Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to Rachel Carson NWR

Prepared For: Dr. Brian Czech, Conservation Biologist

U. S. Fish and Wildlife Service
National Wildlife Refuge System
Division of Natural Resources and Conservation Planning
Conservation Biology Program
4401 N. Fairfax Drive - MS 670
Arlington, VA 22203

December 22, 2008

Jonathan S. Clough & Evan C. Larson, Warren Pinnacle Consulting, Inc.
PO Box 253, Warren VT, 05674
(802)-496-3476

Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to Rachel Carson NWR

Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). The International Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) suggested that global sea level will increase by approximately 30 cm to 100 cm by 2100 (IPCC 2001). Rahmstorf (2007) suggests that this range may be too conservative and that the feasible range by 2100 could be 50 to 140 cm. Pfeffer et al. (2008) suggests that 200 cm by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. Rising sea level may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat migration as salt marshes transgress landward and replace tidal freshwater and brackish marsh (Park et al. 1991).

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

Model Summary

Changes in tidal marsh area and habitat type in response to sea-level rise were modeled using the Sea Level Affecting Marshes Model (SLAMM 5.0) that accounts for the dominant processes involved in wetland conversion and shoreline modifications during long-term sea level rise (Park et al. 1989; www.warrenpinnacle.com/prof/SLAMM).

Successive versions of the model have been used to estimate the impacts of sea level rise on the coasts of the U.S. (Titus et al., 1991; Lee, J.K., R.A. Park, and P.W. Mausel. 1992; Park, R.A., J.K. Lee, and D. Canning 1993; Galbraith, H., R. Jones, R.A. Park, J.S. Clough, S. Herrod-Julius, B. Harrington, and G. Page. 2002; National Wildlife Federation et al., 2006; Glick, Clough, et al. 2007; Craft et al., 2009.

Within SLAMM, there are five primary processes that affect wetland fate under different scenarios of sea-level rise:

- **Inundation:** The rise of water levels and the salt boundary are tracked by reducing elevations of each cell as sea levels rise, thus keeping mean tide level (MTL) constant at zero. The effects on each cell are calculated based on the minimum elevation and slope of that cell.
- **Erosion:** Erosion is triggered based on a threshold of maximum fetch and the proximity of the marsh to estuarine water or open ocean. When these conditions are met, horizontal erosion occurs at a rate based on site-specific data.
- **Overwash:** Barrier islands of under 500 meters width are assumed to undergo overwash during each 25-year time-step due to storms. Beach migration and transport of sediments are calculated.
- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the fresh water table to rising sea level close to the coast.

- **Accretion:** Sea level rise is offset by sedimentation and vertical accretion using average or site-specific values for each wetland category. Accretion rates may be spatially variable within a given model domain.

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

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

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

All model results are subject to uncertainty due to limitations in input data, incomplete knowledge about factors that control the behavior of the system being modeled, and simplifications of the system (CREM 2008).

Sea-Level Rise Scenarios

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

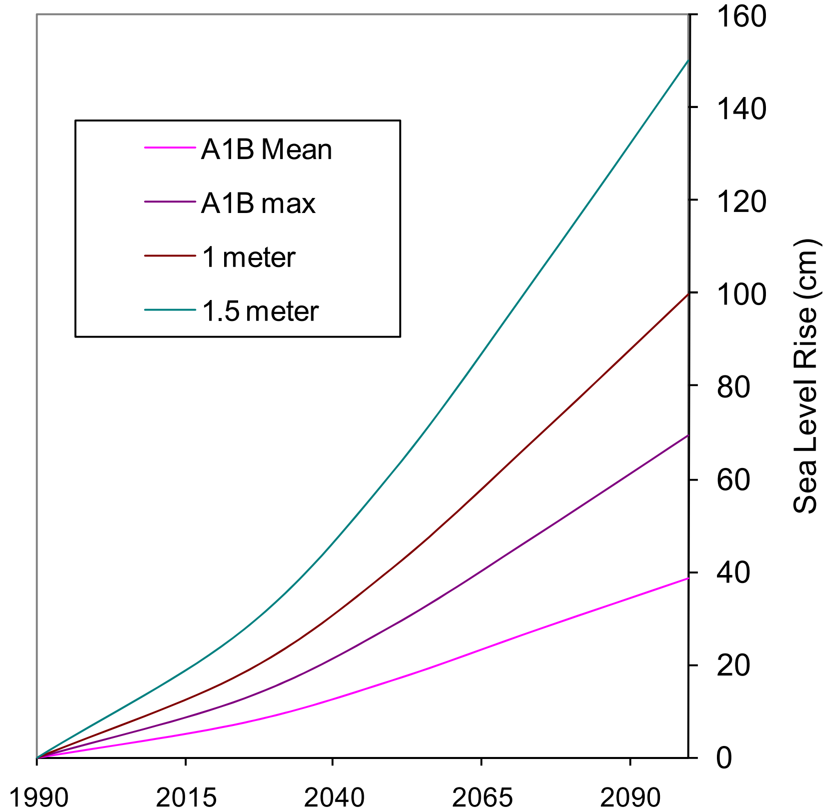
Scenario	Eustatic SLR by 2025 (cm)	Eustatic SLR by 2050 (cm)	Eustatic SLR by 2075 (cm)	Eustatic SLR by 2100 (cm)
A1B Mean	8	17	28	39
A1B Max	14	30	49	69
1 meter	13	28	48	100
1.5 meter	18	41	70	150

Recent literature (Chen et al., 2006, Monaghan et al., 2006) indicates that the eustatic rise in sea levels is progressing more rapidly than was previously assumed, perhaps due to dynamic changes in ice flow omitted within the IPCC report's calculations. A recent paper in the journal *Science* (Rahmstorf, 2007) suggests that, taking into account possible model error, a feasible range by 2100 might be 50 to 140 cm. A recent US intergovernmental report states "Although no ice-sheet model is currently capable of capturing the glacier speedups in Antarctica or Greenland that have been observed over the last decade, including these processes in models will very likely show that IPCC

AR4 projected sea level rises for the end of the 21st century are too low." (US Climate Change Science Program, 2008)

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 meter, 1½ meters of eustatic sea-level rise by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 1).

Figure 1: Summary of SLR Scenarios Utilized



Methods and Data Sources

An extensive set of LiDAR data was found for Rachel Carson NWR. These LiDAR data are quite recent, derived from a 2008 flight date. Elevation data used are based on a combination of the LiDAR and the National Elevation Dataset (NED), though the vast majority of the refuge is covered by high vertical-precision LiDAR data (Fig. 2b).

For the small portion of the refuge that lies outside of the LiDAR footprint, the NED was derived from a 1956 survey as illustrated within USGS topographic map shown below (Fig. 2a). The contour intervals in this map are twenty feet.

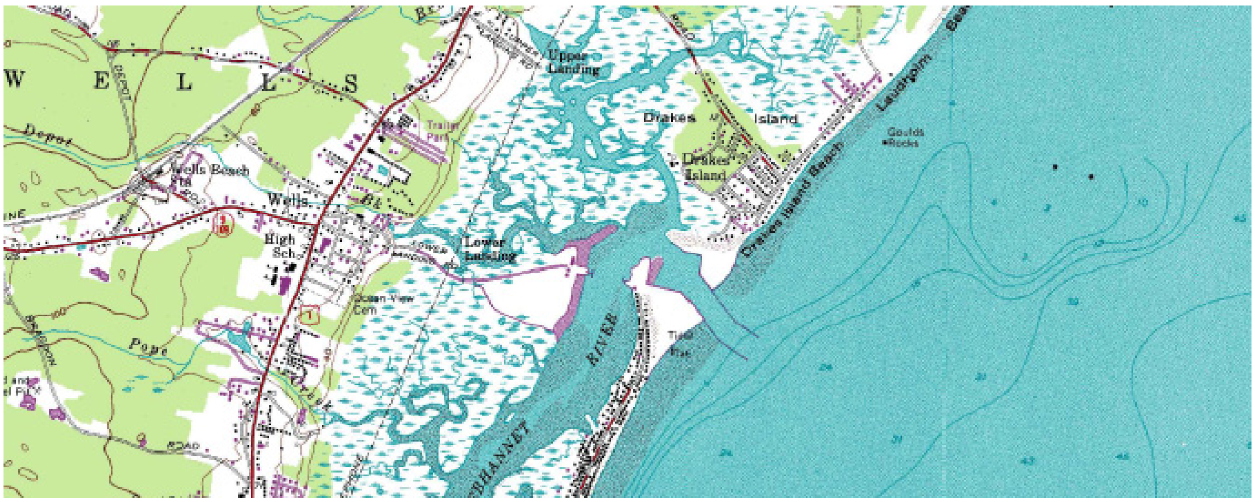


Figure 2a: Rachel Carson Excerpt from USGS Map.

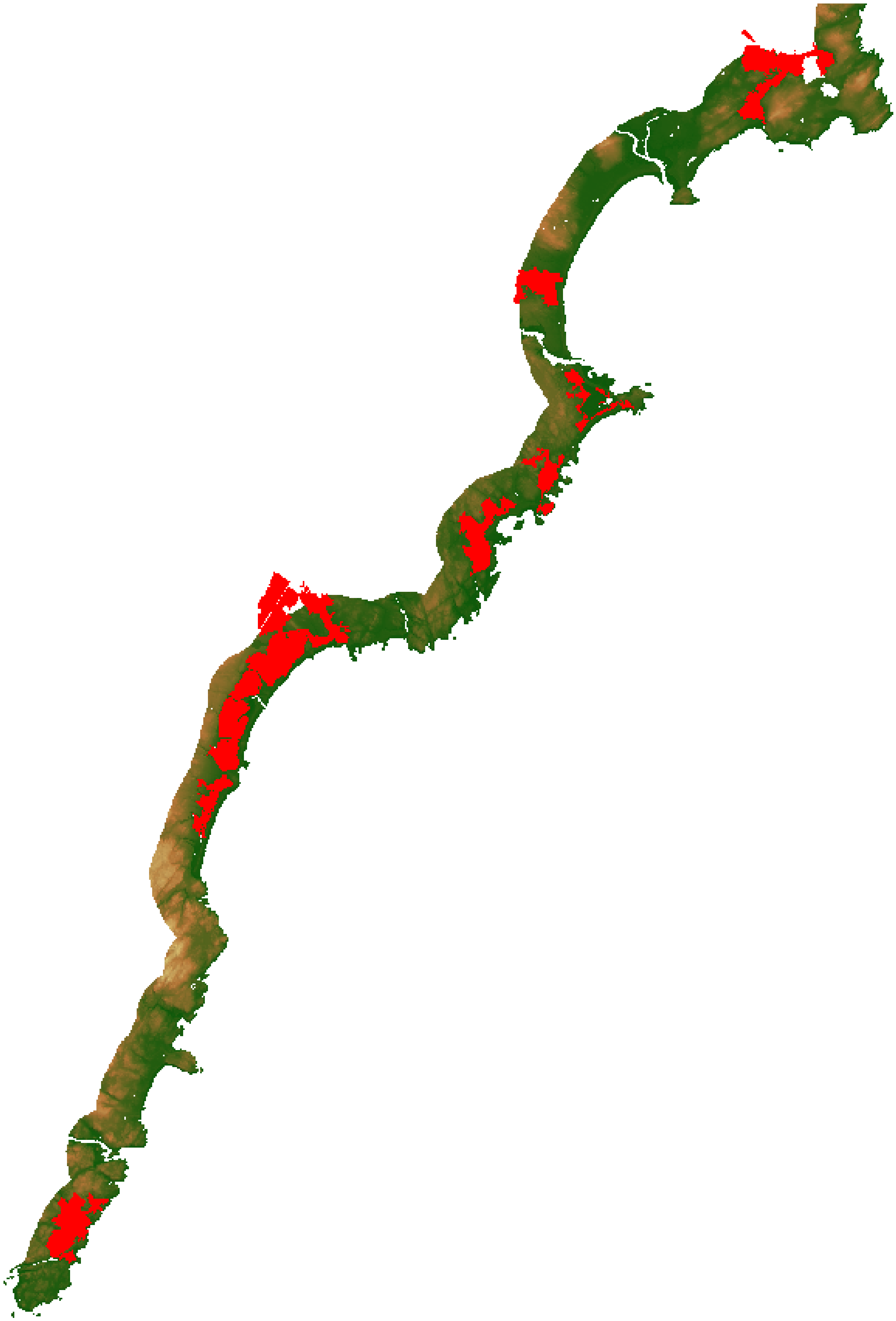


Figure 2b: Rachel Carson NWR (red) over LiDAR coverage map.

The National Wetlands Inventory for Rachel Carson is based on a photo date of 2004. An examination of the NWI map overlaid on recent satellite photos indicates no changes since the inventory was taken.

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

Brackish Marsh	35.8%
Dry Land	31.2%
Swamp	10.2%
Tidal Swamp	7.4%
Tidal Flat	4.2%
Estuarine Beach	3.8%
Estuarine Open Water	3.0%
Tidal Fresh Marsh	1.0%

Based on the NWI coverage, there are a few diked and impounded wetlands within the Rachel Carson NWR, although the acreage they occupy is too small to have a significant impact on the study results. Areas demarcated as protected by dikes were, however, assumed to be protected in this modeling analysis.

The historic trend for sea level rise was estimated at 1.79 mm/year using the average values of the two closest stations (8419870, Seavey Island, ME; 8418150, Portland, ME). This measured rate is similar to the global average for the last 100 years (approximately 1.5-2.0 mm/year). Any effects of isostatic rebound that have affected this region for the last 100 years are measured within that historic trend and that same rate of isostatic rebound is projected forward into the next 100 years.

In terms of tide range, the study site was divided into two, with the section of the refuge below Fort Point having a value of 2.87 meters and the areas above Fort Point having a value of 2.92 meters. The tide range at this site was estimated using the average of the seven closest NOAA oceanic gages (8423898, Fort Point, NH;8419590, Seapoint, Cutts Island, ME;8419528, Fort Point, York Harbor, ME;8419317, Wells, ME;8418911, Kennebunkport, Kennebunk River, ME;8418606, Camp Ellis, Saco River, ME;8418445, Pine Point, ME).

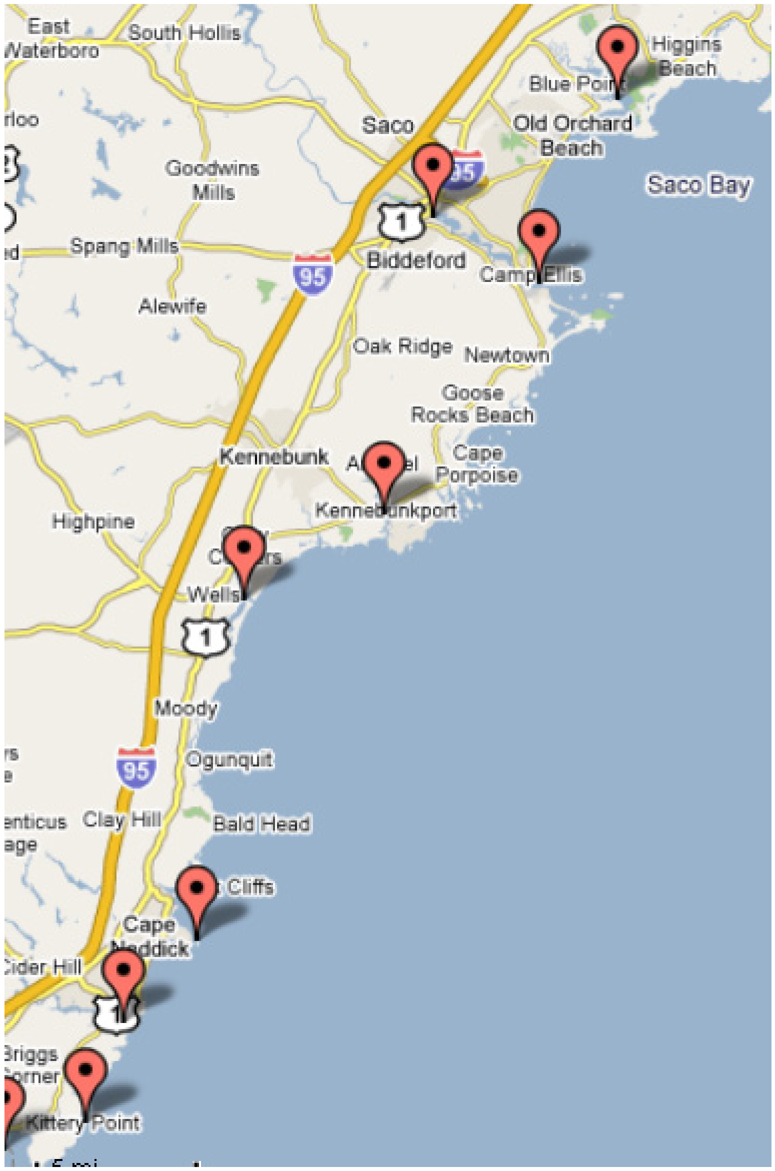


Figure 4: NOAA Gages Relevant to the Study Area.

Accretion rates in salt and brackish marshes were set to 2.58 mm/year, and the rates in tidal fresh marshes to 5.9 mm/year. The values for salt and brackish marshes are from a seventeen year study measuring accretion rates of Maine salt marshes (J.E. Goodman et al., 2006). One of the field sites for this study was located in Scarborough ME, within several km of multiple refuge boundaries.

Modeled U.S. Fish and Wildlife Service refuge boundaries are based on Approved Acquisition Boundaries as published on the FWS "National Wildlife Refuge Data and Metadata" website. Local contact was made with Peter Slovinsky of the Maine Geological Survey, who provided us with a study of the effect of sea level rise on the Drakes Island/Wells Reserve area (Slovinsky, 2006).

The cell-size used for this analysis was 30 meter by 30 meter cells. However, the SLAMM model does track partial conversion of cells based on elevation and slope. (Note that since the LiDAR data produce a more accurate DEM, only the elevations of wetlands classes lying outside of the LiDAR data (in the NED data) in Rachel Carson were overwritten as a function of the local tidal range using the SLAMM elevation pre-processor.)

SUMMARY OF SLAMM INPUT PARAMETERS FOR RACHEL CARSON

Description	Rachel Carson North Lidar	Rachel Carson South Lidar	Rachel Carson
DEM Source Date (yyyy)	2008	2008	1956
NWI_photo_date (yyyy)	2004	2004	2004
Direction_OffShore (N|S|E|W)	E	E	E
Historic_trend (mm/yr)	1.79	1.79	1.79
NAVD88_correction (MTL-NAVD88 in meters)	-0.063	-0.063	-0.063
Water Depth (m below MLW- N/A)	2	2	2
TideRangeOcean (meters: MHHW-MLLW)	2.92	2.87	2.895
TideRangeInland (meters)	2.92	2.87	2.895
Mean High Water Spring (m above MTL)	1.942	1.909	1.925
MHSW Inland (m above MTL)	1.942	1.909	1.925
Marsh Erosion (horz meters/year)	1.8	1.8	1.8
Swamp Erosion (horz meters/year)	1	1	1
TFlat Erosion (horz meters/year) [from 0.5]	0.5	0.5	0.5
Salt marsh vertical accretion (mm/yr) Final	2.58	2.58	2.58
Brackish March vert. accretion (mm/yr) Final	2.58	2.58	2.58
Tidal Fresh vertical accretion (mm/yr) Final	5.9	5.9	5.9
Beach/T.Flat Sedimentation Rate (mm/yr)	0.5	0.5	0.5
Frequency of Large Storms (yr/washover)	50	50	50
Use Elevation Preprocessor for Wetlands	FALSE	FALSE	TRUE

Results

Rachel Carson National Wildlife Refuge is predicted to show effects from sea level rise, especially under more accelerated scenarios. Loss of irregularly flooded marsh (labeled as "brackish" marsh herein) – which constitutes more than 30% of the NWR – is predicted to be moderate in scenarios below one meter. Roughly half of brackish marsh is lost in the one meter scenario, and three quarters is lost in the 1.5 meter scenario. Loss of dry land ranges from 20-30% within these scenarios. Loss of tidal swamp and estuarine beach – which combined constitute around 10% of the NWR – is predicted to be substantial in all scenarios.

SLR by 2100 (m)	0.39	0.69	1	1.5
Brackish Marsh	17%	24%	44%	76%
Dry Land	20%	23%	25%	29%
Tidal Swamp	44%	57%	64%	73%
Estuarine Beach	54%	47%	52%	64%
Tidal Fresh Marsh	1%	4%	12%	26%

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

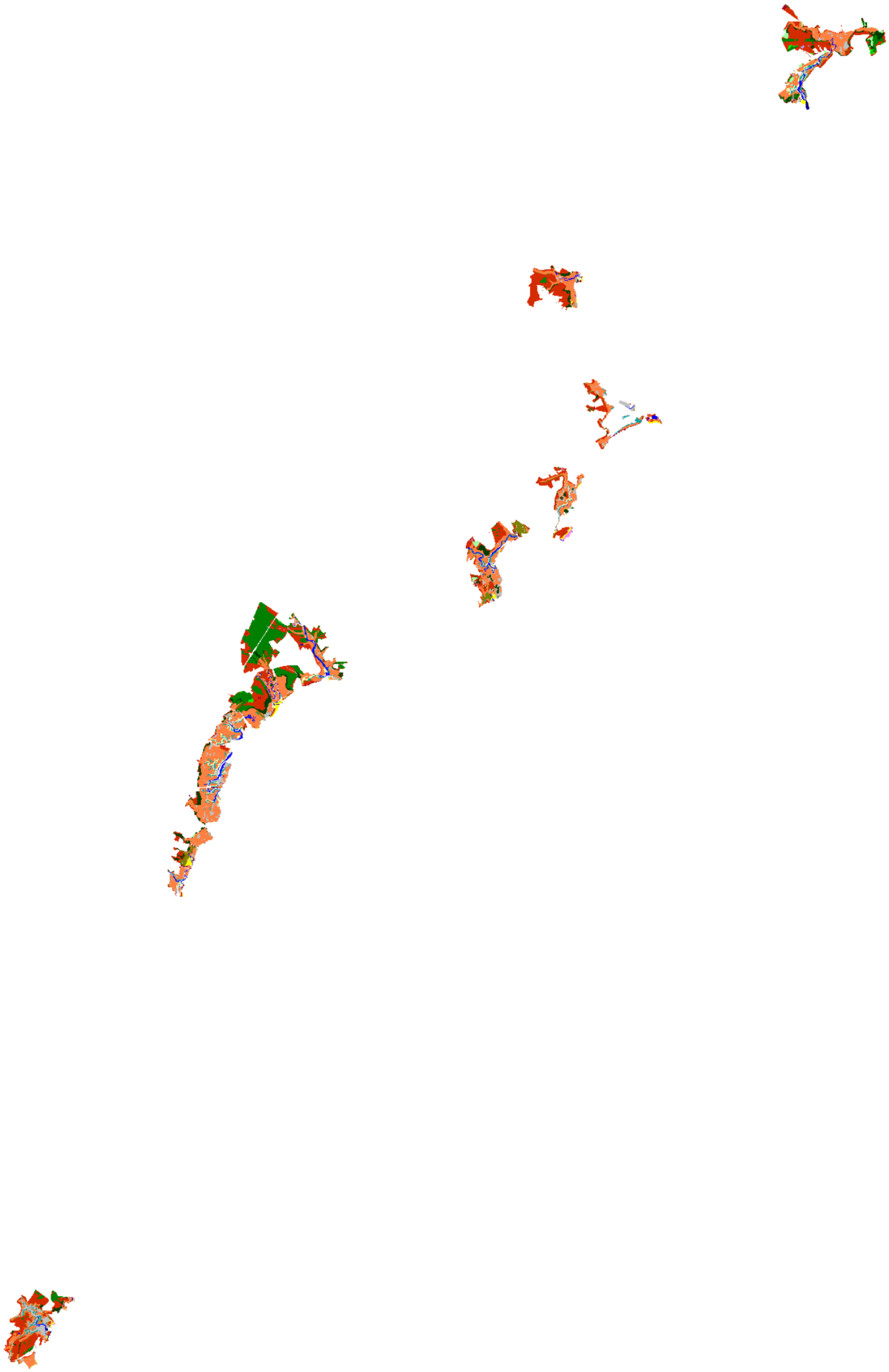
Maps of SLAMM input and output to follow will use the following legend:

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

Results in Acres

	Initial	2025	2050	2075	2100
Brackish Marsh	3152.0	2883.6	2753.6	2673.4	2612.0
Undev. Dry Land	2745.9	2295.9	2239.8	2210.1	2183.6
Swamp	902.0	1081.1	1113.6	1110.8	1098.0
Tidal Swamp	648.9	496.2	454.6	408.6	361.7
Tidal Flat	372.3	634.6	720.3	719.4	712.9
Estuarine Beach	333.4	201.3	179.7	163.4	153.0
Estuarine Open Water	264.2	354.5	523.1	677.2	803.6
Tidal Fresh Marsh	86.5	85.4	85.4	85.4	85.4
Dev. Dry Land	83.4	83.4	83.4	83.4	83.4
Ocean Beach	62.9	95.7	95.7	93.7	93.7
Saltmarsh	43.4	264.4	349.7	361.0	381.6
Trans. Salt Marsh	27.1	239.9	114.3	123.4	136.8
Inland Fresh Marsh	26.7	26.7	26.7	26.7	26.7
Rocky Intertidal	18.2	17.9	17.7	17.4	17.0
Inland Open Water	16.0	18.5	18.6	18.6	18.0
Open Ocean	15.1	19.0	21.9	25.6	30.7
Tidal Creek	2.7	2.7	2.7	2.7	2.7
Ocean Flat	0.7	0.7	0.7	0.7	0.7
Total (incl. water)	**8801.5**	**8801.5**	**8801.5**	**8801.5**	**8801.5**

Rachel Carson NWR, Initial Condition



Rachel Carson NWR, 2025, Scenario A1B Mean Protect Developed Dry Land

Rachel Carson NWR, 2050, Scenario A1B Mean Protect Developed Dry Land

Rachel Carson NWR, 2075, Scenario A1B Mean Protect Developed Dry Land

Rachel Carson NWR, 2100, Scenario A1B Mean Protect Developed Dry Land

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

Results in Acres

	Initial	2025	2050	2075	2100
Brackish Marsh	3152.0	2880.2	2734.6	2593.5	2380.1
Undev. Dry Land	2745.9	2286.8	2216.4	2167.0	2122.0
Swamp	902.0	1082.8	1111.2	1089.8	1063.1
Tidal Swamp	648.9	485.0	415.6	328.8	281.7
Tidal Flat	372.3	639.2	753.4	787.8	770.6
Estuarine Beach	333.4	252.8	216.6	191.0	177.5
Estuarine Open Water	264.2	356.7	534.0	709.4	877.1
Tidal Fresh Marsh	86.5	85.2	85.0	84.5	83.3
Dev. Dry Land	83.4	83.4	83.4	83.4	83.4
Ocean Beach	62.9	95.8	94.8	93.2	91.7
Saltmarsh	43.4	278.2	367.5	448.6	613.4
Trans. Salt Marsh	27.1	189.2	97.6	127.8	154.5
Inland Fresh Marsh	26.7	26.7	26.7	26.7	26.7
Rocky Intertidal	18.2	17.8	17.4	16.7	15.9
Inland Open Water	16.0	18.6	18.7	17.7	16.8
Open Ocean	15.1	19.8	25.1	32.2	40.3
Tidal Creek	2.7	2.7	2.7	2.7	2.7
Ocean Flat	0.7	0.7	0.7	0.7	0.6
Total (incl. water)	**8801.5**	**8801.5**	**8801.5**	**8801.5**	**8801.5**

Rachel Carson NWR, Initial Condition

Rachel Carson NWR, 2025, Scenario A1B Maximum Protect Developed Dry Land

Rachel Carson NWR, 2050, Scenario A1B Maximum Protect Developed Dry Land

Rachel Carson NWR, 2075, Scenario A1B Maximum Protect Developed Dry Land

Rachel Carson NWR, 2100, Scenario A1B Maximum Protect Developed Dry Land

Rachel Carson NWR
1 Meter Eustatic SLR by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Brackish Marsh	3152.0	2875.6	2699.2	2382.5	1761.9
Undev. Dry Land	2745.9	2277.7	2193.8	2125.9	2060.9
Swamp	902.0	1083.7	1099.7	1066.6	1027.0
Tidal Swamp	648.9	471.2	368.6	287.3	235.3
Tidal Flat	372.3	643.3	783.2	832.7	850.6
Estuarine Beach	333.4	249.2	206.3	177.4	158.4
Estuarine Open Water	264.2	359.7	548.0	748.8	964.3
Tidal Fresh Marsh	86.5	84.9	83.9	80.1	75.8
Dev. Dry Land	83.4	83.4	83.4	83.4	83.4
Ocean Beach	62.9	95.9	94.6	92.3	86.9
Saltmarsh	43.4	296.2	440.6	673.6	1218.1
Trans. Salt Marsh	27.1	193.7	106.7	150.5	162.1
Inland Fresh Marsh	26.7	26.7	26.7	26.7	26.7
Rocky Intertidal	18.2	17.8	17.1	16.0	14.9
Inland Open Water	16.0	18.6	18.2	17.0	16.4
Open Ocean	15.1	20.6	28.0	37.3	55.7
Tidal Creek	2.7	2.7	2.7	2.7	2.7
Ocean Flat	0.7	0.7	0.7	0.6	0.3
Total (incl. water)	**8801.5**	**8801.5**	**8801.5**	**8801.5**	**8801.5**

Rachel Carson NWR, Initial Condition

Rachel Carson NWR, 2025, 1 meter Protect Developed Dry Land

Rachel Carson NWR, 2050, 1 meter Protect Developed Dry Land

Rachel Carson NWR, 2075, 1 meter Protect Developed Dry Land

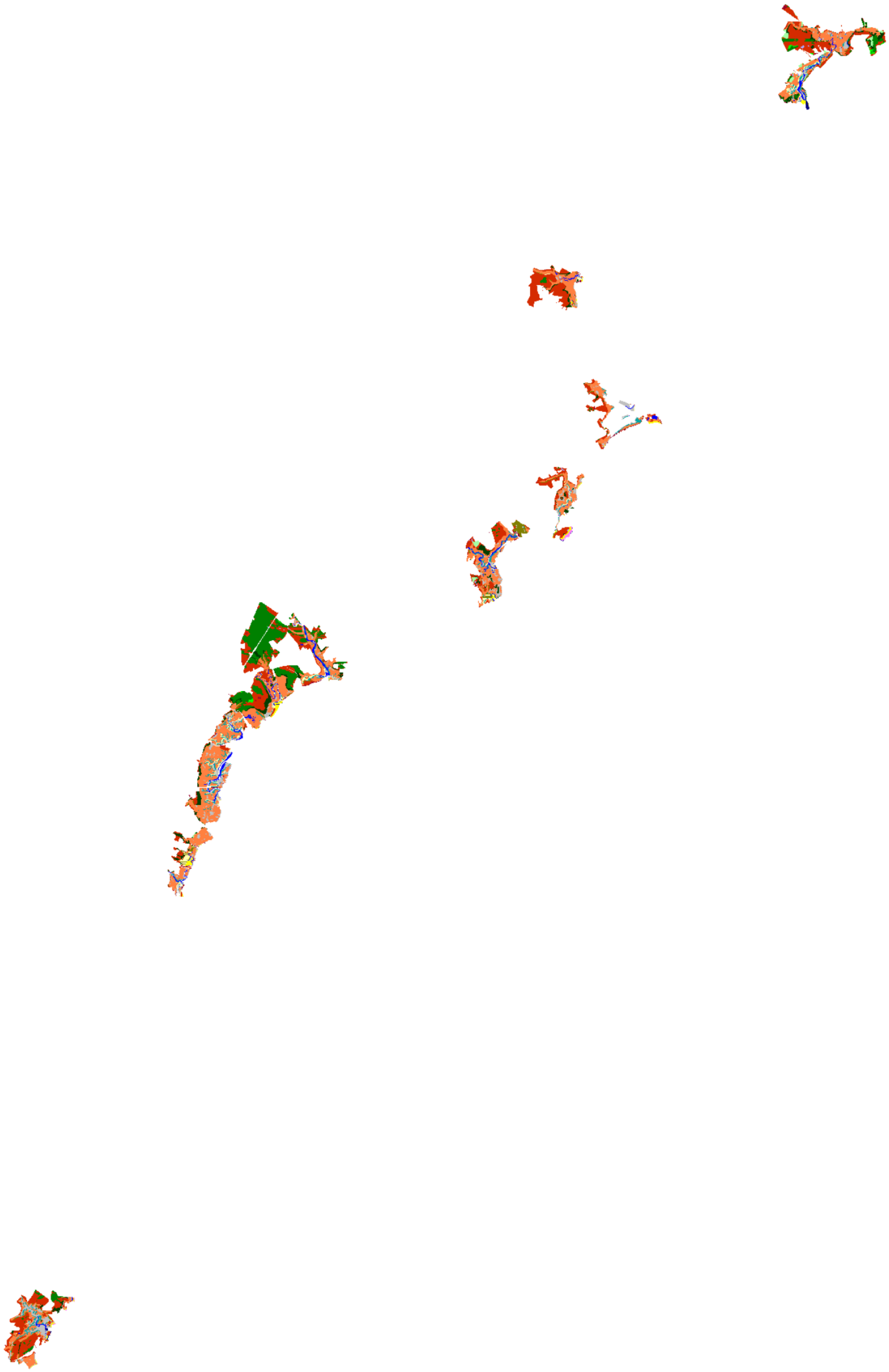
Rachel Carson NWR, 2100, 1 meter Protect Developed Dry Land

Rachel Carson NWR
1.5 Meters Eustatic SLR by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Brackish Marsh	3152.0	2866.4	2553.7	1611.6	765.9
Undev. Dry Land	2745.9	2263.2	2152.6	2055.3	1953.9
Swamp	902.0	1084.8	1079.4	1030.2	972.0
Tidal Swamp	648.9	446.8	313.7	233.3	173.1
Tidal Flat	372.3	650.9	843.1	928.0	1242.0
Estuarine Beach	333.4	243.2	190.5	150.7	120.8
Estuarine Open Water	264.2	364.5	575.0	854.8	1163.1
Tidal Fresh Marsh	86.5	84.4	79.6	70.9	64.0
Dev. Dry Land	83.4	83.4	83.4	83.4	83.4
Ocean Beach	62.9	95.9	81.7	2.2	4.0
Saltmarsh	43.4	328.4	608.8	1421.6	1849.3
Trans. Salt Marsh	27.1	201.2	129.2	158.3	132.4
Inland Fresh Marsh	26.7	26.7	26.7	26.7	26.7
Rocky Intertidal	18.2	17.6	16.5	14.9	12.4
Inland Open Water	16.0	18.7	17.8	16.7	15.1
Open Ocean	15.1	21.9	46.5	140.1	220.7
Tidal Creek	2.7	2.7	2.7	2.7	2.7
Ocean Flat	0.7	0.7	0.7	0.2	0.0
Total (incl. water)	**8801.5**	**8801.5**	**8801.5**	**8801.5**	**8801.5**

Rachel Carson NWR, Initial Condition



Rachel Carson NWR, 2025, 1.5 meter Protect Developed Dry Land

Rachel Carson NWR, 2050, 1.5 meter Protect Developed Dry Land

Rachel Carson NWR, 2075, 1.5 meter Protect Developed Dry Land

Rachel Carson NWR, 2100, 1.5 meter Protect Developed Dry Land

Discussion:

Model results for Rachel Carson indicate that, under lower rates of sea level rise, up to one quarter of irregularly flooded marsh will convert to regularly flooded marshes. Swamp lands are predicted to increase in these scenarios due to soil saturation within dry lands.

However, because of the initial condition elevation of marshes at this site, and also due to the relatively large tidal range, marshes are predicted to be more resilient at this site than many other national wildlife refuges. Even given 1.5 meters of eustatic sea level rise by 2100, 85% of all marsh categories (salt marsh, brackish marsh, and transitional marsh combined) are predicted to remain at the end of the simulation. Increased flooding, is predicted to significantly change the ecological balance of marsh from brackish marsh to more regularly flooded saltmarsh.

Model results are primarily based on high-quality LiDAR elevation data for this site. This reduces uncertainty in model results. Accretion rates for marshes are assumed to remain constant over time in this simulation, which is an additional source of model uncertainty.

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

References

Cahoon, D.R., J. W. Day, Jr., and D. J. Reed, 1999. "The influence of surface and shallow subsurface soil processes on wetland elevation: A synthesis." *Current Topics in Wetland Biogeochemistry*, 3, 72-88.

Chen, J. L., Wilson, C. R., Tapley, B. D., 2006 "Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet" *Science* 2006 0: 1129007

Clough, J.S. and R.A. Park, 2007, *Technical Documentation for SLAMM 5.0.1* February 2008, Jonathan S. Clough, Warren Pinnacle Consulting, Inc, Richard A. Park, Eco Modeling. http://warrenpinnacle.com/prof/SLAMM

Craft C, Clough J, Ehman J, Guo H, Joye S, Machmuller M, Park R, and Pennings S. Effects of Accelerated Sea Level Rise on Delivery of Ecosystem Services Provided by Tidal Marshes: A Simulation of the Georgia (USA) Coast. *Frontiers in Ecology and the Environment.* 2009; 7, doi:10.1890/070219

Council for Regulatory Environmental Modeling, (CREM) 2008. *Draft guidance on the development, evaluation, and application of regulatory environmental* models P Pascual, N Stiber, E Sunderland - Washington DC: Draft, August 2008

Galbraith, H., R. Jones, R.A. Park, J.S. Clough, S. Herrod-Julius, B. Harrington, and G. Page. 2002. Global Climate Change and Sea Level Rise: Potential Losses of Intertidal Habitat for Shorebirds. *Waterbirds* 25:173-183.

Glick, Clough, et al. *Sea-level Rise and Coastal Habitats in the Pacific Northwest An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon* July 2007 http://www.nwf.org/sealevelrise/pdfs/PacificNWSeaLevelRise.pdf

Goodman, J. E., Wood, M. E. & Gehrels, W. R. (2007) A 17-yr record of sediment accretion in the salt marshes of Maine (USA). Marine Geology, 242, 109-121.

Grismer, M.E., Kollar, J, and Syder, J, "Assessment of Hydraulic Restoration of San Pablo Marsh, California" *Environmental Monitoring and Assessment,* 98: 69-92, 2004.

IPCC, 2001: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K.Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

Lee, J.K., R.A. Park, and P.W. Mausel. 1992. Application of Geoprocessing and Simulation Modeling to Estimate Impacts of Sea Level Rise on the Northeast Coast of Florida. *Photogrammetric Engineering and Remote Sensing* 58:11:1579-1586.

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ and Zhao ZC. 2007. Global climate projections. Pp. 747-845. In: Solomon S, Qin, D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor, M and Miller HL, (eds.) *Climate change 2007: The physical science basis.*

Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

Monaghan, A. J. *et al,* 2006 "Insignificant Change in Antarctic Snowfall Since the International Geophysical Year" *Science* 2006 313: 827-831.

Moorhead, KK and Brinson MM. 1995. Response of wetlands to rising sea level in the lower coastal plain of North Carolina. *Ecological Applications* 5: 261-271.

National Wildlife Fed 'n et al., *An Unfavorable Tide: Global Warming, Coastal Habitats and Sportfishing in Florida* 4, 6 (2006). http://www.targetglobalwarming.org/files/AnUnfavorableTideReport.pdf

Park, R.A., J.K. Lee, and D. Canning. 1993. Potential Effects of Sea Level Rise on Puget Sound Wetlands. *Geocarto International* 8(4):99-110.

Park, R.A., M.S. Trehan, P.W. Mausel, and R.C. Howe. 1989a. The Effects of Sea Level Rise on U.S. Coastal Wetlands. In *The Potential Effects of Global Climate Change on the United States: Appendix B - Sea Level Rise,* edited by J.B. Smith and D.A. Tirpak, 1-1 to 1-55. EPA-230-05-89-052. Washington, D.C.: U.S. Environmental Protection Agency.

Patrick, W. H., Jr., And R. D. Delaune. 1990. Subsidence, accretion and sea level rise in south San Francisco Bay marshes. *Limnol. Oceanogr.* 35: 1389-l 395.

Pfeffer, Harper, O'Neel, 2008. Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise. *Science*, Vol. 321, No. 5894. (5 September 2008), pp. 1340-134

Rahmstorf, Stefan 2007, "A Semi-Empirical Approach to Projecting Future Sea-Level Rise," *Science* 2007 315: 368-370.

Reed, D.J., "Understanding Tidal Marsh Sedimentation in the Sacramento-San Joaquin Delta, California," *Journal of Coastal Research,* Special Issue 36, 2002.

Reed, D.J., D.A. Bishara, D.R. Cahoon, J. Donnelly, M. Kearney, A.S. Kolker, L.L. Leonard, R.A. Orson, and J.C. Stevenson, 2008: "Site-Specific Scenarios for Wetlands Accretion in the Mid-Atlantic Region. Section 2.1" in *Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea Level Rise*, J.G. Titus and E.M. Strange (eds.), EPA430R07004, Washington, DC: U.S. EPA. http://www.epa.gov/climatechange/effects/downloads/section2_1.pdf

Slovinsky, Peter, Stephen M Dickson. "Impacts of Future Sea Level Rise on the Coastal Floodplain," Maine Planning Office/Maine Geological Survey, p. 6, 2006.

Stevenson and Kearney, 2008, "Impacts of Global Climate Change and Sea-Level Rise on Tidal Wetlands" Pending chapter of manuscript by University of California Press.

Titus, J.G., R.A. Park, S.P. Leatherman, J.R. Weggel, M.S. Greene, P.W. Mausel, M.S. Trehan, S. Brown, C. Grant, and G.W. Yohe. 1991. Greenhouse Effect and Sea Level Rise: Loss of Land and the Cost of Holding Back the Sea. *Coastal Management* 19:2:171-204.

US Climate Change Science Program, 2008, Abrupt *Climate Change, Final Report, Synthesis and Assessment Product 3.4*, U.S. Climate Change Science Program And the Subcommittee on Global Change Research, Lead Agency U. S. Geological Survey, Contributing Agencies National Oceanic and Atmospheric Administration, National Science Foundation.

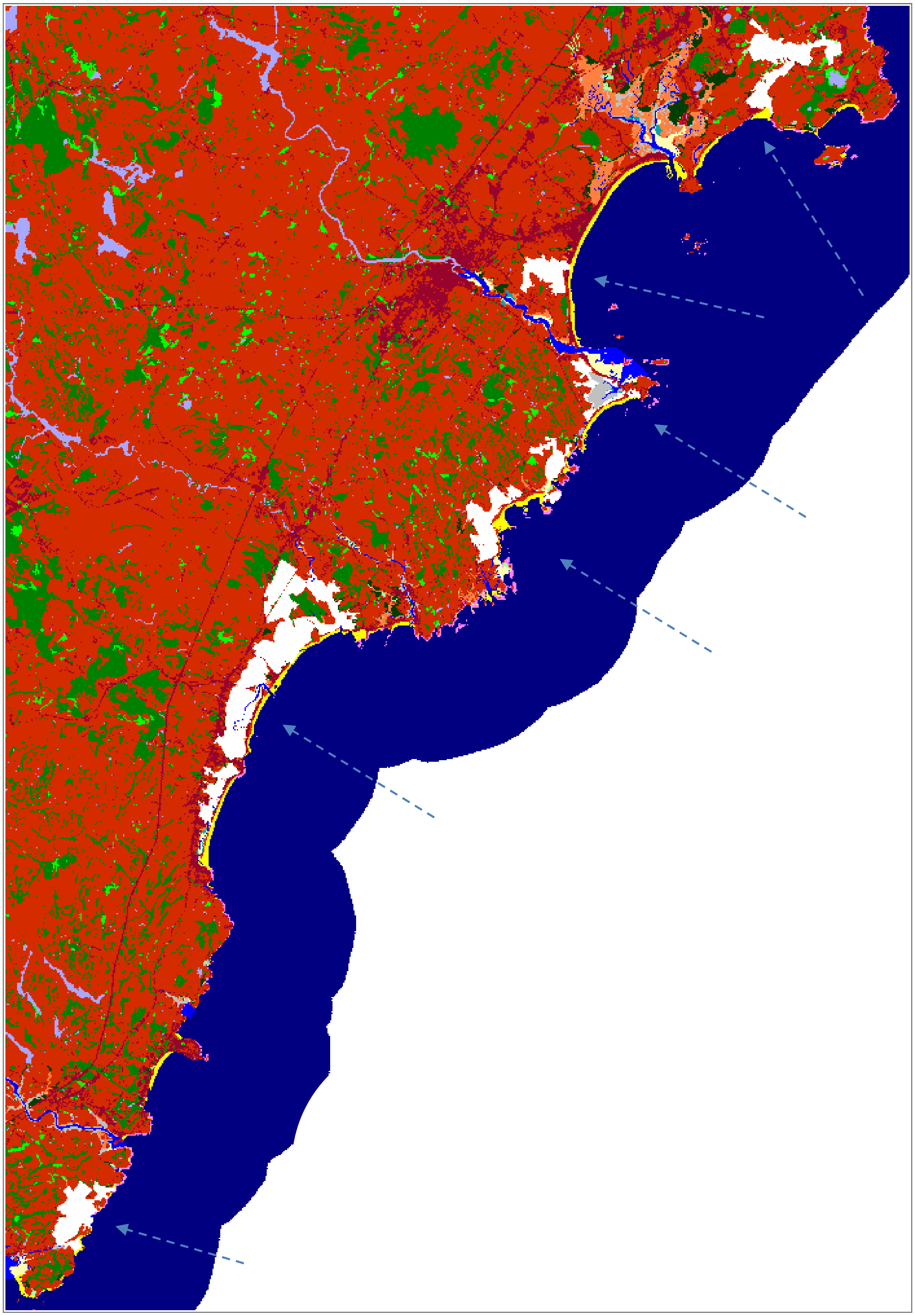
Weis, D. A., Callaway, A. B. and Gersberg, R. M., (2001).Vertical accretion rates and heavy metal chronologies in wetland sediments of the Tijuana Estuary. *Estuaries*, **24**(6A)**,** 840-850.

Appendix A: Contextual Results

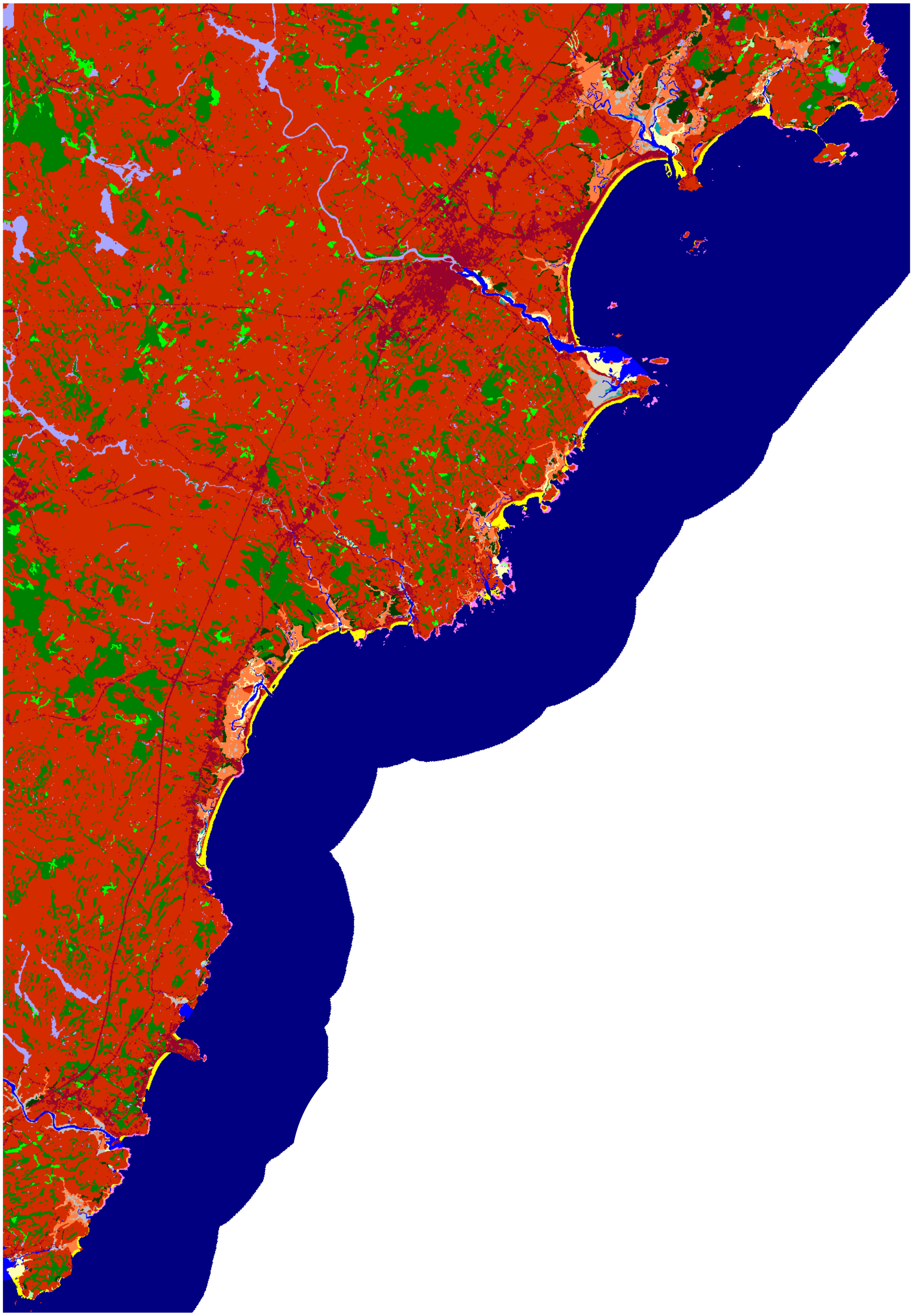
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

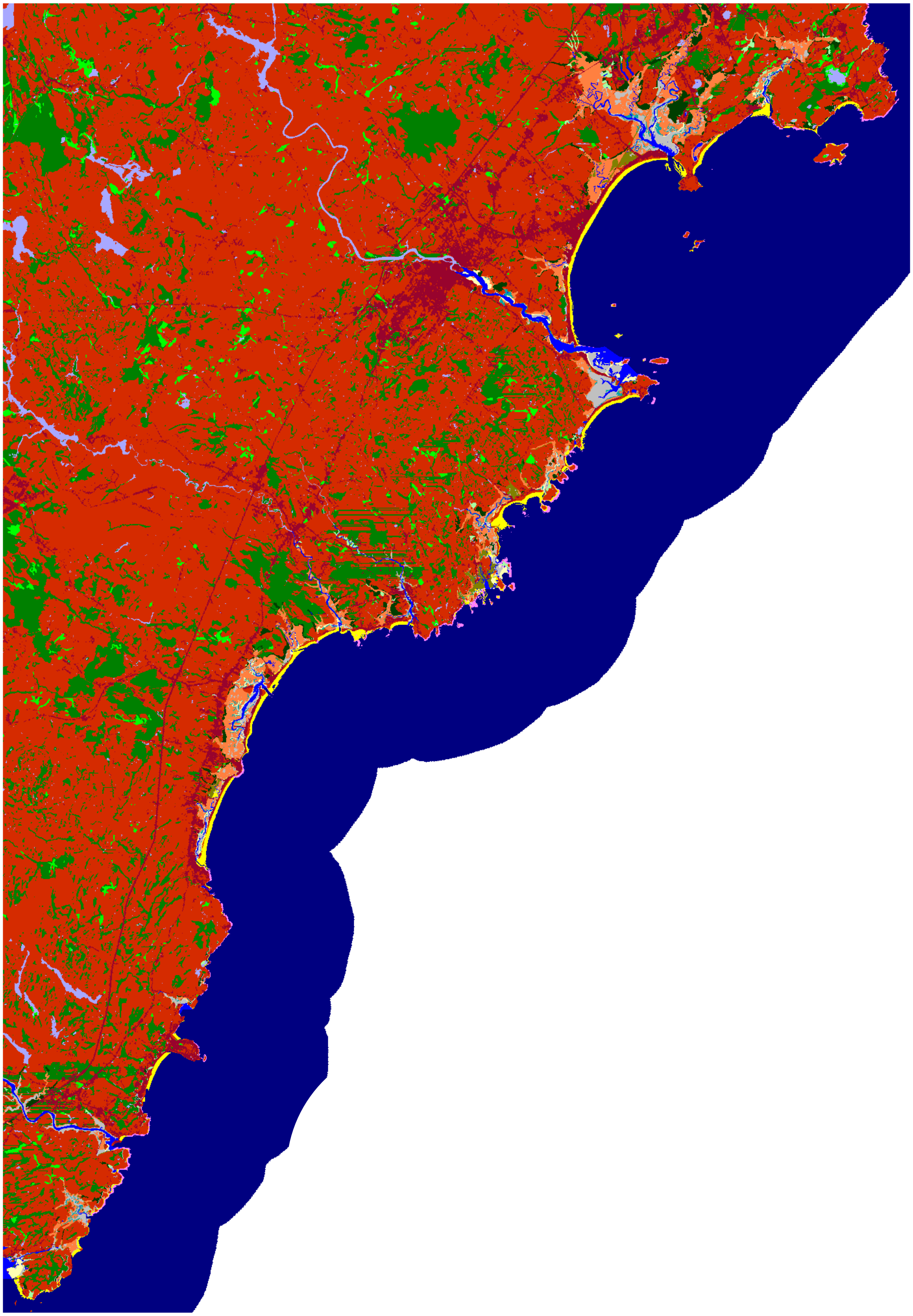
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



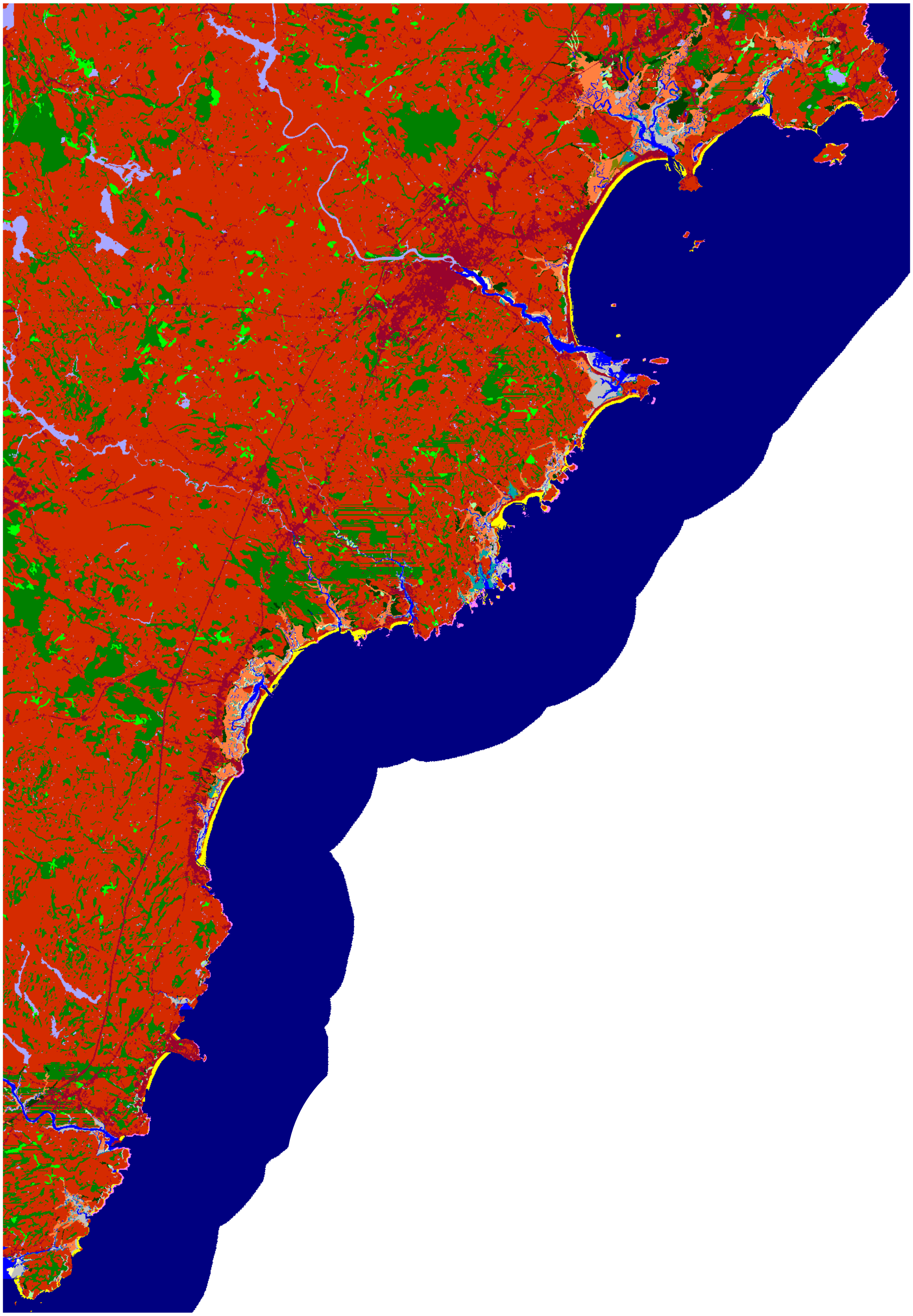
Location of Rachel Carson National Wildlife Refuge (white) within simulation context



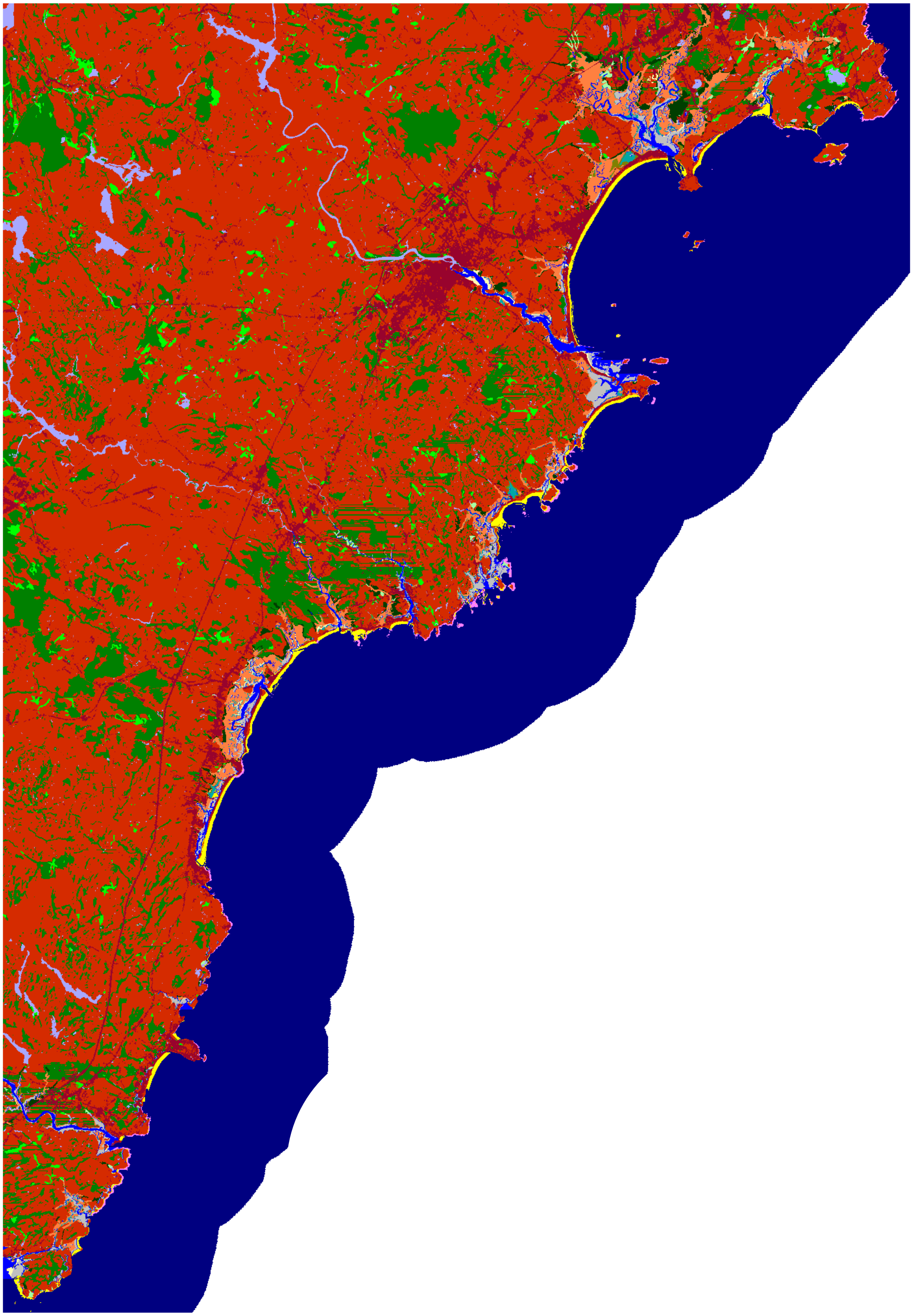
Rachel Carson NWR, Initial Condition



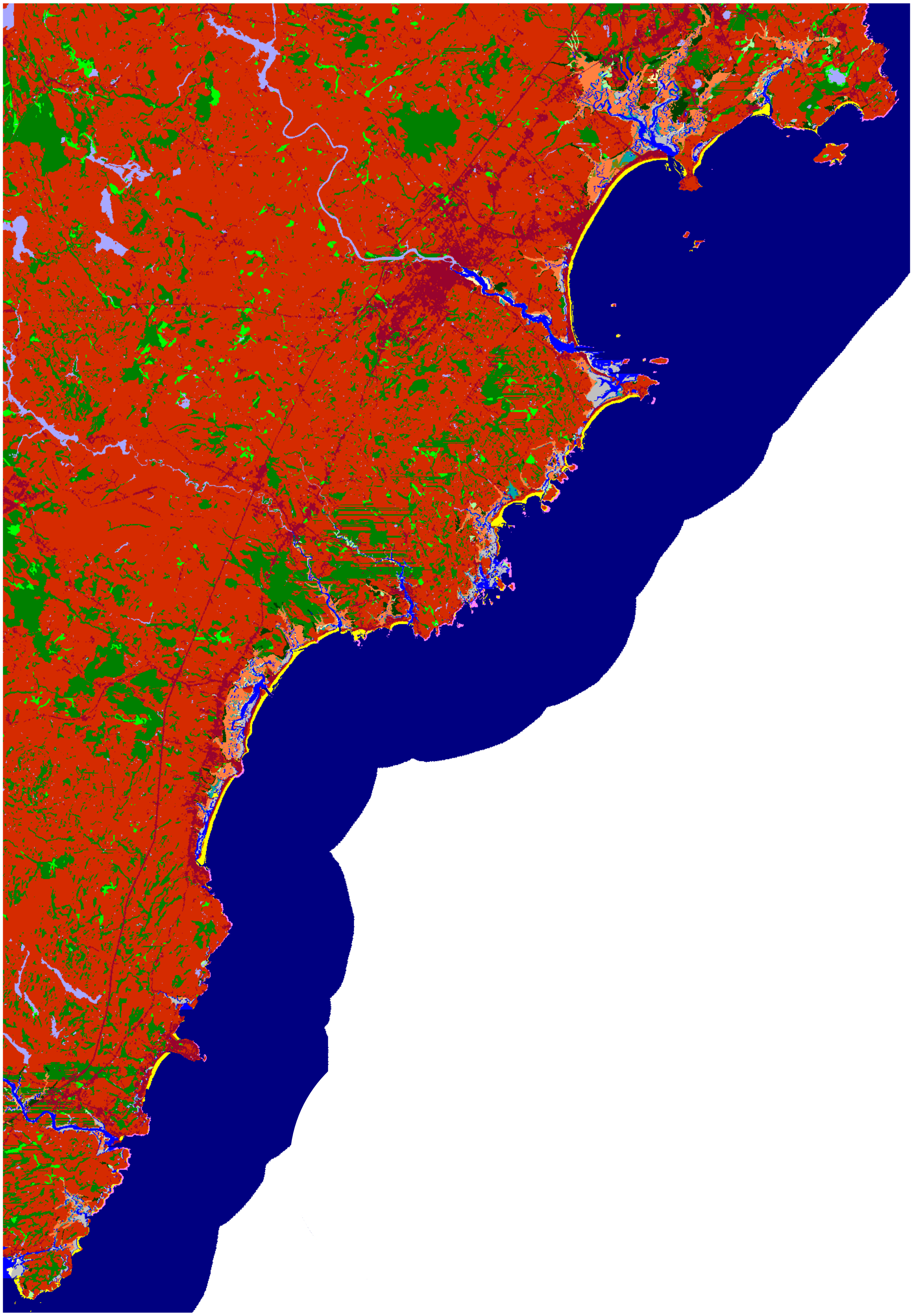
Rachel Carson NWR, 2025, Scenario A1B Mean Protect Developed Dry Land



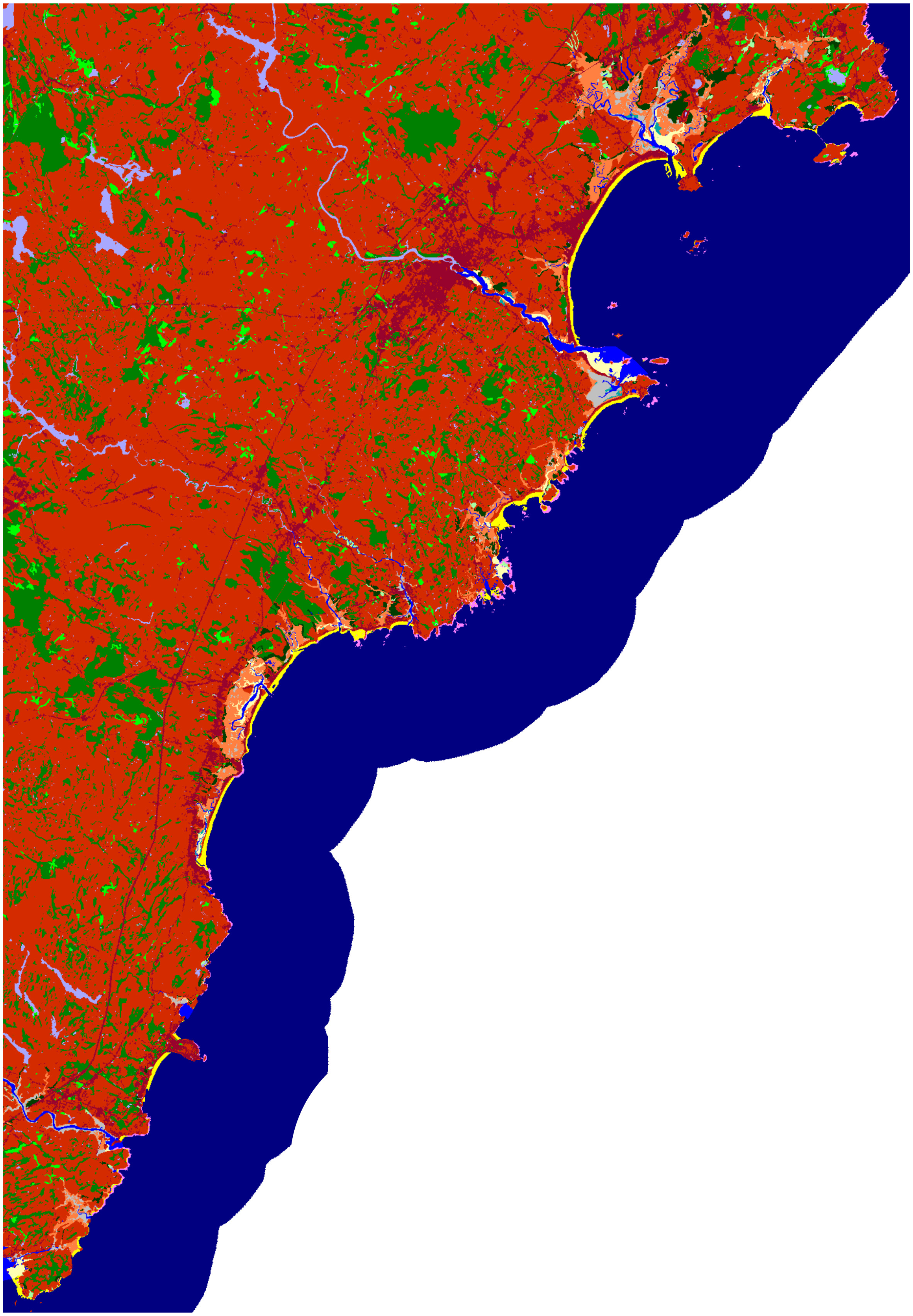
Rachel Carson NWR, 2050, Scenario A1B Mean Protect Developed Dry Land



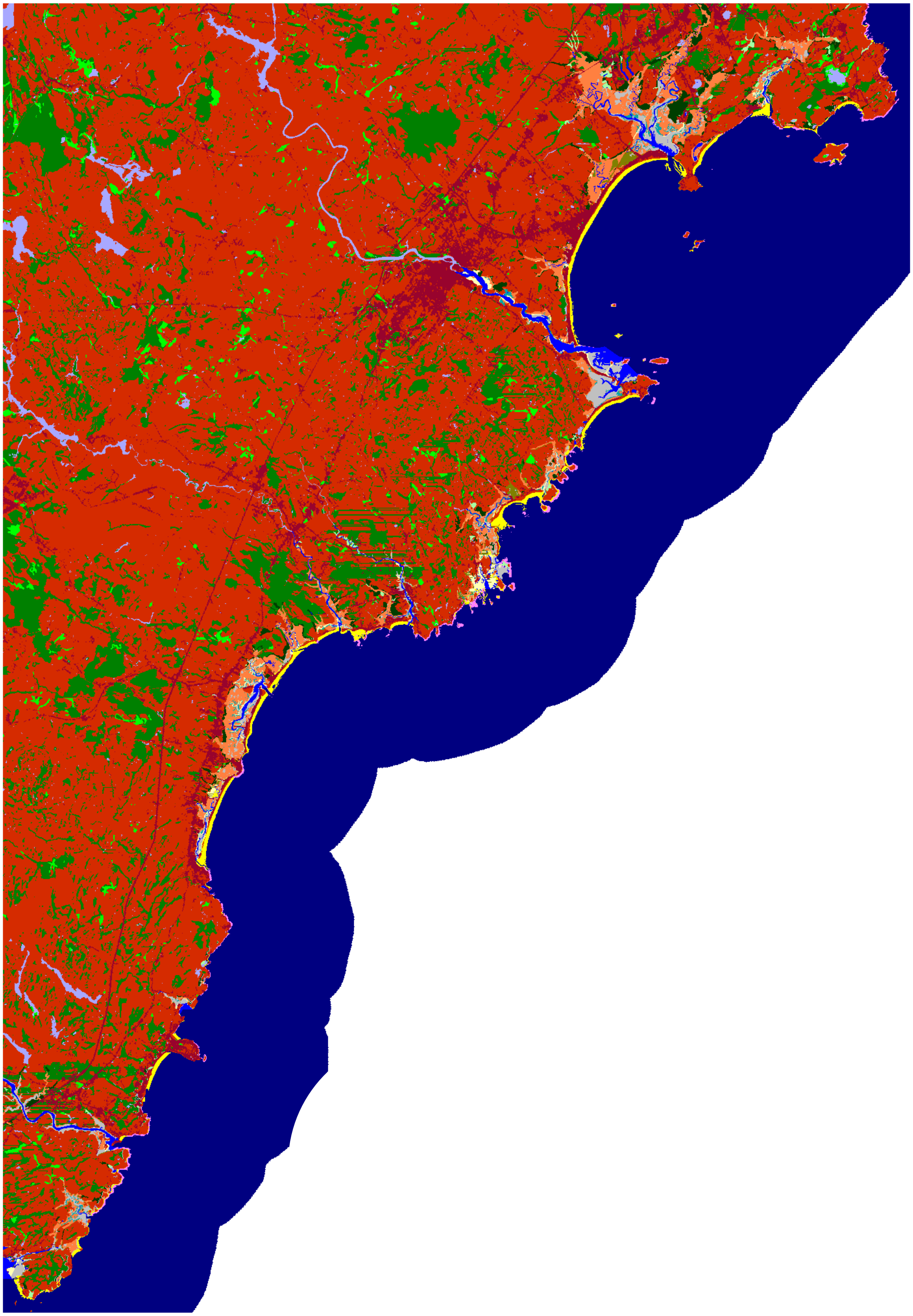
Rachel Carson NWR, 2075, Scenario A1B Mean Protect Developed Dry Land



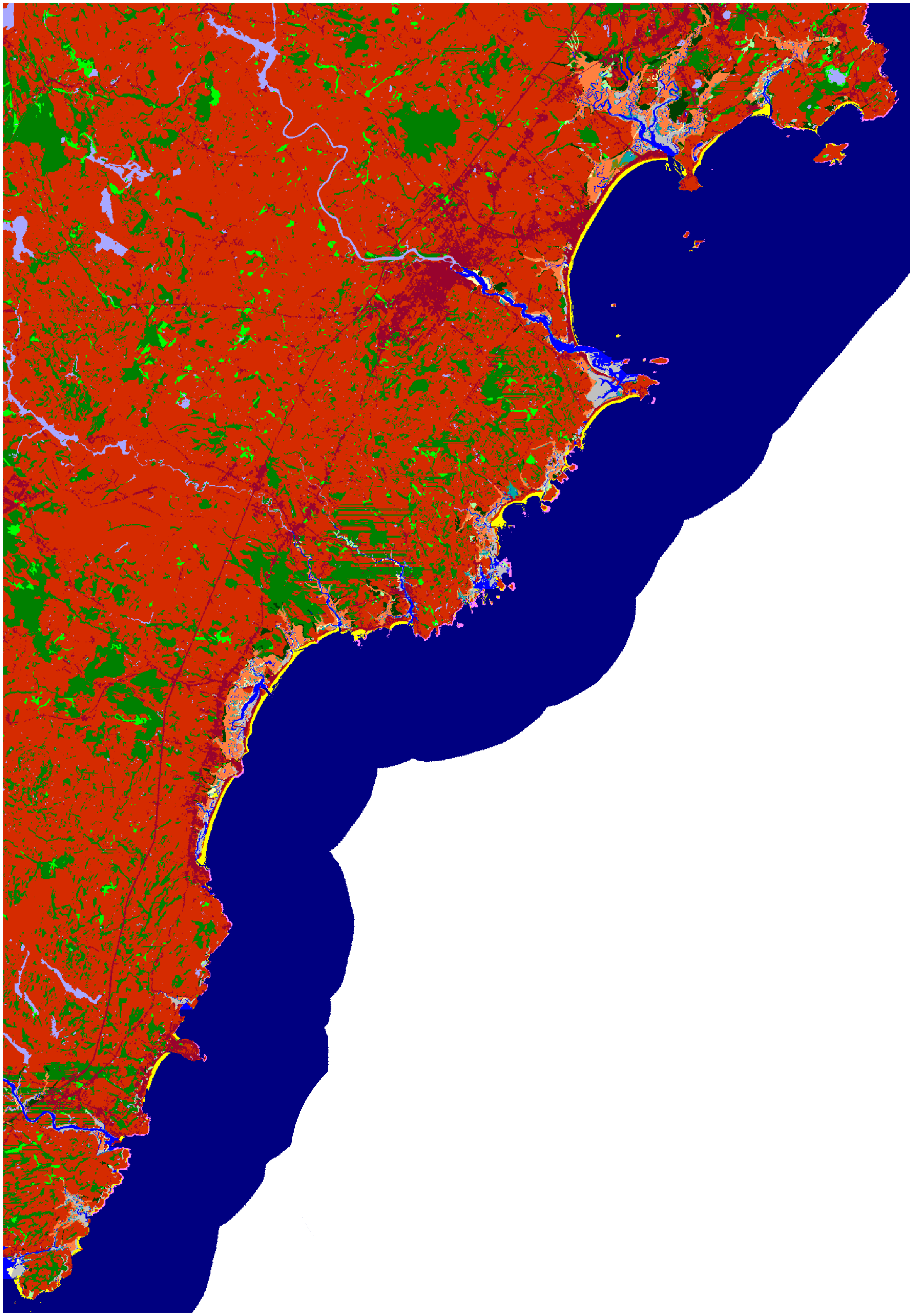
Rachel Carson NWR, 2100, Scenario A1B Mean Protect Developed Dry Land



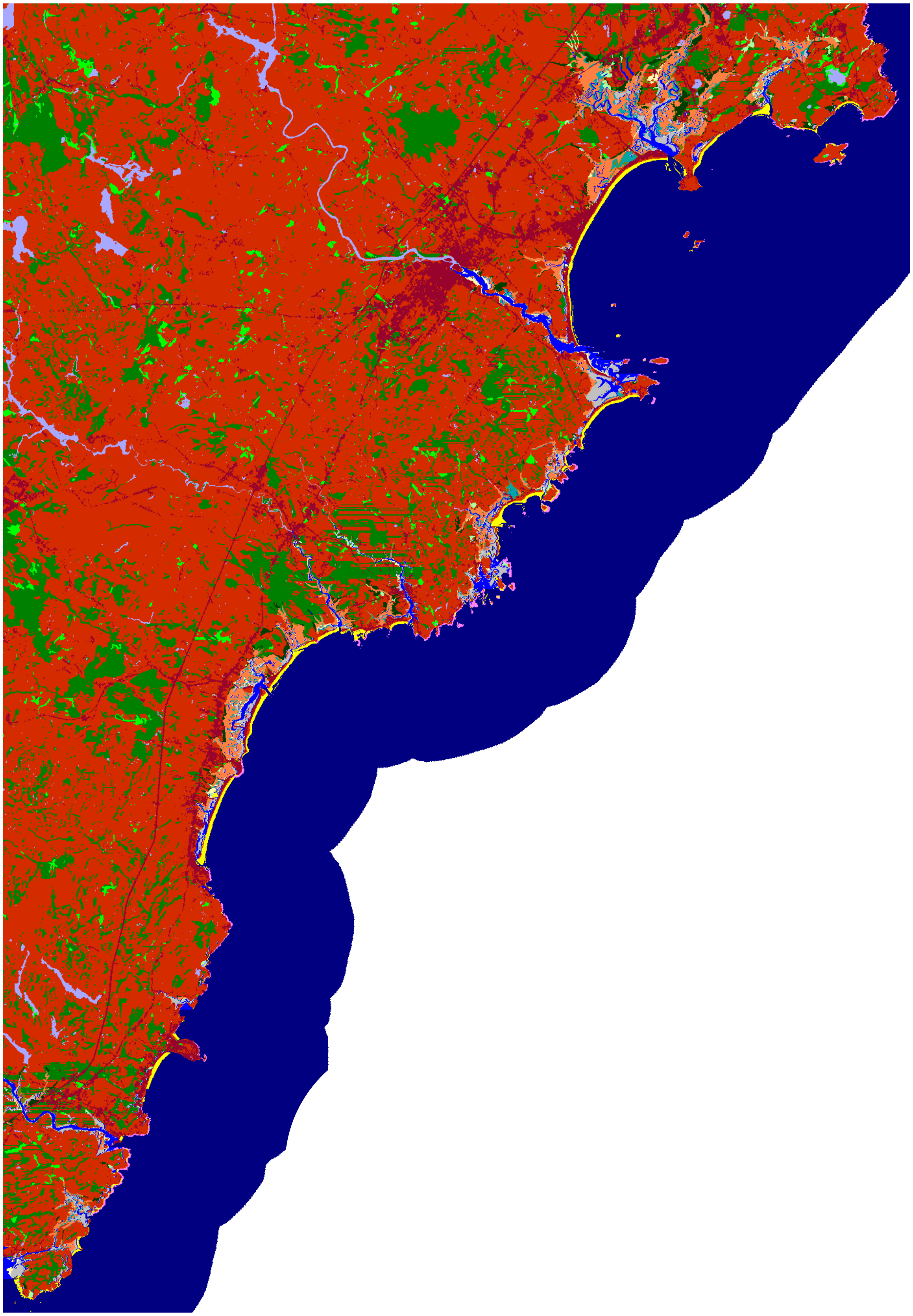
Rachel Carson NWR, Initial Condition



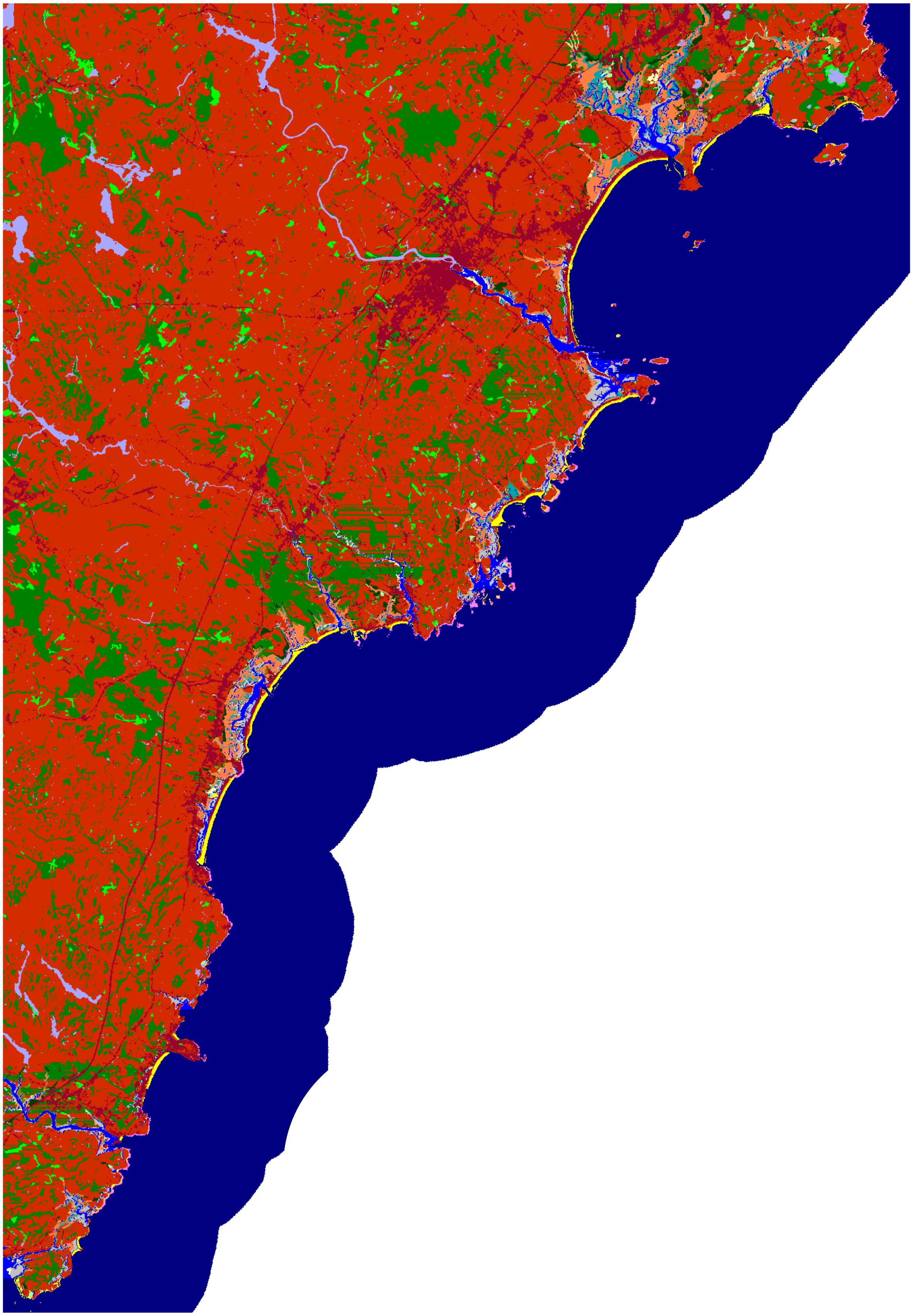
Rachel Carson NWR, 2025, Scenario A1B Maximum Protect Developed Dry Land



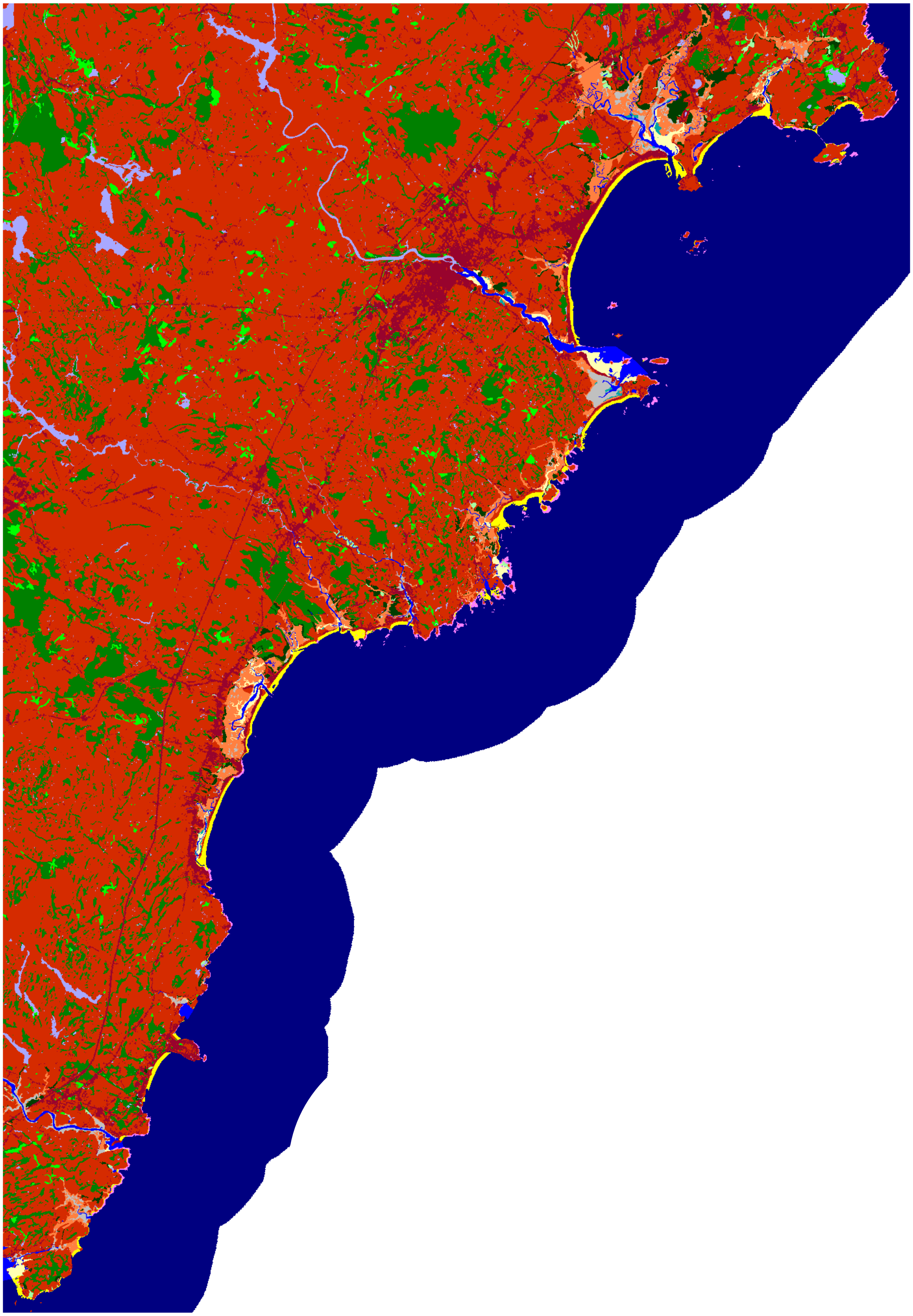
Rachel Carson NWR, 2050, Scenario A1B Maximum Protect Developed Dry Land



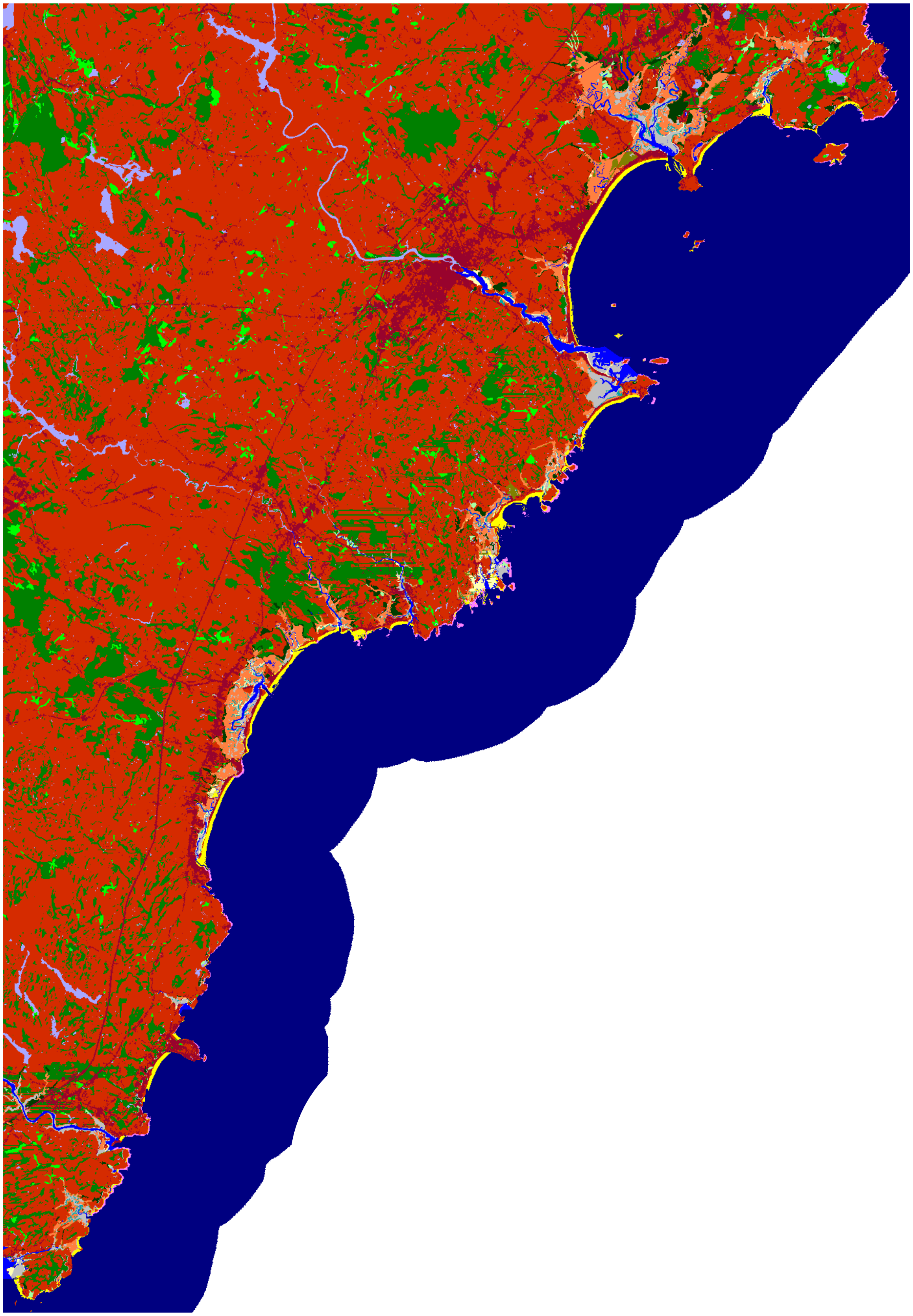
Rachel Carson NWR, 2075, Scenario A1B Maximum Protect Developed Dry Land



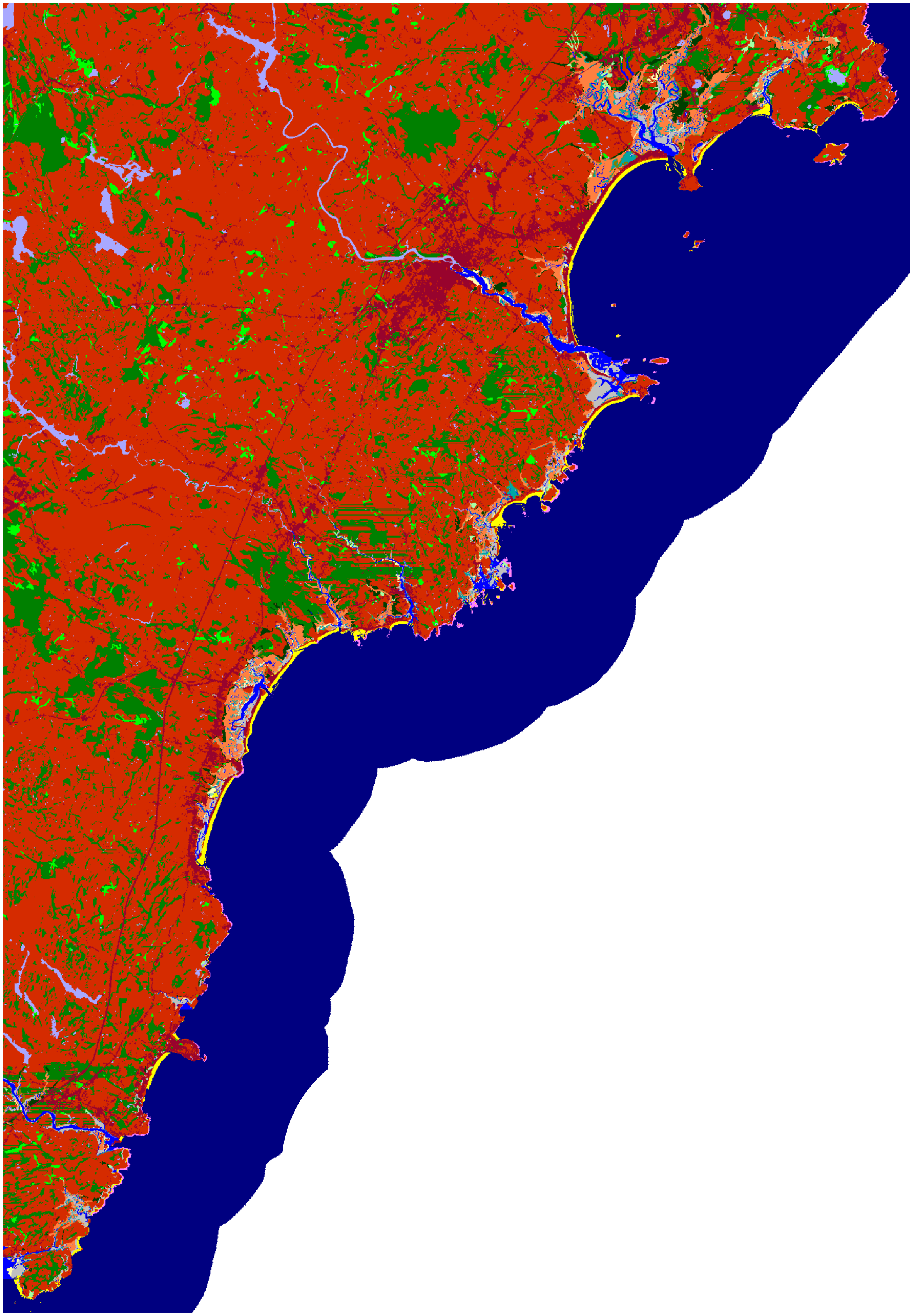
Rachel Carson NWR, 2100, Scenario A1B Maximum Protect Developed Dry Land



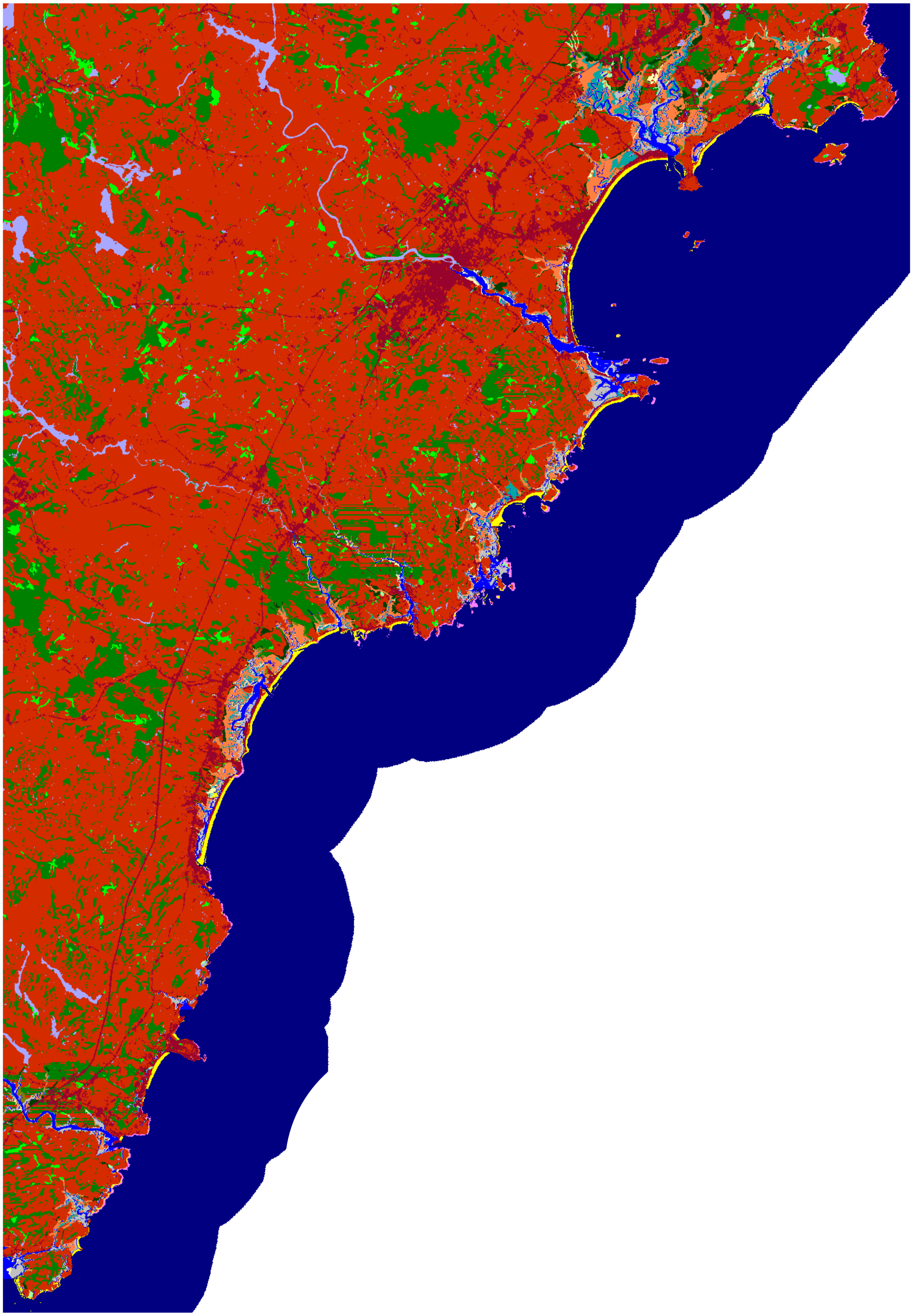
Rachel Carson NWR, Initial Condition



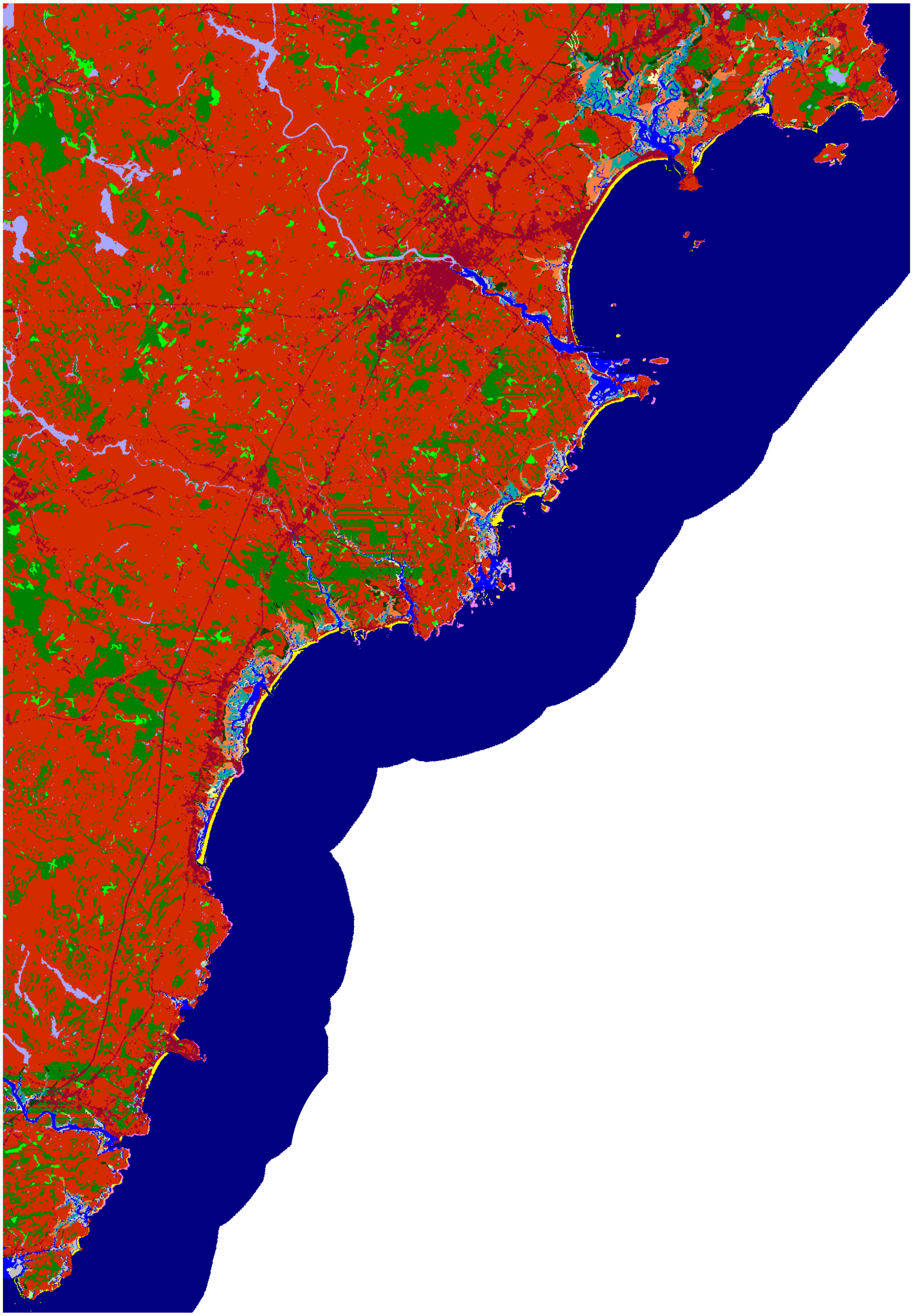
Rachel Carson NWR, 2025, 1 meter Protect Developed Dry Land



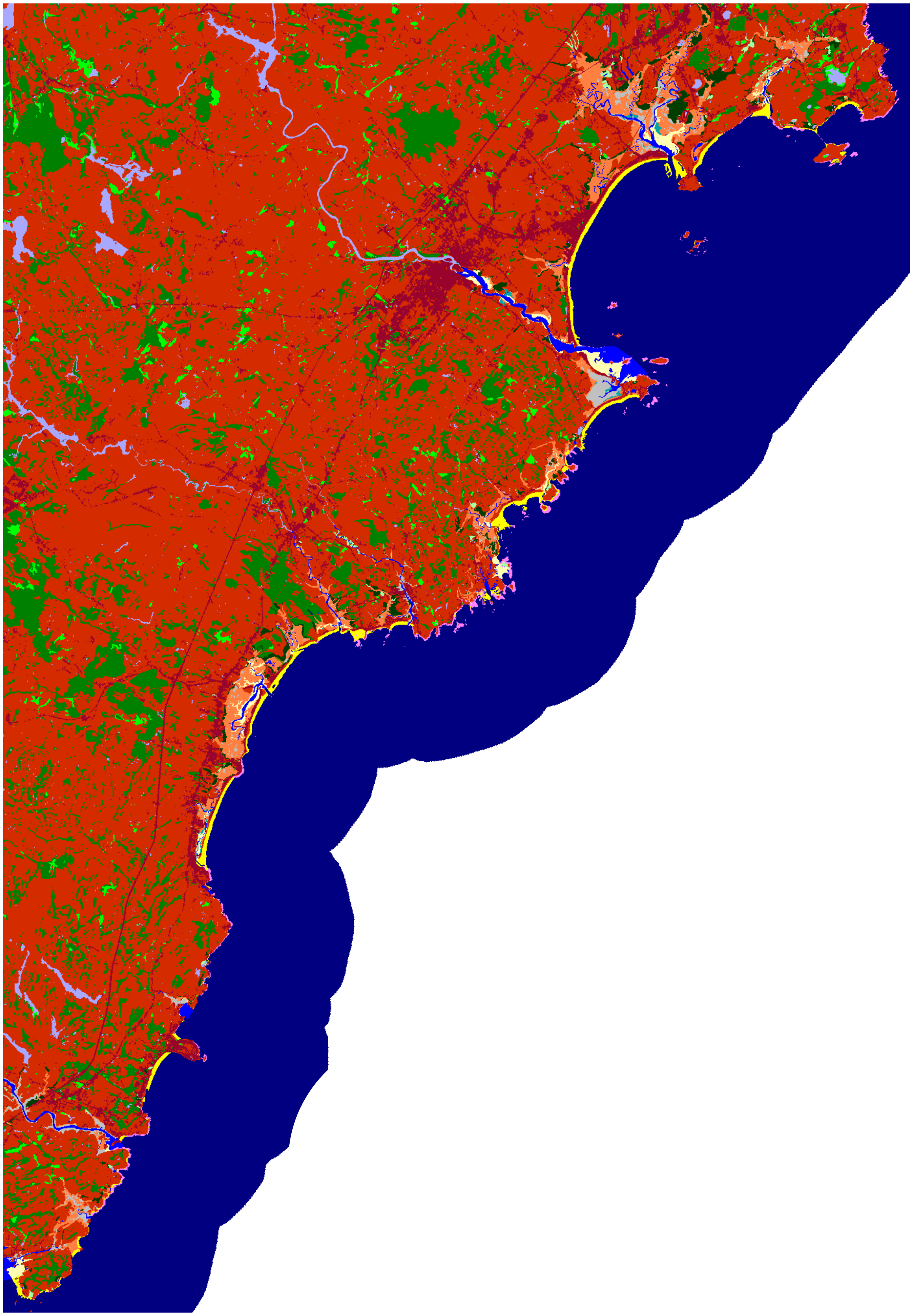
Rachel Carson NWR, 2050, 1 meter Protect Developed Dry Land



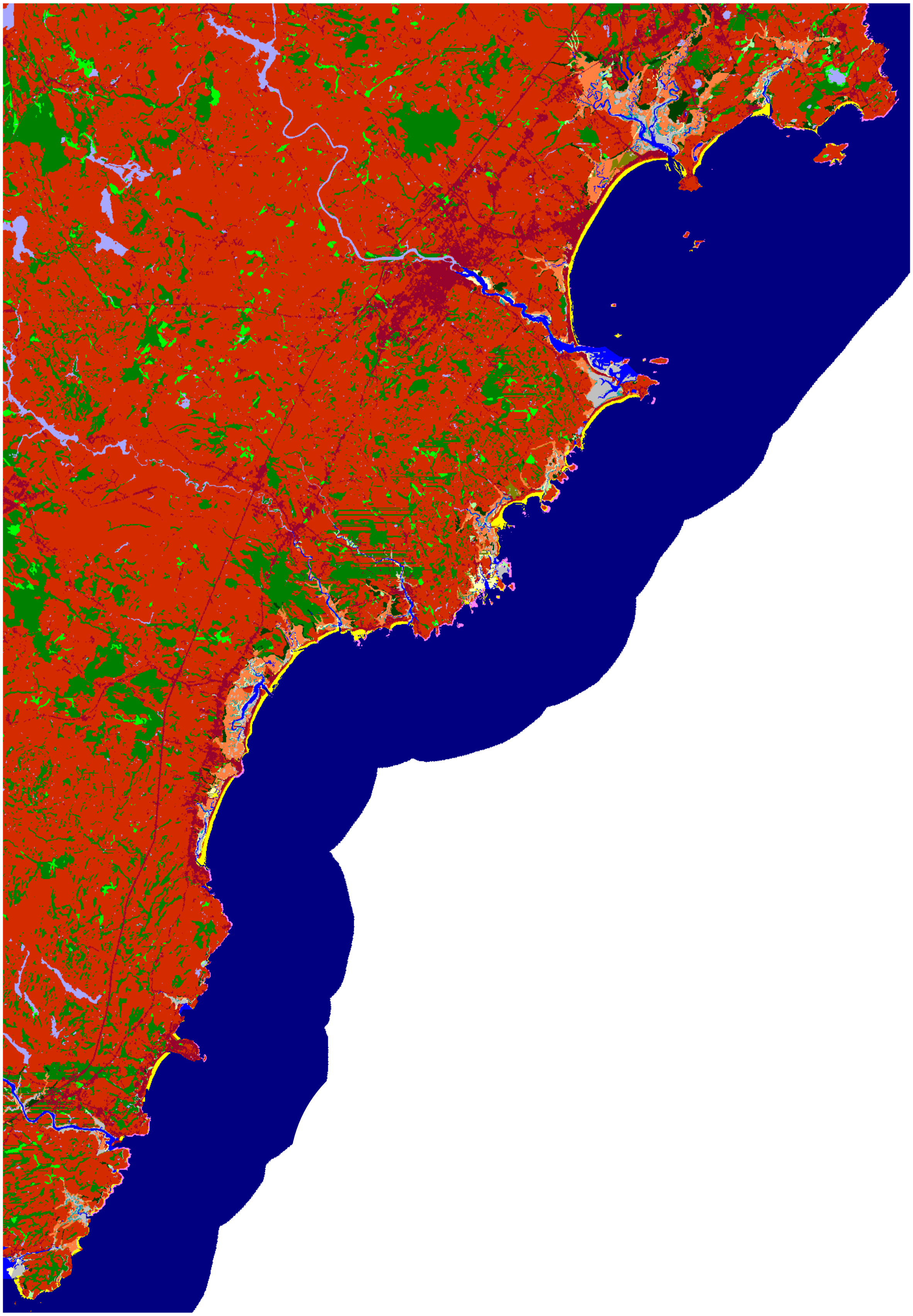
Rachel Carson NWR, 2075, 1 meter Protect Developed Dry Land



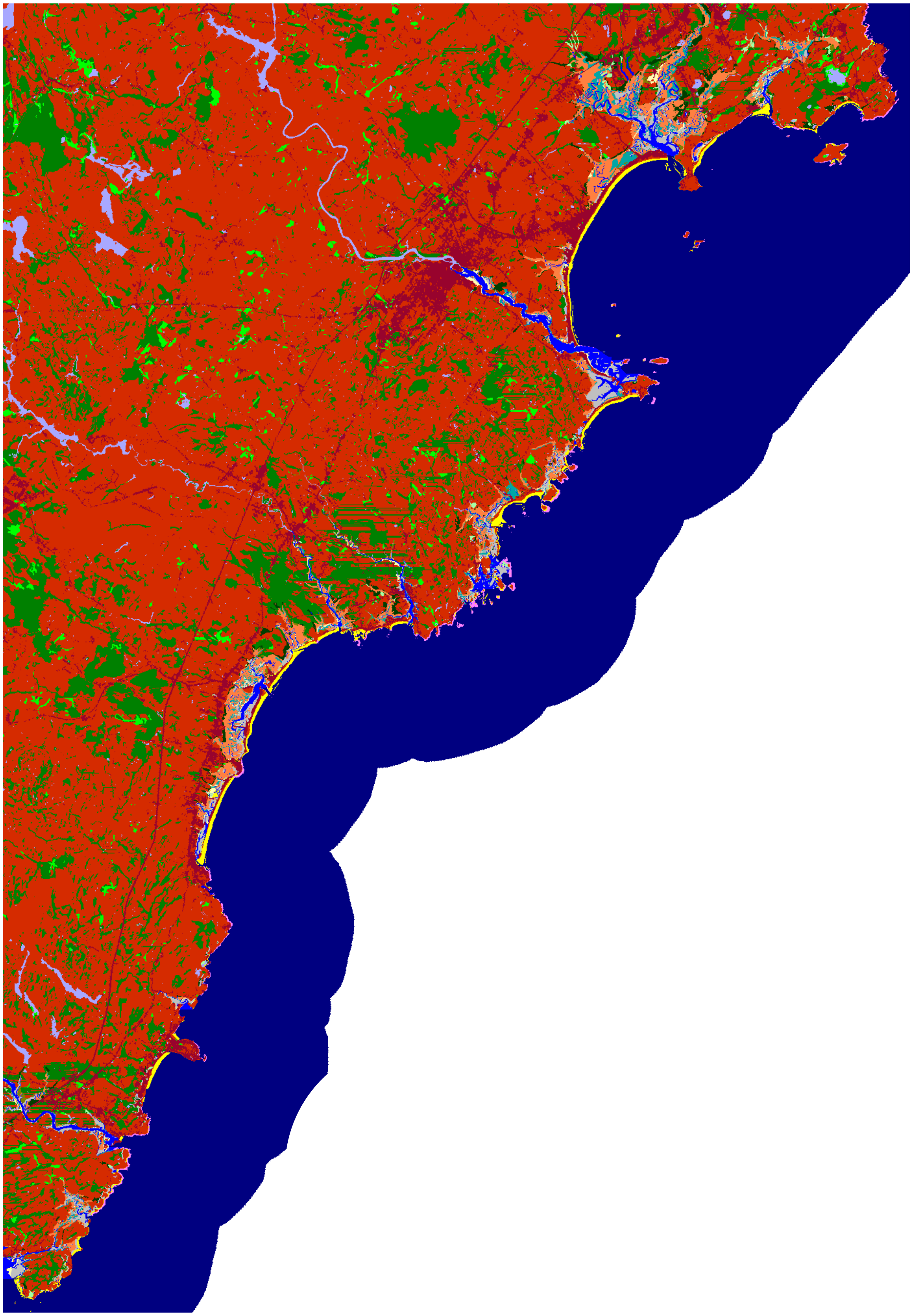
Rachel Carson NWR, 2100, 1 meter Protect Developed Dry Land



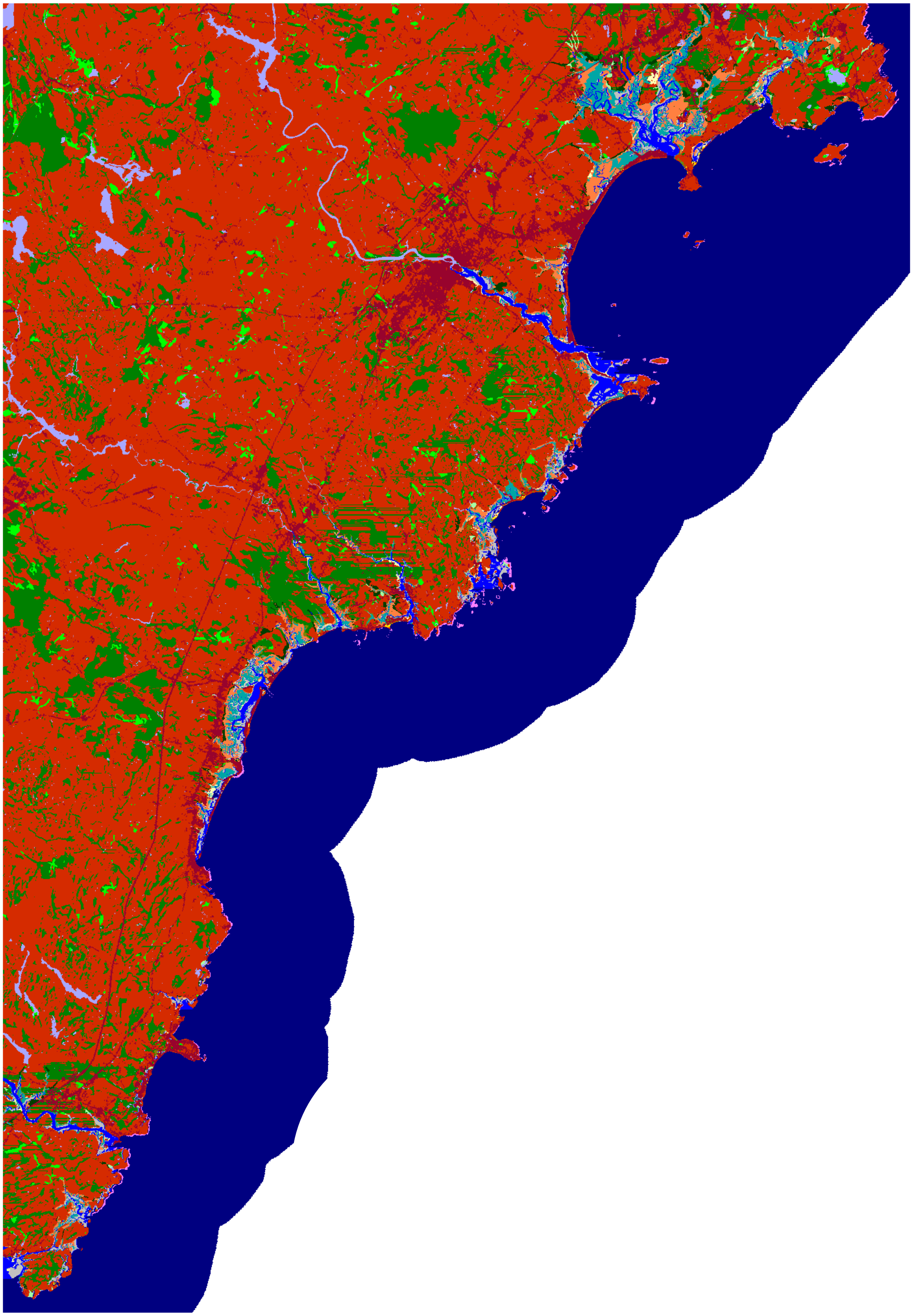
Rachel Carson NWR, Initial Condition



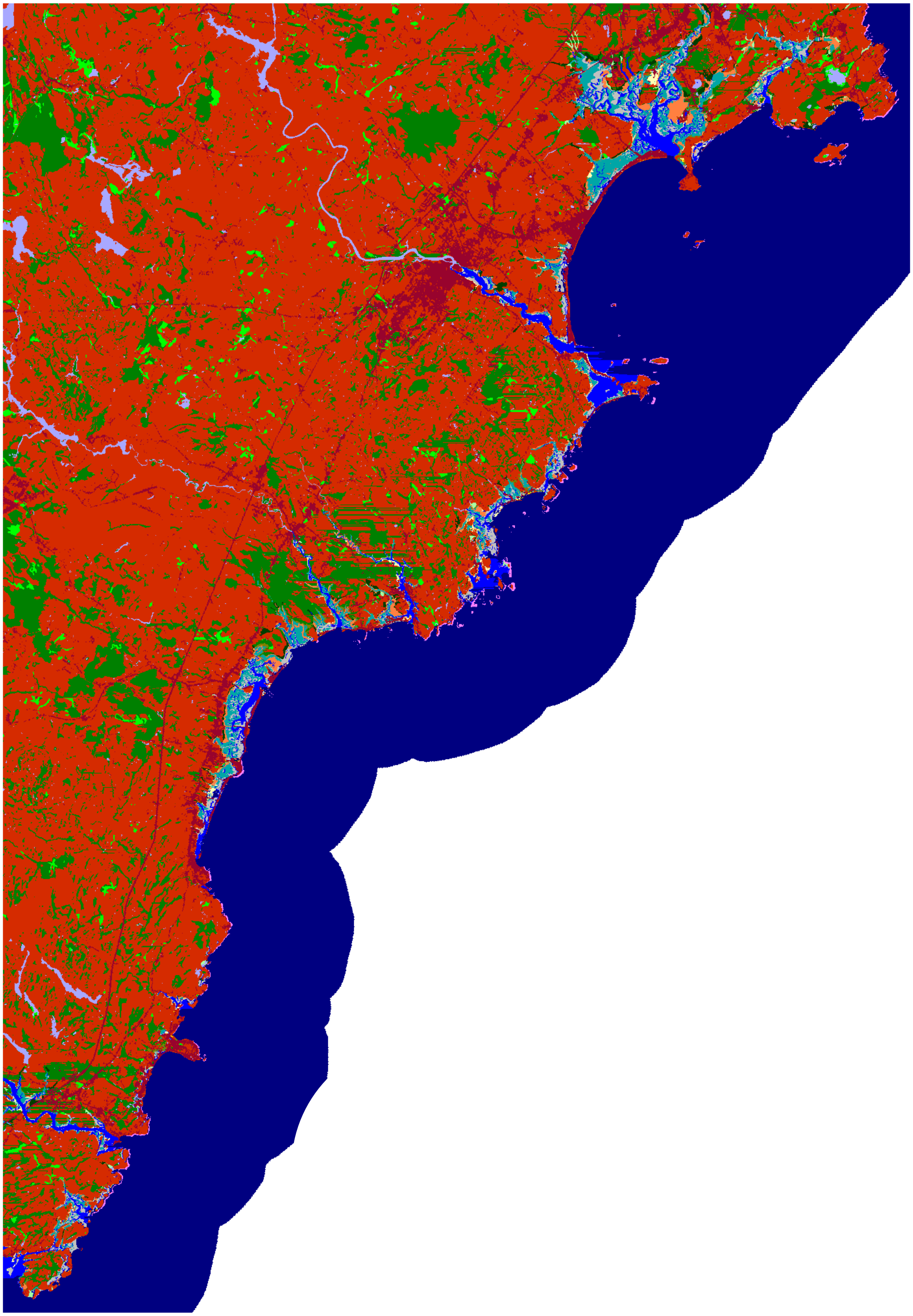
Rachel Carson NWR, 2025, 1.5 meter Protect Developed Dry Land



Rachel Carson NWR, 2050, 1.5 meter Protect Developed Dry Land



Rachel Carson NWR, 2075, 1.5 meter Protect Developed Dry Land



Rachel Carson NWR, 2100, 1.5 meter Protect Developed Dry Land