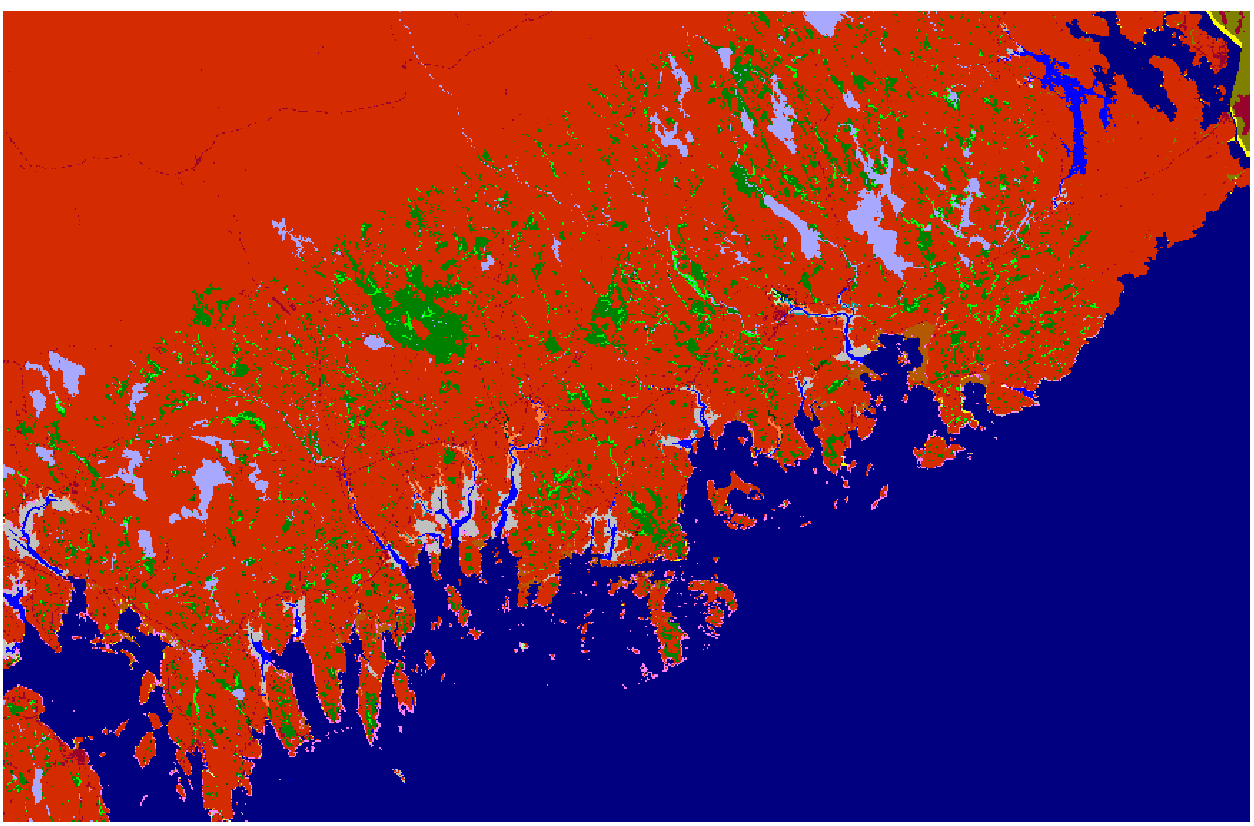
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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

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

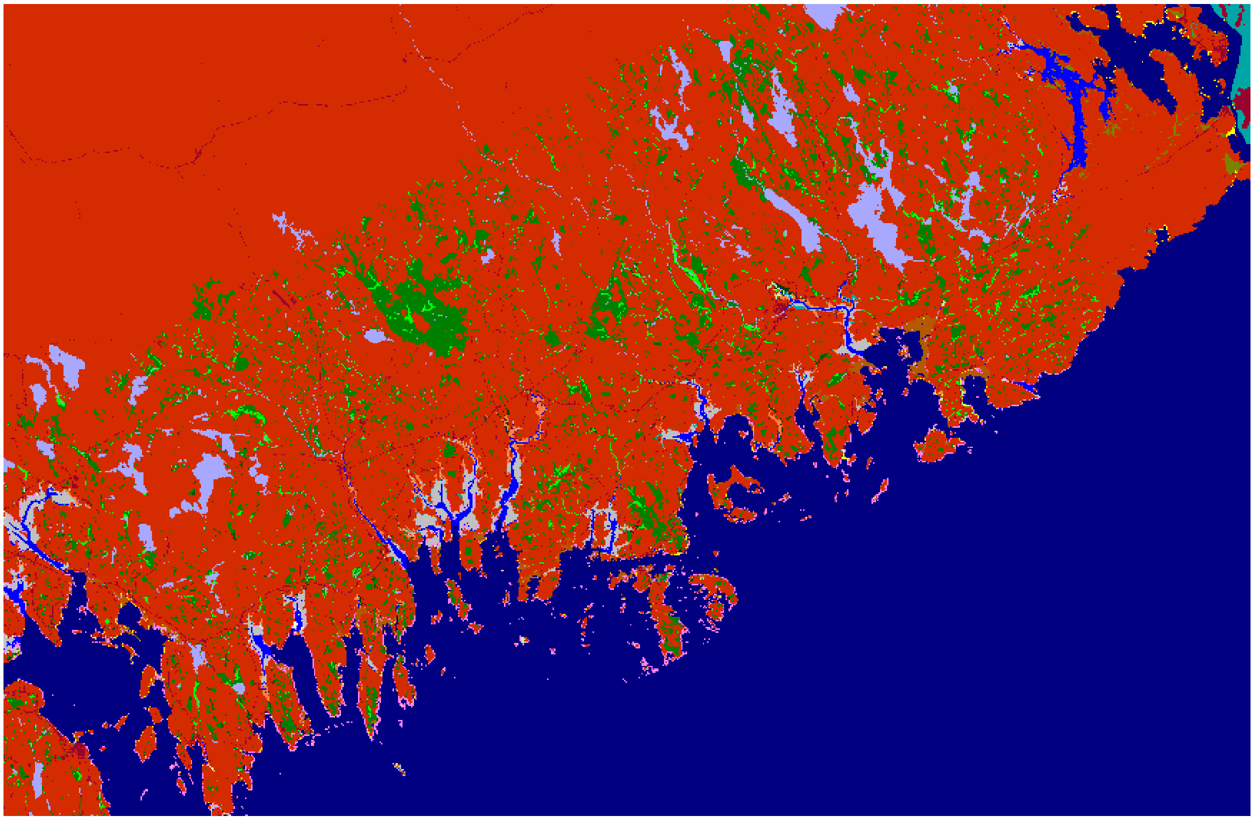
Open Ocean
Estuarine Open Water
Undeveloped Dry Land
Inland Fresh Marsh
Regularly Flooded Marsh
Irregularly Flooded Marsh
Estuarine Beach
Inland Open Water
Developed Dry Land
Swamp
Tidal Flat
Ocean Beach
Inland Shore
Mangrove
Tidal Fresh Marsh
Riverine Tidal
Tidal Swamp
Needle-Leaved Swamp
Transitional Salt Marsh



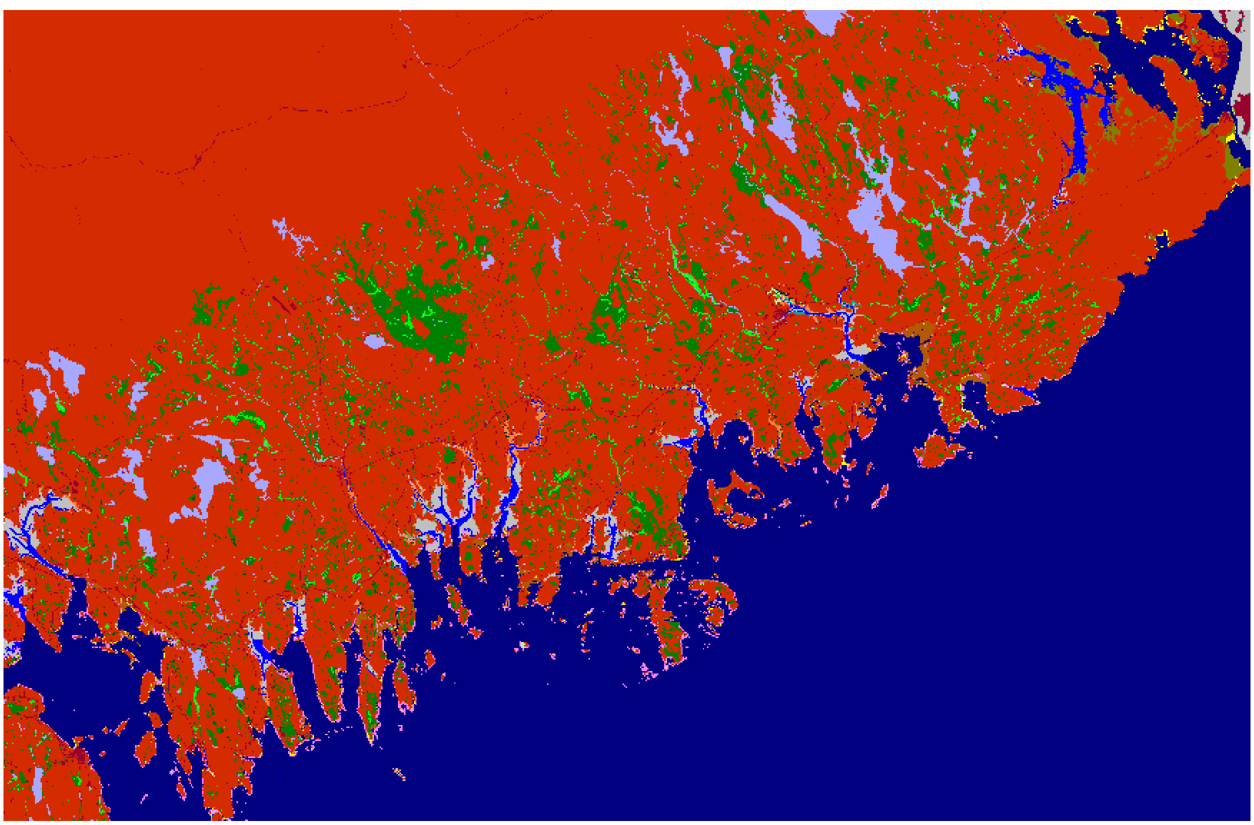
Petit Manan Section A Context, Initial Condition



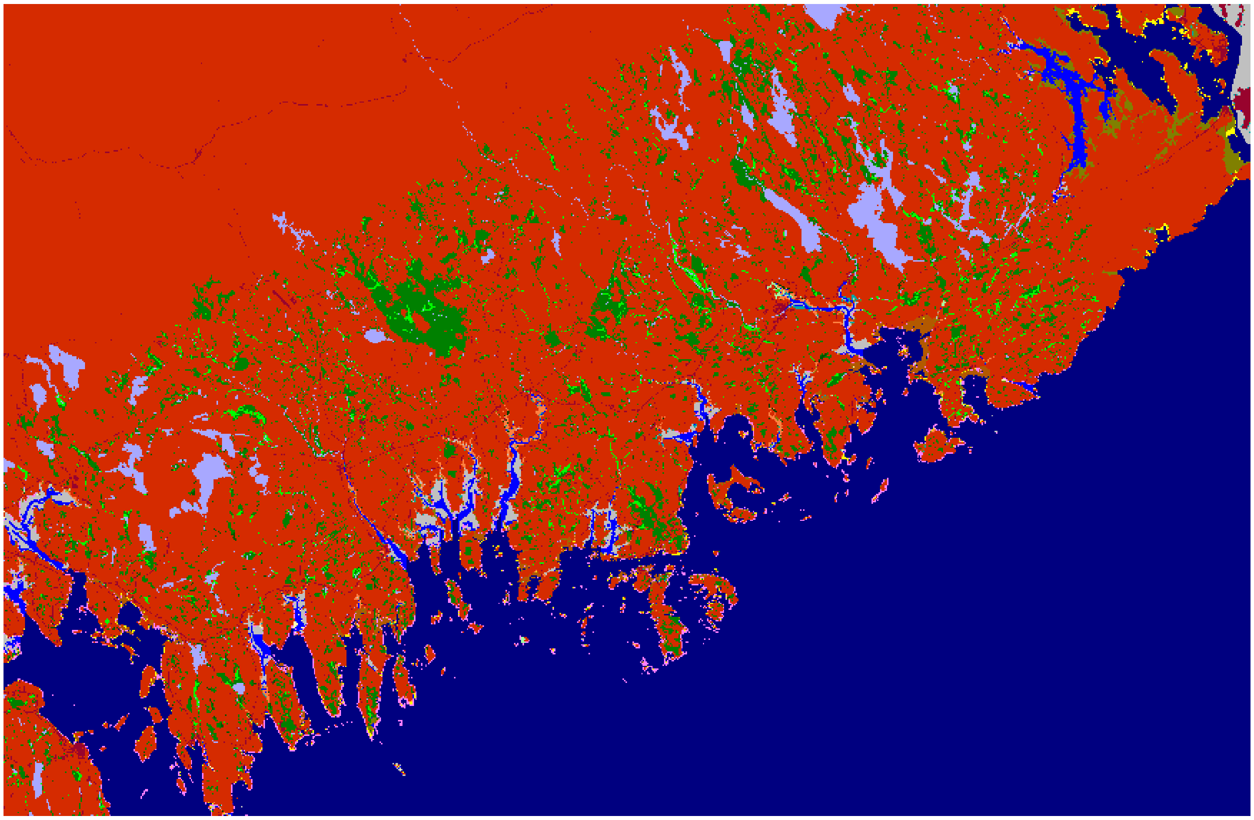
Petit Manan Section A Context, 2025, Scenario A1B Mean



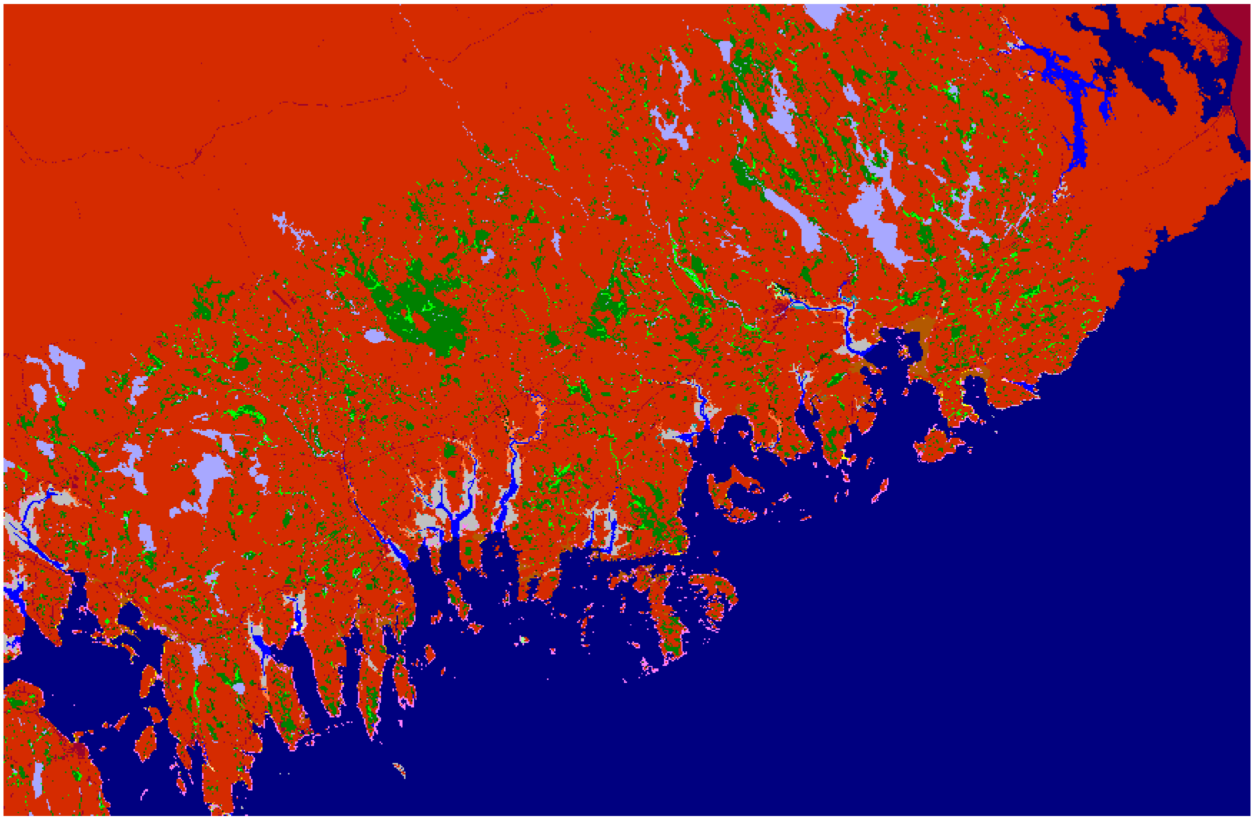
Petit Manan Section A Context, 2050, Scenario A1B Mean

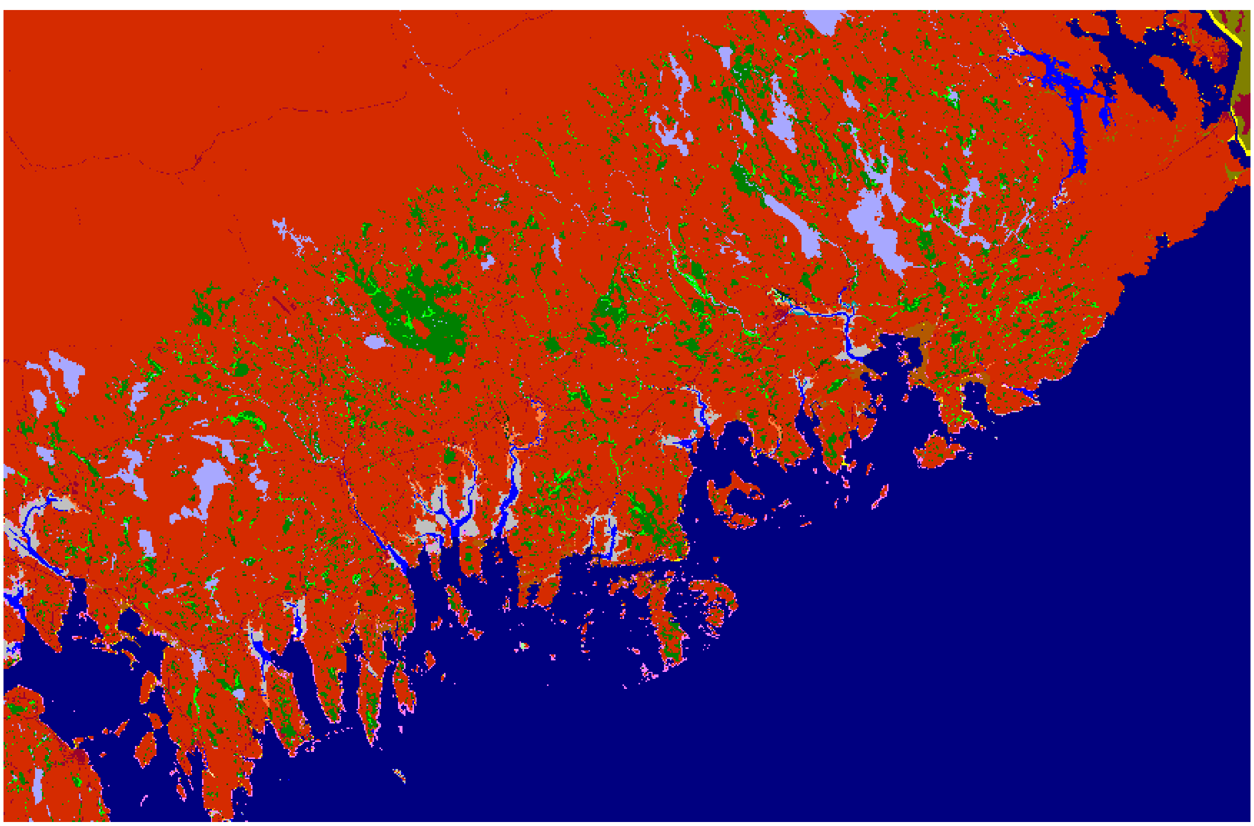


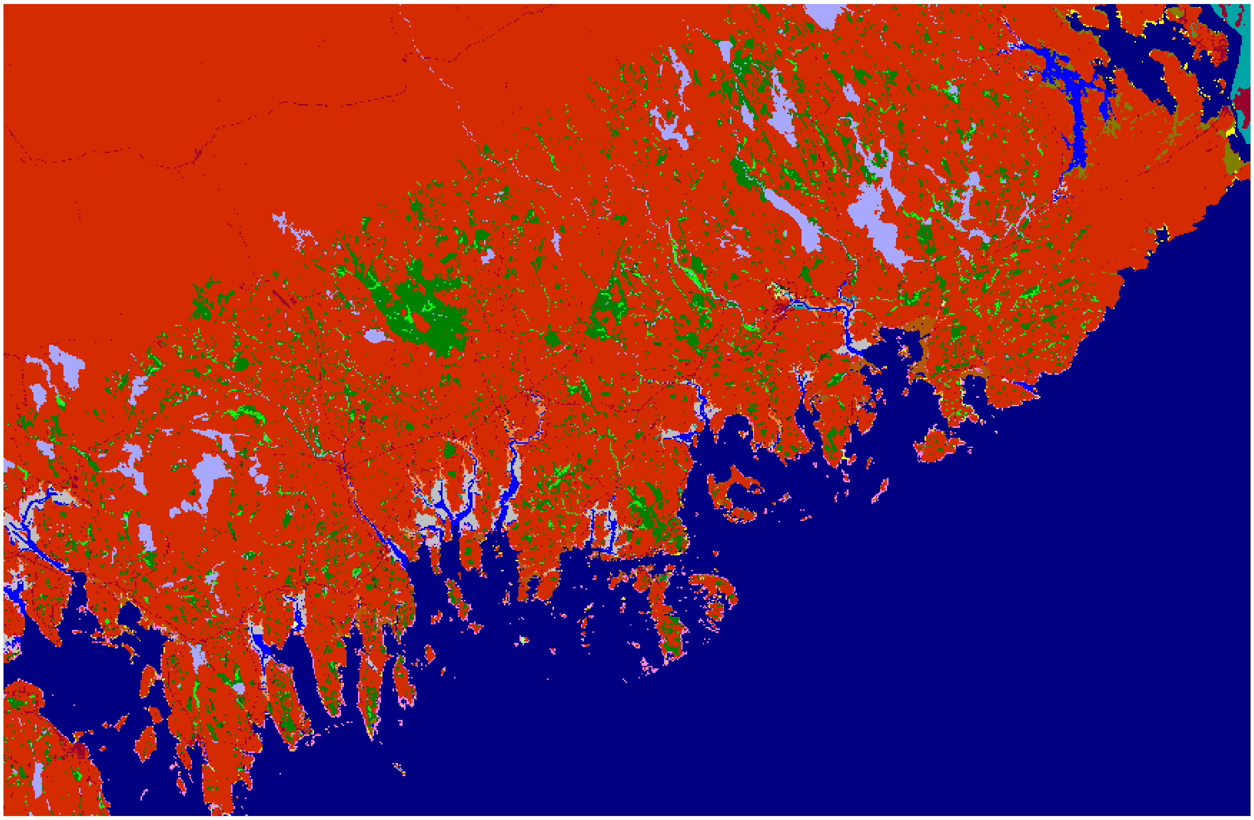
Petit Manan Section A Context, 2075, Scenario A1B Mean



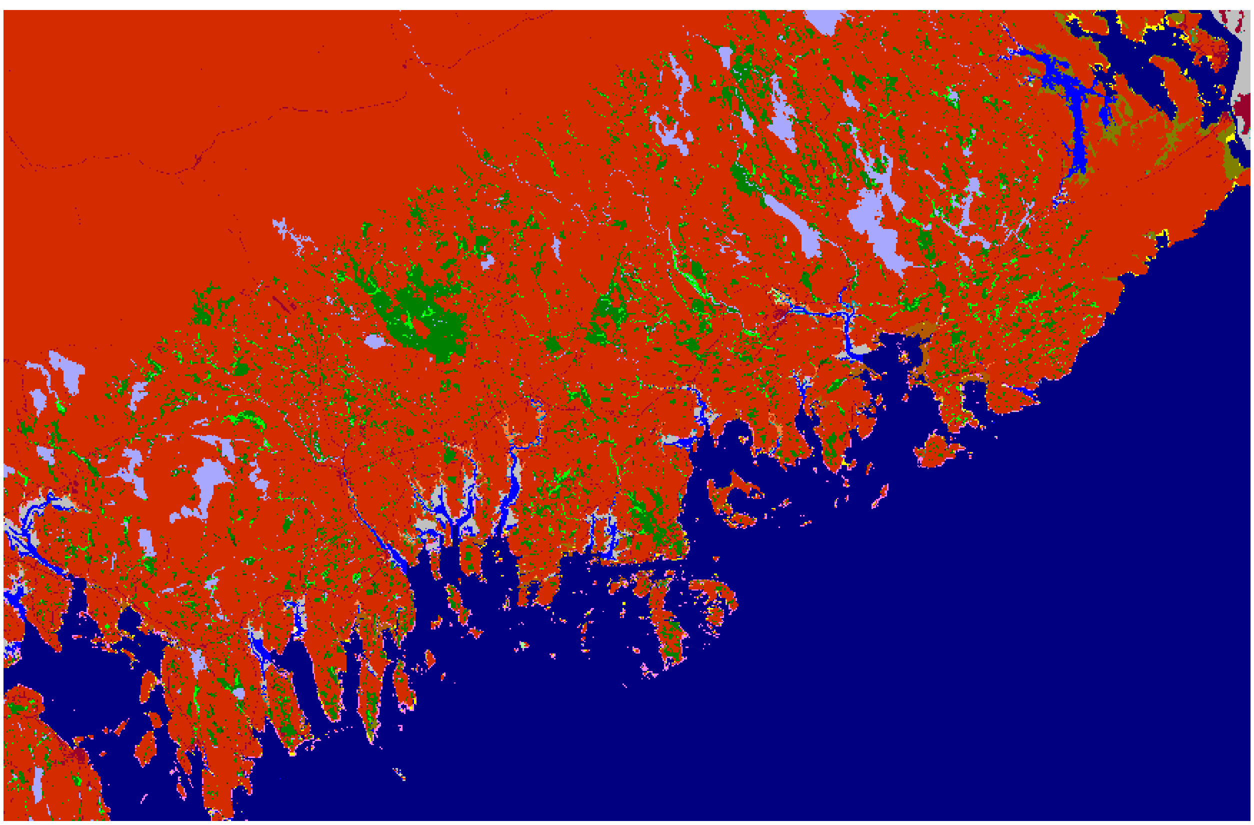
Petit Manan Section A Context, 2100, Scenario A1B Mean


Petit Manan Section A Context, Initial Condition

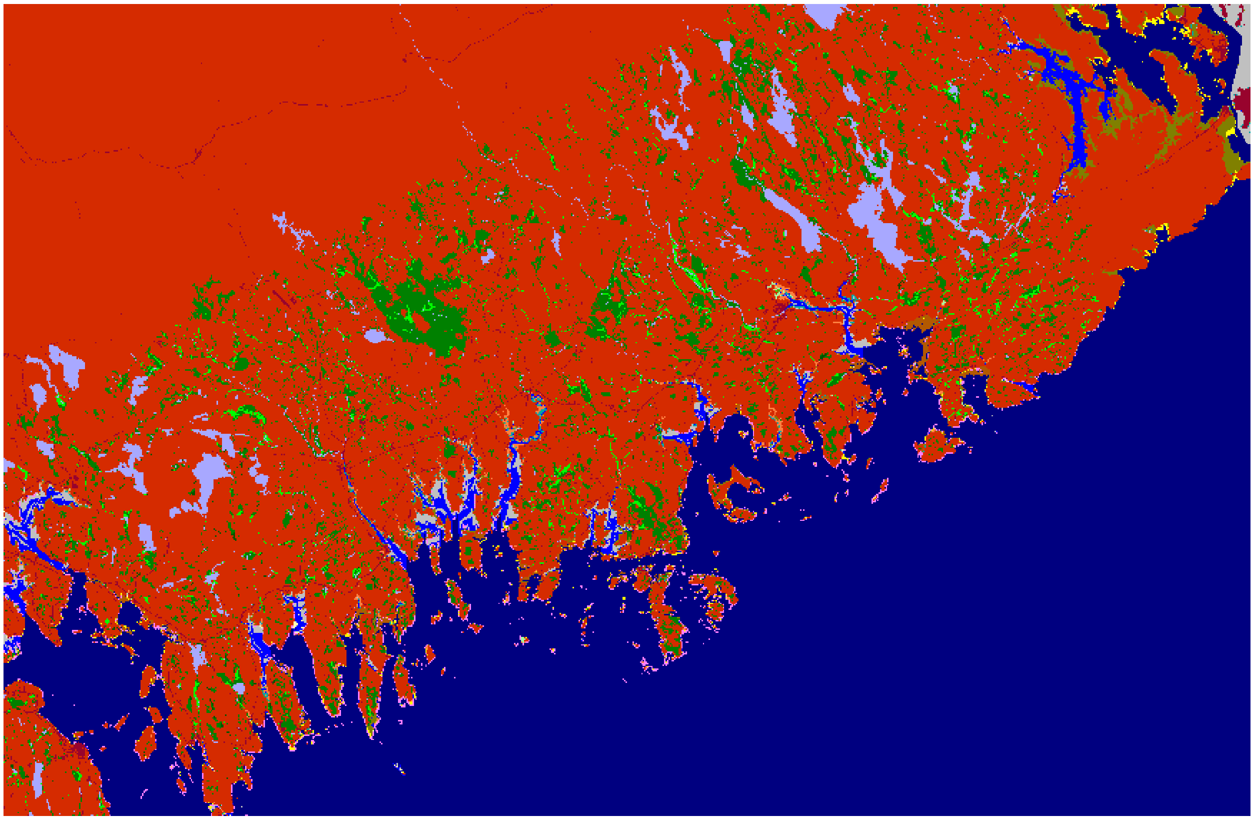

Petit Manan Section A Context, 2025, Scenario A1B Maximum



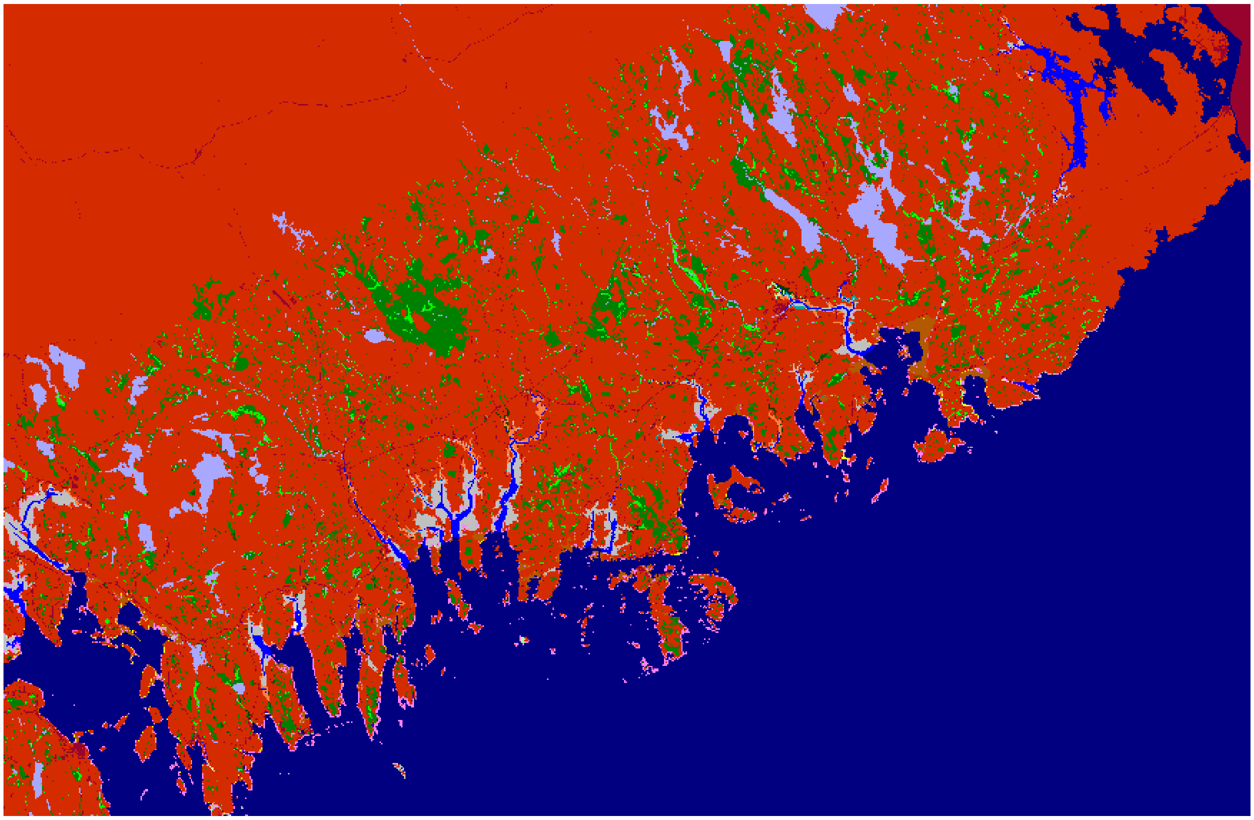
Petit Manan Section A Context, 2050, Scenario A1B Maximum



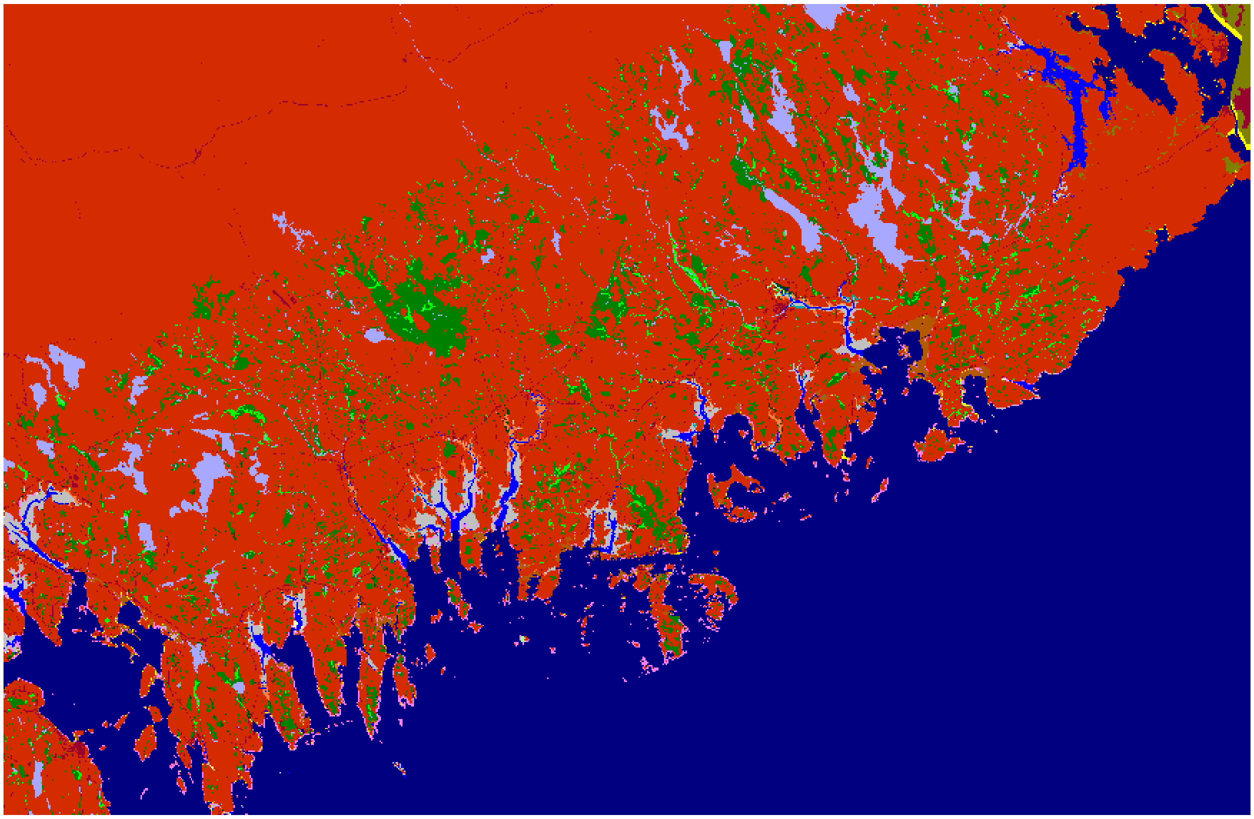
Petit Manan Section A Context, 2075, Scenario A1B Maximum



Petit Manan Section A Context, 2100, Scenario A1B Maximum



Petit Manan Section A Context, Initial Condition



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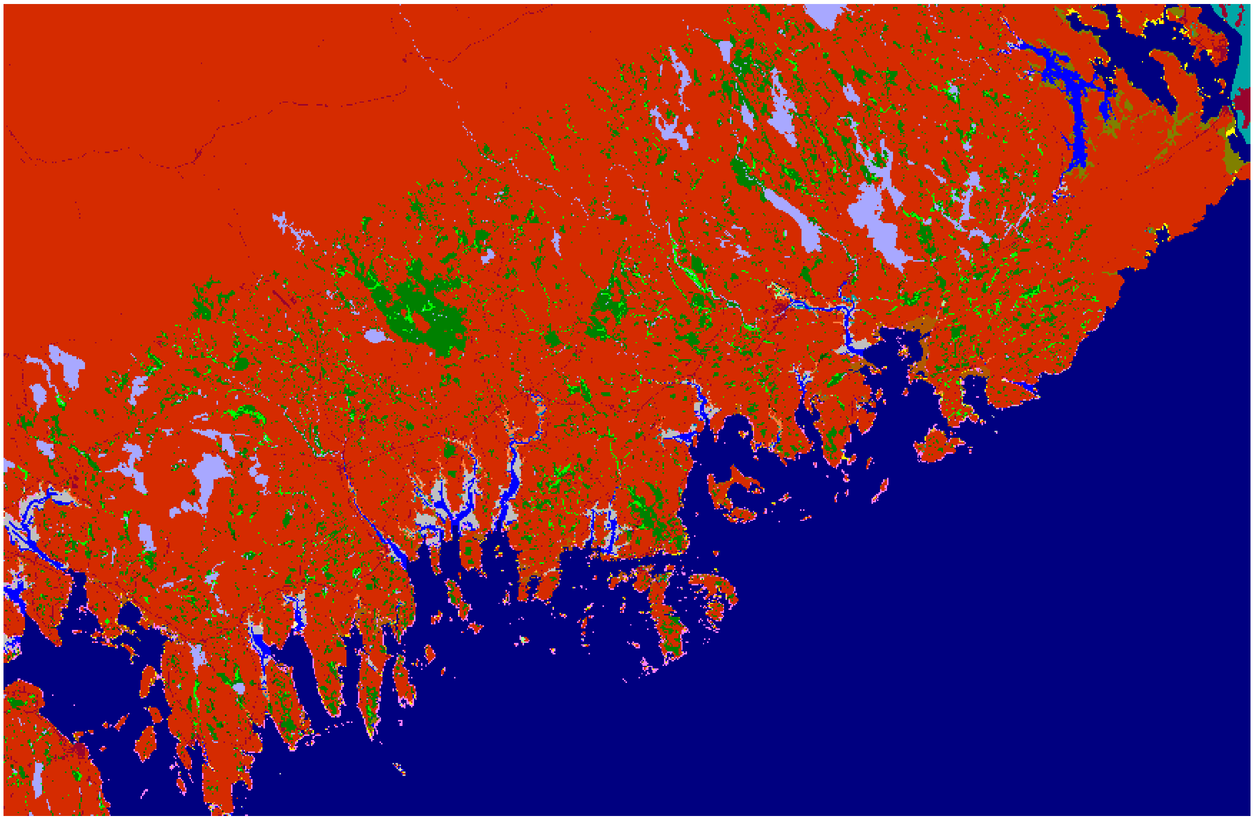

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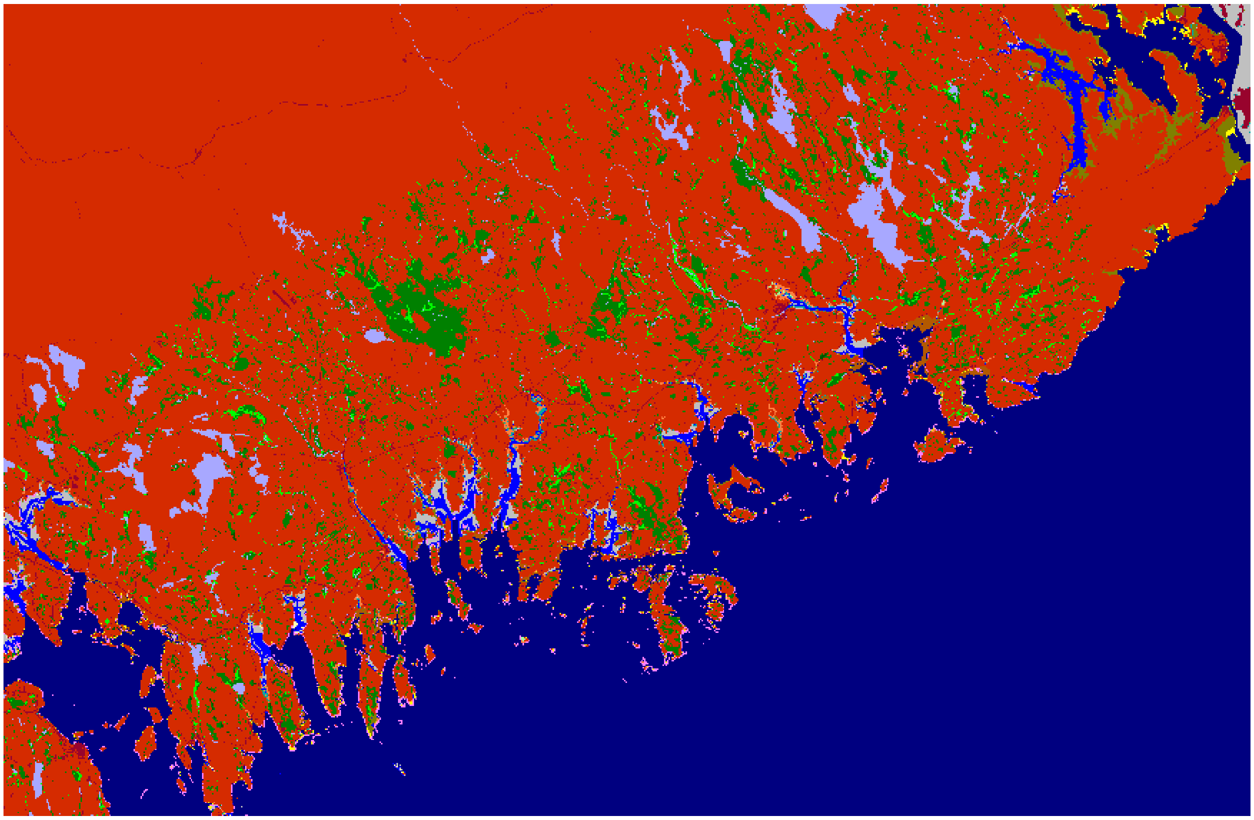

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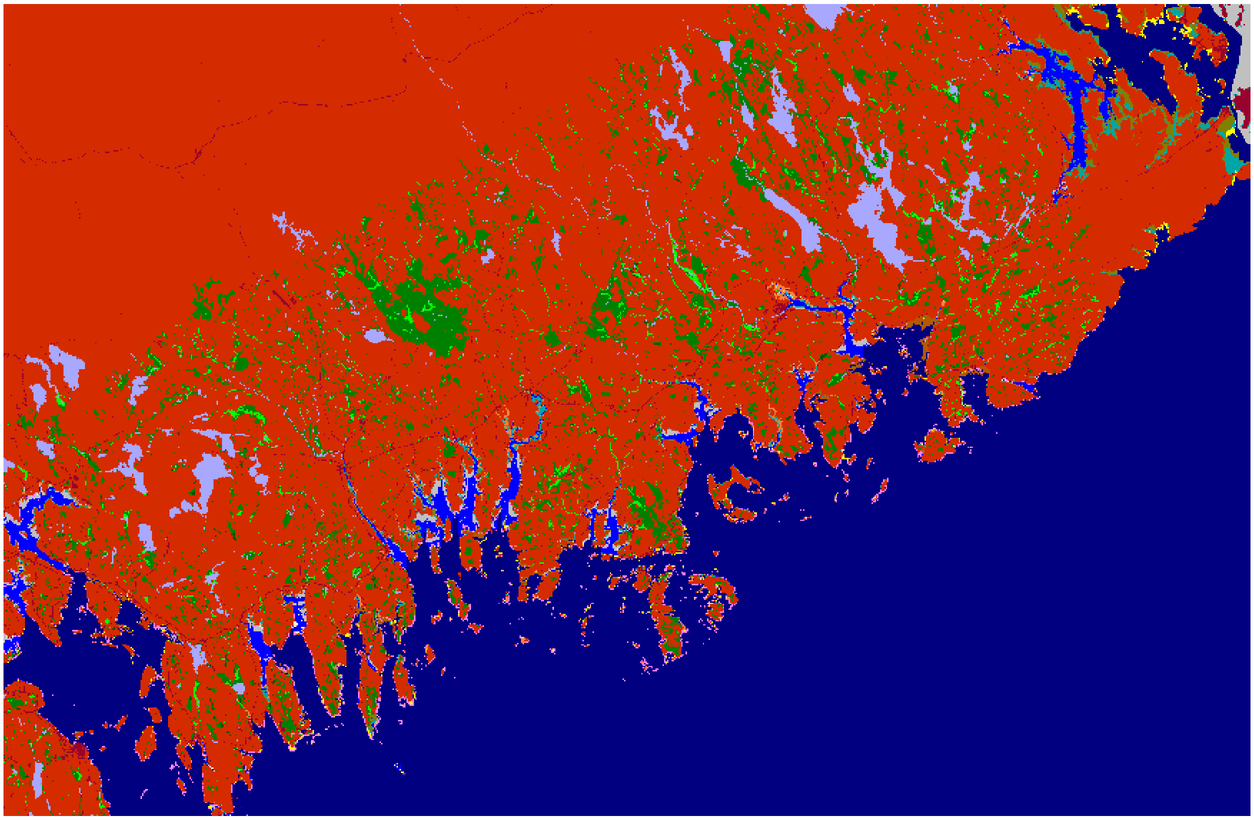
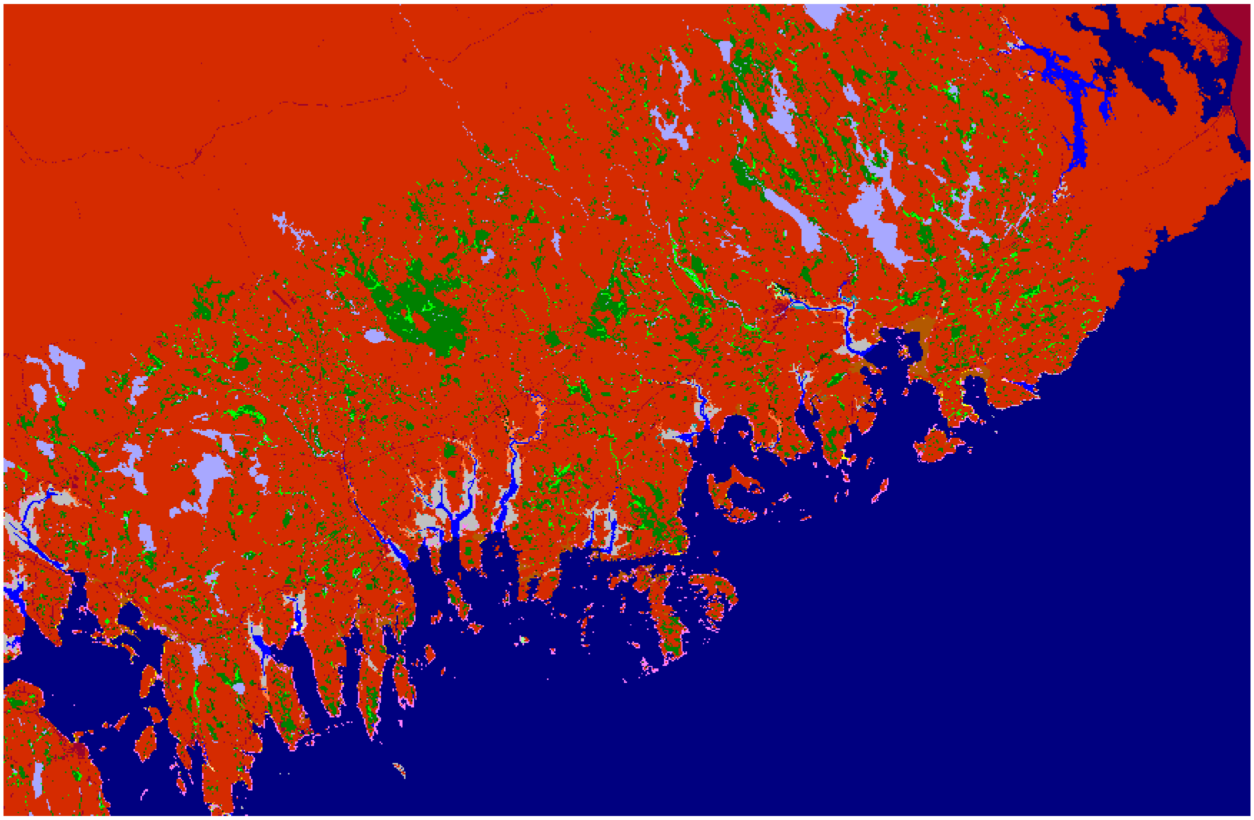
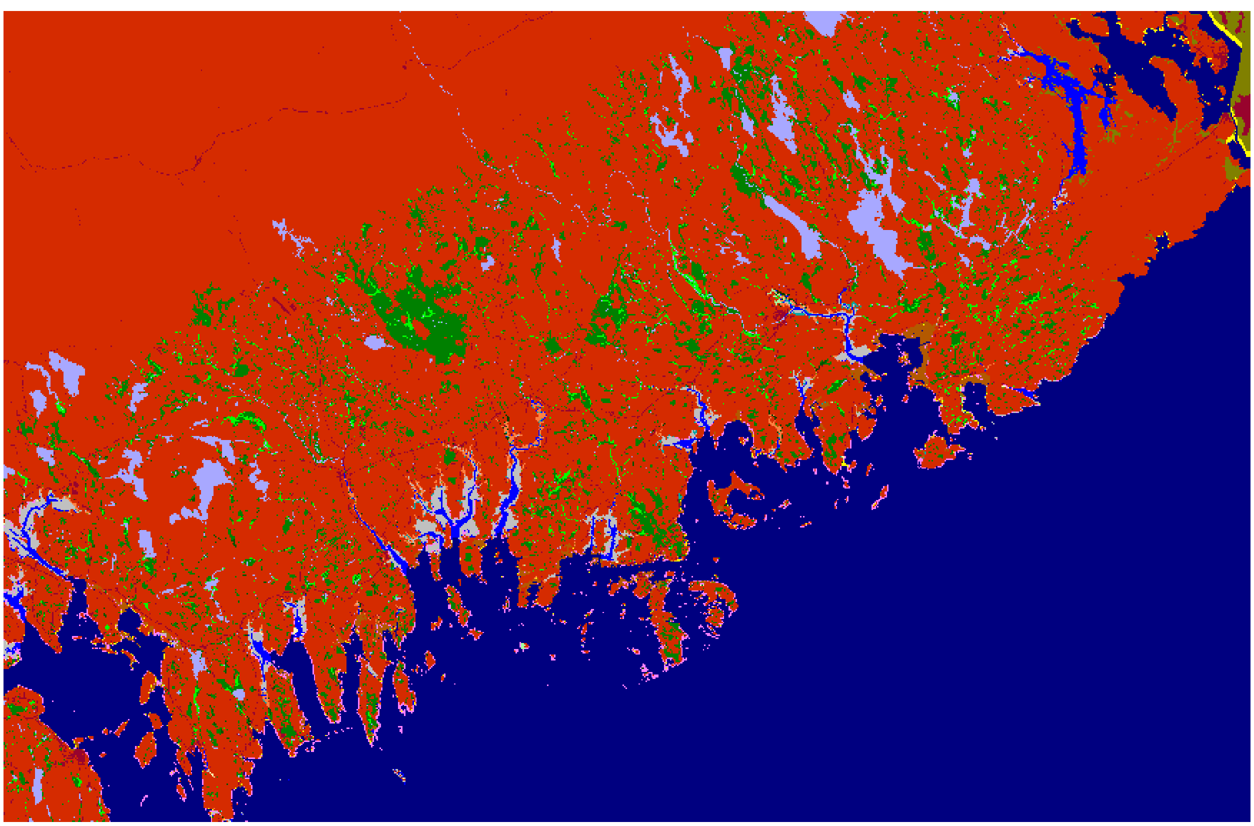


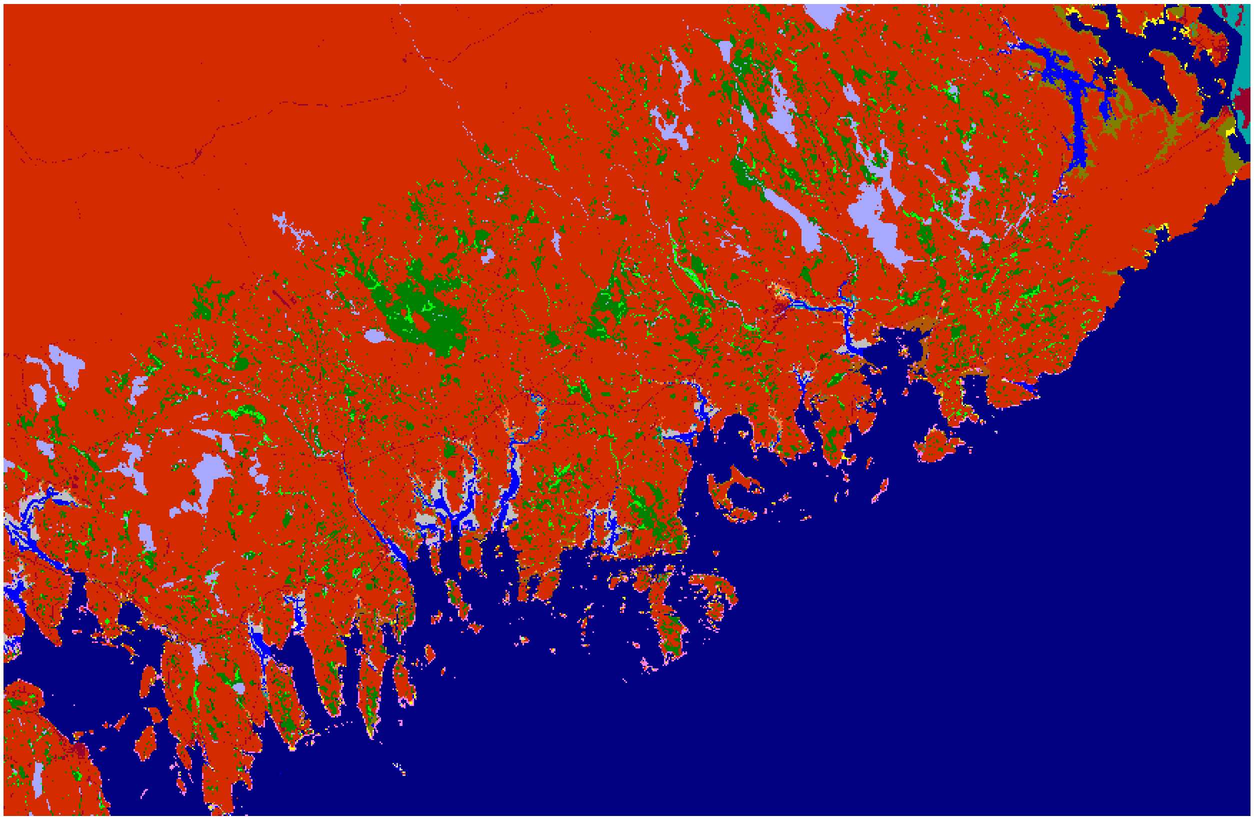
Petit Manan Section A Context, 2100, 1 Meter



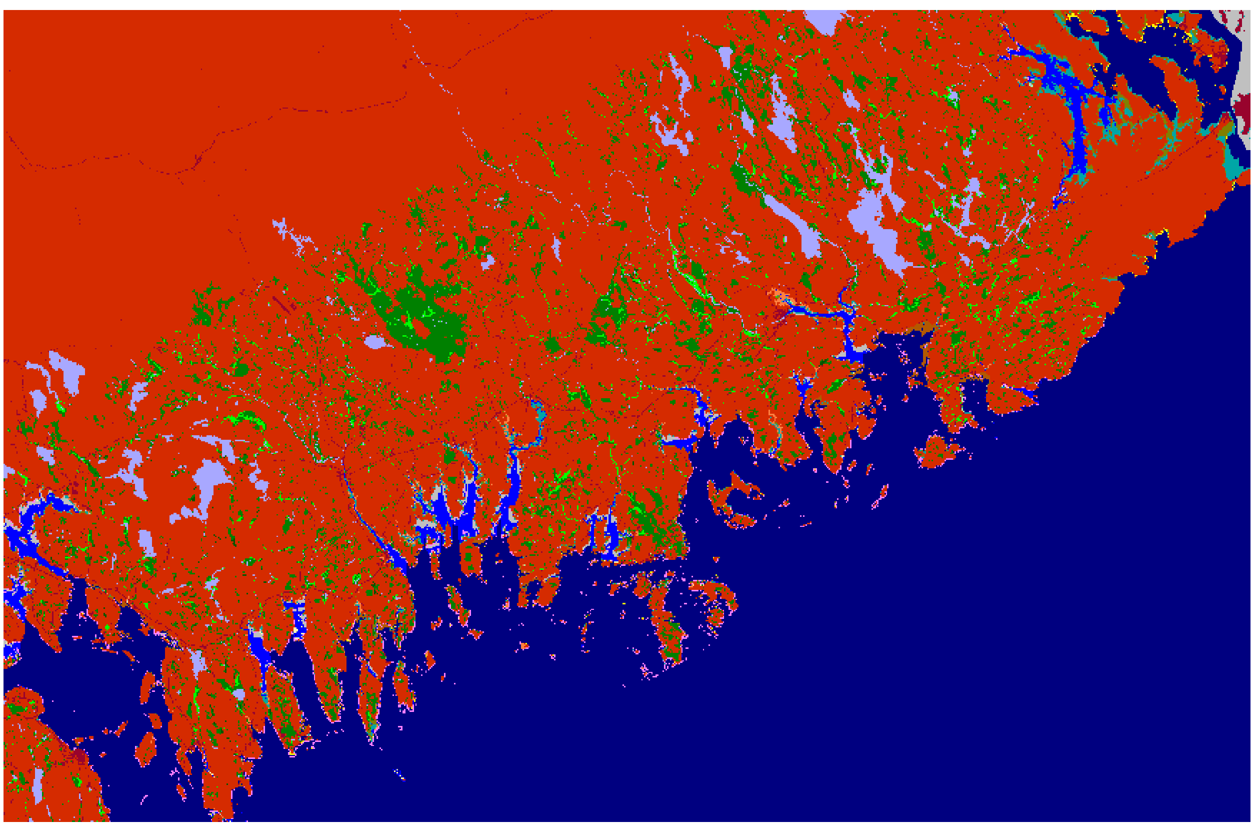
Petit Manan Section A Context, Initial Condition



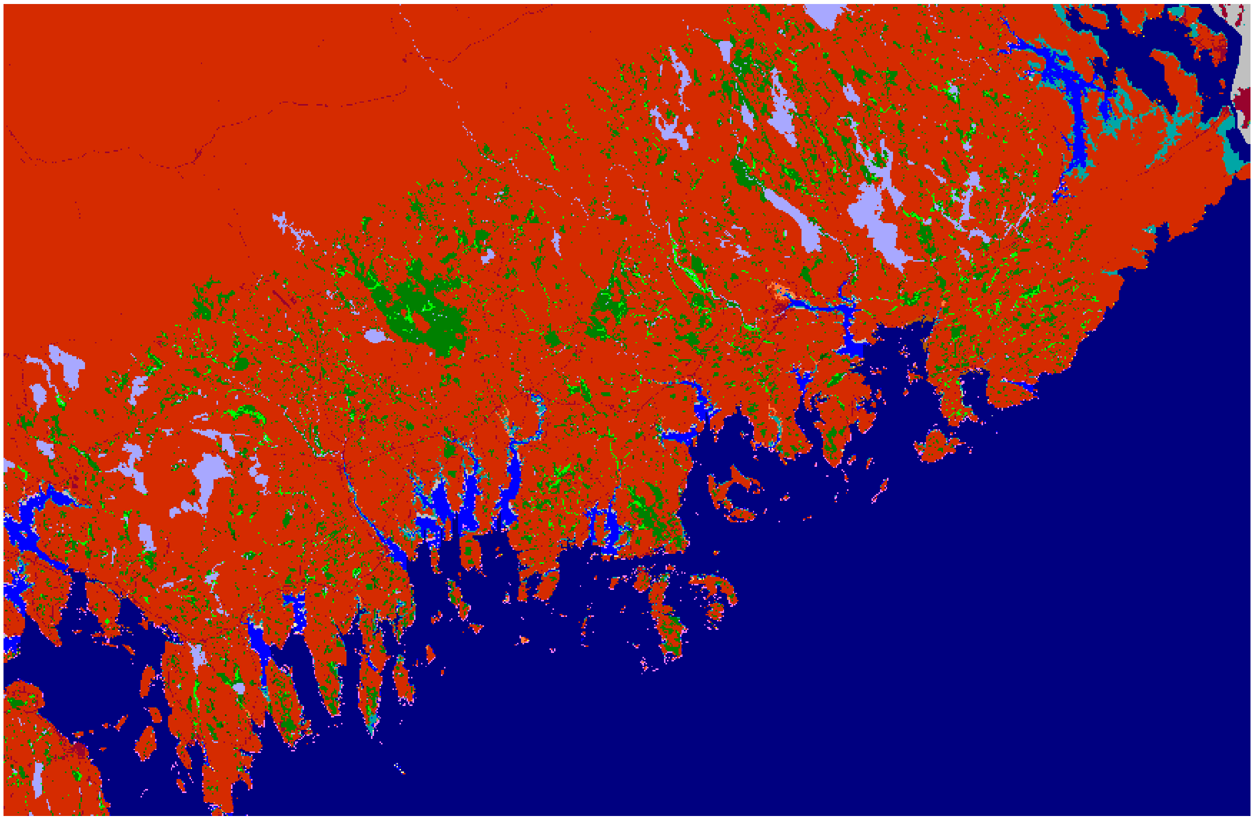
Petit Manan Section A Context, 2025, 1.5 Meters



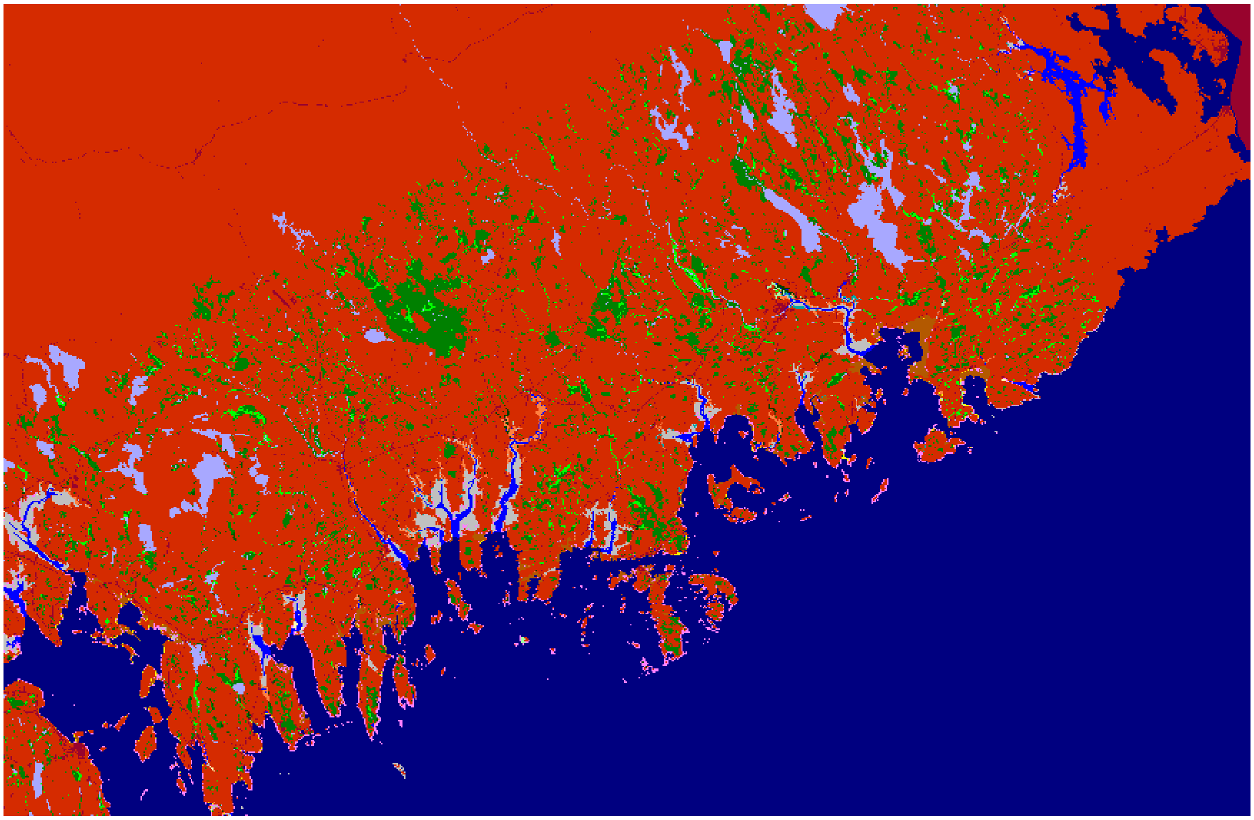
Petit Manan Section A Context, 2050, 1.5 Meters



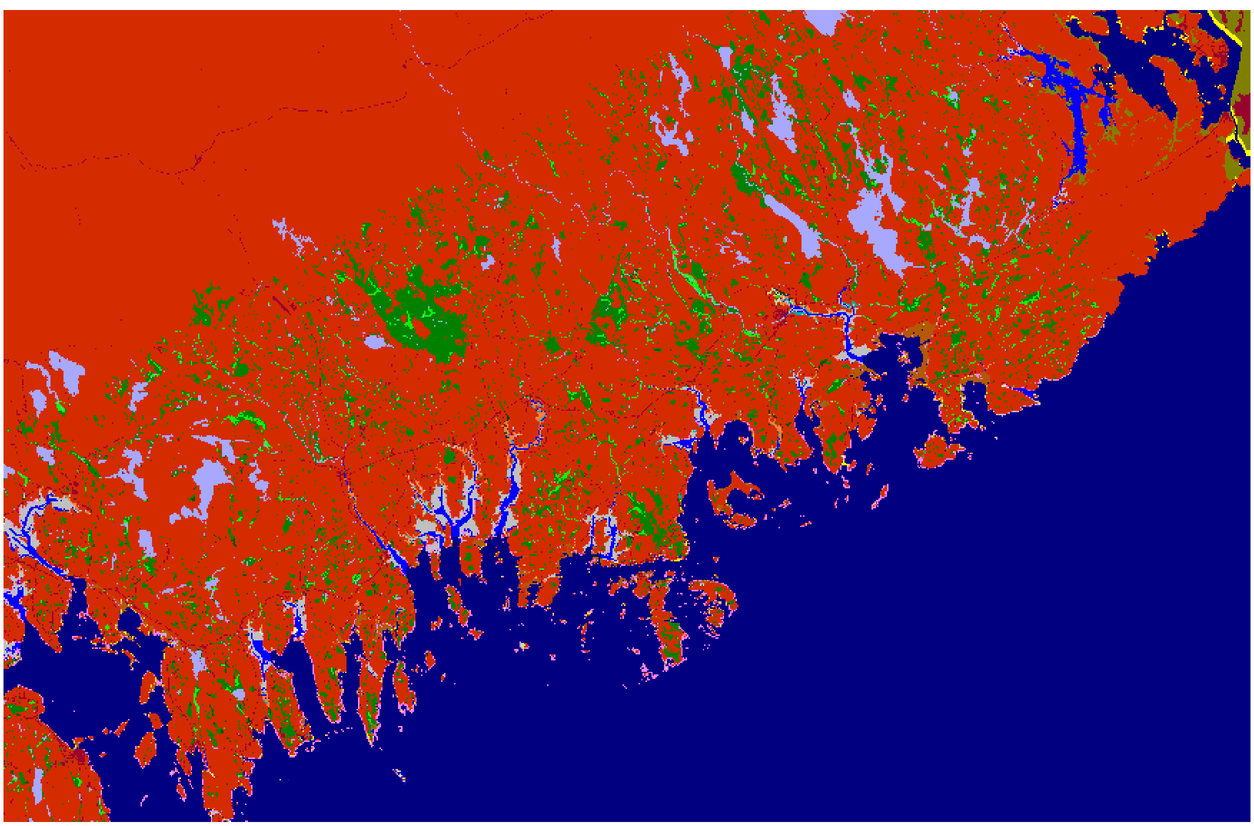
Petit Manan Section A Context, 2075, 1.5 Meters



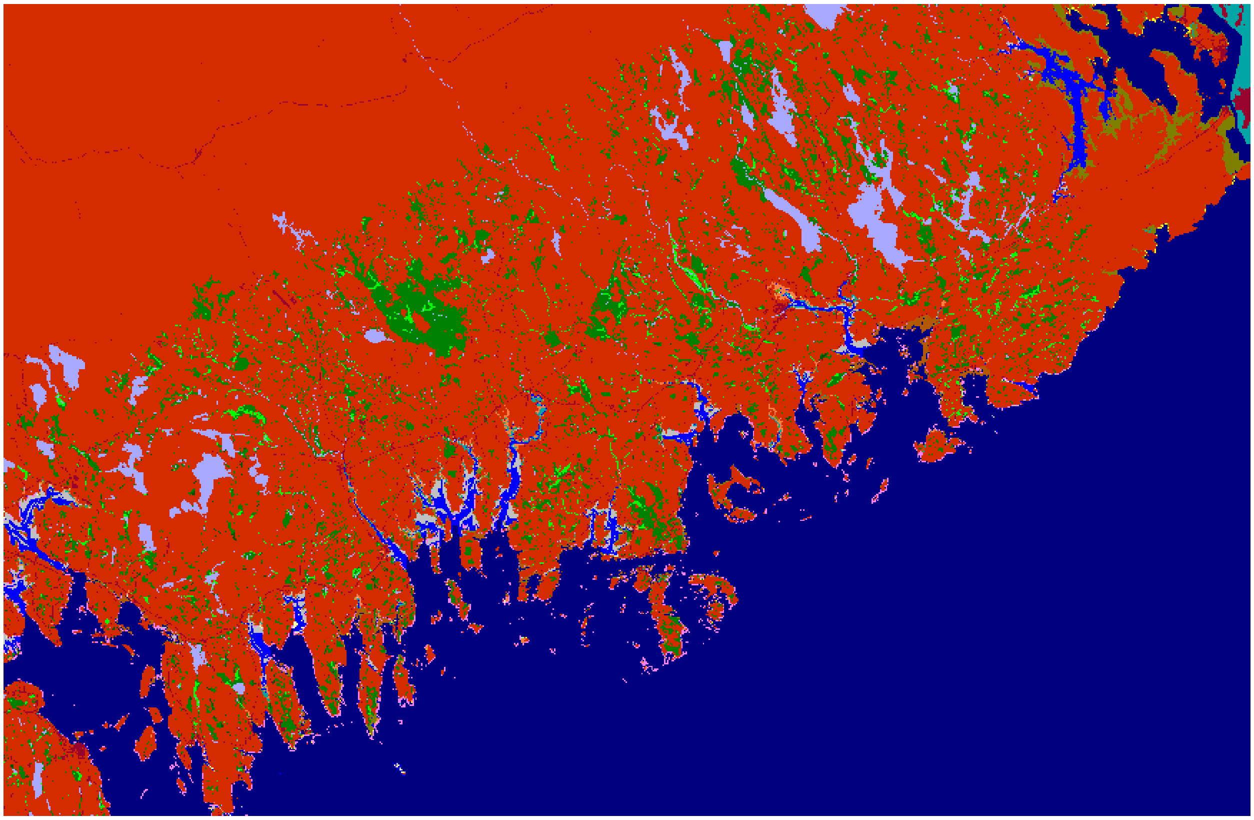
Petit Manan Section A Context, 2100, 1.5 Meters



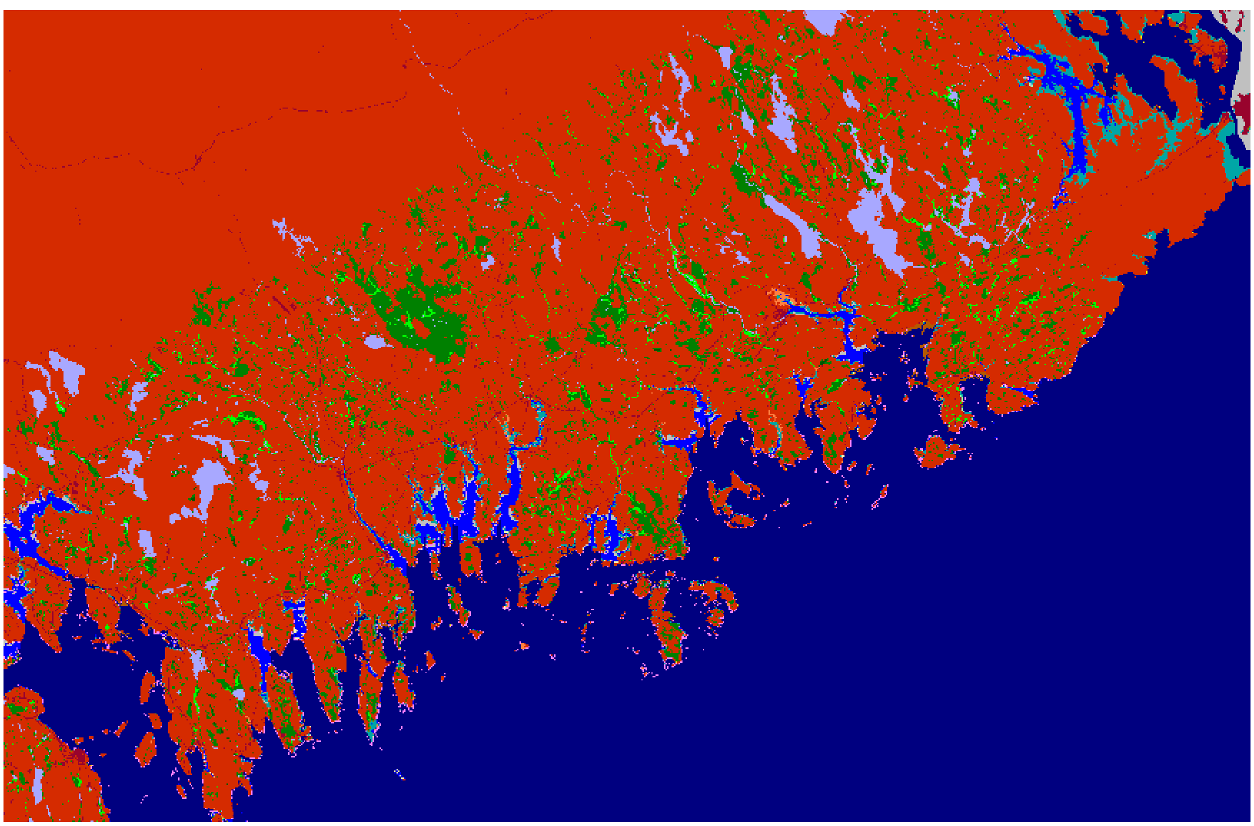
Petit Manan Section A Context, Initial Condition



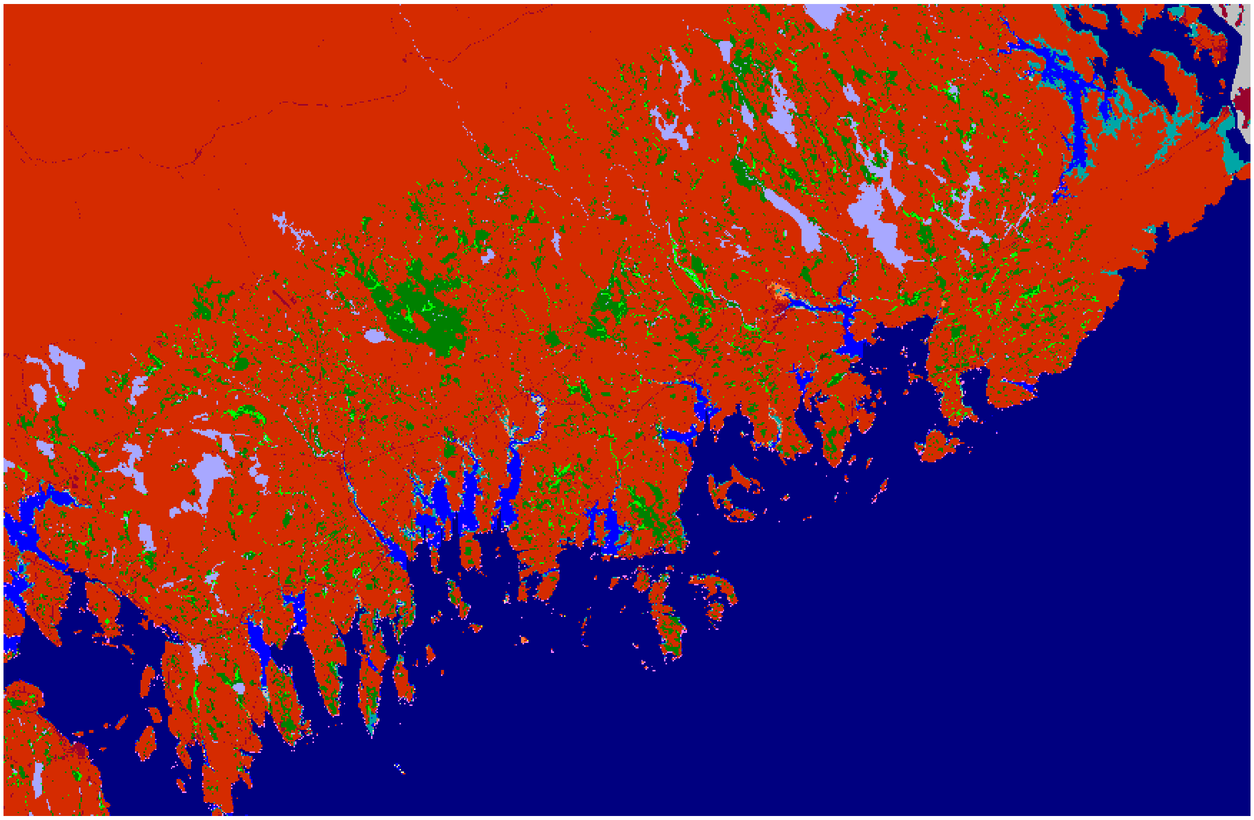
Petit Manan Section A Context, 2025, 2 Meters



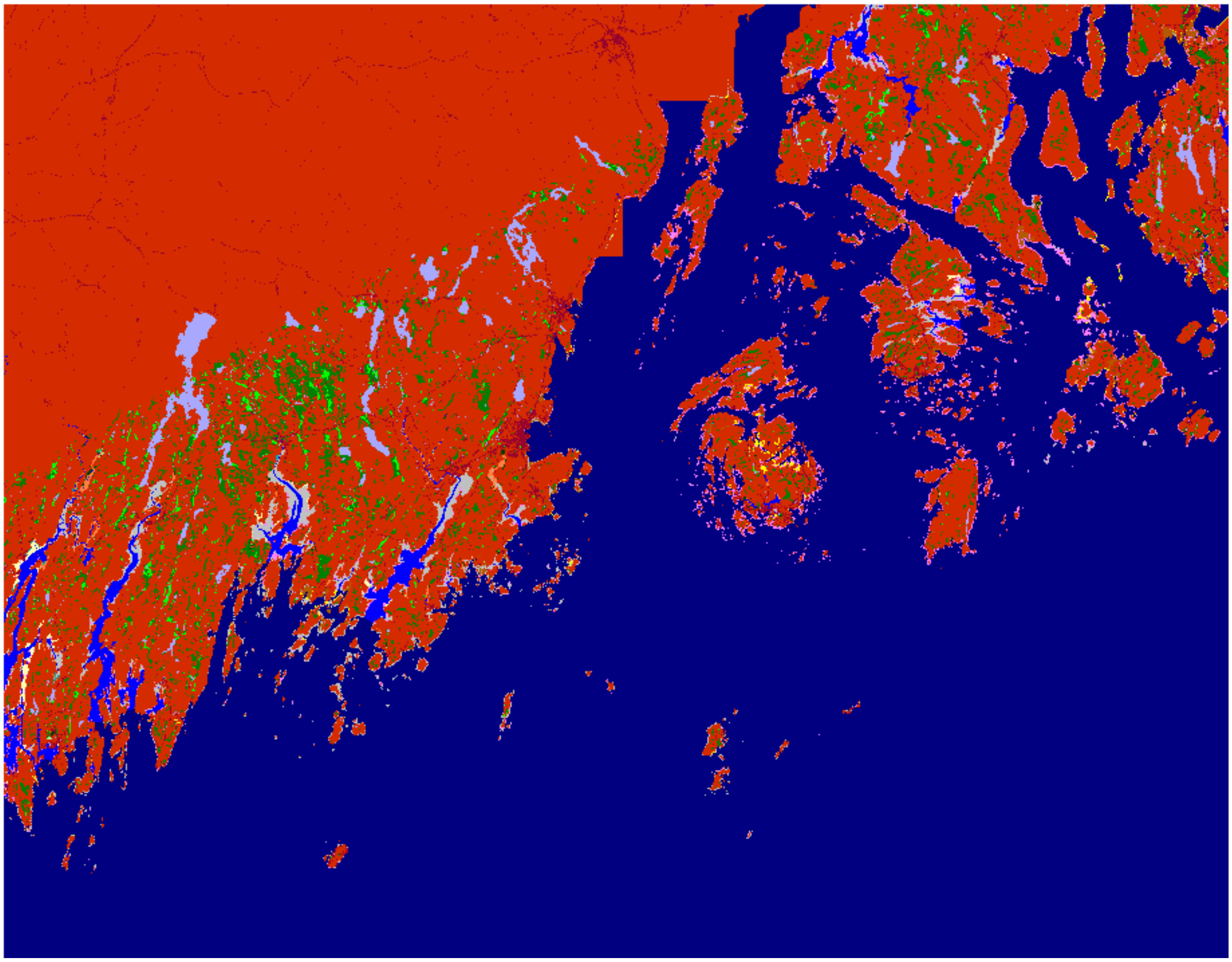
Petit Manan Section A Context, 2050, 2 Meters



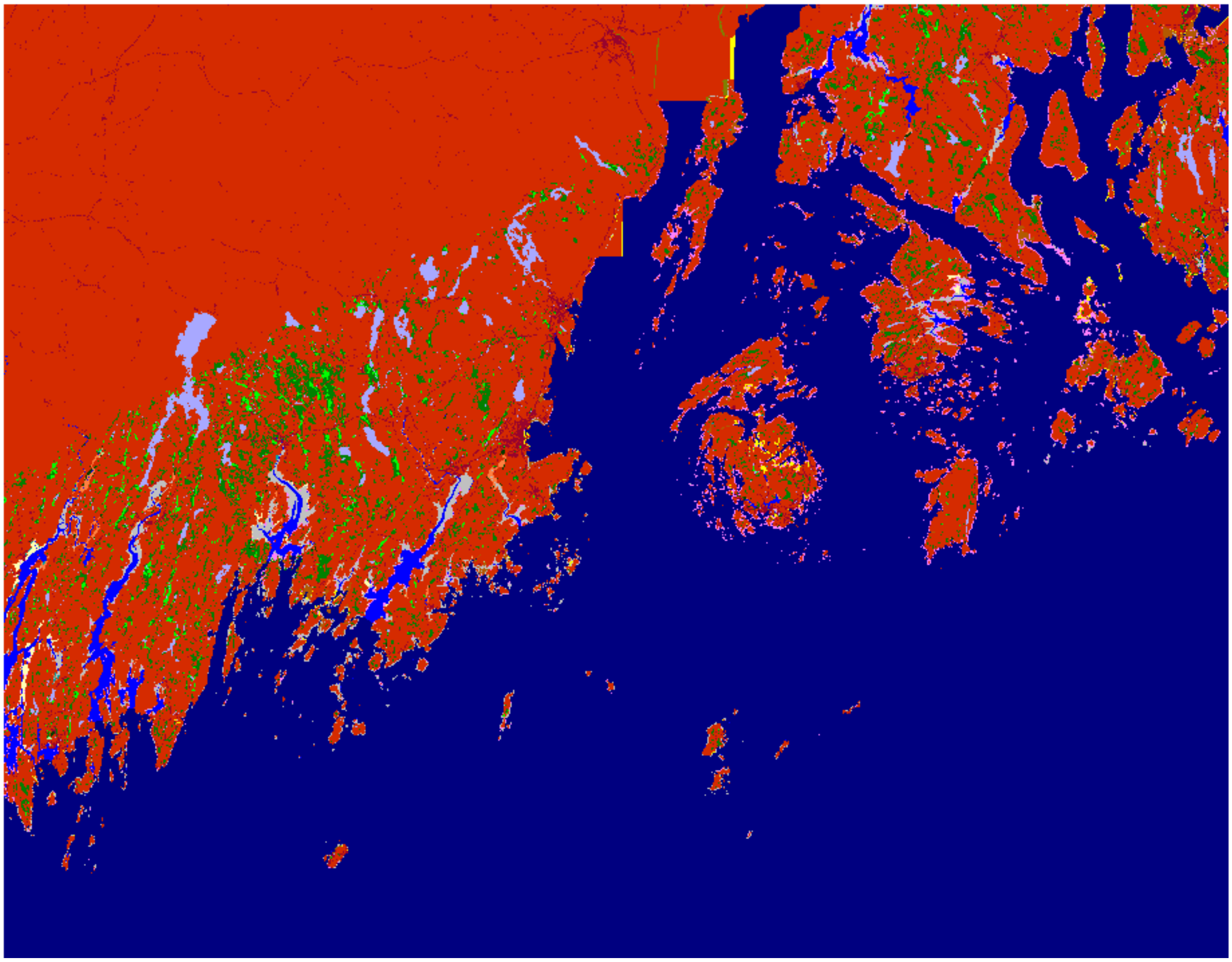
Petit Manan Section A Context, 2075, 2 Meters



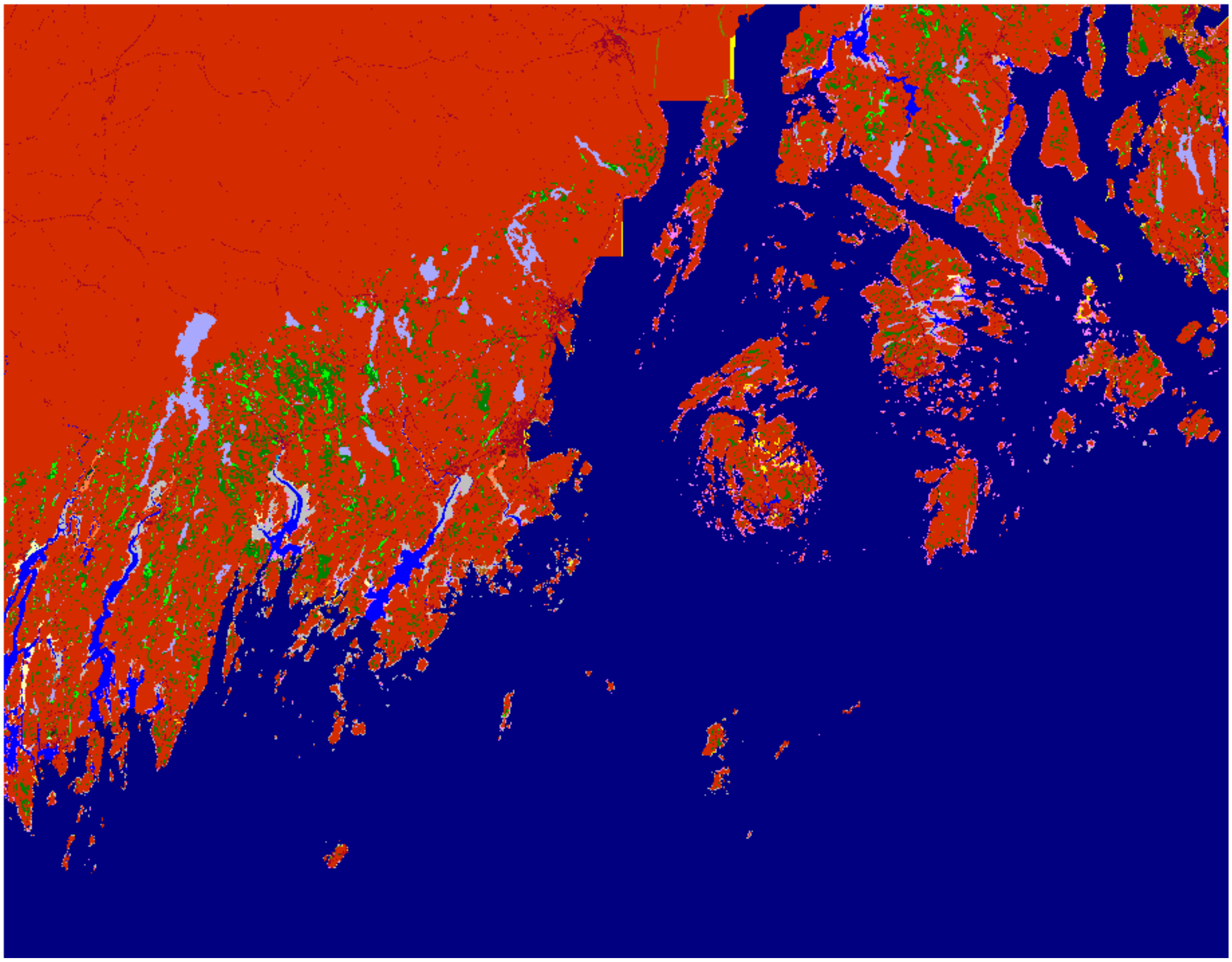
Petit Manan Section A Context, 2100, 2 Meters



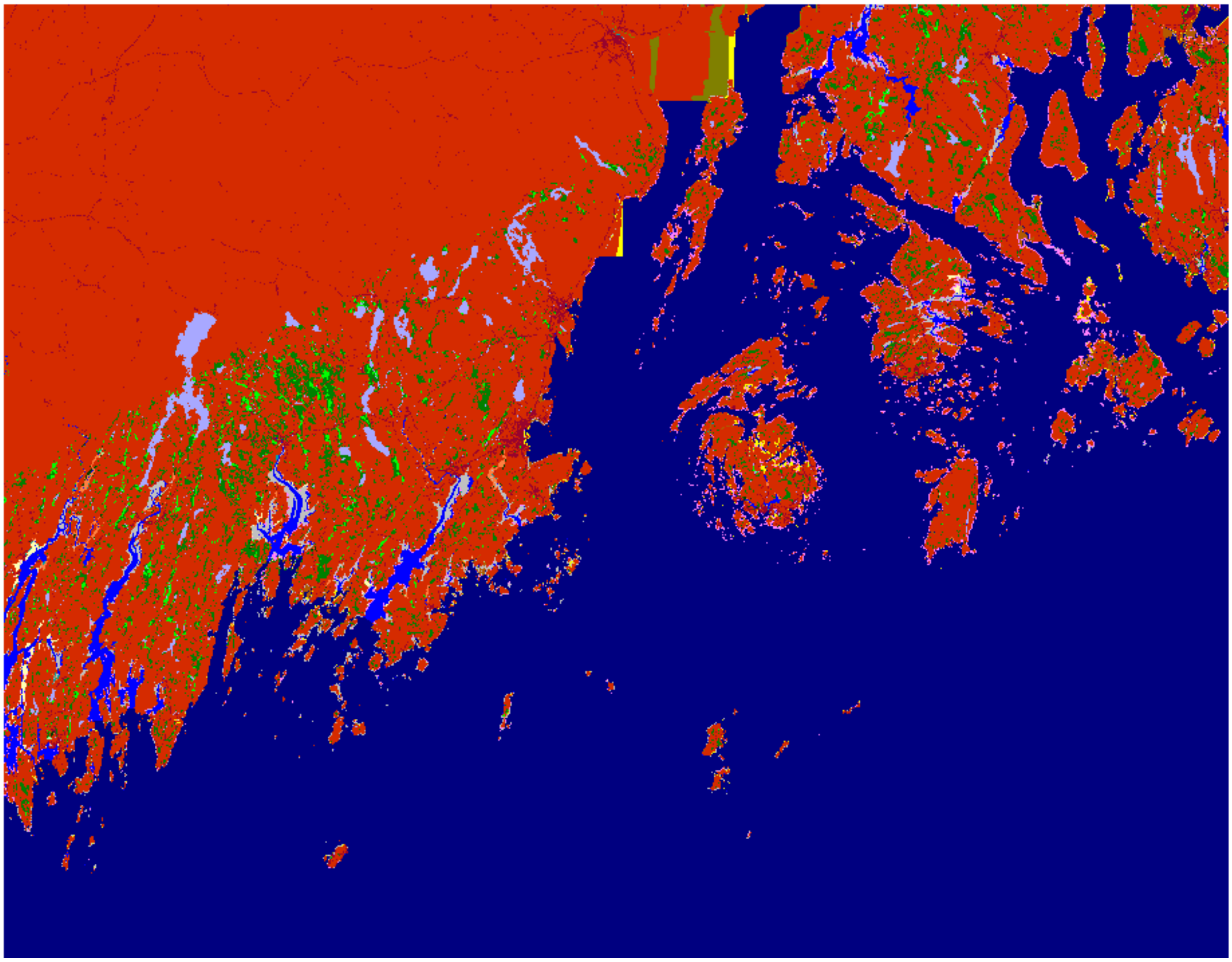
Petit Manan Section B Context, Initial Condition



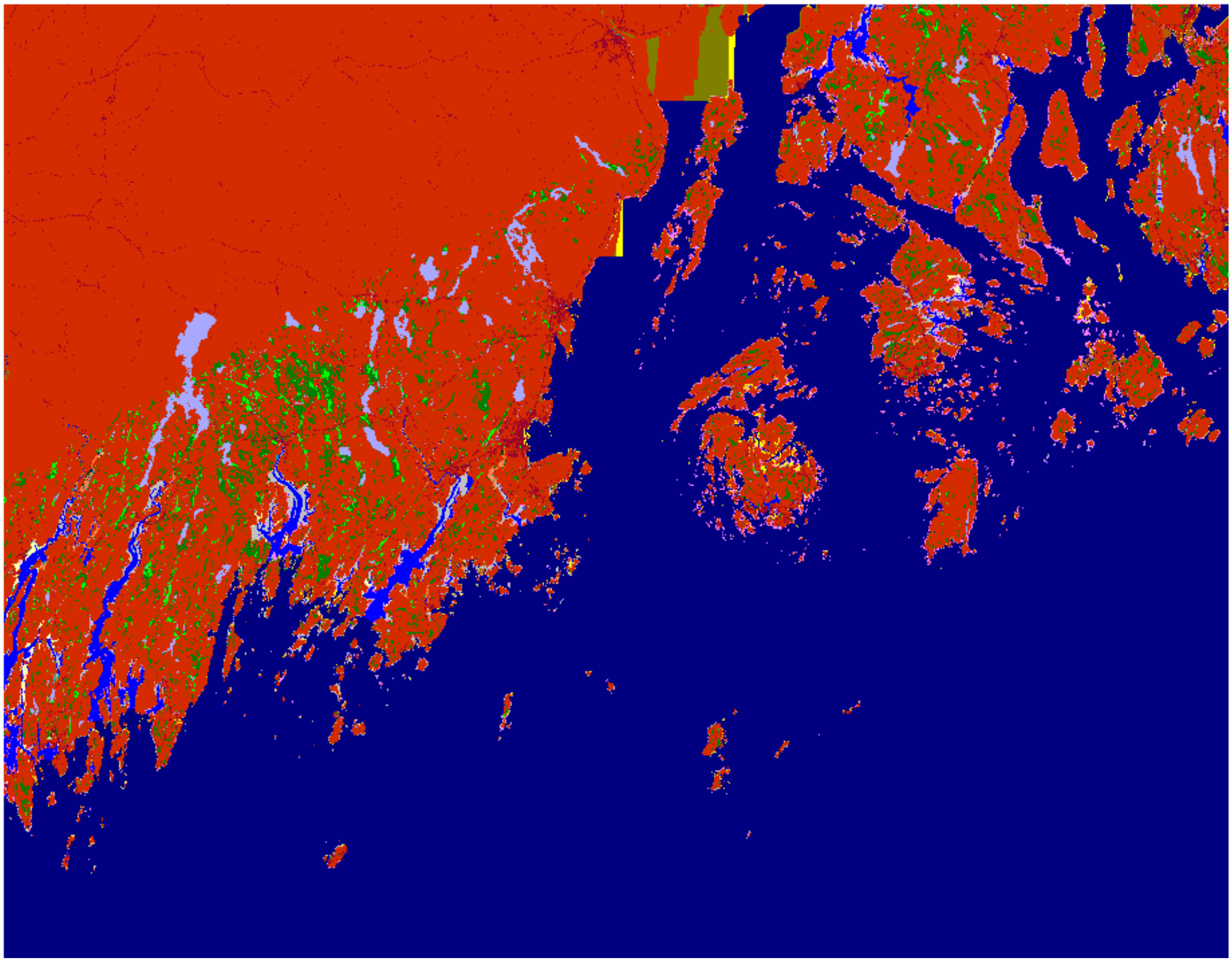
Petit Manan Section B Context, 2025, Scenario A1B Mean



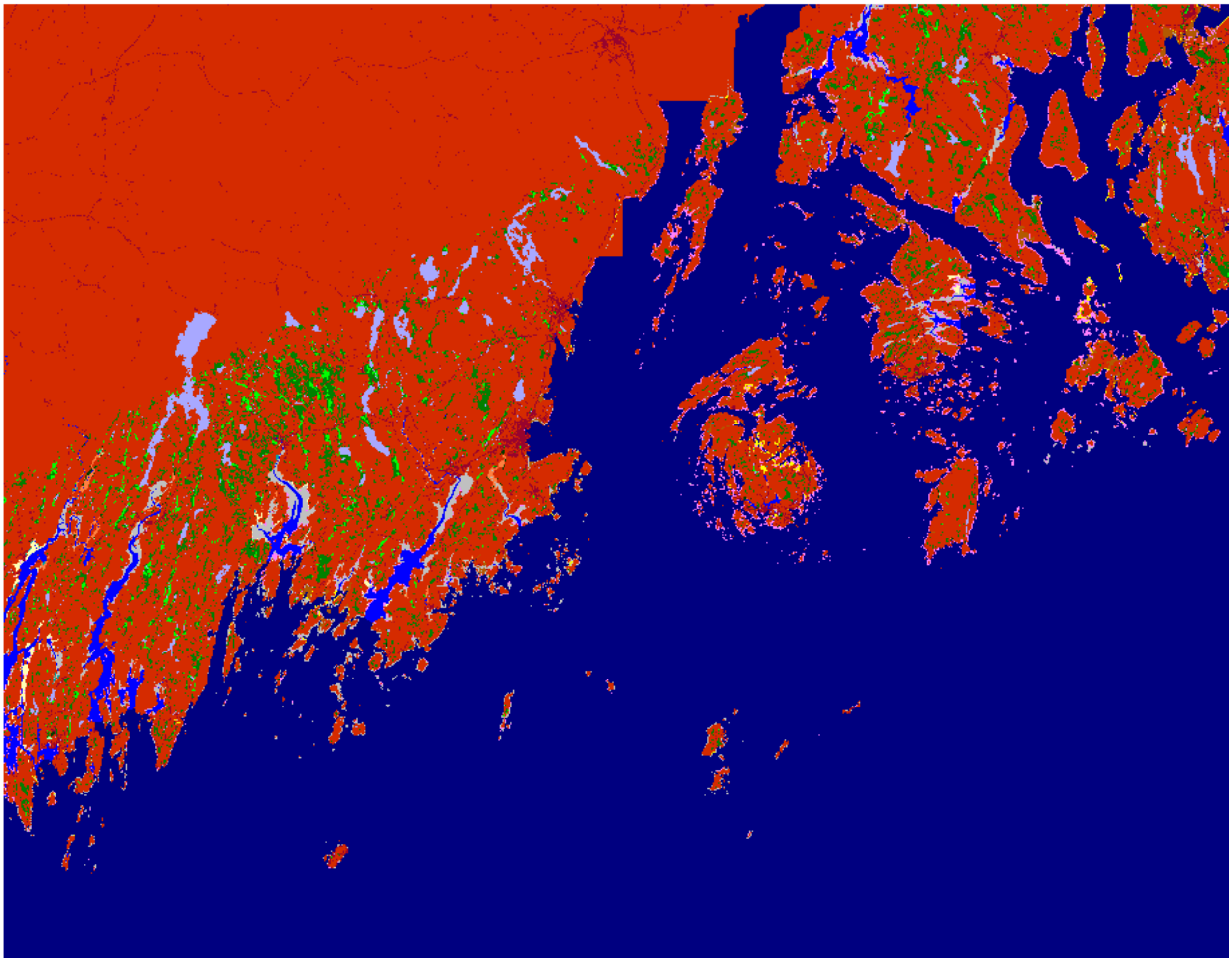
Petit Manan Section B Context, 2050, Scenario A1B Mean



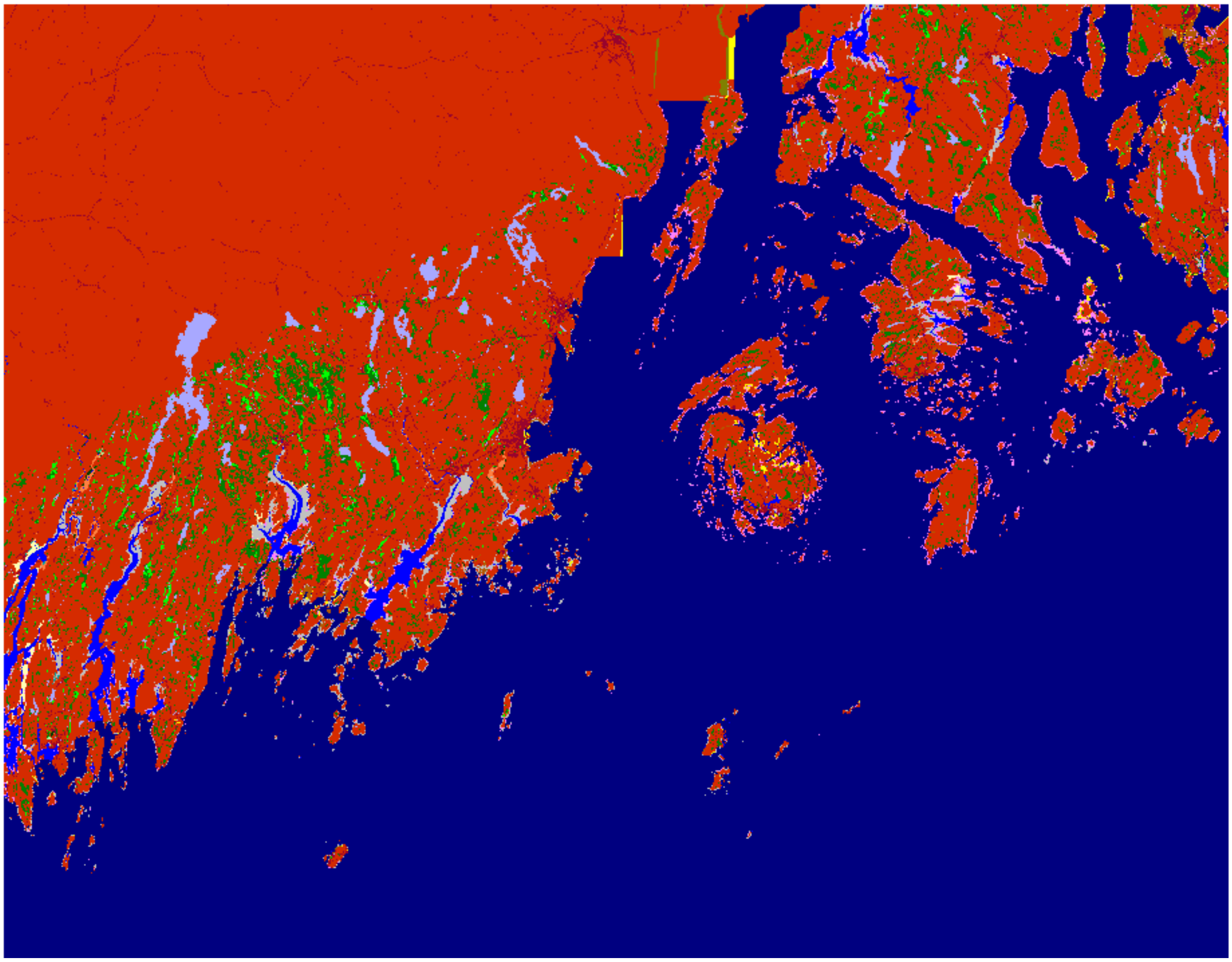
Petit Manan Section B Context, 2075, Scenario A1B Mean



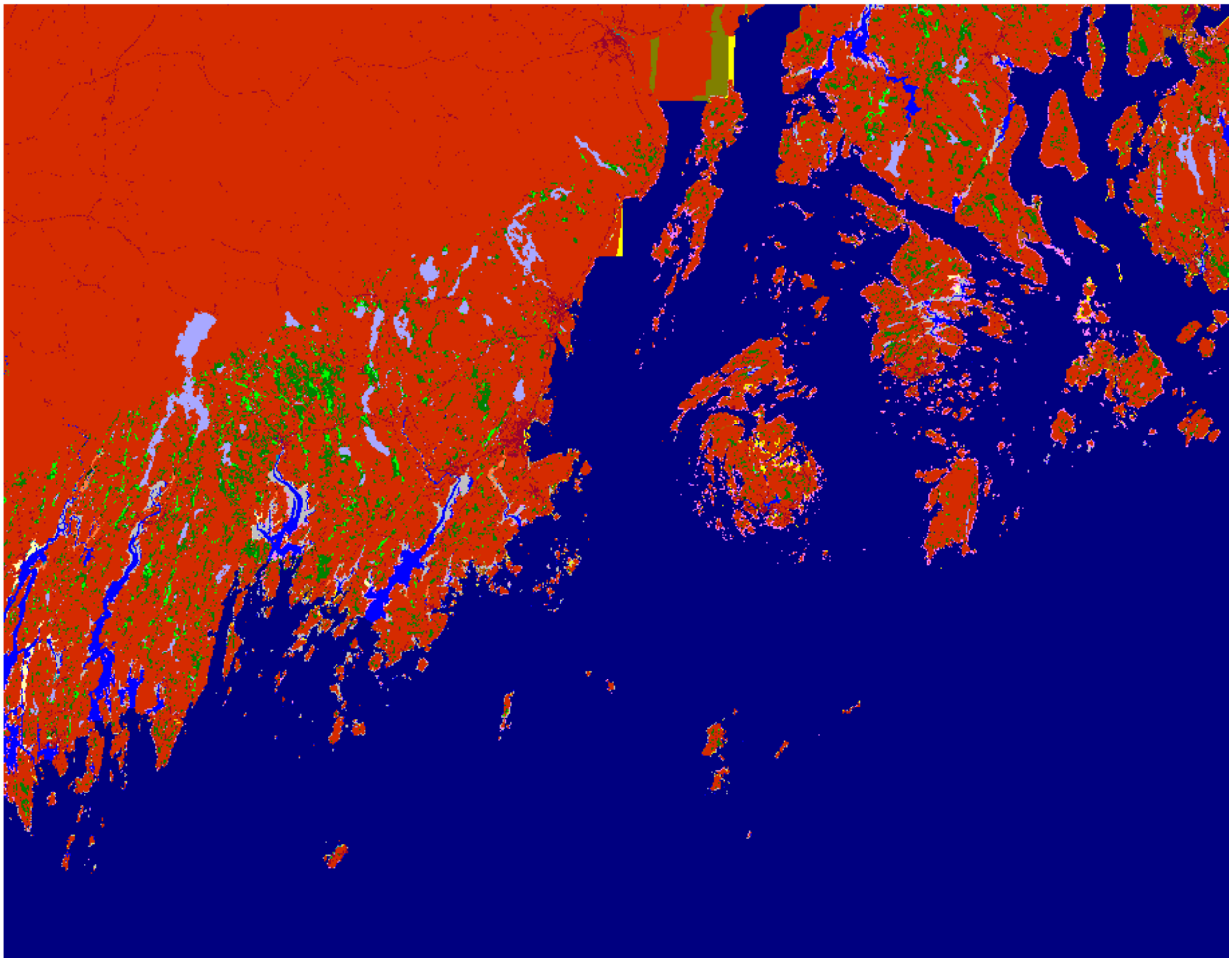
Petit Manan Section B Context, 2100, Scenario A1B Mean



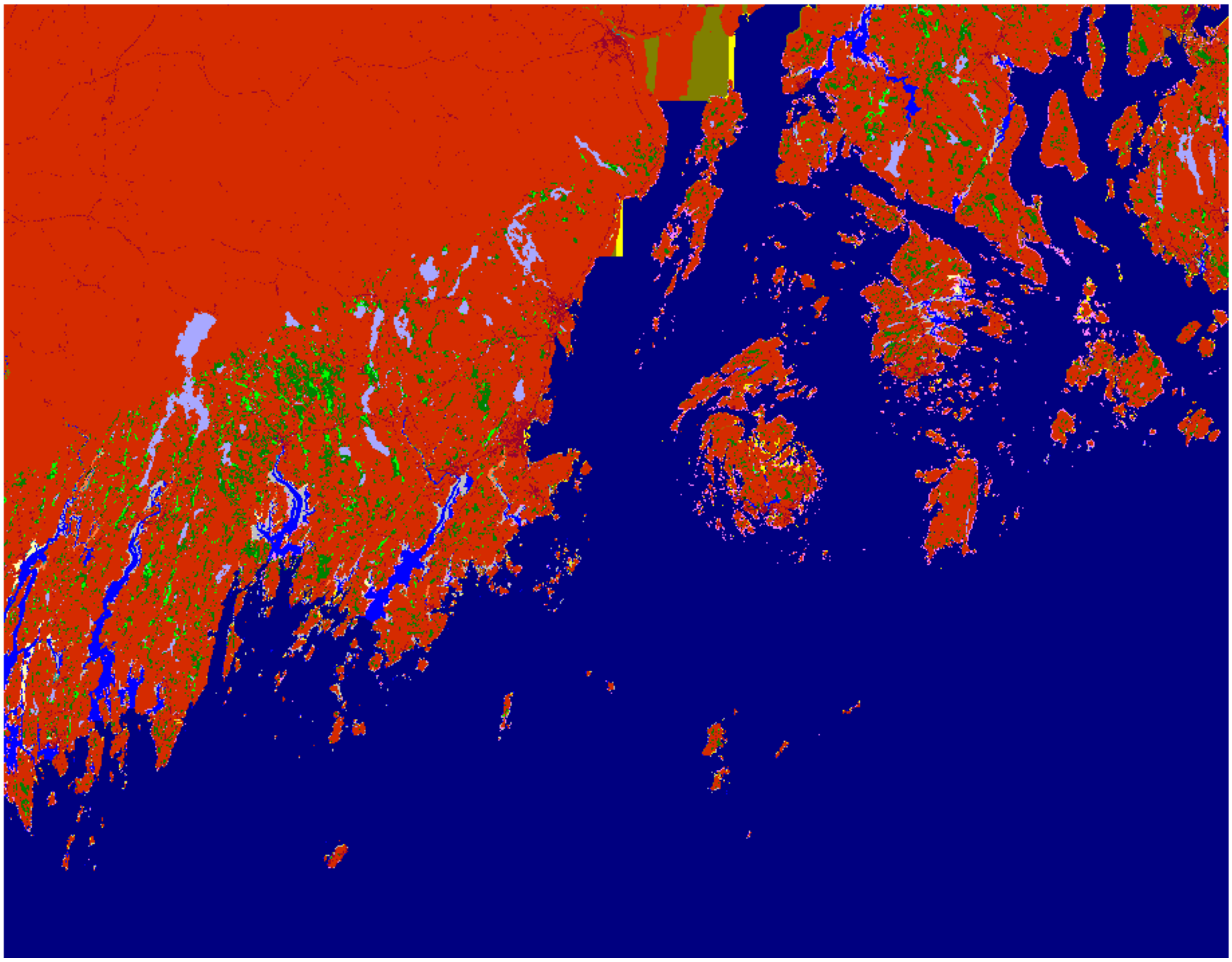
Petit Manan Section B Context, Initial Condition



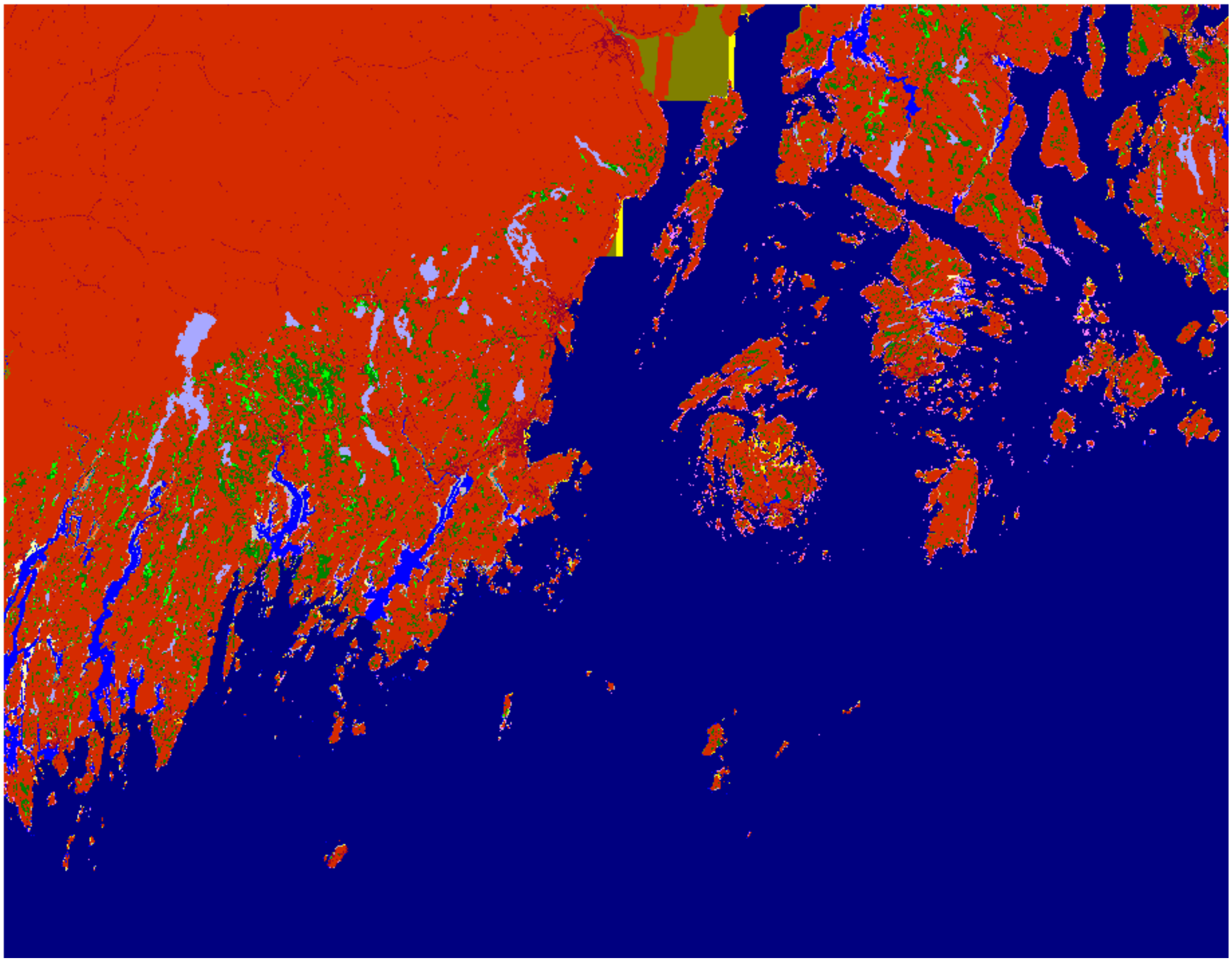
Petit Manan Section B Context, 2025, Scenario A1B Maximum



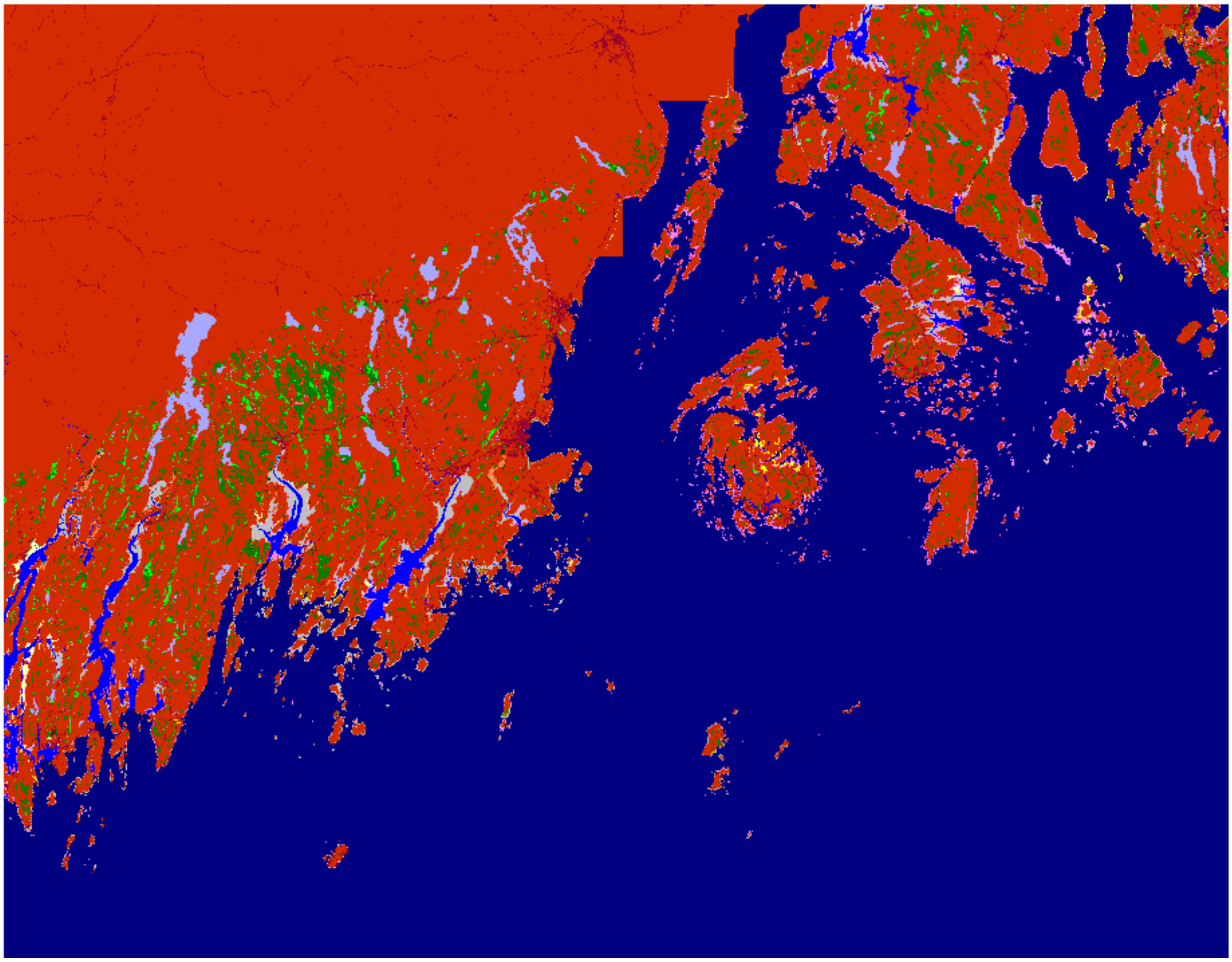
Petit Manan Section B Context, 2050, Scenario A1B Maximum



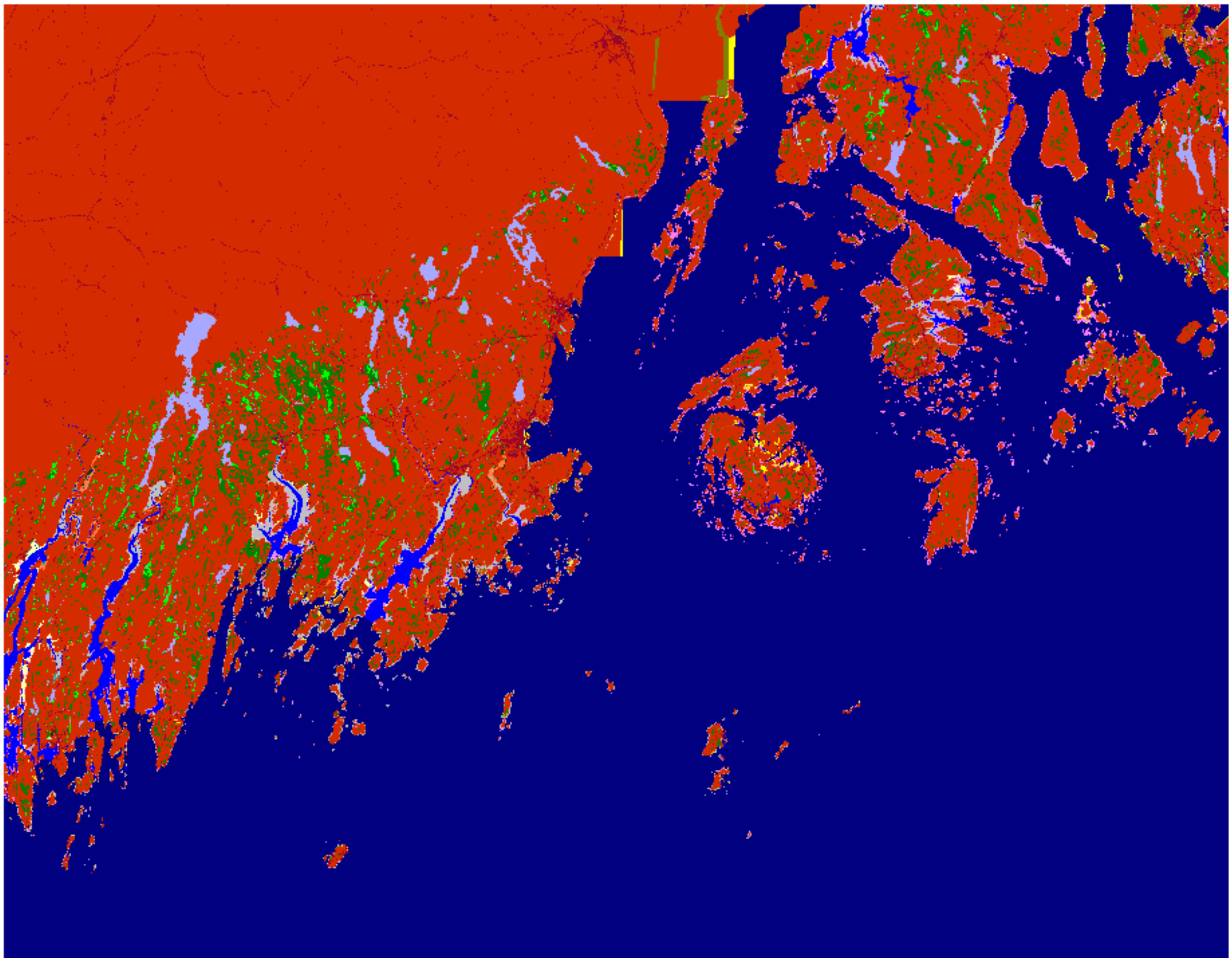
Petit Manan Section B Context, 2075, Scenario A1B Maximum



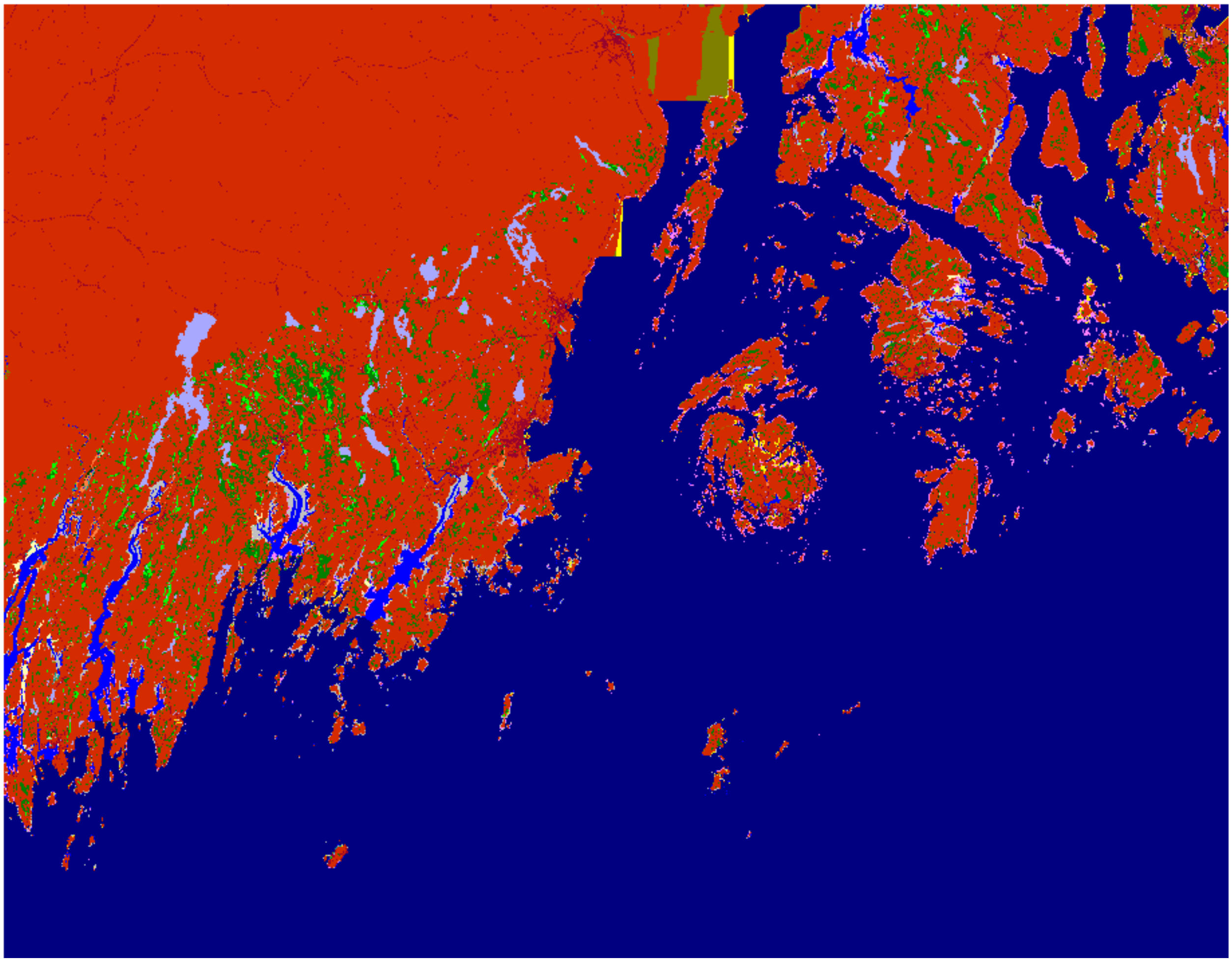
Petit Manan Section B Context, 2100, Scenario A1B Maximum



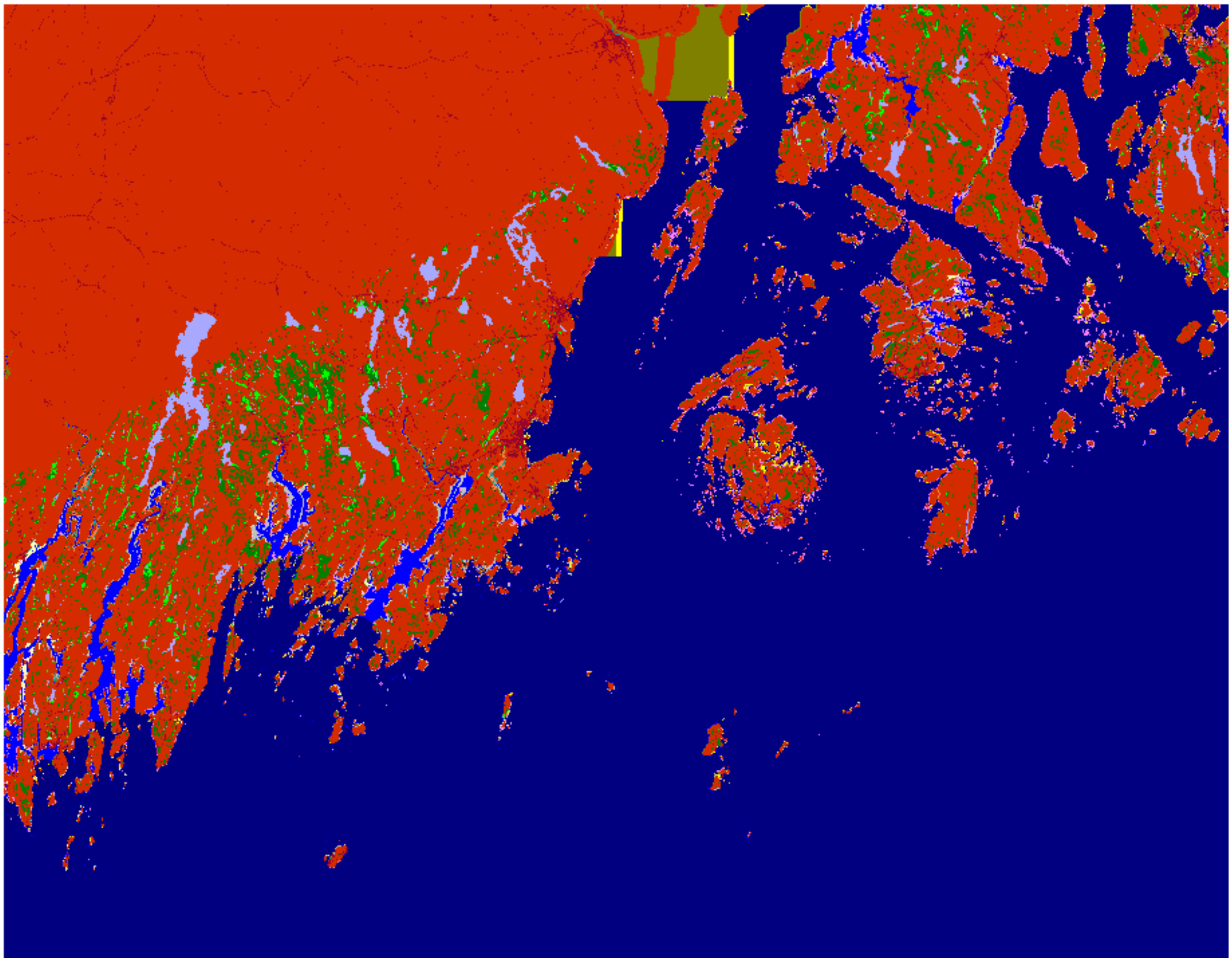
Petit Manan Section B Context, Initial Condition



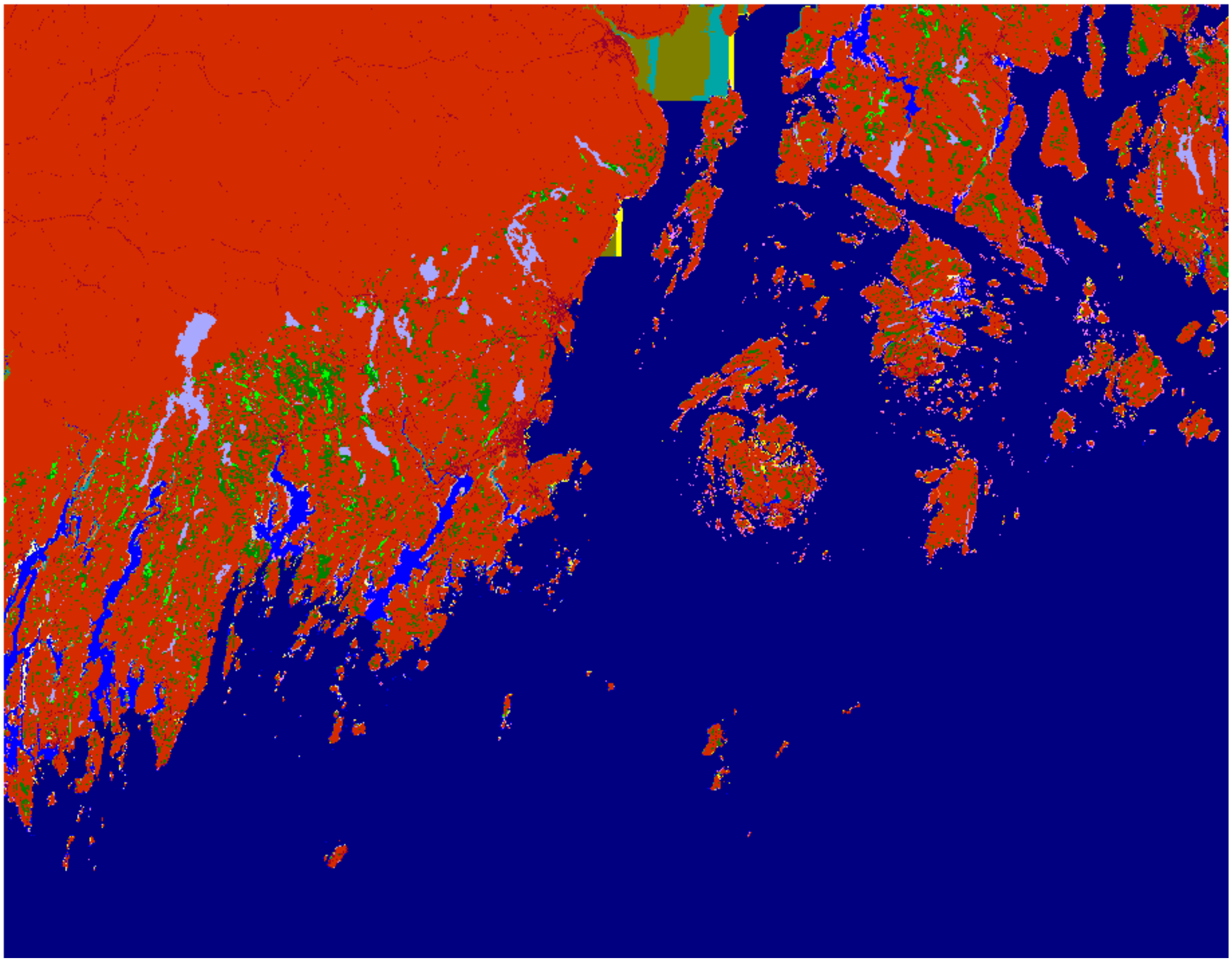
Petit Manan Section B Context, 2025, 1 Meter



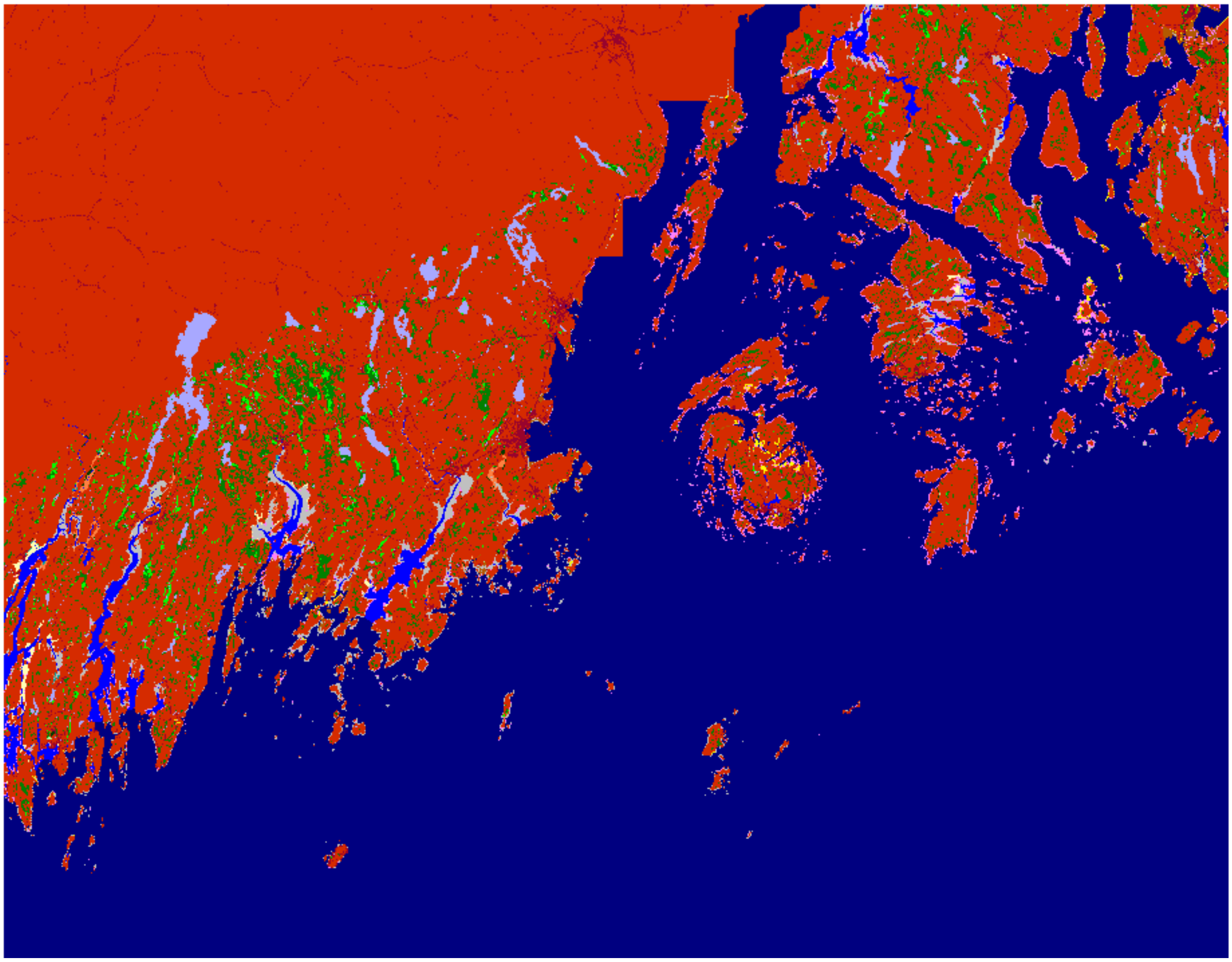
Petit Manan Section B Context, 2050, 1 Meter



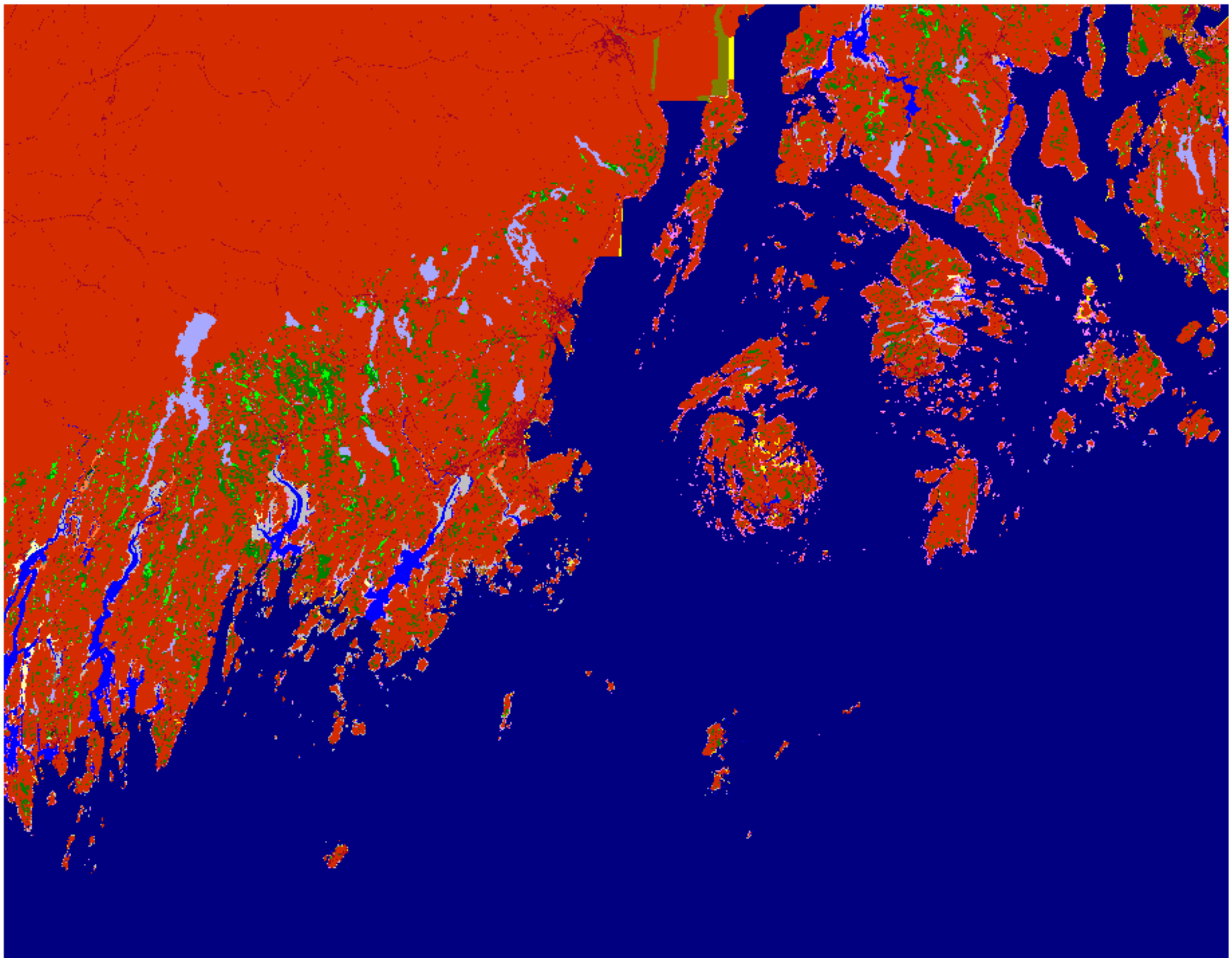
Petit Manan Section B Context, 2075, 1 Meter



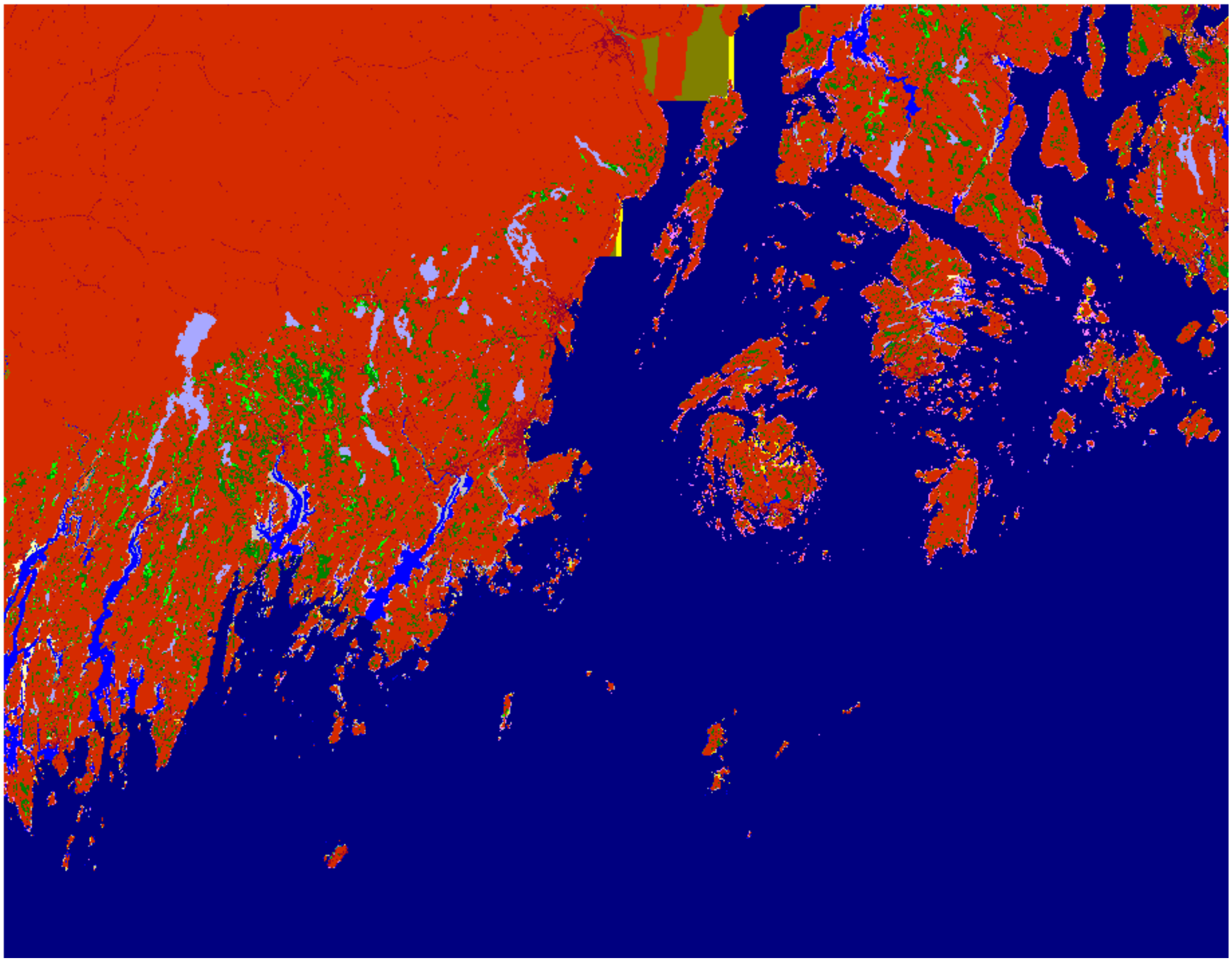
Petit Manan Section B Context, 2100, 1 Meter



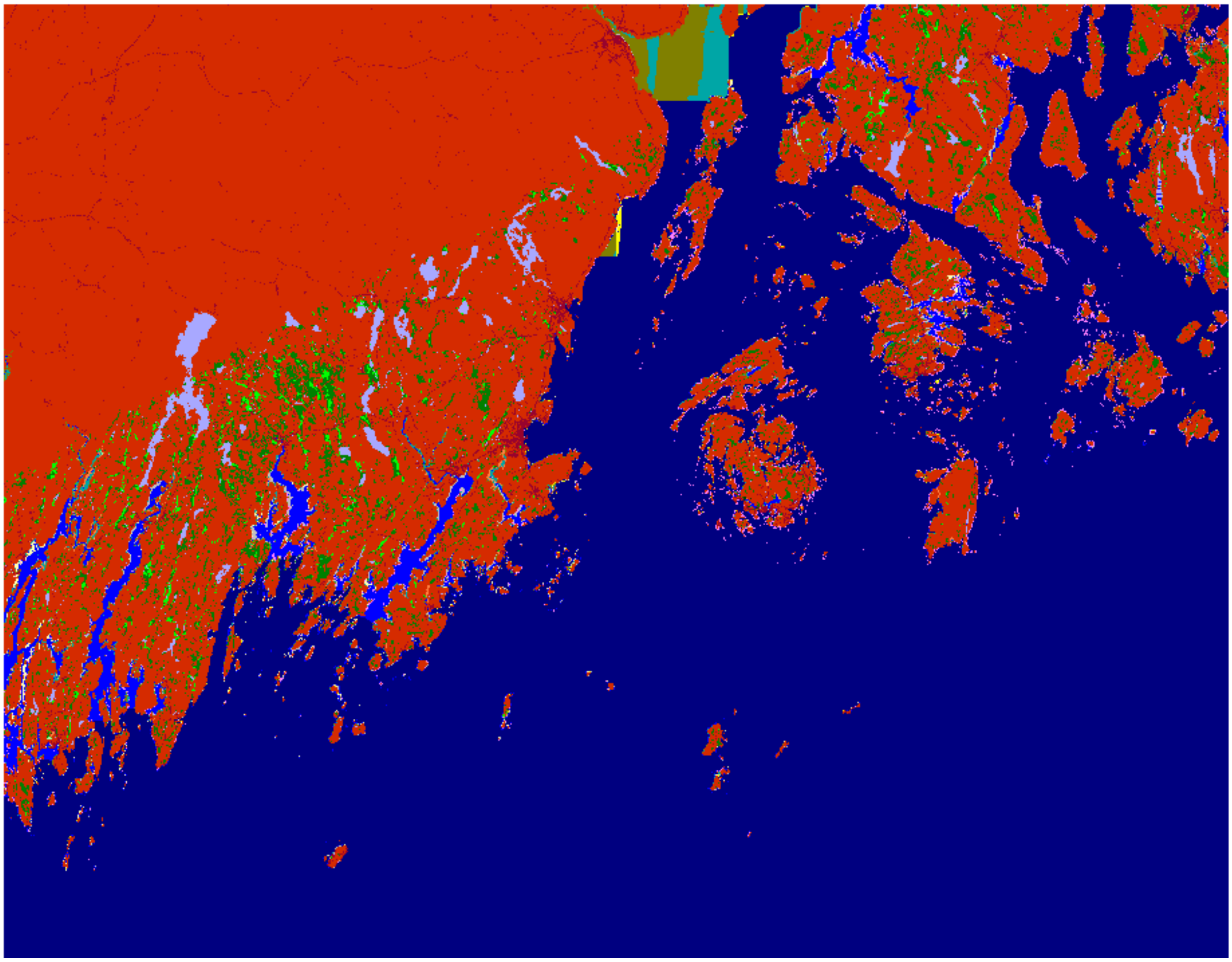
Petit Manan Section B Context, Initial Condition



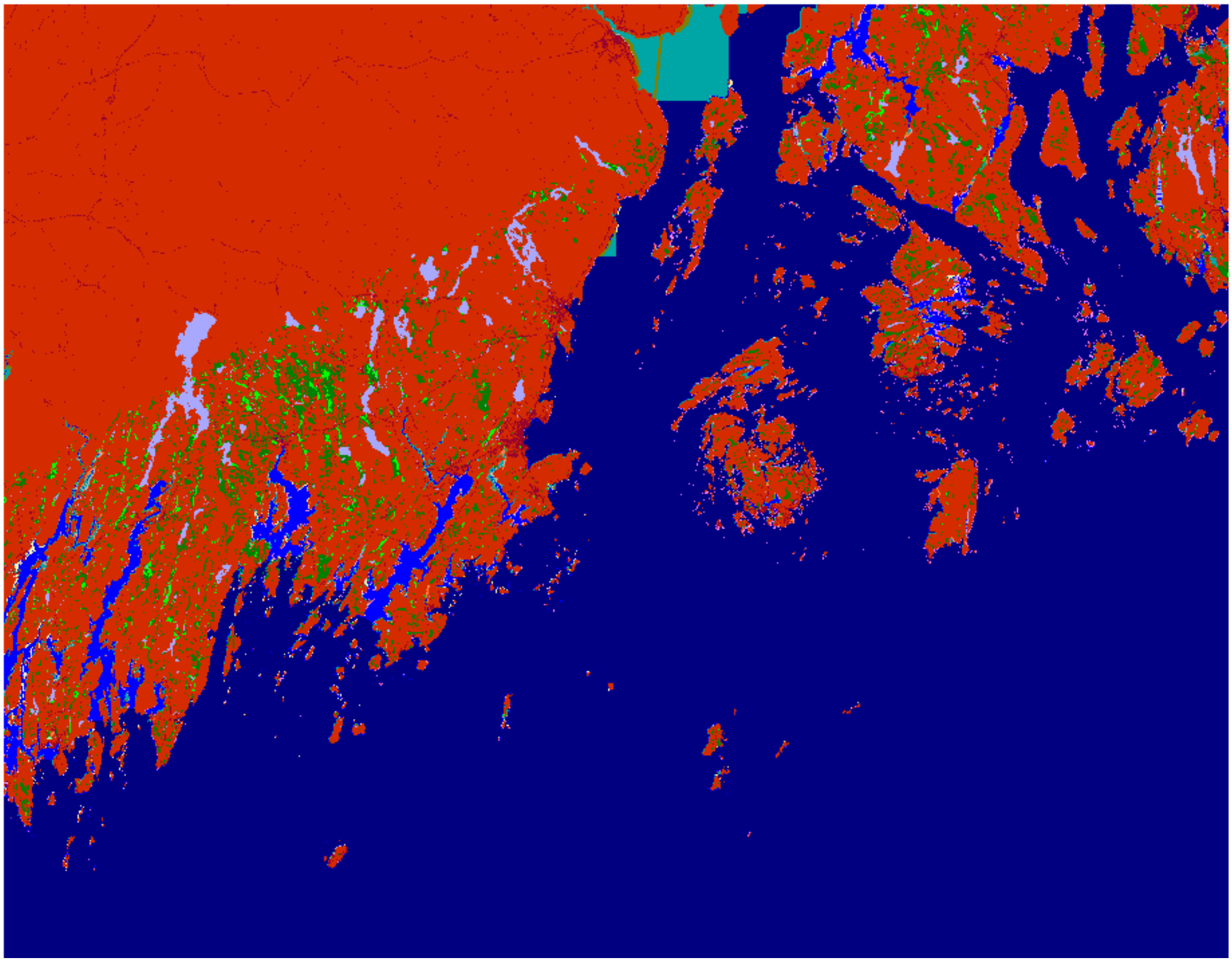
Petit Manan Section B Context, 2025, 1.5 Meters



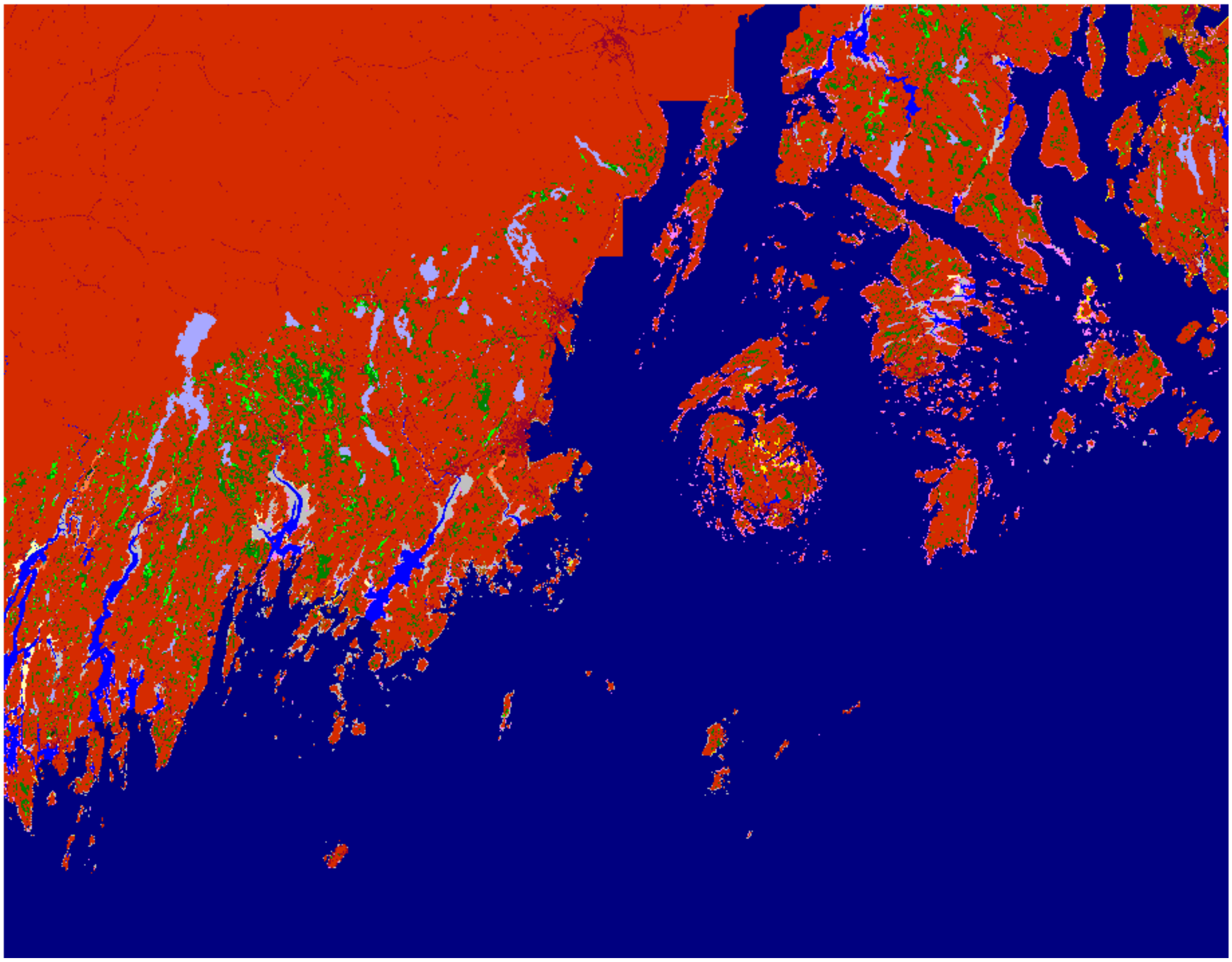
Petit Manan Section B Context, 2050, 1.5 Meters



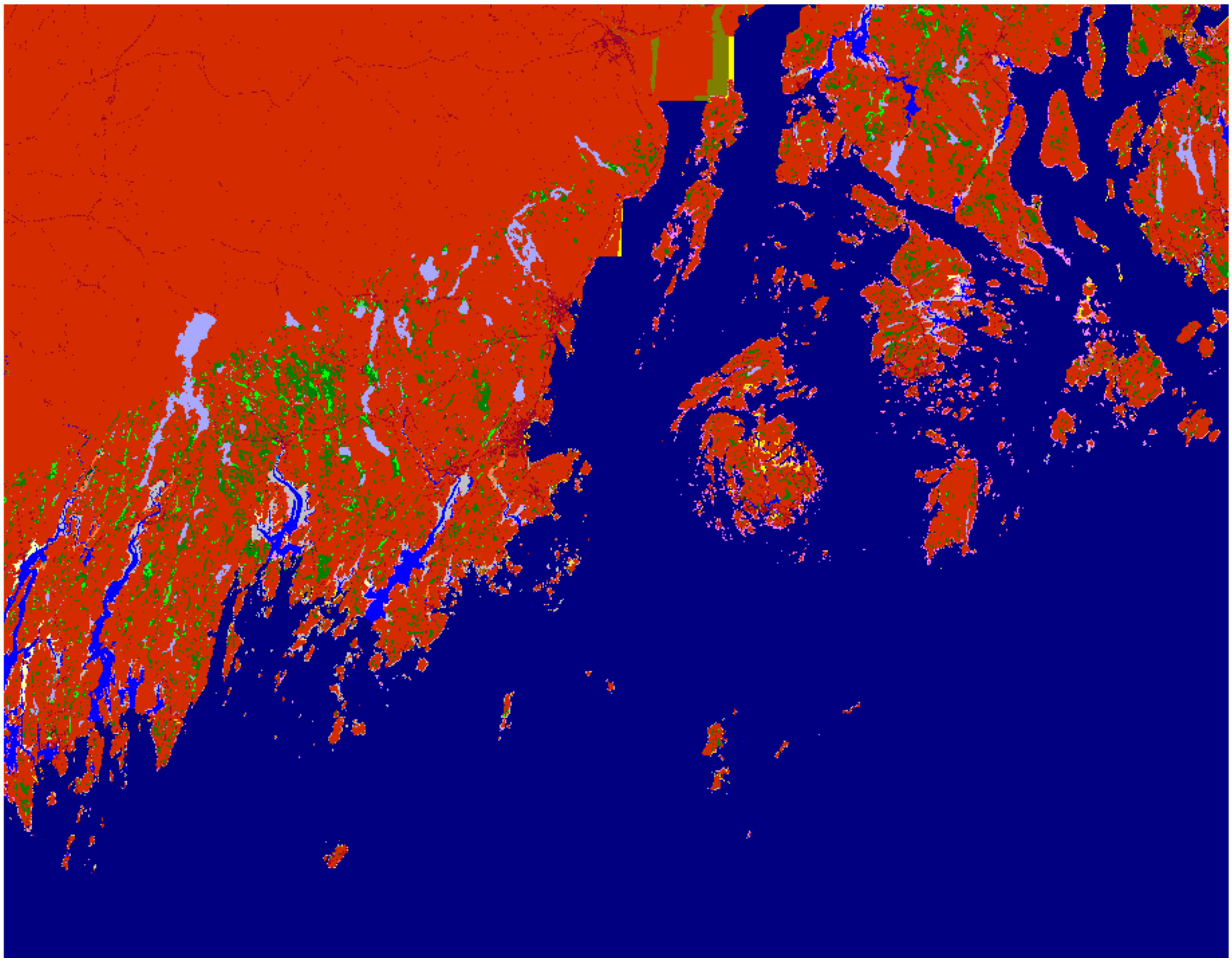
Petit Manan Section B Context, 2075, 1.5 Meters



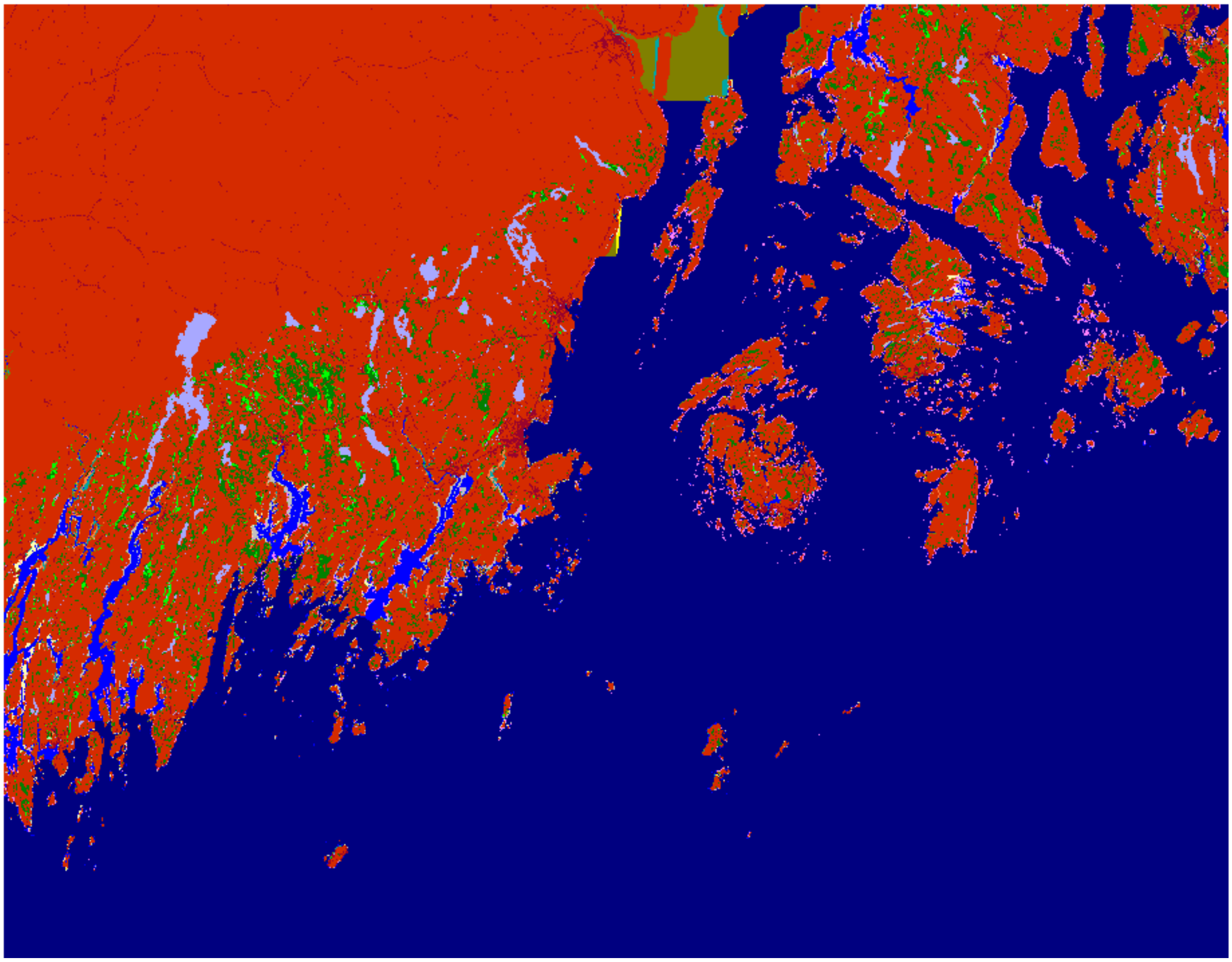
Petit Manan Section B Context, 2100, 1.5 Meters



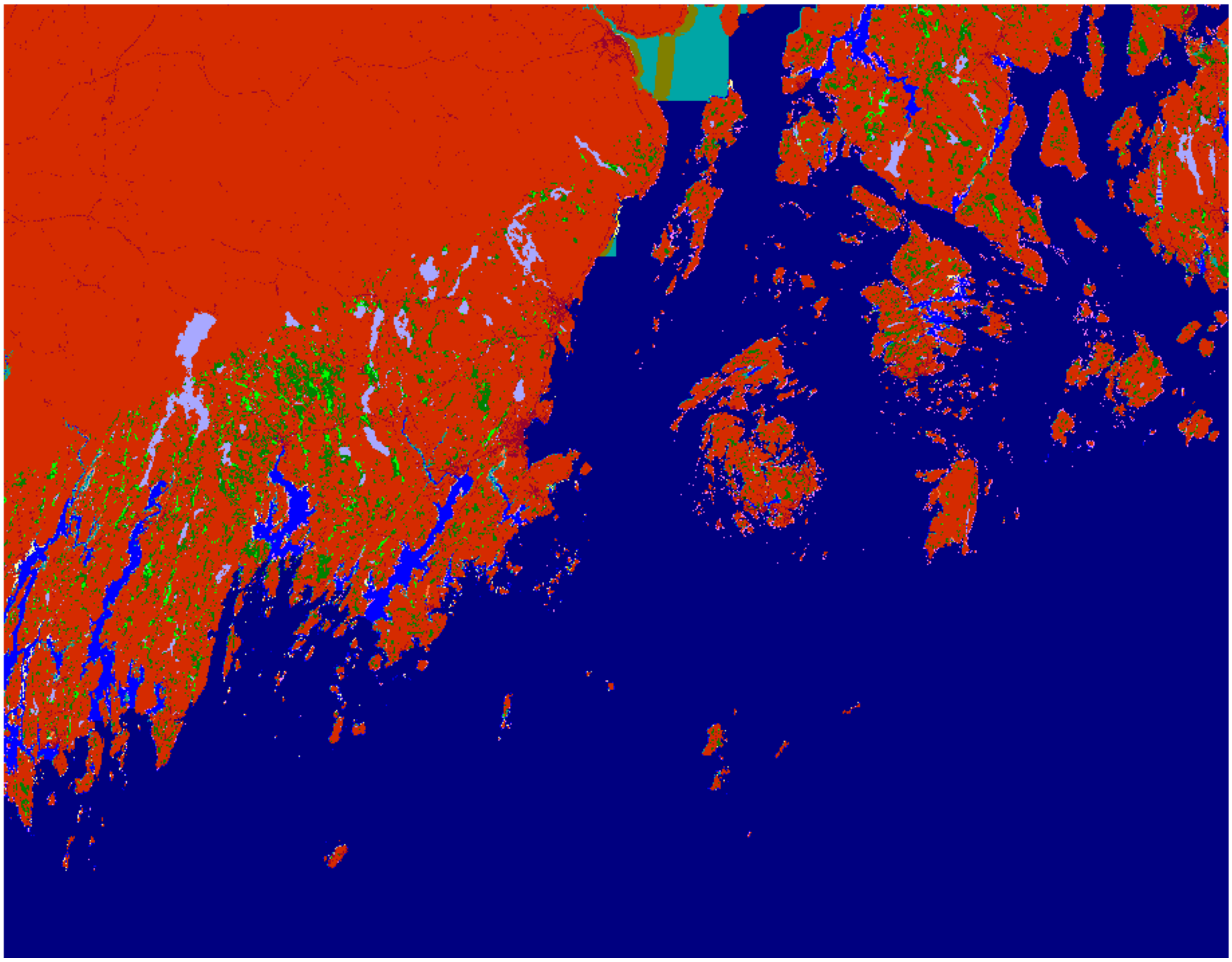
Petit Manan Section B Context, Initial Condition



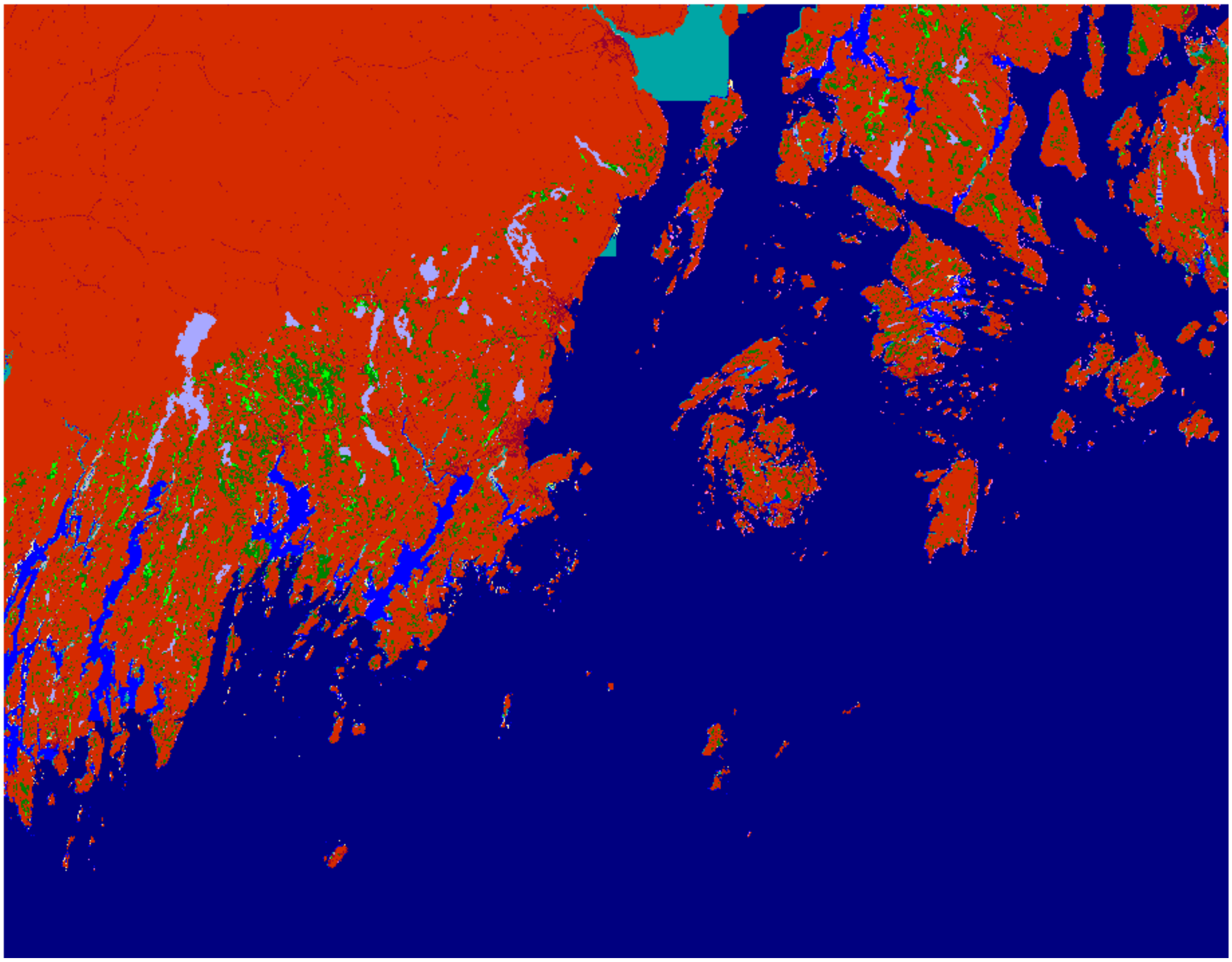
Petit Manan Section B Context, 2025, 2 Meters



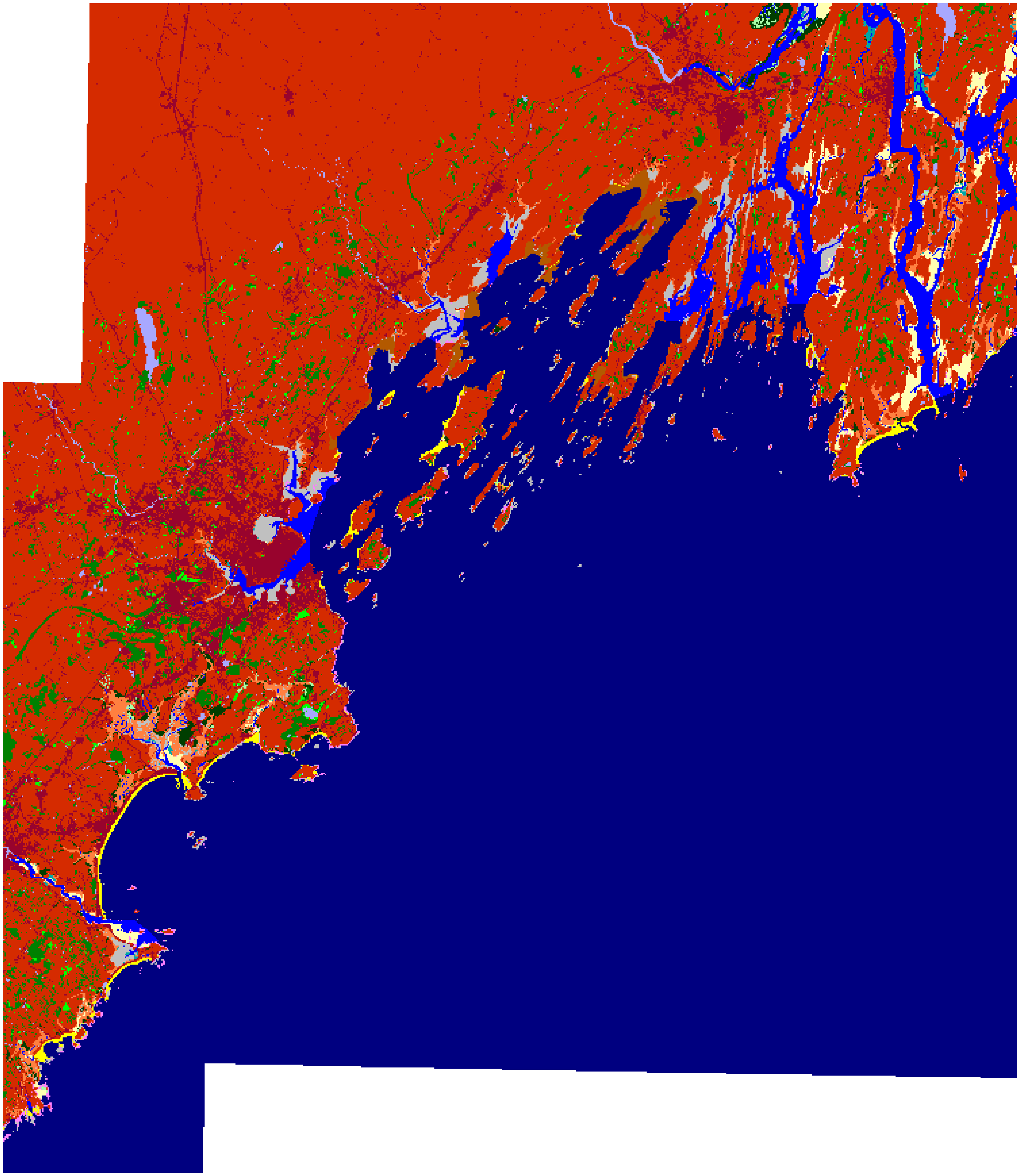
Petit Manan Section B Context, 2050, 2 Meters



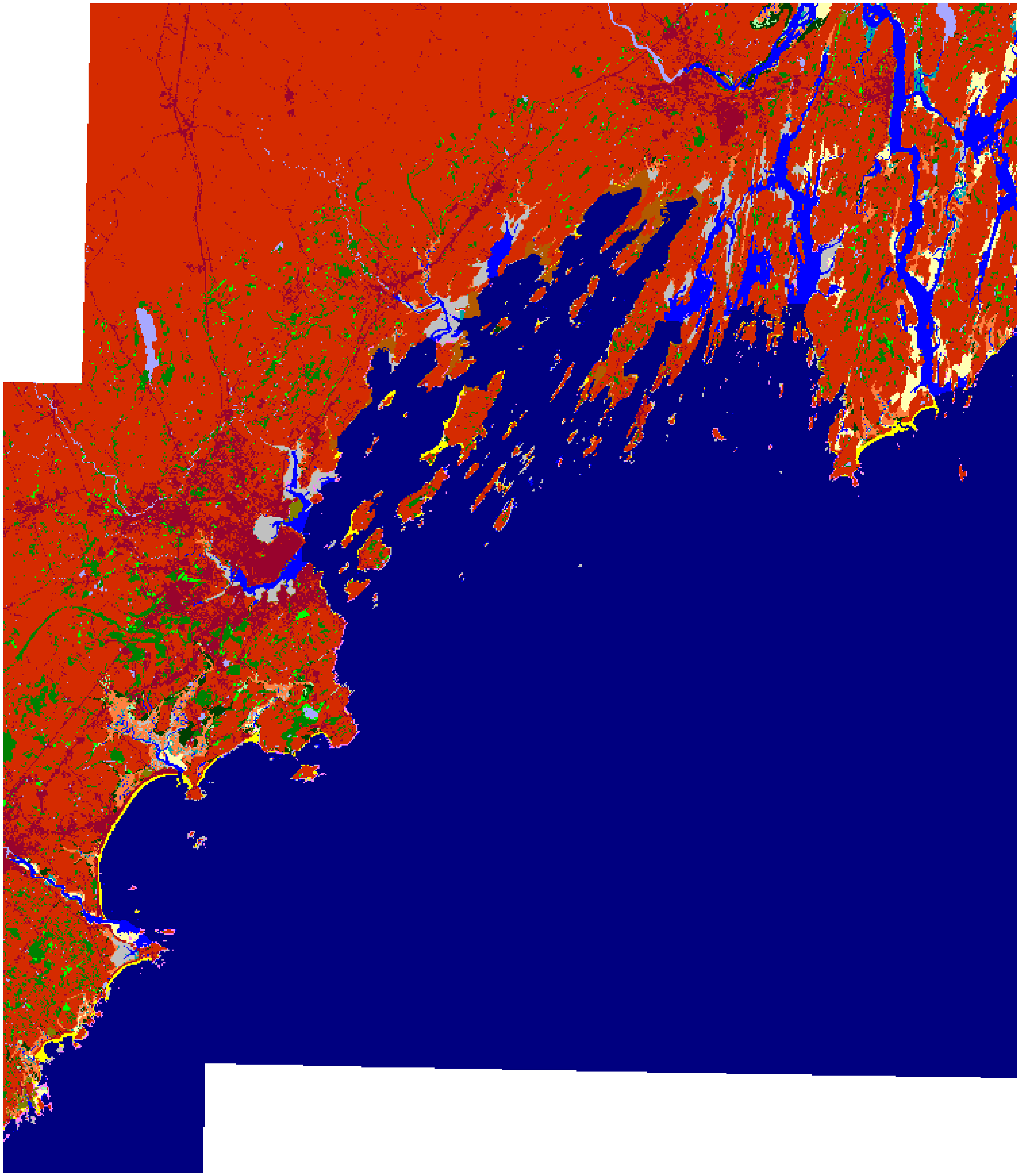
Petit Manan Section B Context, 2075, 2 Meters



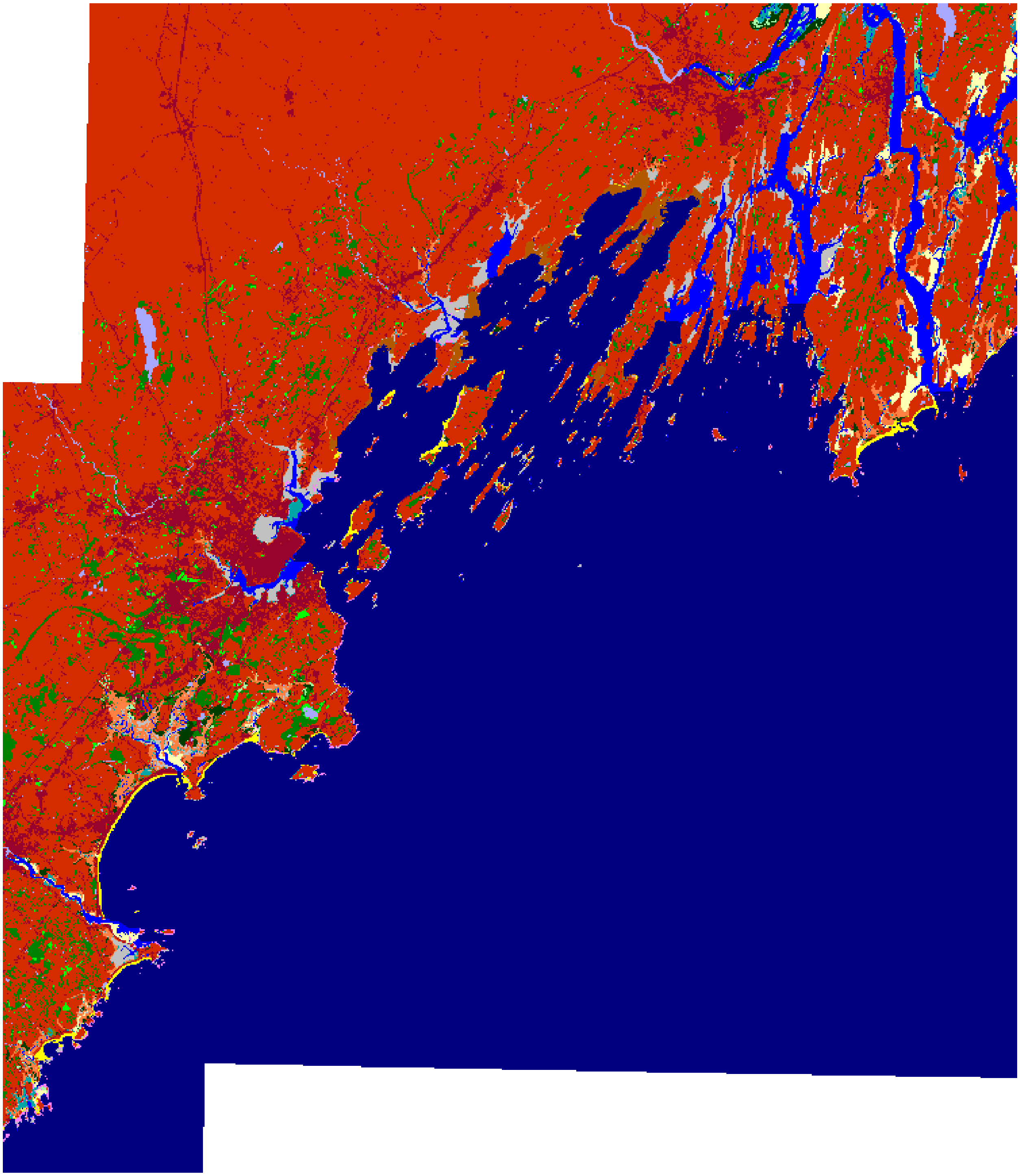
Petit Manan Section B Context, 2100, 2 Meters



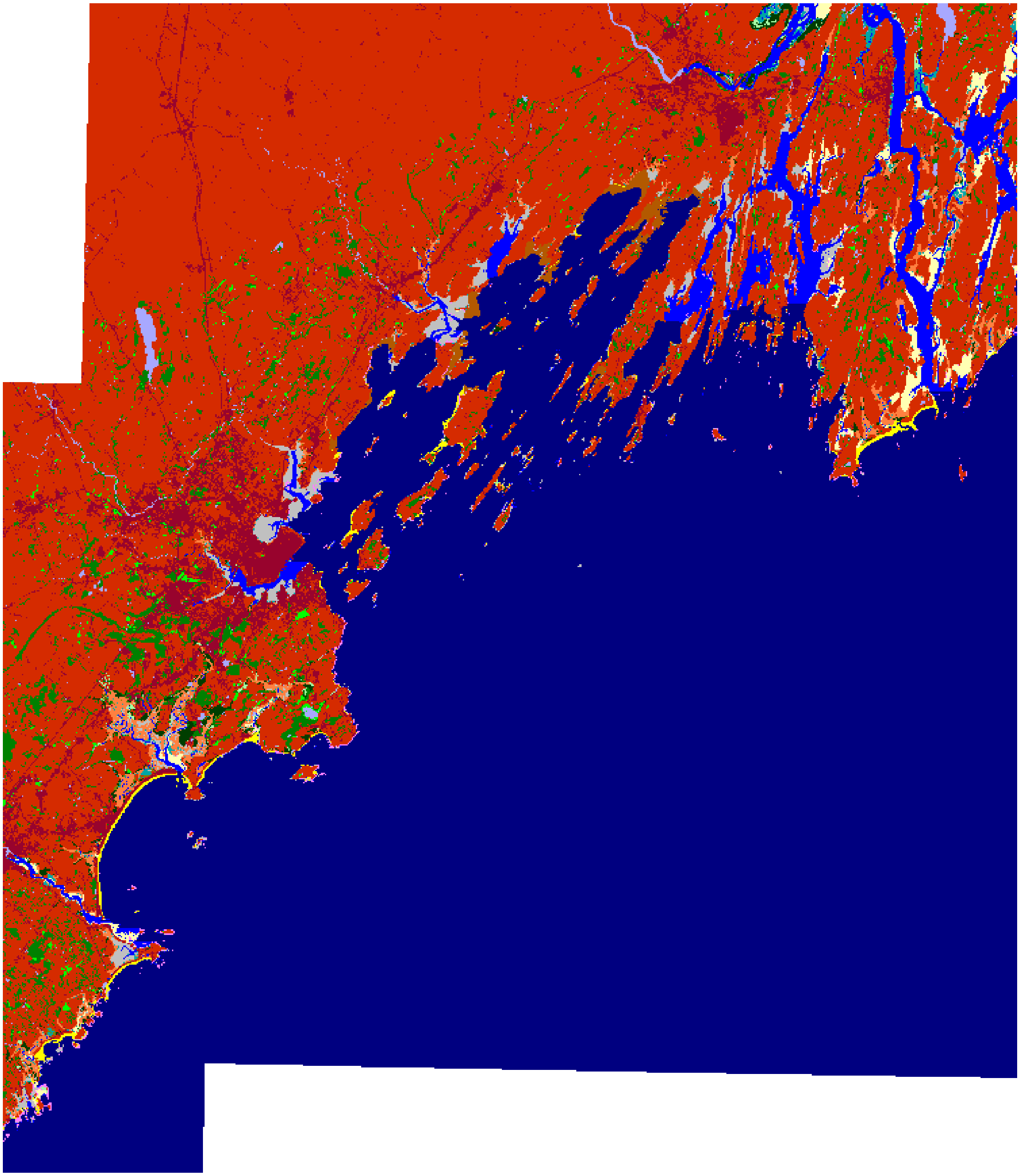
Petit Manan Section C Context, Initial Condition



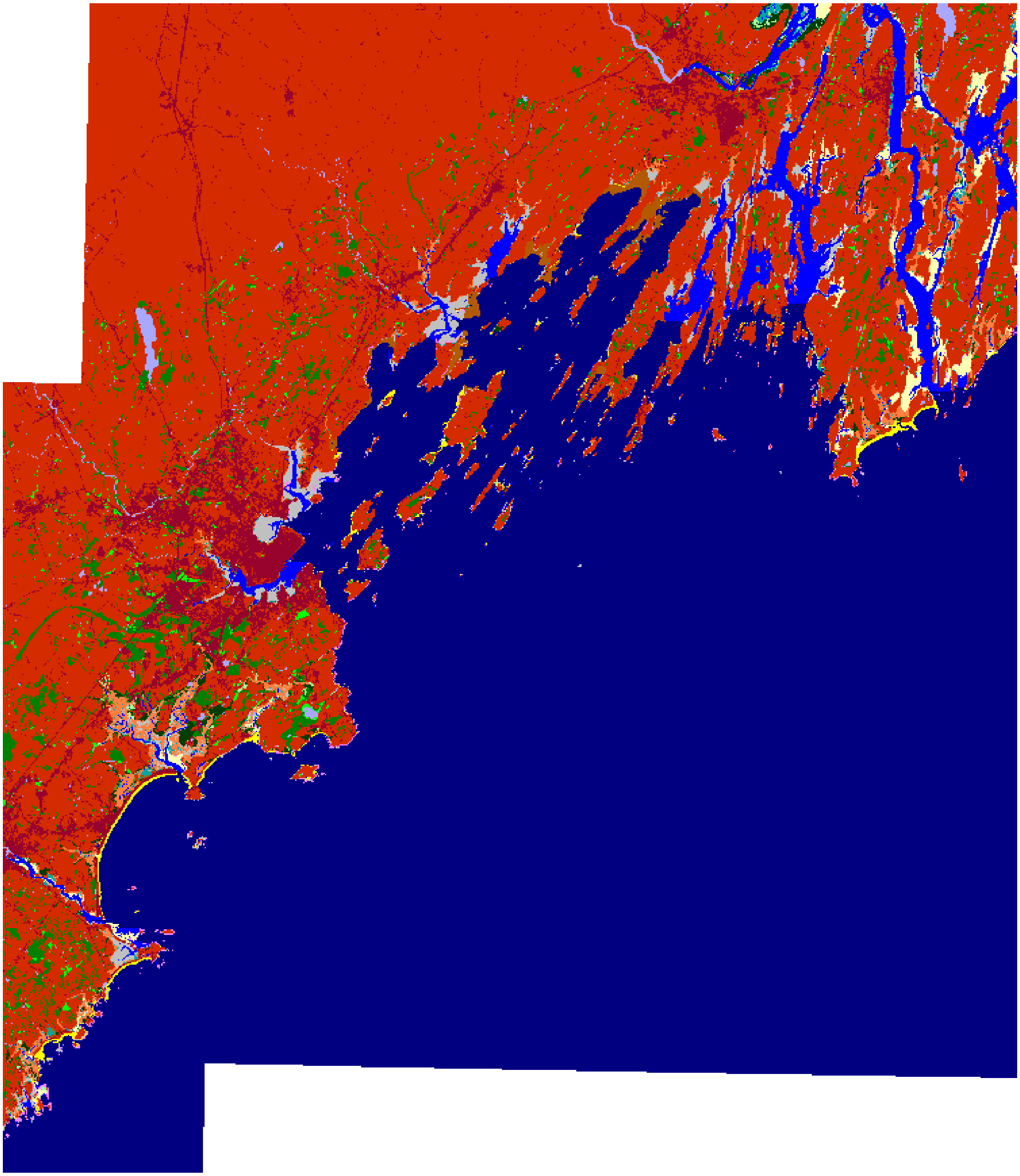
Petit Manan Section C Context, 2025, Scenario A1B Mean



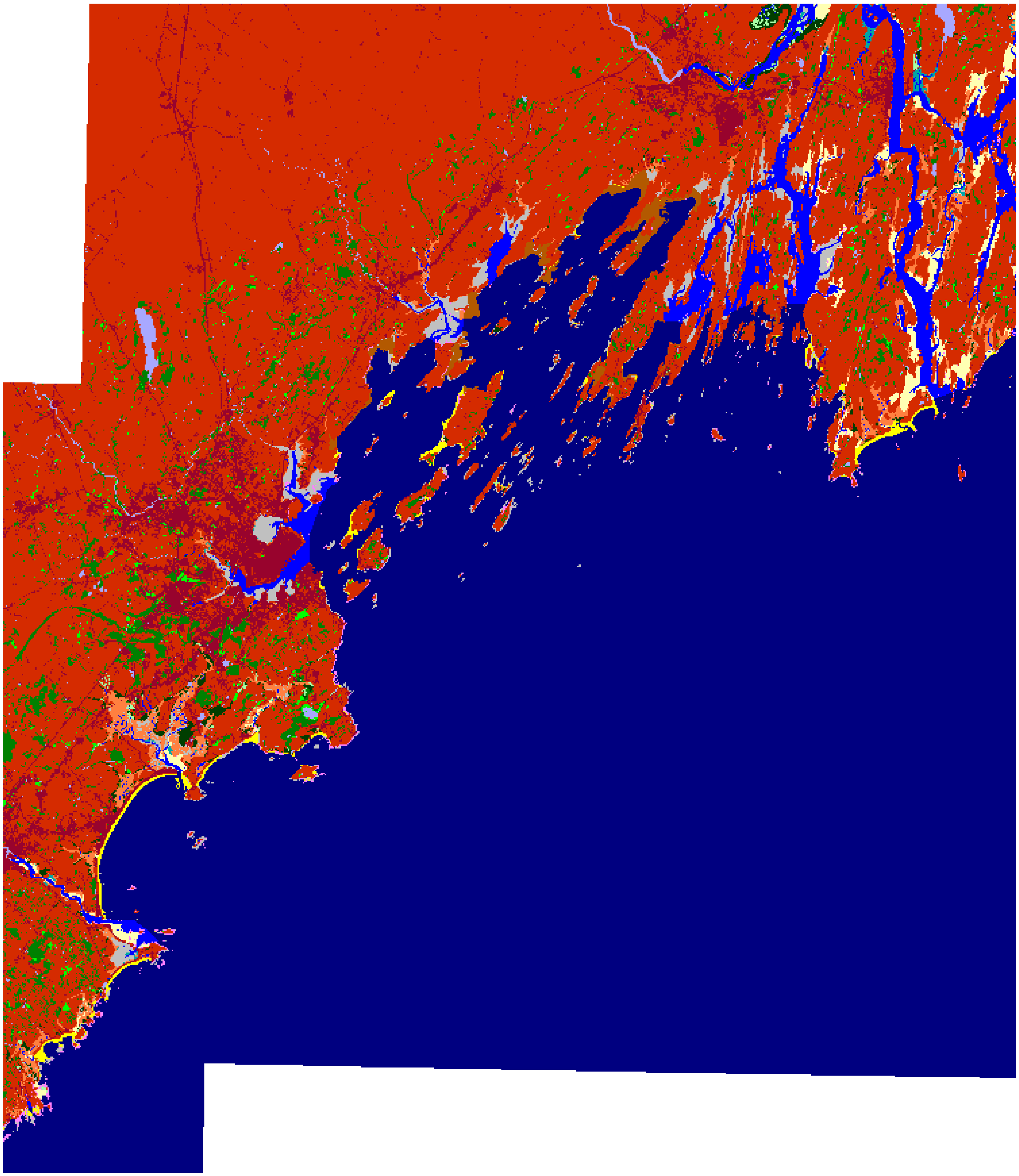
Petit Manan Section C Context, 2050, Scenario A1B Mean



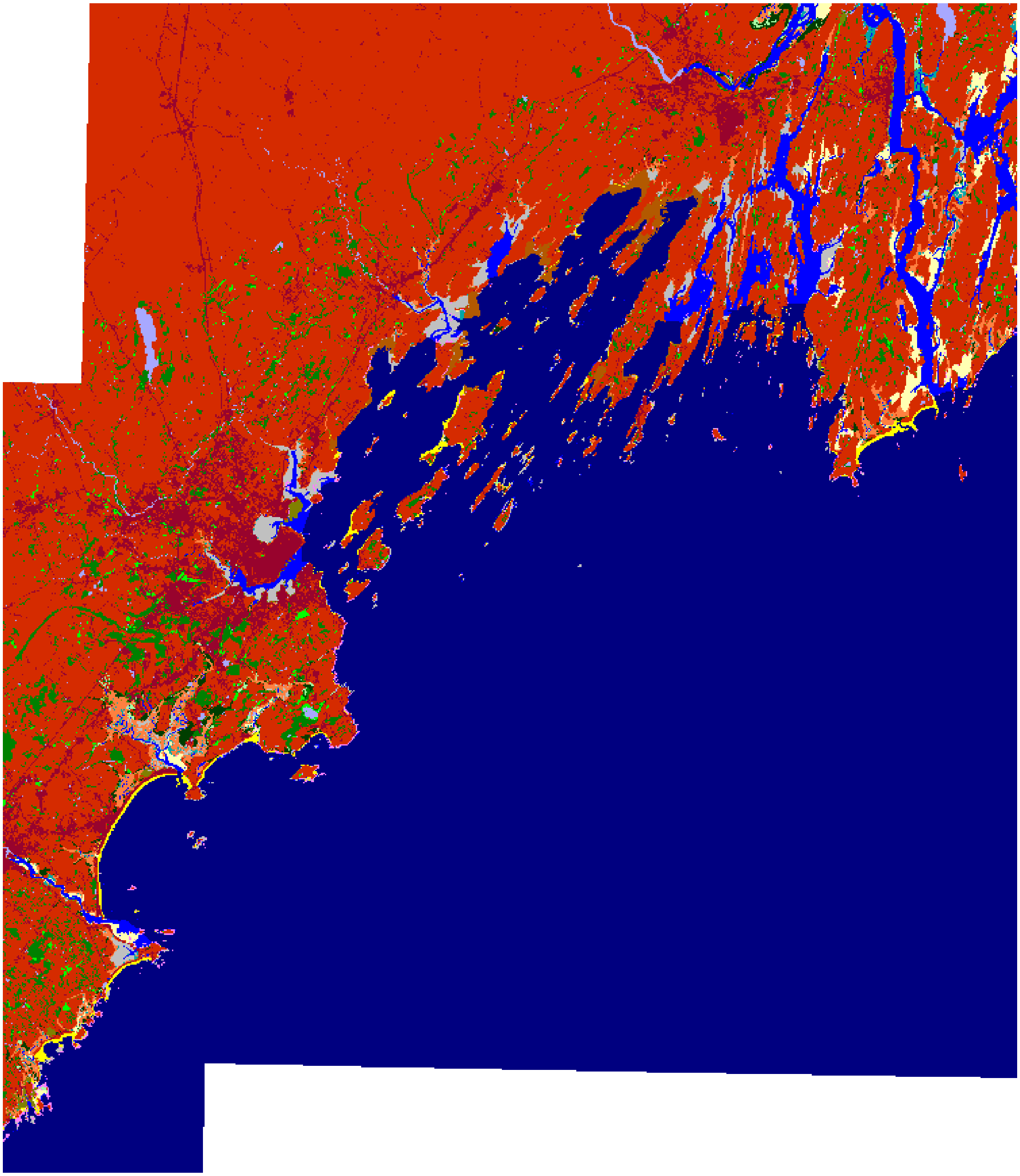
Petit Manan Section C Context, 2075, Scenario A1B Mean



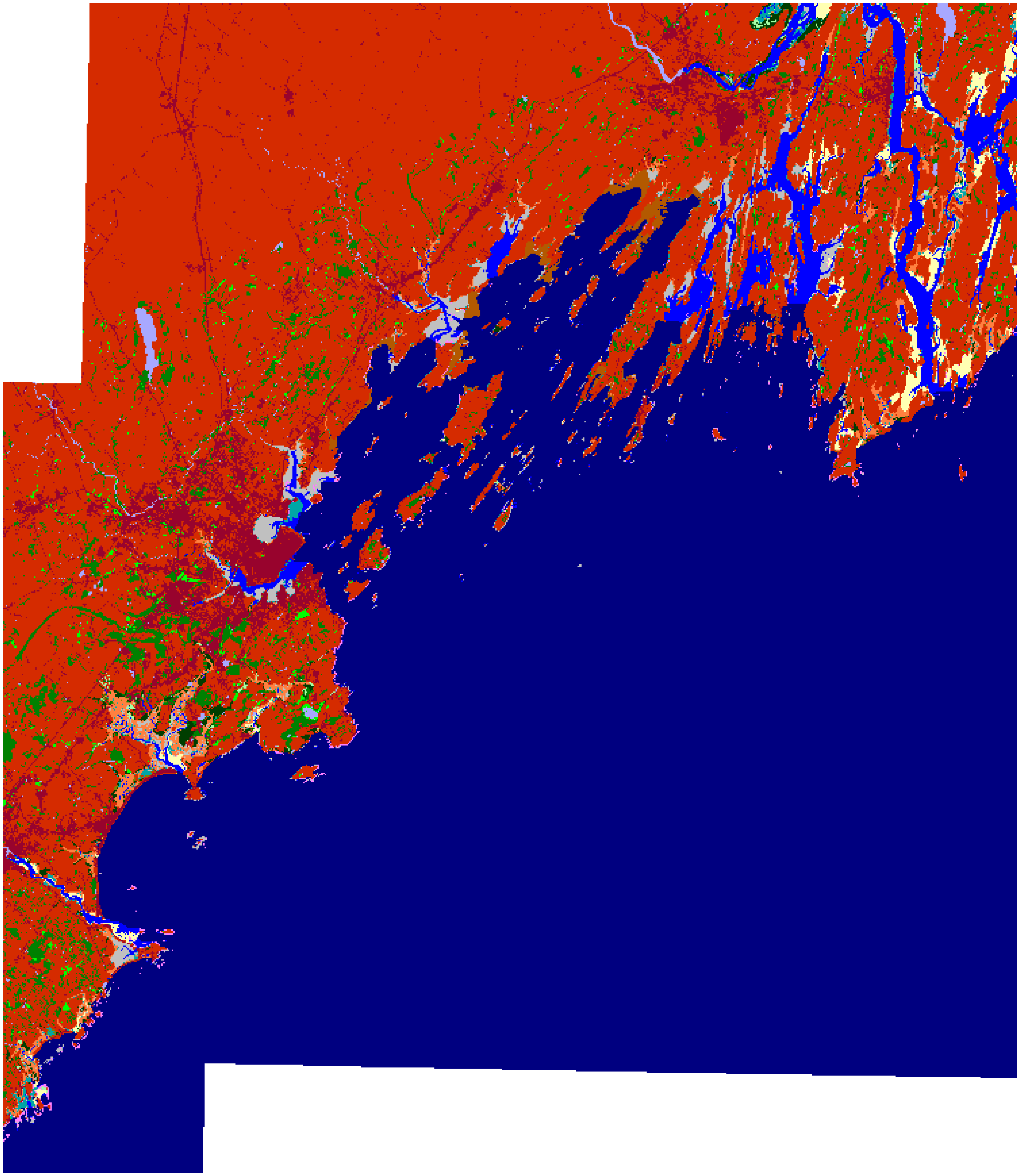
Petit Manan Section C Context, 2100, Scenario A1B Mean



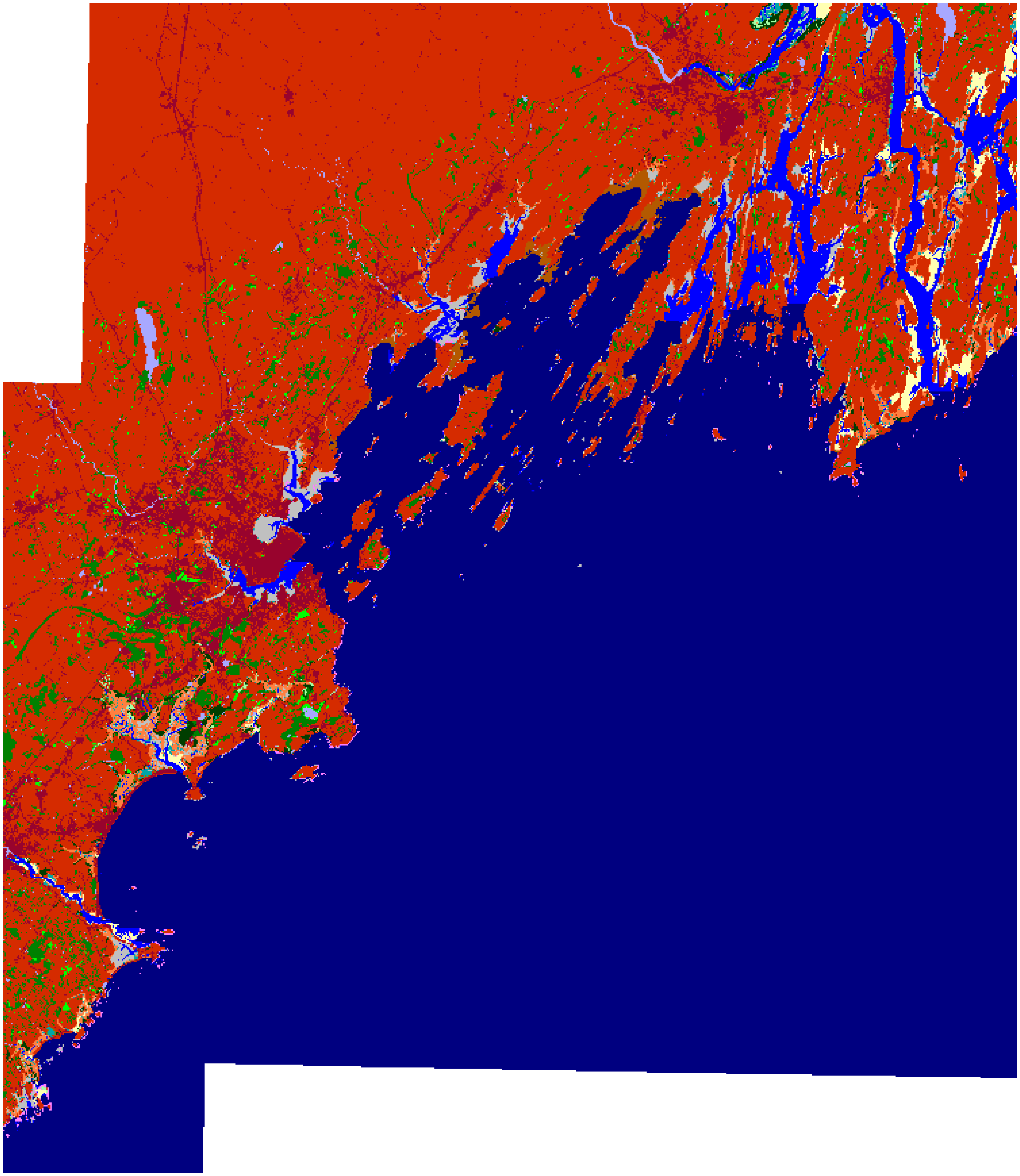
Petit Manan Section C Context, Initial Condition



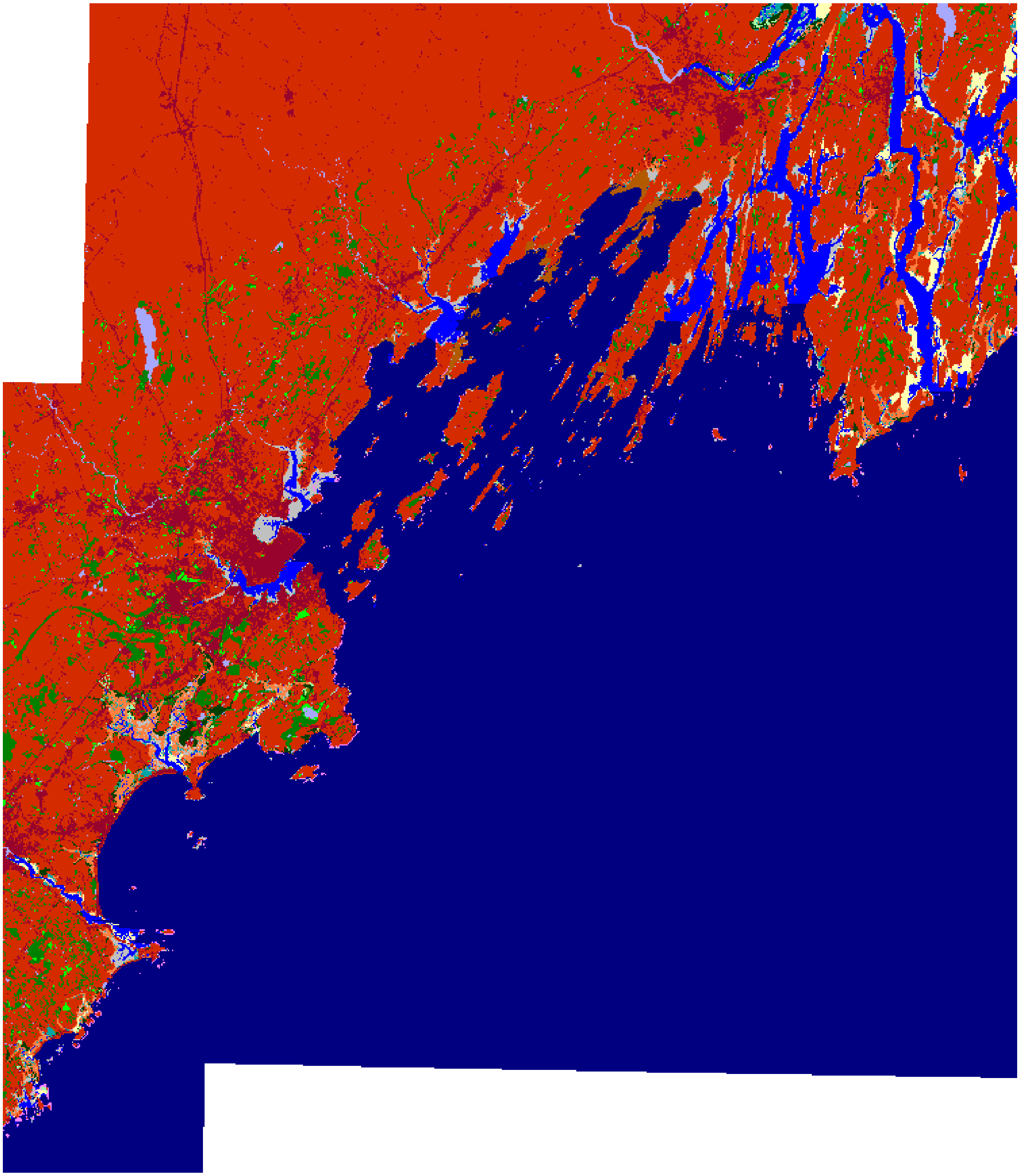
Petit Manan Section C Context, 2025, Scenario A1B Maximum



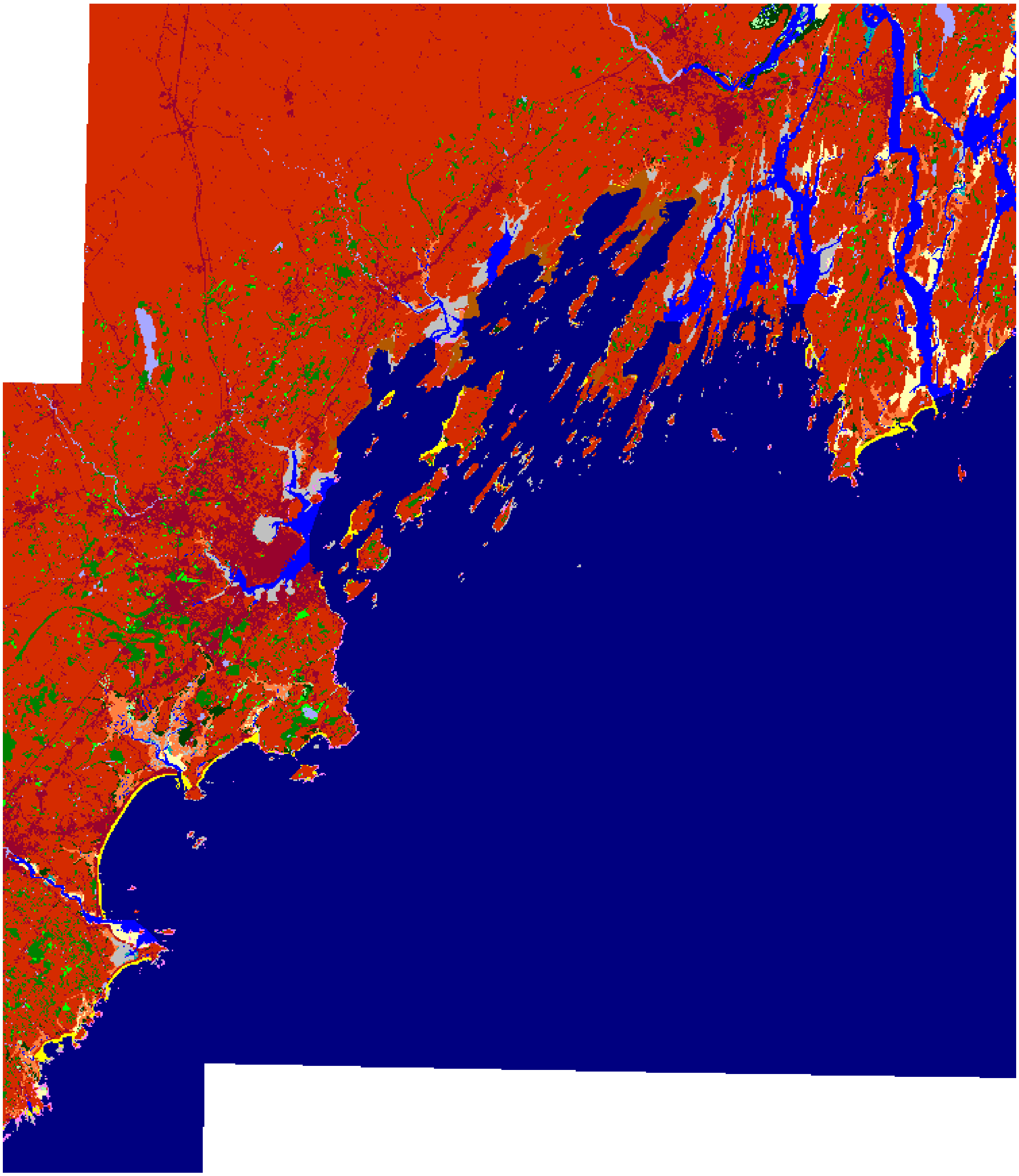
Petit Manan Section C Context, 2050, Scenario A1B Maximum



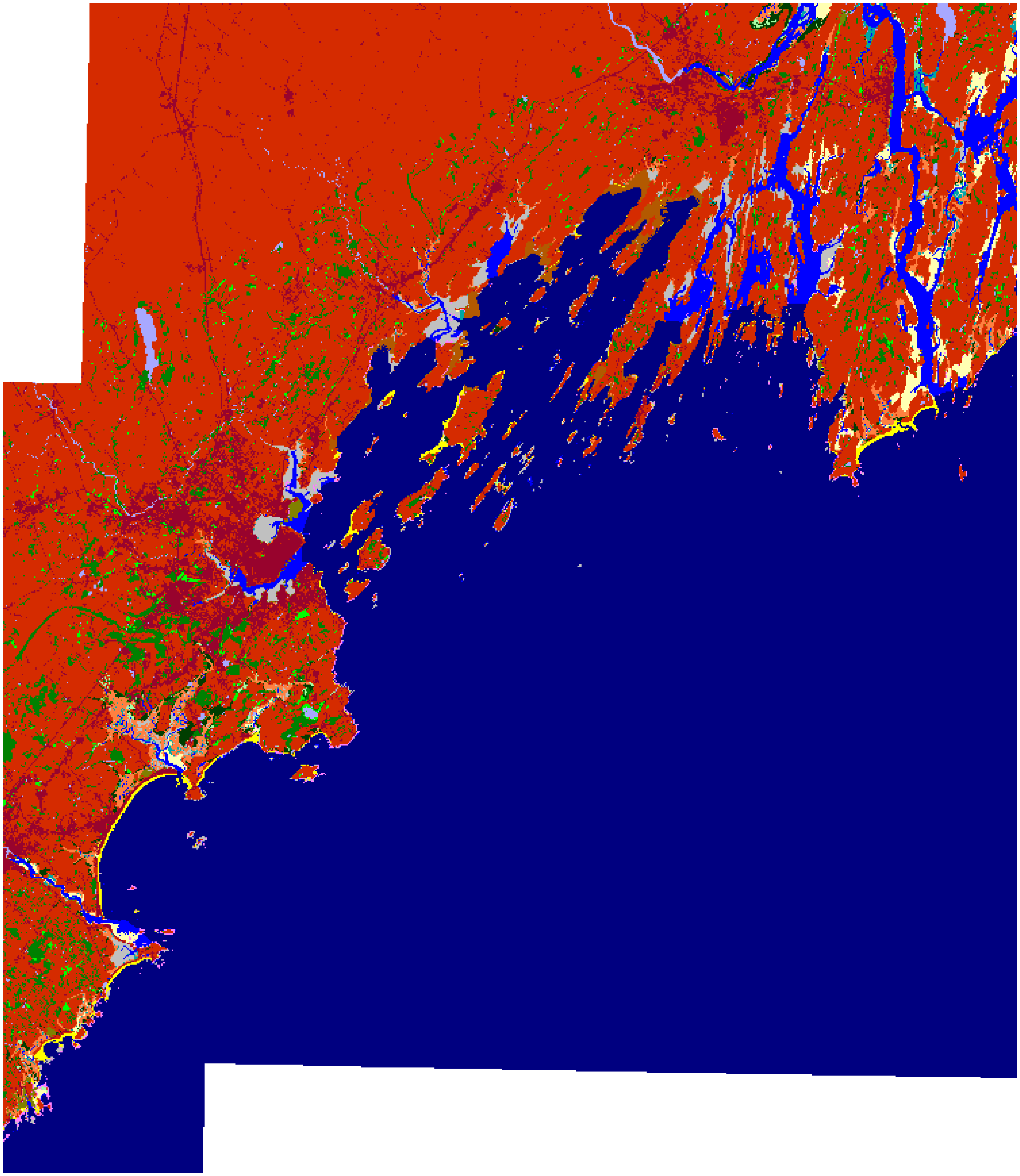
Petit Manan Section C Context, 2075, Scenario A1B Maximum



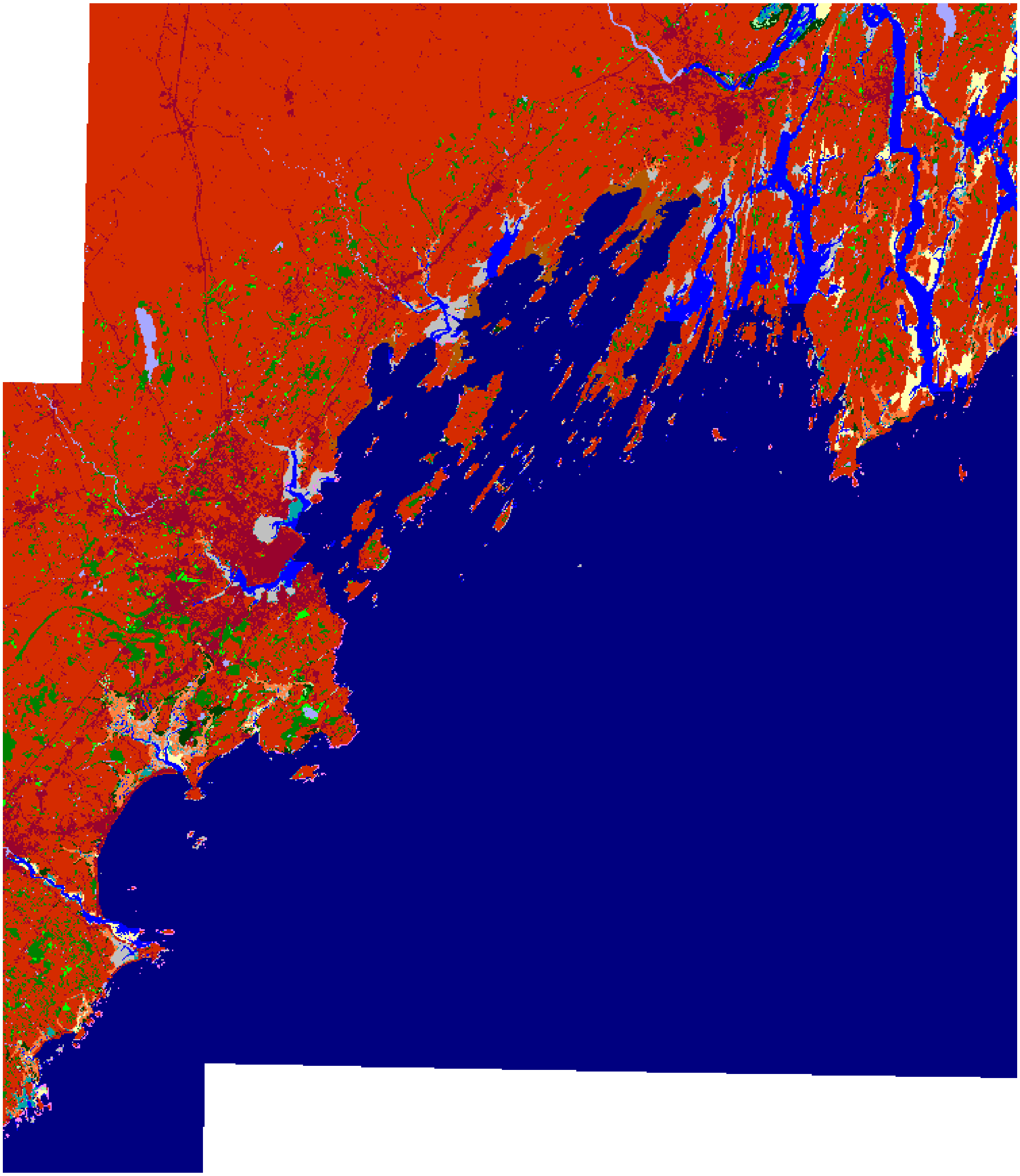
Petit Manan Section C Context, 2100, Scenario A1B Maximum



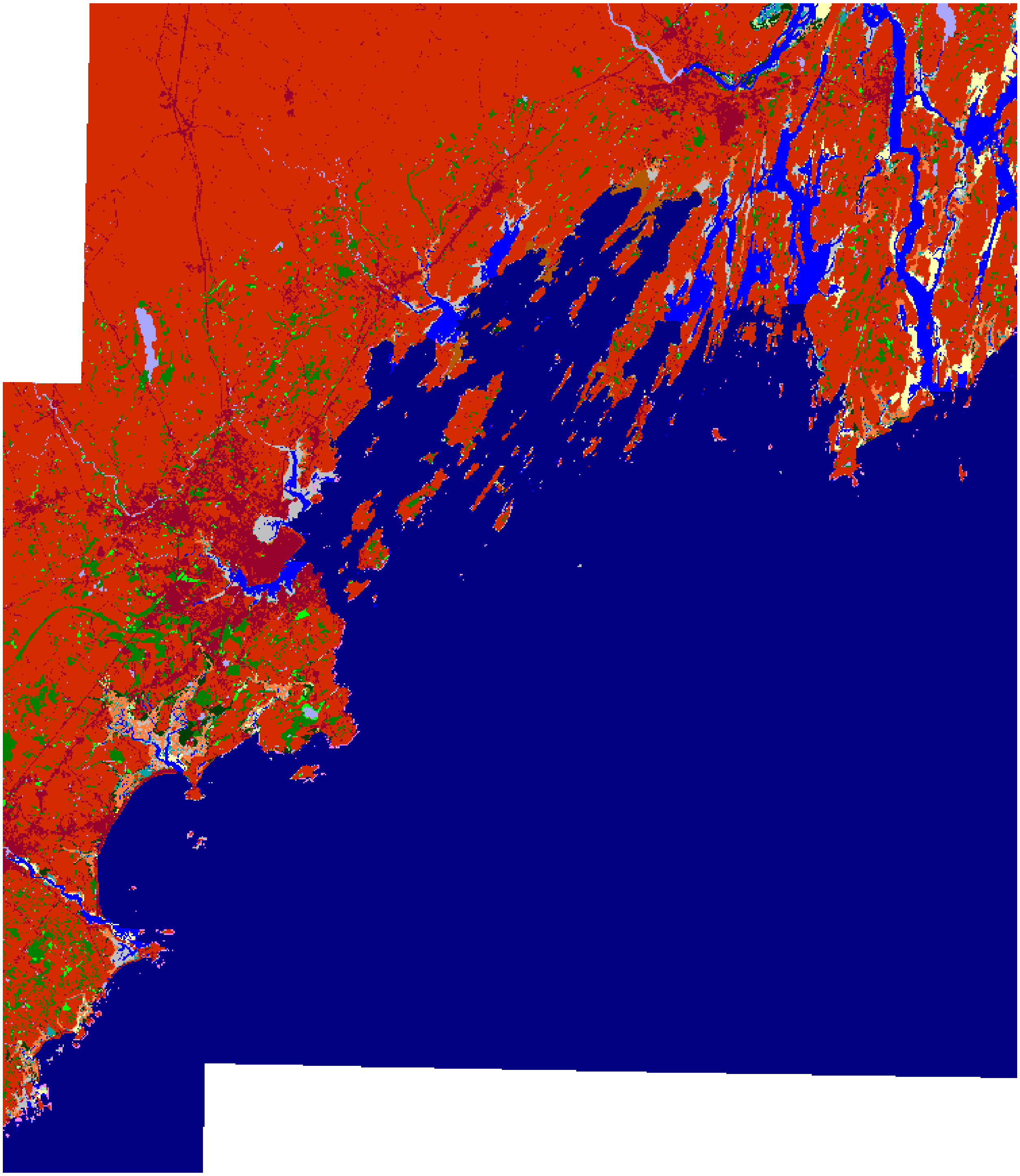
Petit Manan Section C Context, Initial Condition



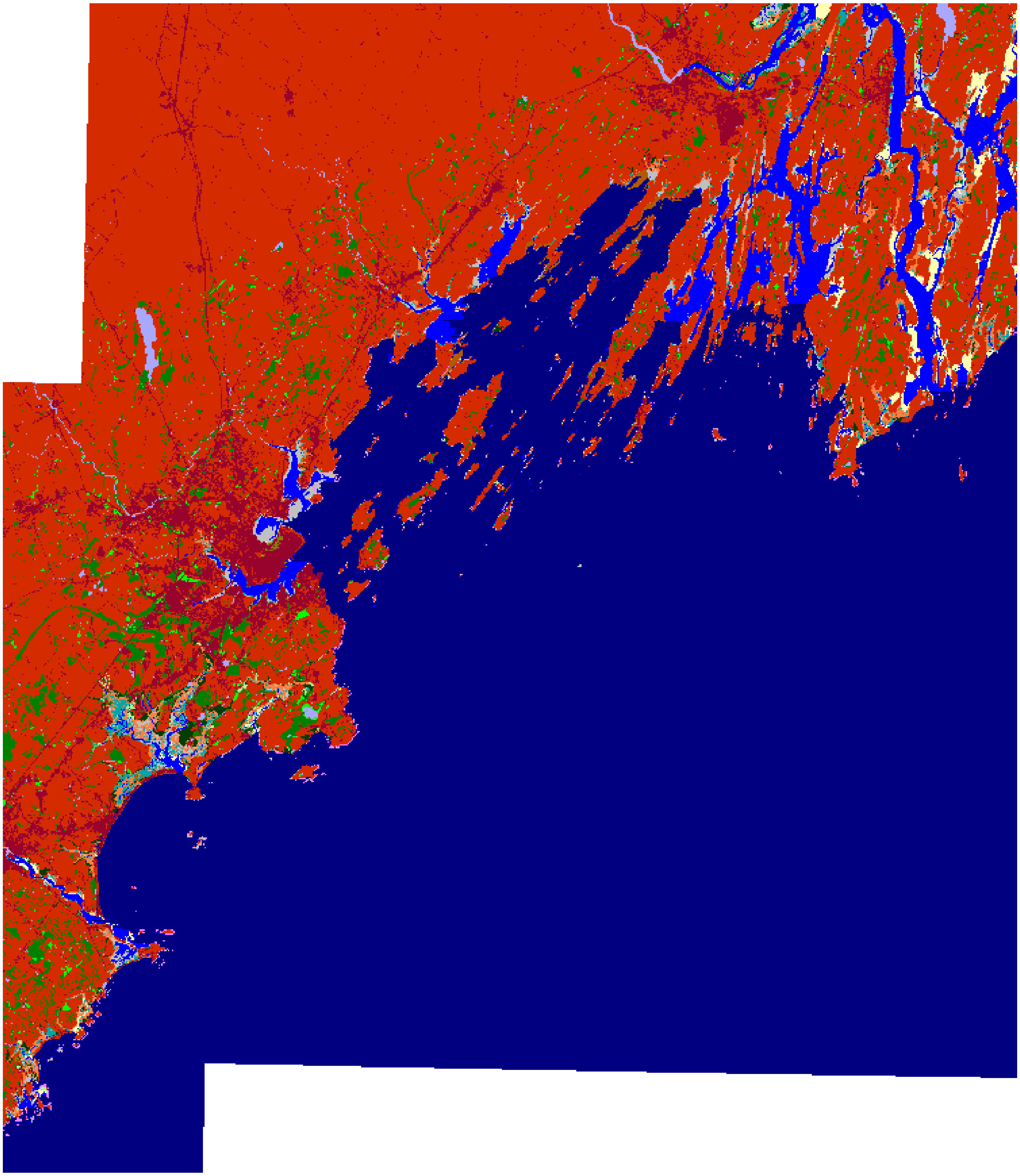
Petit Manan Section C Context, 2025, 1 Meter



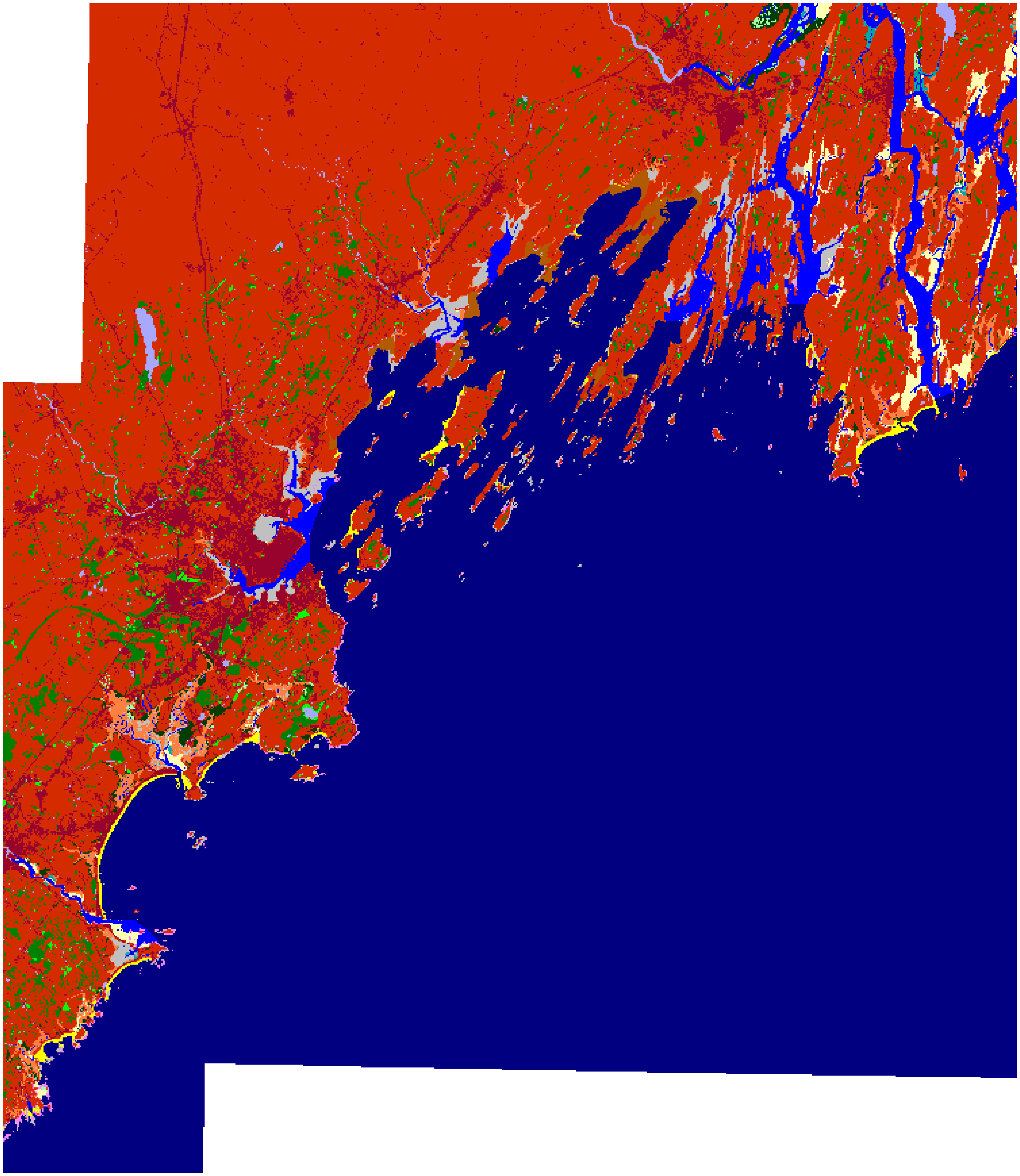
Petit Manan Section C Context, 2050, 1 Meter



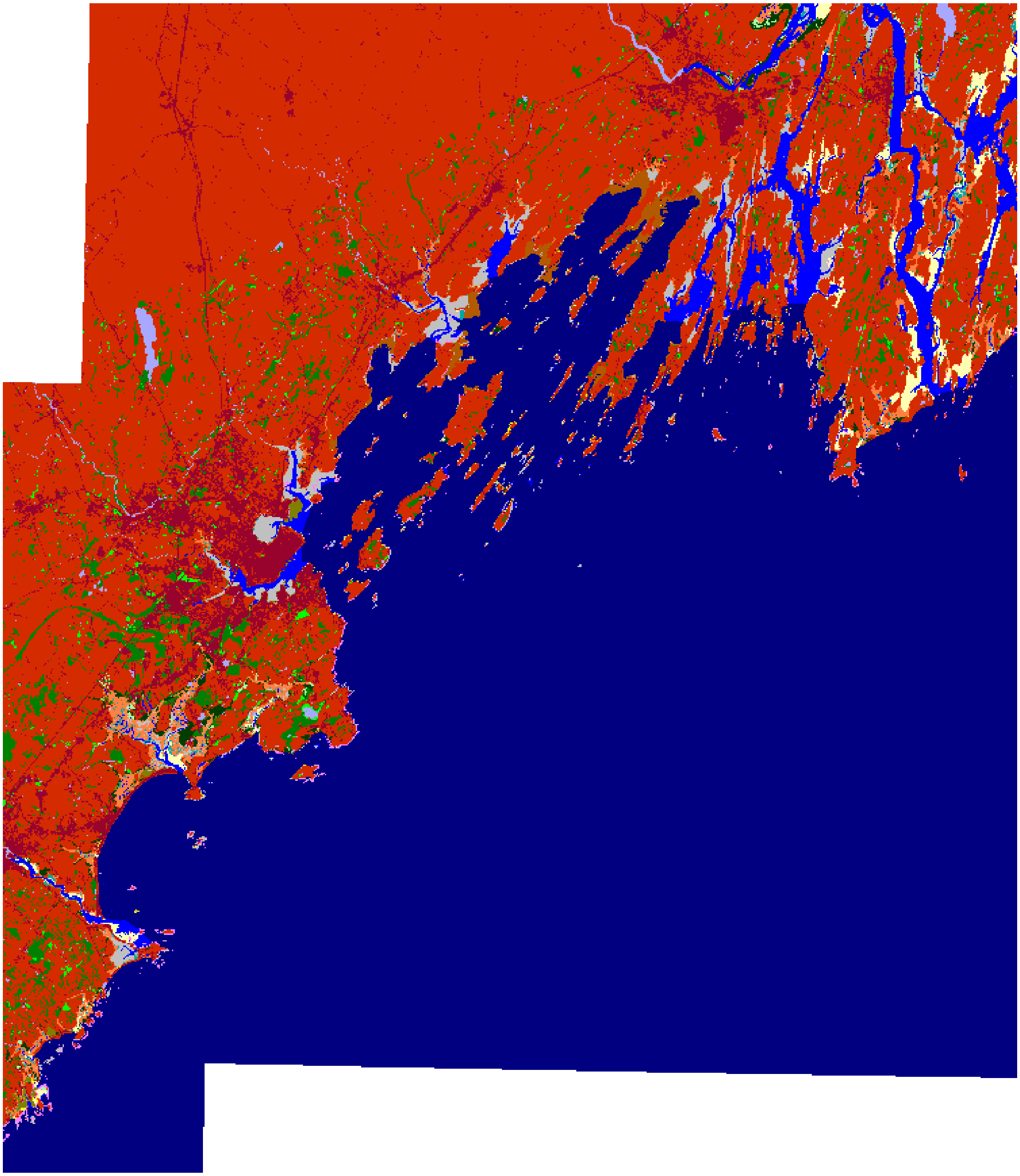
Petit Manan Section C Context, 2075, 1 Meter



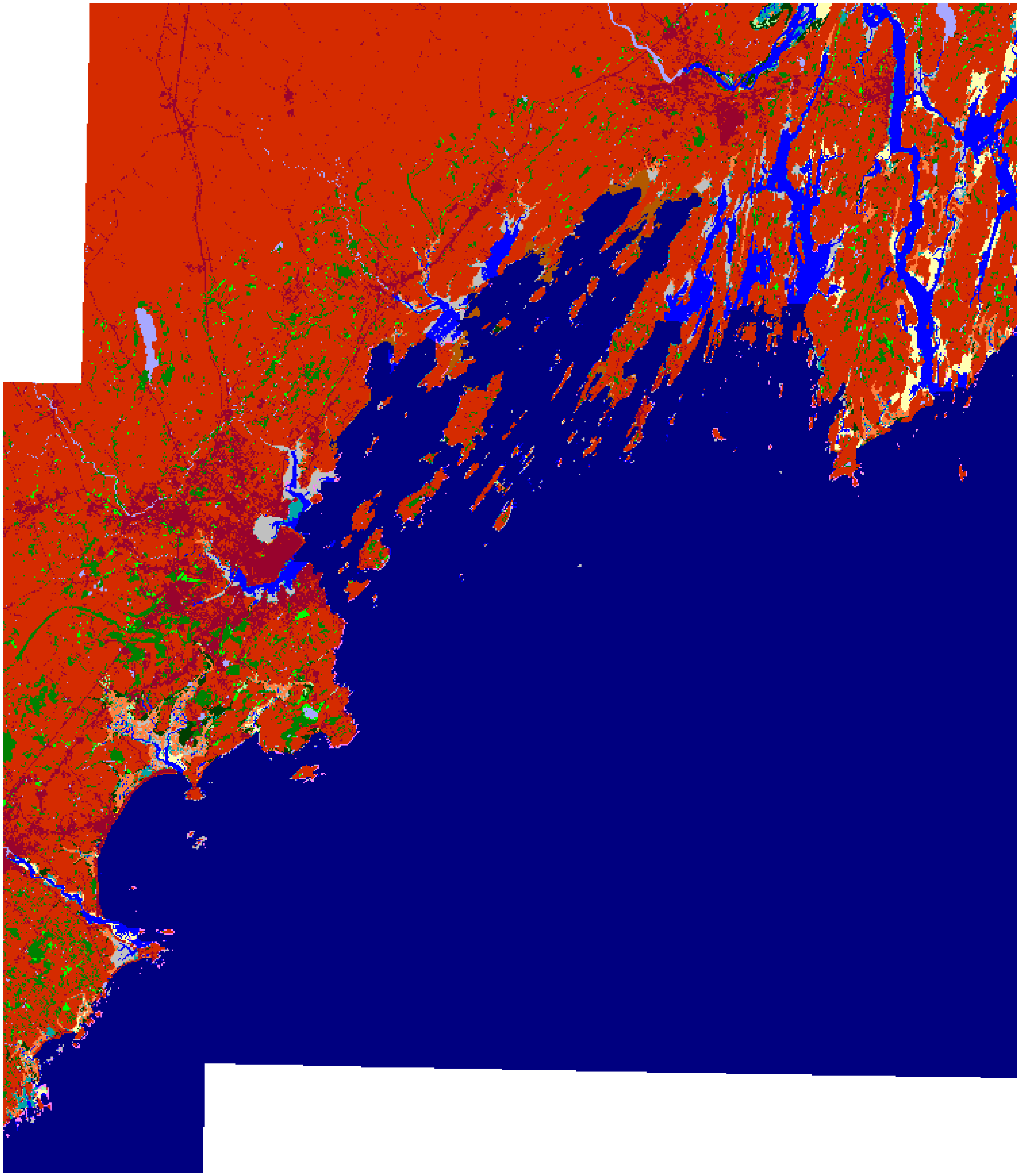
Petit Manan Section C Context, 2100, 1 Meter



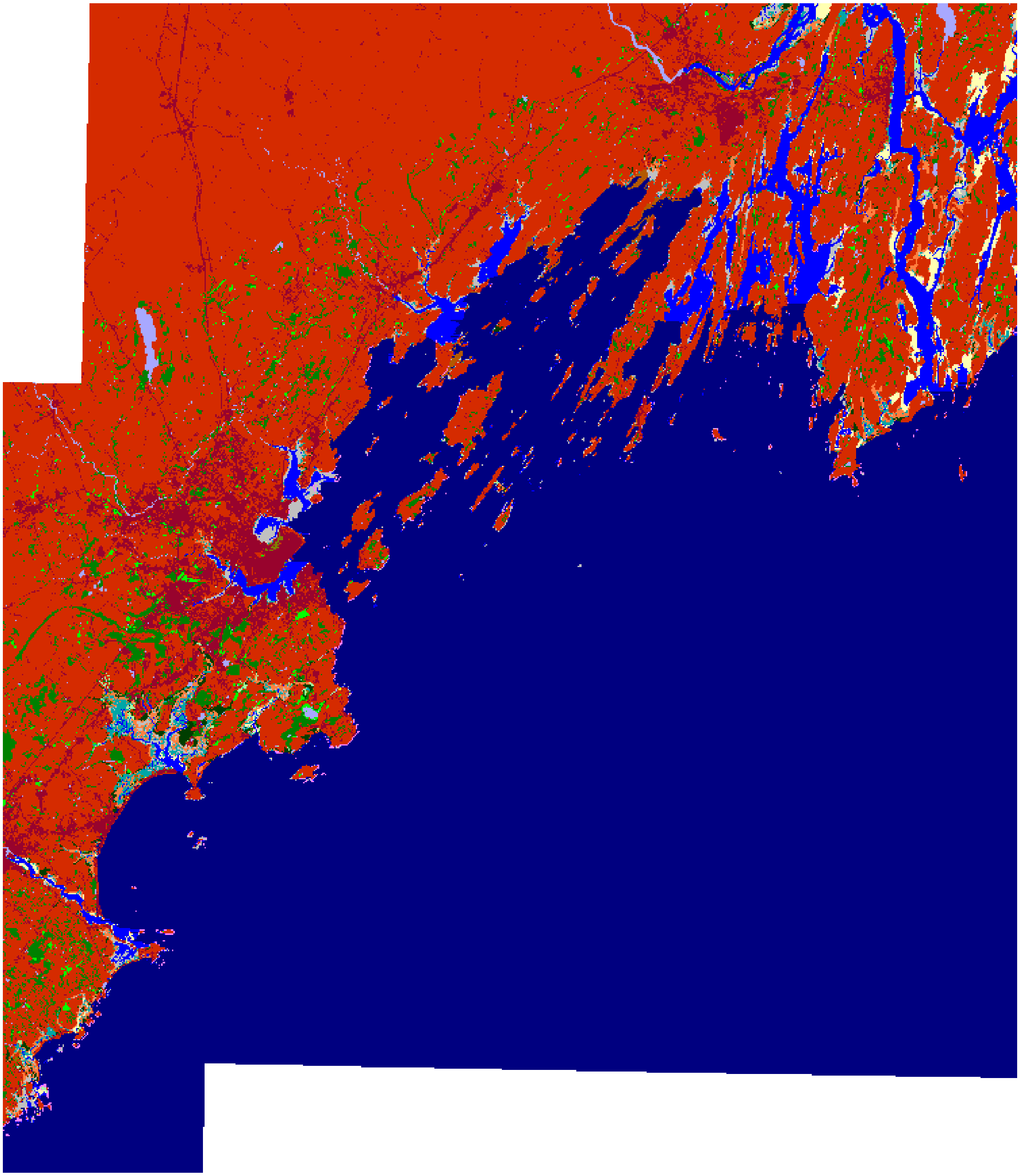
Petit Manan Section C Context, Initial Condition



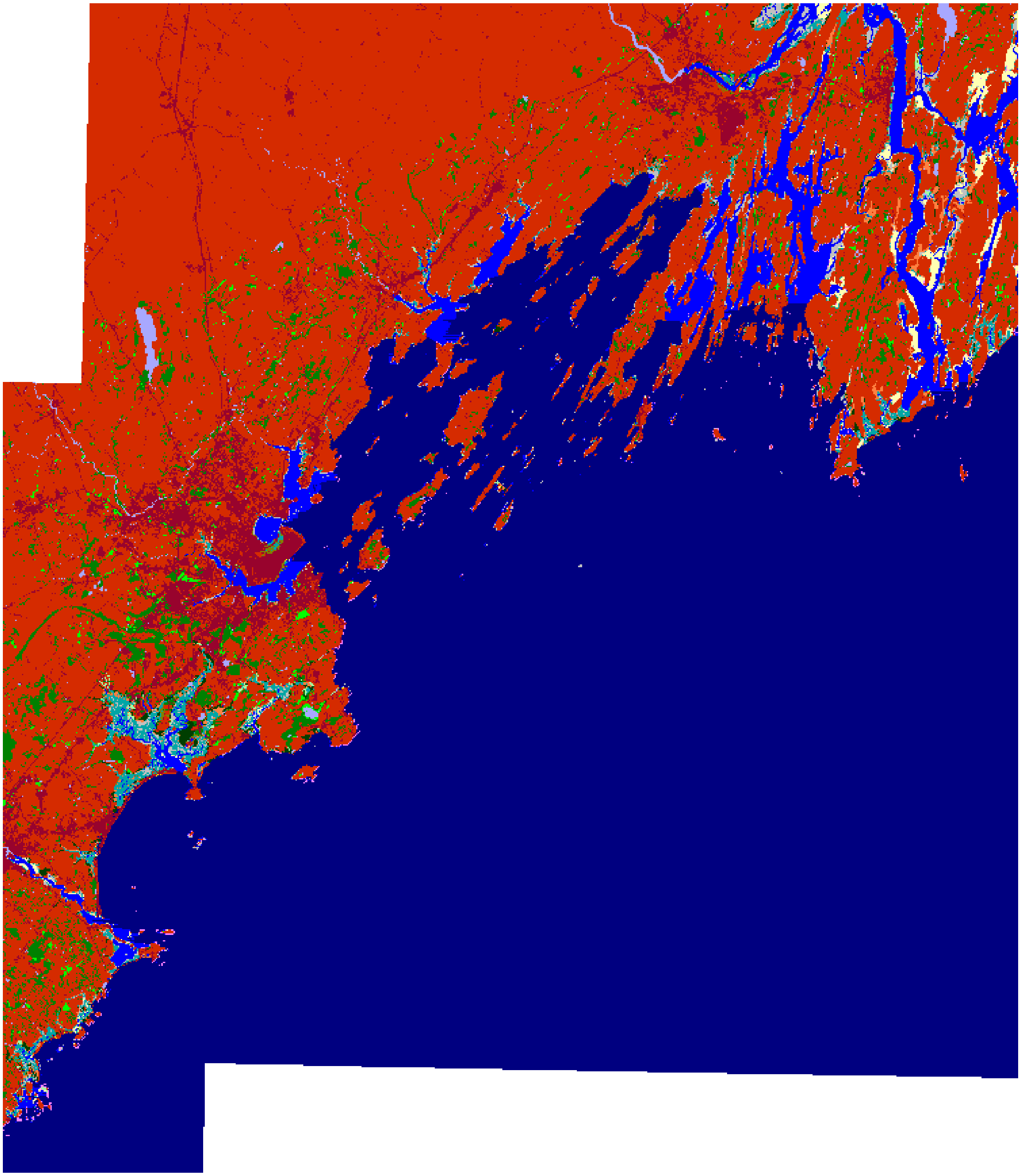
Petit Manan Section C Context, 2025, 1.5 Meters



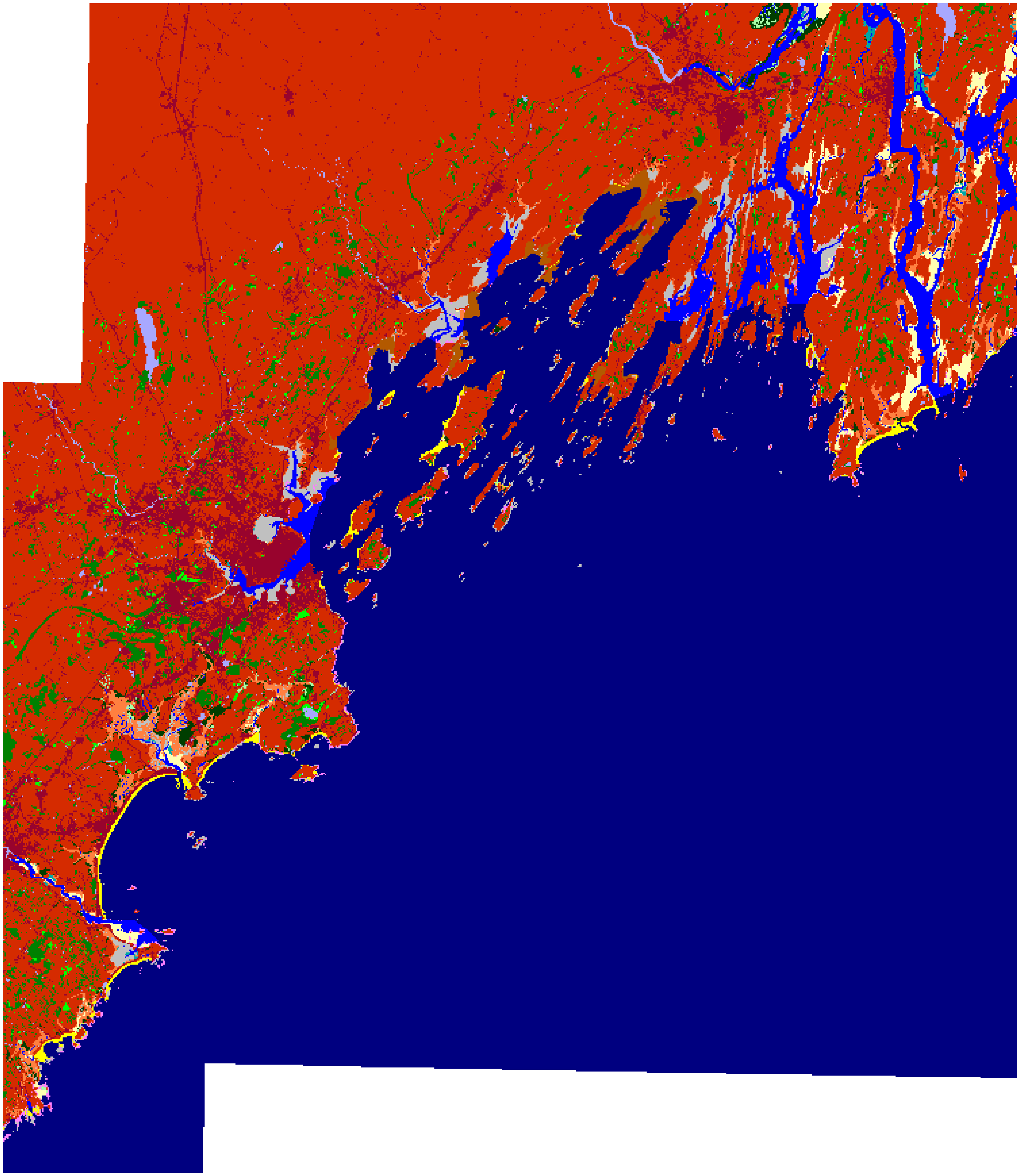
Petit Manan Section C Context, 2050, 1.5 Meters



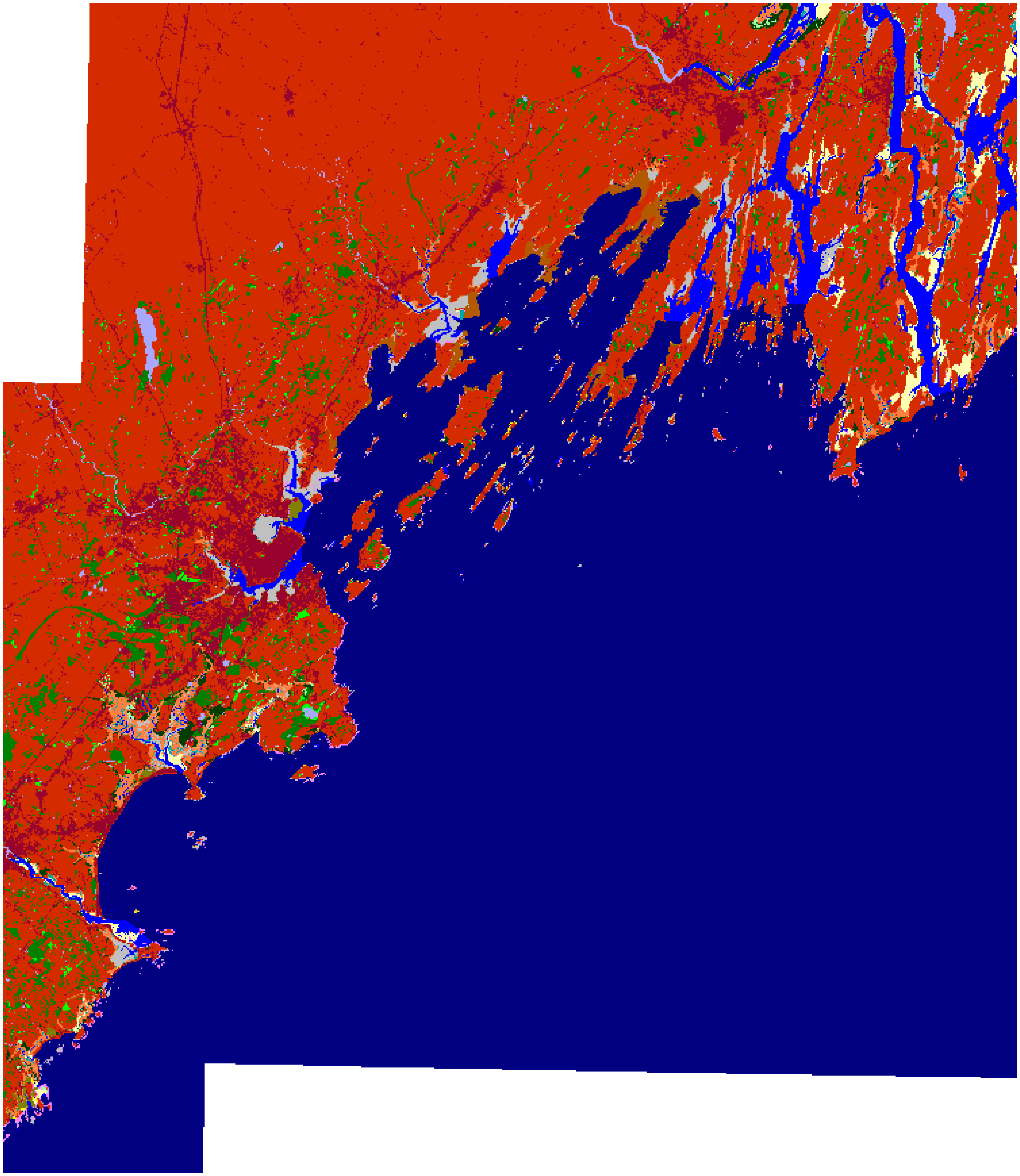
Petit Manan Section C Context, 2075, 1.5 Meters



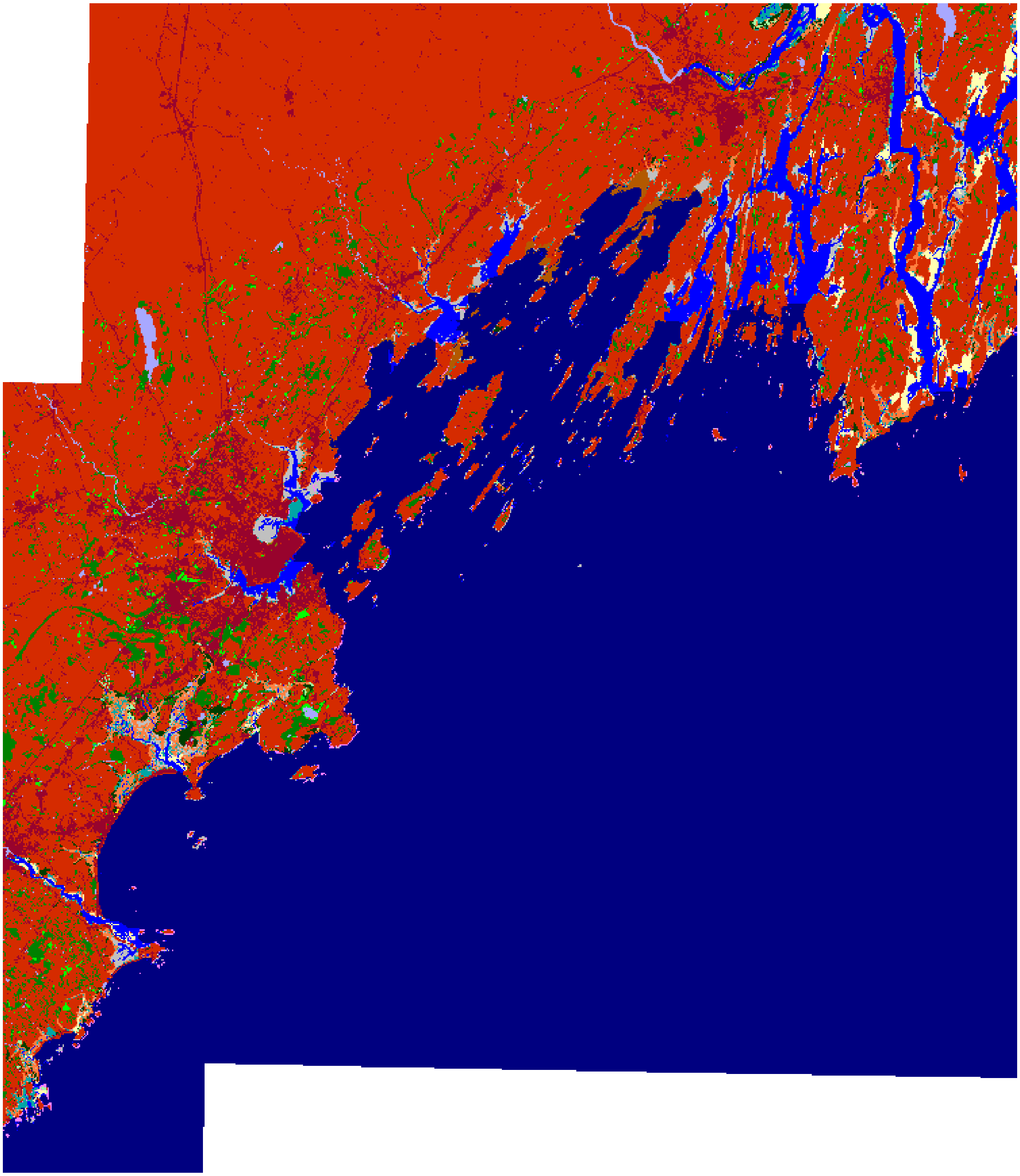
Petit Manan Section C Context, 2100, 1.5 Meters



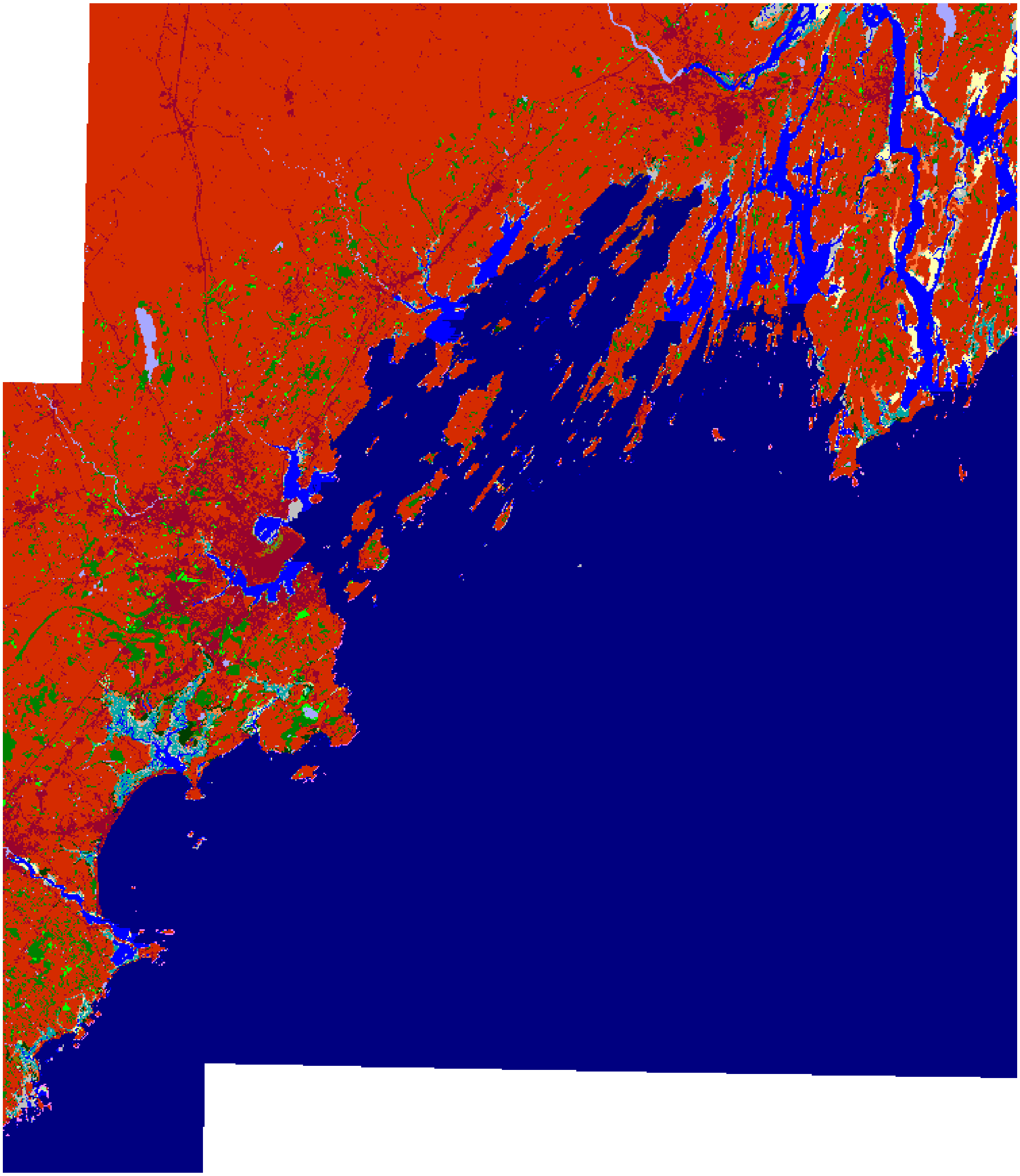
Petit Manan Section C Context, Initial Condition



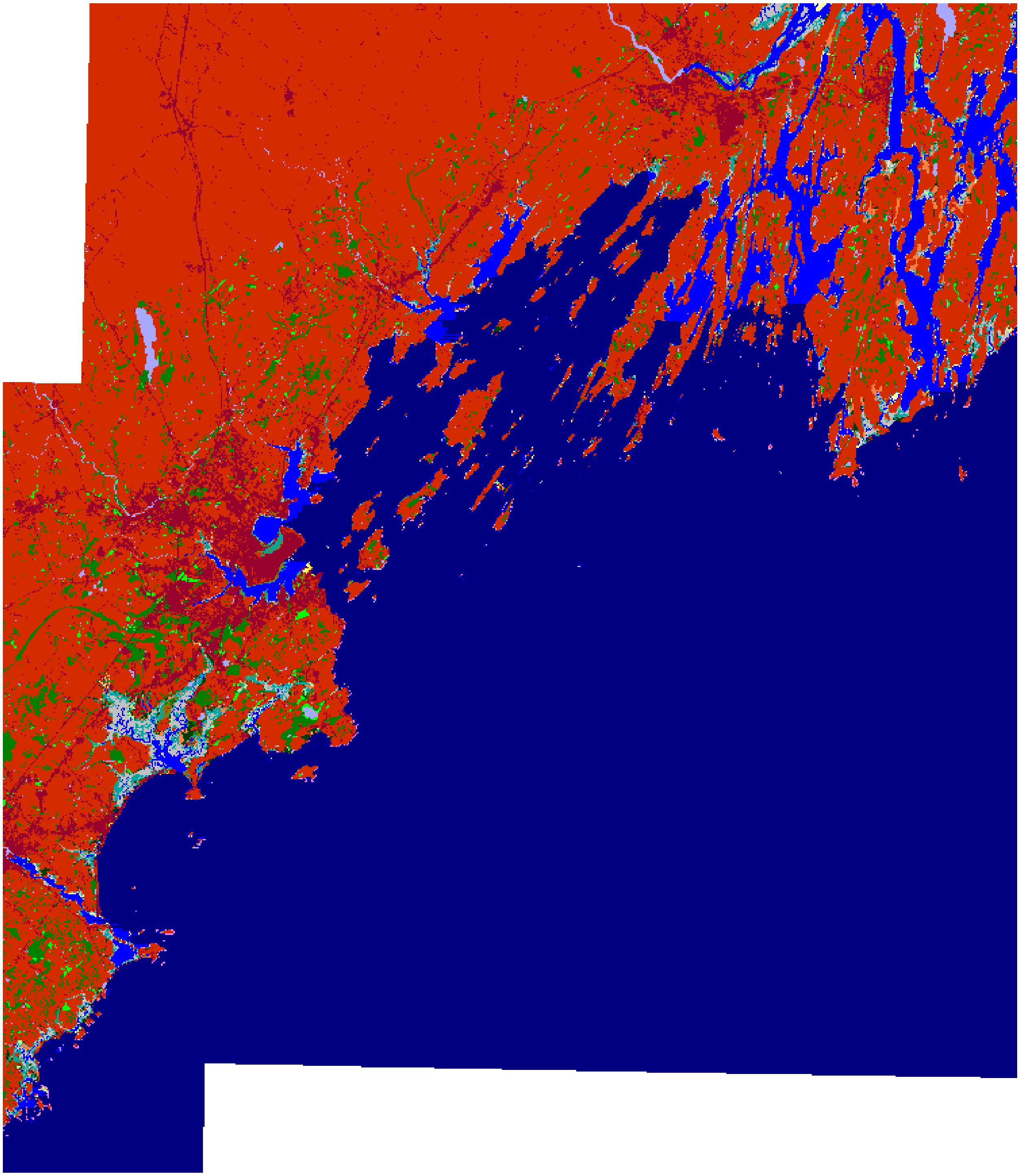
Petit Manan Section C Context, 2025, 2 Meters



Petit Manan Section C Context, 2050, 2 Meters



Petit Manan Section C Context, 2075, 2 Meters

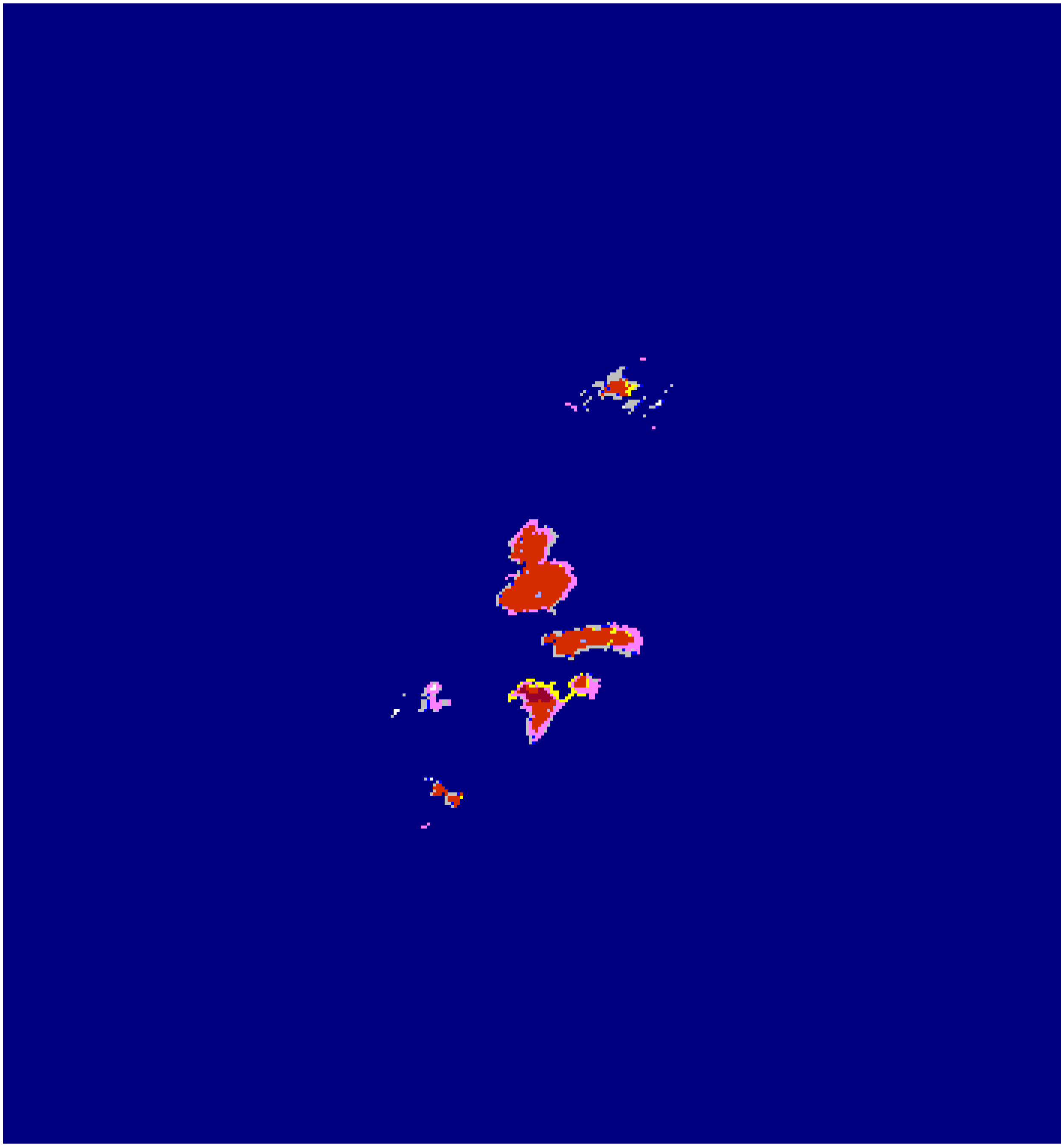


Petit Manan Section C Context, 2100, 2 Meters

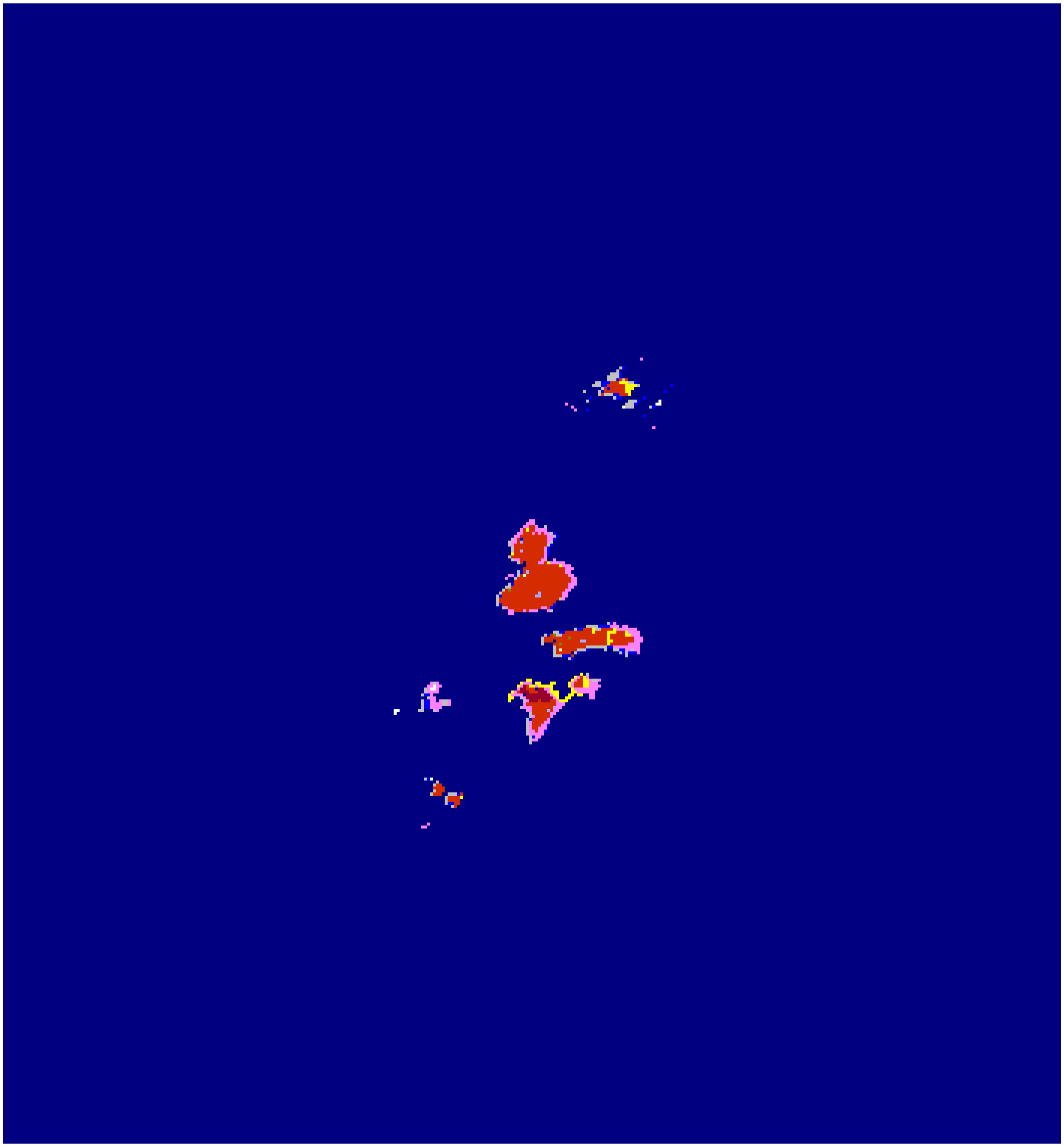
Petit Manan Section D Context, Initial Condition

Petit Manan Section D Context, 2025, Scenario A1B Mean

Petit Manan Section D Context, 2050, Scenario A1B Mean



Petit Manan Section D Context, 2075, Scenario A1B Mean

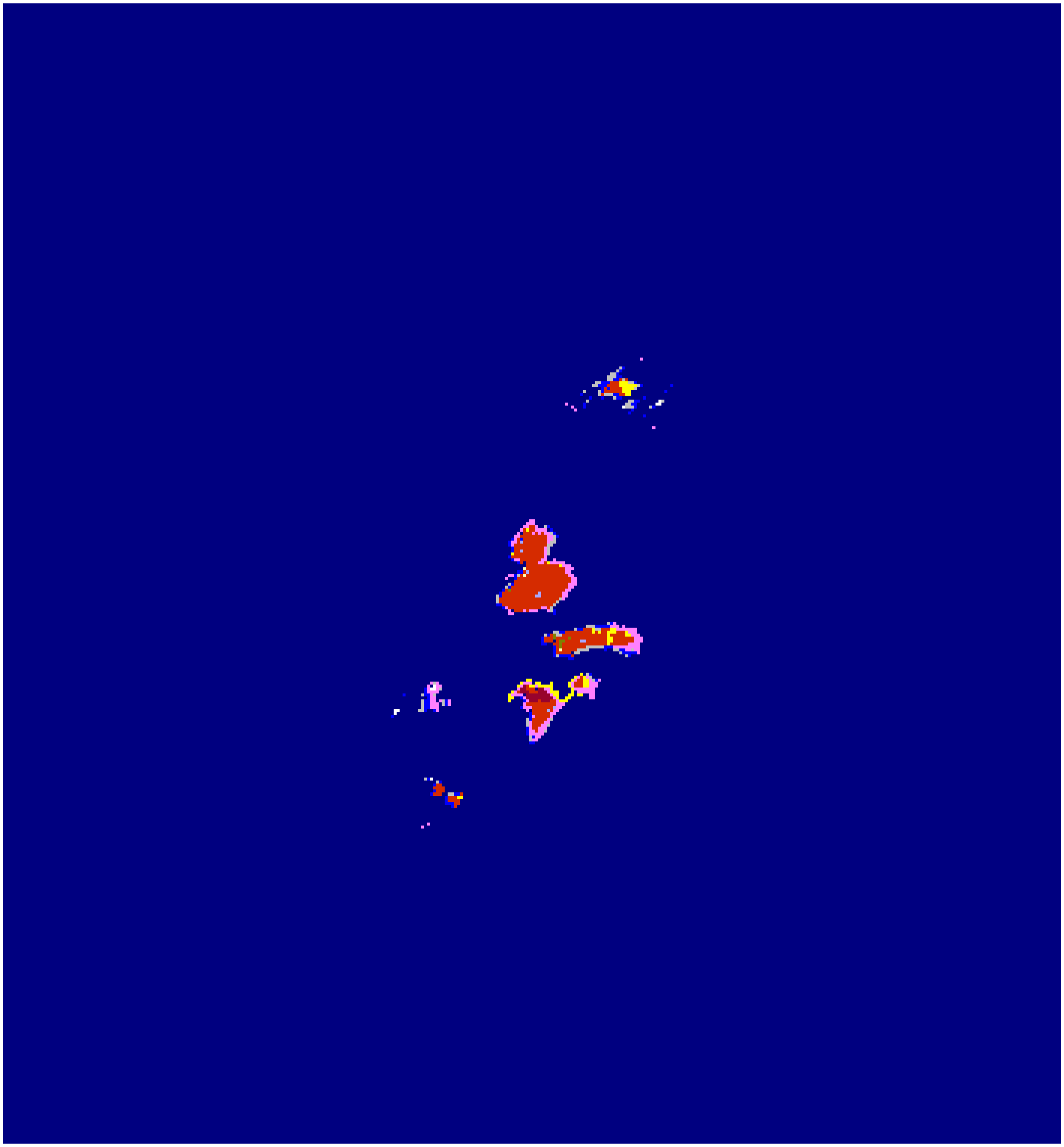


Petit Manan Section D Context, 2100, Scenario A1B Mean

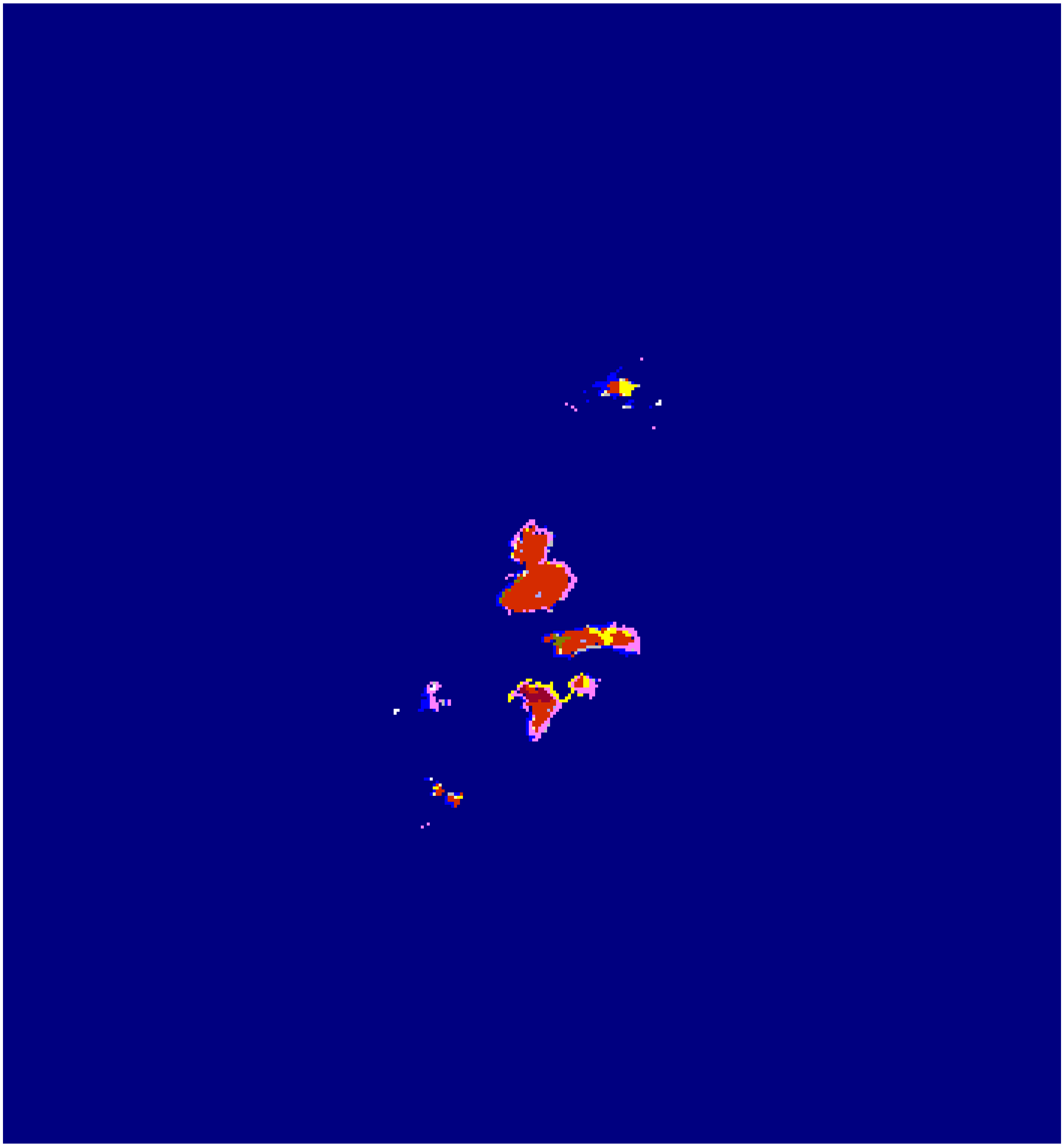
Petit Manan Section D Context, Initial Condition

Petit Manan Section D Context, 2025, Scenario A1B Maximum

Petit Manan Section D Context, 2050, Scenario A1B Maximum



Petit Manan Section D Context, 2075, Scenario A1B Maximum

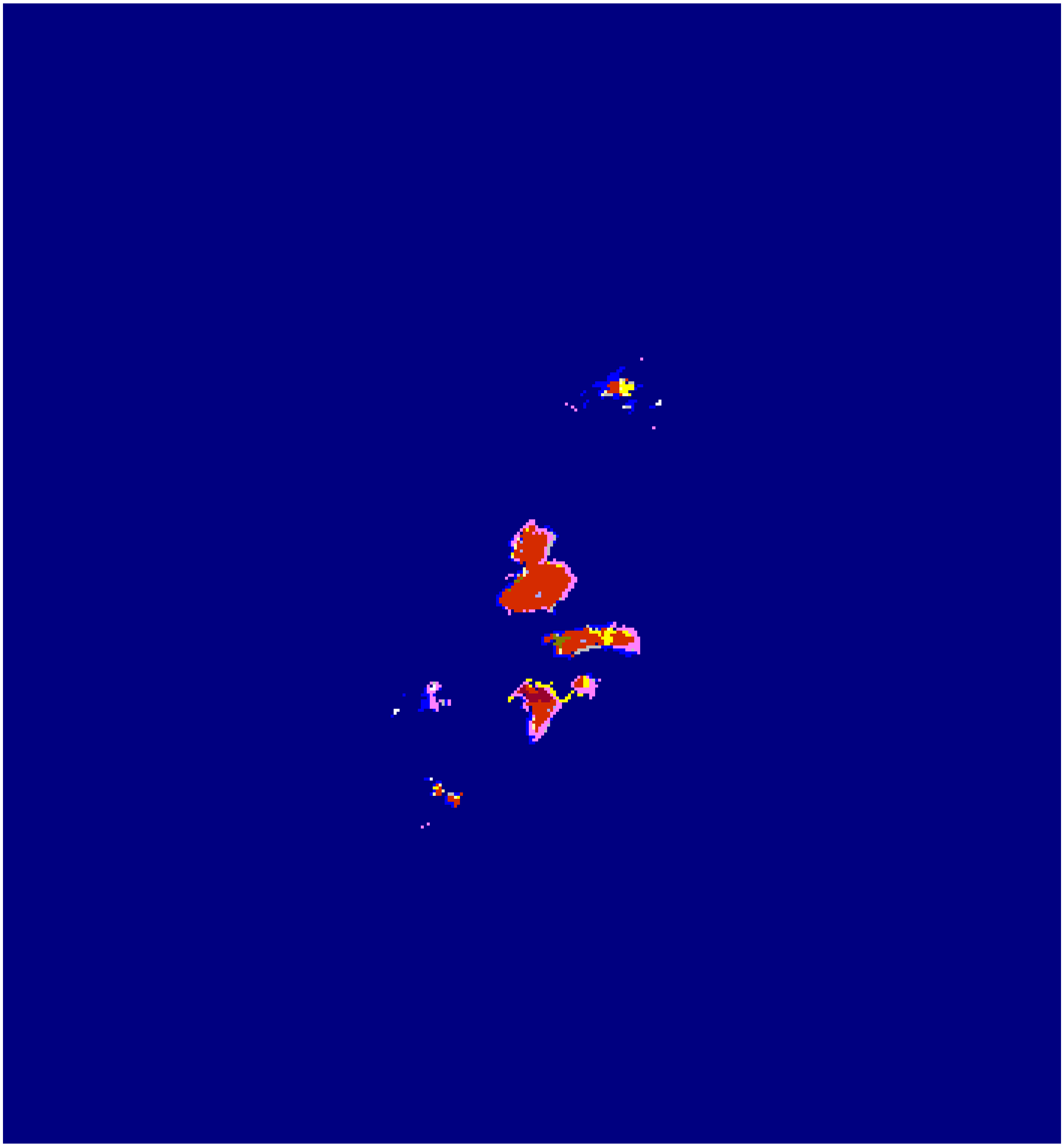


Petit Manan Section D Context, 2100, Scenario A1B Maximum

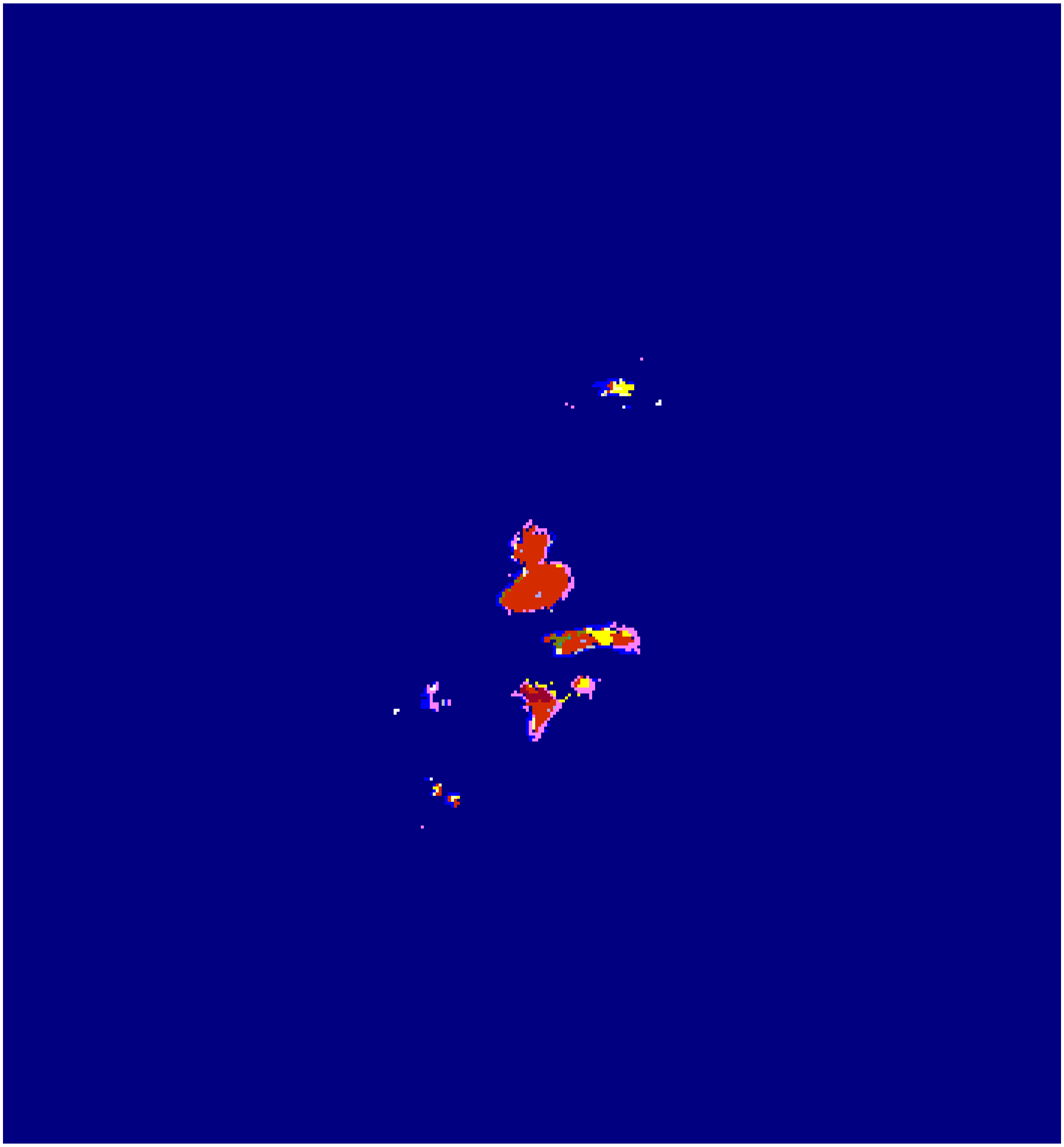
Petit Manan Section D Context, Initial Condition

Petit Manan Section D Context, 2025, 1 Meter

Petit Manan Section D Context, 2050, 1 Meter



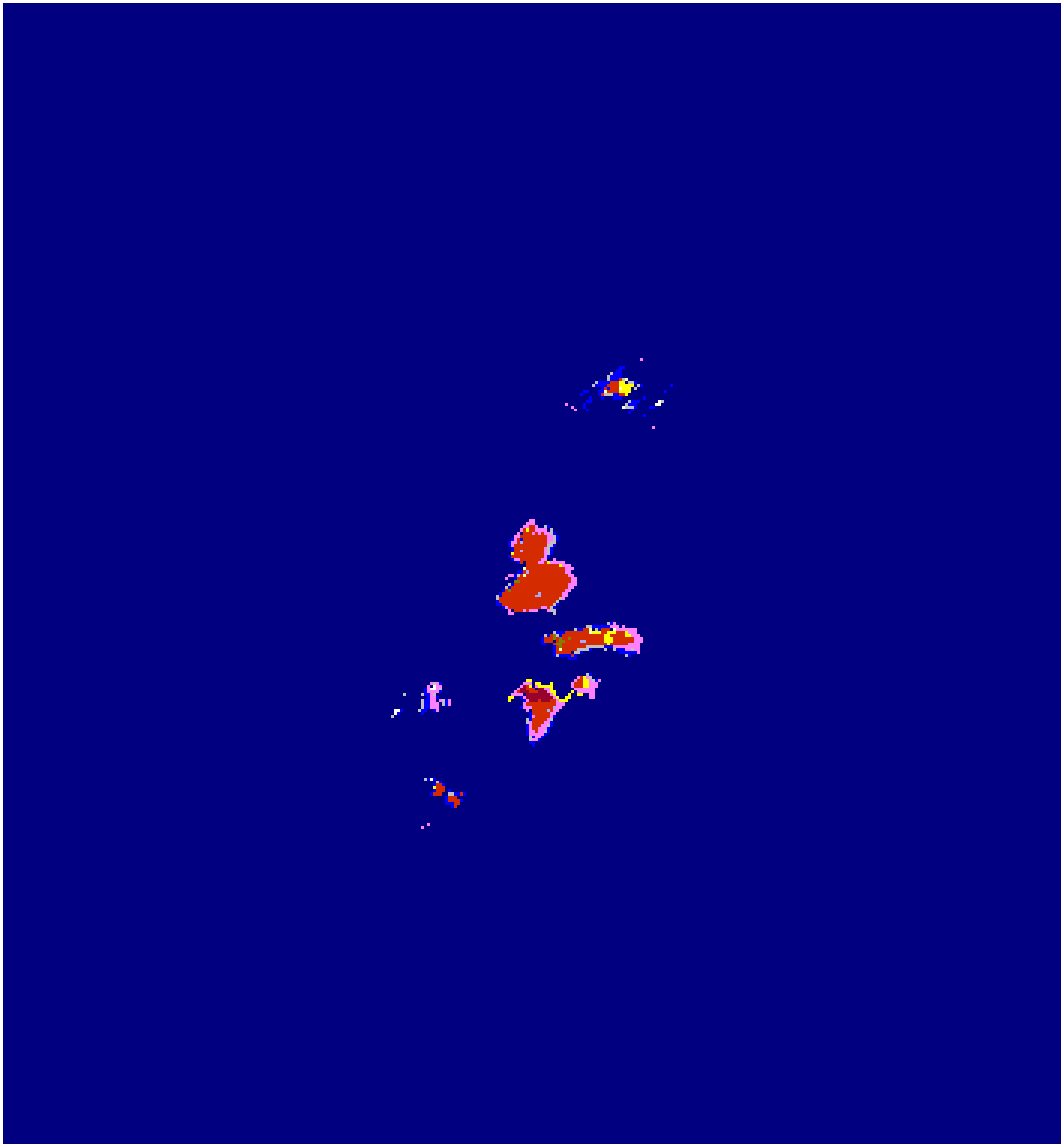
Petit Manan Section D Context, 2075, 1 Meter



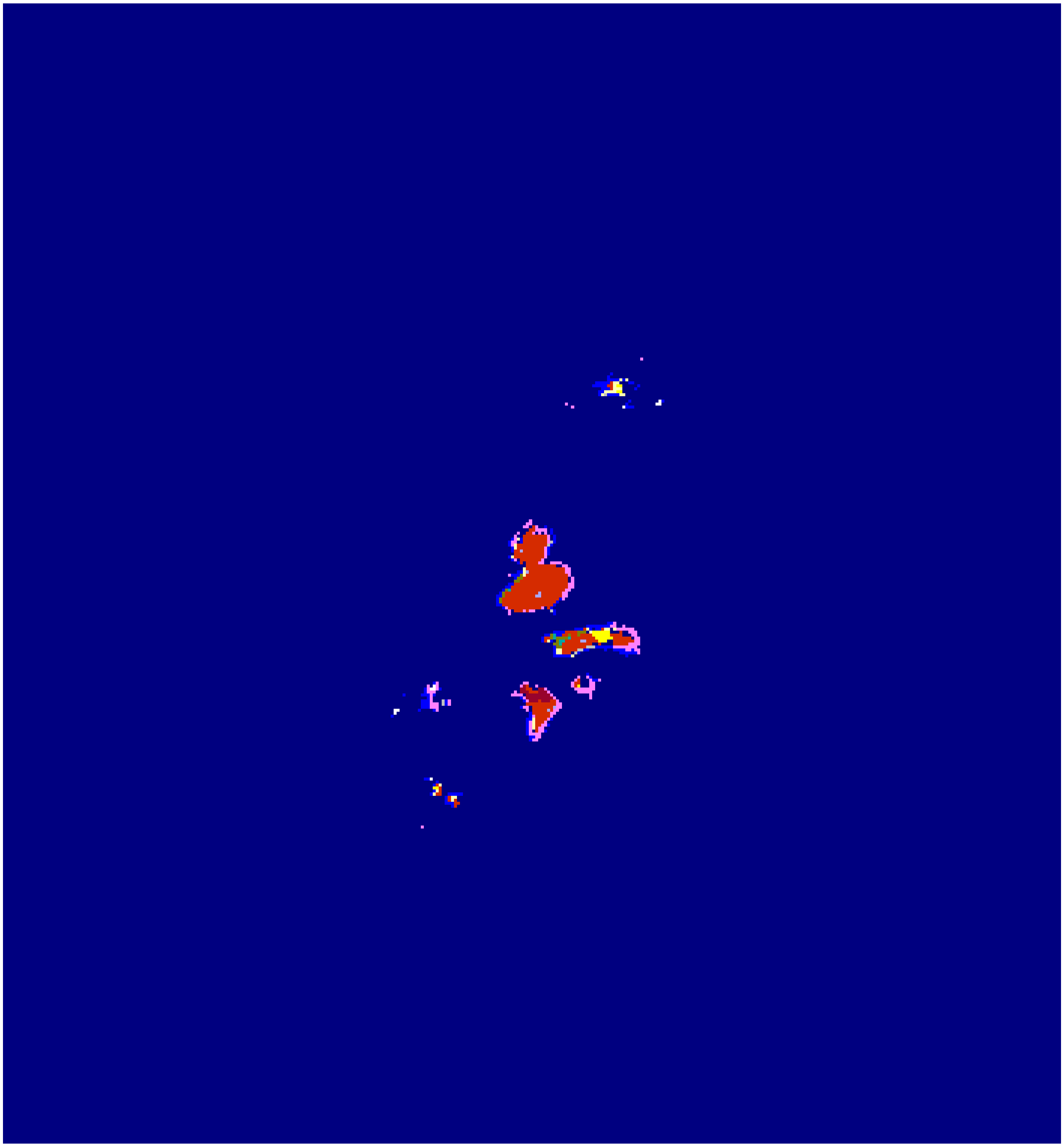
Petit Manan Section D Context, 2100, 1 Meter

Petit Manan Section D Context, Initial Condition

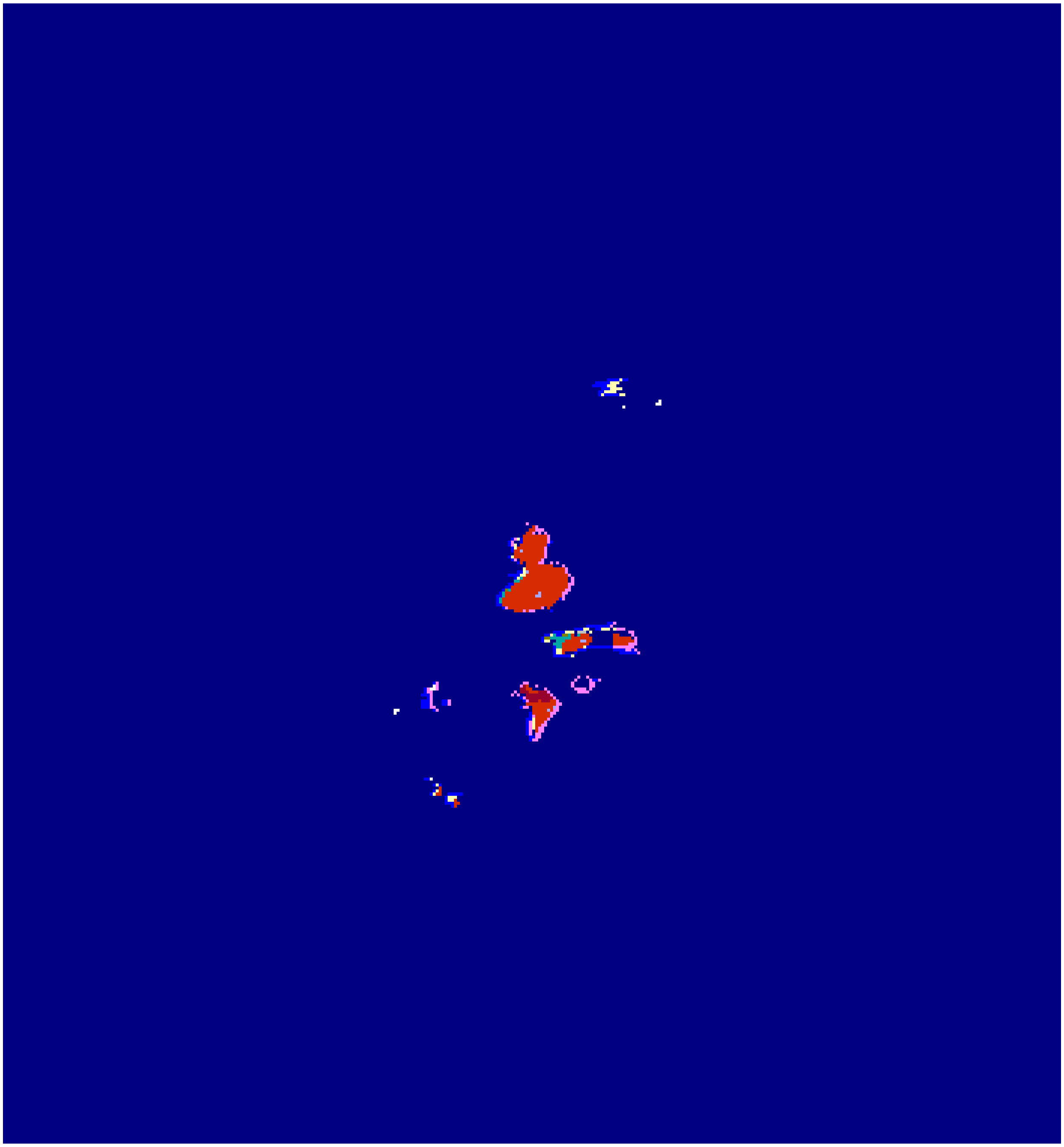
Petit Manan Section D Context, 2025, 1.5 Meters



Petit Manan Section D Context, 2050, 1.5 Meters



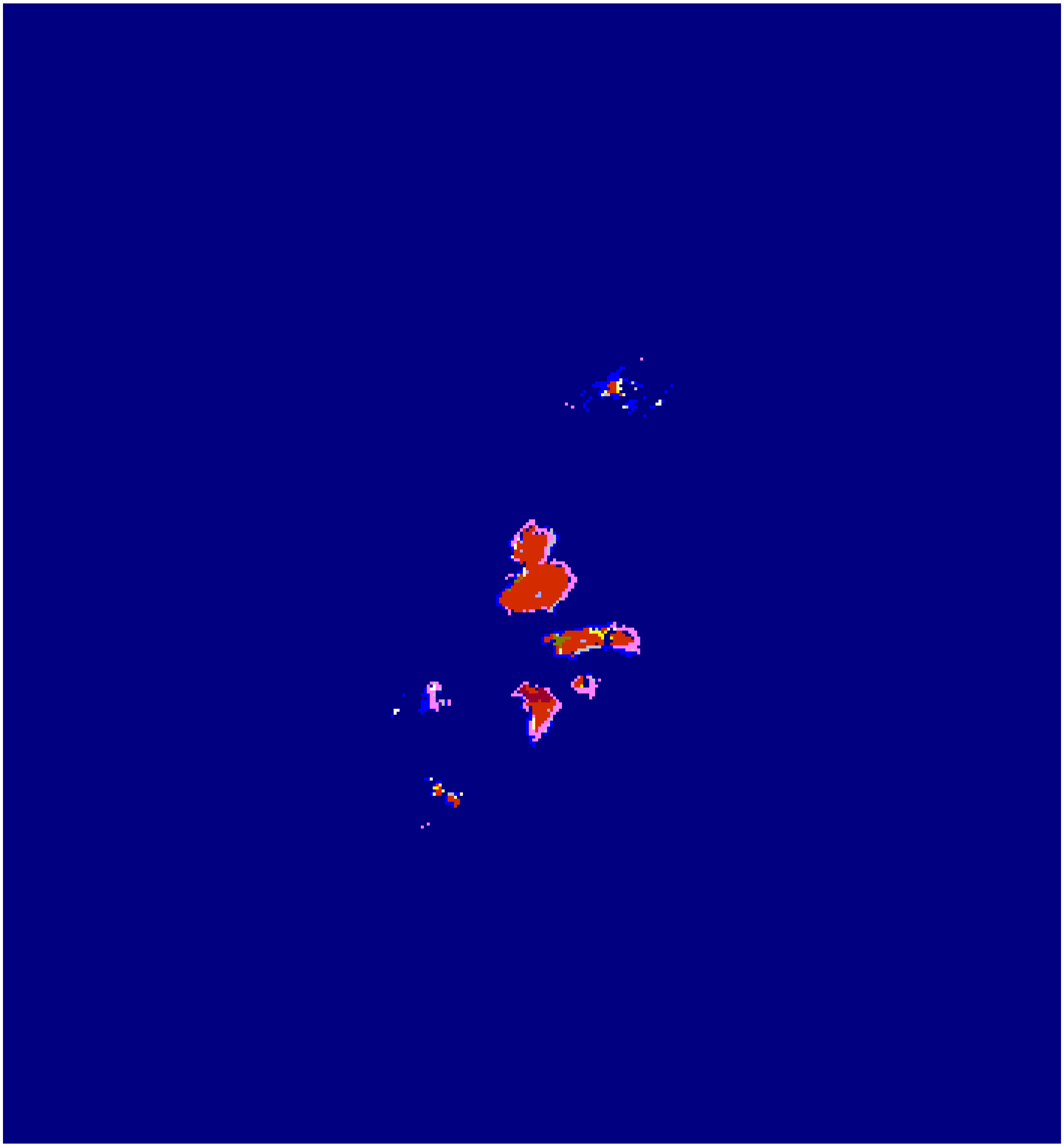
Petit Manan Section D Context, 2075, 1.5 Meters



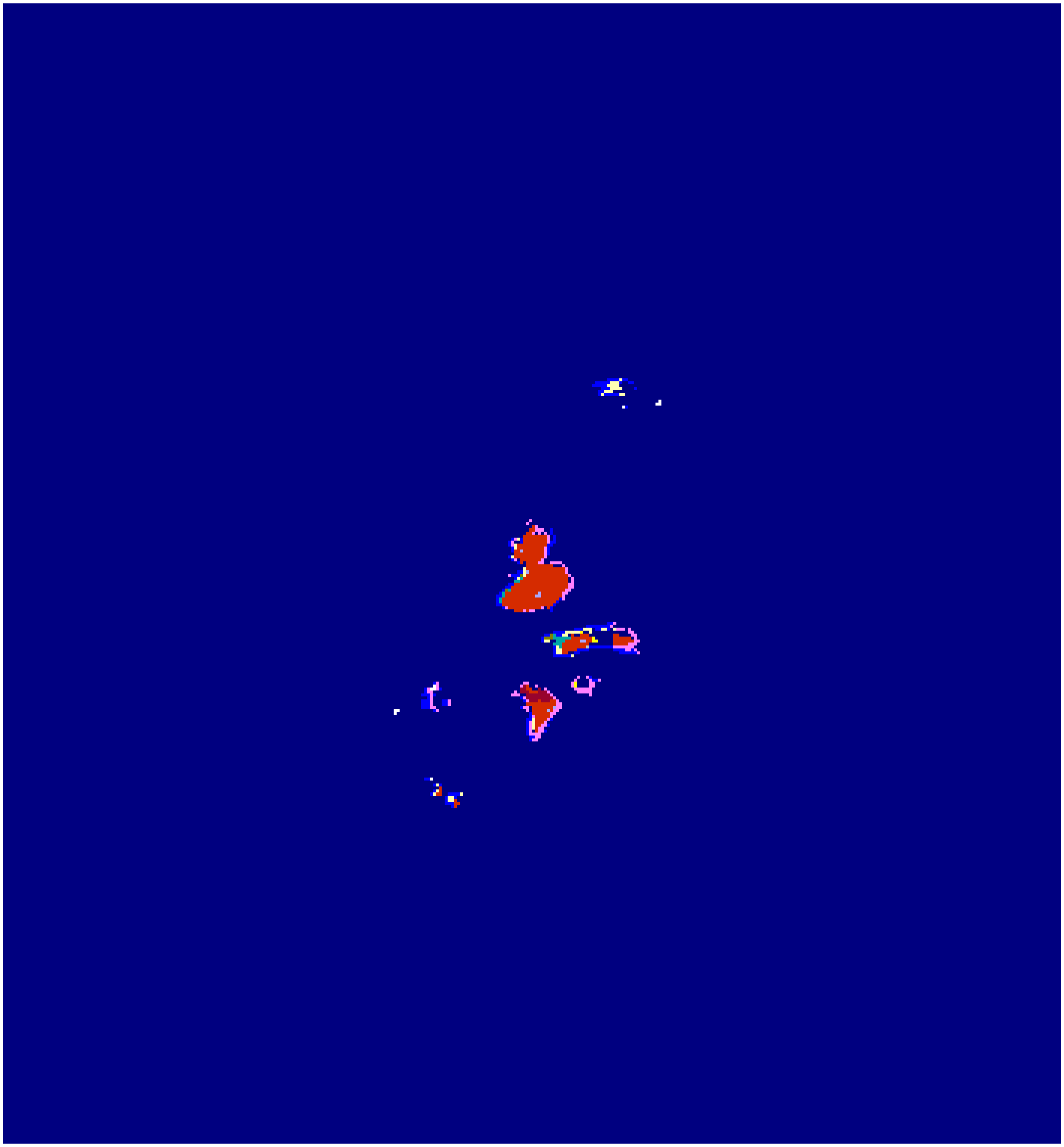
Petit Manan Section D Context, 2100, 1.5 Meters

Petit Manan Section D Context, Initial Condition

Petit Manan Section D Context, 2025, 2 Meters



Petit Manan Section D Context, 2050, 2 Meters



Petit Manan Section D Context, 2075, 2 Meters

Petit Manan Section D Context, 2100, 2 Meters