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

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Introduction

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

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

Model Summary

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

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

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

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

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

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

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

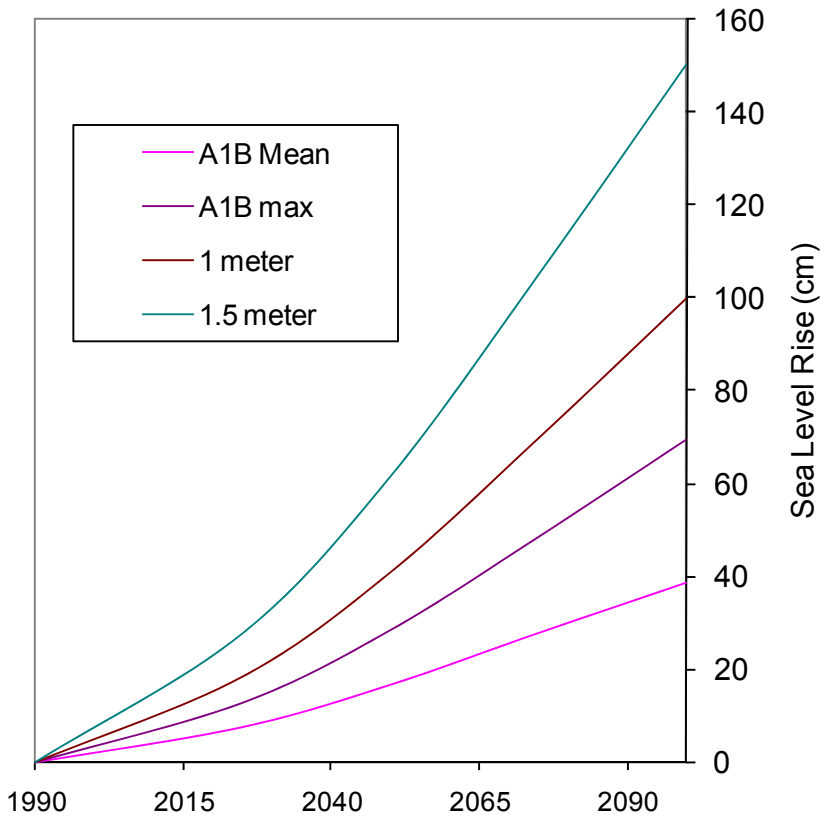
Scenario	Eustatic SLR by 2025 (cm)	Eustatic SLR by 2050 (cm)	Eustatic SLR by 2075 (cm)	Eustatic SLR by 2100 (cm)
A1B Mean	8	17	28	39
A1B Max	14	30	49	69
1 meter	13	28	48	100
1.5 meter	18	41	70	150

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

LIDAR elevation data are unavailable for this National Wildlife Refuge (NWR). Elevation data used are based on National Elevation Data (NED). An examination of the NED metadata indicates that this digital elevation map (DEM) was derived from a 1949 survey (Fig. 2). The contour interval used to derive the DEM was twenty feet. Despite this contour interval, many contour lines appear within the wildlife refuge indicating significant vertical relief for this refuge. Still, considerable uncertainty exists as to the precise elevations between the shoreline and the twenty foot contour interval.

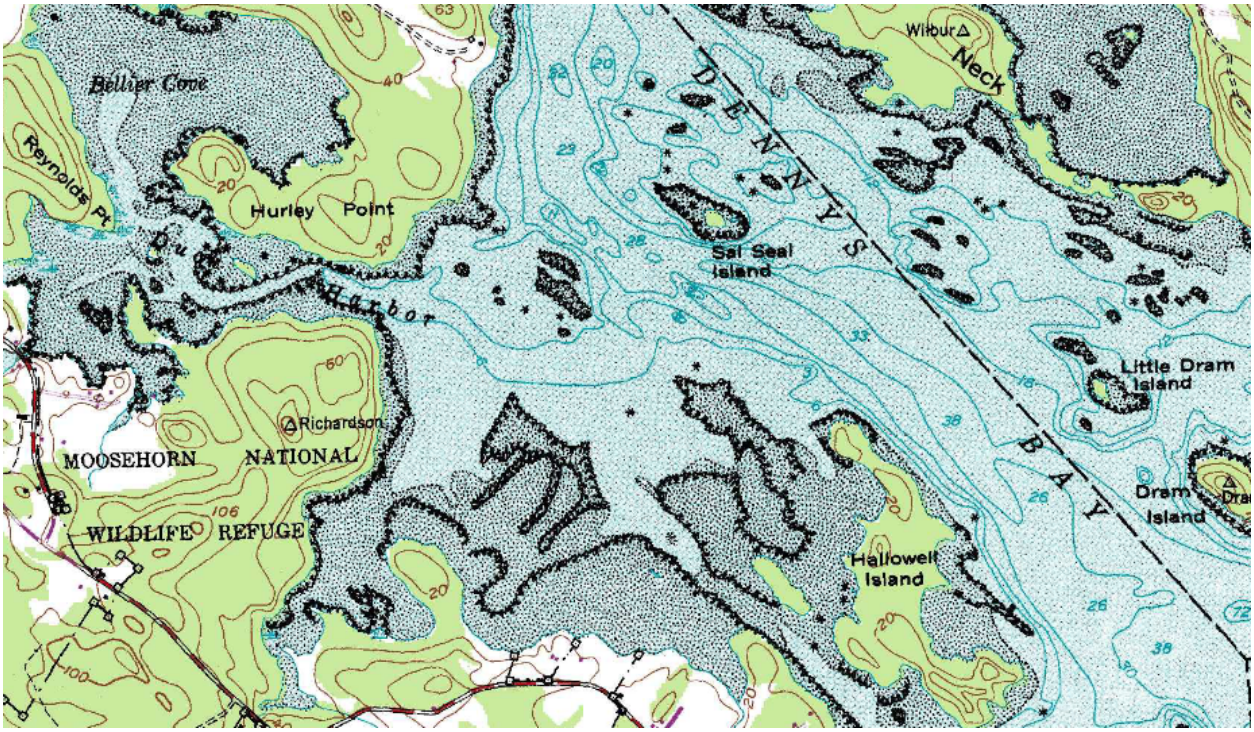


Figure 2: Moosehorn Excerpt from USGS Map.

The National Wetlands Inventory for Moosehorn is based on a photo date of 1983. Comparing this coverage with recent satellite photos indicates only minor changes since the inventory was taken. An updated NWI coverage is unlikely to considerably change model results.

Converting the NWI survey into 30 meter cells indicates that the approximately twenty six thousand acre refuge (approved acquisition boundary including water) was primarily composed of the categories below:

Dry Land	84.0%
Swamp	7.9%
Inland Fresh Marsh	3.7%
Inland Open Water	3.5%

According to the NWI coverage, there are small regions of diked and impounded wetlands within the Moosehorn NWR. Areas demarcated as protected by dikes were assumed to be protected in this modeling analysis.

The historic trend for sea level rise was estimated at 2.0 mm/year using the value of the closest oceanic gage (8410140, Eastport, ME). This measured rate is similar to the global average for the last 100 years (approximately 1.5-2.0 mm/year). Any elevation changes from isostatic rebound that have affected this region for the last 100 years are measured within that historic trend and that same rate of isostatic rebound is projected forward into the next 100 years.

The average tide range at this site was estimated at 6.0 meters using the average of the two closest NOAA oceanic gages (8410140, Eastport, ME; 8410715, Garnet Point, Hersey Neck, ME).

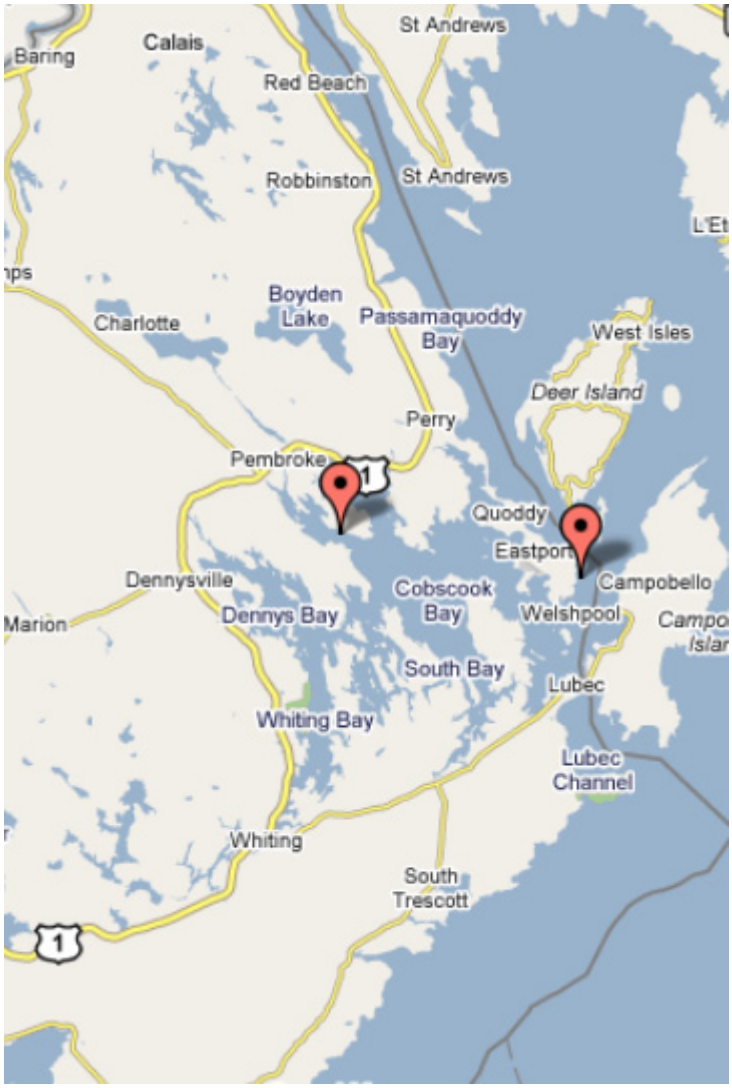


Figure 4: NOAA Gages Relevant to the Study Area.

Accretion rates in salt and brackish marshes were set to 3.39 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).

Modeled U.S. Fish and Wildlife Service refuge boundaries are based on Approved Acquisition Boundaries as published on the FWS "National Wildlife Refuge Data and Metadata" website.

The cell-size used for this analysis was 30 meter by 30 meter cells. 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 Moosehorn were overwritten as a function of the local tidal range using the SLAMM elevation pre-processor.)

SUMMARY OF SLAMM INPUT PARAMETERS FOR MOOSEHORN

Description	Moosehorn
DEM Source Date (yyyy)	1949
NWI_photo_date (yyyy)	1983
Direction_OffShore (N|S|E|W)	E
Historic_trend (mm/yr)	2
NAVD88_correction (MTL-NAVD88 in meters)	-0.096
Water Depth (m below MLW- N/A)	2
TideRangeOcean (meters: MHHW-MLLW)	6
TideRangeInland (meters)	6
Mean High Water Spring (m above MTL)	3.990
MHSW Inland (m above MTL)	3.990
Marsh Erosion (horz meters/year)	1.8
Swamp Erosion (horz meters/year)	1
TFlat Erosion (horz meters/year) [from 0.5]	0.5
Salt marsh vertical accretion (mm/yr) Final	3.39
Brackish March vert. accretion (mm/yr) Final	3.39
Tidal Fresh vertical accretion (mm/yr) Final	5.9
Beach/T.Flat Sedimentation Rate (mm/yr)	0.5
Frequency of Large Storms (yr/washover)	50
Use Elevation Preprocessor for Wetlands	TRUE

Results

Moosehorn National Wildlife Refuge is predicted to be resilient to sea level rise. Loss of dry land – the great majority of the NWR – is predicted to be only 2% in the most extreme scenario. Inland fresh marsh is not predicted to be affected. Loss of brackish marsh – which comprises less than one half of 1% of the NWR – is predicted to be over 29% in scenarios of 1 meter and above.

SLR by 2100 (m)	0.39	0.69	1	1.5
Dry Land	1%	1%	1%	2%
Inland Fresh Marsh	0%	0%	0%	0%
Brackish Marsh	2%	14%	29%	56%

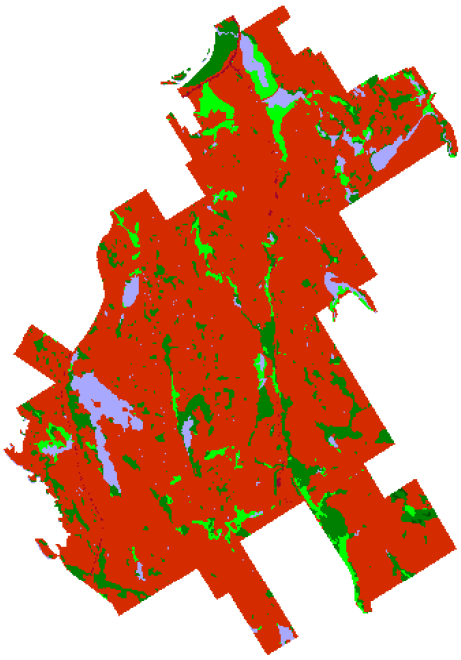
Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

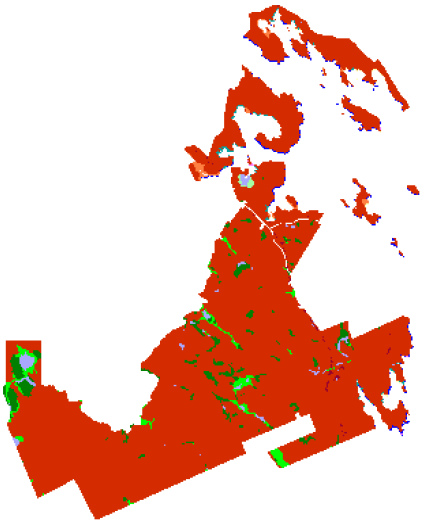
Maps of SLAMM input and output to follow will use the following legend:

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

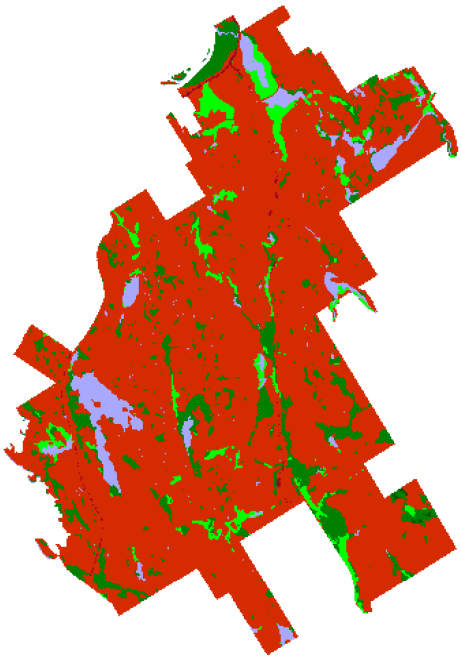
Results in Acres

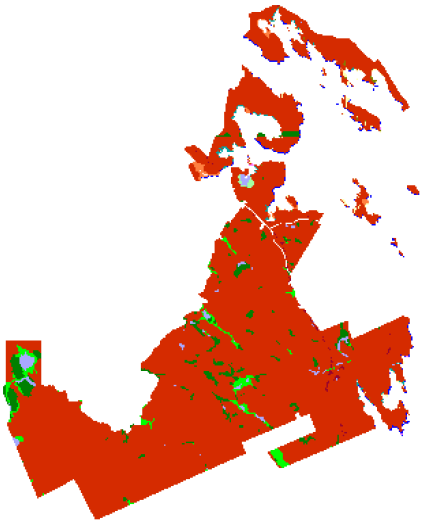
	Initial	2025	2050	2075	2100
Undev. Dry Land	21999.9	21942.1	21879.6	21824.8	21785.2
Swamp	2056.0	2077.1	2078.0	2077.5	2077.0
Inland Fresh Marsh	960.7	960.7	960.7	960.7	960.7
Inland Open Water	913.6	914.0	914.0	914.0	914.0
Dev. Dry Land	76.5	76.5	76.5	76.5	76.5
Estuarine Open Water	71.2	72.0	72.8	73.9	74.9
Brackish Marsh	36.7	36.7	36.7	36.5	36.1
Saltmarsh	29.6	29.6	29.6	29.6	29.7
Cypress Swamp	12.2	12.2	12.2	12.2	12.2
Estuarine Beach	10.0	35.6	74.6	102.1	120.3
Tidal Fresh Marsh	9.3	9.3	9.3	9.3	9.3
Rocky Intertidal	2.9	2.8	2.8	2.7	2.7
Trans. Salt Marsh	0.0	9.8	31.7	58.8	79.8
Total (incl. water)	**26178.7**	**26178.7**	**26178.7**	**26178.7**	**26178.7**



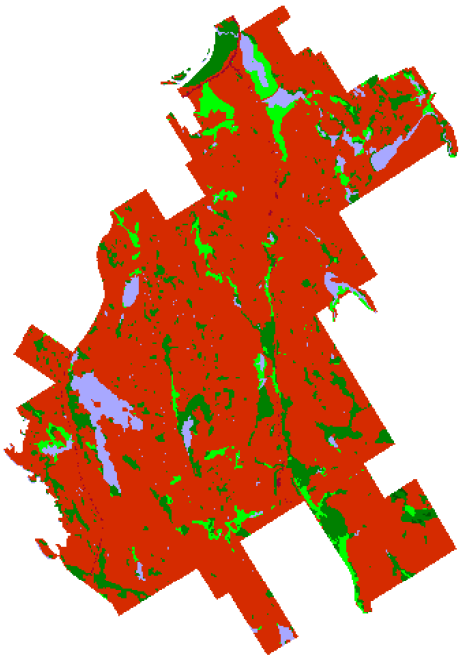


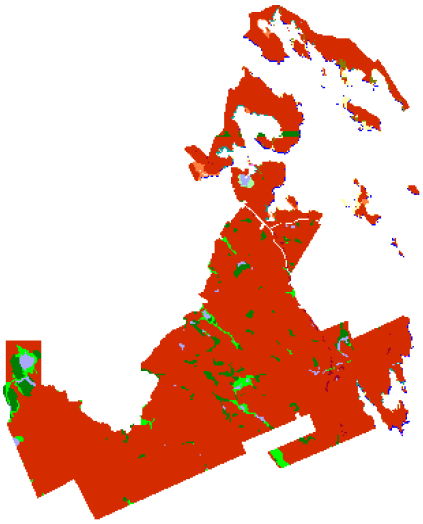
Moosehorn NWR, Initial Condition



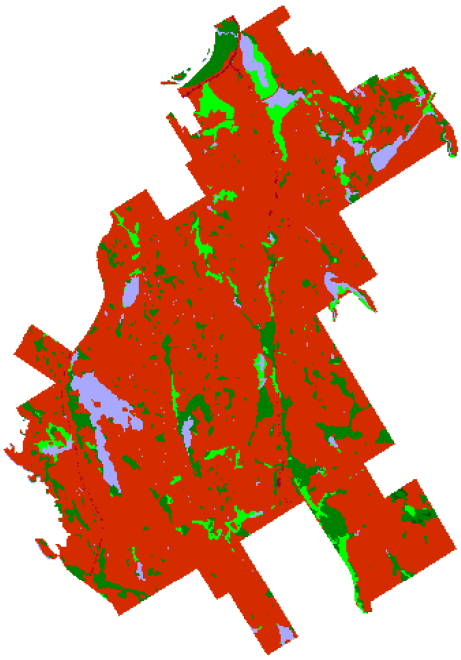


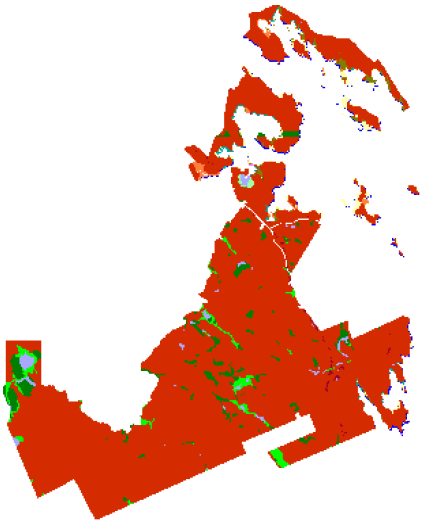
Moosehorn NWR, 2025, Scenario A1B Mean Protect Developed Dry Land



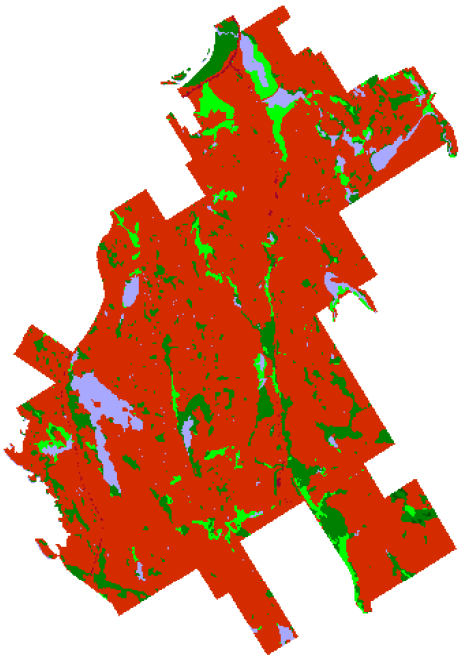


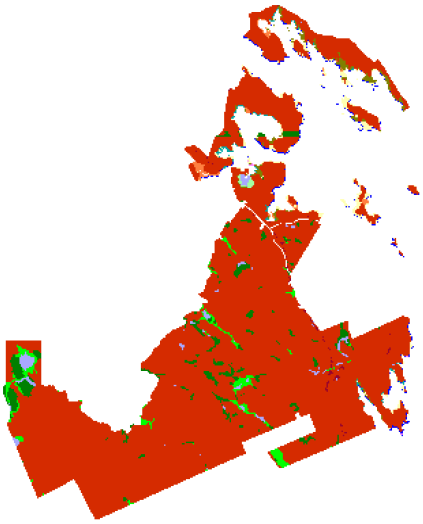
Moosehorn NWR, 2050, Scenario A1B Mean Protect Developed Dry Land





Moosehorn NWR, 2075, Scenario A1B Mean Protect Developed Dry Land



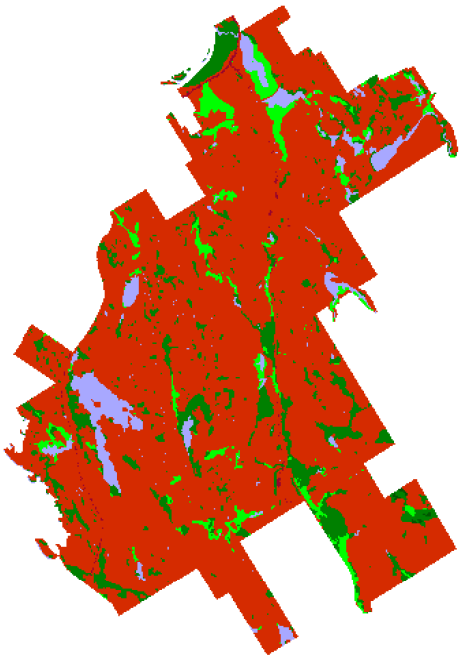


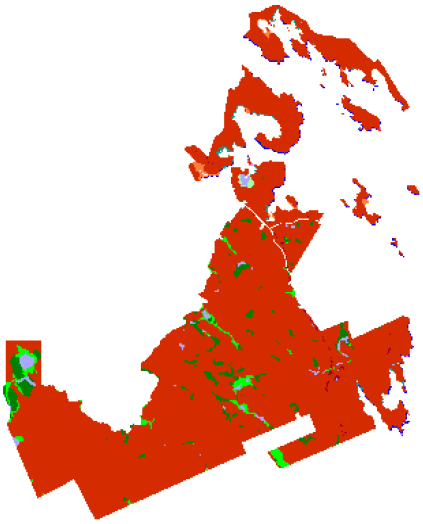
Moosehorn NWR, 2100, Scenario A1B Mean Protect Developed Dry Land

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

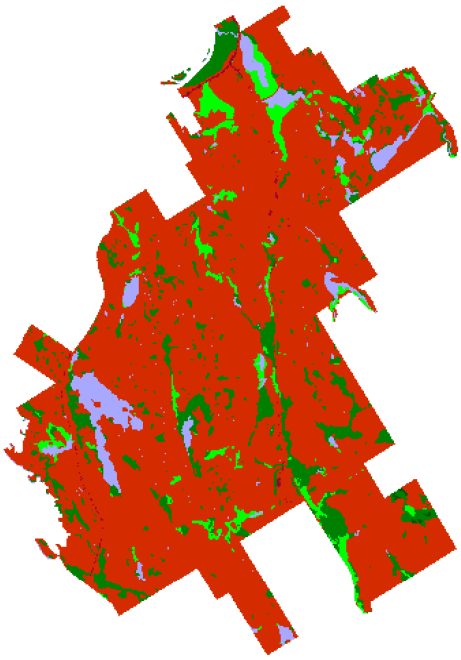
Results in Acres

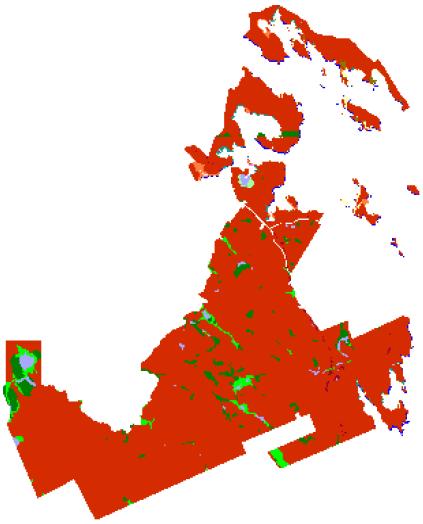
	Initial	2025	2050	2075	2100
Undev. Dry Land	21999.9	21913.6	21827.3	21768.0	21736.6
Swamp	2056.0	2077.0	2077.6	2076.9	2076.7
Inland Fresh Marsh	960.7	960.7	960.7	960.7	960.7
Inland Open Water	913.6	914.0	914.0	914.0	914.0
Dev. Dry Land	76.5	76.5	76.5	76.5	76.5
Estuarine Open Water	71.2	72.6	74.5	76.8	79.0
Brackish Marsh	36.7	36.5	35.6	33.9	31.7
Saltmarsh	29.6	29.6	29.8	30.5	31.5
Cypress Swamp	12.2	12.2	12.2	12.2	12.2
Estuarine Beach	10.0	54.5	100.9	128.0	142.0
Tidal Fresh Marsh	9.3	9.3	9.3	9.3	9.3
Rocky Intertidal	2.9	2.8	2.7	2.6	2.5
Trans. Salt Marsh	0.0	19.1	57.3	88.8	105.7
Tidal Flat	0.0	0.1	0.0	0.1	0.1
Total (incl. water)	**26178.7**	**26178.7**	**26178.7**	**26178.7**	**26178.7**



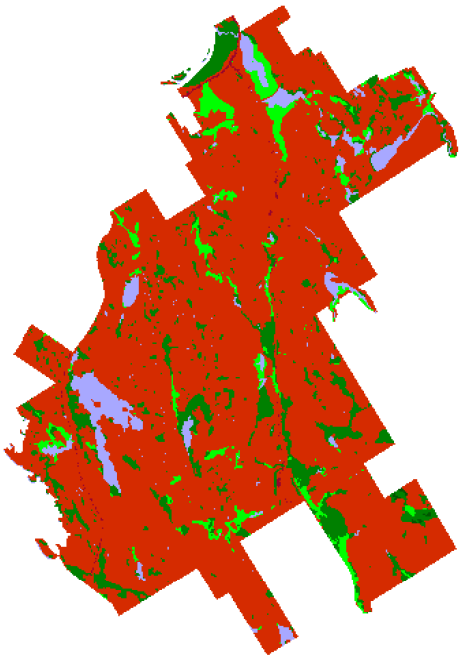


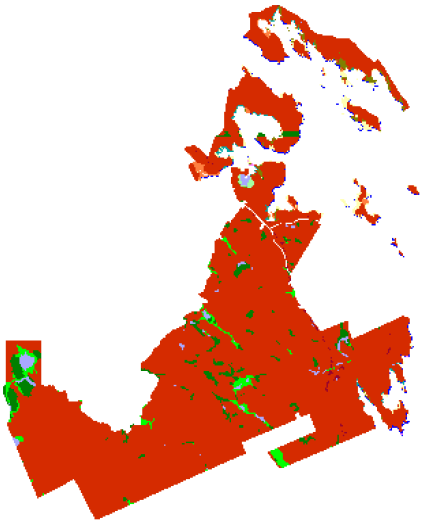
Moosehorn NWR, Initial Condition



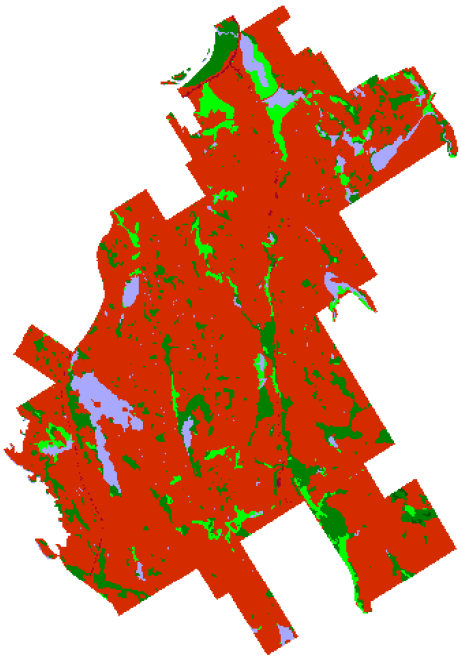


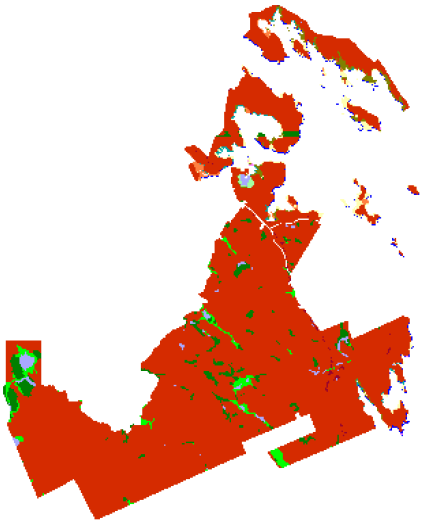
Moosehorn NWR, 2025, Scenario A1B Maximum Protect Developed Dry Land



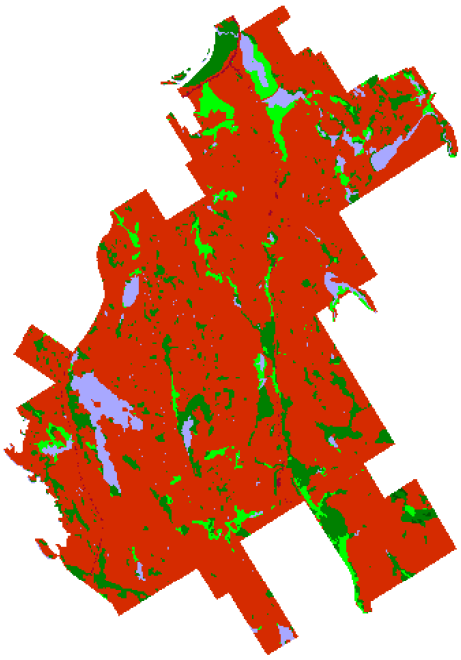


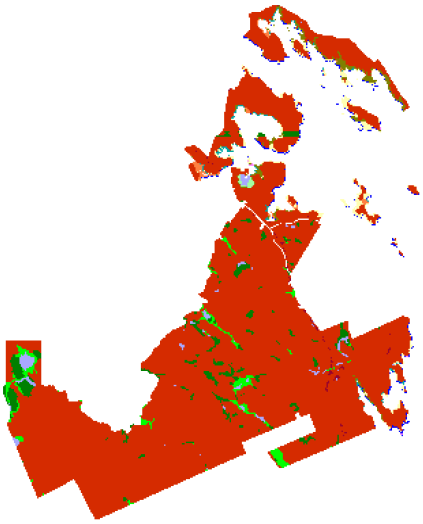
Moosehorn NWR, 2050, Scenario A1B Maximum Protect Developed Dry Land





Moosehorn NWR, 2075, Scenario A1B Maximum Protect Developed Dry Land



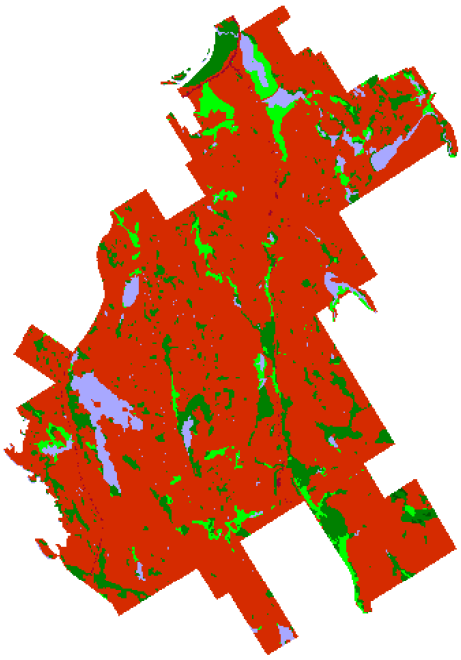


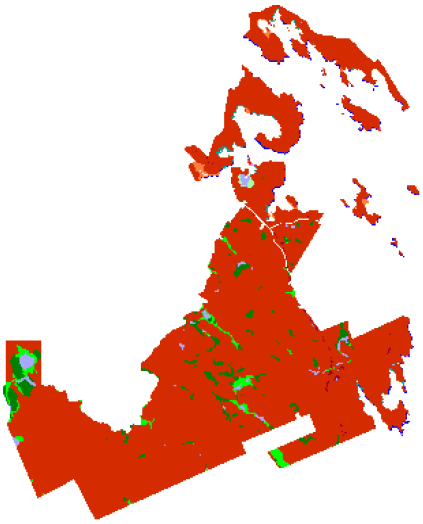
Moosehorn NWR, 2100, Scenario A1B Maximum Protect Developed Dry Land

Moosehorn NWR
1 Meter Eustatic SLR by 2100

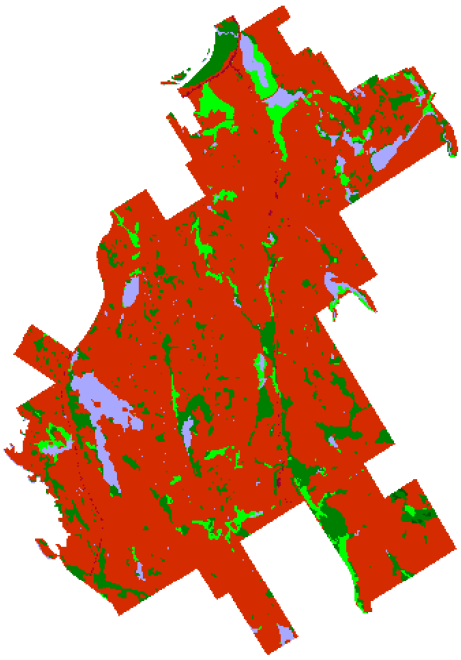
Results in Acres

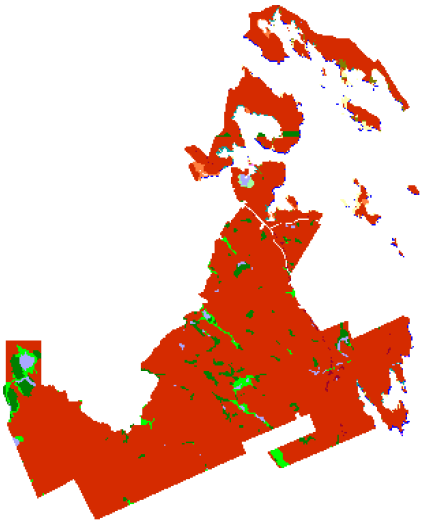
	Initial	2025	2050	2075	2100
Undev. Dry Land	21999.9	21878.3	21785.8	21737.4	21703.7
Swamp	2056.0	2076.4	2077.2	2076.8	2076.6
Inland Fresh Marsh	960.7	960.7	960.7	960.7	960.7
Inland Open Water	913.6	914.0	914.0	914.0	914.0
Dev. Dry Land	76.5	76.5	76.5	76.5	76.5
Estuarine Open Water	71.2	73.5	76.3	79.4	82.4
Brackish Marsh	36.7	35.9	34.0	30.4	26.0
Saltmarsh	29.6	29.7	30.4	32.2	34.6
Cypress Swamp	12.2	12.2	12.2	12.2	12.2
Estuarine Beach	10.0	76.2	120.6	142.0	159.7
Tidal Fresh Marsh	9.3	9.3	9.3	9.3	9.3
Rocky Intertidal	2.9	2.8	2.7	2.5	2.4
Trans. Salt Marsh	0.0	32.9	78.7	104.8	120.1
Tidal Flat	0.0	0.1	0.2	0.3	0.4
Total (incl. water)	**26178.7**	**26178.7**	**26178.7**	**26178.7**	**26178.7**



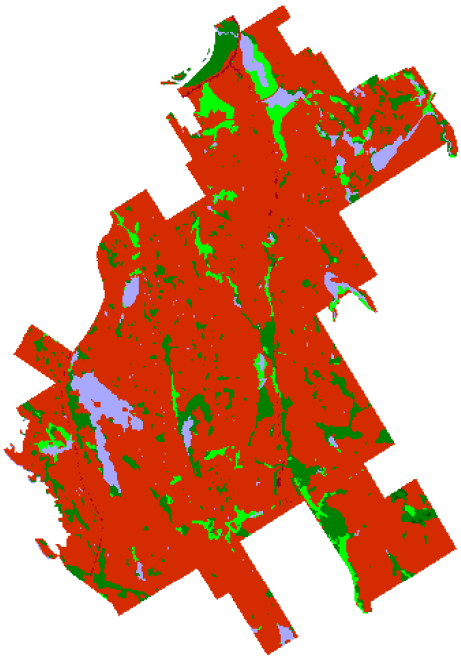


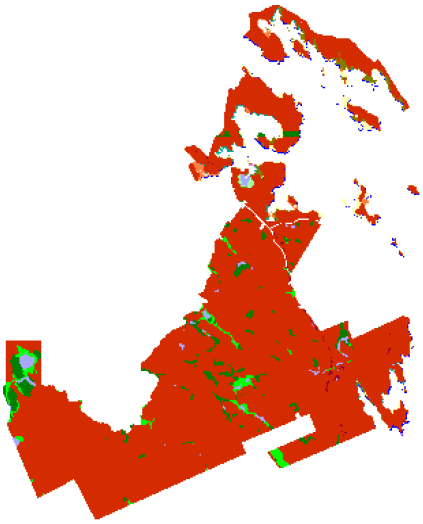
Moosehorn NWR, Initial Condition



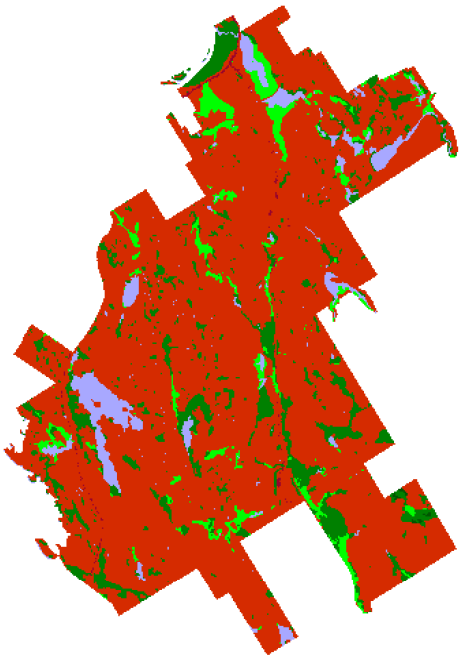


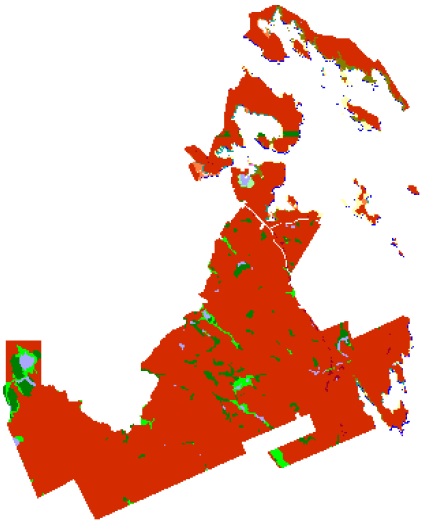
Moosehorn NWR, 2025, 1 meter Protect Developed Dry Land



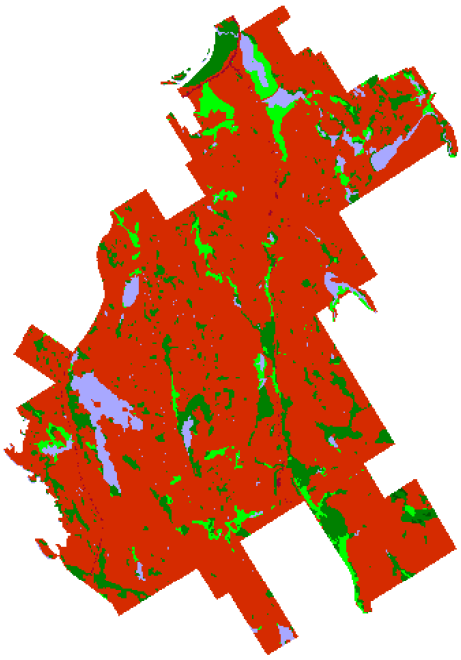


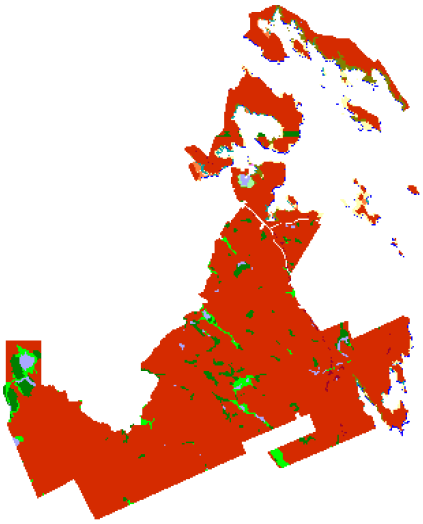
Moosehorn NWR, 2050, 1 meter Protect Developed Dry Land





Moosehorn NWR, 2075, 1 meter Protect Developed Dry Land



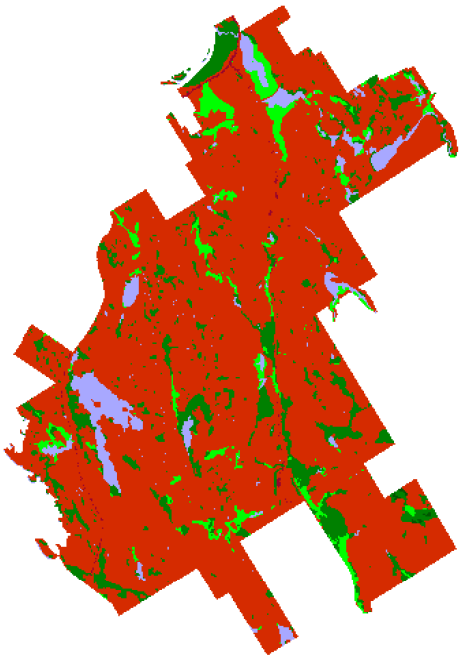


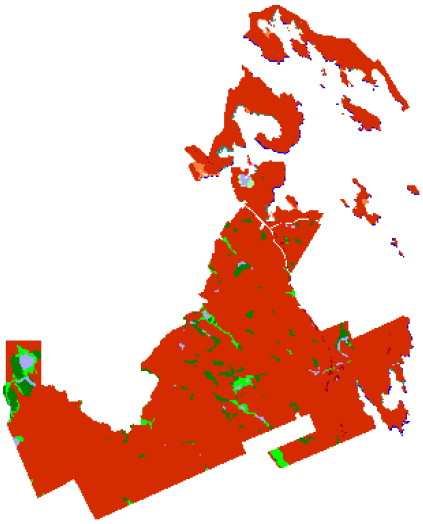
Moosehorn NWR, 2100, 1 meter Protect Developed Dry Land

Moosehorn NWR
1.5 Meters Eustatic SLR by 2100

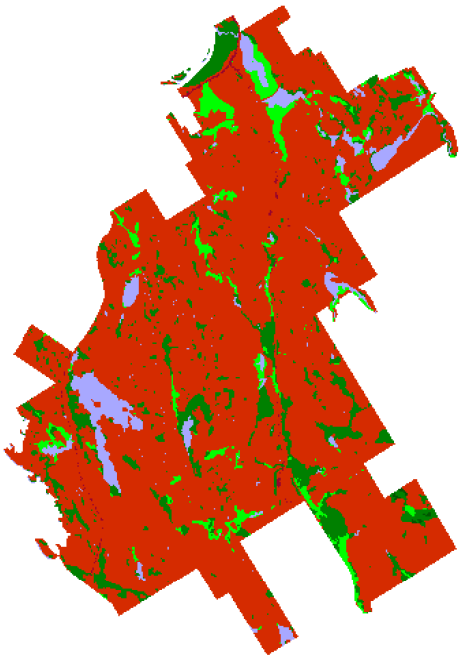
Results in Acres

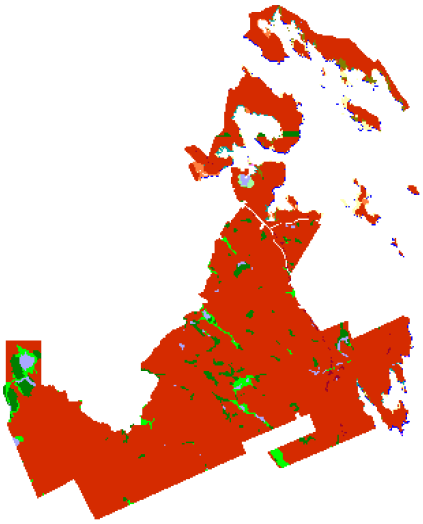
	Initial	2025	2050	2075	2100
Undev. Dry Land	21999.9	21835.8	21749.4	21700.0	21658.0
Swamp	2056.0	2076.2	2077.1	2076.7	2076.9
Inland Fresh Marsh	960.7	960.7	960.7	960.7	960.7
Inland Open Water	913.6	914.0	914.0	914.0	914.0
Dev. Dry Land	76.5	76.5	76.5	76.5	76.5
Estuarine Open Water	71.2	74.8	78.8	83.0	87.4
Brackish Marsh	36.7	34.9	30.6	23.3	16.3
Saltmarsh	29.6	30.1	32.1	36.1	105.2
Cypress Swamp	12.2	12.2	12.2	12.2	12.2
Estuarine Beach	10.0	97.7	135.9	161.4	184.9
Tidal Fresh Marsh	9.3	9.3	9.3	9.3	9.3
Rocky Intertidal	2.9	2.7	2.6	2.4	2.0
Trans. Salt Marsh	0.0	53.4	98.8	121.7	73.4
Tidal Flat	0.0	0.2	0.6	1.1	1.7
Total (incl. water)	**26178.7**	**26178.7**	**26178.7**	**26178.7**	**26178.7**



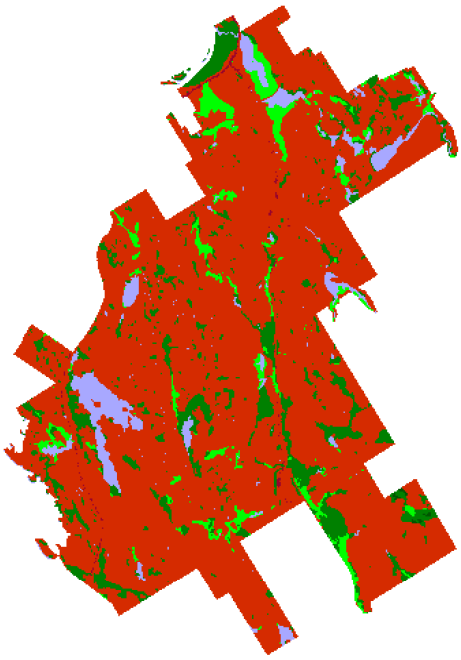


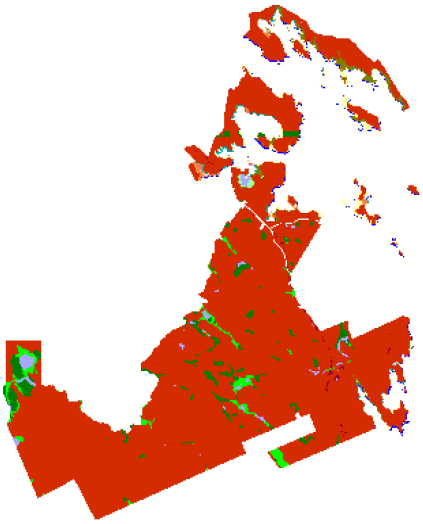
Moosehorn NWR, Initial Condition



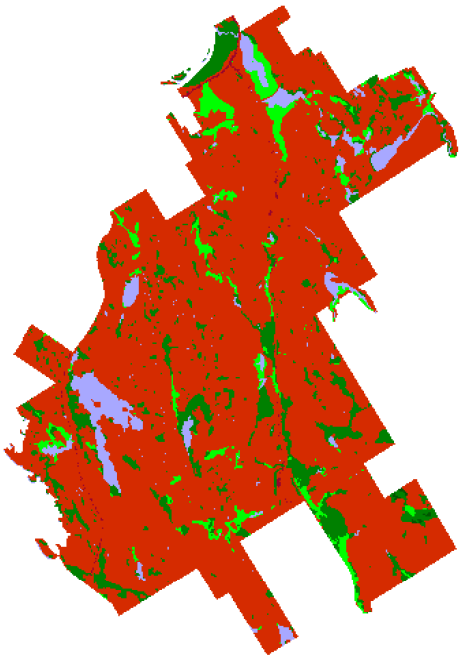


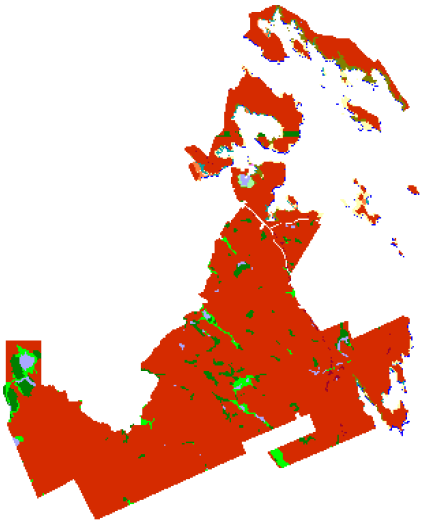
Moosehorn NWR, 2025, 1.5 meter Protect Developed Dry Land



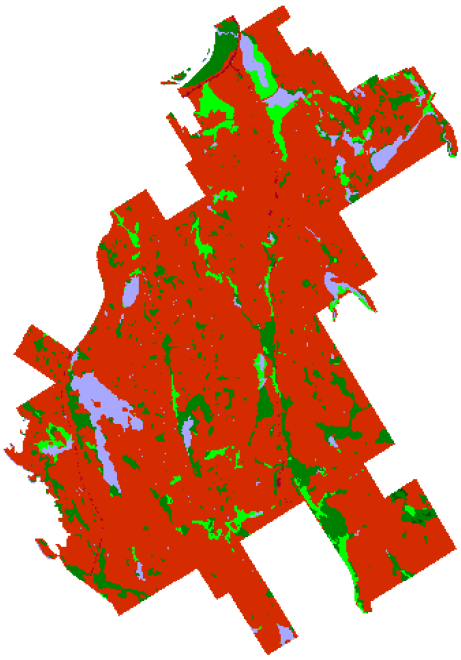


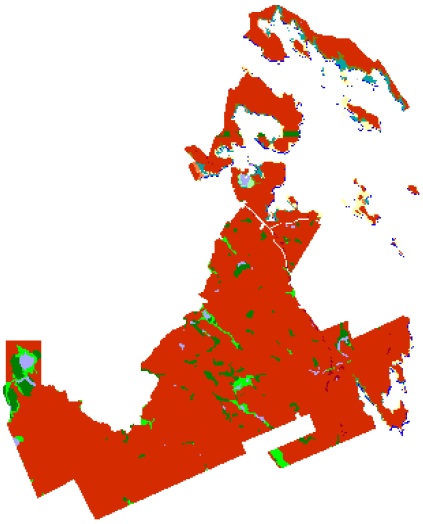
Moosehorn NWR, 2050, 1.5 meter Protect Developed Dry Land





Moosehorn NWR, 2075, 1.5 meter Protect Developed Dry Land





Moosehorn NWR, 2100, 1.5 meter Protect Developed Dry Land

Discussion:

Moosehorn NWR is predicted to be quite resilient to the effects of sea level rise. In even the most extreme scenario, there is little conversion to open water and only minor wetland losses. The NWR's high tide range (approximately 6 meters) combined with the significant vertical relief at this site help to explain the predictions of resilience to sea level rise.

There is some model uncertainty due to the elevation data (DEM) for Moosehorn NWR. This DEM is 60 years old and that has a low vertical resolution (based on 20 foot contours). A future analysis of Moosehorn NWR would benefit from higher quality elevation data. This would more precisely characterize land lost between the shoreline and the twenty foot contour. However, those areas of the refuge located above the 20 foot contour will certainly remain resilient to sea level rise.

The SLAMM model accounts for the local effects of isostatic rebound by taking into account the historical sea level rise for each site modeled. The historical rate of land movement is predicted to continue through the year 2100. This means that within this modeling, the rate of isostatic rebound is assumed to remain constant.

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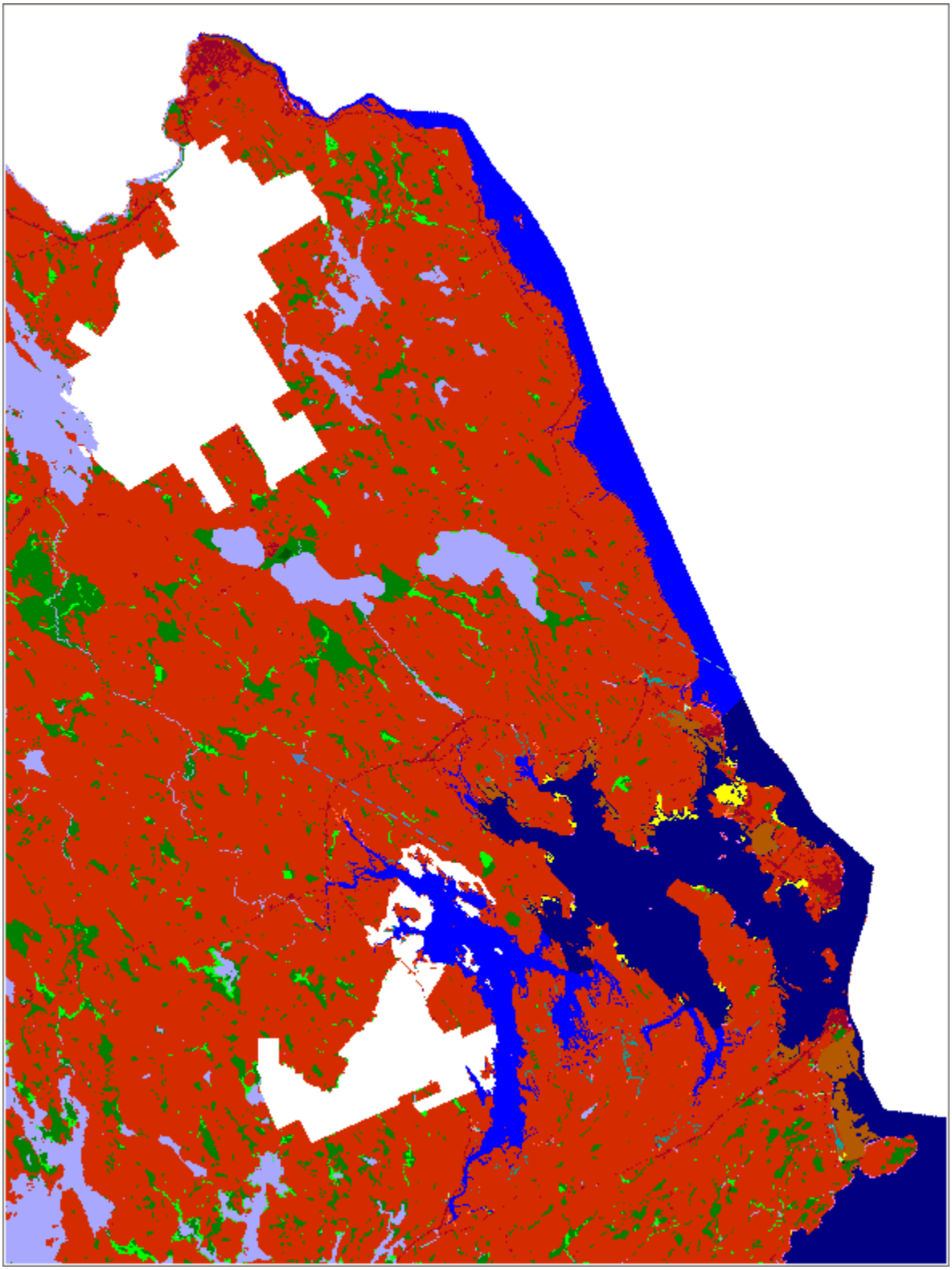
Appendix A: Contextual Results

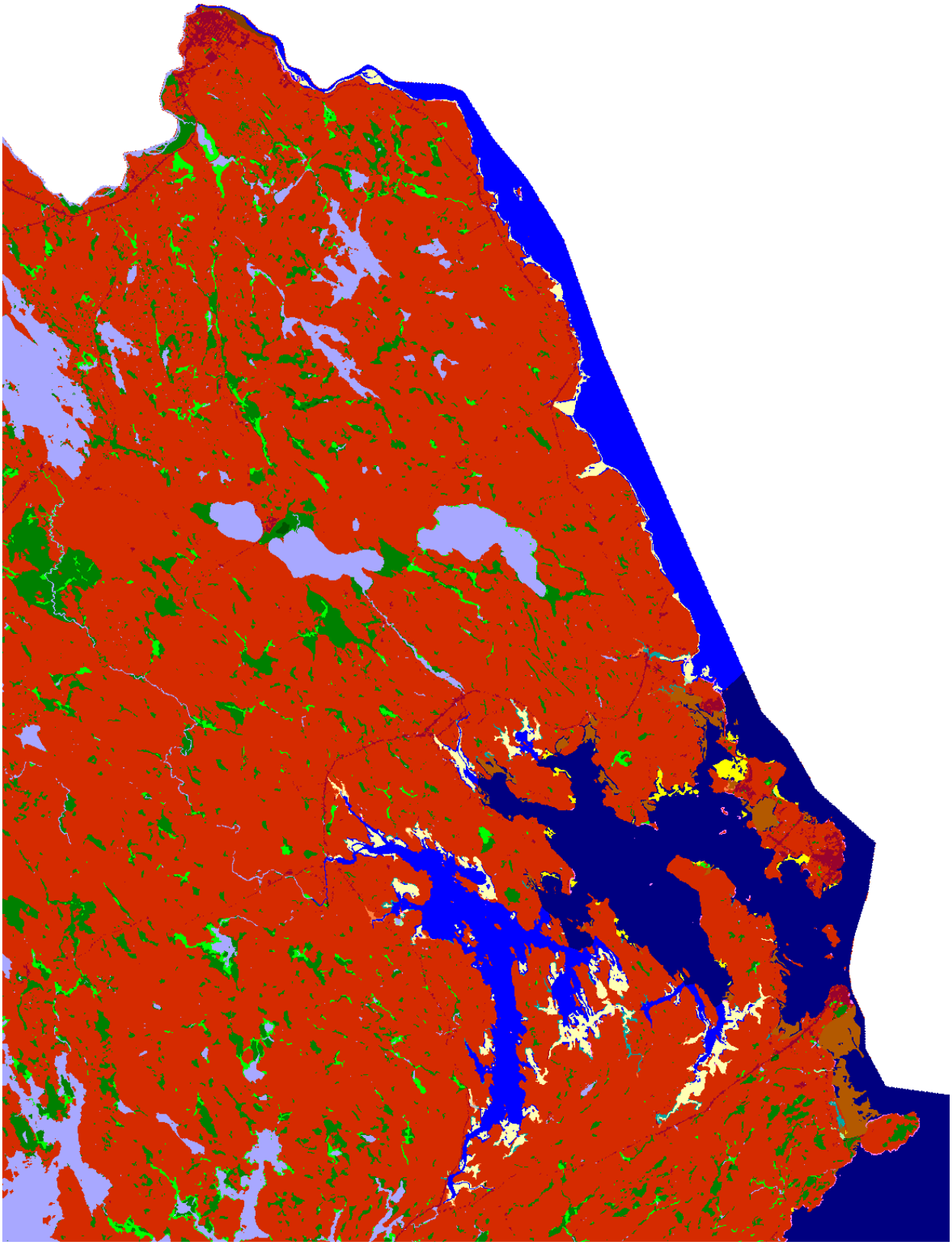
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

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

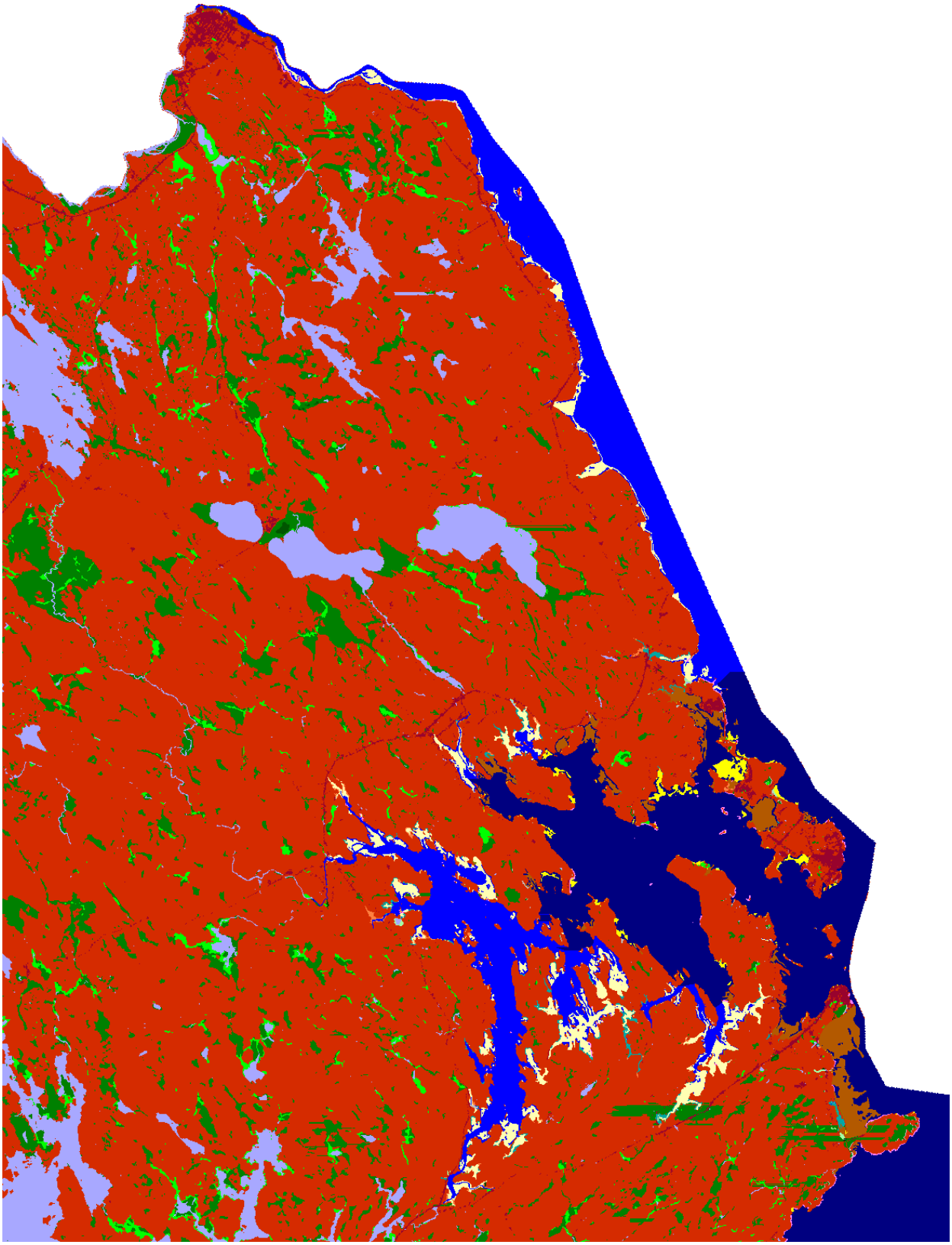
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



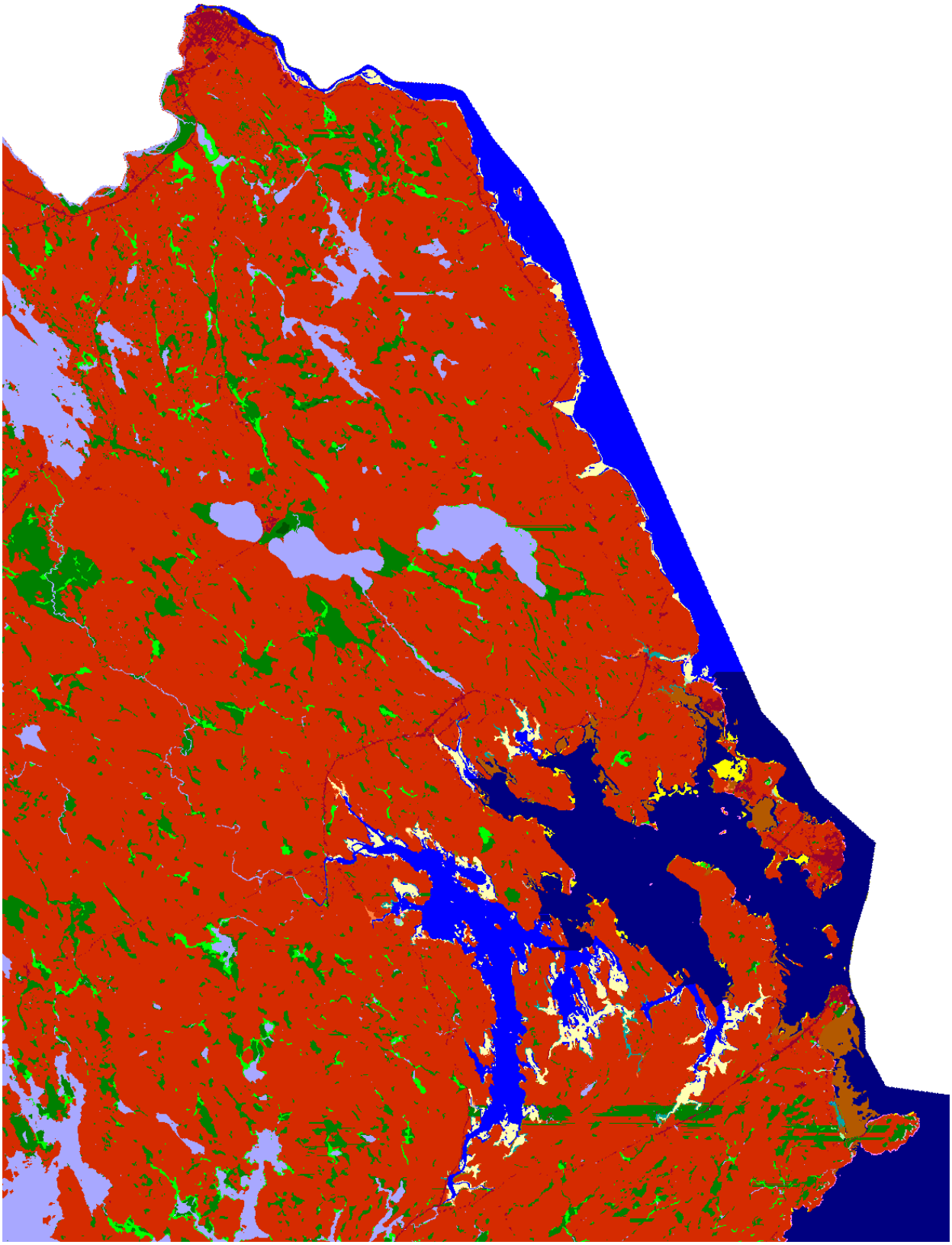
Location of Moosehorn National Wildlife Refuge (white) within simulation context



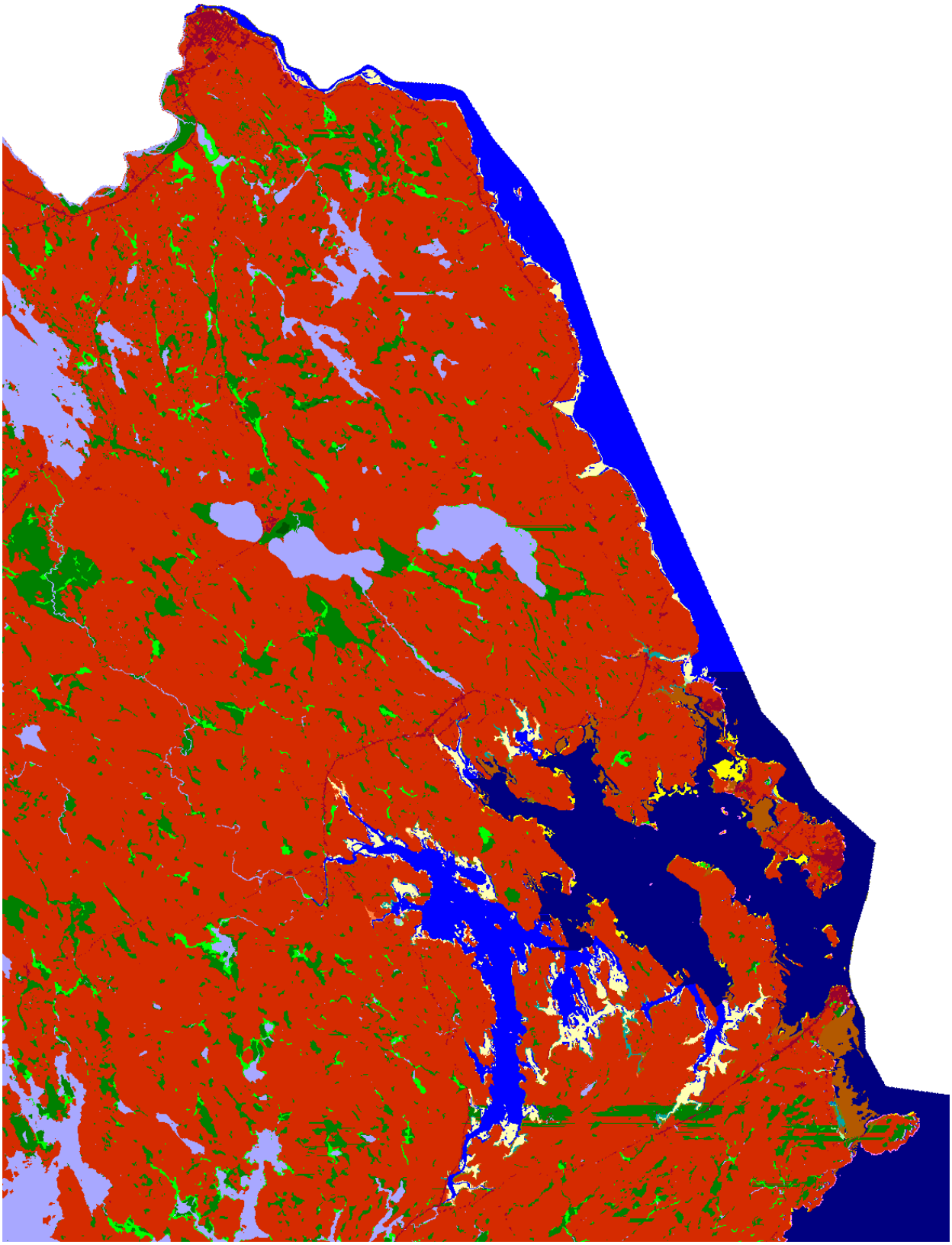
Moosehorn NWR, Initial Condition



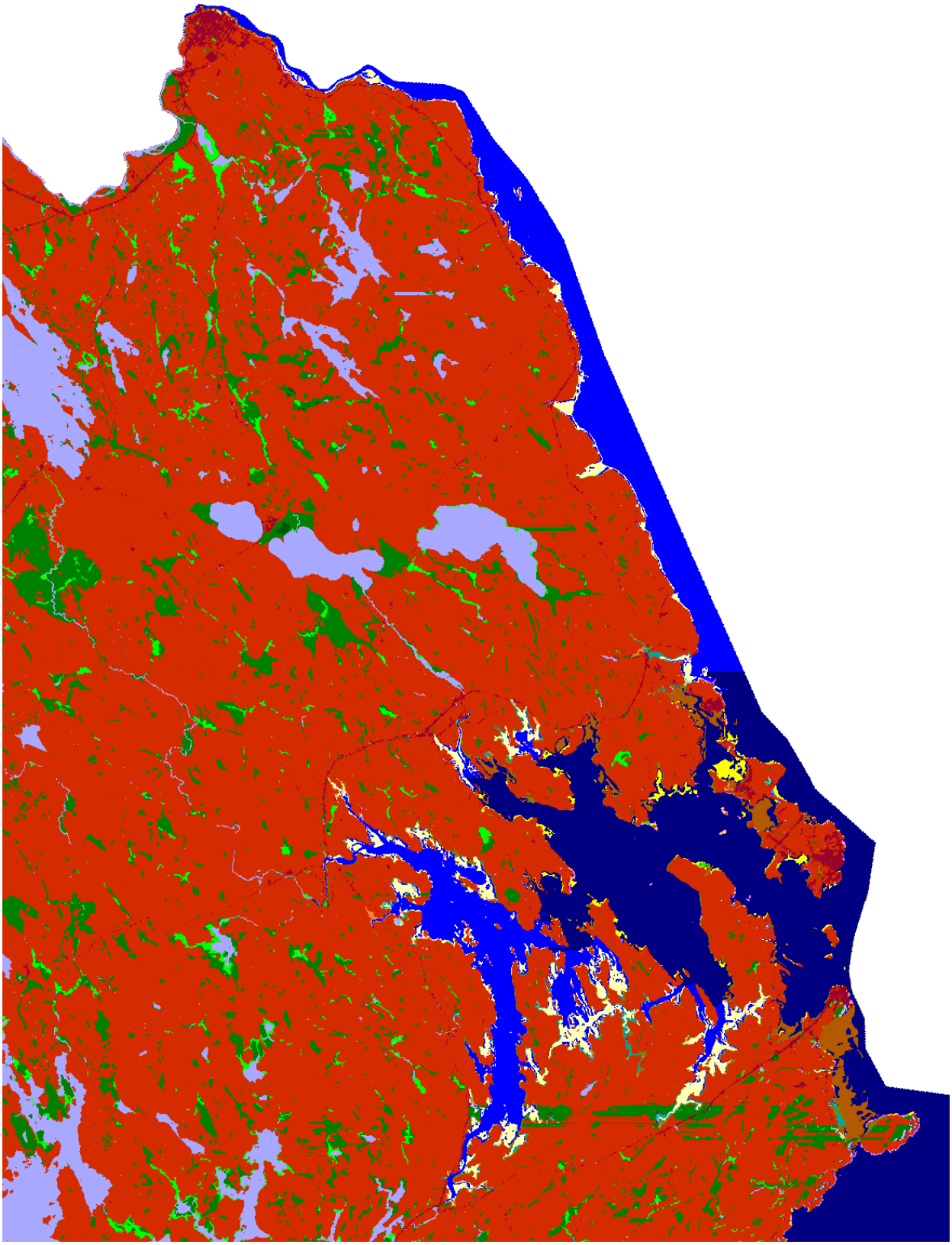
Moosehorn NWR, 2025, Scenario A1B Mean Protect Developed Dry Land



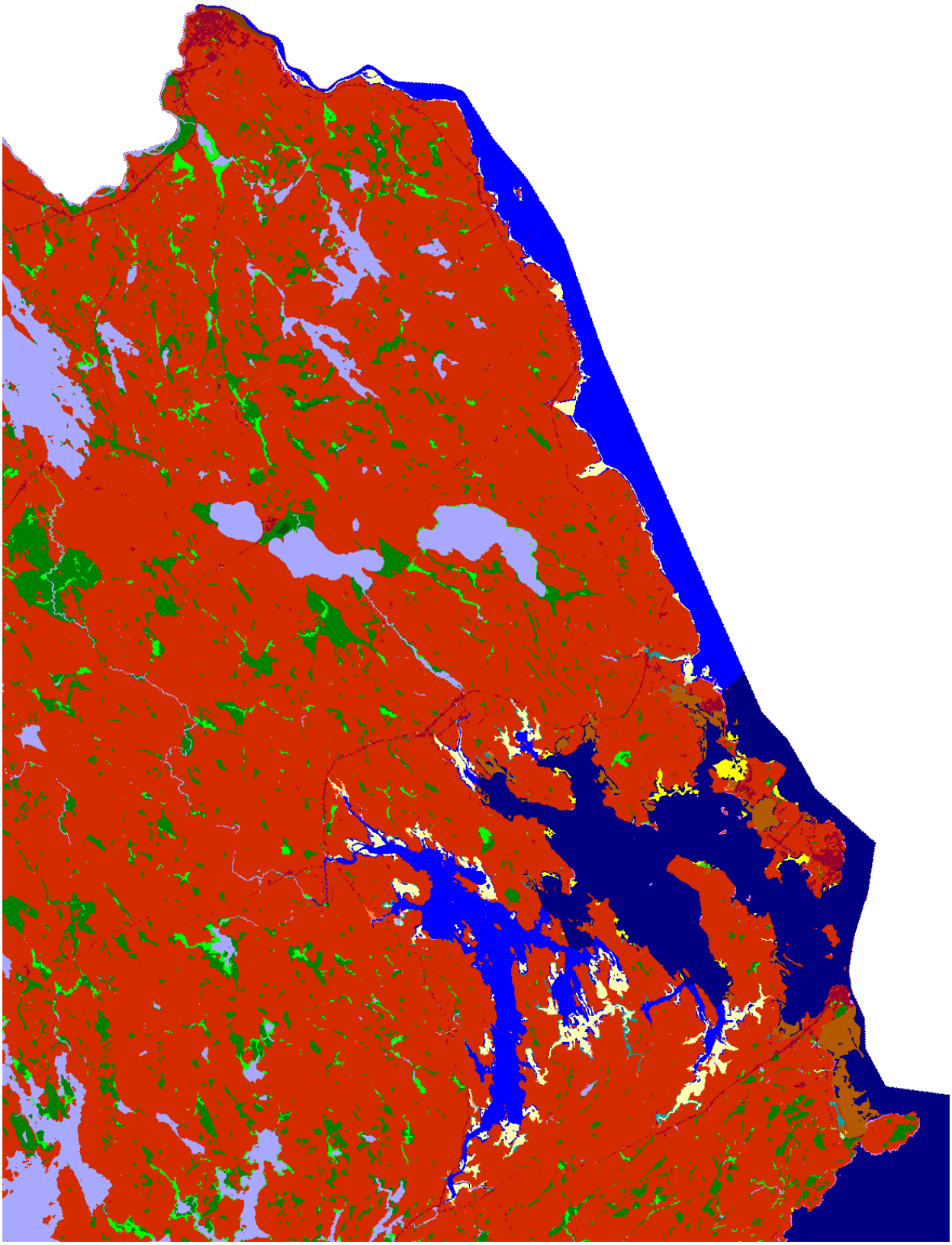
Moosehorn NWR, 2050, Scenario A1B Mean Protect Developed Dry Land



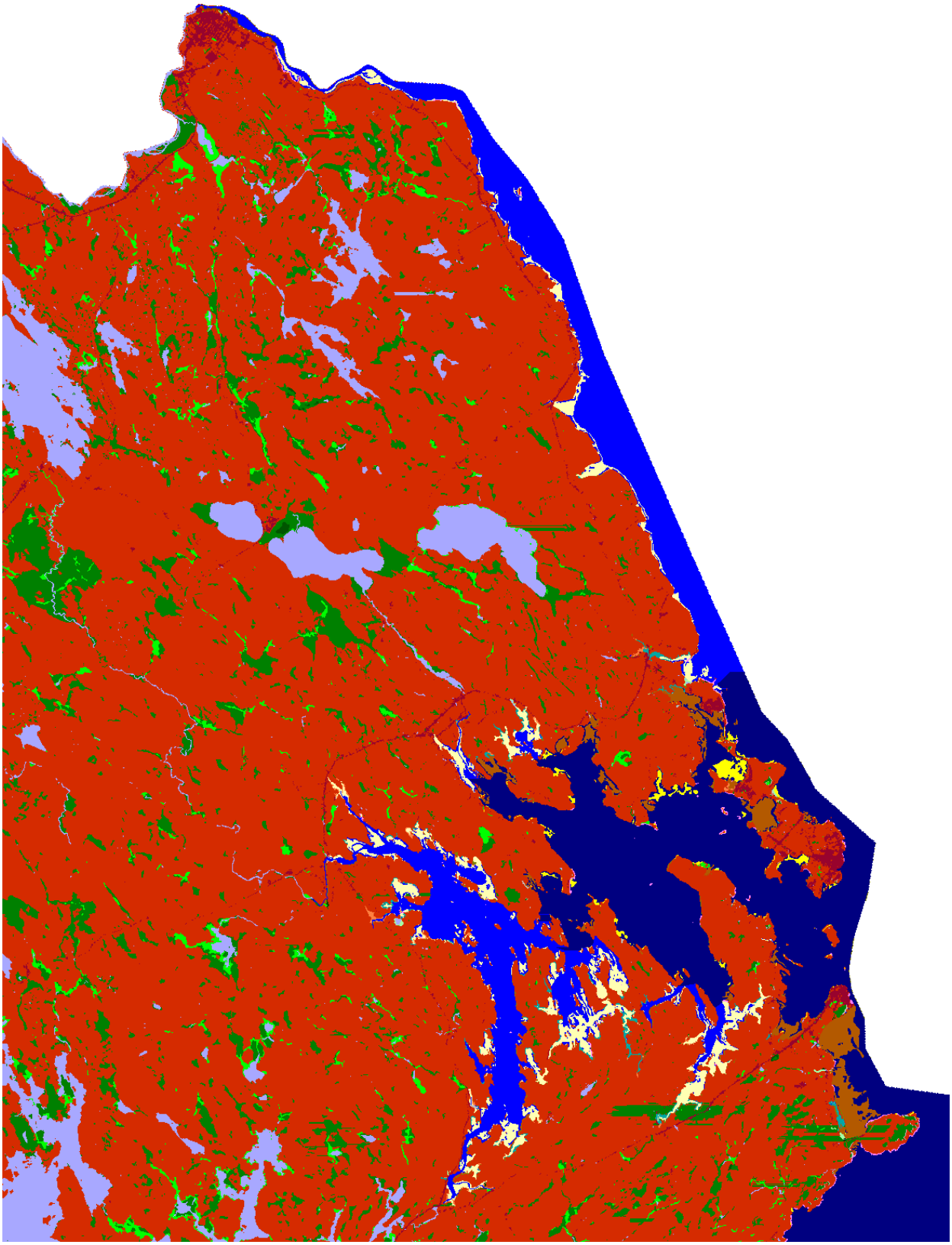
Moosehorn NWR, 2075, Scenario A1B Mean Protect Developed Dry Land



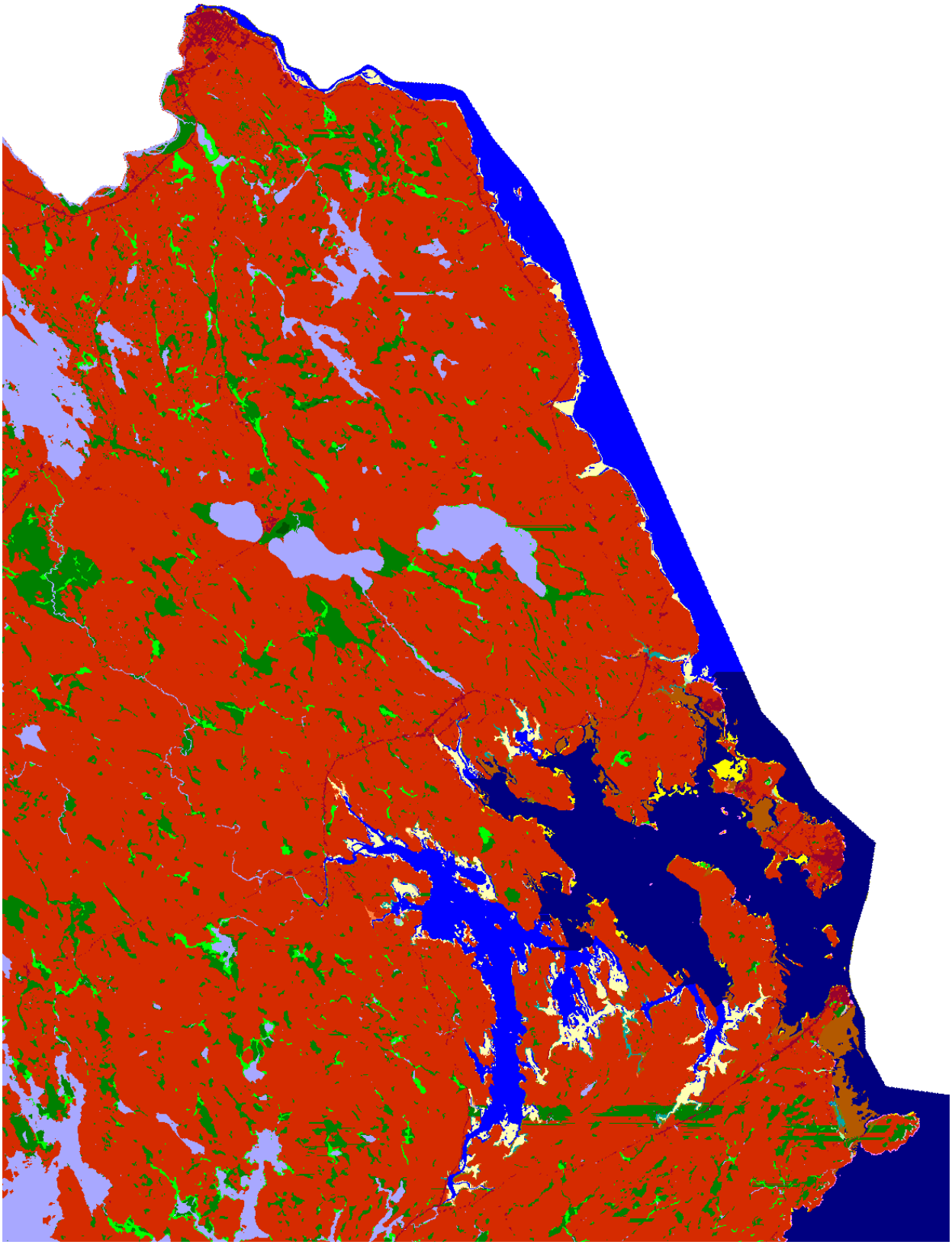
Moosehorn NWR, 2100, Scenario A1B Mean Protect Developed Dry Land



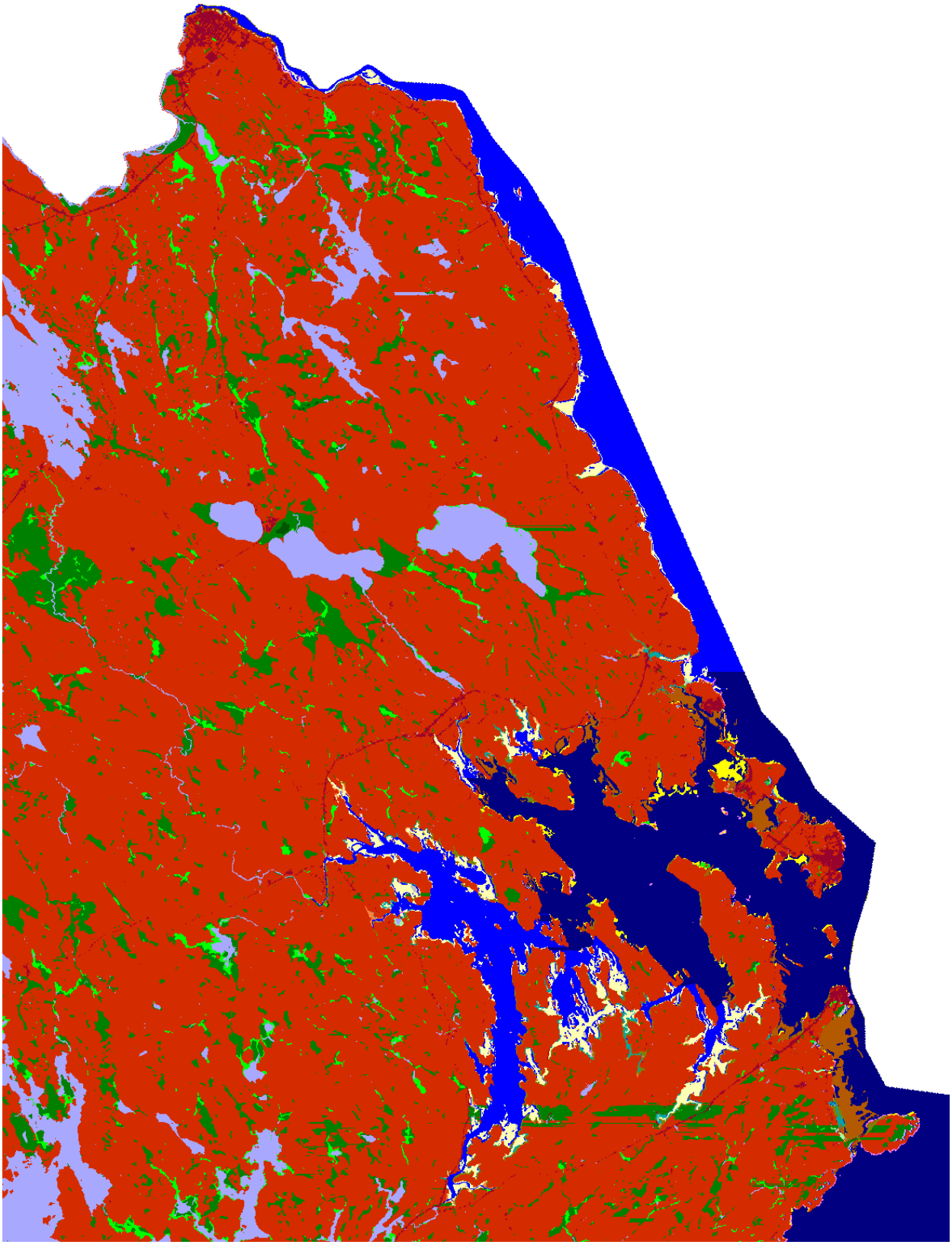
Moosehorn NWR, Initial Condition



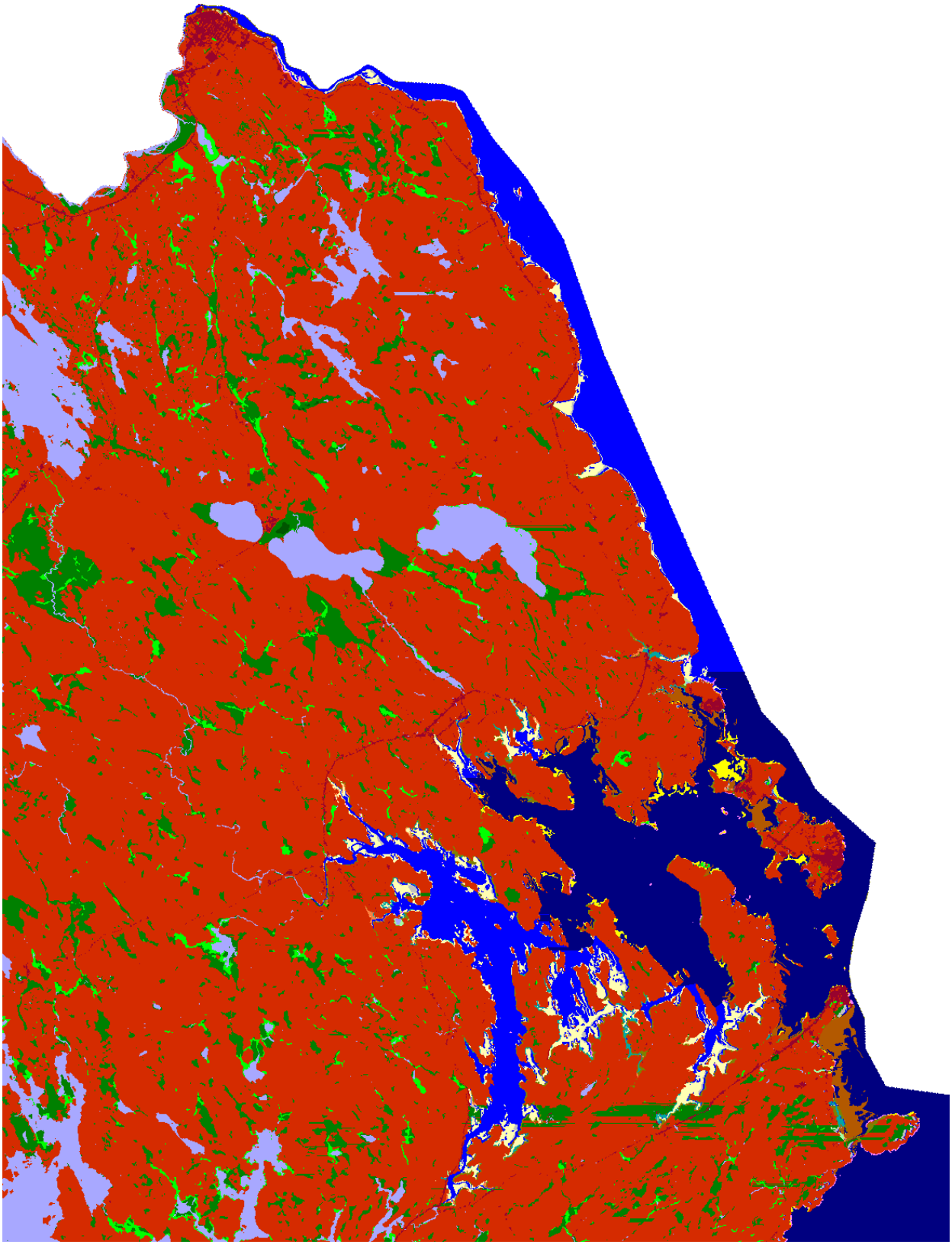
Moosehorn NWR, 2025, Scenario A1B Maximum Protect Developed Dry Land



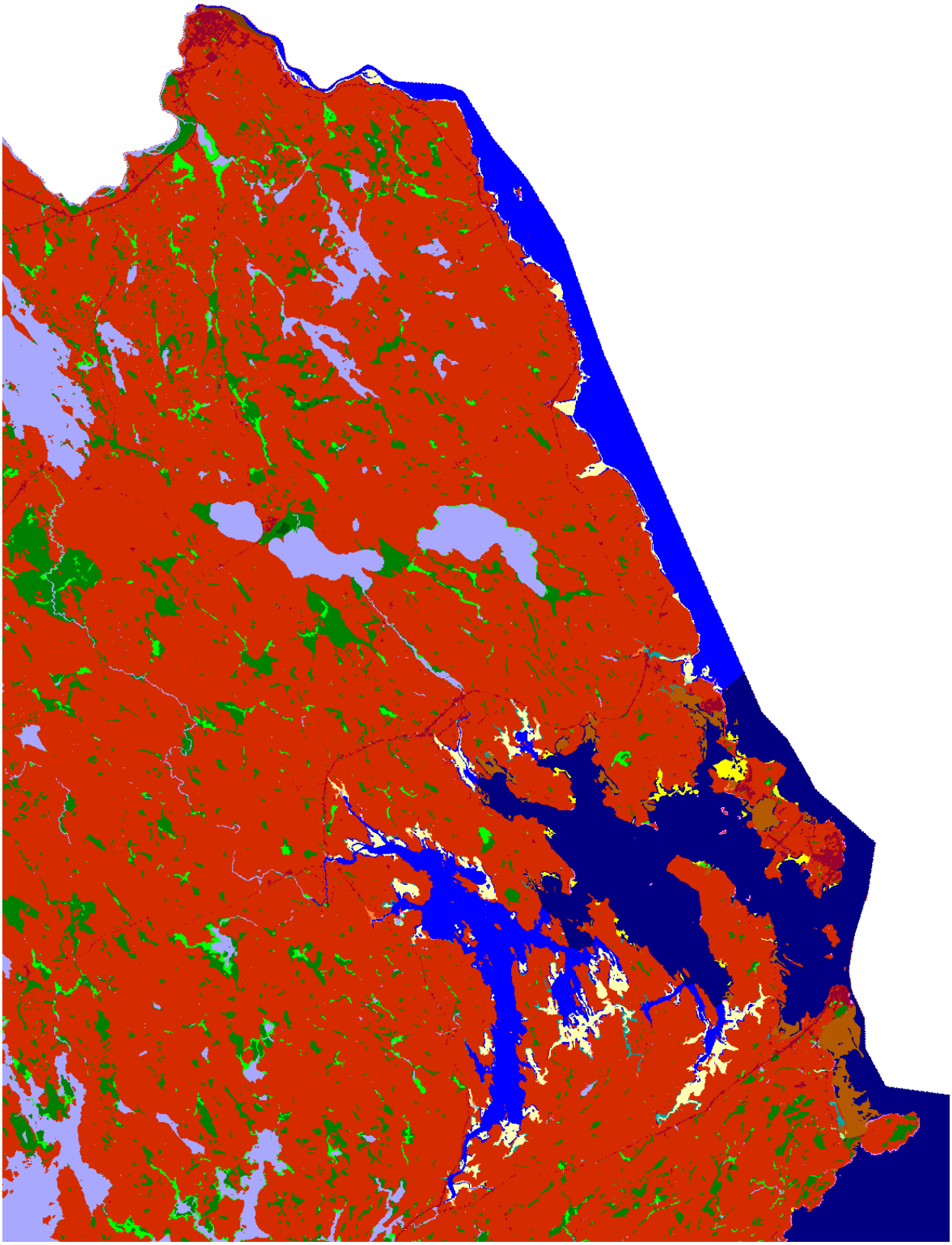
Moosehorn NWR, 2050, Scenario A1B Maximum Protect Developed Dry Land



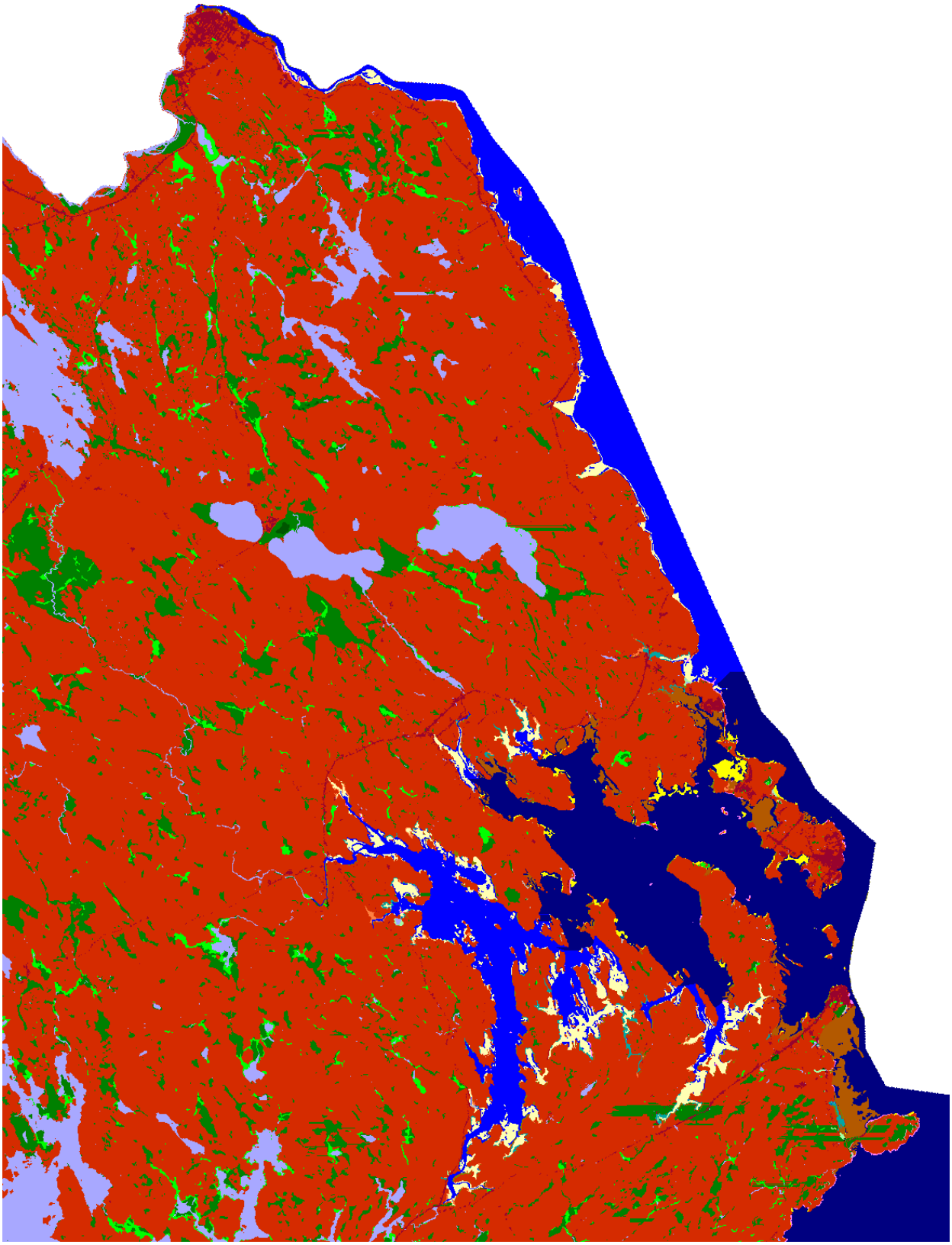
Moosehorn NWR, 2075, Scenario A1B Maximum Protect Developed Dry Land



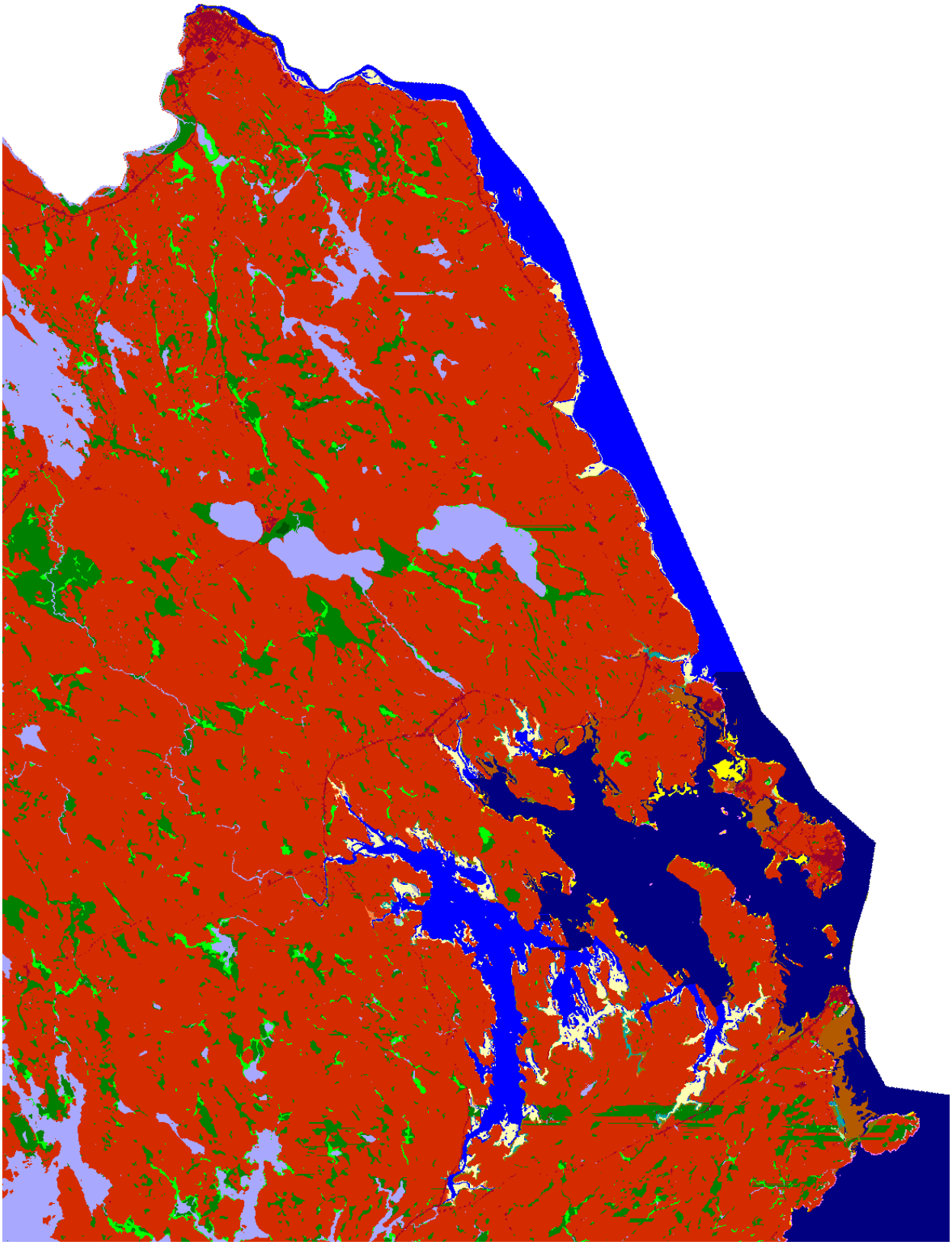
Moosehorn NWR, 2100, Scenario A1B Maximum Protect Developed Dry Land



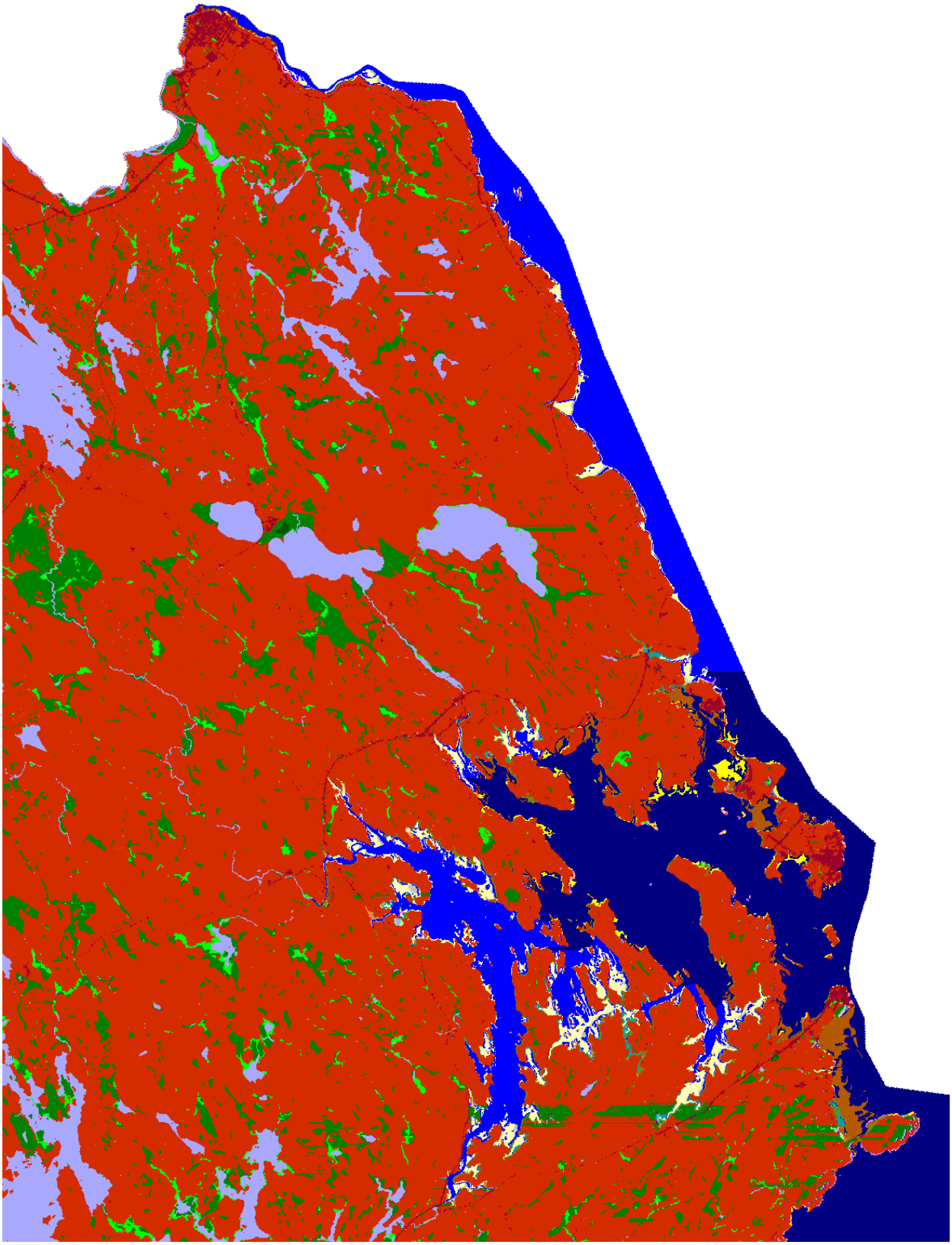
Moosehorn NWR, Initial Condition



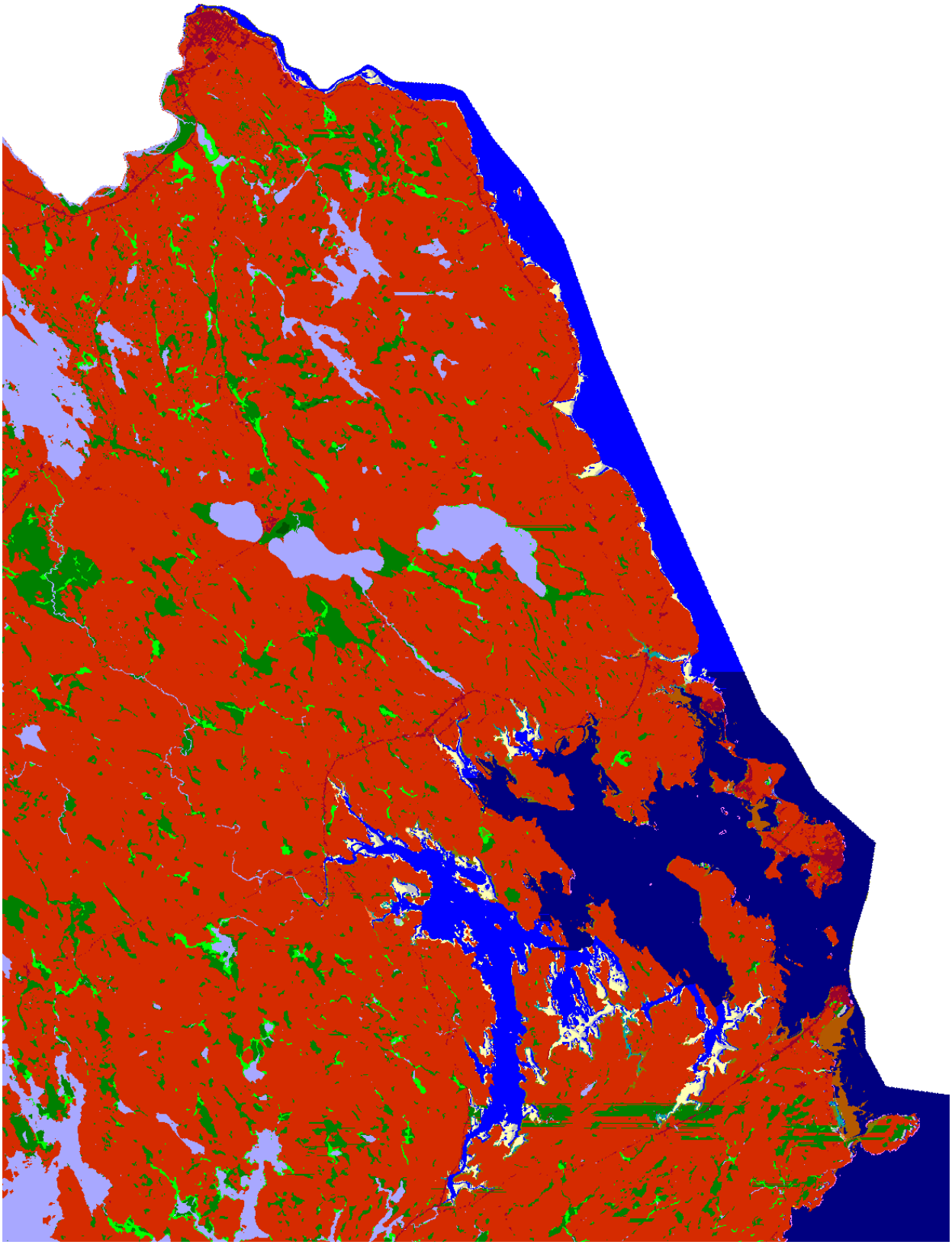
Moosehorn NWR, 2025, 1 meter Protect Developed Dry Land



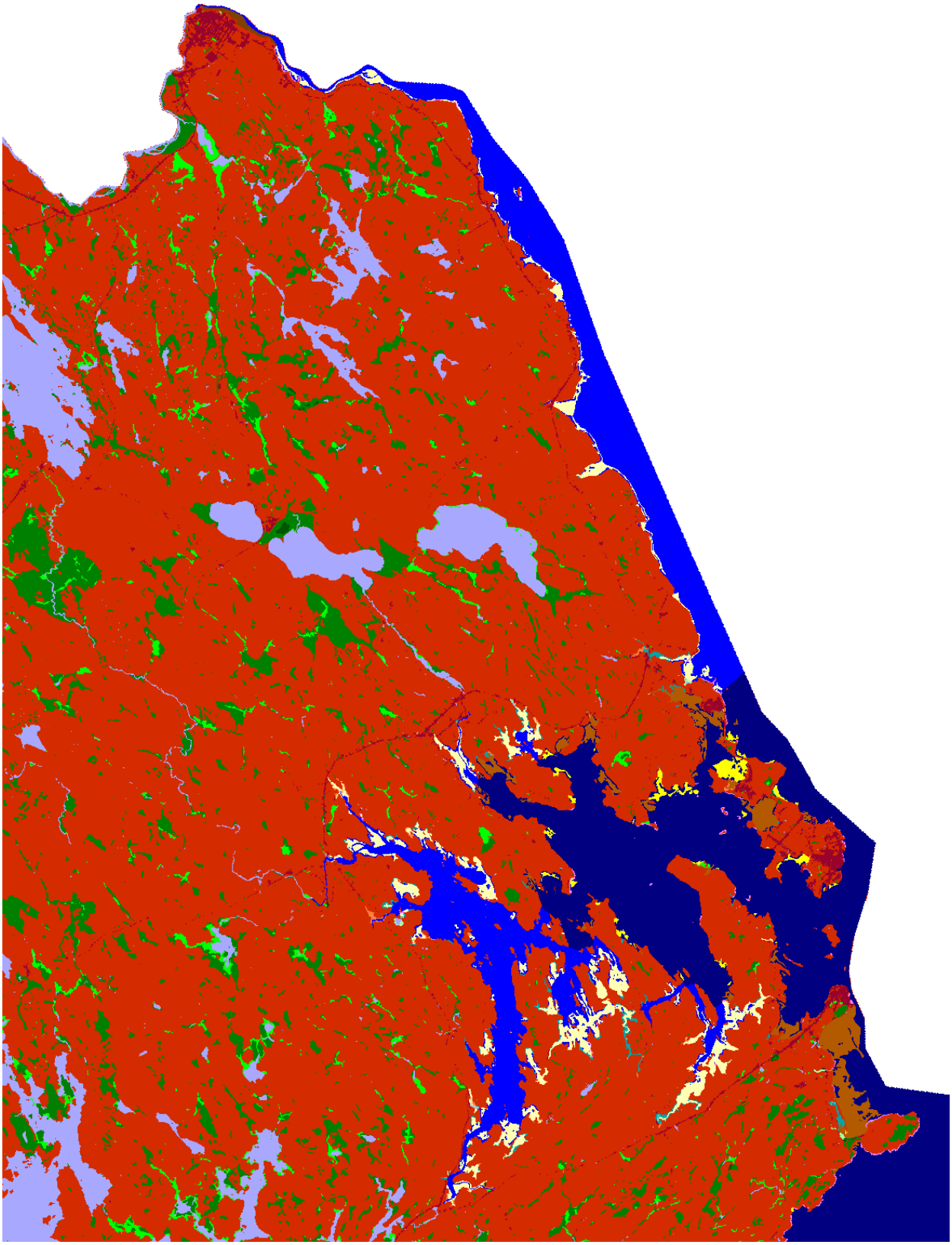
Moosehorn NWR, 2050, 1 meter Protect Developed Dry Land



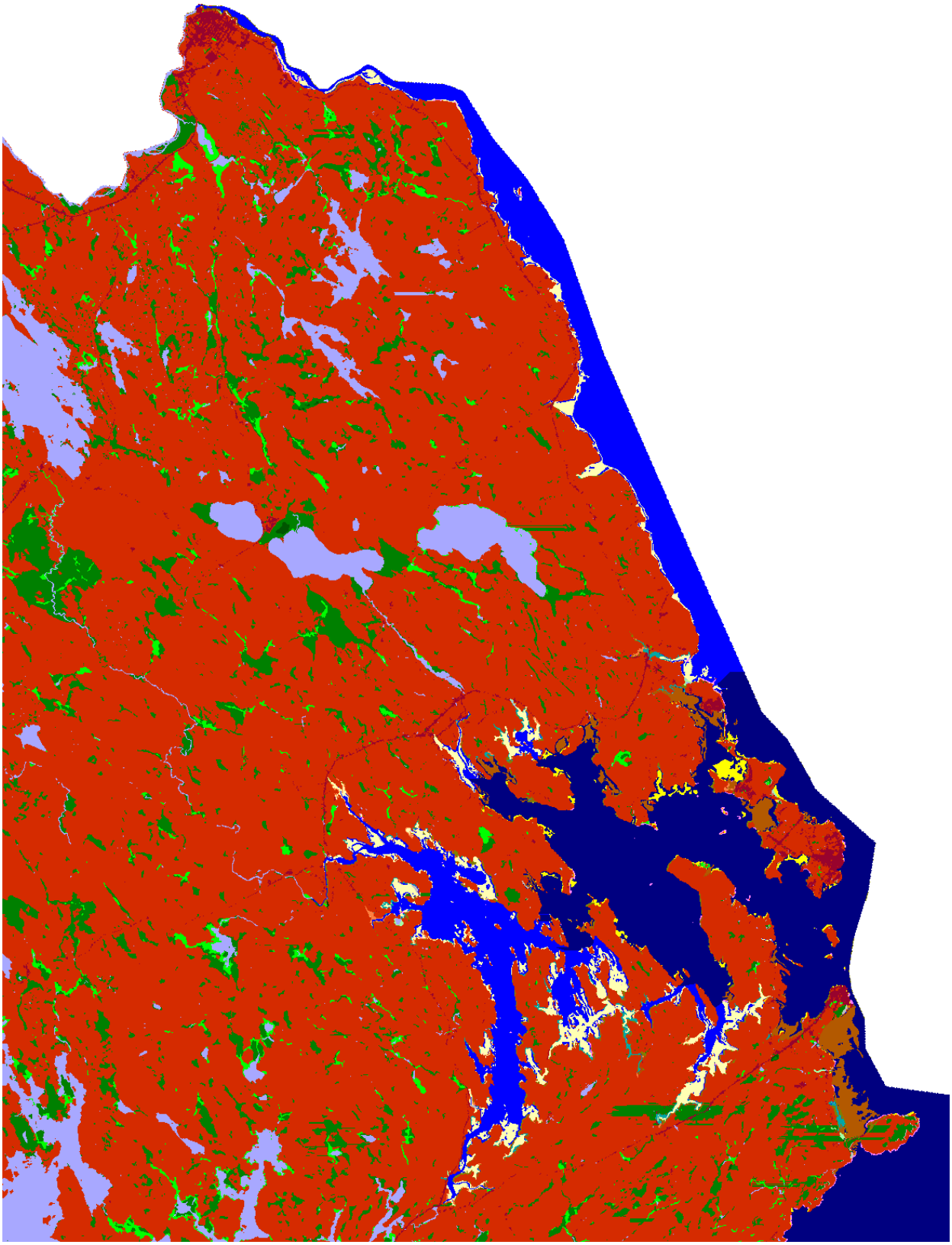
Moosehorn NWR, 2075, 1 meter Protect Developed Dry Land



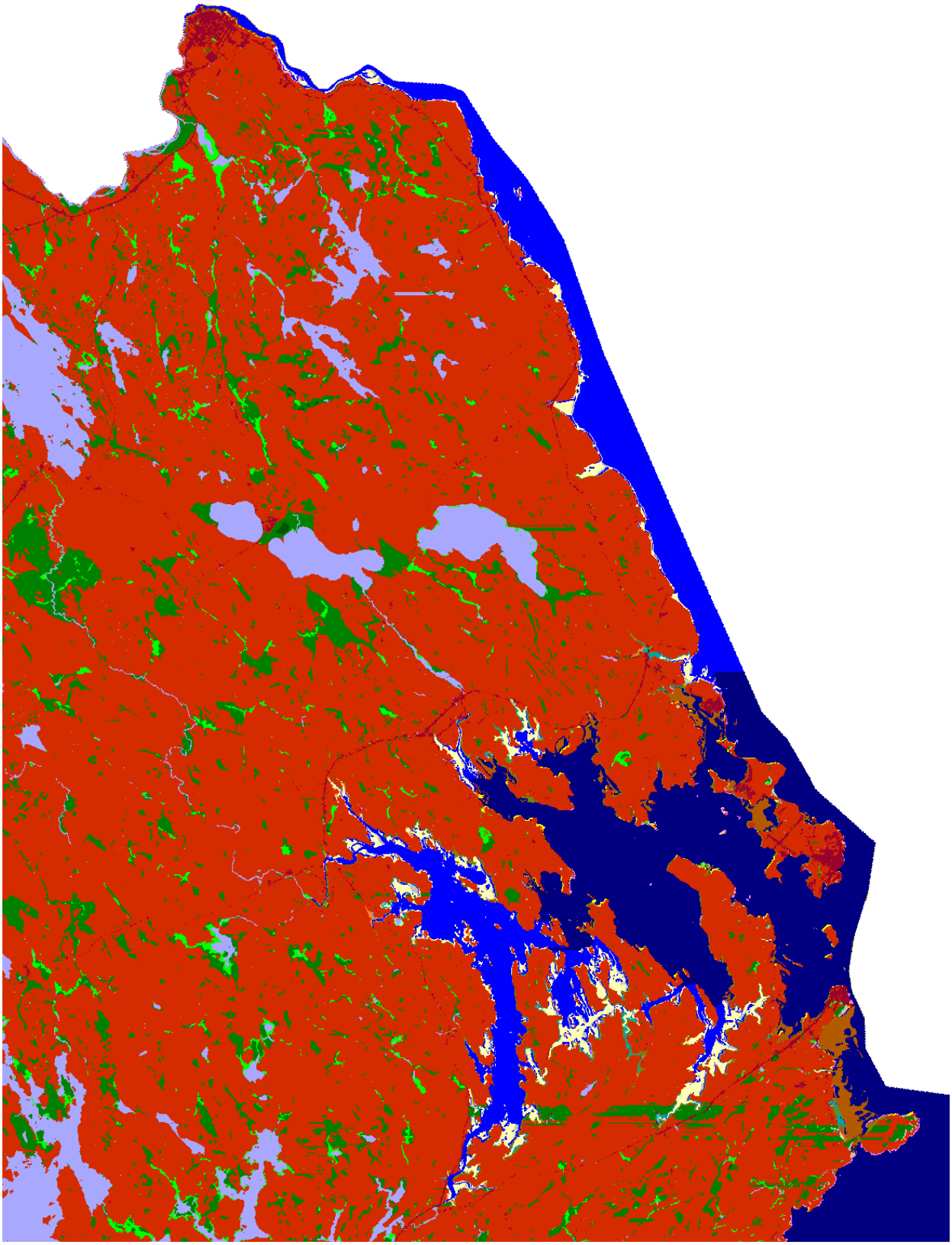
Moosehorn NWR, 2100, 1 meter Protect Developed Dry Land



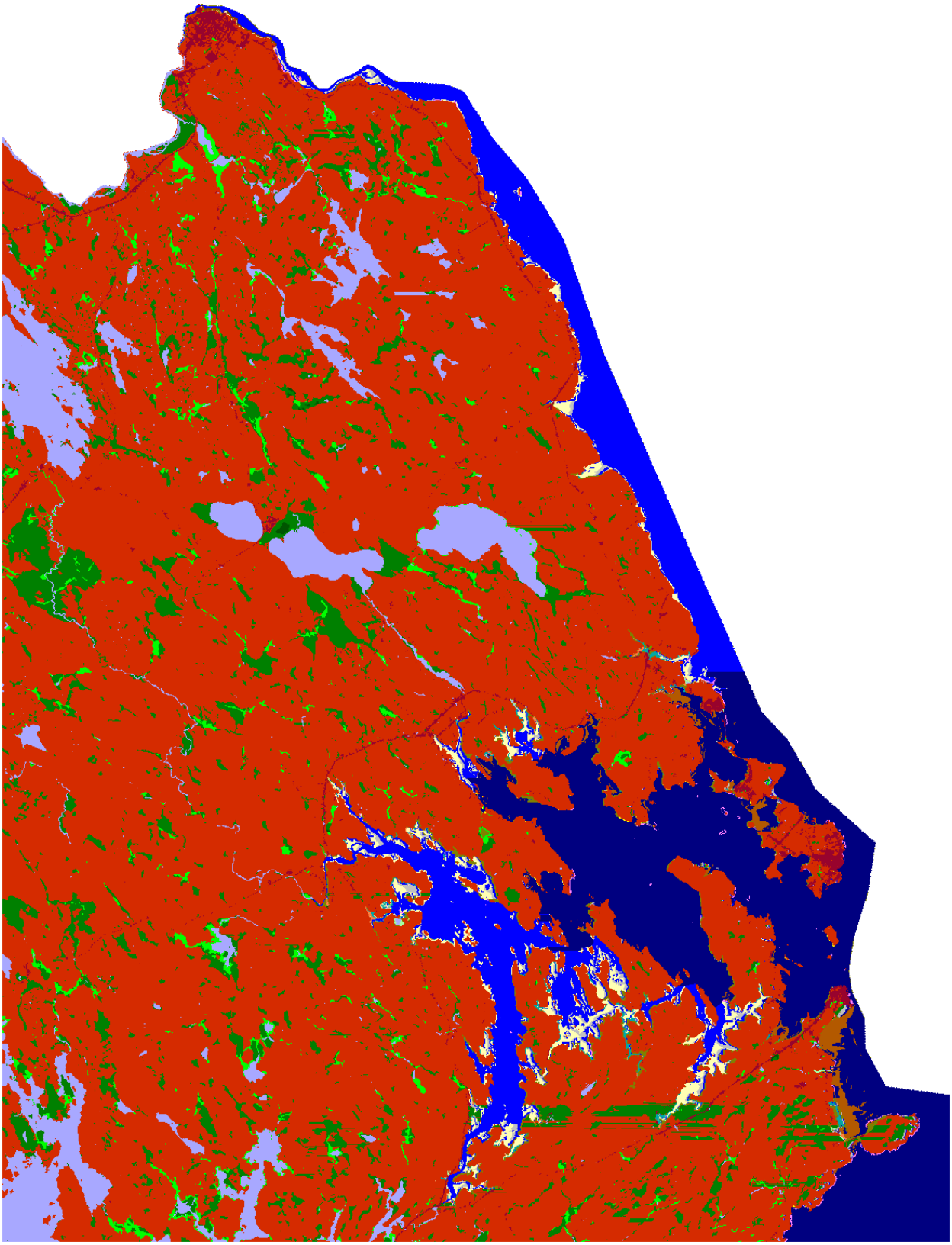
Moosehorn NWR, Initial Condition



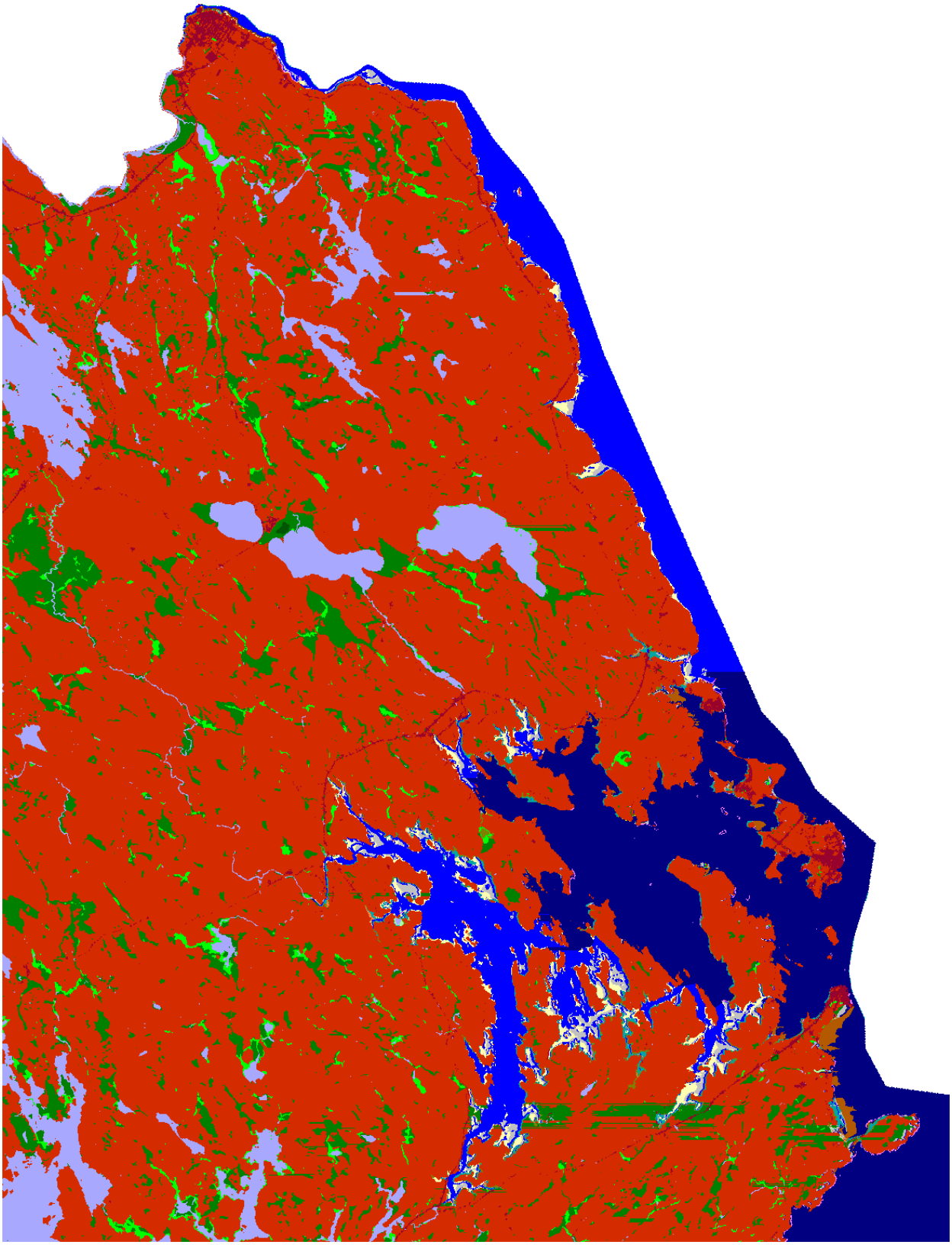
Moosehorn NWR, 2025, 1.5 meter Protect Developed Dry Land



Moosehorn NWR, 2050, 1.5 meter Protect Developed Dry Land



Moosehorn NWR, 2075, 1.5 meter Protect Developed Dry Land



Moosehorn NWR, 2100, 1.5 meter Protect Developed Dry Land