Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to James Campbell 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. 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 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 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 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 or can be specified to respond to feedbacks such as frequency of inundation.

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 confirm the SLAMM conceptual model at each site.
- 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.

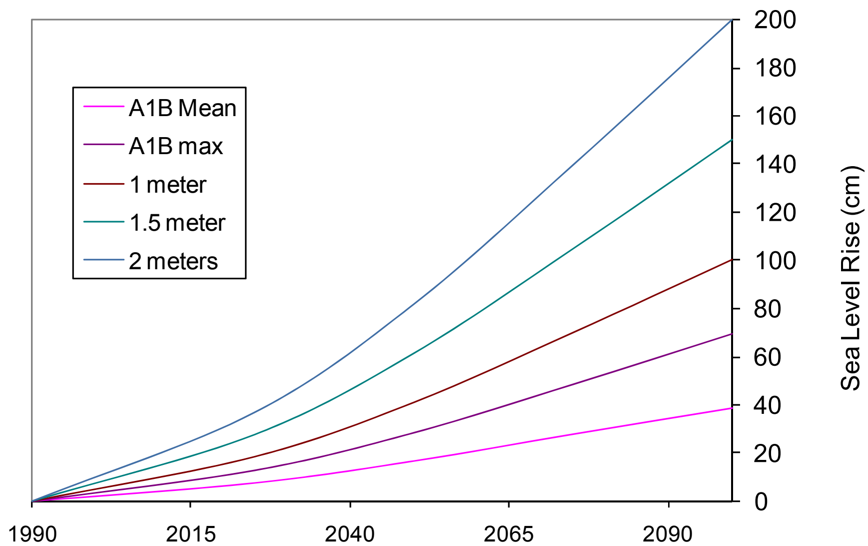
Sea Level Rise Scenarios

SLAMM 6 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 scenario assumes that the future world includes very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. In particular, the A1B scenario assumes that energy sources will be balanced across all sources. Under the A1B scenario, the IPCC WGI Fourth Assessment Report (IPC, 2007) suggests a likely range of 0.21 to 0.48 meters of sea level rise by 2090-2099 “excluding future rapid dynamical changes in ice flow.” The A1B-mean scenario that was run as a part of this project falls near the middle of this estimated range, predicting 0.40 meters of global sea level rise by 2100.

The latest literature (Chen et al., 2006, Monaghan et al., 2006) indicates that the eustatic rise in sea levels is progressing more rapidly than was previously assumed, perhaps due to the dynamic changes in ice flow omitted within the IPCC report's calculations. A recent paper in the journal *Science* (Rahmstorf, 2007) suggests that, taking into account possible model error, a feasible range by 2100 might be 50 to 140 cm. This work was recently updated and the ranges were increased to 75 to 190 cm (Vermeer and Rahmstorf, 2009). Pfeffer et al. (2008) suggests that 2 meters by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. A recent US intergovernmental report states "Although no ice-sheet model is currently capable of capturing the glacier speedups in Antarctica or Greenland that have been observed over the last decade, including these processes in models will very likely show that IPCC AR4 projected sea level rises for the end of the 21st century are too low." (US Climate Change Science Program, 2008) A recent paper by Grinsted et. al. (2009) states that "sea level 2090-2099 is projected to be 0.9 to 1.3 m for the A1B scenario, with low probability of the rise being within Intergovernmental Panel on Climate Change (IPCC) confidence limits."

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 meter, 1½ meters, and 2 meters of eustatic sea-level rise by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 1).

Figure 1: Summary of SLR Scenarios Utilized



Methods and Data Sources

The digital elevation map used in this simulation was supplied by FEMA (Federal Emergency Management Agency) and is based on high-resolution LiDAR with a 2007 photo date (Figure 1).

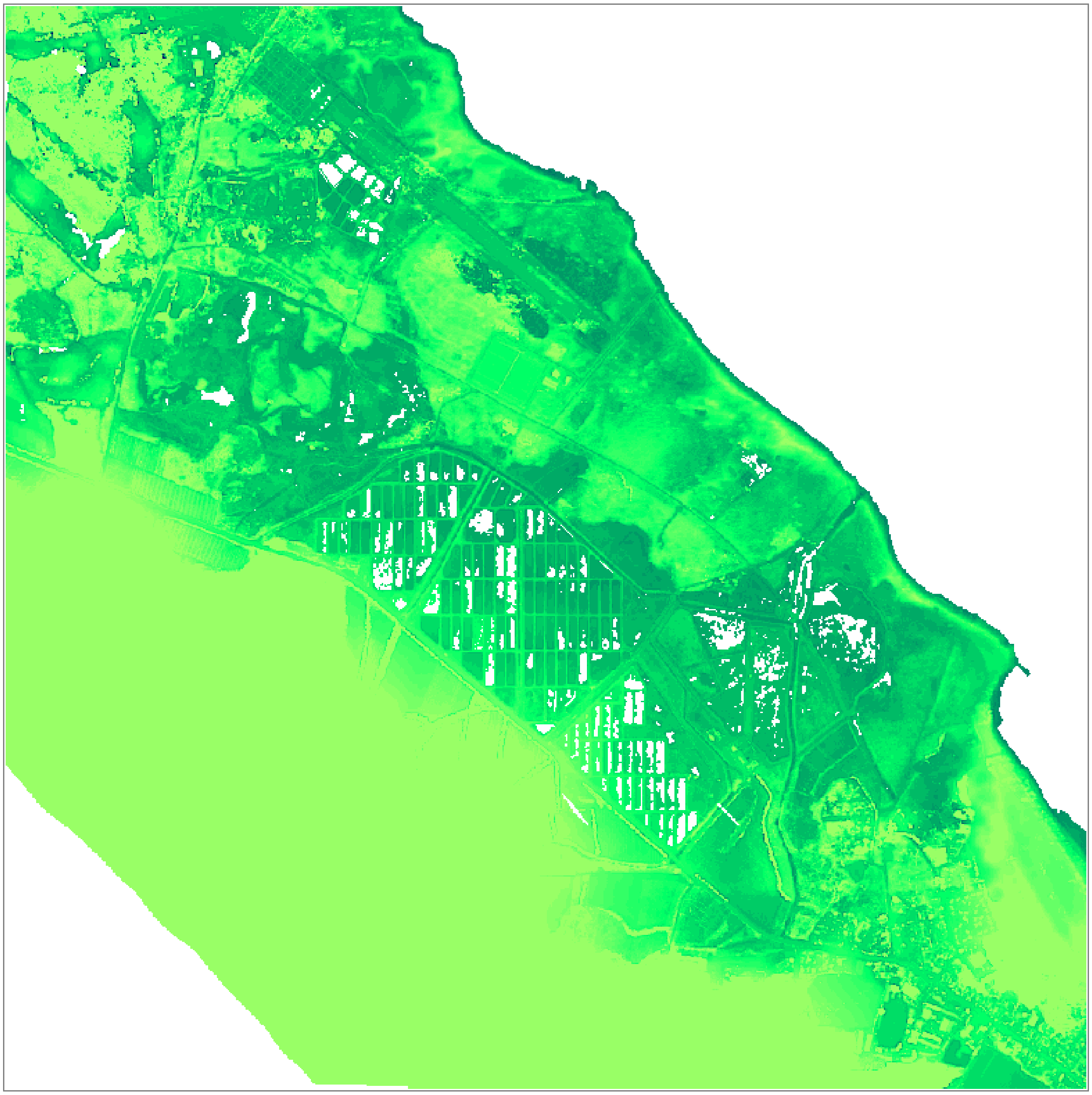


Figure 1: James Campbell elevation map as produced by SLAMM. Lower elevations are darker.

The wetlands layer for the study area was produced by the National Wetlands Inventory and is based on a 2005 photo date. Converting the NWI survey into 5 meter cells indicates that the approximately one thousand acre refuge (approved acquisition boundary including water) is composed of primarily the following categories:

Undeveloped Dry Land	62.3%
Inland Fresh Marsh	18.2%
Inland Open Water	11.9%
Developed Dry Land	5.7%
Riverine Tidal	1.1%

A large quantity of the inland fresh marsh in the Ki'i Unit of the refuge is diked, along with the shrimp ponds between the Ki'I and Punamano Units. Refer to Figure 2 for the dike coverage.

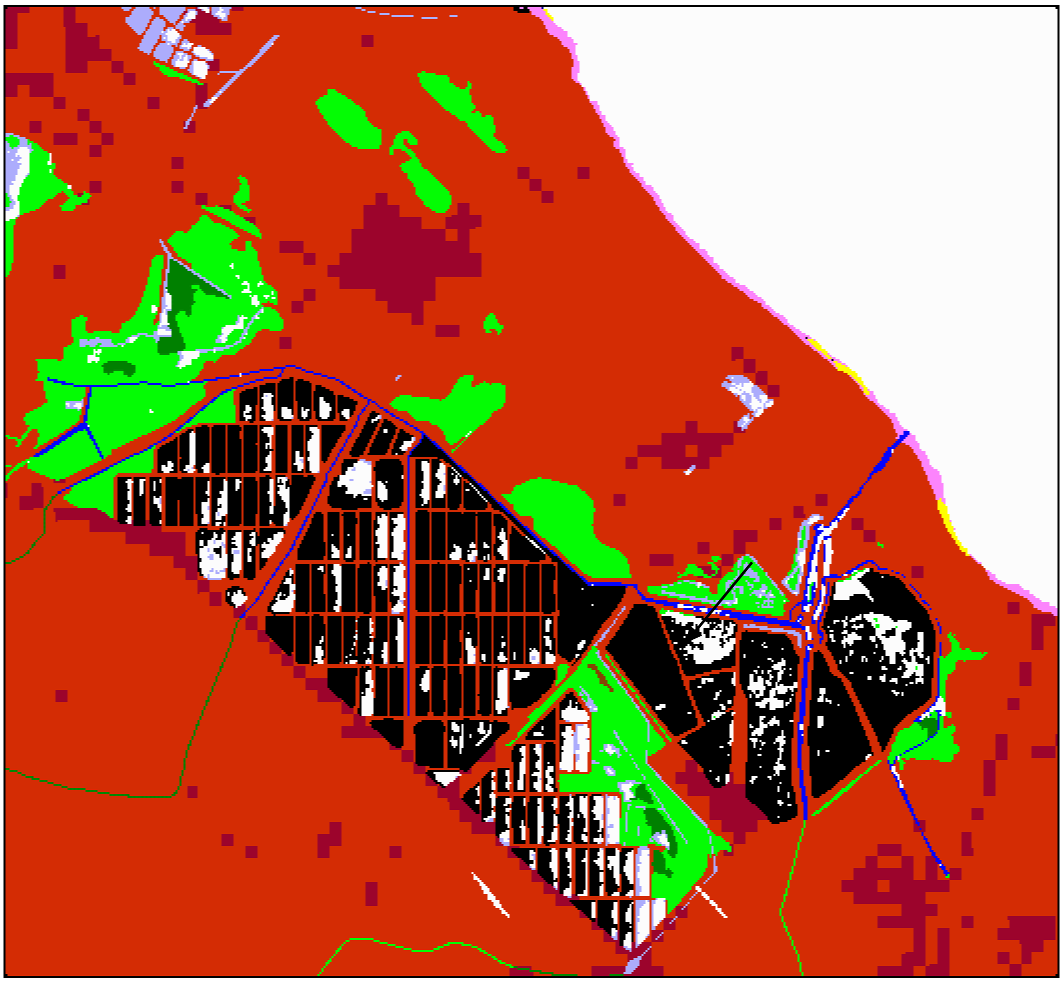


Figure 2: Dike layer in black. White artifacts are areas with no elevation data.

The historic trend for sea level rise was estimated at 1.31 mm/year using the nearest NOAA gage with historic SLR data (1612480, Mokuoloe, HI). The rate of sea level rise for this refuge is similar to the global average for the last 100 years (approximately 1.7 mm/year).

The tide range was estimated at 0.588 meters (great diurnal range or GT) using the closest NOAA tide gage (1612668, Haleiwa, Waialua Bay, Oahu Is, HI).

Studies of vertical accretion or erosion of marshes within Hawaii were not available. Therefore, this model application utilized default parameter values. This assumption will only have minimal effects on model results, however, as there are no regularly flooded or irregularly flooded marshes in the site's initial condition.

No MTL to NAVD correction was required for this simulation because the vertical datum of the elevation data was not NAVD88 but Mean Sea Level. (SLAMM requires that elevation data be expressed in a tidal basis.)

Modeled U.S. Fish and Wildlife Service refuge boundaries for Hawaii 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 5 meter by 5 meter cells. Note that the SLAMM model will track partial conversion of cells based on elevation and slope.

The biologist for the USFWS Hawaii, Mike Silbernagle, indicated the large extent of impounded areas within the refuge. The final dike layer used in model simulation is more extensive than the dike layer provided by NWI. Mr. Silbernagle also noted the existence of a tide gate in the Ki'I Unit of the refuge (Figure 3 and Figure 4). The areas behind the tide gate were originally designated by NWI as riverine tidal, but considering the tide gate negates any tidal influence in these canals, they were re-designated to inland open water.

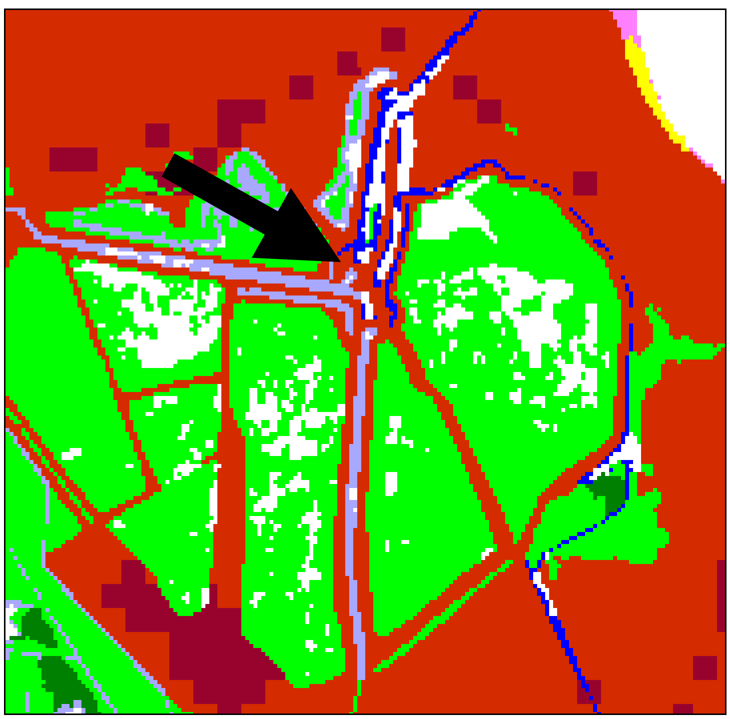


Figure 3: Location of tide gate as seen in SLAMM simulation.

Figure 4: Location of tide gate as seen in satellite image.

Due to immediate inundation of some dry lands during preliminary runs, an additional feature was added to the SLAMM model and utilized for these model runs. Within the refuge, some lands below the mean tide level were predicted to be subject to immediate saline inundation. These lands are actually protected by natural land contours producing protective barriers against the sea.

In response to this problem SLAMM now has an "eight sided" connectivity model in the manner of Poulter and Halpin, (2007). At each time-step, inland cells are examined to see if there is a connective channel (composed of land with elevations below the salt boundary) between the cell and the open water. This determines if high waters are able to flood those lands during the time-period in question. The new connectivity algorithm provided much better initial-condition fits for model data and was therefore utilized in the current model application.

In later years when sea level rises sufficiently to allow for water penetration over these natural levees, low lying areas become subject to inundation (for example, see the map for year 2100, Scenario A1B Maximum on page 21).

SUMMARY OF SLAMM INPUT PARAMETERS FOR JAMES CAMPBELL NWR

Parameter	**Global**
Description	James Campbell
NWI Photo Date (YYYY)	2005
DEM Date (YYYY)	2007
Direction Offshore [n,s,e,w]	East
Historic Trend (mm/yr)	1.31
MTL-NAVD88 (m)	0
GT Great Diurnal Tide Range (m)	0.588
Salt Elev. (m above MTL)	0.506
Marsh Erosion (horz. m /yr)	1.8
Swamp Erosion (horz. m /yr)	1
T.Flat Erosion (horz. m /yr)	2
Reg. Flood Marsh Accr (mm/yr)	3.9
Irreg. Flood Marsh Accr (mm/yr)	4.7
Tidal Fresh Marsh Accr (mm/yr)	5.9
Beach Sed. Rate (mm/yr)	0.5
Freq. Overwash (years)	0
Use Elev Pre-processor [True,False]	FALSE

Results

The SLAMM simulation of James Campbell NWR predicts non-diked areas to be vulnerable to the effects of sea level rise. Between 4% and 54% of refuge undeveloped dry land – which comprises the majority of the refuge -- is predicted to be lost across all sea level rise (SLR) scenarios. Between 5% and 62% of the refuge inland fresh marsh – which makes up around 20% of the refuge – is predicted to be lost across all SLR scenarios.

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Undeveloped Dry Land	4%	14%	24%	39%	54%
Inland Fresh Marsh	5%	21%	33%	48%	62%
Developed Dry Land	1%	6%	13%	23%	32%

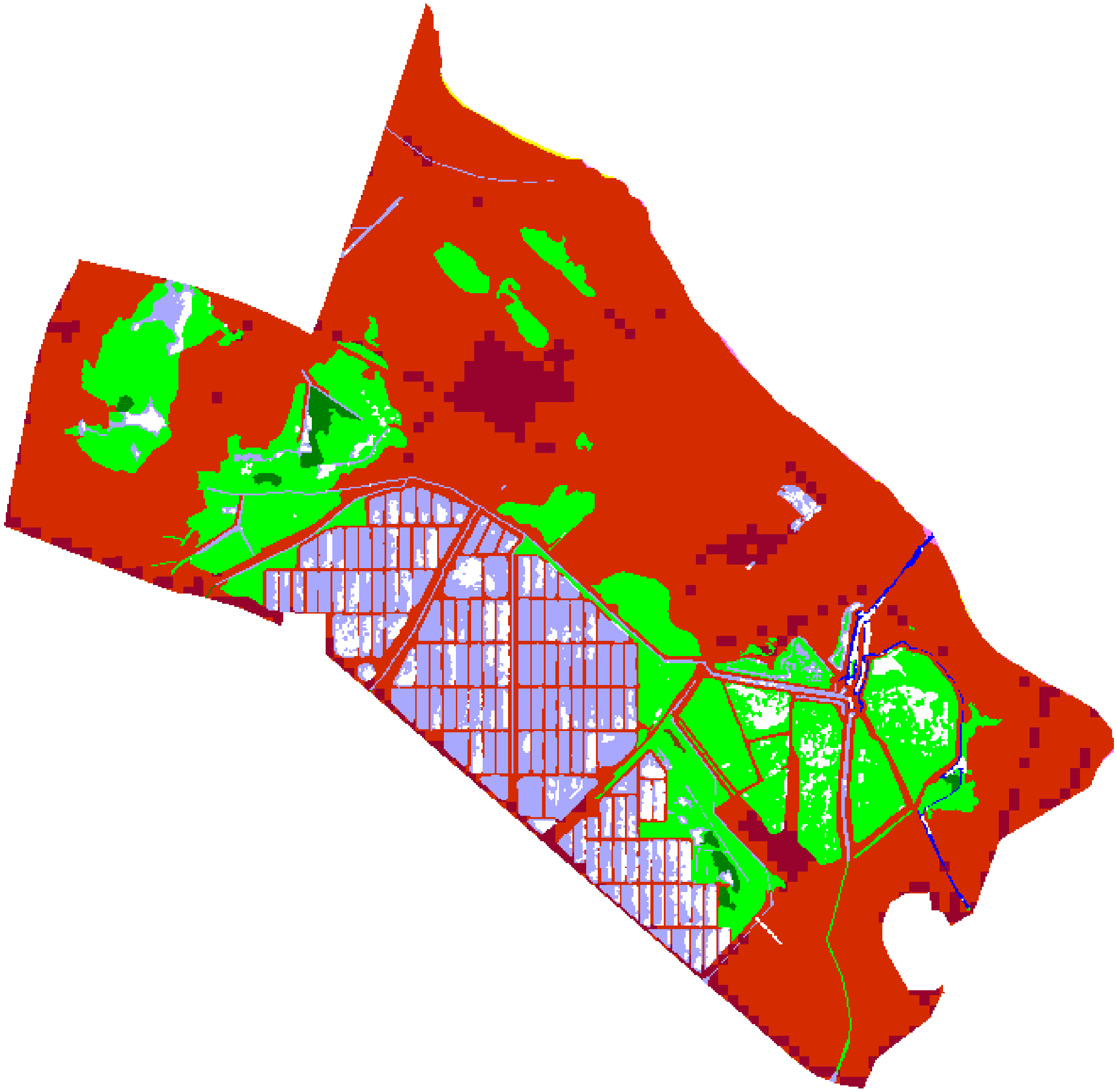
Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

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

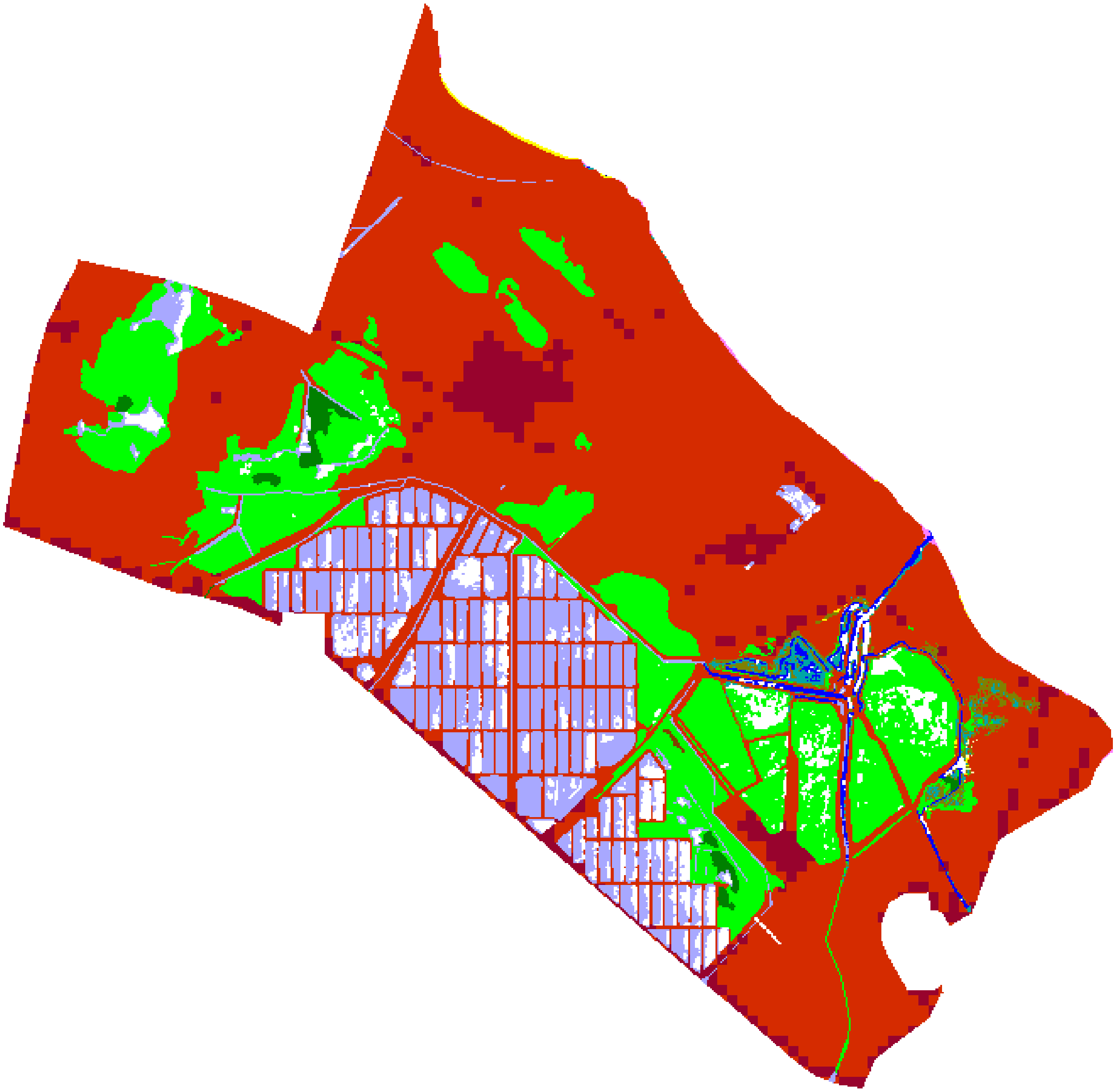
James Campbell Raster
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

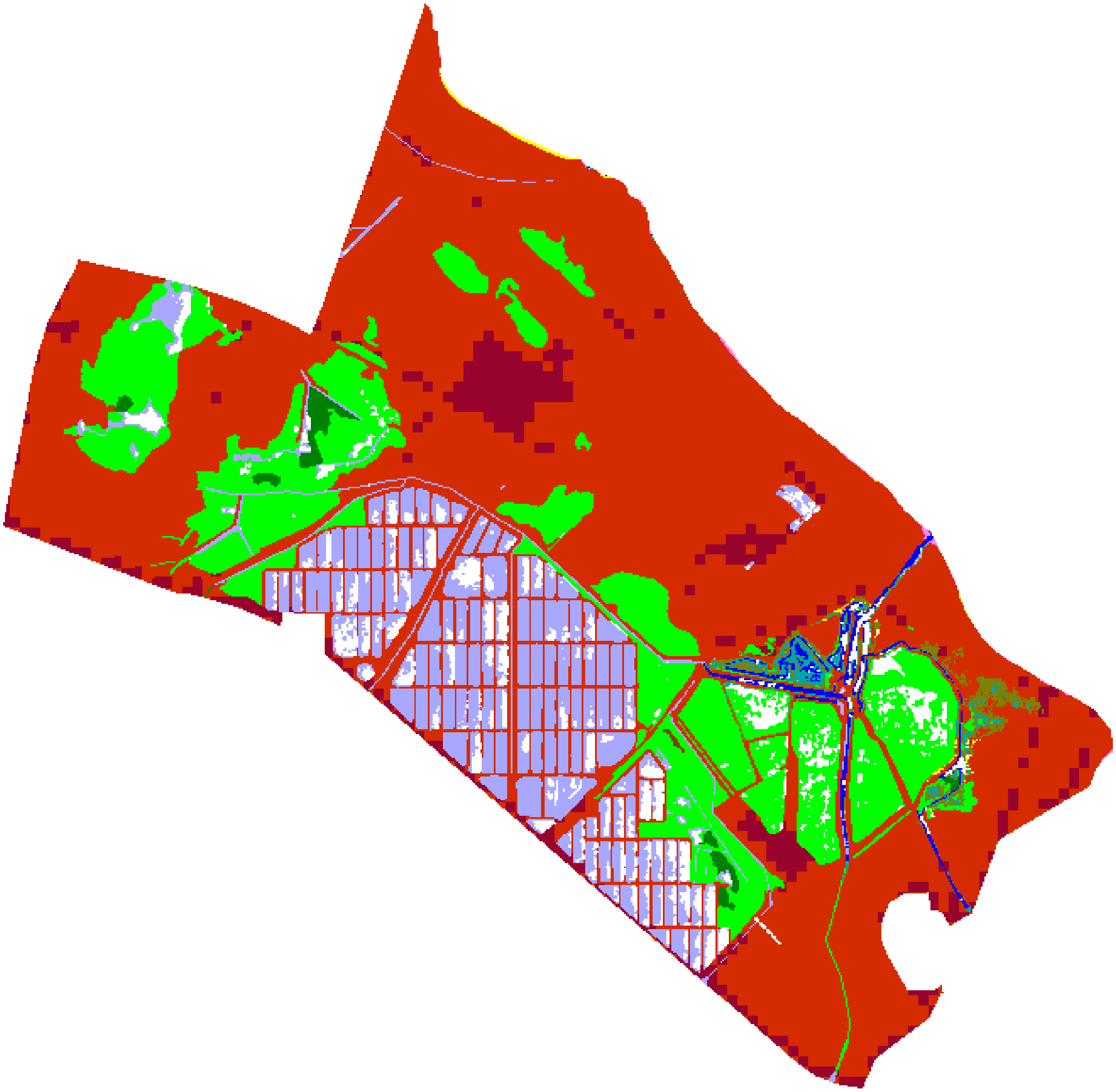
	Initial	2025	2050	2075	2100
Undeveloped Dry Land	647.5	639.0	636.1	630.5	620.0
Inland Fresh Marsh	189.4	182.3	181.8	180.8	171.2
Inland Open Water	132.0	127.2	127.2	127.0	126.5
Dev. Dry Land	58.8	58.6	58.5	58.3	57.9
Swamp	6.5	6.5	6.5	6.4	6.4
Riverine Tidal	3.0	1.2	1.0	0.6	0.3
Ocean Beach	0.9	1.1	1.4	1.8	2.6
Rocky Intertidal	0.7	0.7	0.7	0.7	0.7
Estuarine Open Water	0.4	7.1	7.4	8.1	9.6
Inland Shore	0.3	0.3	0.3	0.3	0.3
Saltmarsh	0.0	8.8	8.7	9.5	10.8
Trans. Salt Marsh	0.0	6.8	7.2	9.4	24.2
Tidal Flat	0.0	0.0	2.7	5.1	7.7
Estuarine Beach	0.0	0.1	0.3	1.2	1.5
Total (incl. water)	**1039.6**	**1039.6**	**1039.6**	**1039.6**	**1039.6**



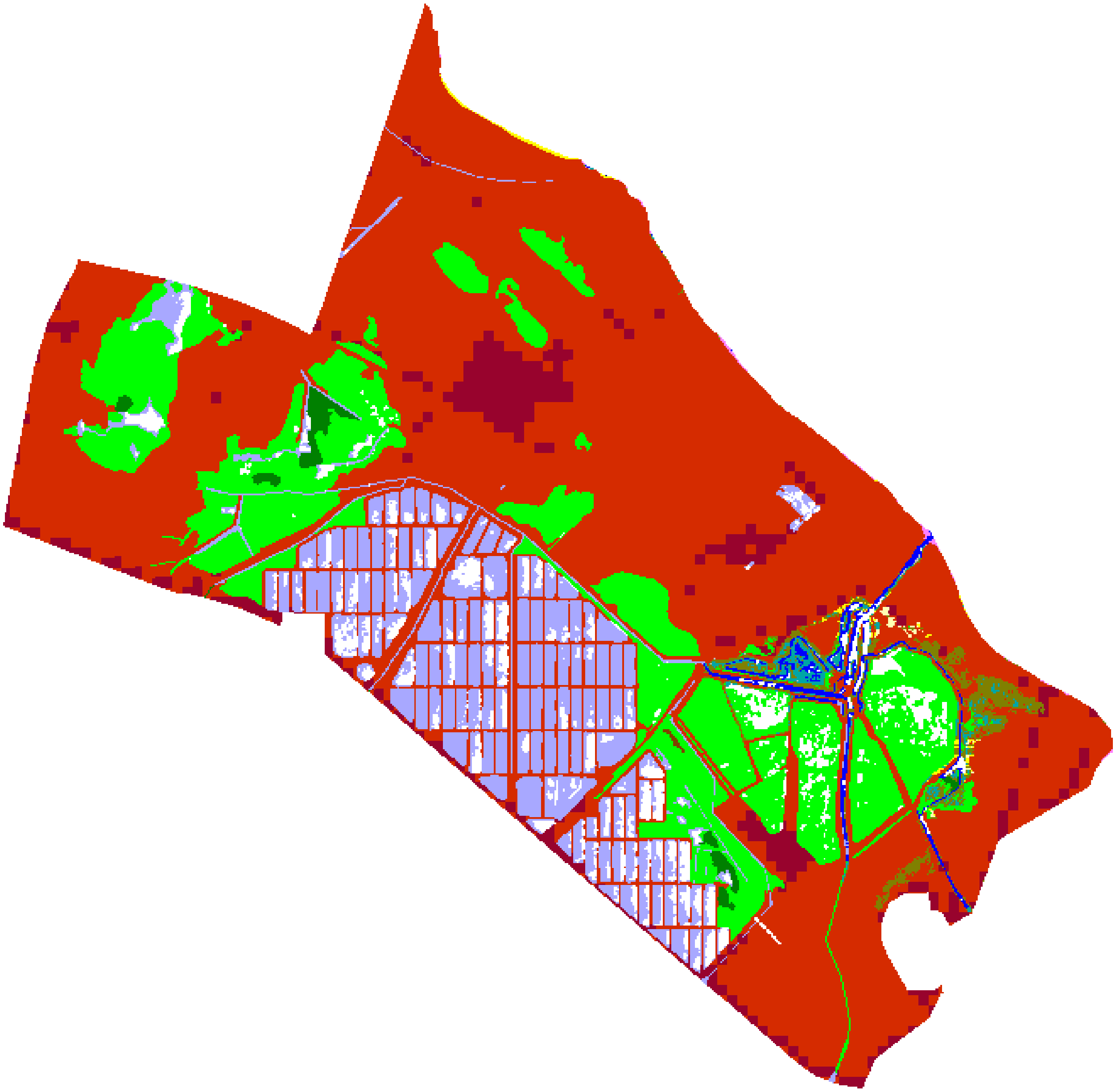
James Campbell NWR, Initial Condition



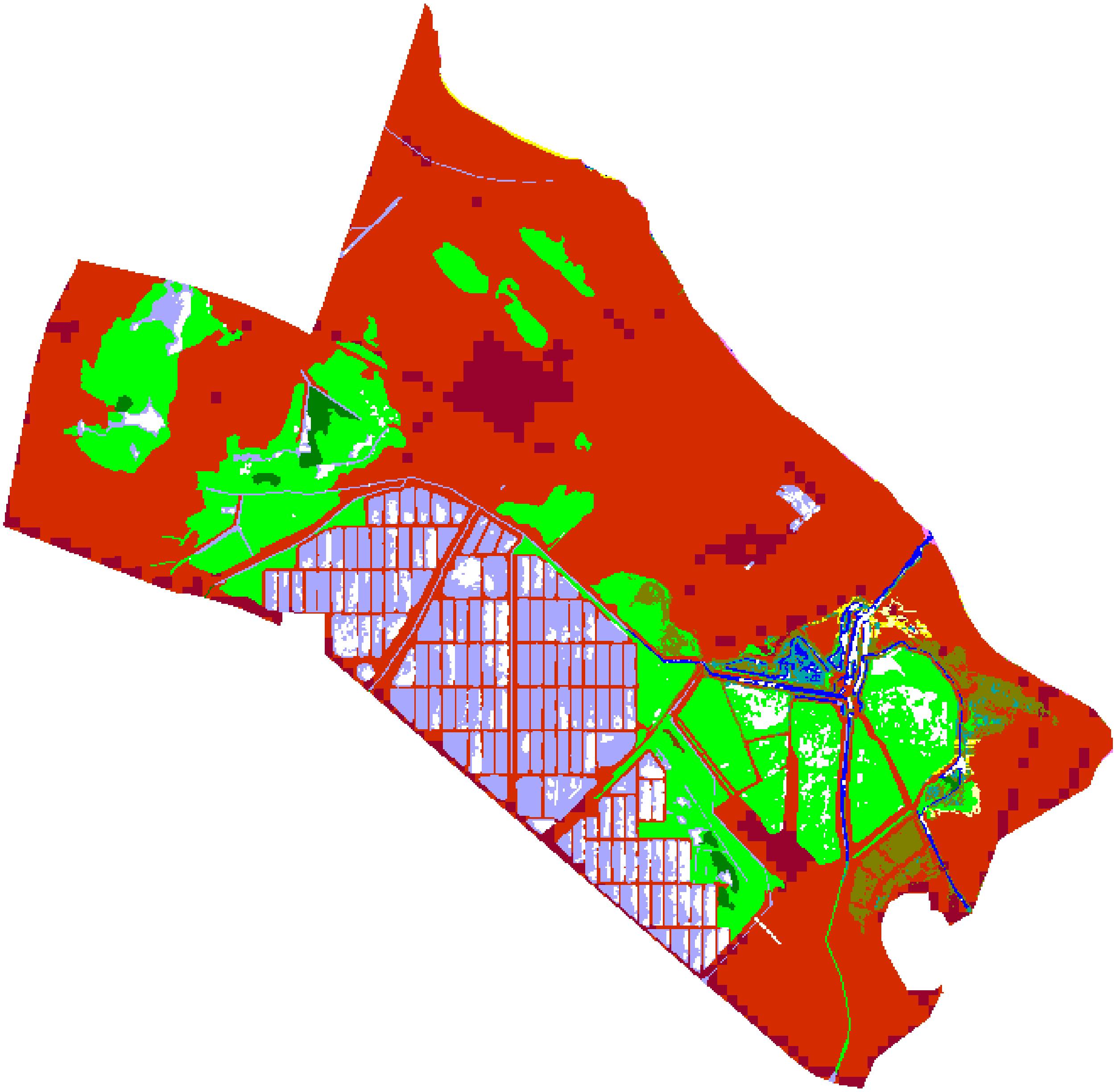
James Campbell NWR, 2025, Scenario A1B Mean



James Campbell NWR, 2050, Scenario A1B Mean



James Campbell NWR, 2075, Scenario A1B Mean

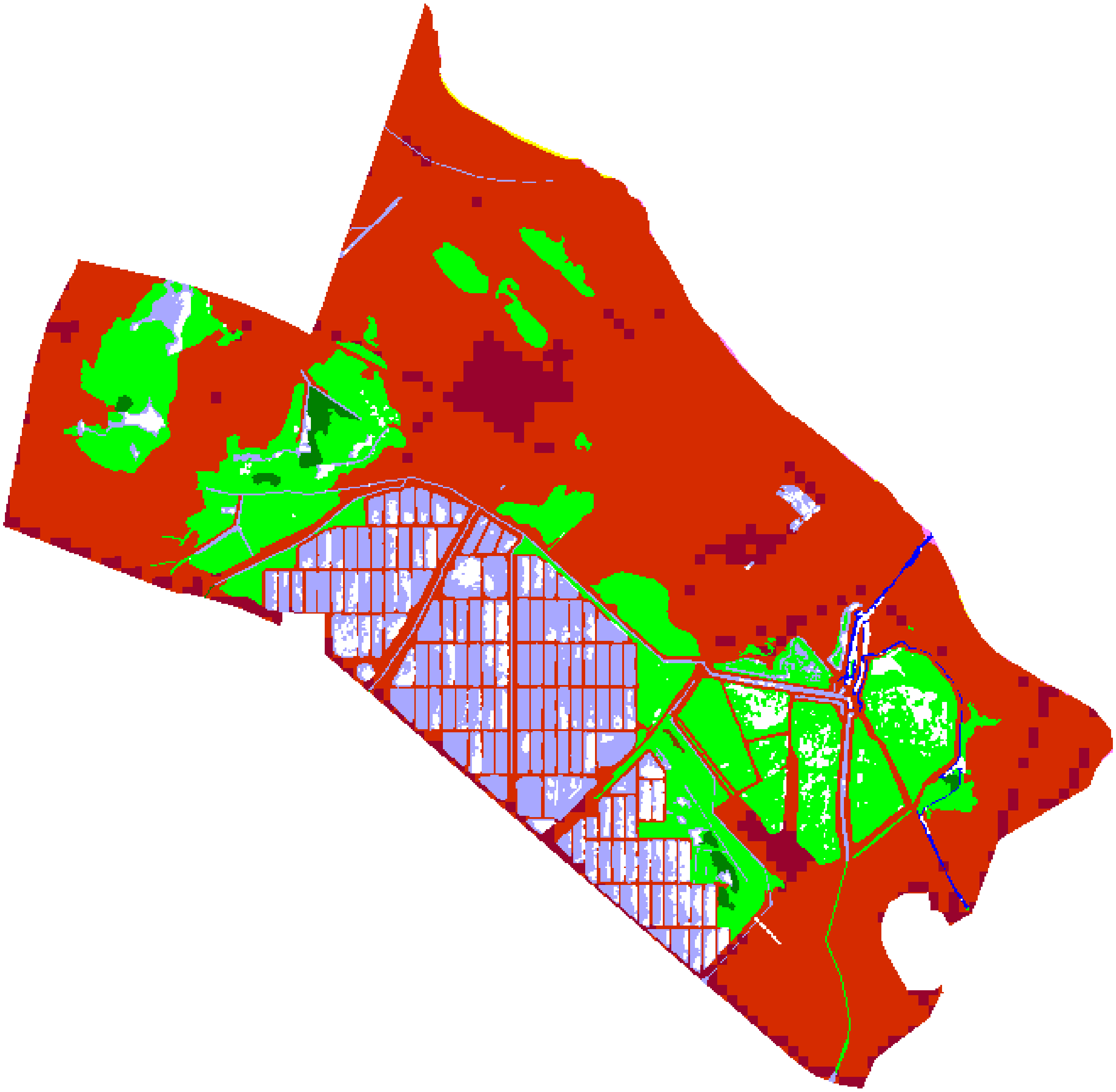


James Campbell NWR, 2100, Scenario A1B Mean

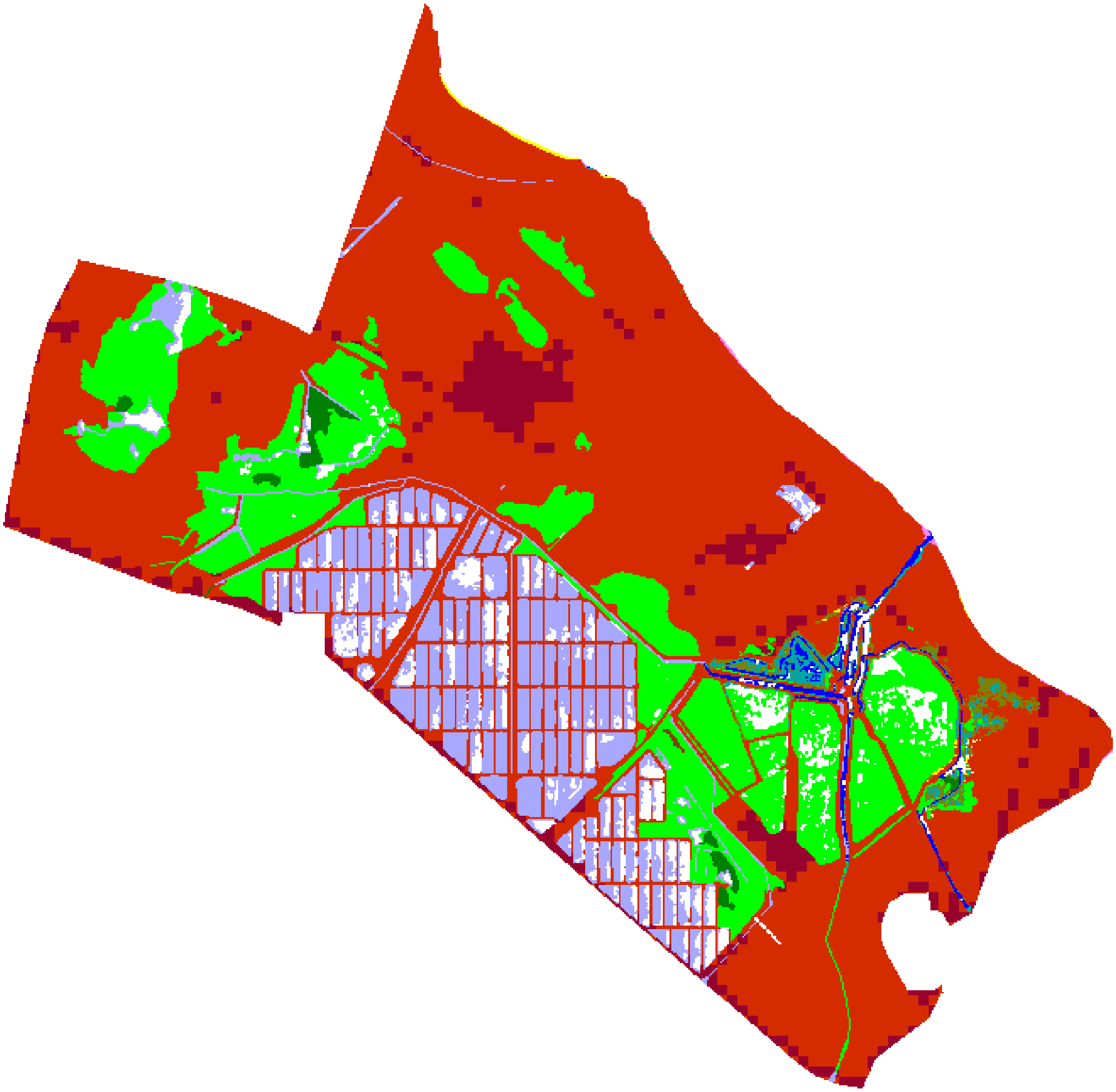
James Campbell Raster
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

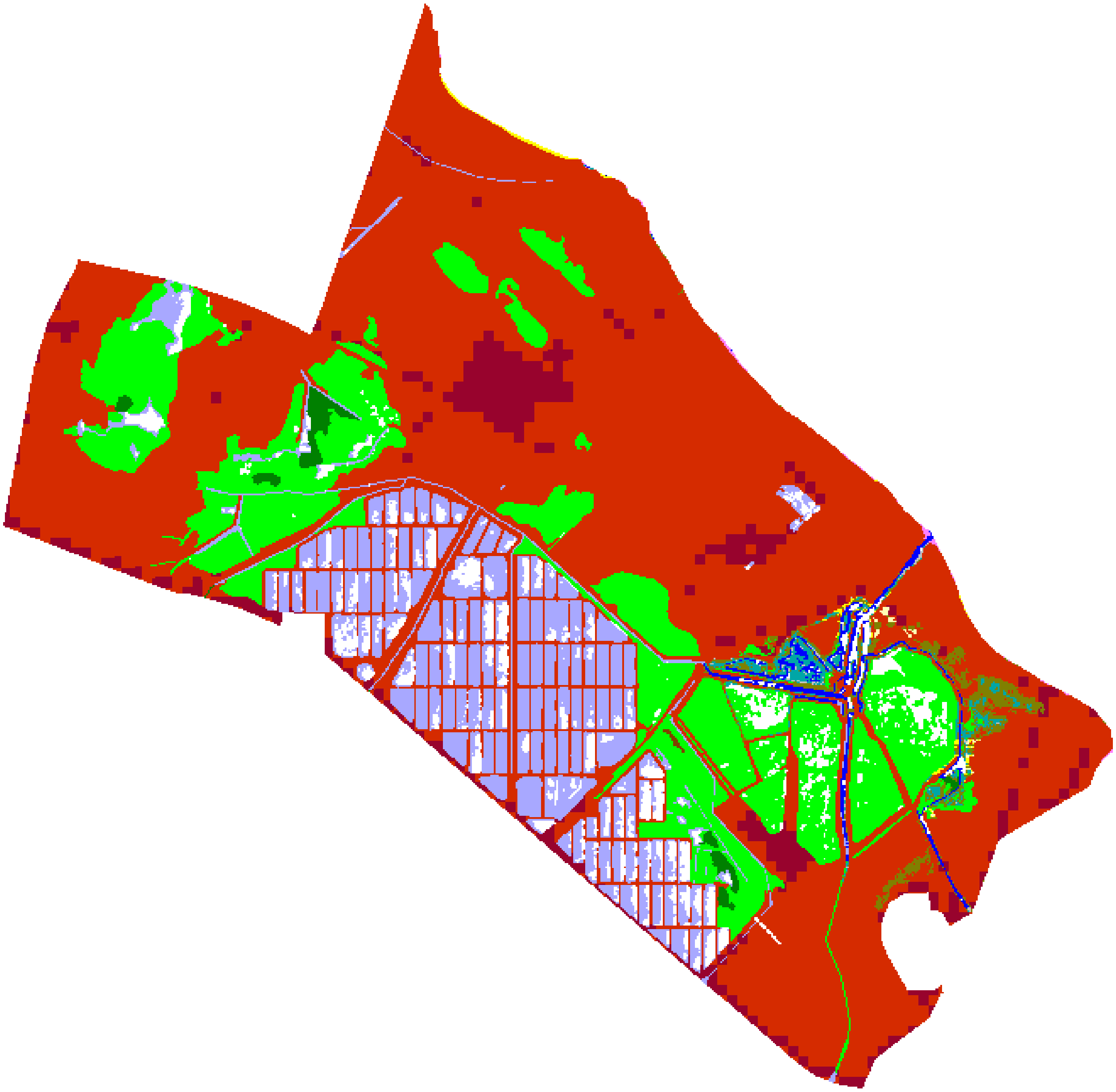
	Initial	2025	2050	2075	2100
Undeveloped Dry Land	647.5	638.0	630.8	603.1	551.8
Inland Fresh Marsh	189.4	182.2	180.9	167.5	116.4
Inland Open Water	132.0	127.2	127.0	126.3	125.3
Dev. Dry Land	58.8	58.6	58.4	57.1	55.0
Swamp	6.5	6.5	6.4	6.4	4.3
Riverine Tidal	3.0	1.1	0.7	0.3	0.1
Ocean Beach	0.9	1.3	1.6	2.9	4.7
Rocky Intertidal	0.7	0.7	0.7	0.6	0.6
Estuarine Open Water	0.4	7.2	7.8	11.3	18.0
Inland Shore	0.3	0.3	0.3	0.3	0.3
Saltmarsh	0.0	9.6	9.3	12.0	44.3
Trans. Salt Marsh	0.0	6.8	9.6	41.0	103.9
Tidal Flat	0.0	0.0	5.1	8.9	11.3
Estuarine Beach	0.0	0.2	1.0	1.9	3.4
Open Ocean	0.0	0.0	0.0	0.1	0.2
Total (incl. water)	**1039.6**	**1039.6**	**1039.6**	**1039.6**	**1039.6**



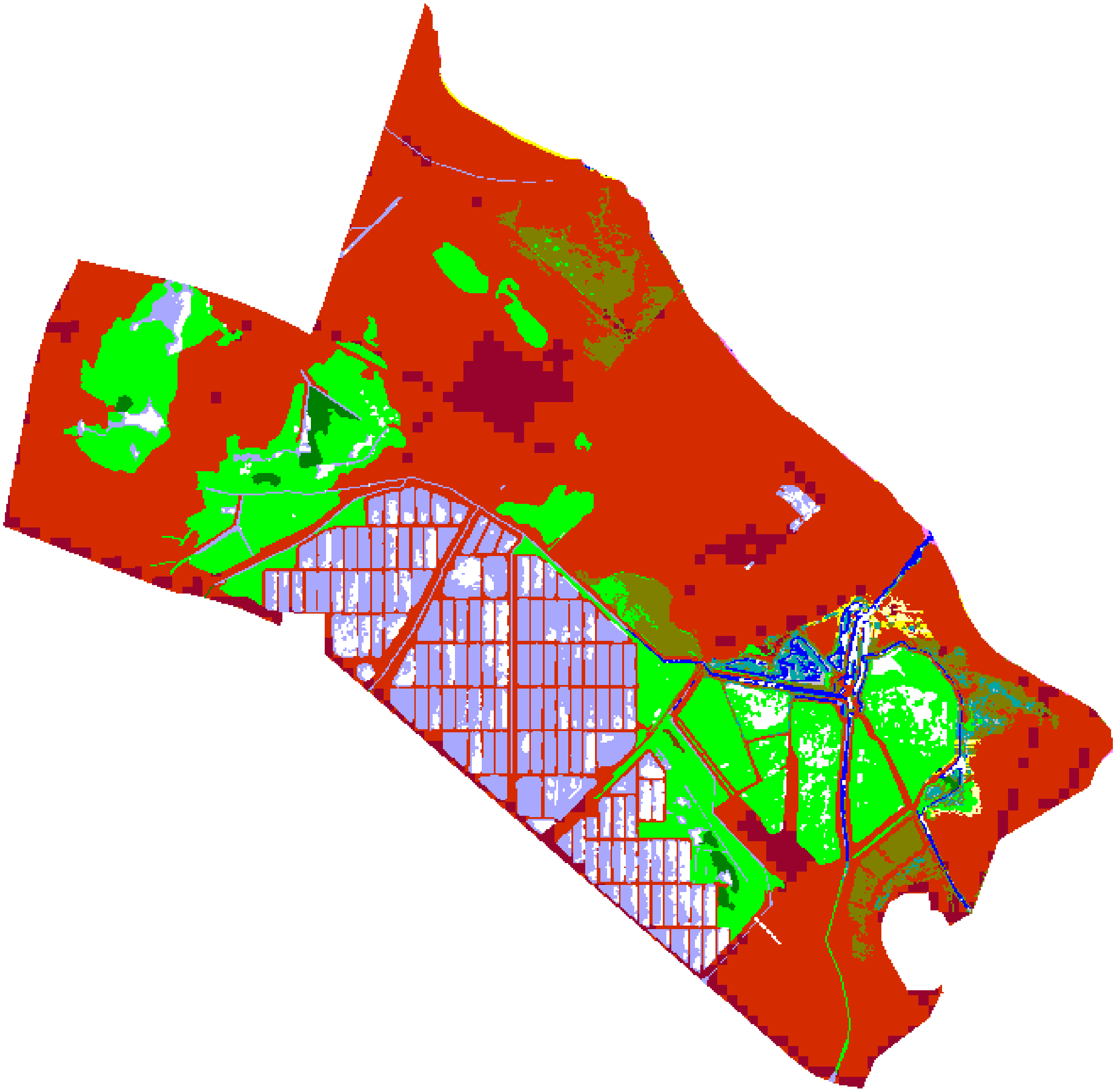
James Campbell NWR, Initial Condition



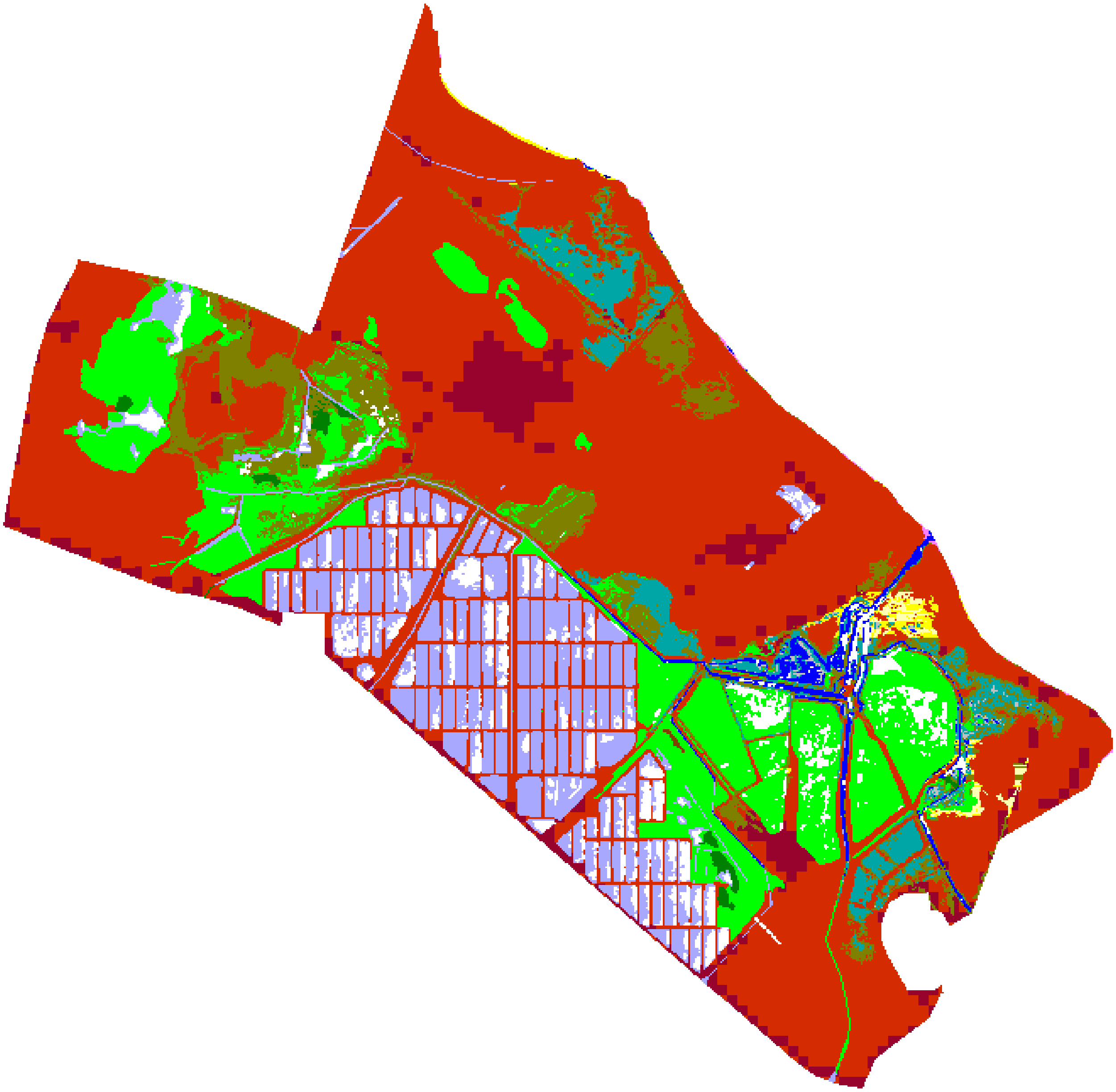
James Campbell NWR, 2025, Scenario A1B Maximum



James Campbell NWR, 2050, Scenario A1B Maximum



James Campbell NWR, 2075, Scenario A1B Maximum

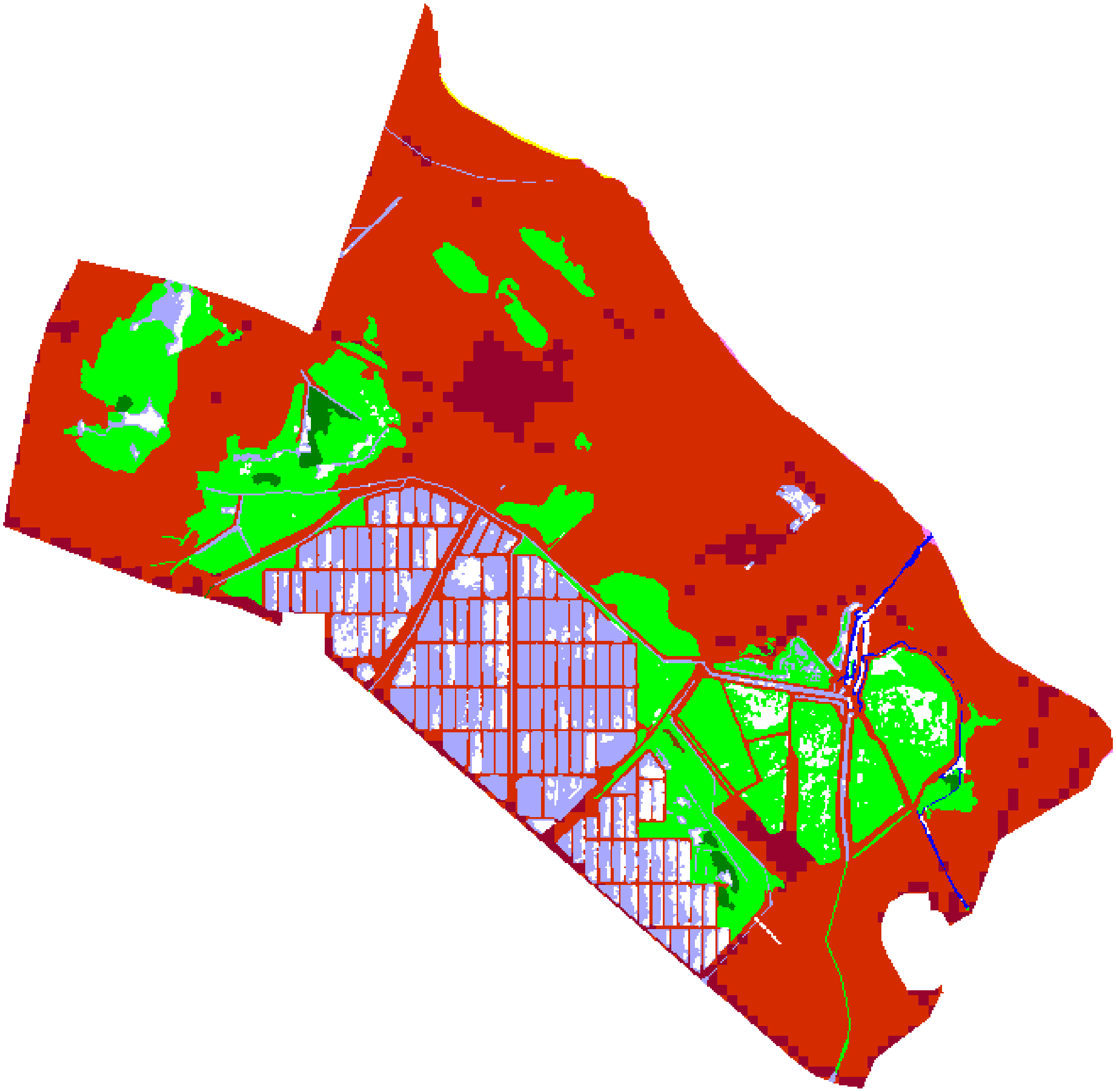


James Campbell NWR, 2100, Scenario A1B Maximum

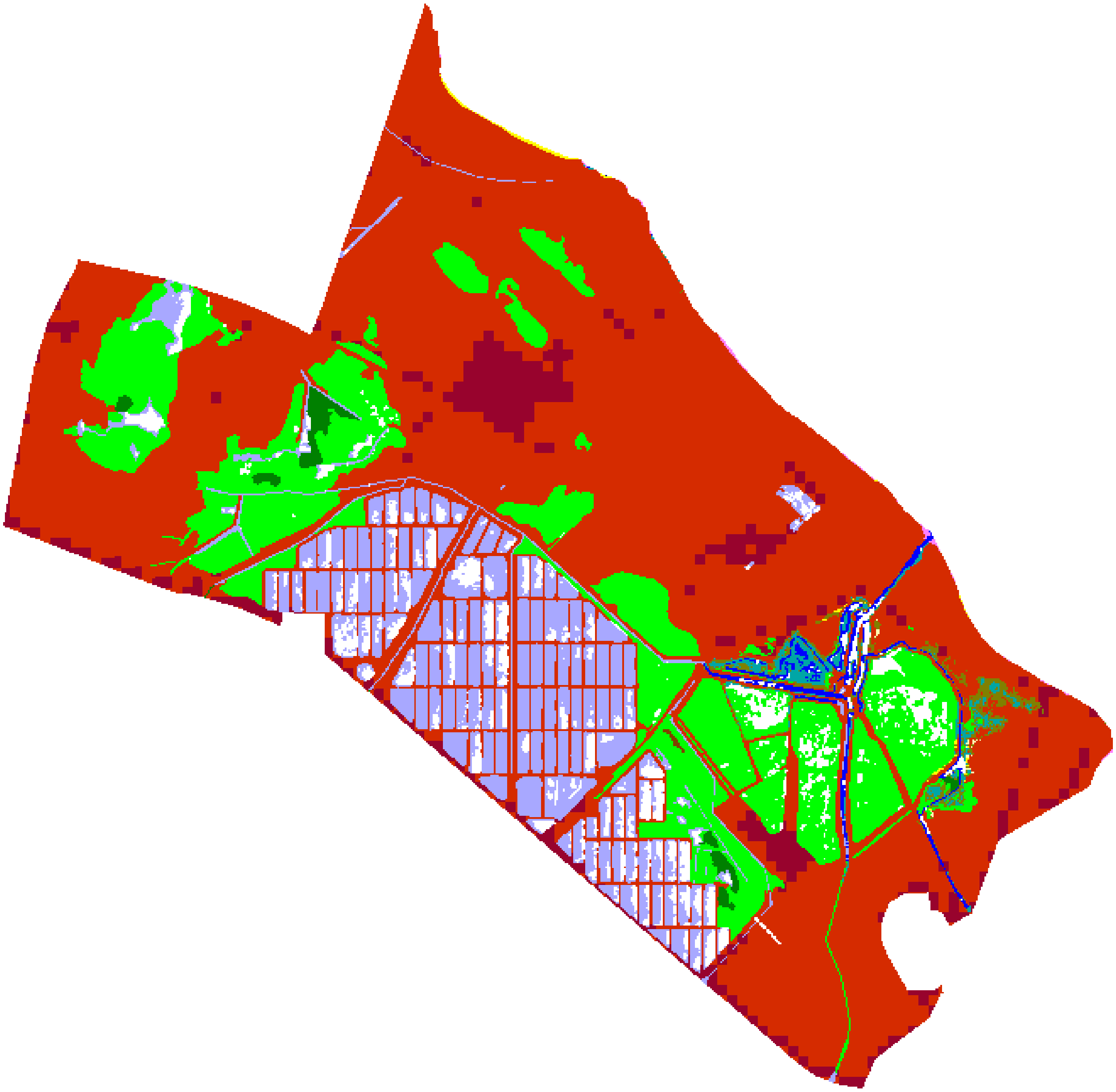
James Campbell Raster
1 Meter Eustatic SLR by 2100

Results in Acres

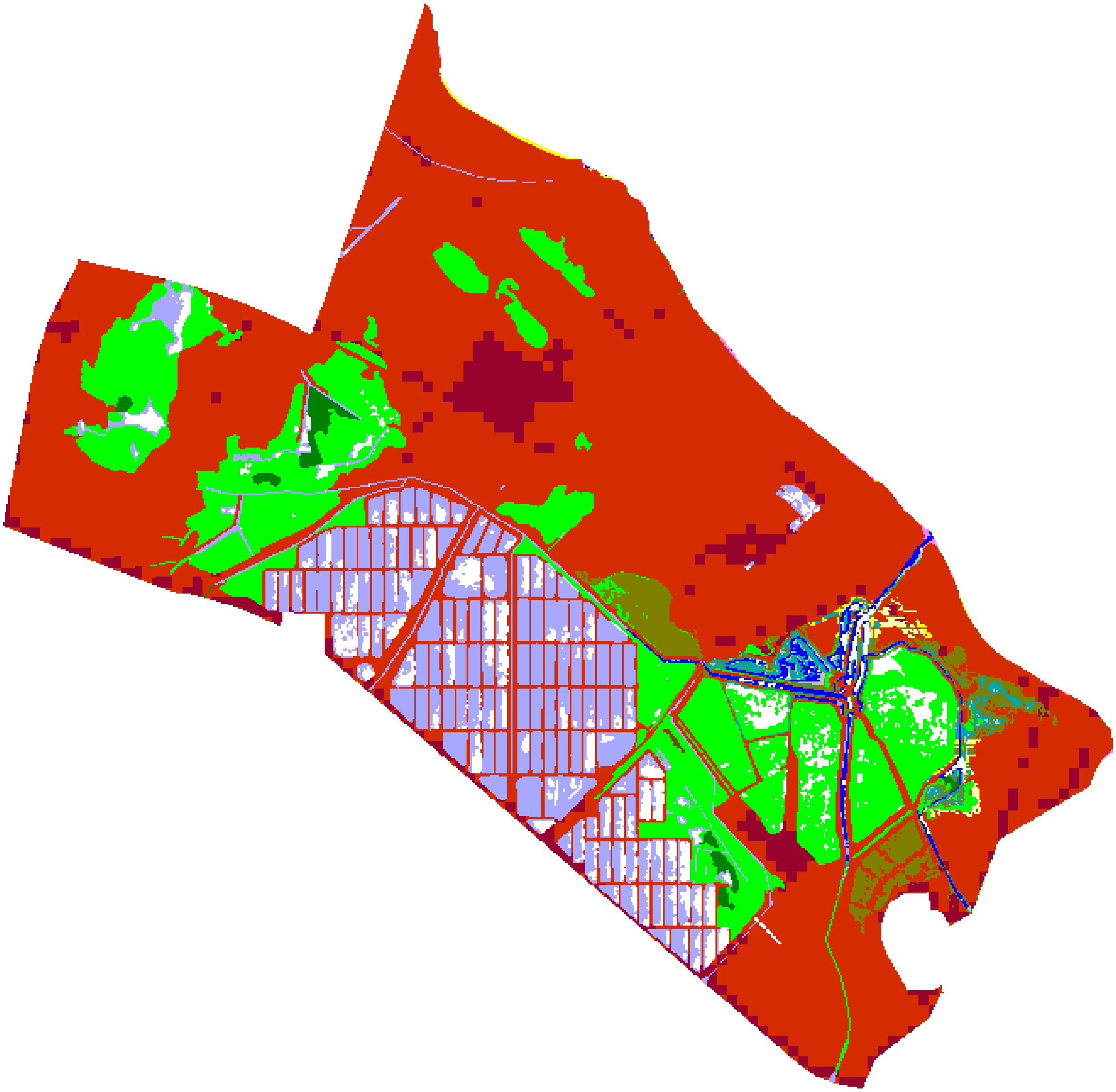
	Initial	2025	2050	2075	2100
Undeveloped Dry Land	647.5	636.8	620.1	554.0	488.6
Inland Fresh Marsh	189.4	182.0	171.3	116.8	91.8
Inland Open Water	132.0	127.2	126.6	125.4	114.9
Dev. Dry Land	58.8	58.6	58.0	55.2	51.3
Swamp	6.5	6.5	6.4	4.3	2.6
Riverine Tidal	3.0	1.1	0.5	0.1	0.0
Ocean Beach	0.9	1.3	2.0	4.1	7.9
Rocky Intertidal	0.7	0.7	0.7	0.6	0.5
Estuarine Open Water	0.4	7.3	8.4	17.7	38.0
Inland Shore	0.3	0.3	0.3	0.3	0.3
Saltmarsh	0.0	10.6	9.4	26.0	121.6
Trans. Salt Marsh	0.0	7.3	25.6	121.6	89.1
Tidal Flat	0.0	0.0	8.3	9.8	26.3
Estuarine Beach	0.0	0.3	1.9	3.6	6.2
Open Ocean	0.0	0.0	0.0	0.2	0.5
Total (incl. water)	**1039.6**	**1039.6**	**1039.6**	**1039.6**	**1039.6**



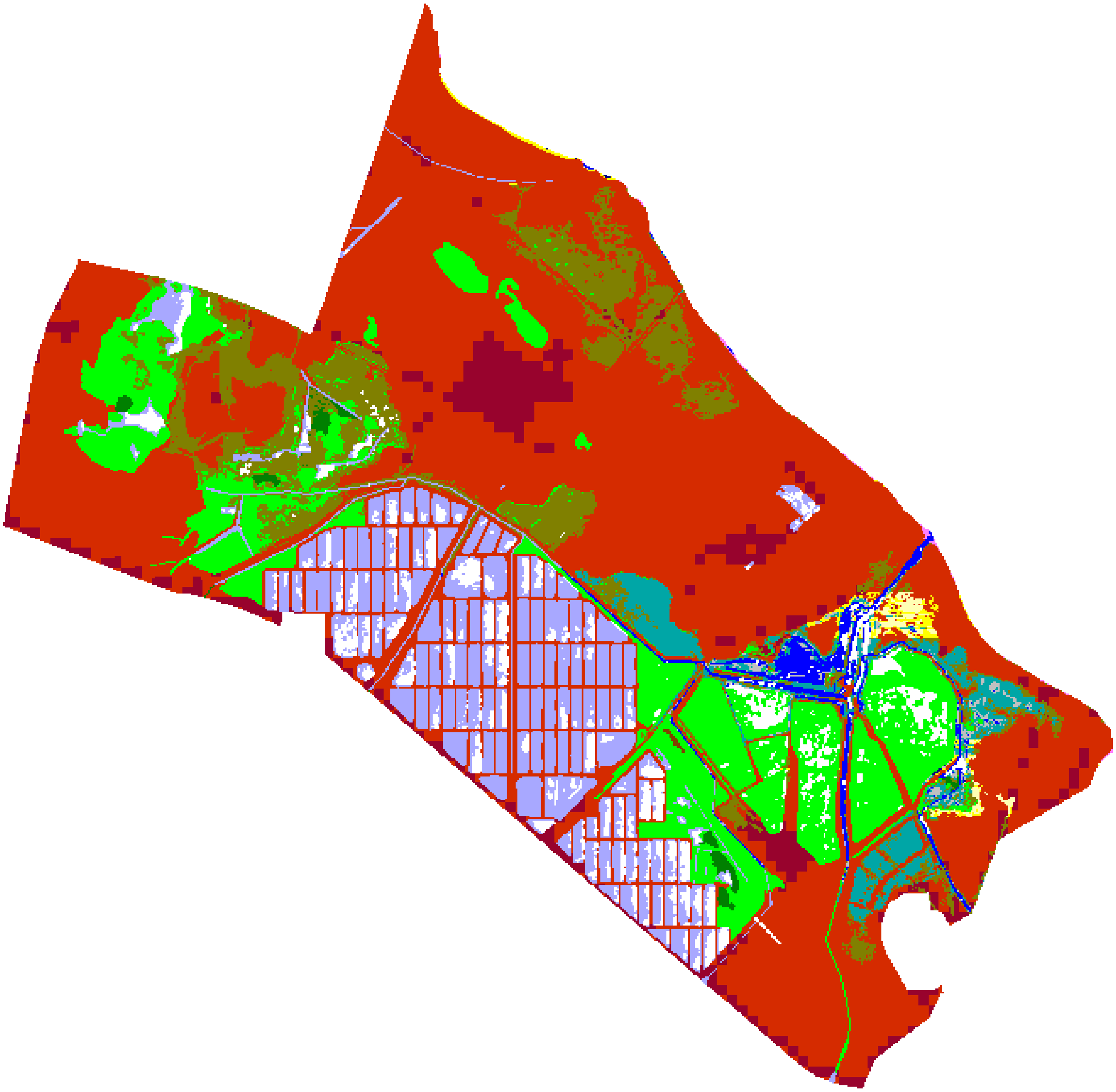
James Campbell NWR, Initial Condition



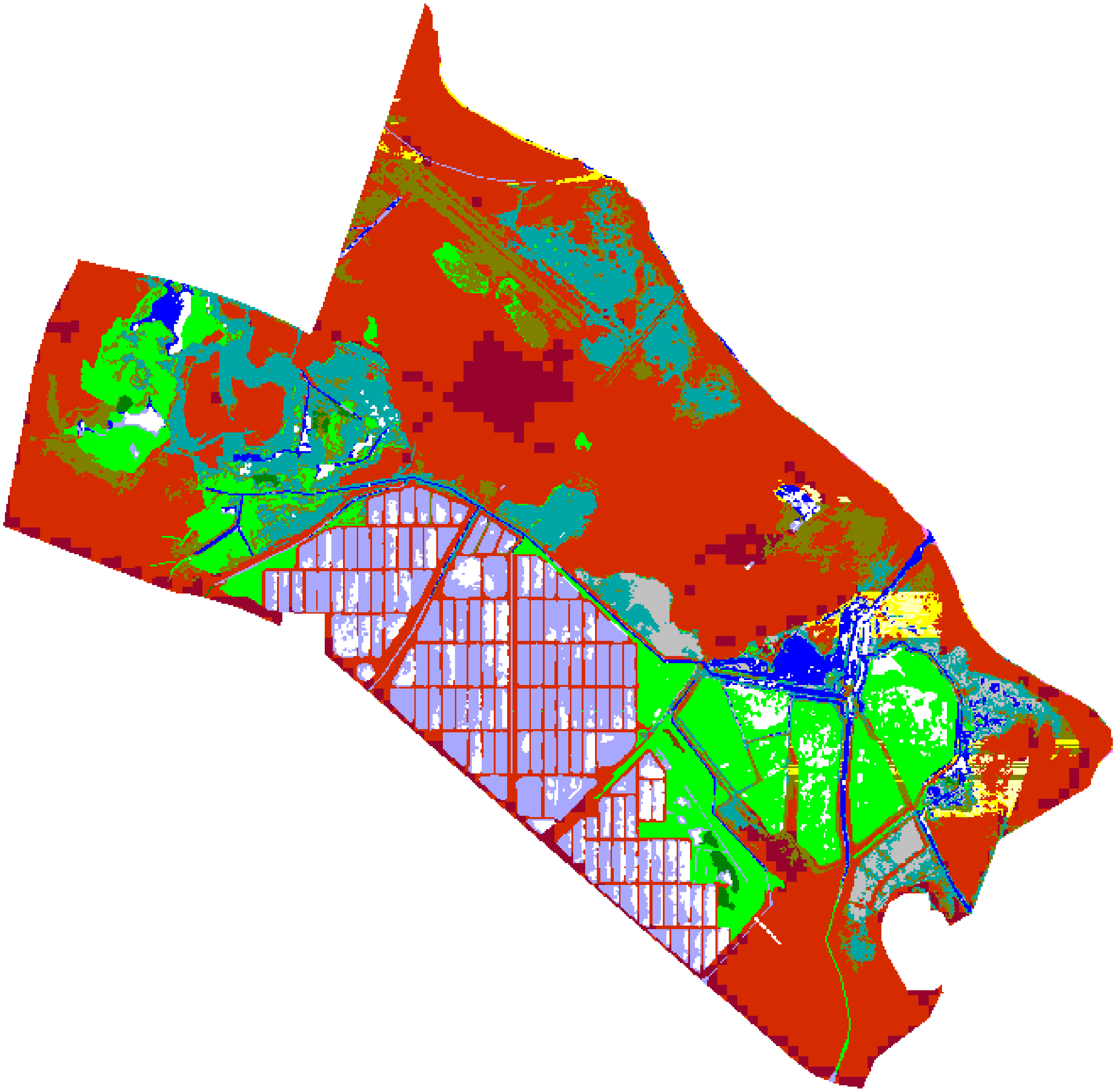
James Campbell NWR, 2025, 1 meter

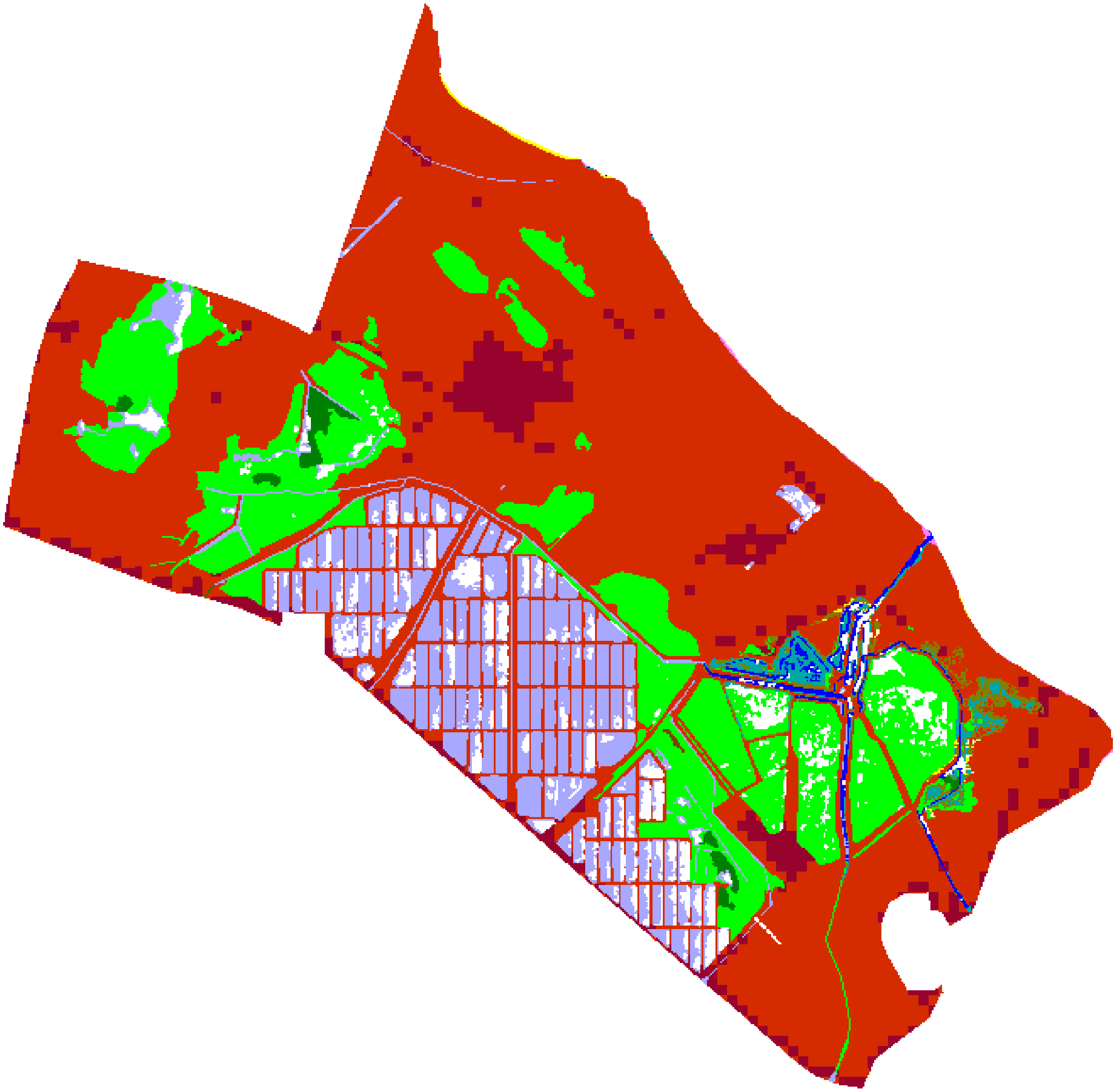


James Campbell NWR, 2050, 1 meter



James Campbell NWR, 2075, 1 meter



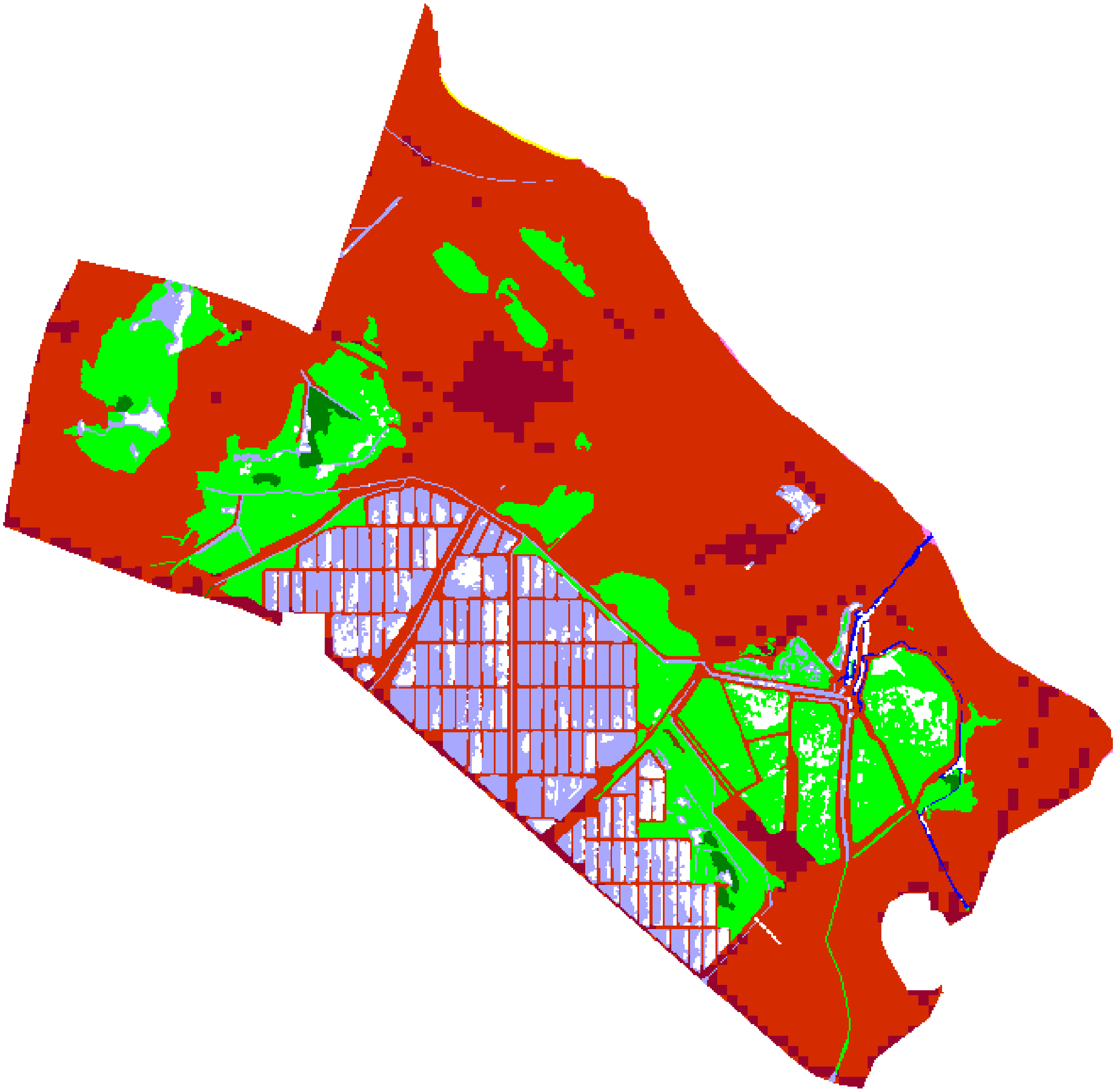


James Campbell NWR, 2100, 1 meter

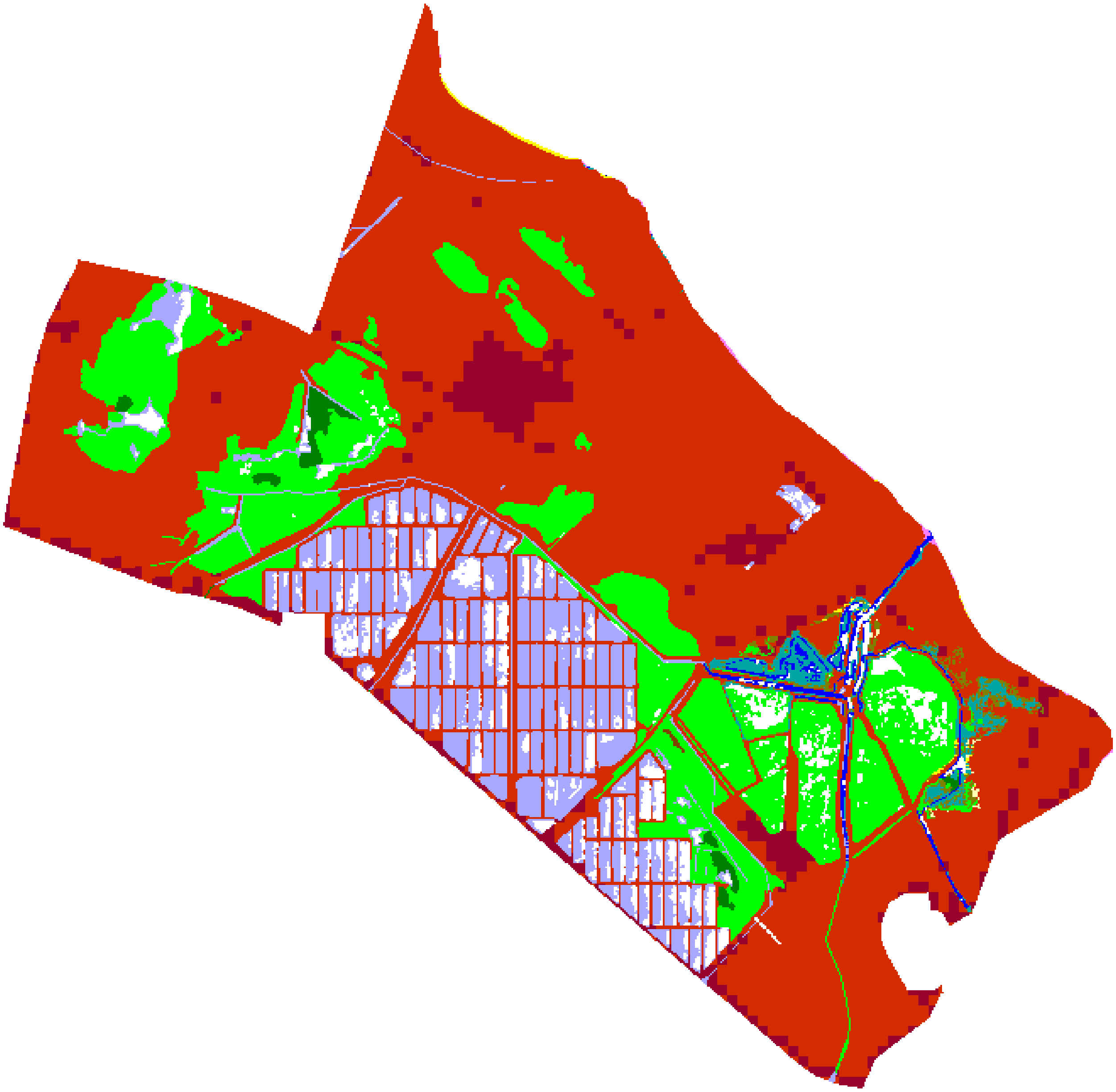
James Campbell Raster
1.5 Meters Eustatic SLR by 2100

Results in Acres

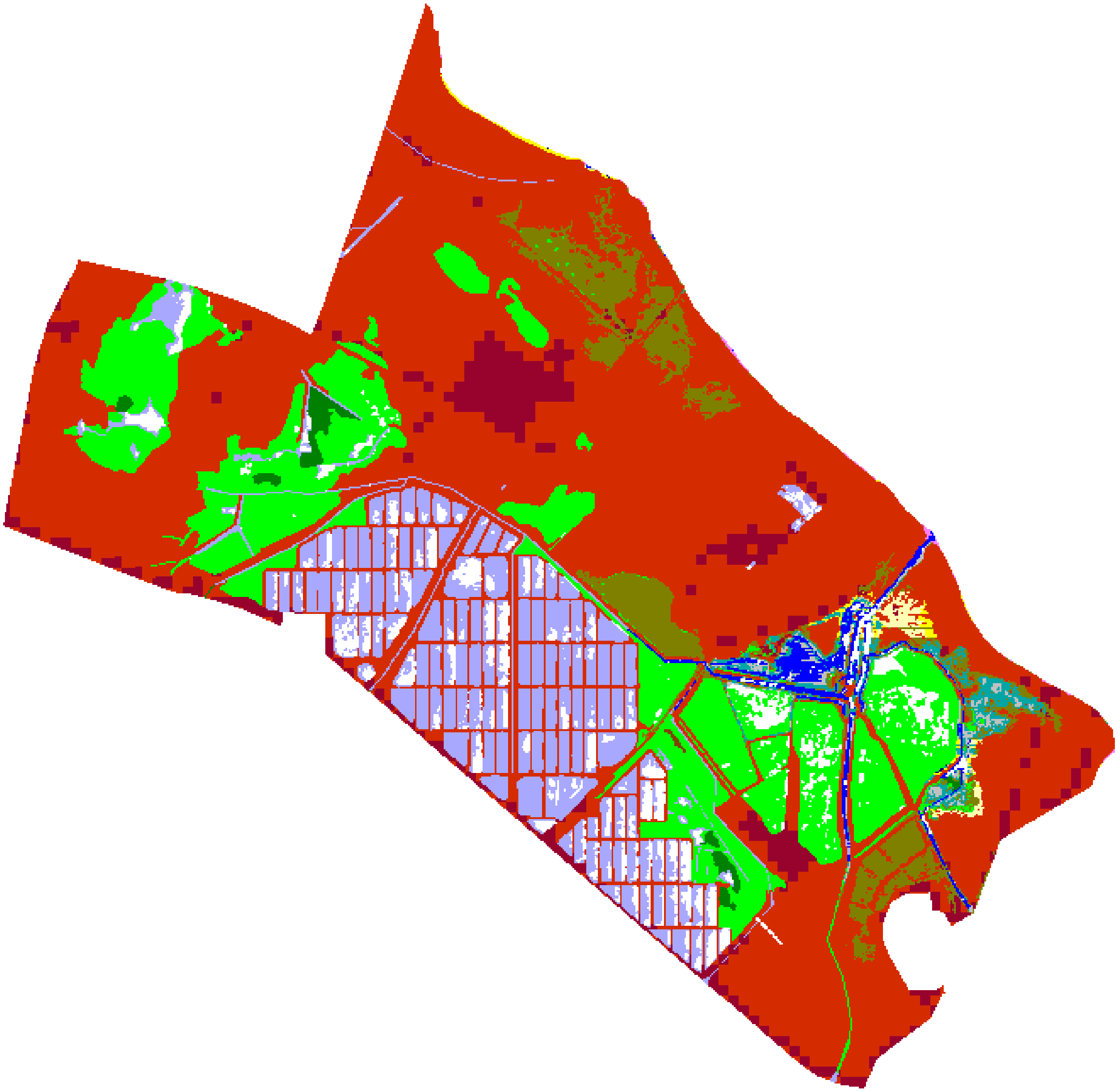
	Initial	2025	2050	2075	2100
Undeveloped Dry Land	647.5	634.8	590.7	484.9	395.8
Inland Fresh Marsh	189.4	181.4	167.3	91.1	70.0
Inland Open Water	132.0	127.1	126.3	123.1	112.6
Dev. Dry Land	58.8	58.5	56.7	51.0	45.5
Swamp	6.5	6.5	6.4	2.5	1.4
Riverine Tidal	3.0	0.9	0.2	0.0	0.0
Ocean Beach	0.9	1.4	2.7	6.8	19.1
Rocky Intertidal	0.7	0.7	0.6	0.4	0.2
Estuarine Open Water	0.4	7.5	9.0	25.2	47.8
Inland Shore	0.3	0.3	0.3	0.3	0.1
Saltmarsh	0.0	12.1	8.0	56.0	182.3
Trans. Salt Marsh	0.0	8.0	56.0	182.3	97.6
Tidal Flat	0.0	0.0	12.1	7.9	56.0
Estuarine Beach	0.0	0.5	3.2	7.4	7.8
Open Ocean	0.0	0.0	0.1	0.5	3.5
Total (incl. water)	**1039.6**	**1039.6**	**1039.6**	**1039.6**	**1039.6**



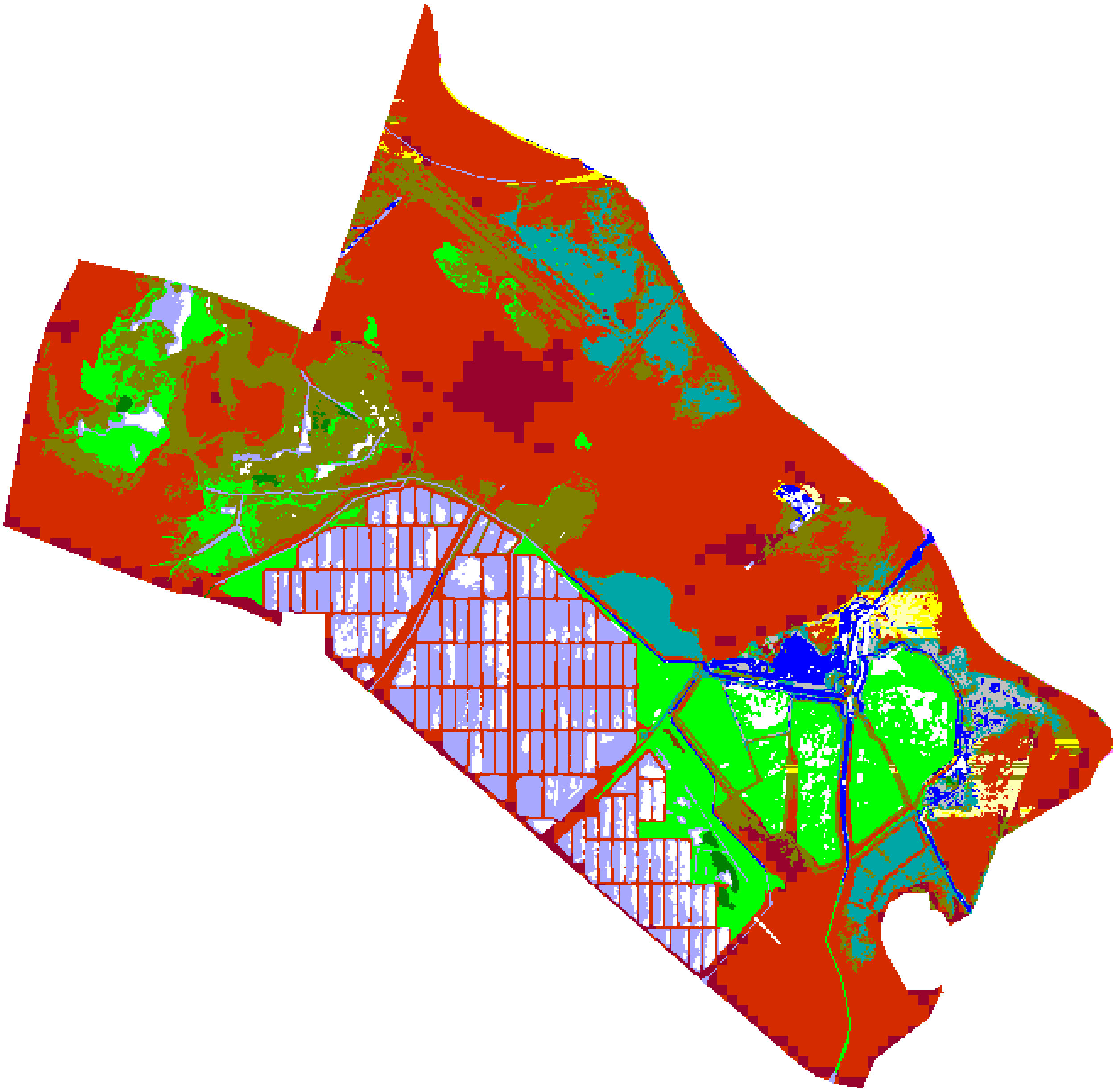
James Campbell NWR, Initial Condition



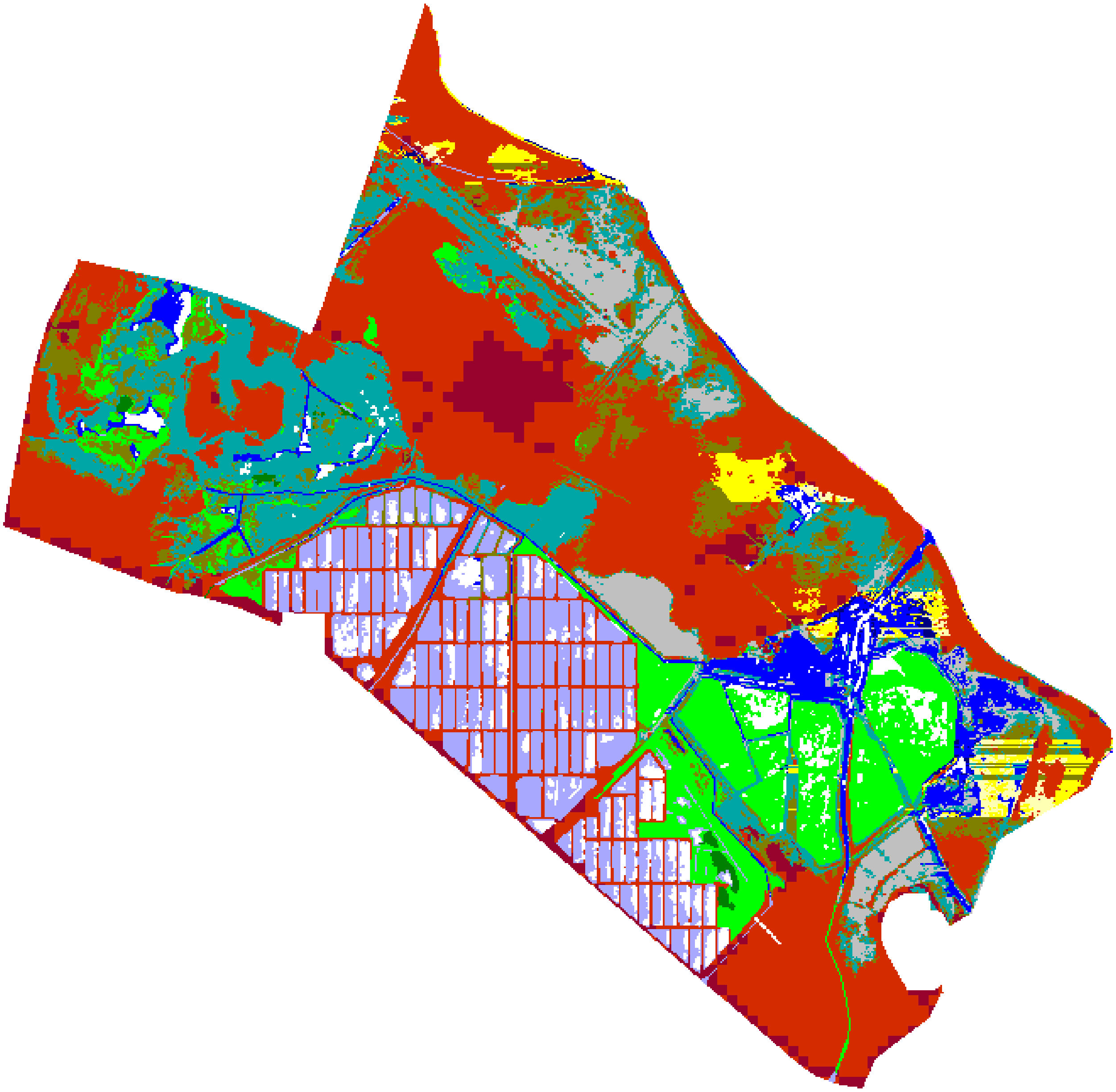
James Campbell NWR, 2025, 1.5 meter



James Campbell NWR, 2050, 1.5 meter



James Campbell NWR, 2075, 1.5 meter

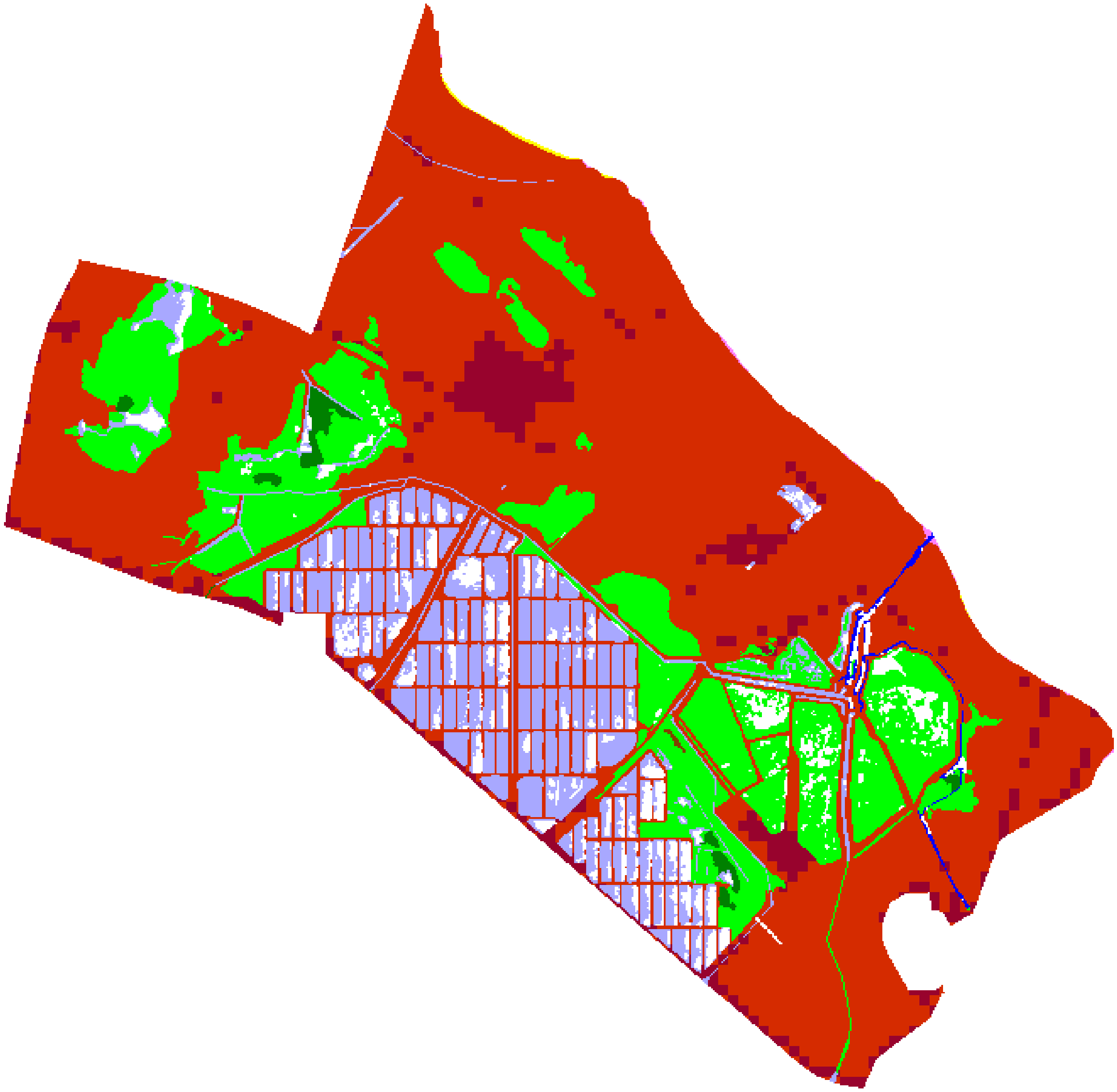


James Campbell NWR, 2100, 1.5 meter

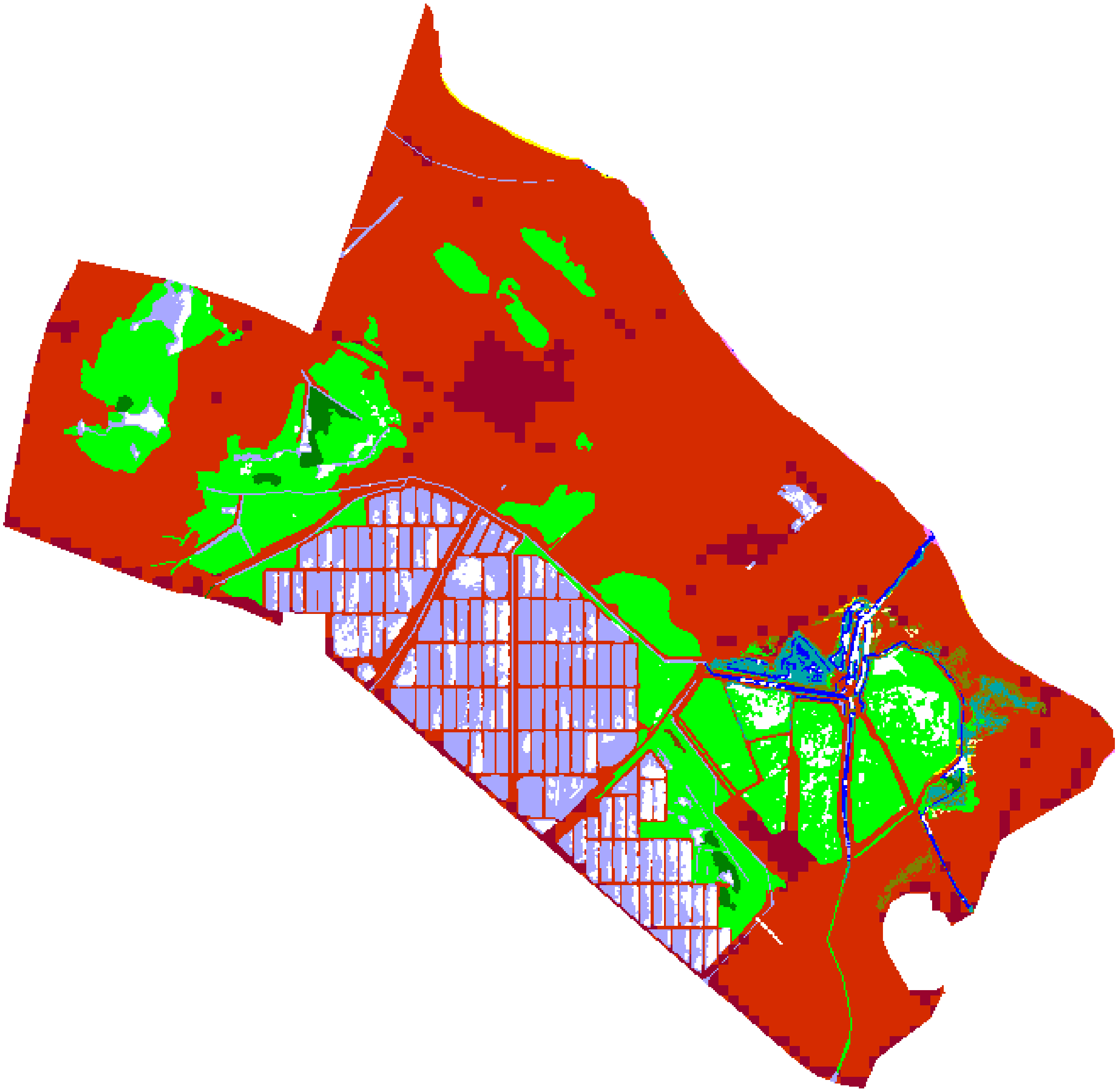
James Campbell Raster
2 Meters Eustatic SLR by 2100

Results in Acres

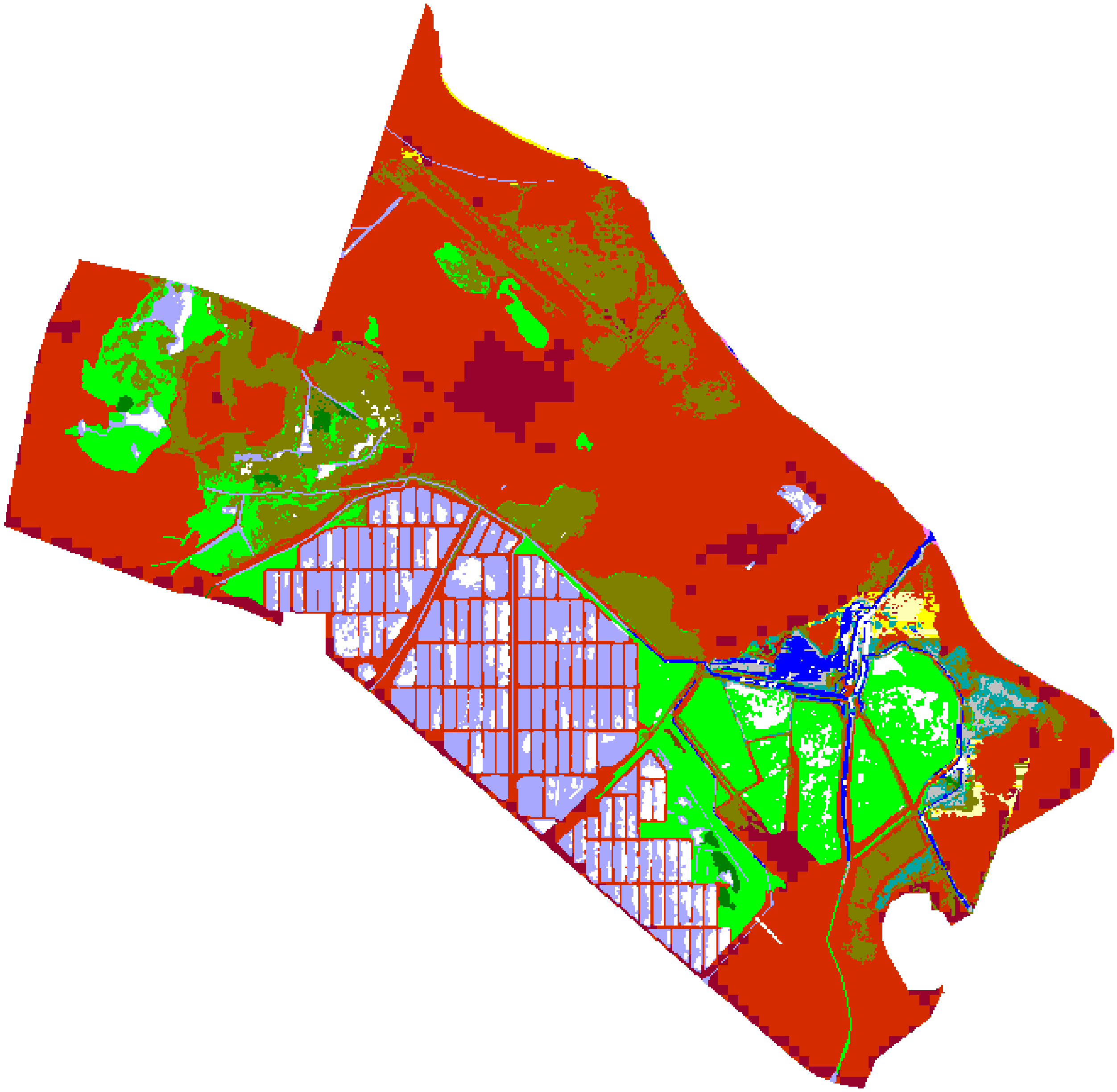
	Initial	2025	2050	2075	2100
Undeveloped Dry Land	647.5	631.3	541.1	419.5	295.9
Inland Fresh Marsh	189.4	181.0	111.6	74.0	64.3
Inland Open Water	132.0	127.0	125.8	113.5	110.3
Dev. Dry Land	58.8	58.4	54.7	46.6	39.9
Swamp	6.5	6.4	4.1	1.6	1.0
Riverine Tidal	3.0	0.8	0.1	0.0	0.0
Ocean Beach	0.9	1.5	4.4	17.5	15.6
Rocky Intertidal	0.7	0.7	0.6	0.3	0.1
Estuarine Open Water	0.4	7.7	9.8	38.6	57.6
Inland Shore	0.3	0.3	0.3	0.2	0.0
Saltmarsh	0.0	13.7	10.0	159.1	147.8
Trans. Salt Marsh	0.0	10.0	159.1	147.8	127.0
Tidal Flat	0.0	0.0	13.7	10.0	159.0
Estuarine Beach	0.0	0.9	4.2	8.6	5.7
Open Ocean	0.0	0.0	0.2	2.3	15.5
Total (incl. water)	**1039.6**	**1039.6**	**1039.6**	**1039.6**	**1039.6**



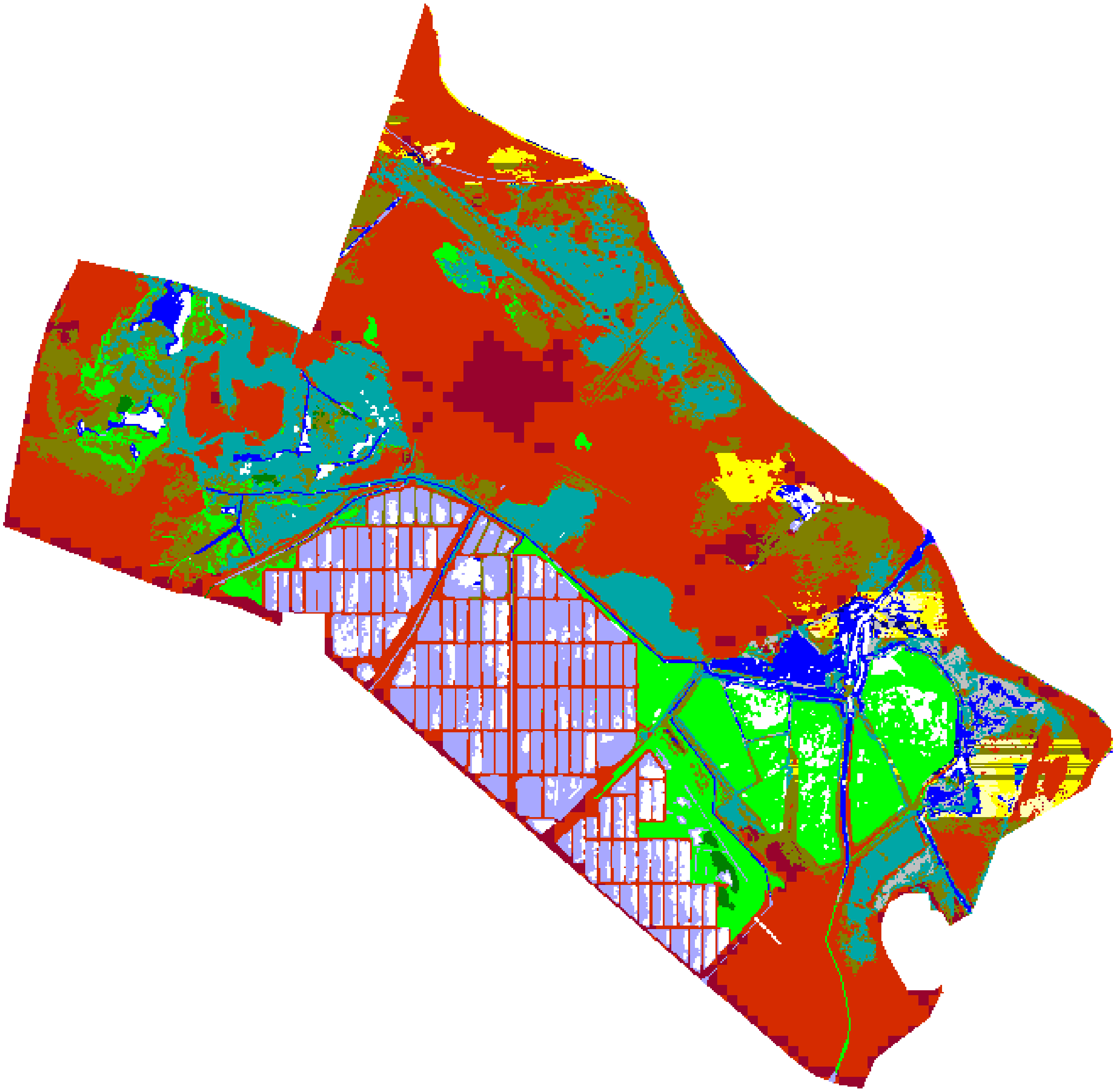
James Campbell NWR, Initial Condition



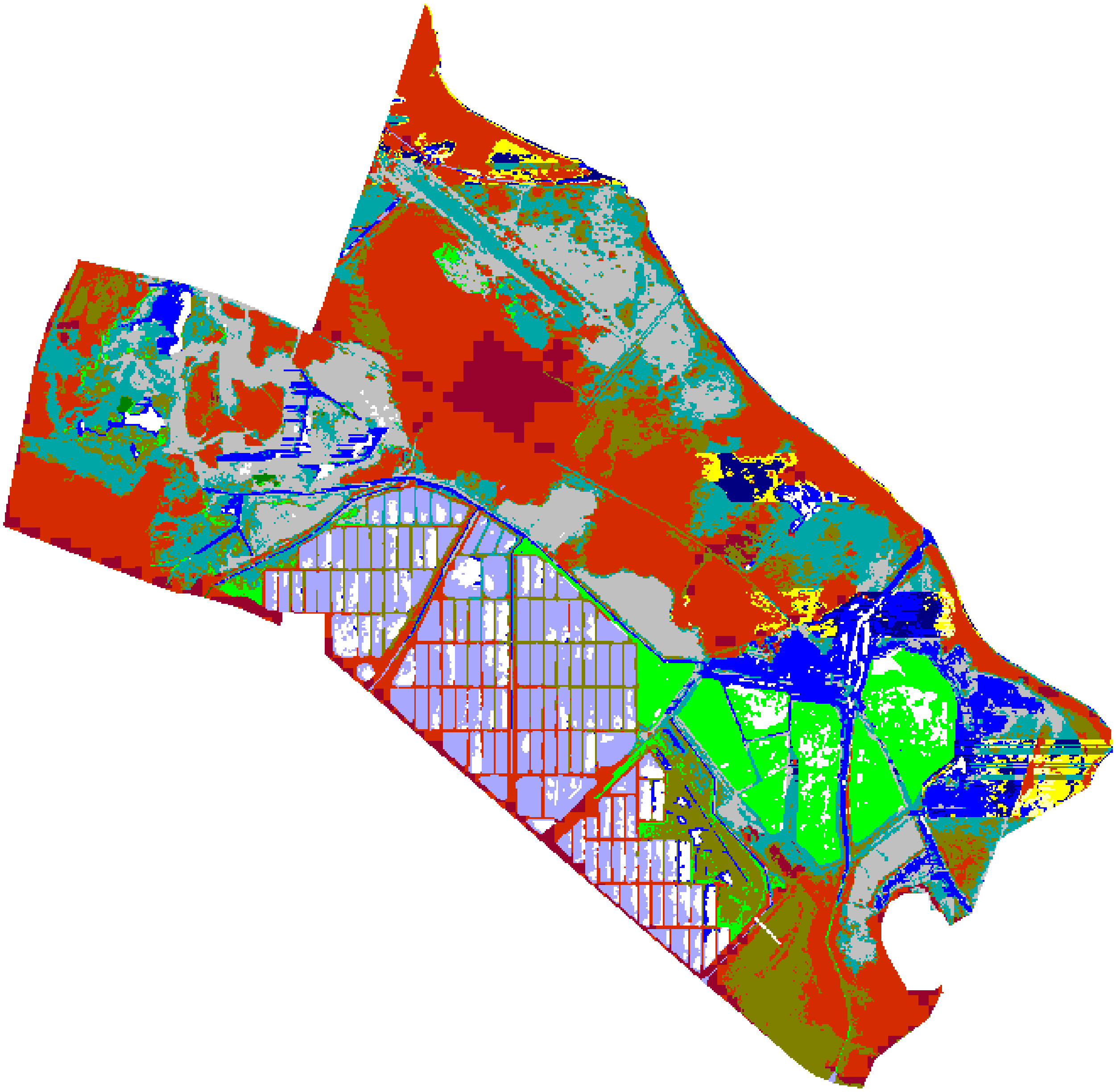
James Campbell NWR, 2025, 2 meters



James Campbell NWR, 2050, 2 meters



James Campbell NWR, 2075, 2 meters



James Campbell NWR, 2100, 2 meters

Discussion

Model results suggest that inland inundation within this refuge will occur given SLR scenarios of approximately one half meter (eustatic) and beyond. There are two major channels through which saline inundation will occur, one being a channel at the northeast of the site (Figure 5) and one being in the region of the refuge's tidal gate (Figure 4).

The most recent addition to the refuge includes the military base along the coast. Model results suggest that much of this area could become inundated in higher SLR scenarios. These inundated areas include the Kahuku Airstrip and areas south and east of the strip. Unlike the rest of the coast, inundated zones near the airstrip are not protected by high dunes.

High resolution LiDAR data available for this site and the capability to model with a five meter cell-size resolution reduce model uncertainty to some degree. There does remain some uncertainty as to land disposition after flooding—SLAMM assumes that land close to the ocean will convert to beach and inland regions will convert to transitional salt marshes, salt marshes, and mudflats.

Figure 5: Predicted location of water inflow in the event of SLR exceeding 0.5 meters eustatic.
(Approximately Latitude 21.699 Longitude -157.957)

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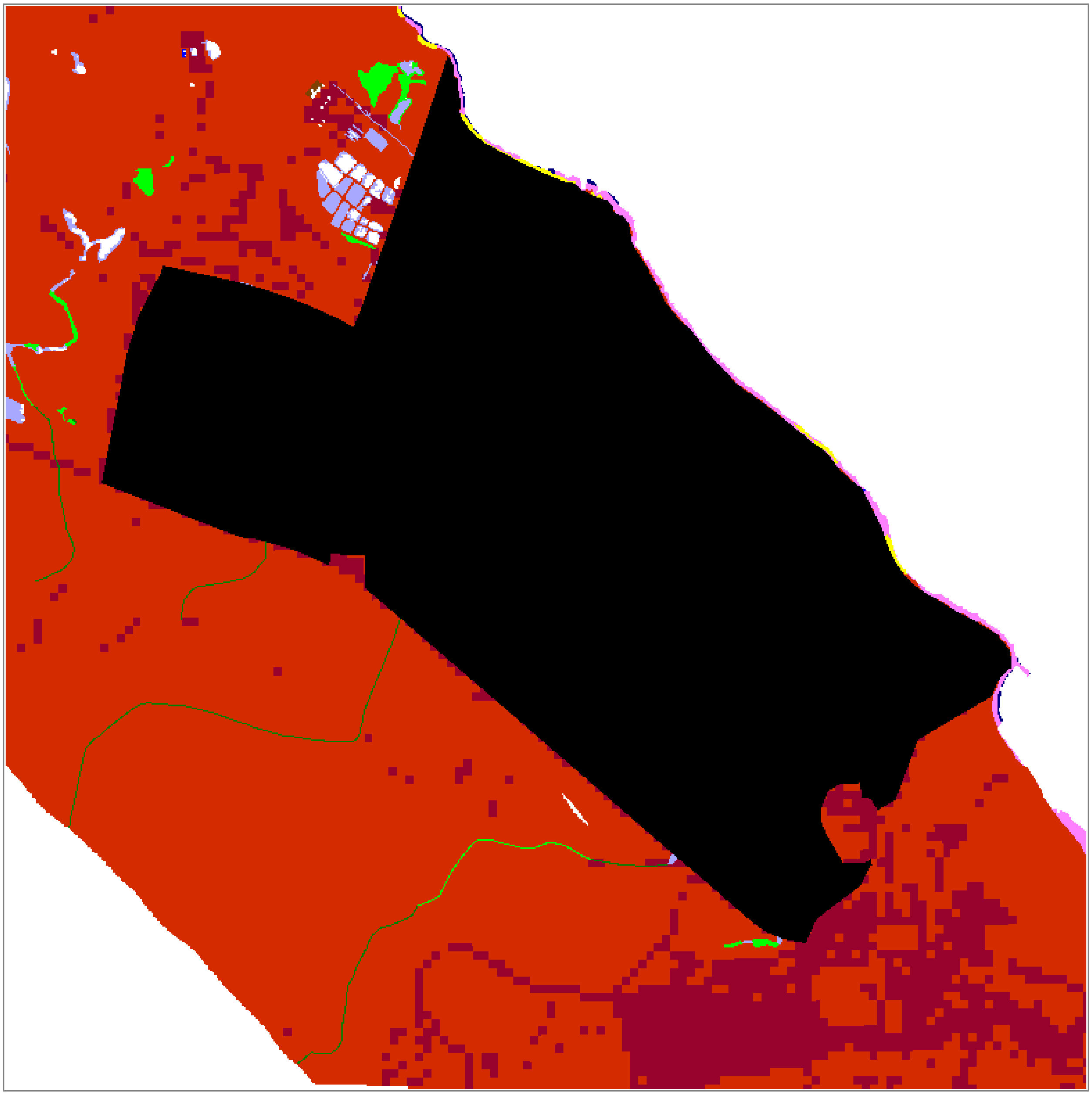
Appendix A: Contextual Results

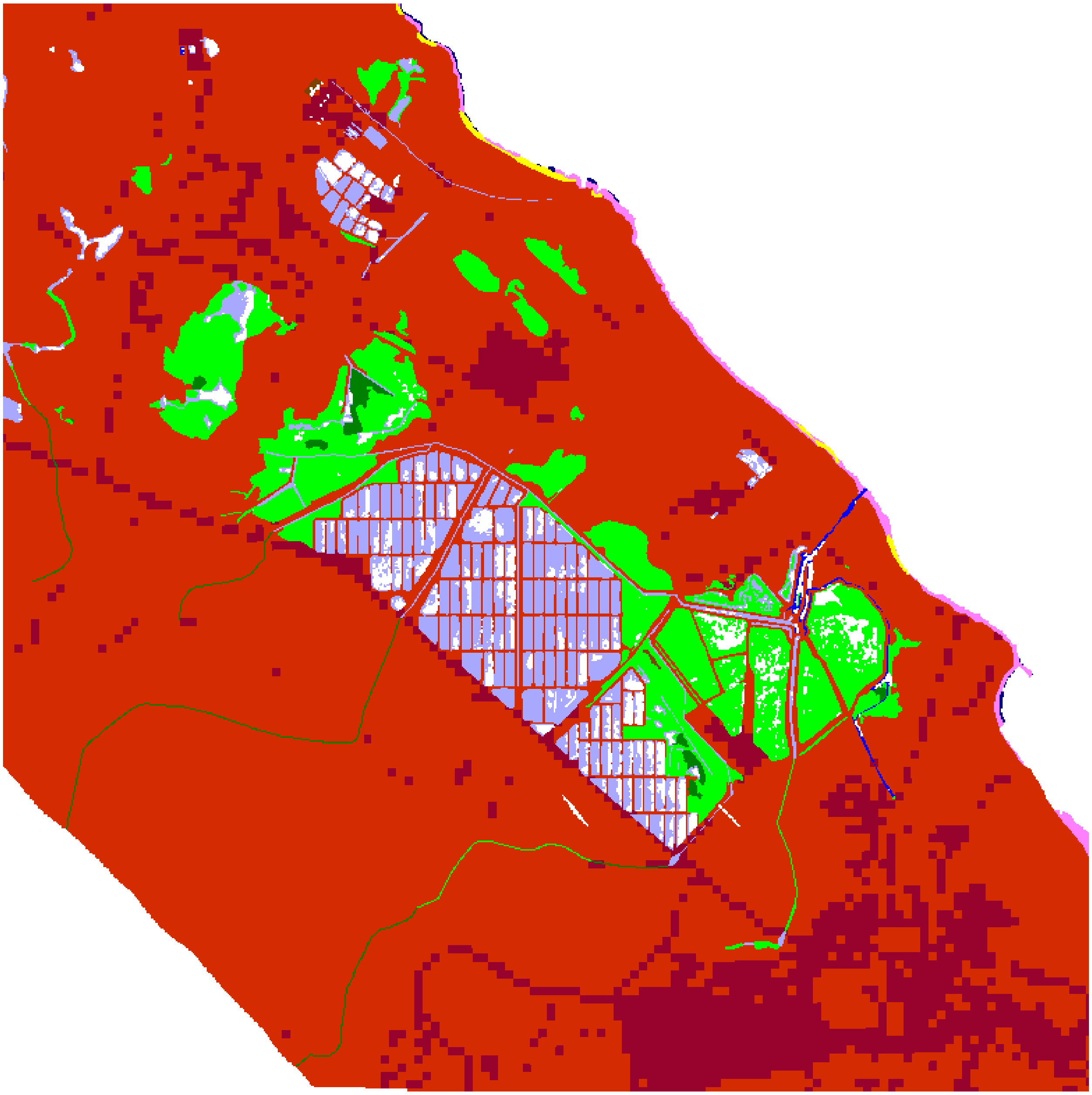
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

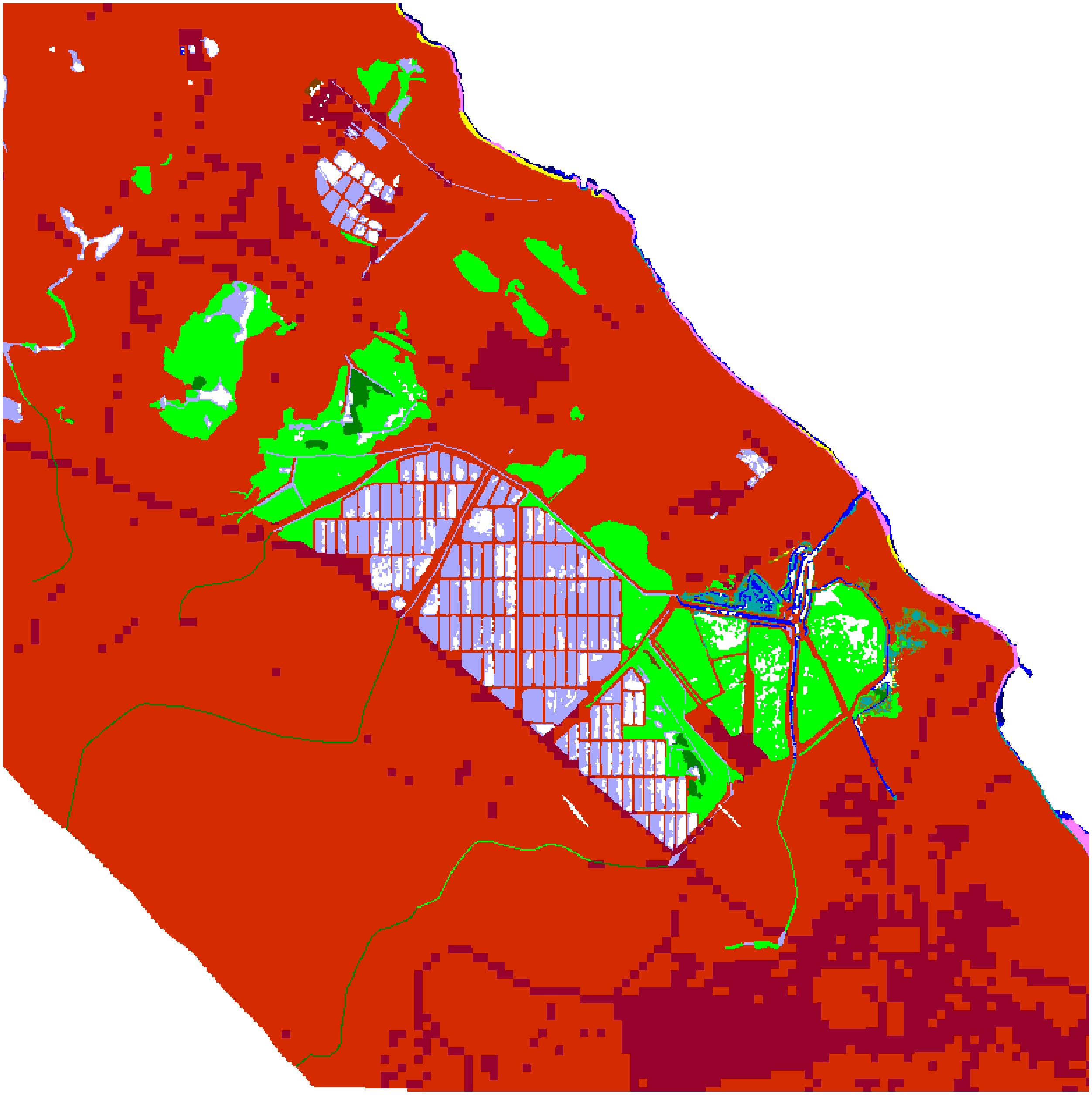
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



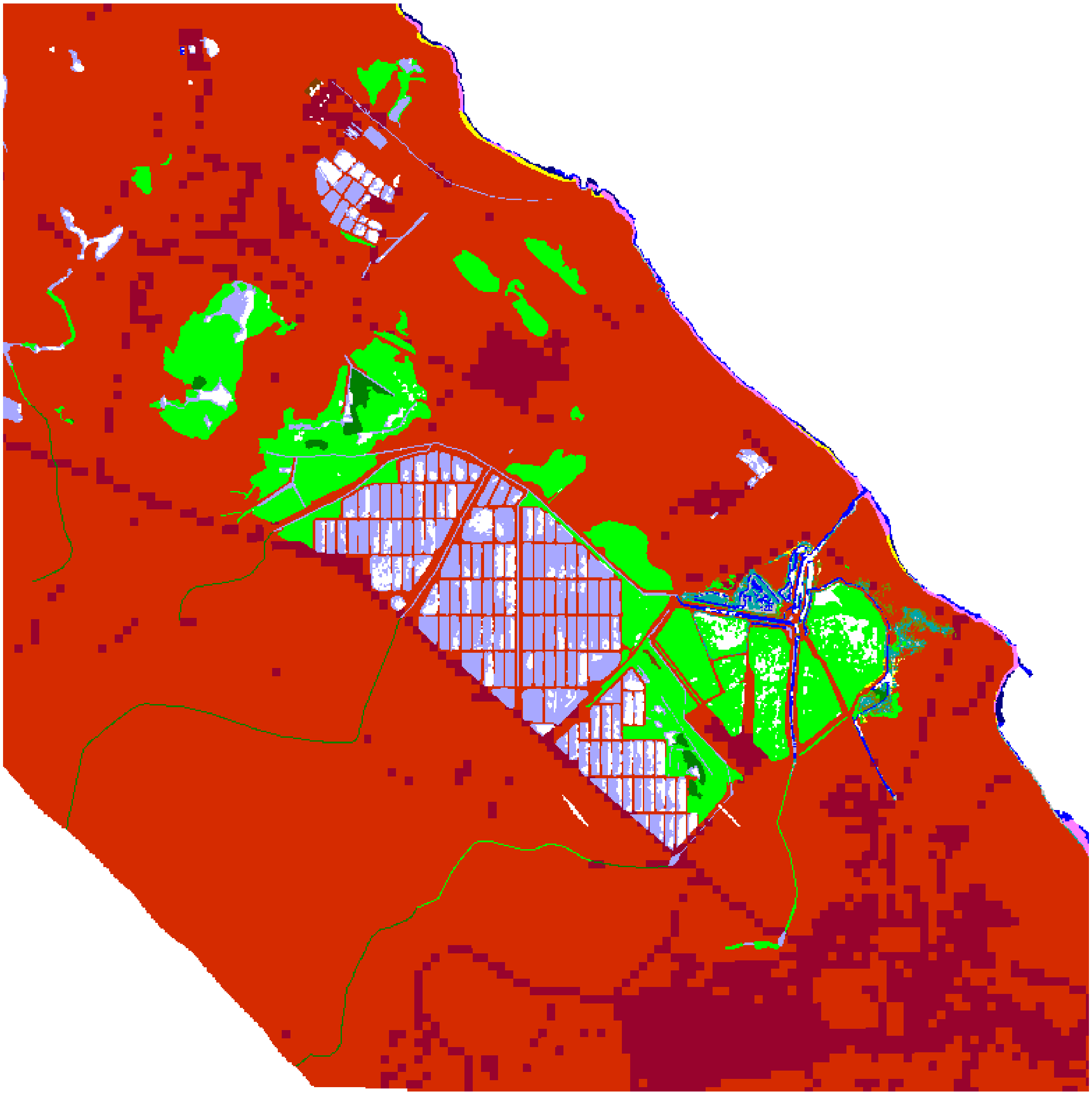
Location of James Campbell National Wildlife Refuge within simulation context (black).



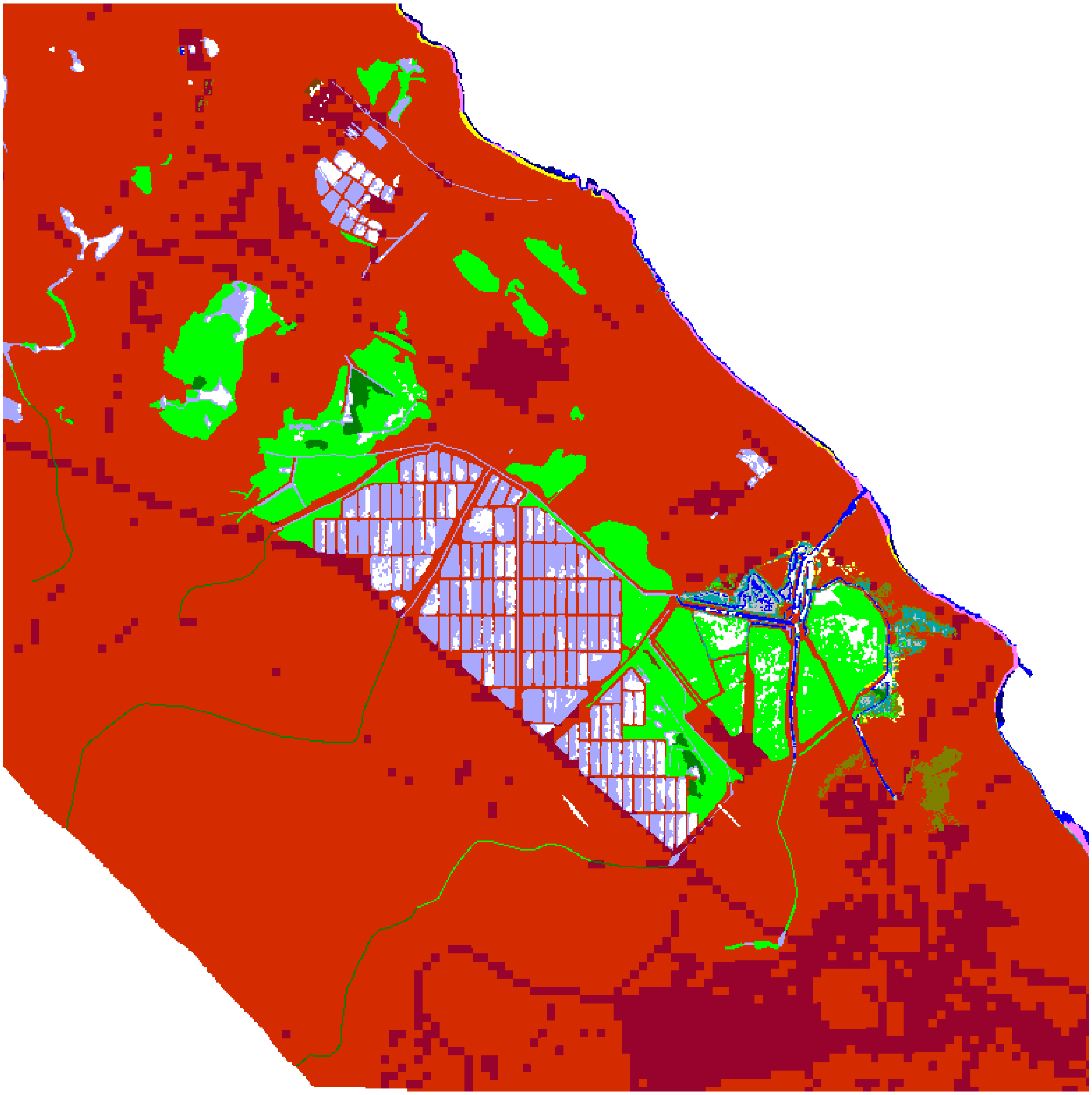
James Campbell Context, Initial Condition



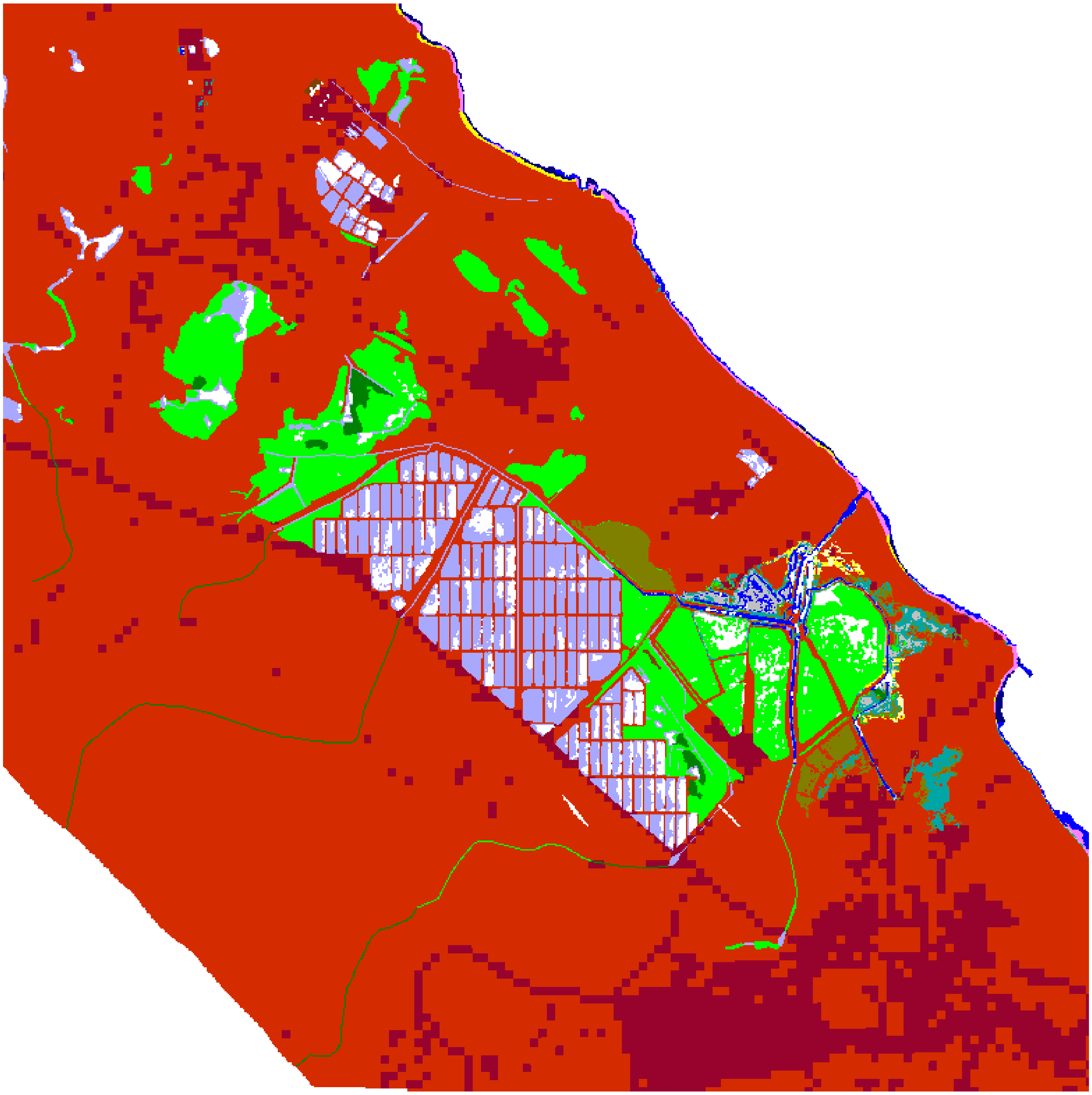
James Campbell Context, 2025, Scenario A1B Mean



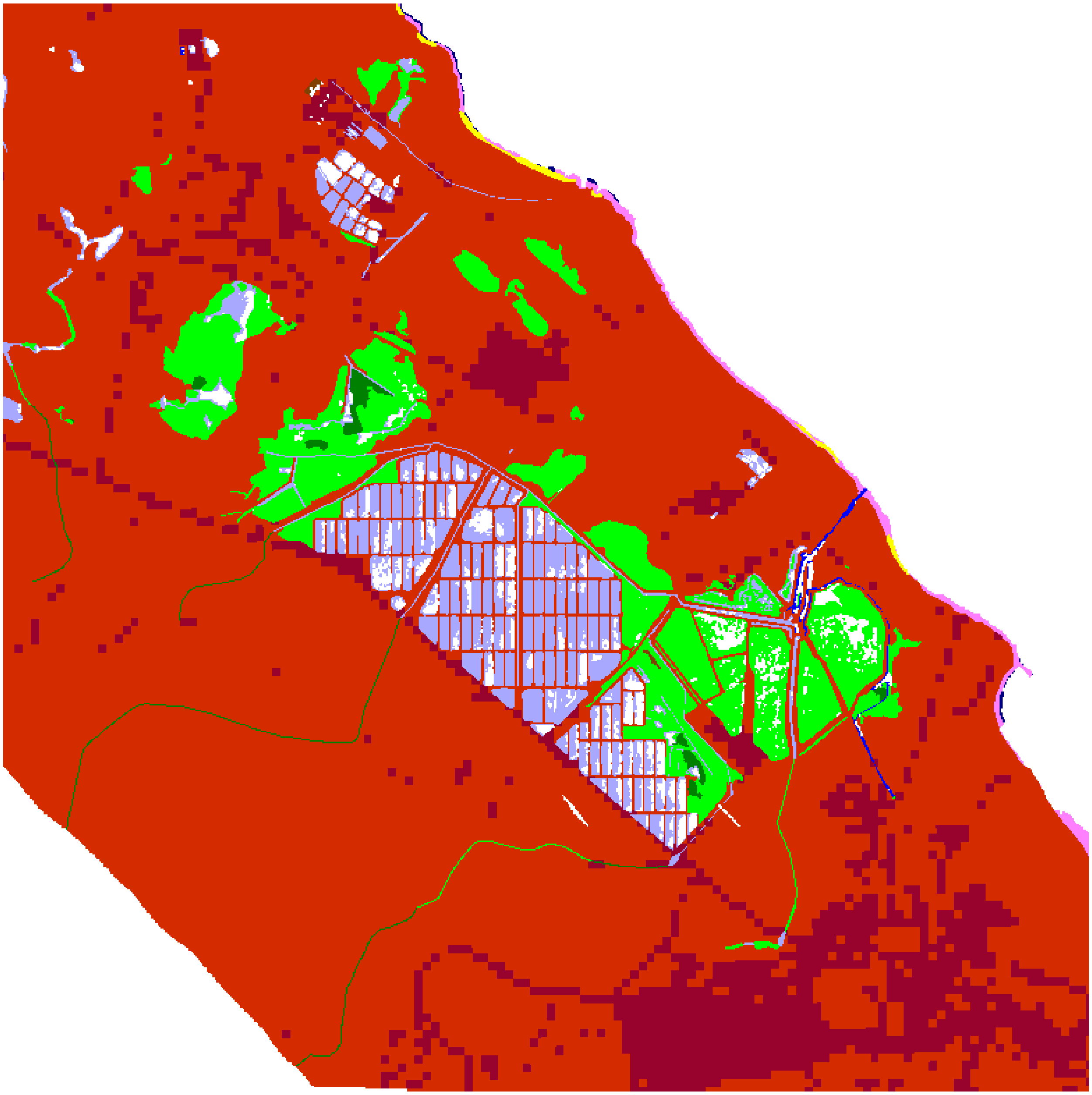
James Campbell Context, 2050, Scenario A1B Mean



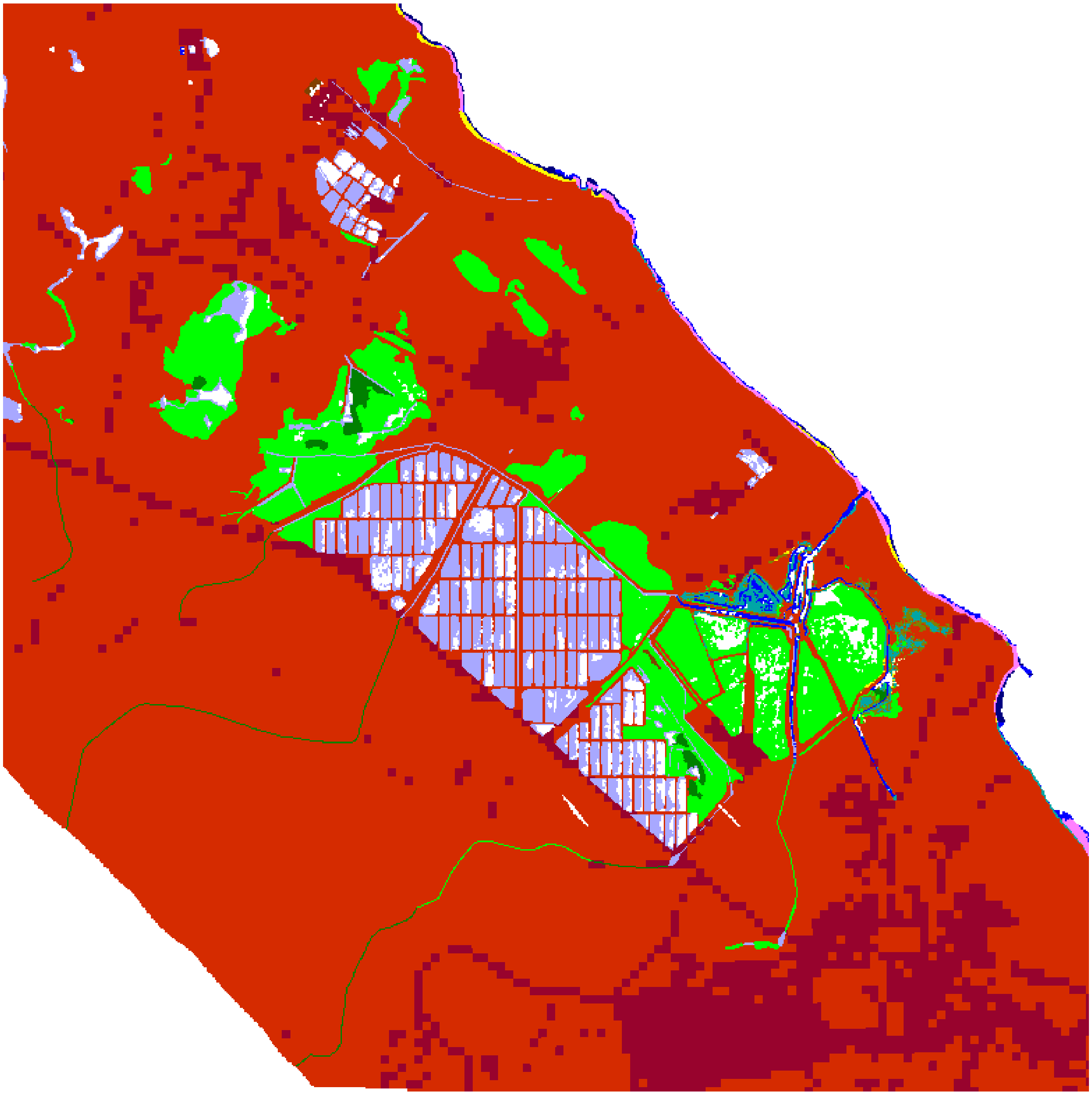
James Campbell Context, 2075, Scenario A1B Mean



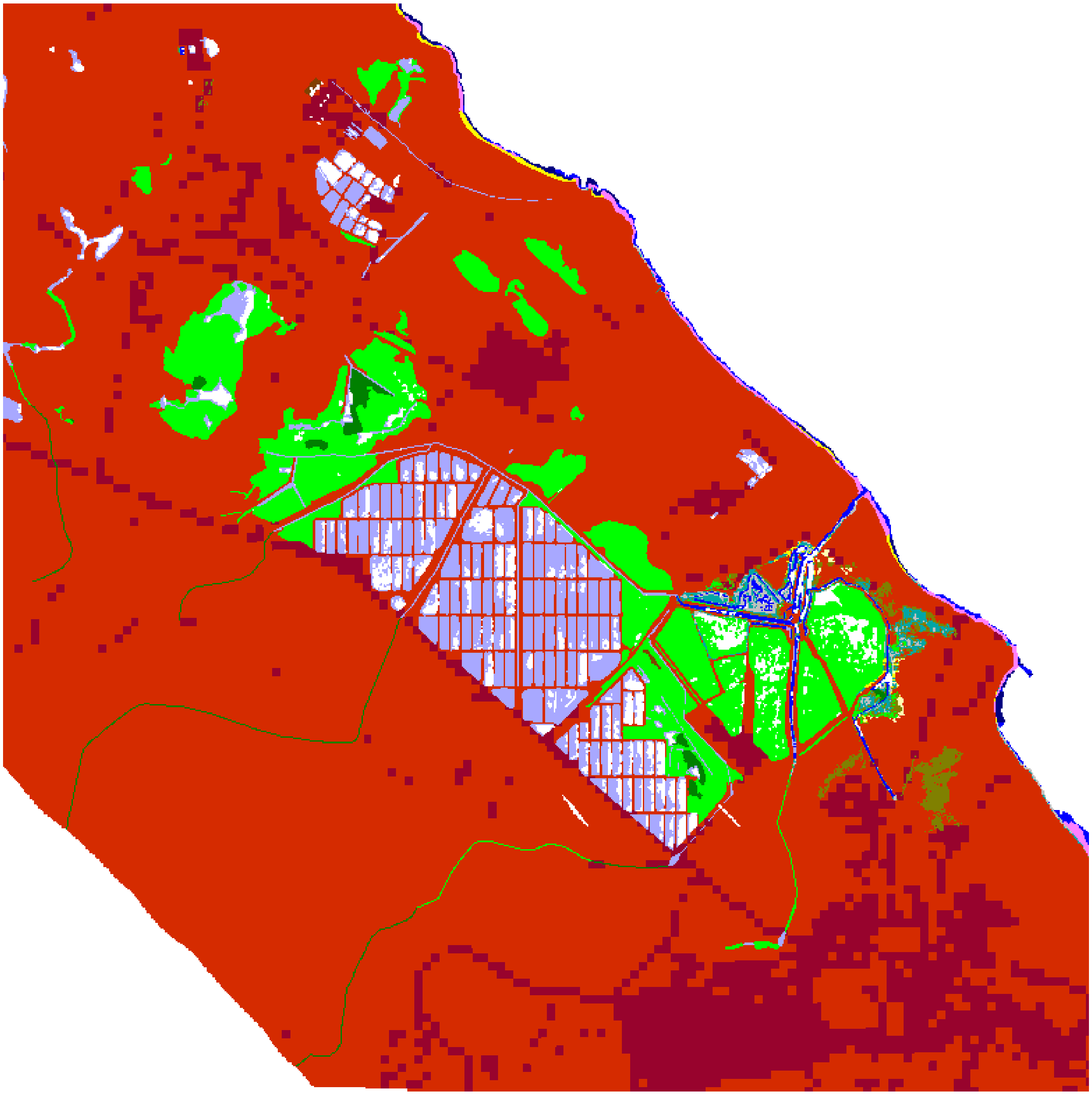
James Campbell Context, 2100, Scenario A1B Mean



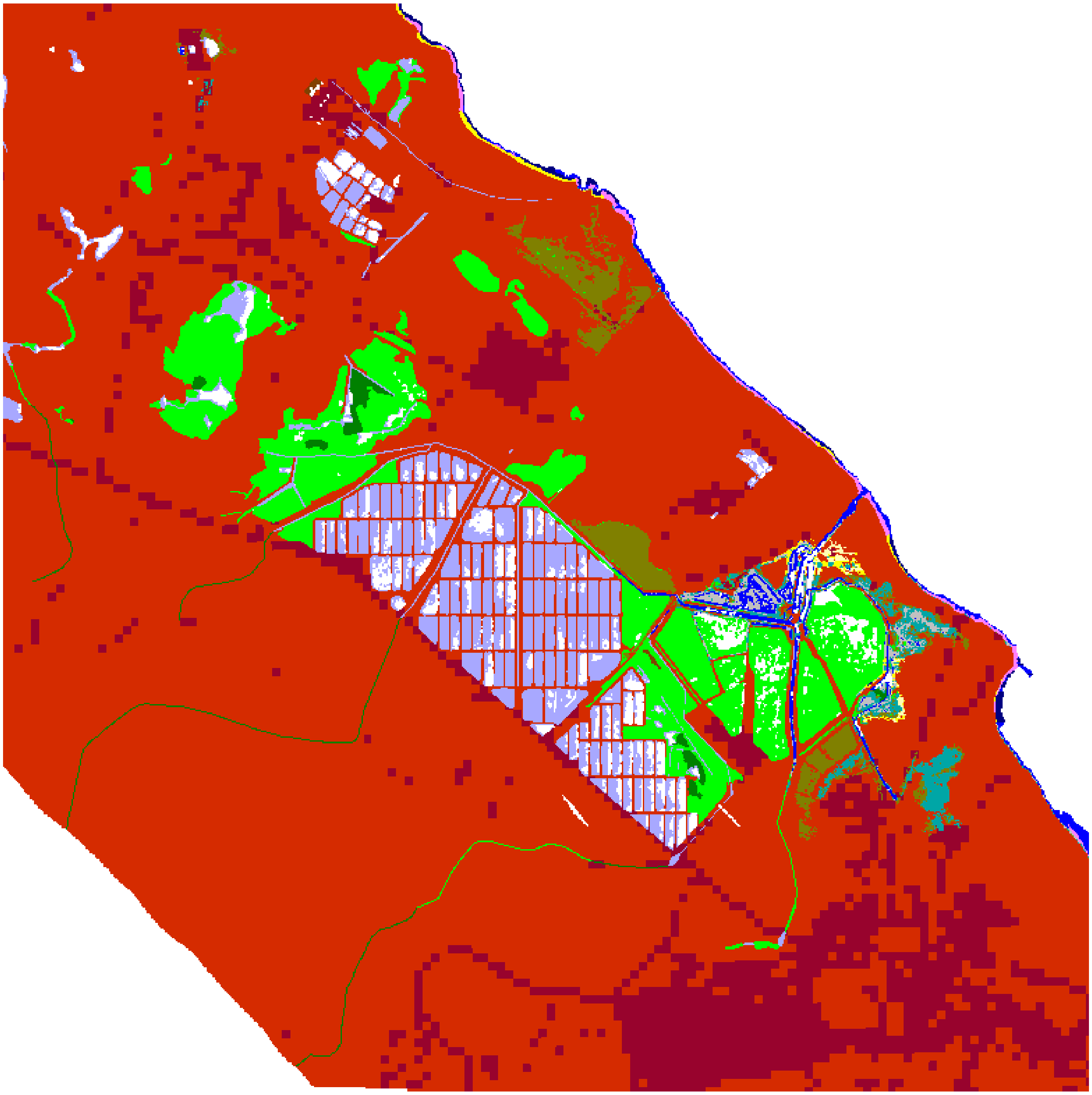
James Campbell Context, Initial Condition



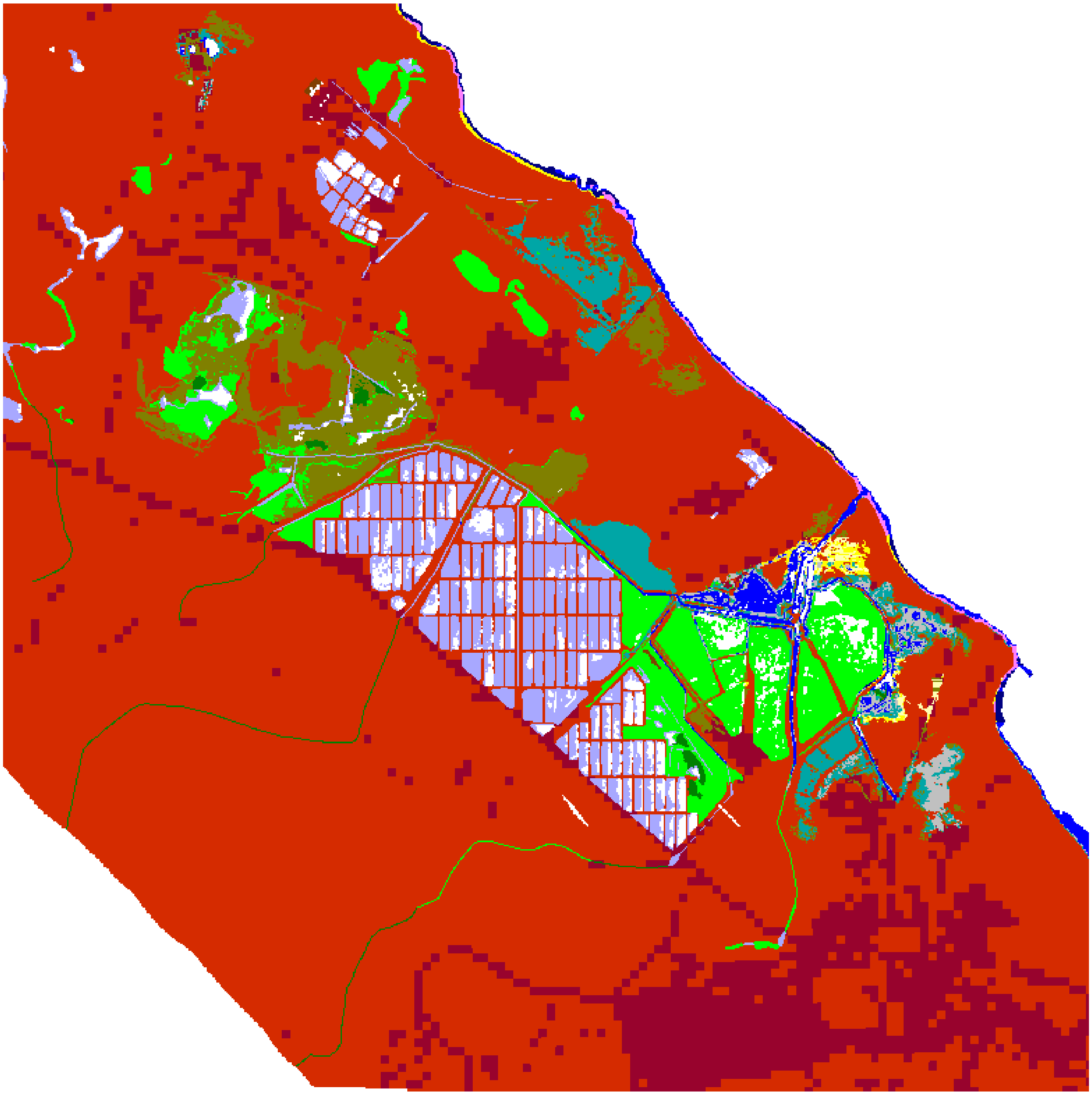
James Campbell Context, 2025, Scenario A1B Maximum



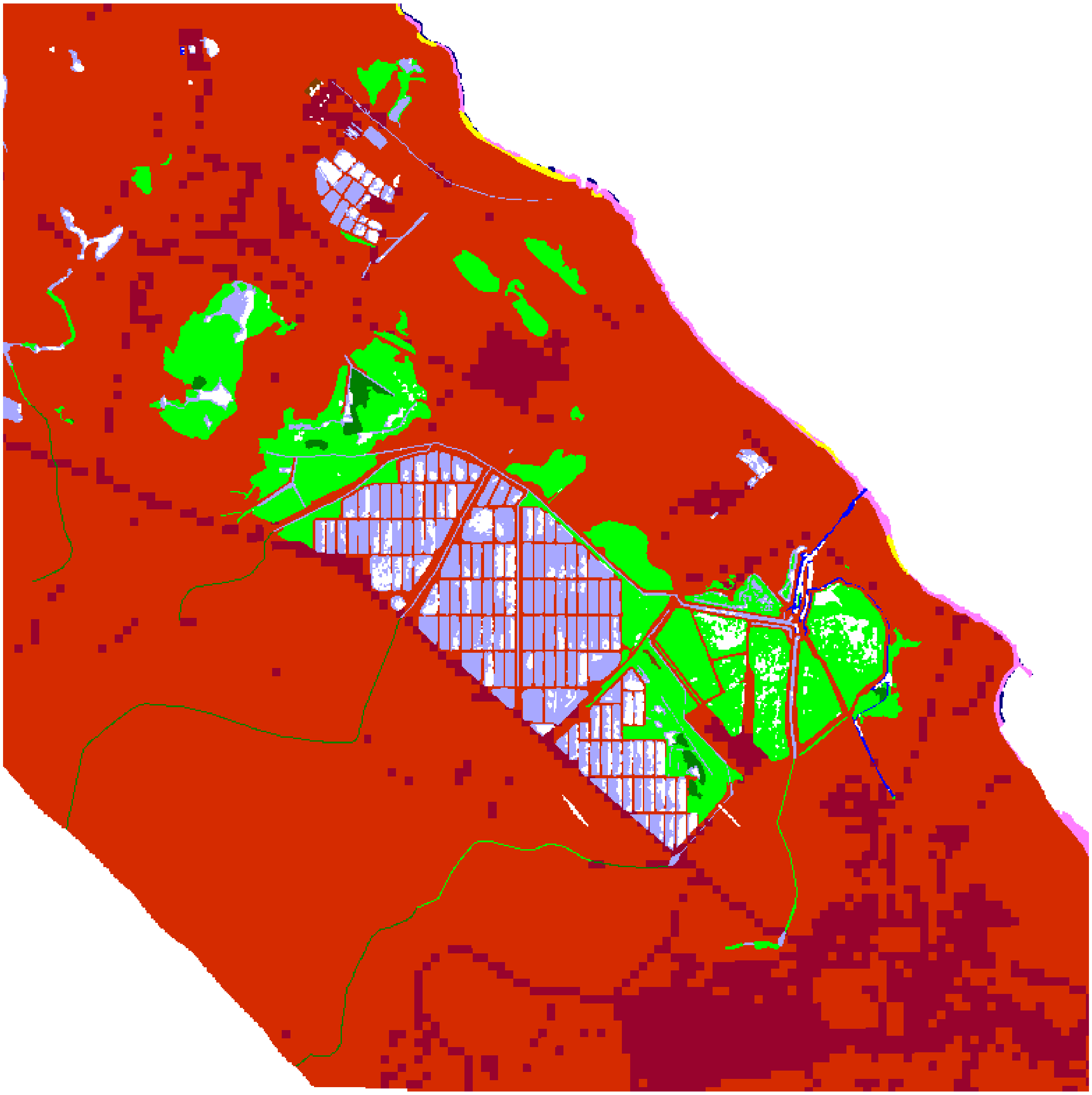
James Campbell Context, 2050, Scenario A1B Maximum



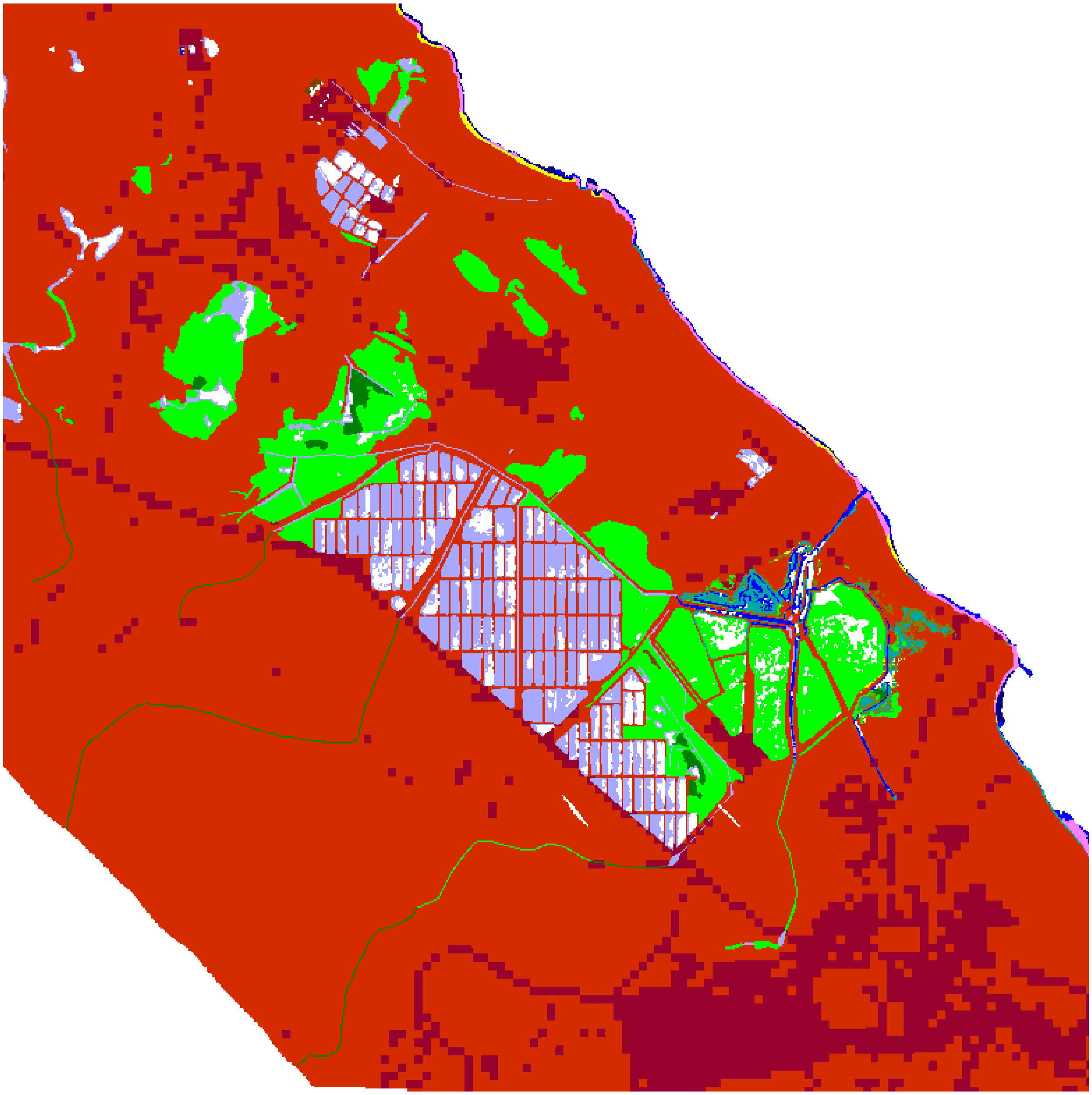
James Campbell Context, 2075, Scenario A1B Maximum



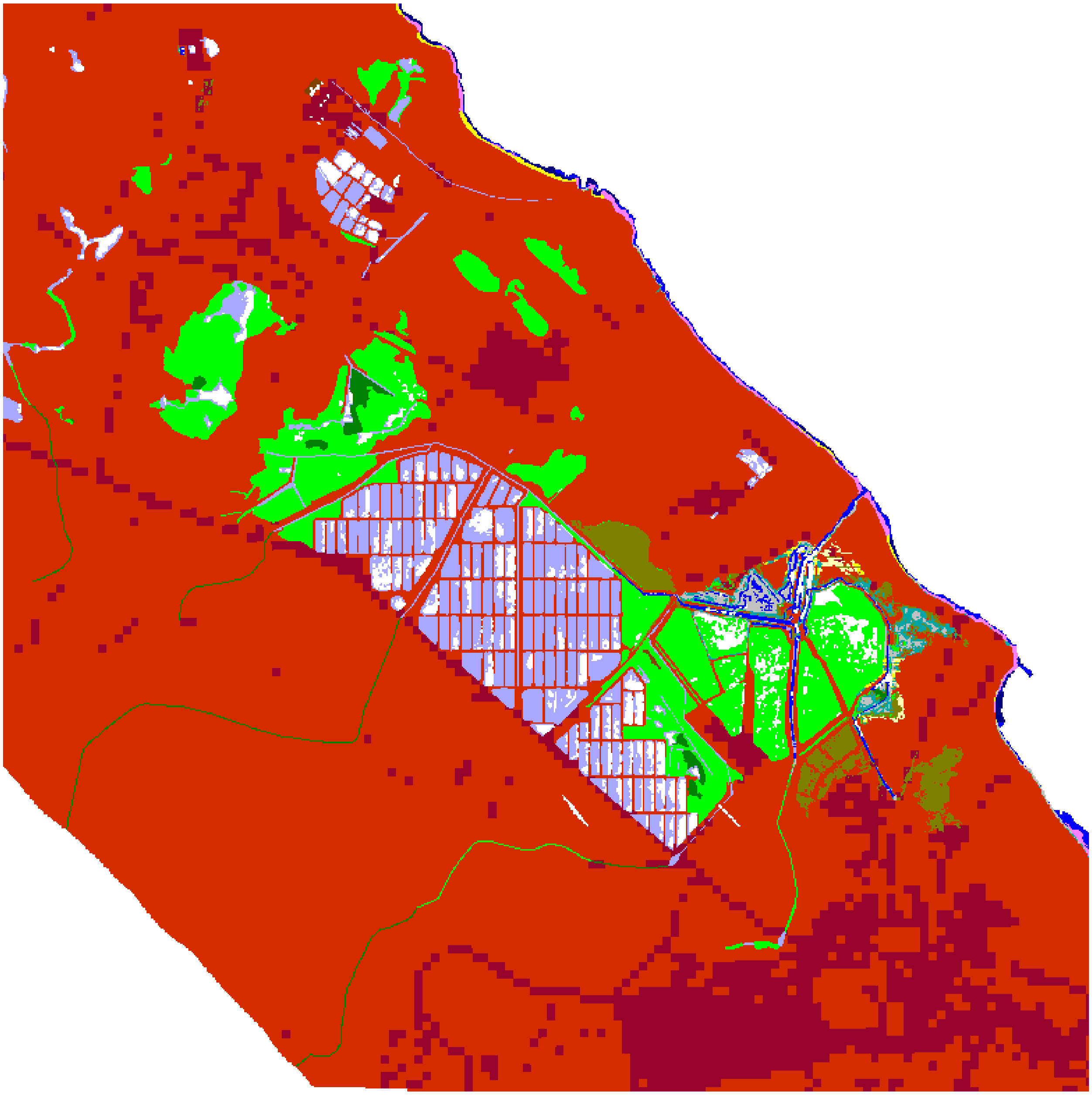
James Campbell Context, 2100, Scenario A1B Maximum



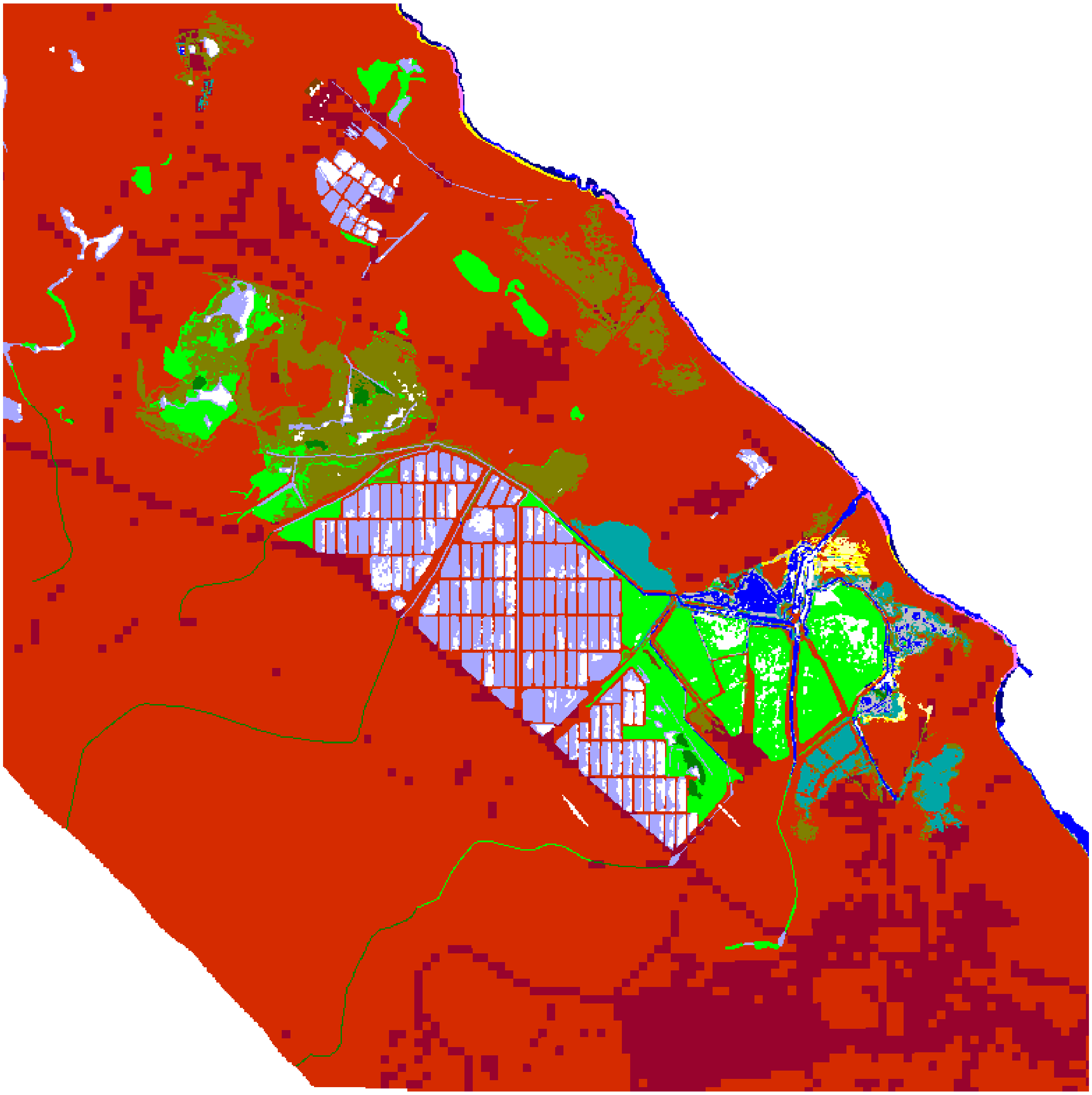
James Campbell Context, Initial Condition



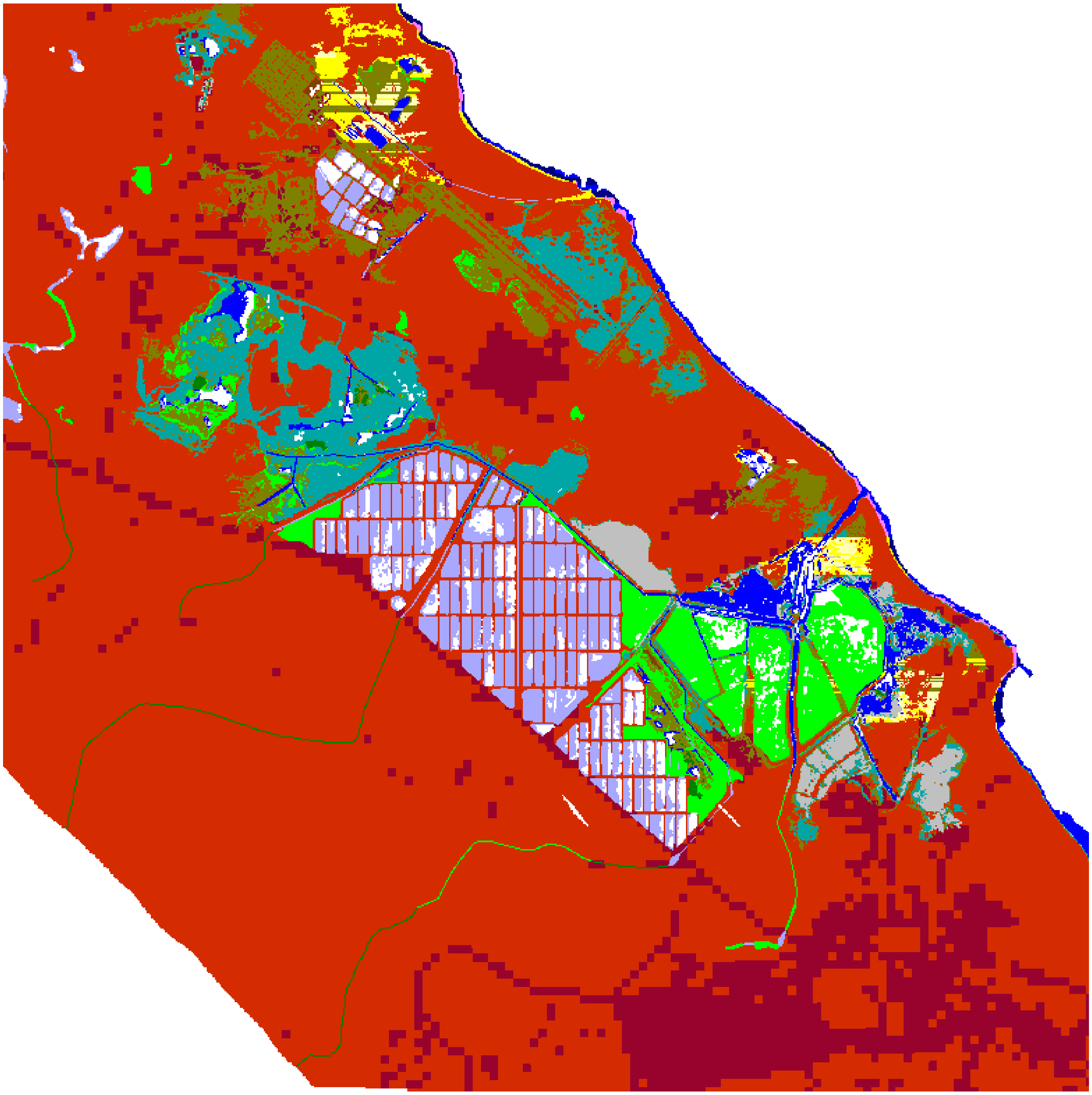
James Campbell Context, 2025, 1 meter



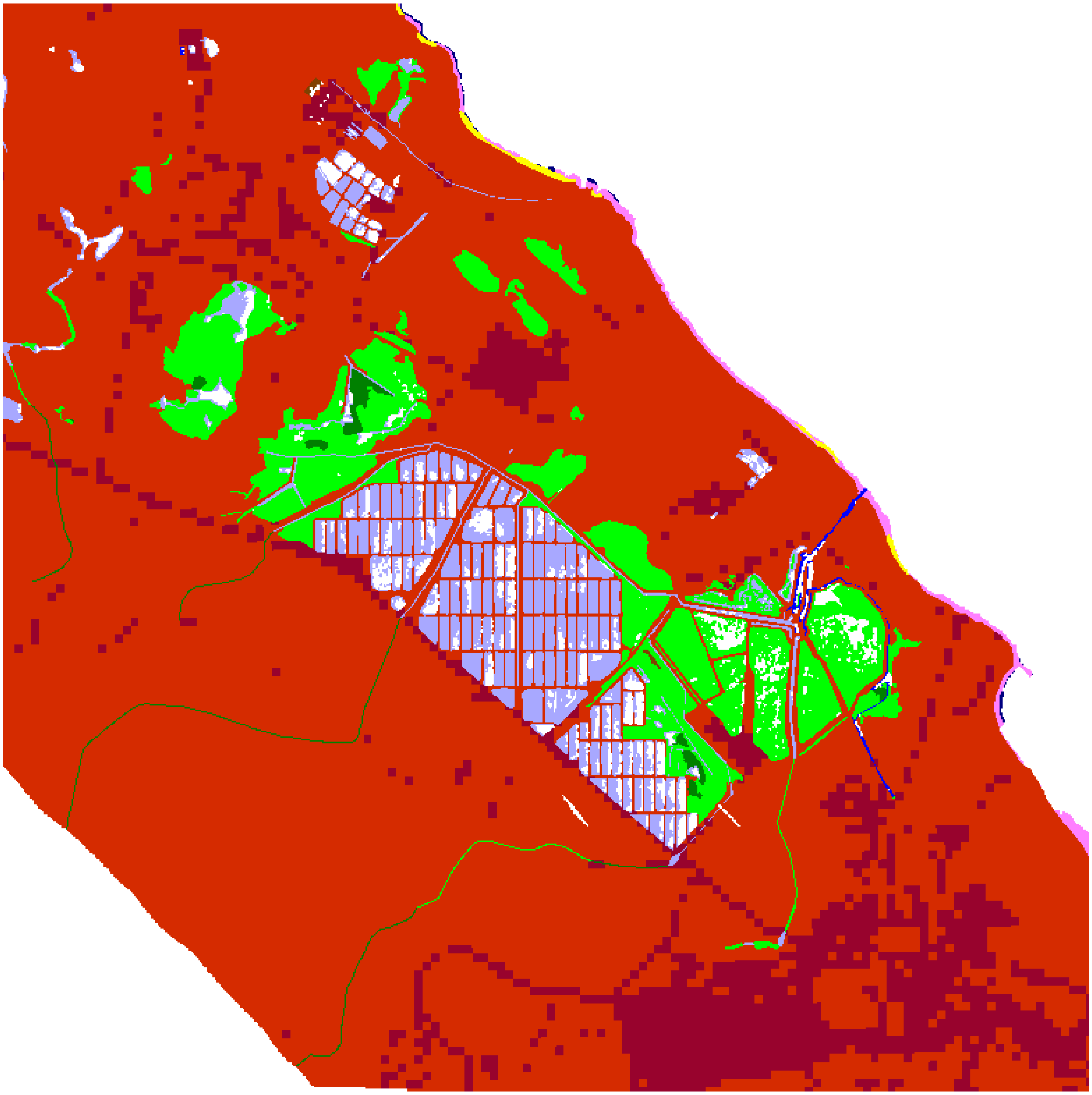
James Campbell Context, 2050, 1 meter



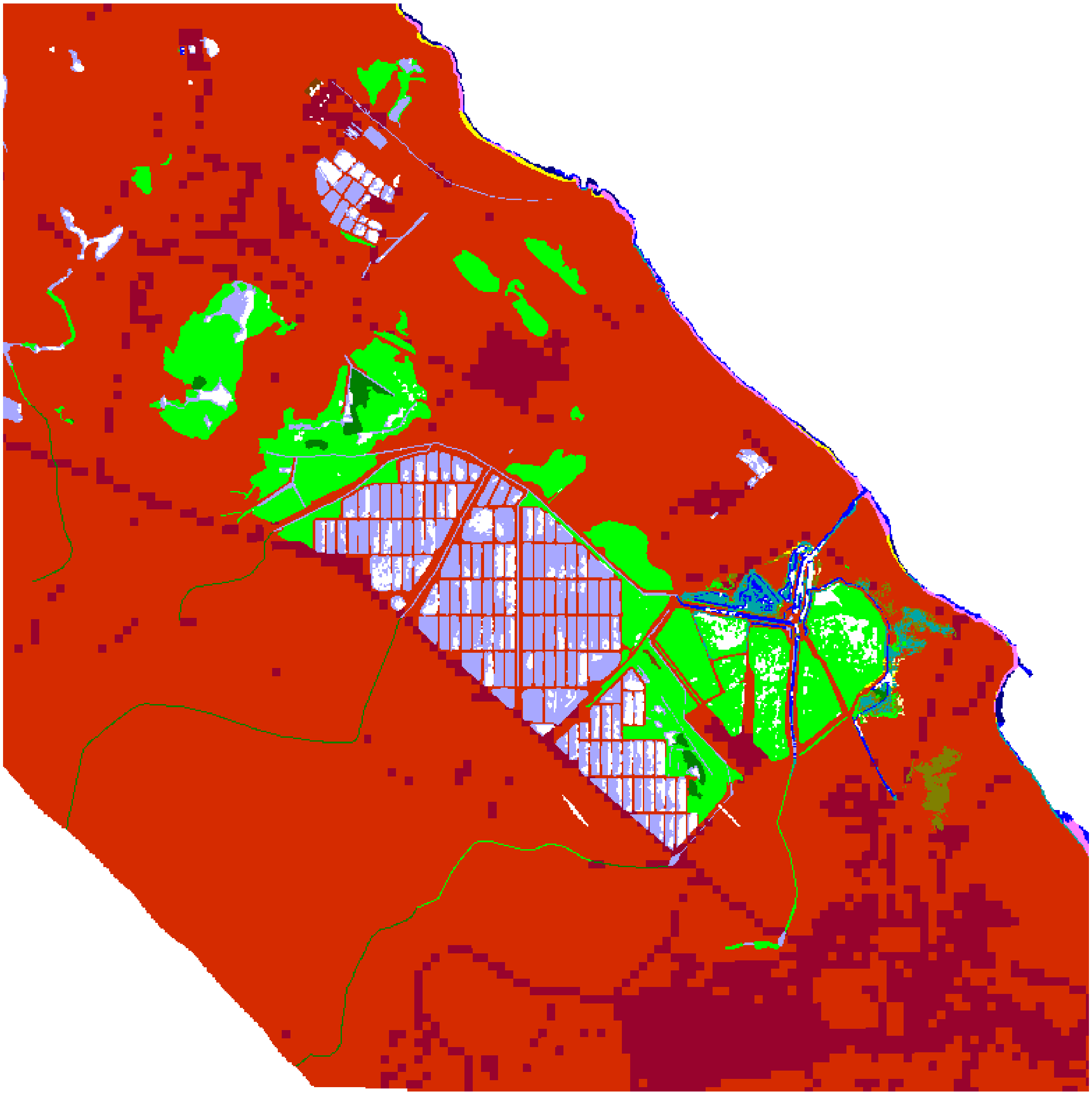
James Campbell Context, 2075, 1 meter



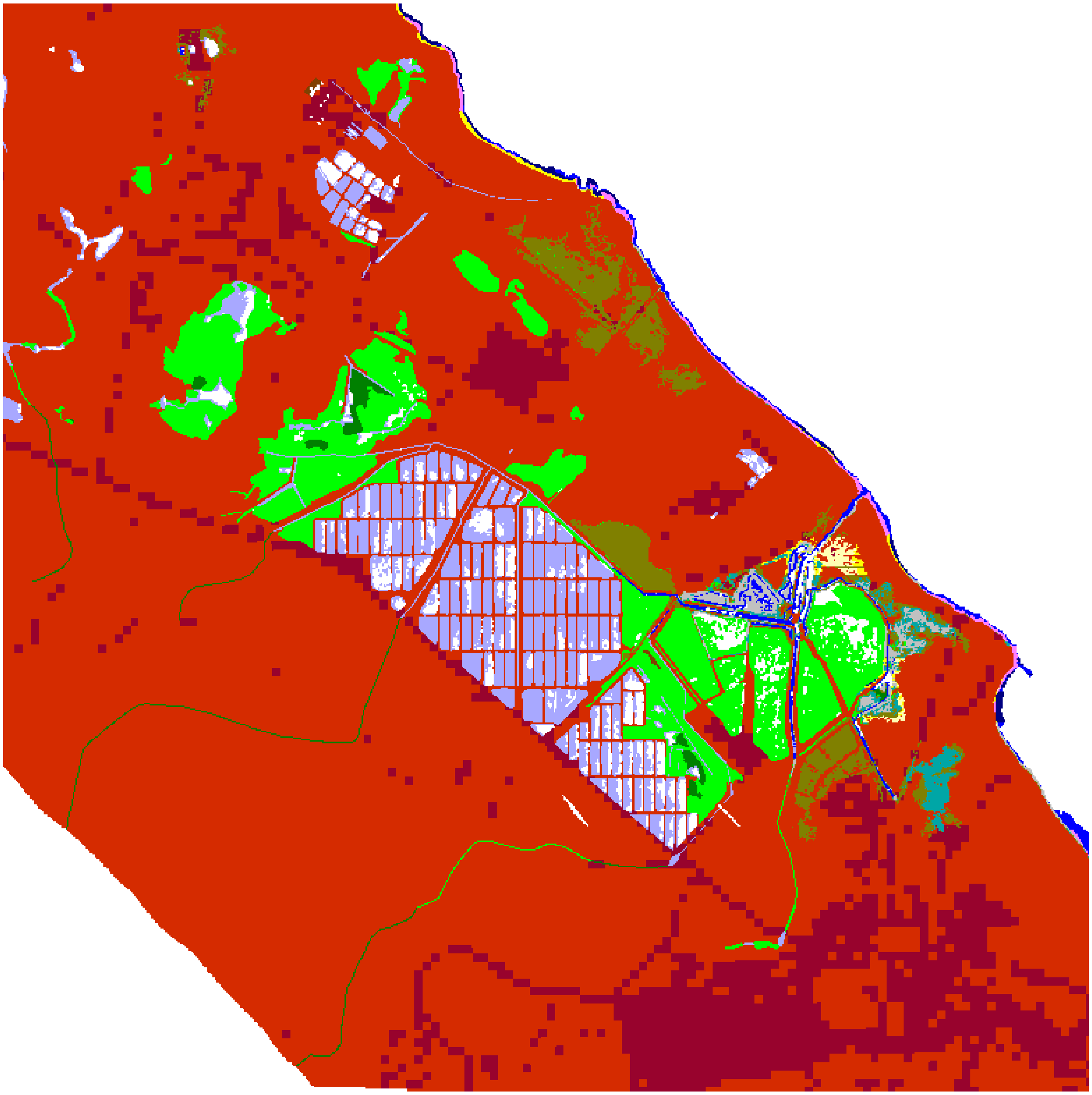
James Campbell Context, 2100, 1 meter



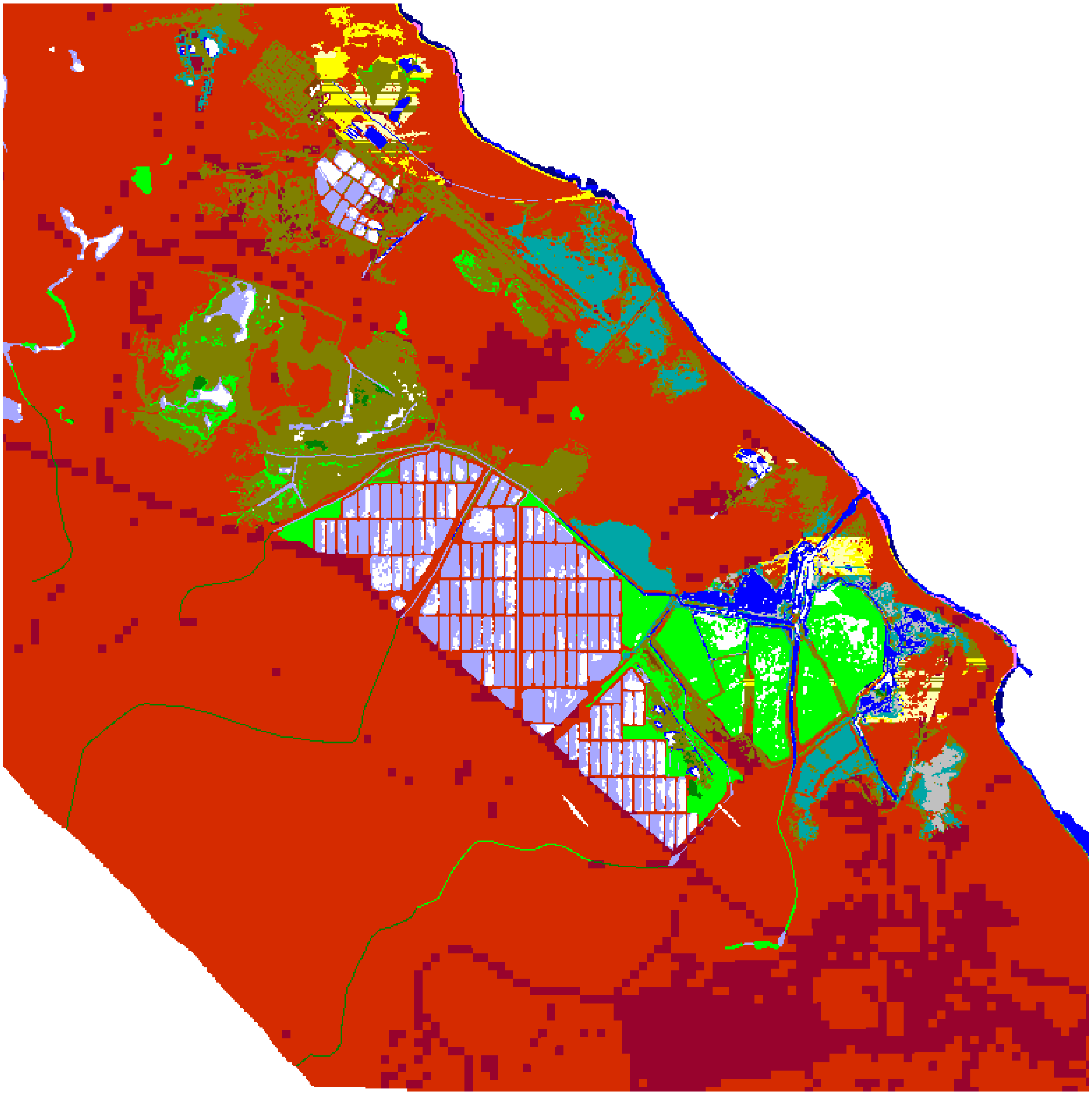
James Campbell Context, Initial Condition



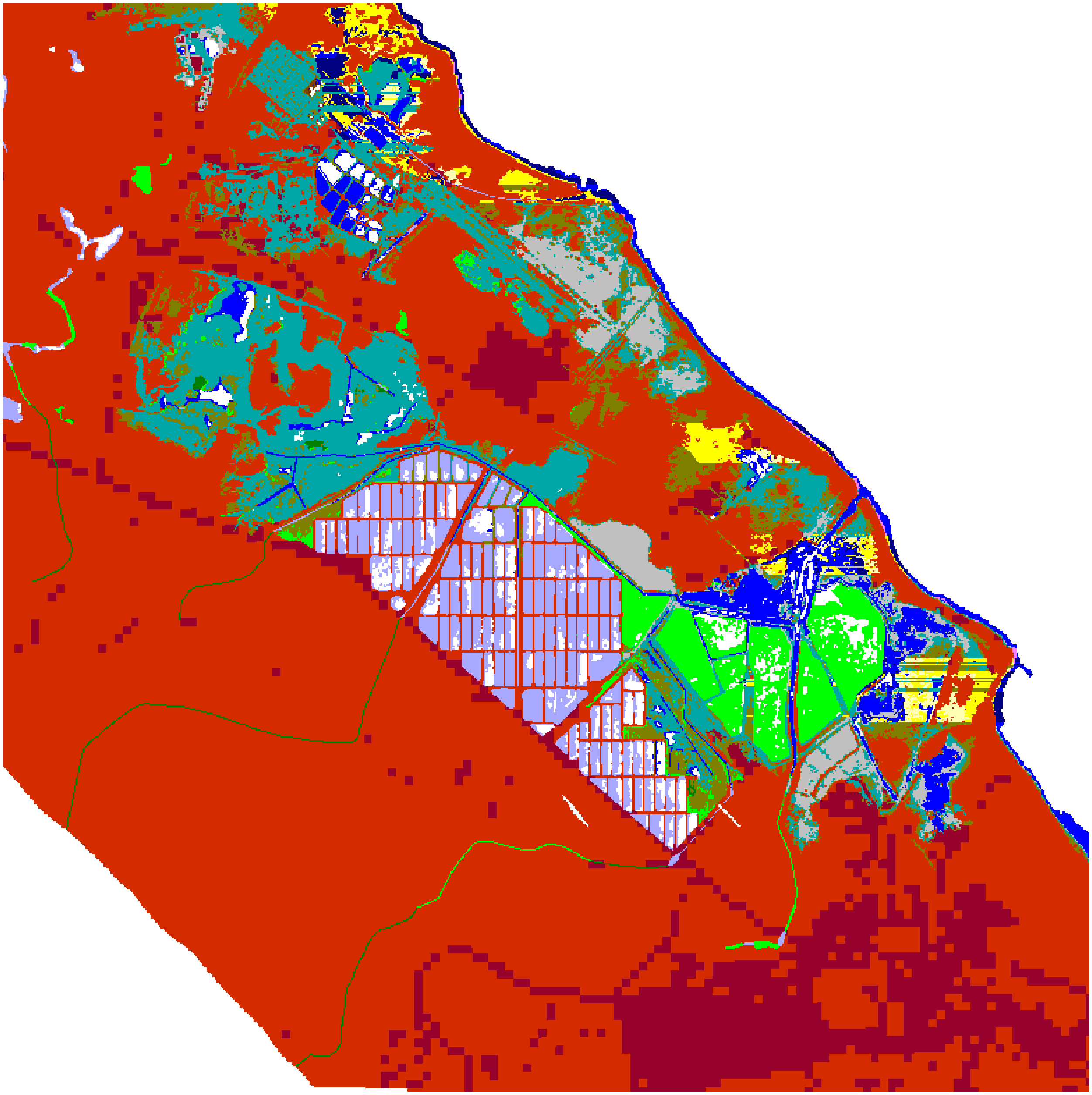
James Campbell Context, 2025, 1.5 meter



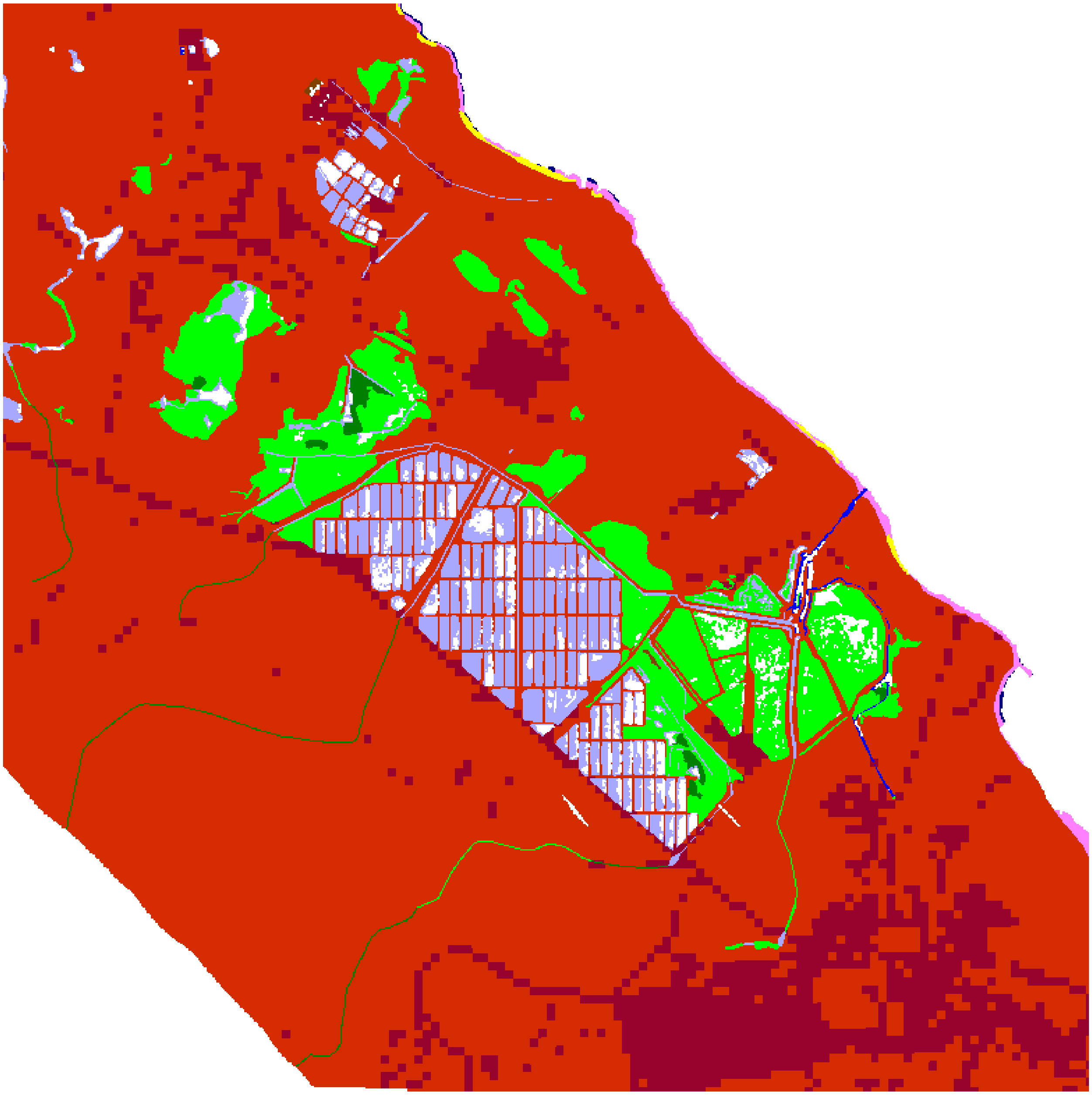
James Campbell Context, 2050, 1.5 meter



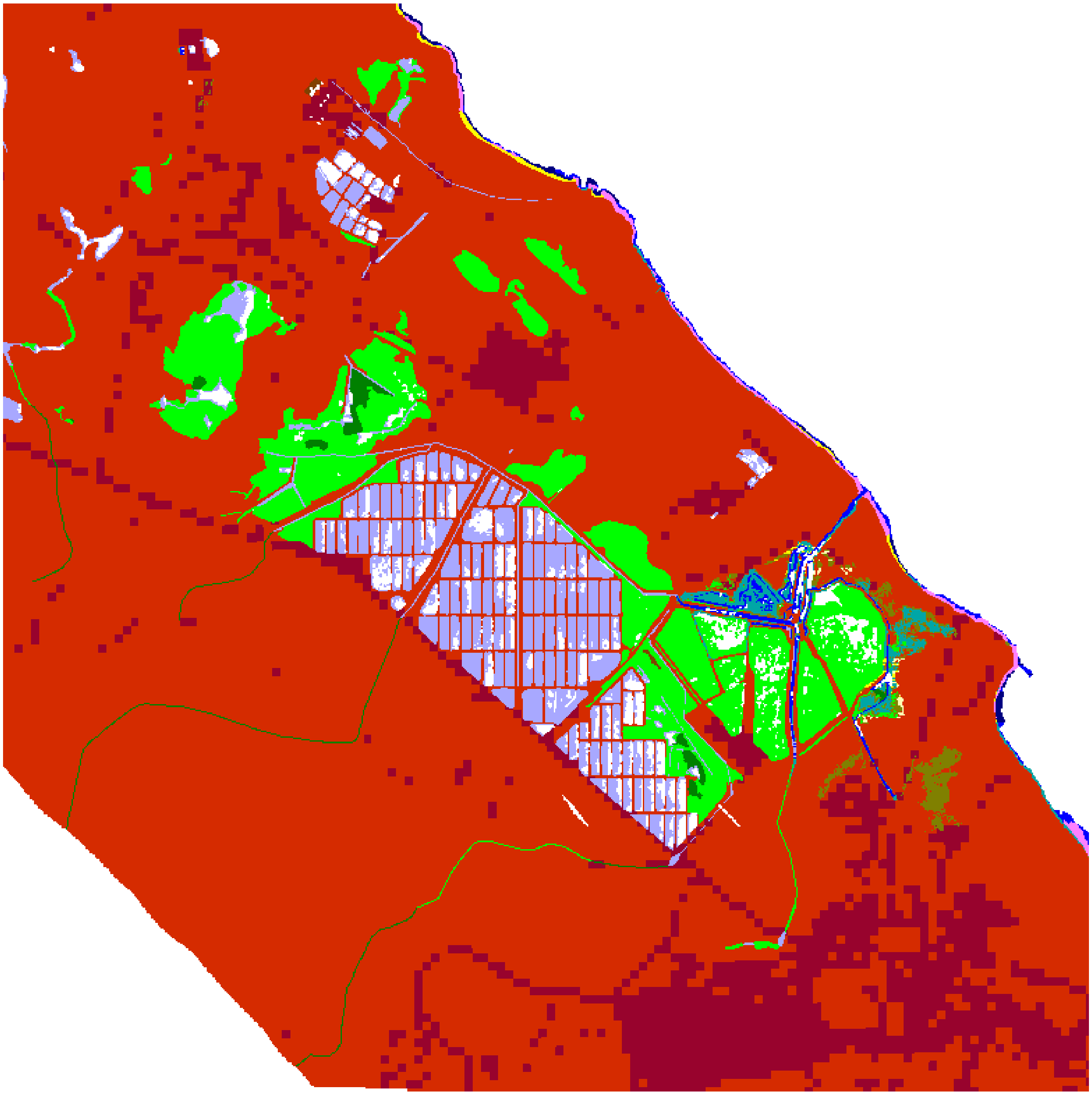
James Campbell Context, 2075, 1.5 meter



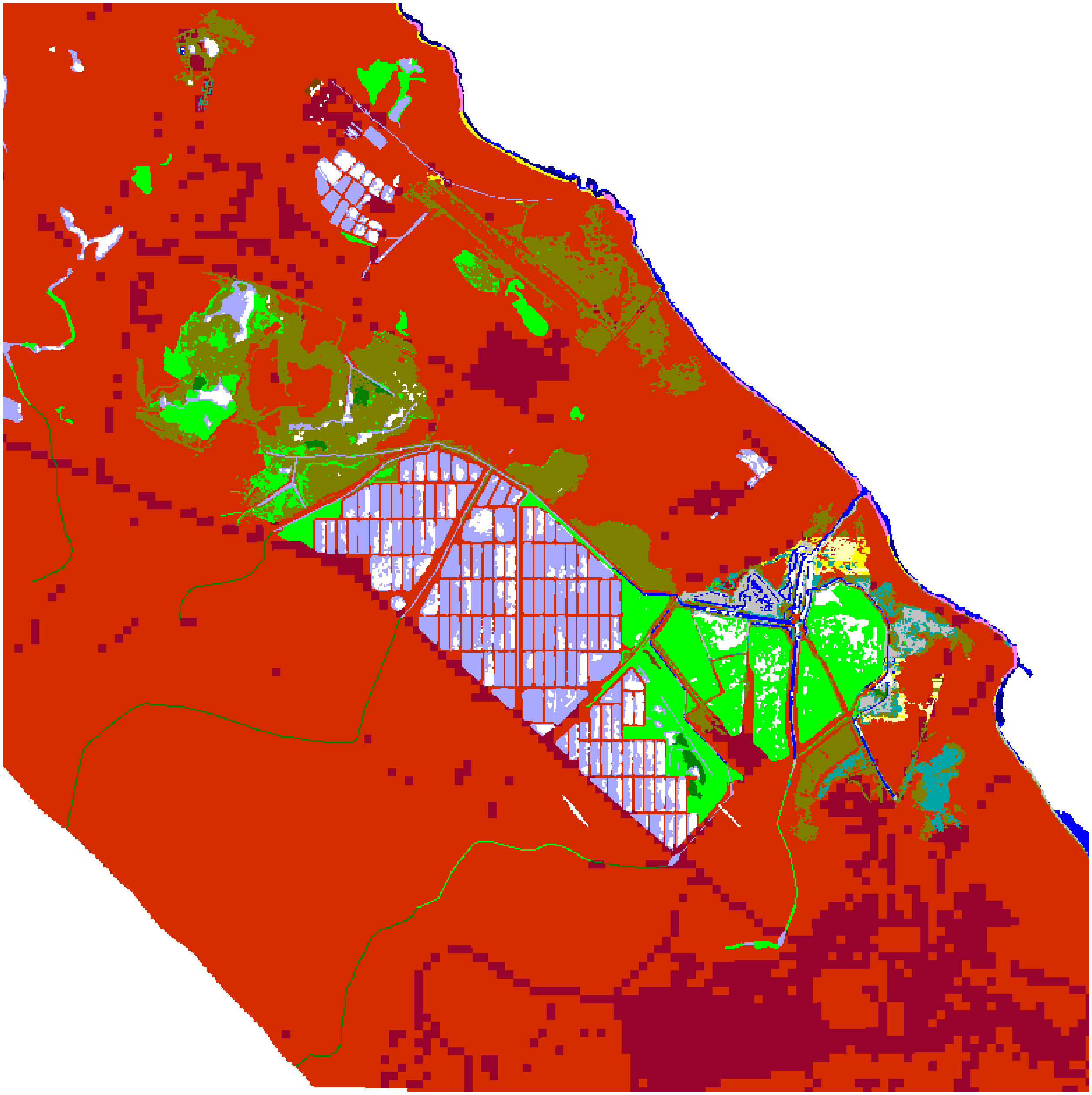
James Campbell Context, 2100, 1.5 meter



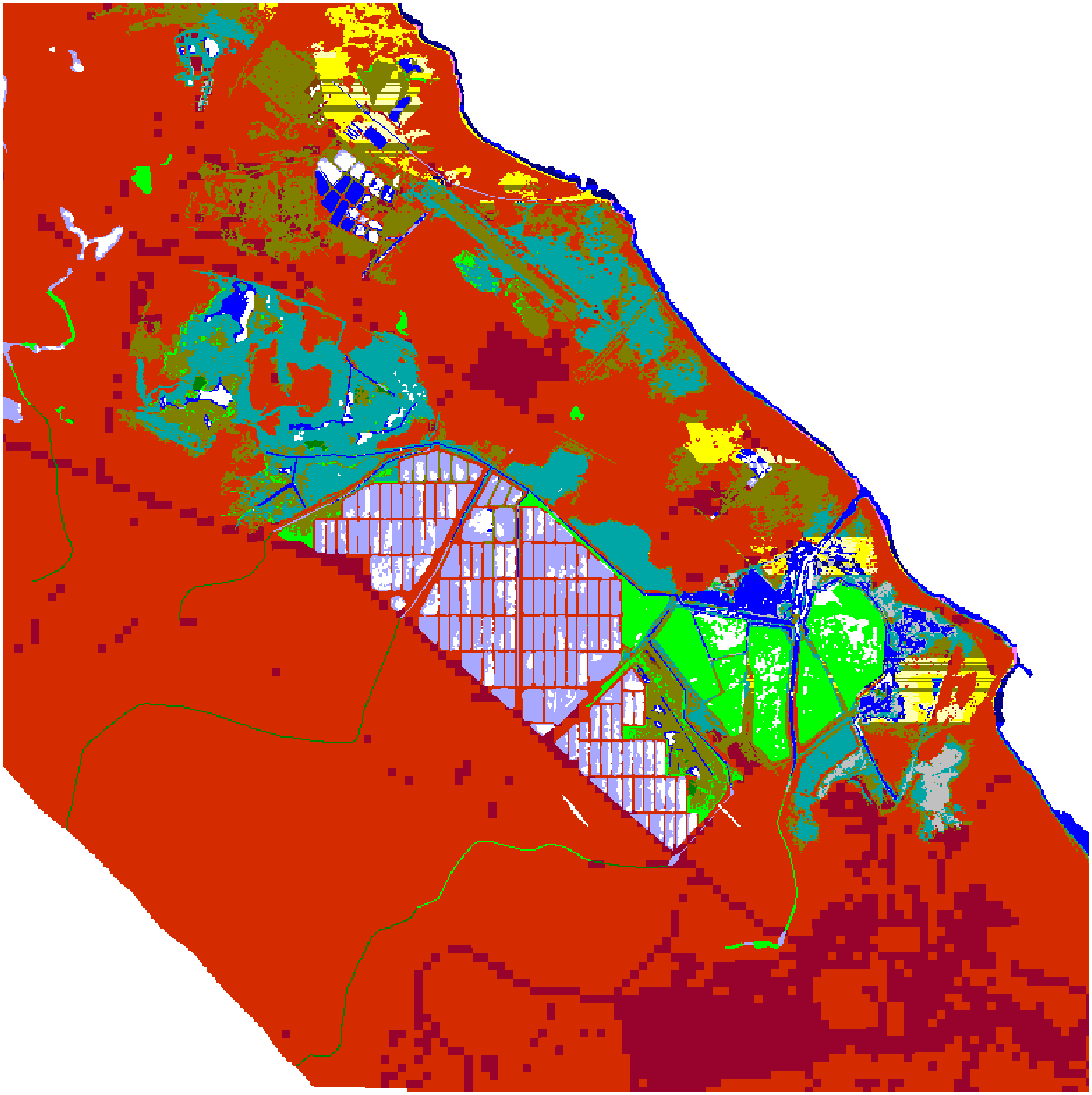
James Campbell Context, Initial Condition



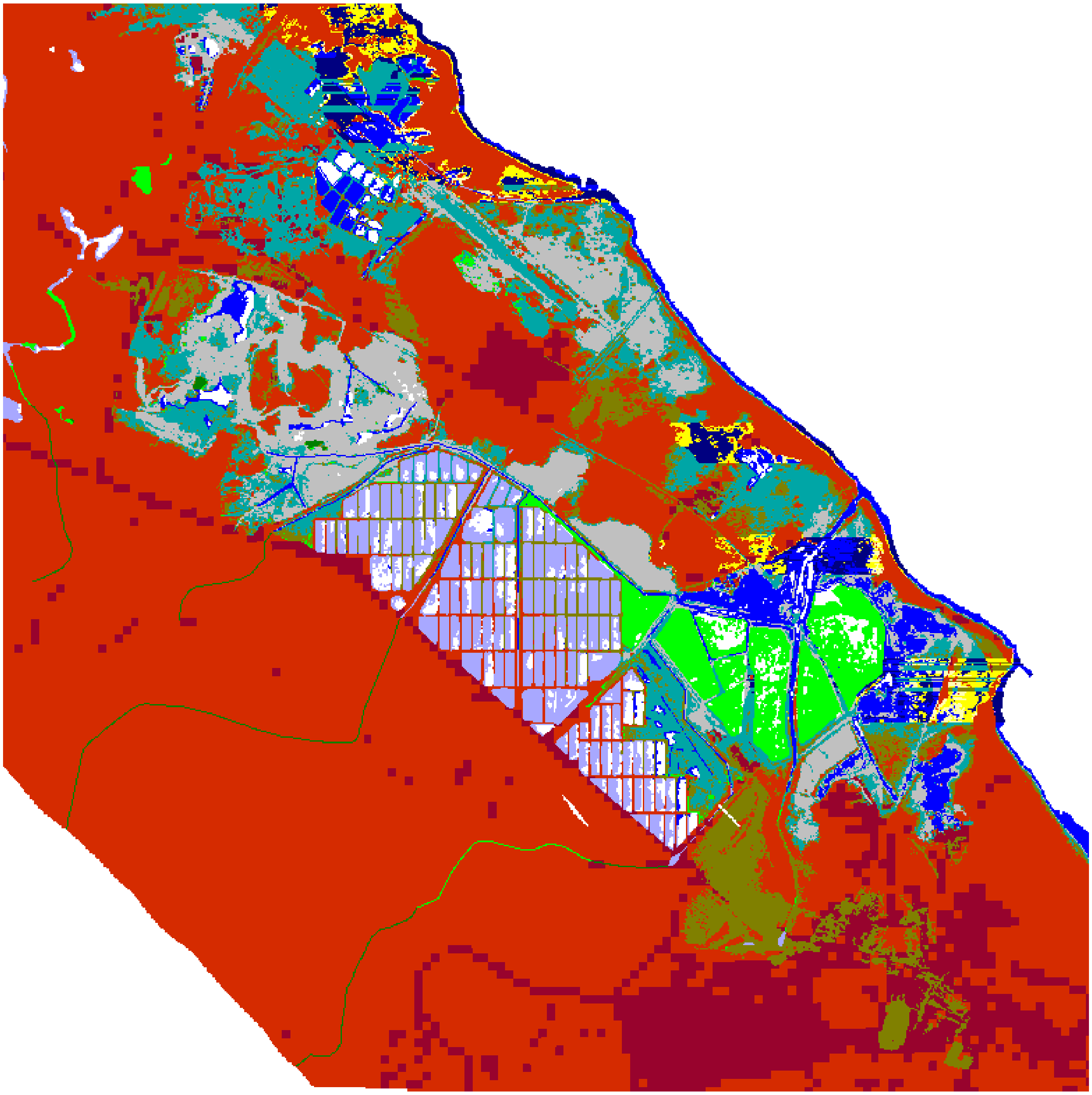
James Campbell Context, 2025, 2 meter



James Campbell Context, 2050, 2 meter



James Campbell Context, 2075, 2 meter



James Campbell Context, 2100, 2 meter