Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Lower Rio Grande Valley NWR

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) suggested that global sea level will increase by approximately 30 cm to 100 cm by 2100 (IPCC 2001). Rahmstorf (2007) suggests that this range may be too conservative and that the feasible range by 2100 is 50 to 140 cm. Rising sea levels may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat "migration" as salt marshes transgress landward and replace tidal freshwater and irregularly flooded marsh (R. A. 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 many coastal Region 2 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 et al. 1992; Park et al. 1993; Galbraith et al. 2002; National Wildlife Federation & Florida Wildlife Federation 2006; Glick 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 (m) width are assumed to undergo overwash during each specified interval for large storms. Beach migration and transport of sediments are calculated.
- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the fresh water table to rising sea level close to the coast.

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

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

- Accretion Feedback Component: Feedbacks based on wetland elevation, distance to channel, and salinity may be specified. This feedback will be used in USFWS simulations, but only where adequate data exist for parameterization.
- Salinity Model: Multiple time-variable freshwater flows may be specified. Salinity is estimated and mapped at MLLW, MHHW, and MTL. Habitat switching may be specified as a function of salinity. This optional sub-model is not utilized in USFWS simulations.
- Integrated Elevation Analysis: SLAMM will summarize site-specific categorized elevation ranges for wetlands as derived from LiDAR data or other high-resolution data sets. This functionality is used in USFWS simulations to test the SLAMM conceptual model at each site. The causes of any discrepancies are then tracked down and reported on within the model application report.
- Flexible Elevation Ranges for land categories: If site-specific data indicate that wetland elevation ranges are outside of SLAMM defaults, a different range may be specified within the interface. In USFWS simulations values outside of SLAMM defaults are 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 et al. 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 (Council for Regulatory Environmental Modeling 2008). Site-specific factors that increase or decrease model uncertainty may be covered in the *Discussion* section of this report.

Sea Level Rise Scenarios

SLAMM 6 was run using scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 family of scenarios assumes that the future world includes rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. In particular, the A1B scenario assumes that energy sources will be balanced across all sources. Under the A1B scenario, the IPCC WGI Fourth Assessment Report (IPCC 2007) suggests a likely range of 0.21 to 0.48 m of SLR by 2090-2099 "excluding future rapid dynamical changes in ice flow." The A1B-mean scenario that was run as a part of this project falls near the middle of this estimated range, predicting 0.39 m of global SLR by 2100. A1B-maximum predicts 0.69 m of global SLR by 2100.

The latest literature (Chen et al. 2006; Monaghan et al. 2006) indicates that the eustatic rise in sea levels is progressing more rapidly than was previously assumed, perhaps due to the dynamic changes in ice flow omitted within the IPCC report's calculations. A recent paper in the journal *Science* (Rahmstorf 2007) suggests that, taking into account possible model error, a feasible range by 2100 of 50 to 140 cm. This work was recently updated and the ranges were increased to 75 to 190 cm (Vermeer and Rahmstorf 2009). Pfeffer et al. (2008) suggests that 2 m 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 SLRs for the end of the 21st century are too low" (Clark 2009). A recent paper by Grinsted et al. (2009) states that "sea level 2090-2099 is projected to be 0.9 to 1.3 m for the A1B scenario…" Grinsted also states that there is a "low probability" that SLR will match the lower IPCC estimates.

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 m, 1.5 m, and 2 m of eustatic SLR by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 1).

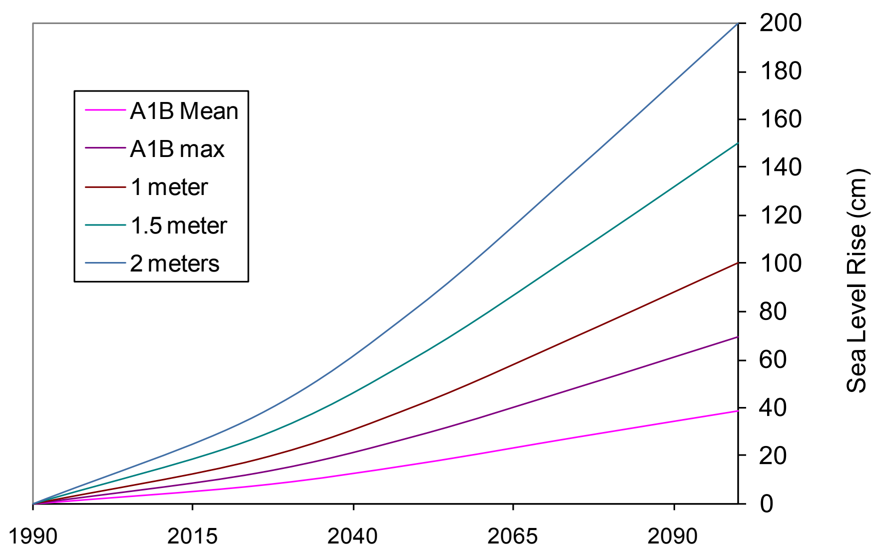


Figure 1. Summary of SLR scenarios utilized

Data Sources and Methods

Wetland layer. Figure 2 shows the most recent wetland layer obtained from a National Wetlands Inventory (NWI) photo dated 1994. The approved acquisition boundary (including water) extends far inland, covering Hidalgo and Starr counties in their in entirety. However, as these regions are far from the ocean and have elevations higher than 15 m, the study area only considers Willacy and Cameron counties. Converting the NWI survey into 30 m cells indicated that the approximately 1,359,000 acre of the study area is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Undeveloped Dry Land	949,491	70
	Estuarine Open Water	135,285	10
	Developed Dry Land	76,152	6
	Estuarine Beach	64,720	5
	Inland Fresh Marsh	48,753	4
	Tidal Flat	35,343	3
	Inland Open Water	24,336	2
	Irregularly Flooded Marsh	11,027	<1
	Inland Shore	7,568	<1
	Regularly Flooded Marsh	2,412	<1
	Swamp	1,280	<1
	Open Ocean	838	<1
	Riverine Tidal	735	<1
	Transitional Salt Marsh	315	<1
	Ocean Beach	199	<1
	Tidal Fresh Marsh	5	<1
	Total (incl. water)	**1358458**	**100**

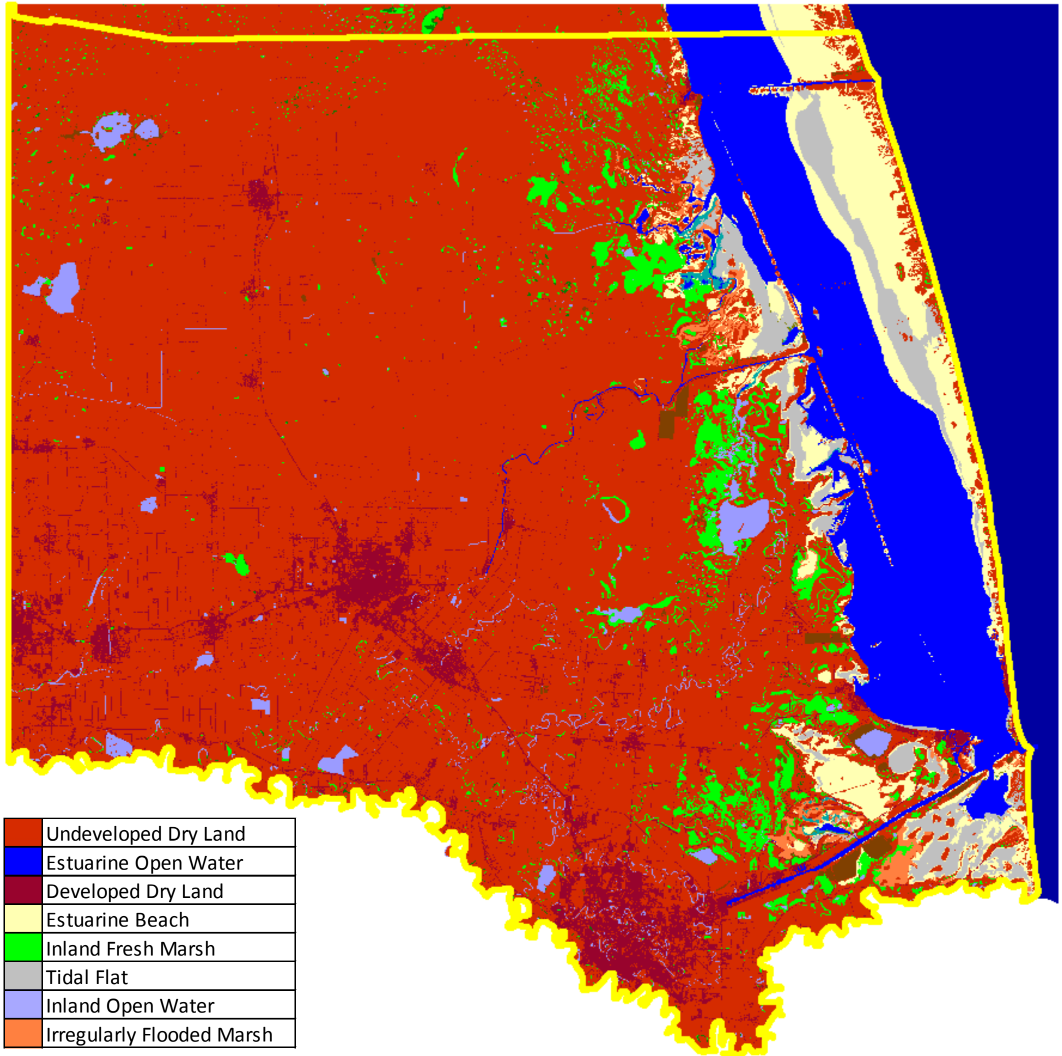


Figure 2. Wetland coverage of the study area. Modeling boundaries indicated in yellow

Elevation Data. The digital elevation map (DEM) used in this simulation, shown in Figure 3, is a bare-earth dataset that was derived by combining data from a 2006 Texas Water Development Board LiDAR, and an International Boundary and Water Commission LiDAR dated 2005. Elevations for remaining inland regions and open waters were taken from the National Elevation Dataset. Within NED-covered regions, the elevation pre-processor module of SLAMM was used to assign elevations for wetlands as a function of the local tide range. For a more in-depth description of the elevation preprocessor, see the SLAMM 6 technical documentation (Clough et al. 2010). This process causes additional uncertainty in model results as covered in the *Discussion* section below.

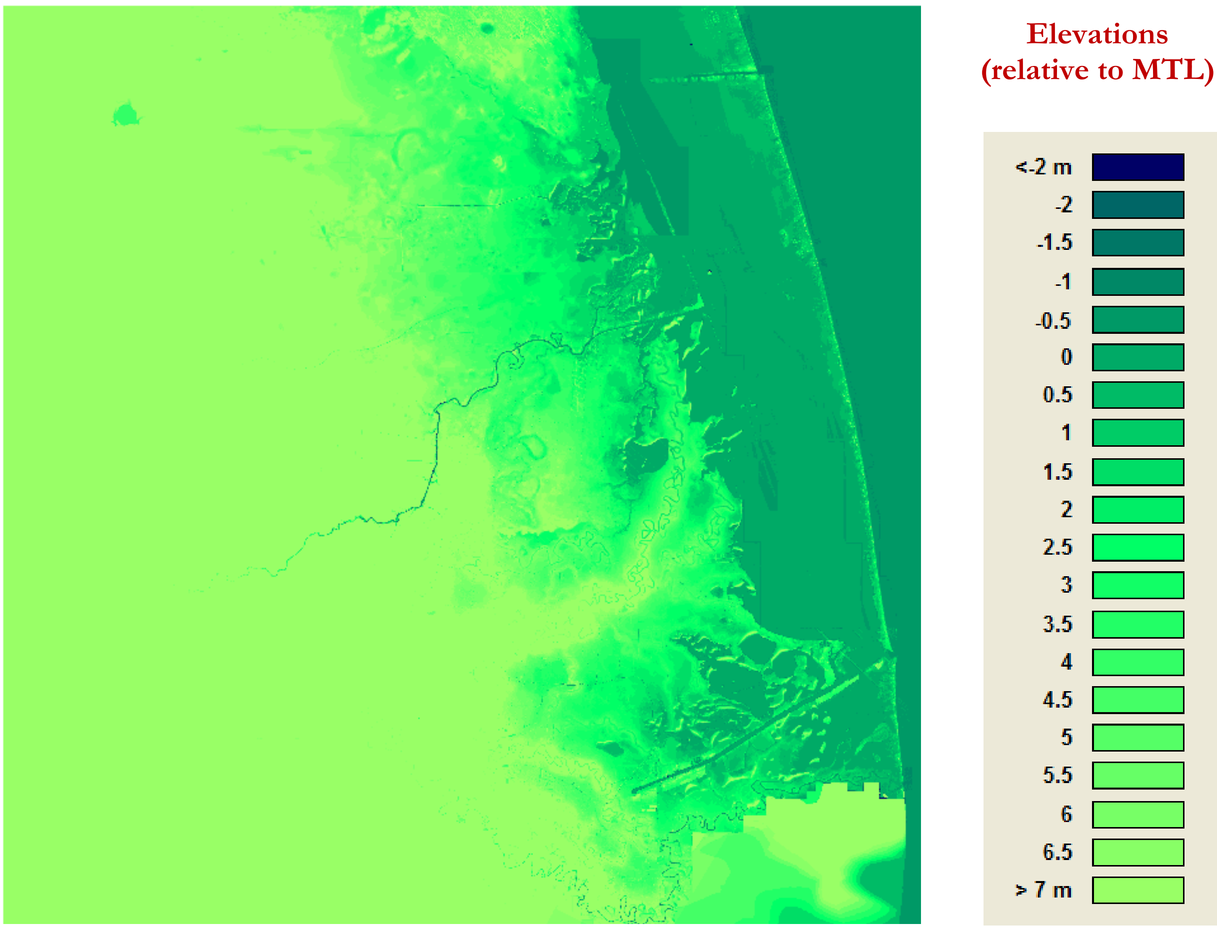


Figure 3. Shade-relief elevation map of the study area.

Model Timesteps. Model forecast outputs were chosen at years 2025, 2050, 2075 and 2100 with the initial condition date set to 1994 (the most recent wetland data available).

Dikes and Impoundments. According to the National Wetland Inventory, there are some inland fresh marsh and open water areas that are protected by dikes, as shown in Figure 4.

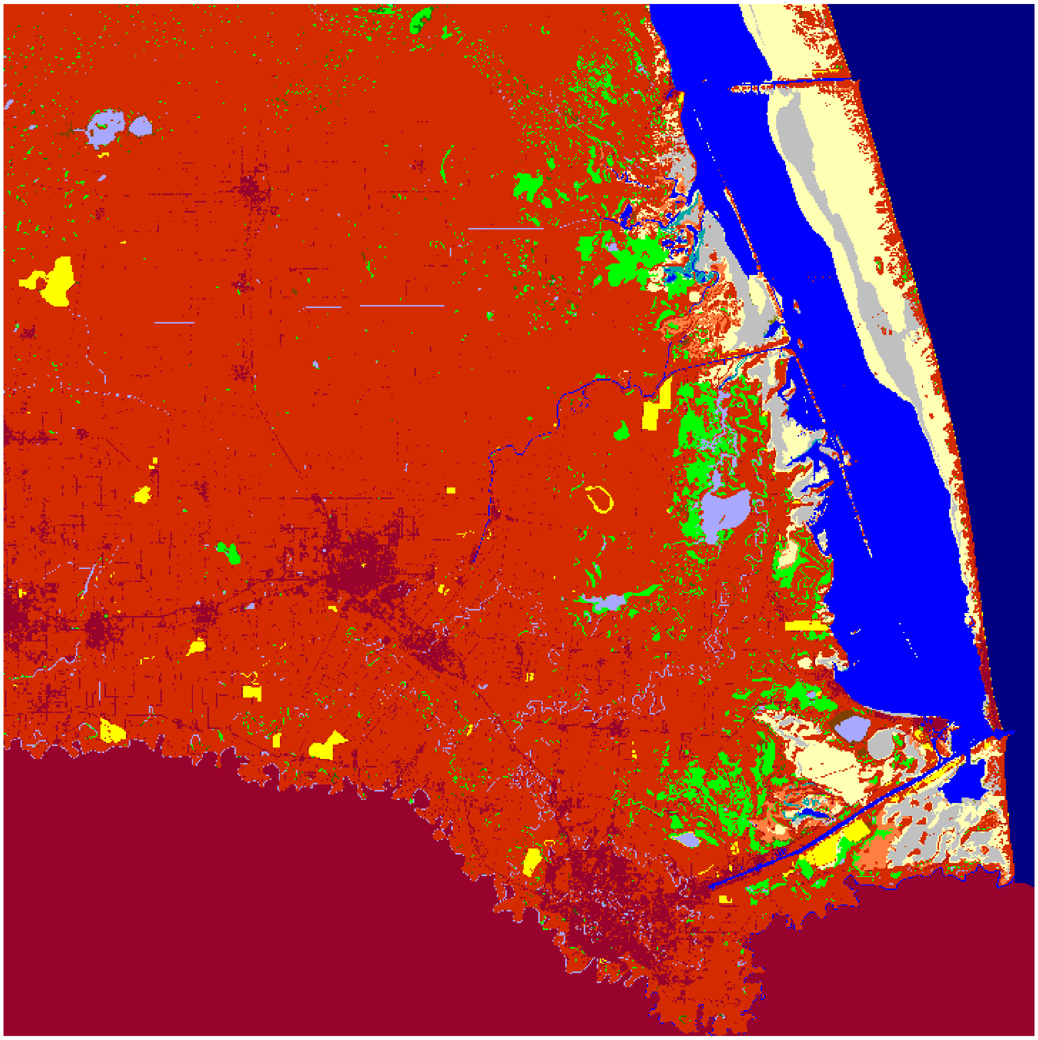


Figure 4. Dikes present in the study area (represented in yellow)

Historic sea-level rise rates. In the southern portion of the study area, at the NOAA gauge stations of Port Isabel (ID 8779770) and Padre Island (ID 8779750), measured historic rates of SLR are similar and average 3.64 mm/yr. Further north, at the Port Mansfield, gauge station (ID 8778490), just in front of the water pass connecting Red Fish Bay and the Gulf of Mexico, the recorded trend is 1.93 mm/yr. At Rockport, in Aransas Bay, historic SLR is 5.16 mm/yr on average. These rates of SLR are higher than the global average for the last 100 years (approximately 1.7 mm/year, IPCC 2007a), potentially reflecting land subsidence at this site. The values recorded at Port Isabel and Padre Island were chosen for this SLAMM simulation they are intermediate between other trends measured in this part of the Gulf of Mexico.

Tide Ranges. Figure 5 shows the locations of the 4 tide gauge stations (red marks) within the study area used to define the tide ranges for this site.

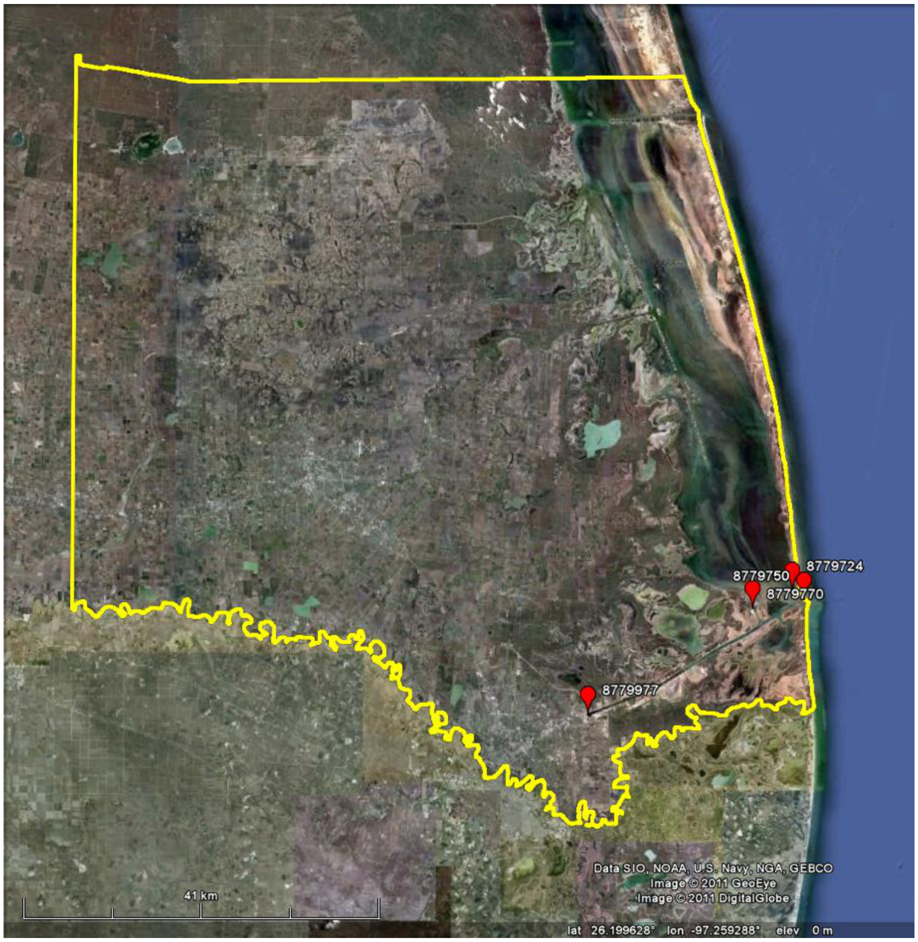


Figure 5. Location of NOAA tides gages used for Lower Rio Grande Valley NWR

The great diurnal tide range was derived by taking the average value of all the four stations observed values, summarized in Table 1, and subsequently set to 0.4 m.

Table 1. NOAA tide gauges and values.

Station ID	Site Name	Tide Range (m)
8779977	Brownsville, TX	0.462
8779770	Port Isabel, TX	0.425
8779750	South Padre Island C.g Station, TX	0.48
8779724	Queen Isabella Causeway, TX	0.391

Salt elevation. This parameter within SLAMM designates the boundary between wet lands and dry lands or saline wetlands and fresh water wetlands. As such, this value may be best derived by examining historical tide gage data. For this application, the salt boundary was defined as the elevation above which inundation is predicted less than once per thirty days using data from the gauge station at Brownsville, TX (ID 8779977) and Port Isabel, TX (ID 87779770). Estimated salt elevations are similar, approximately 2.1 Half Tide Units (HTU). As the great tide range is estimated to be uniform in the study area, 0.4 m above MTL, salt elevation is set to 0.42 m above MTL.

Accretion/erosion rates. Accretion and erosion rates for marshes are summarized in Table 2 and were set to the values used in a recent study of Aransas NWR (Callaway et al. 1997), a little further north of the Lower Rio Grande Valley NWR.

Elevation correction. The MTL to NAVD88 correction of -0.035 m was derived using NOAA gauge stations in the area that have this datum, Port Isabel and Queen Island Causeway (ID 8779739).

Refuge boundaries. Modeled USFWS refuge boundaries for Texas are based on Approved Acquisition Boundaries as published on the USFWS National Wildlife Refuge Data and Metadata website. The cell-size used for this analysis was 30 m by 30 m cells.

Input subsites and parameter summary. Based on the different dates and types of DEMs, five different simulation input subsites were identified as illustrated in Figure 6. Table 2 summarizes all SLAMM input parameters for each subsite of the study area. Values for parameters with no specific local information were kept at their default value.

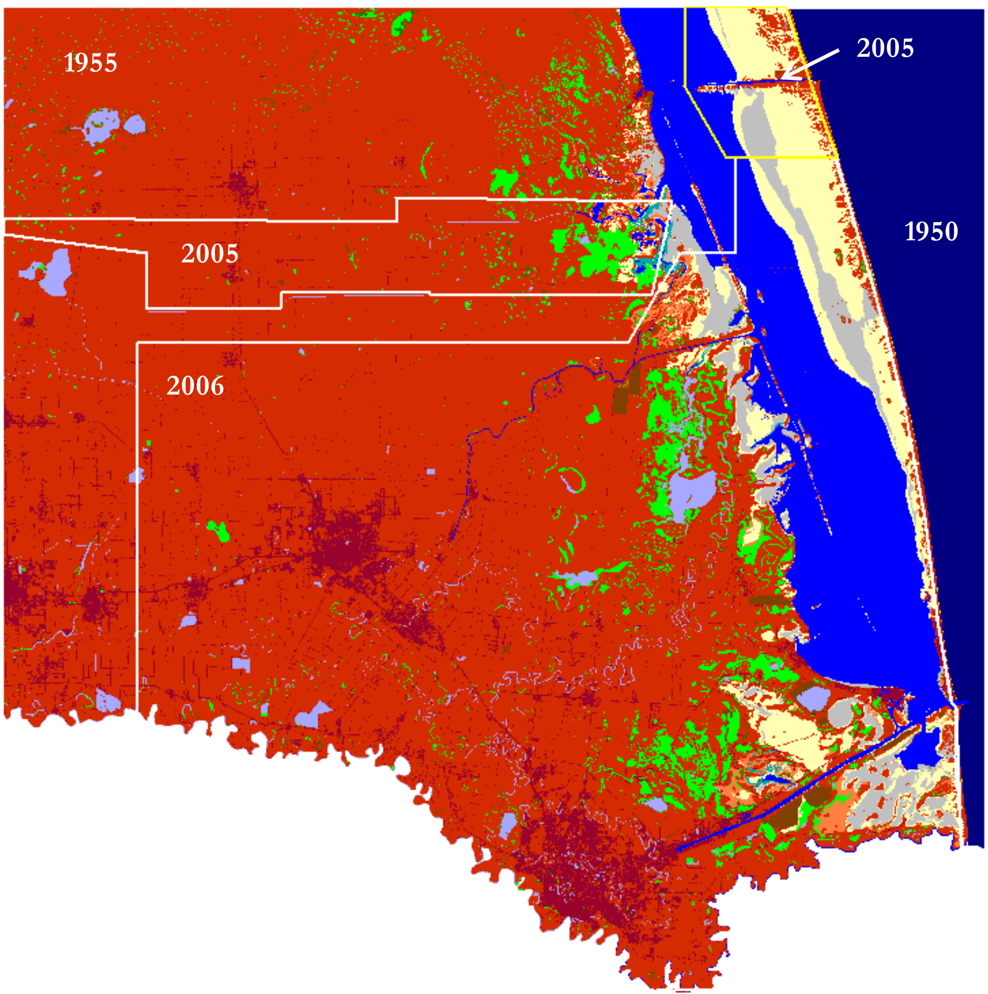


Figure 6. Input subsites for model application.
Portions of the study area with dates before 2000 did not have high-vertical-resolution LiDAR data available.

Table 2. Summary of SLAMM input parameters for Lower Rio Grande Valley NWR

Description	Inland	North Barrier	Lidar 2006	Lidar 2005	Open Ocean
NWI Photo Date (YYYY)	1994	1994	1994	1994	1994
DEM Date (YYYY)	1955	2005	2006	2005	1950
Direction Offshore [n,s,e,w]	East	East	East	East	East
Historic Trend (mm/yr)	3.64	3.64	3.64	3.64	3.64
MTL-NAVD88 (m)	-0.036	-0.036	-0.036	-0.036	-0.036
GT Great Diurnal Tide Range (m)	0.4	0.4	0.4	0.4	0.4
Salt Elev. (m above MTL)	0.42	0.42	0.42	0.42	0.42
Marsh Erosion (horz. m /yr)	1.8	1.8	1.8	1.8	1.8
Swamp Erosion (horz. m /yr)	1	1	1	1	1
T.Flat Erosion (horz. m /yr)	0.5	0.5	0.5	0.5	0.5
Reg.-Flood Marsh Accr (mm/yr)	4.4	4.4	4.4	4.4	4.4
Irreg.-Flood Marsh Accr (mm/yr)	4.4	4.4	4.4	4.4	4.4
Tidal-Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9	5.9	5.9
Inland-Fresh Marsh Accr (mm/yr)	5.9	5.9	5.9	5.9	5.9
Mangrove Accr (mm/yr)	7	7	7	7	7
Tidal Swamp Accr (mm/yr)	1.1	1.1	1.1	1.1	1.1
Swamp Accretion (mm/yr)	0.3	0.3	0.3	0.3	0.3
Beach Sed. Rate (mm/yr)	0.5	0.5	0.5	0.5	0.5
Freq. Overwash (years)	0	0	0	0	0
Use Elev Pre-processor [True,False]	TRUE	FALSE	FALSE	FALSE	TRUE

Results

This simulation of the Lower Rio Grande Valley NWR predicts that refuge wetland covers will be significantly impacted by all SLR scenarios. Table 3 presents the predicted loss of each wetland category by 2100 for each of the five SLR scenarios examined

Table 3. Predicted loss rates of land categories by 2100 given simulated scenarios of eustatic SLR at Lower Rio Grande Valley NWR

Land cover category	Initial coverage (acres)	Land cover loss by 2100 for different SLR scenarios				
		0.39 m	0.69 m	1 m	1.5 m	2 m
Undeveloped Dry Land	949491	1%	2%	3%	4%	7%
Developed Dry Land	76152	1%	1%	2%	3%	5%
Estuarine Beach	64720	44%	76%	91%	95%	97%
Inland Fresh Marsh	48753	0%	1%	4%	12%	36%
Tidal Flat	35343	72%	89%	80%	78%	70%
Irregularly Flooded Marsh	11027	5%	38%	60%	82%	95%
Inland Shore	7568	10%	13%	19%	39%	52%
Regularly Flooded Marsh	2412	-92%([1])	-204%	-199%	-482%	-879%
Swamp	1280	0%	0%	0%	1%	4%
Ocean Beach	199	-205%	-563%	-826%	-510%	-208%
Tidal Fresh Marsh	5	36%	56%	71%	74%	78%

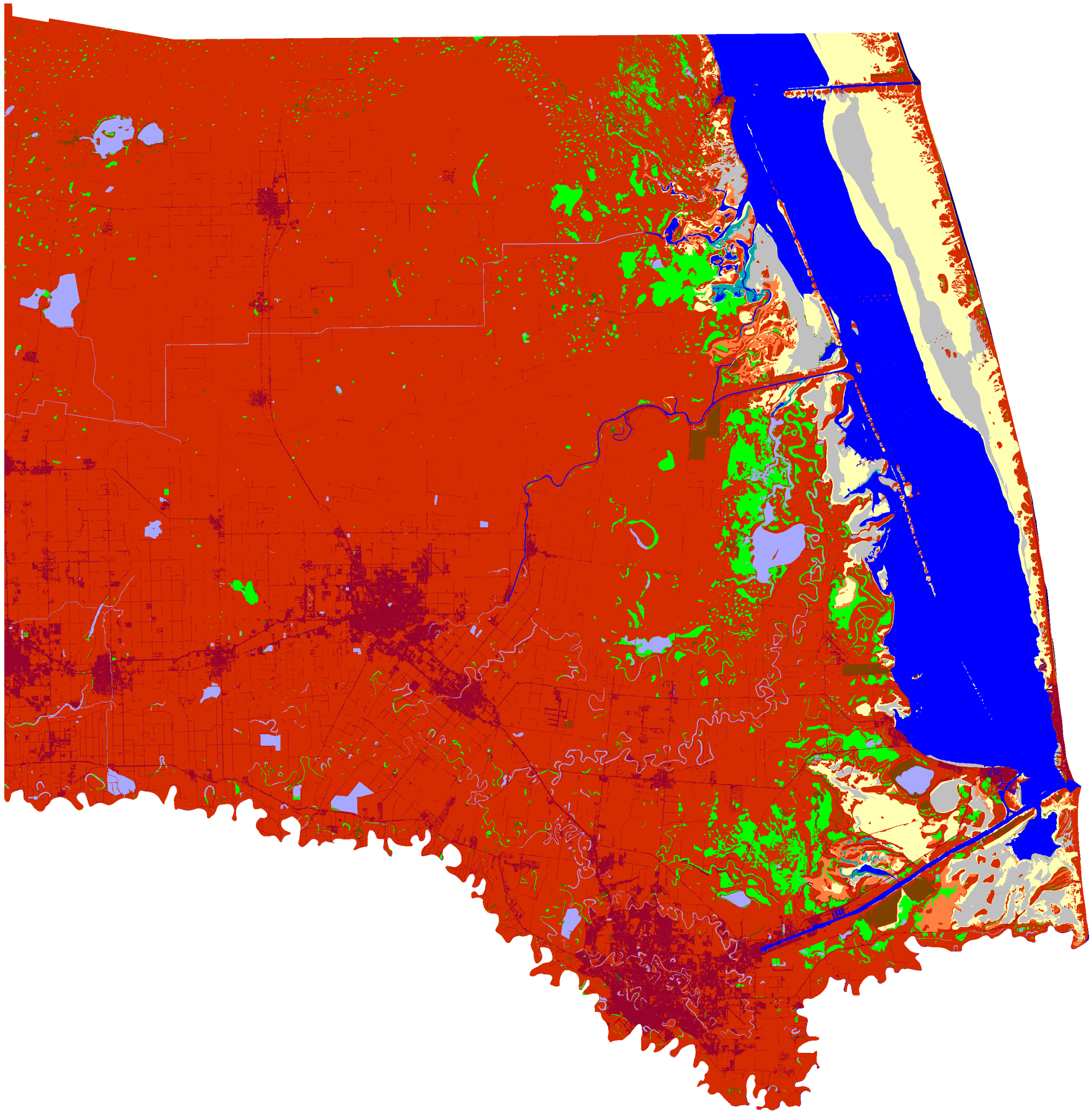
([1]) A negative loss indicates a gain with respect to initial coverage

Approximately 30,000 to 100,000 acres are predicted to be converted into open water by 2100 depending on the SLR scenario considered. Undeveloped-dry land, that today covers around 70% of the area, is predicted to be fairly resilient with a maximum predicted loss of 7% (66,500 acres) of the current coverage. Similarly, developed-dry land appears resilient to SLR due to high elevations or spatial location. Other land-cover types are predicted to be significantly affected. The beaches facing the Intracoastal Waterway, in particular on South Padre Island, may experience losses ranging from 44% to 97%, while for SLR higher than 0.69 m predicted losses for irregularly-flooded marshes are above 60%. Most of these marshes are converted to regularly-flooded marsh, a land cover that is predicted to have significant gains under all SLR scenarios considered. Inland-fresh marsh, because of its elevation and inland location, appears to be resilient to SLR; only in scenarios above 1.5 m SLR do predicted losses exceed 10%. Even more resistant is swamp, which is not expected to lose more than 4% of its current area (the current coverage is only around 1300 acres).

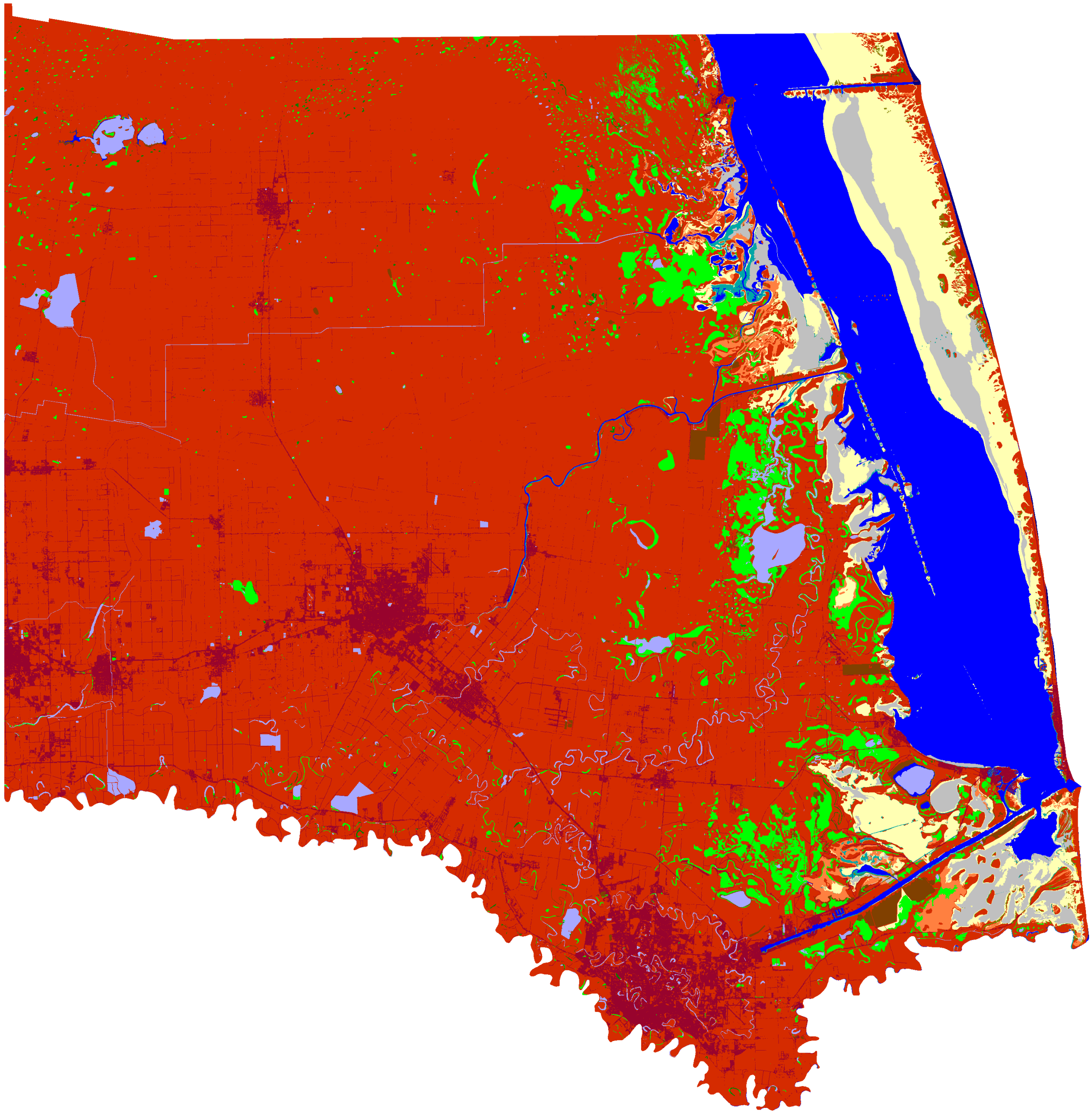
Lower Rio Grande Valley NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

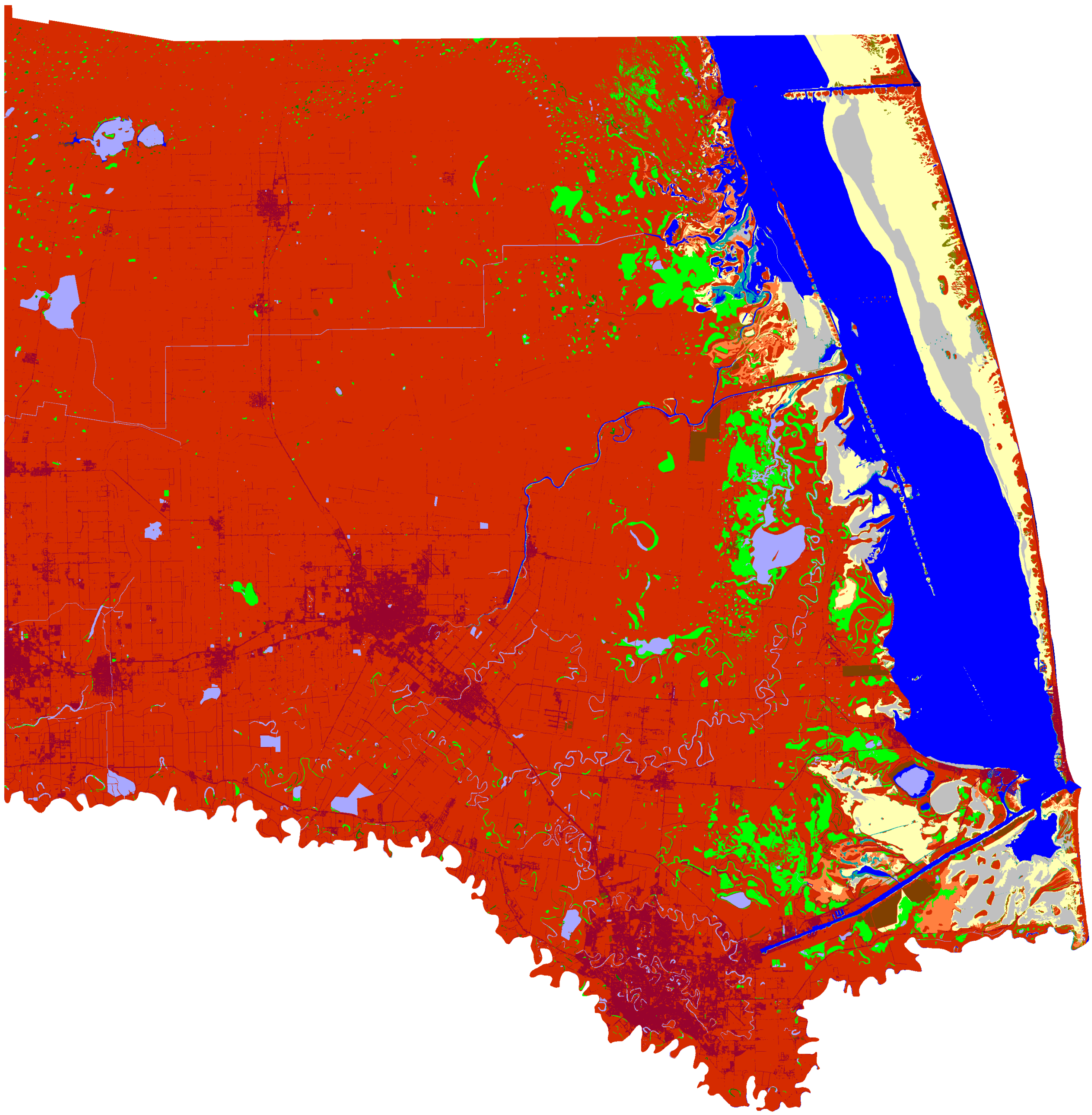
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	949491	944616	943174	941396	939536
	Estuarine Open Water	135285	138479	141651	171723	192606
	Developed Dry Land	76152	75920	75877	75814	75732
	Estuarine Beach	64720	64127	63270	45817	36417
	Inland Fresh Marsh	48753	48680	48670	48658	48653
	Tidal Flat	35343	34167	32626	20713	9752
	Inland Open Water	24336	24310	24096	23815	23718
	Irregularly Flooded Marsh	11027	10718	10718	10687	10469
	Inland Shore	7568	6998	6986	6852	6779
	Regularly Flooded Marsh	2412	4544	4260	4324	4629
	Swamp	1280	1280	1280	1280	1280
	Open Ocean	838	862	891	910	931
	Riverine Tidal	735	344	341	336	332
	Transitional Salt Marsh	315	3223	4403	5763	7014
	Ocean Beach	199	187	211	367	606
	Tidal Fresh Marsh	5	3	3	3	3
	Total (incl. water)	**1358458**	**1358458**	**1358458**	**1358458**	**1358458**



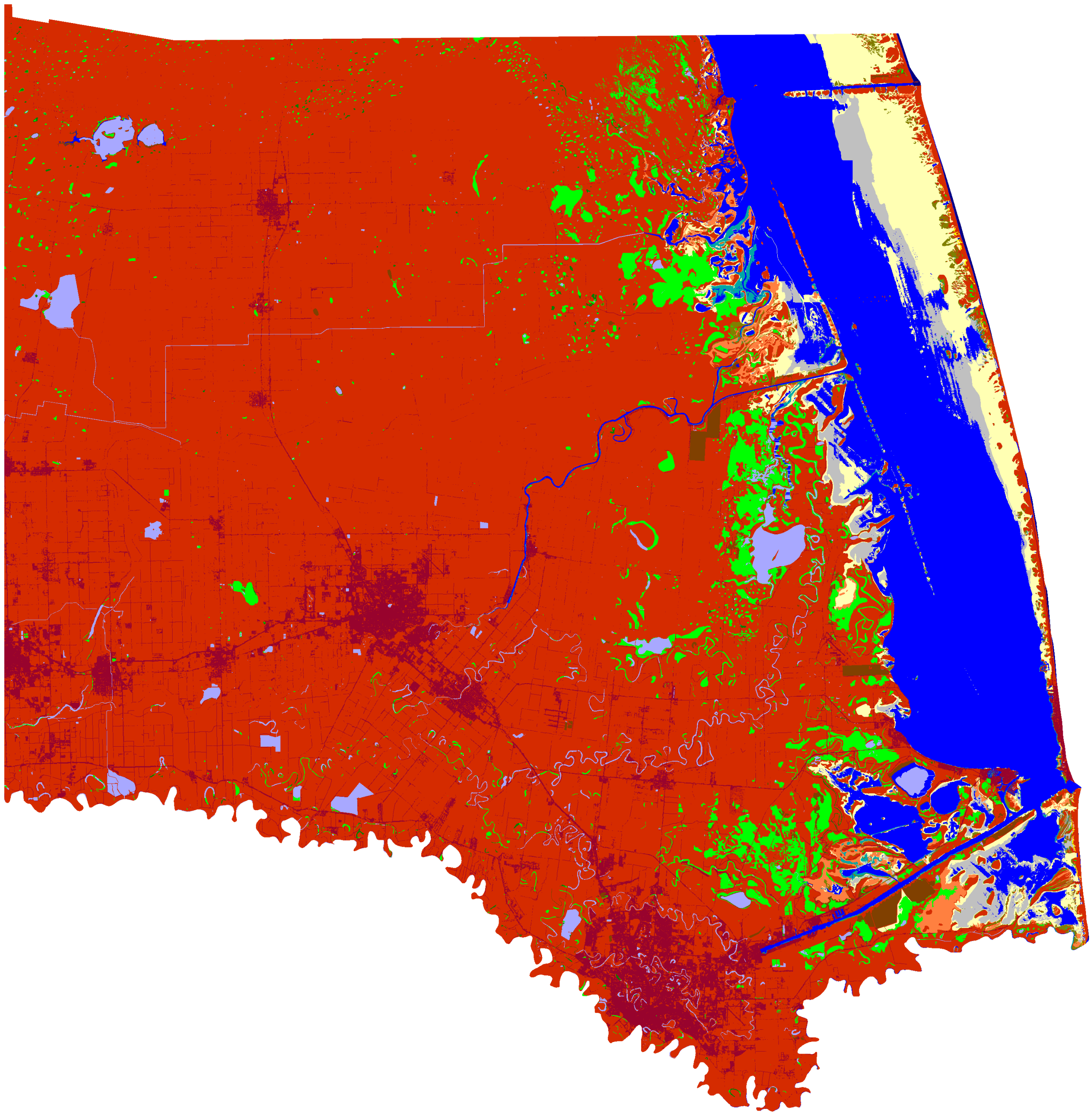
Lower Rio Grande Valley NWR, Initial Condition



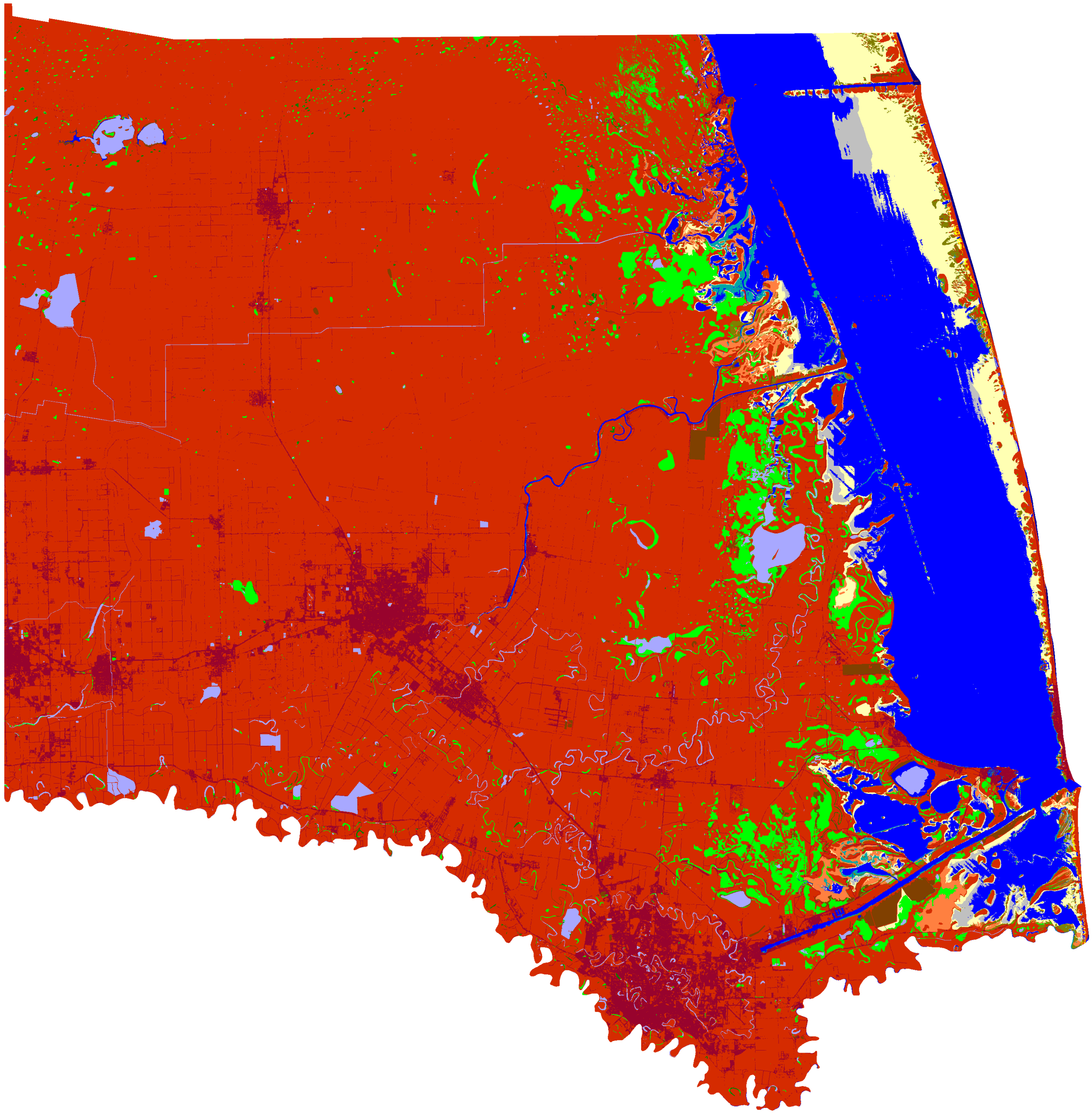
Lower Rio Grande Valley NWR, 2025, Scenario A1B Mean, 0.39 m SLR



Lower Rio Grande Valley NWR, 2050, Scenario A1B Mean, 0.39 m SLR



Lower Rio Grande Valley NWR, 2075, Scenario A1B Mean, 0.39 m SLR

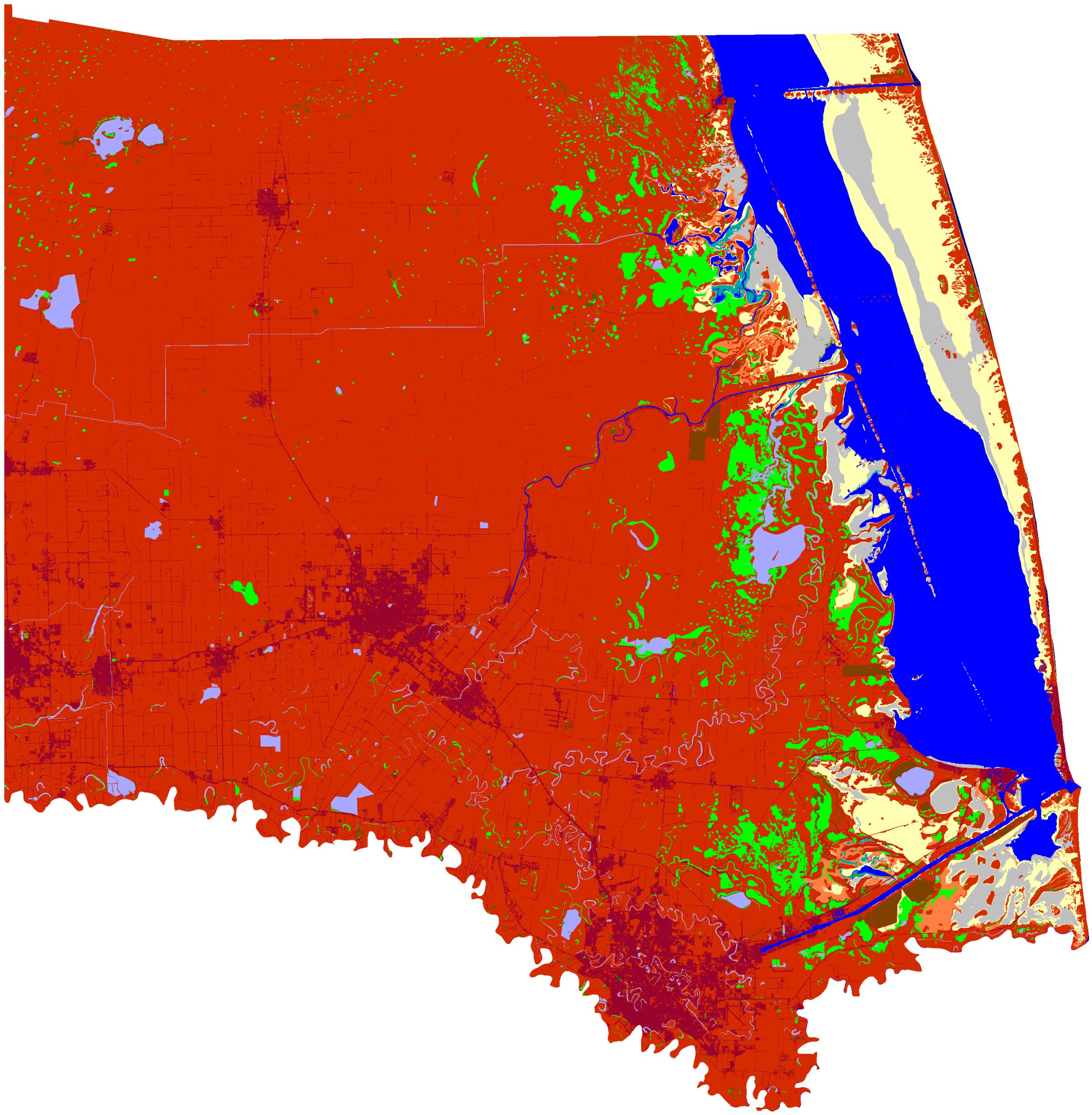


Lower Rio Grande Valley NWR, 2100, Scenario A1B Mean, 0.39 m SLR

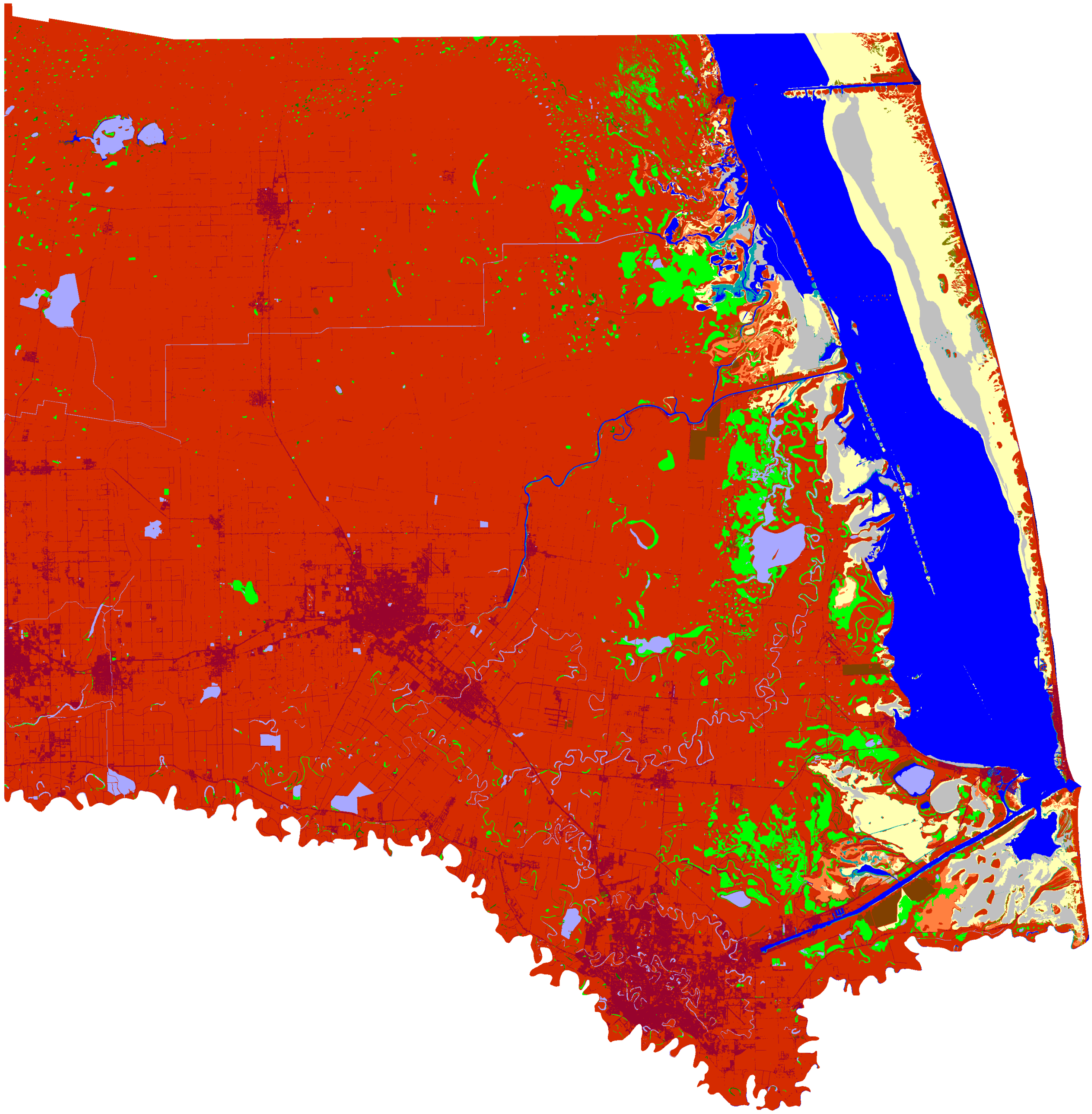
Lower Rio Grande Valley NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

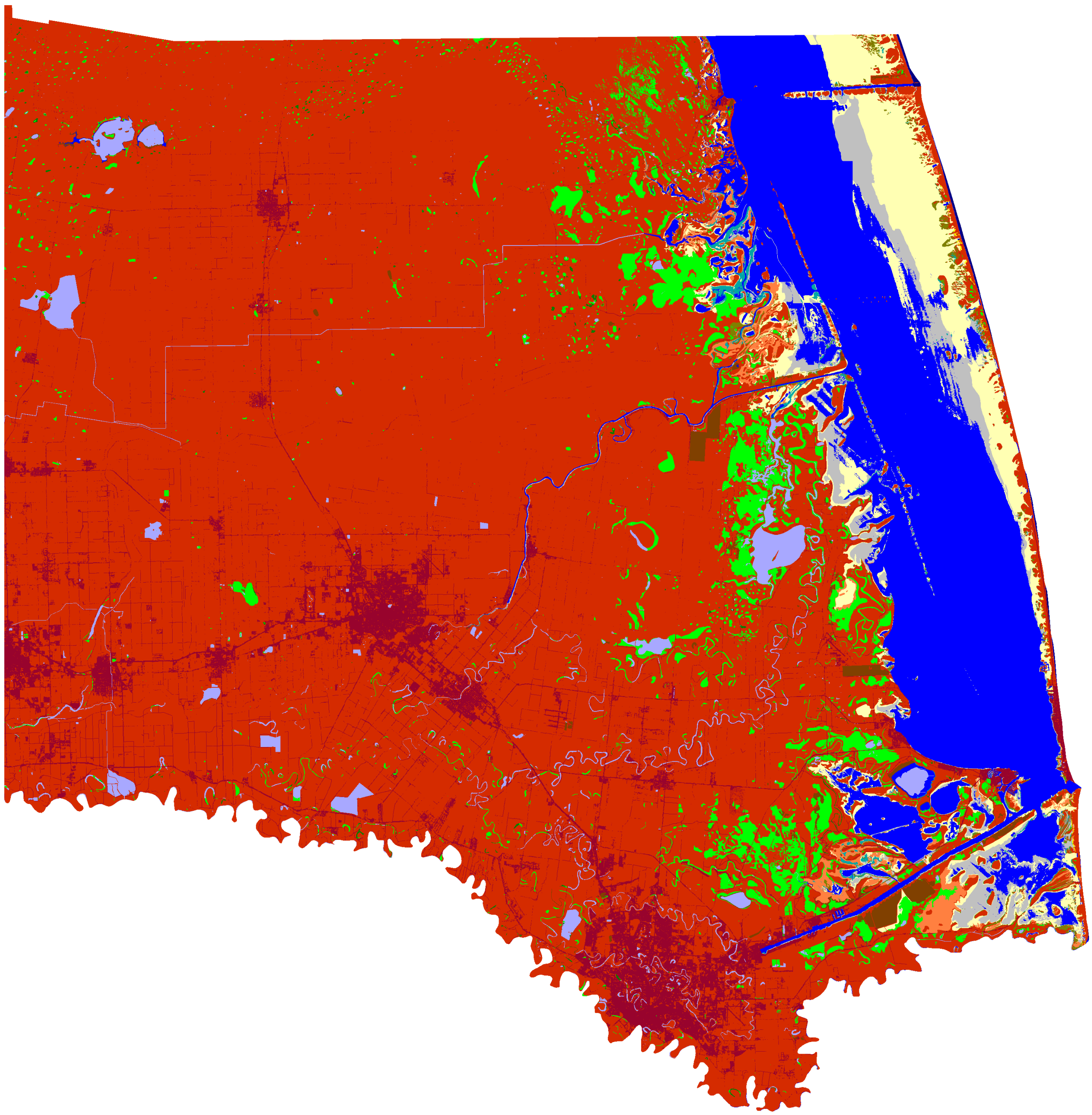
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	949491	943993	941691	938474	934319
	Estuarine Open Water	135285	139614	168465	203643	226825
	Developed Dry Land	76152	75902	75828	75686	75386
	Estuarine Beach	64720	63836	47008	31337	15560
	Inland Fresh Marsh	48753	48670	48626	48548	48226
	Tidal Flat	35343	33386	23712	7354	3999
	Inland Open Water	24336	24308	24090	23670	23506
	Irregularly Flooded Marsh	11027	10610	10030	8677	6810
	Inland Shore	7568	6995	6870	6734	6590
	Regularly Flooded Marsh	2412	4888	4329	5864	7328
	Swamp	1280	1280	1280	1280	1280
	Open Ocean	838	874	931	972	1053
	Riverine Tidal	735	344	338	331	318
	Transitional Salt Marsh	315	3539	4926	5184	5937
	Ocean Beach	199	216	331	701	1319
	Tidal Fresh Marsh	5	3	3	3	2
	Total (incl. water)	**1358458**	**1358458**	**1358458**	**1358458**	**1358458**



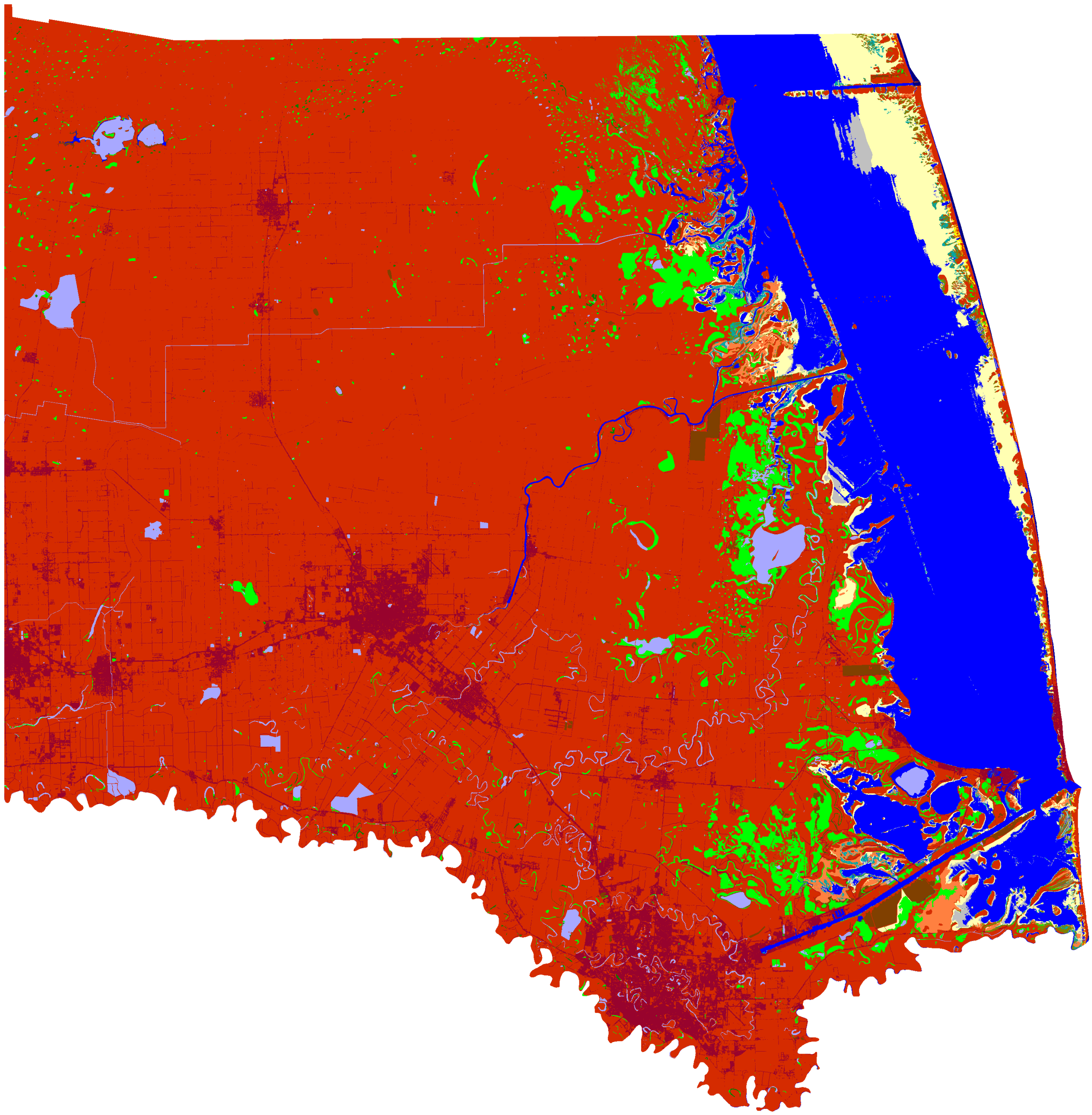
Lower Rio Grande Valley NWR, Initial Condition



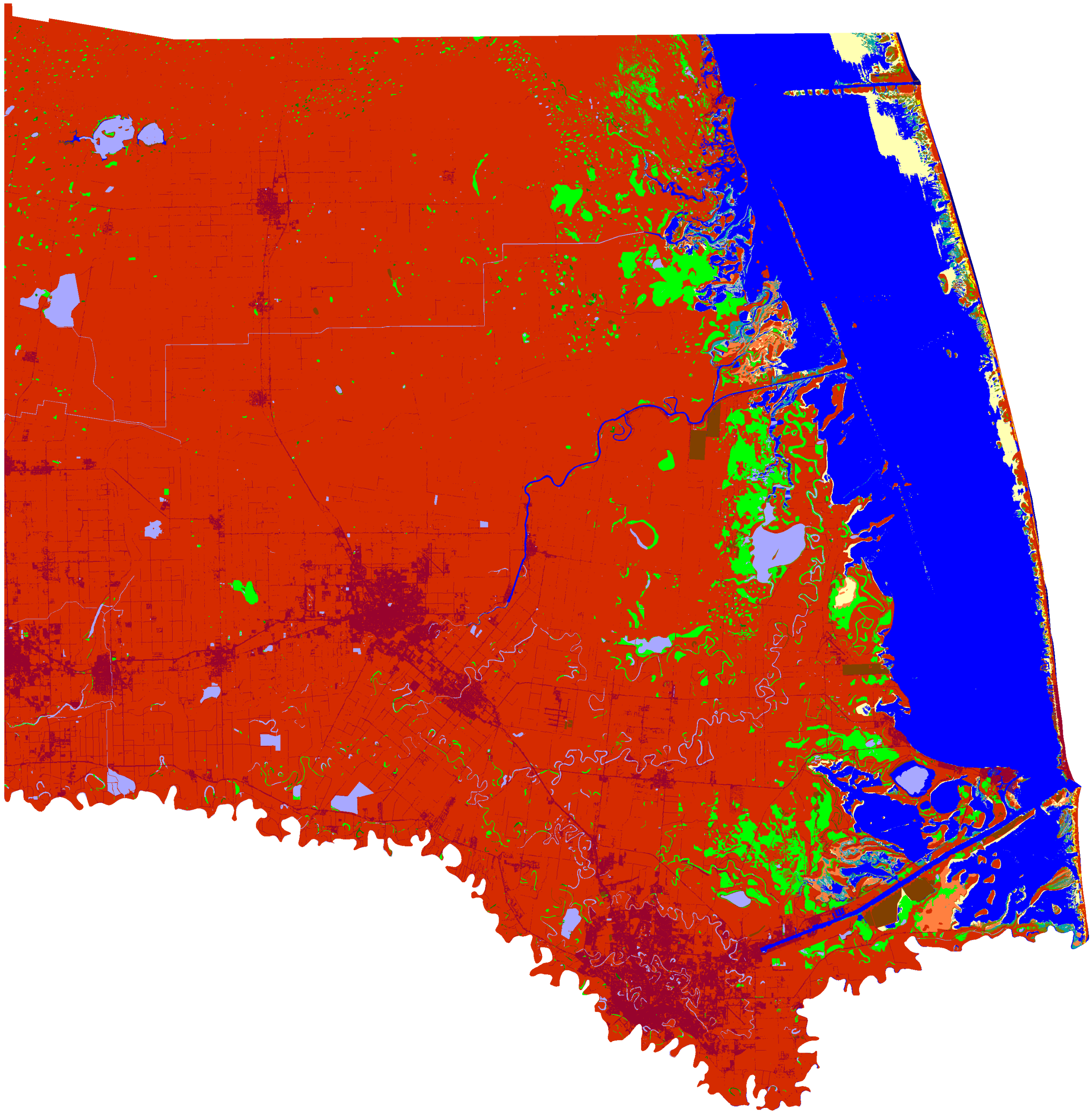
Lower Rio Grande Valley NWR, 2025, Scenario A1B Maximum, 0.69 m SLR



Lower Rio Grande Valley NWR, 2050, Scenario A1B Maximum, 0.69 m SLR



Lower Rio Grande Valley NWR, 2075, Scenario A1B Maximum, 0.69 m SLR

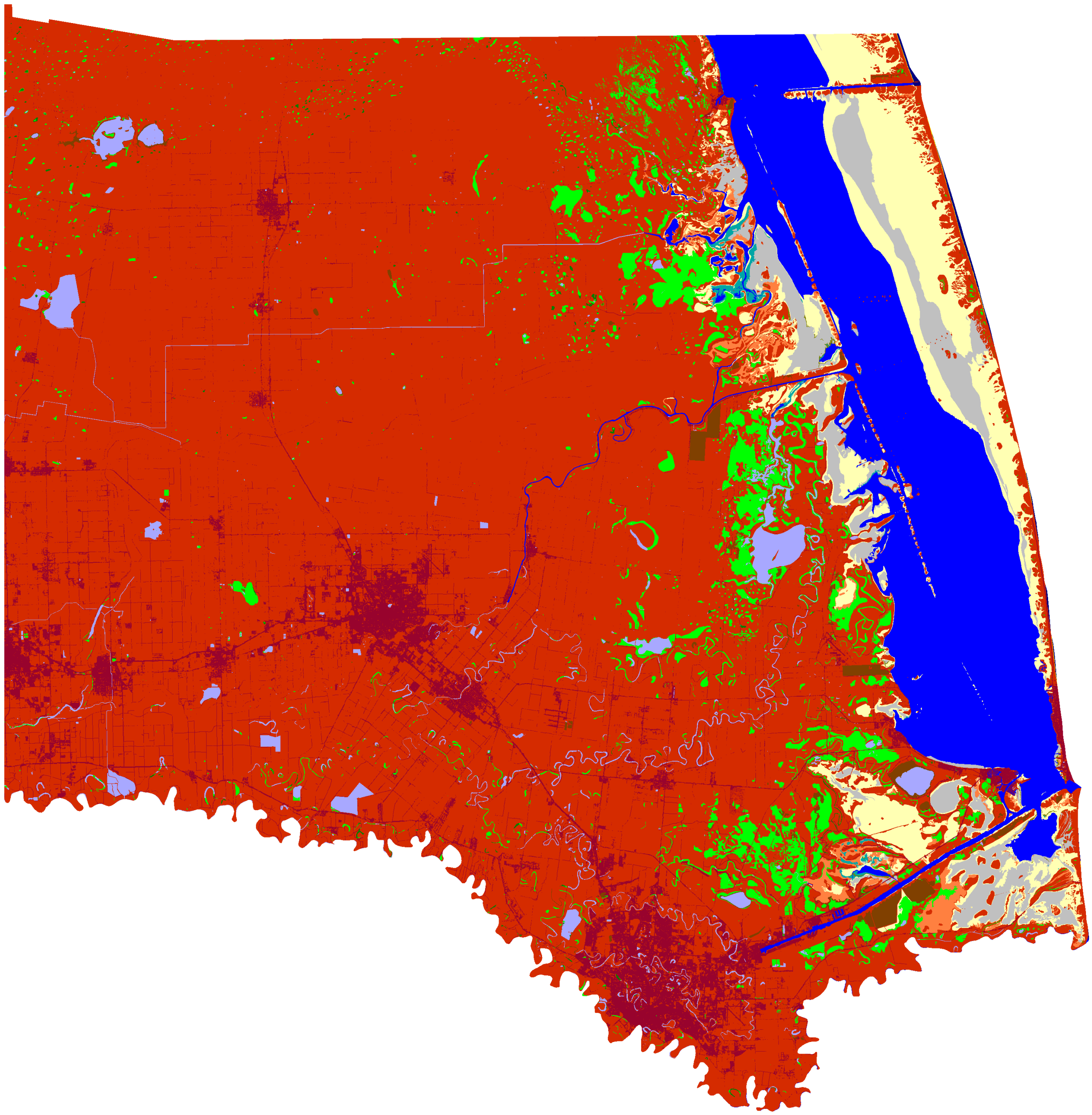


Lower Rio Grande Valley NWR, 2100, Scenario A1B Maximum, 0.69 m SLR

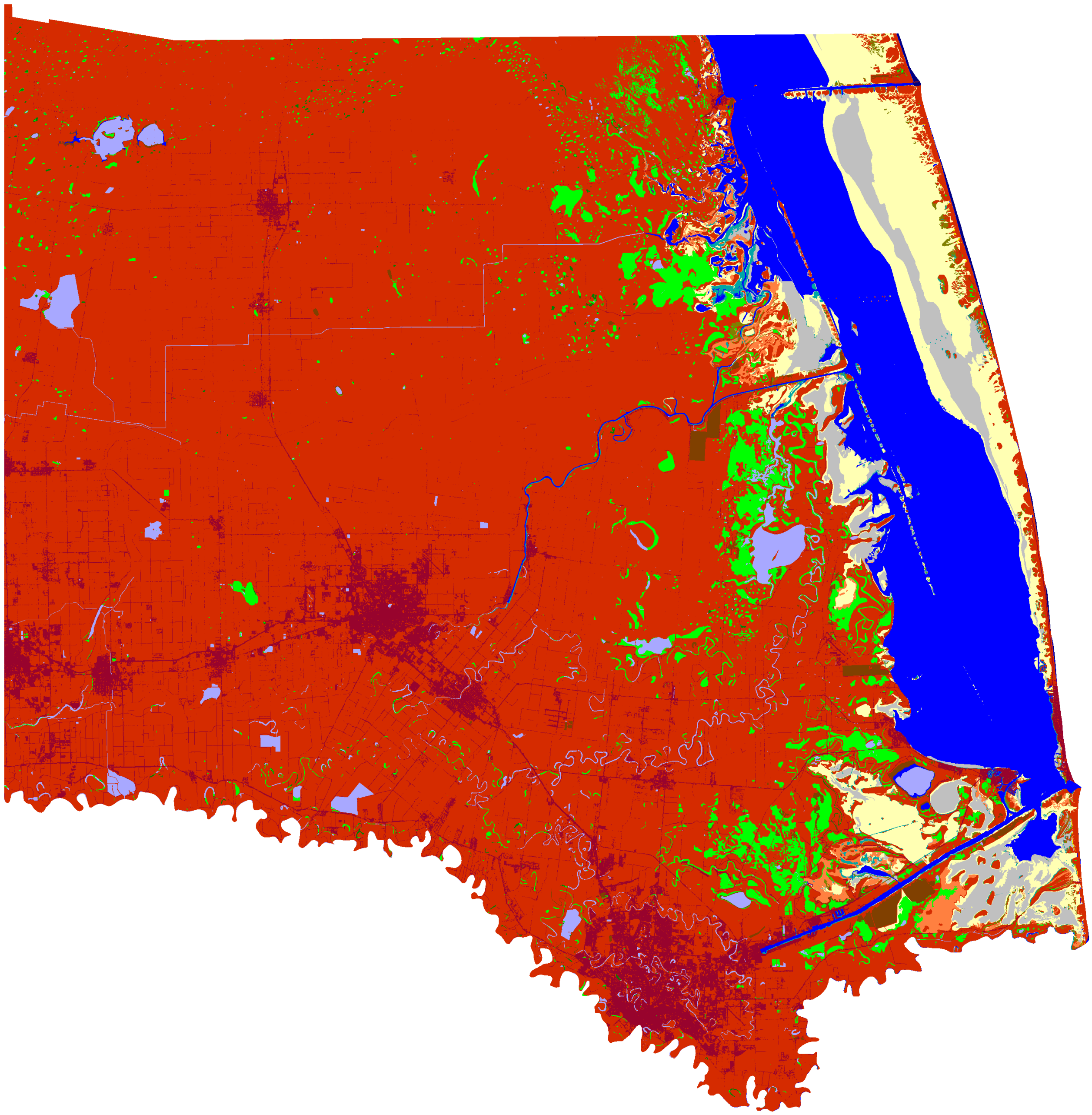
Lower Rio Grande Valley NWR
1 m eustatic SLR by 2100

Results in Acres

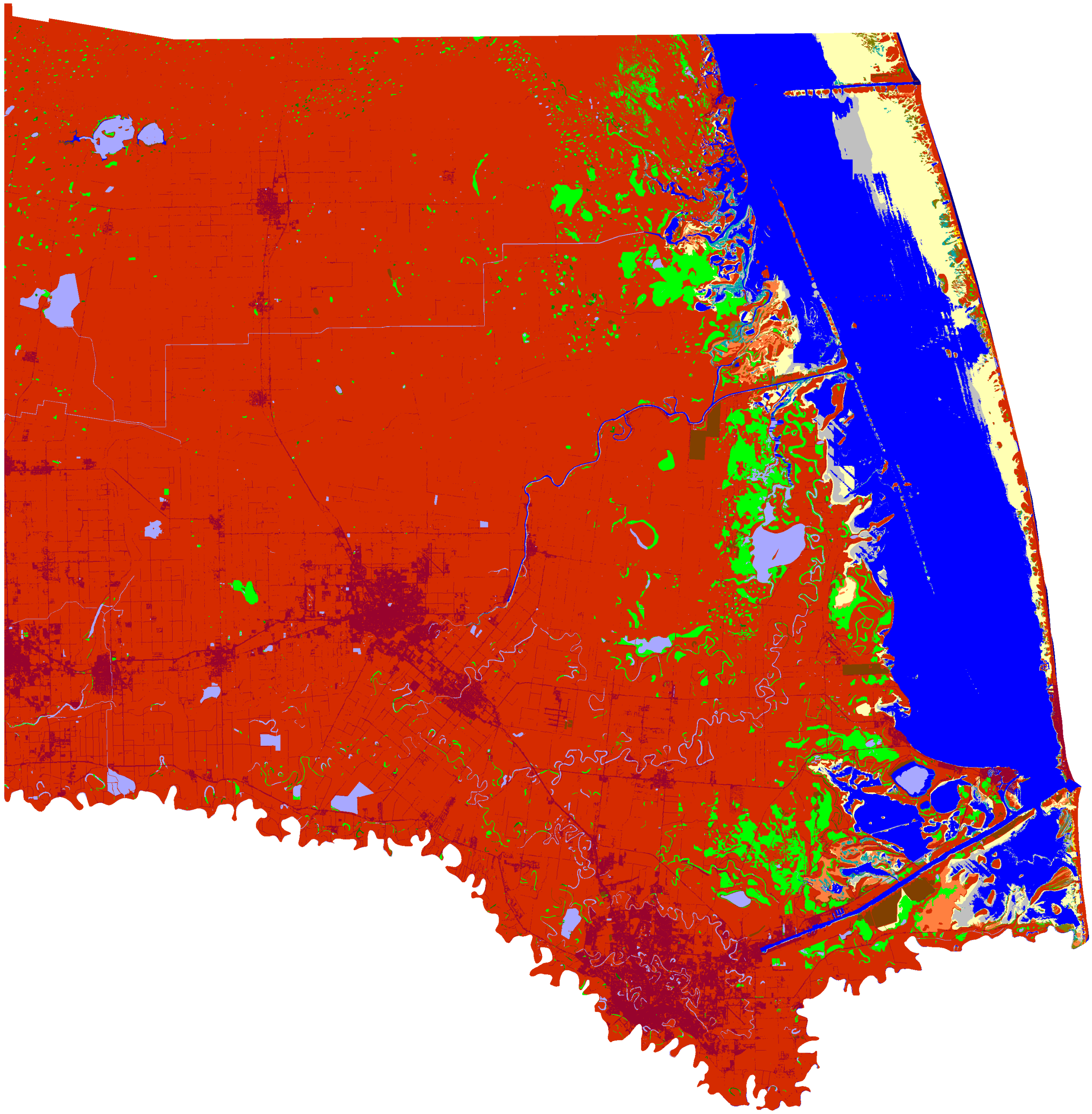
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	949491	943328	940078	934771	925000
	Estuarine Open Water	135285	140944	189383	225187	244068
	Developed Dry Land	76152	75881	75759	75416	74765
	Estuarine Beach	64720	63456	37887	16723	5919
	Inland Fresh Marsh	48753	48633	48521	47673	46884
	Tidal Flat	35343	32876	14276	5845	7080
	Inland Open Water	24336	24306	23828	23505	22315
	Irregularly Flooded Marsh	11027	10251	8677	5989	4462
	Inland Shore	7568	6989	6806	6617	6123
	Regularly Flooded Marsh	2412	5186	5641	6999	7217
	Swamp	1280	1280	1280	1280	1277
	Open Ocean	838	888	964	1047	1393
	Riverine Tidal	735	342	334	320	307
	Transitional Salt Marsh	315	3857	4526	5909	9804
	Ocean Beach	199	235	494	1176	1842
	Tidal Fresh Marsh	5	3	3	2	2
	Total (incl. water)	**1358458**	**1358458**	**1358458**	**1358458**	**1358458**



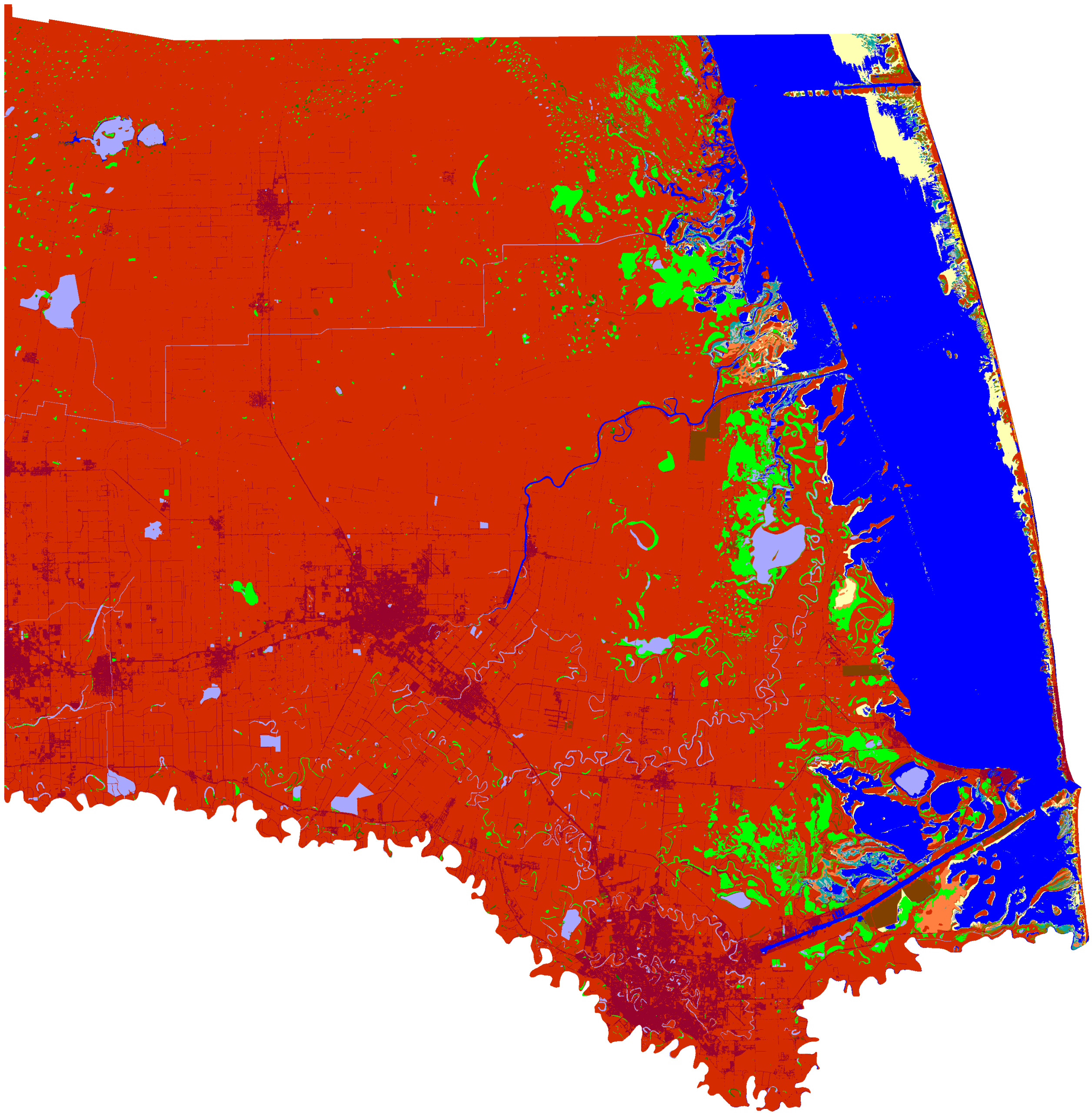
Lower Rio Grande Valley NWR, Initial Condition



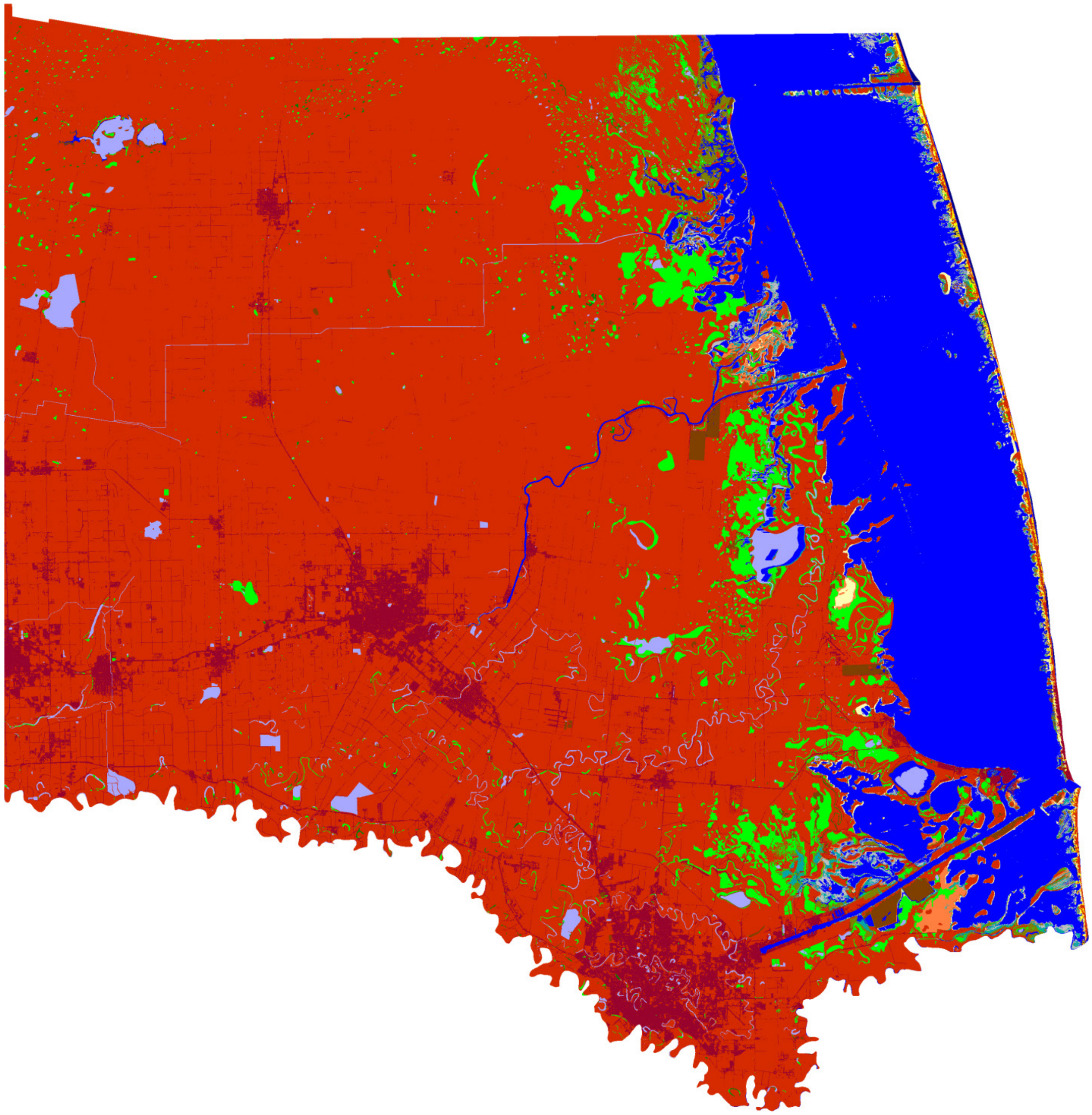
Lower Rio Grande Valley NWR, 2025, 1 m SLR



Lower Rio Grande Valley NWR, 2050, 1 m SLR



Lower Rio Grande Valley NWR, 2075, 1 m SLR

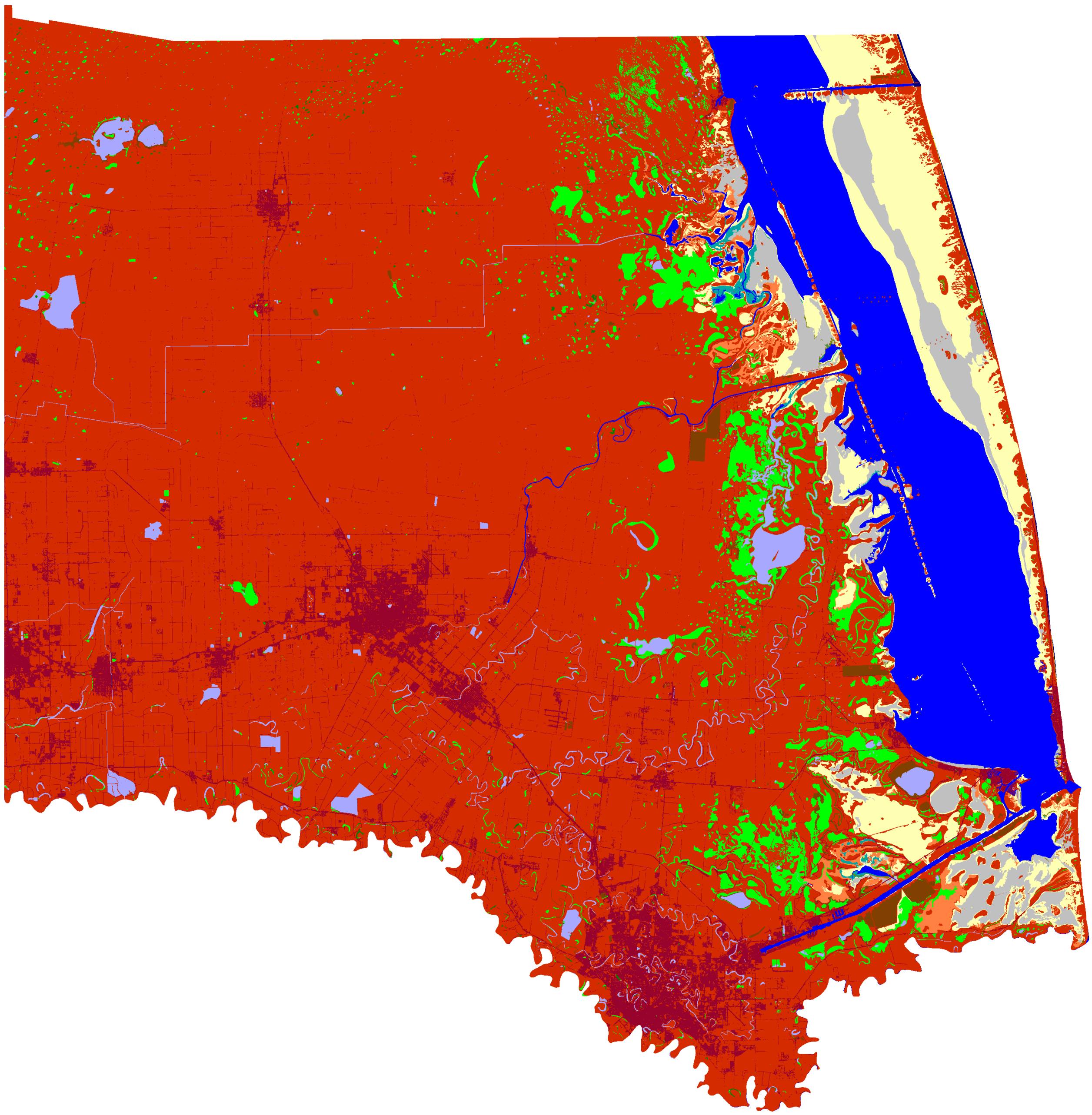


Lower Rio Grande Valley NWR, 2100, 1 m SLR

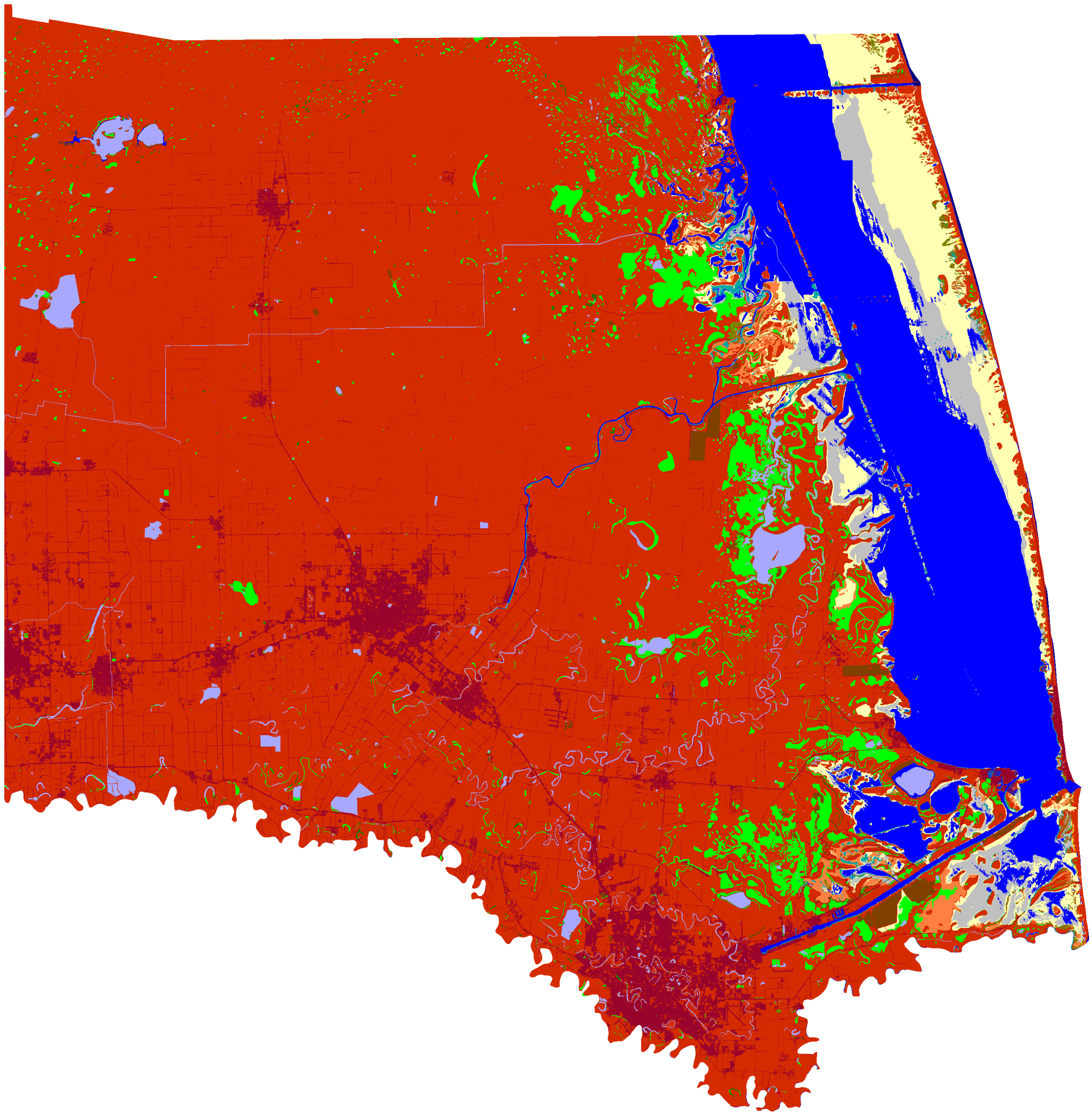
Lower Rio Grande Valley NWR
1.5 m eustatic SLR by 2100

Results in Acres

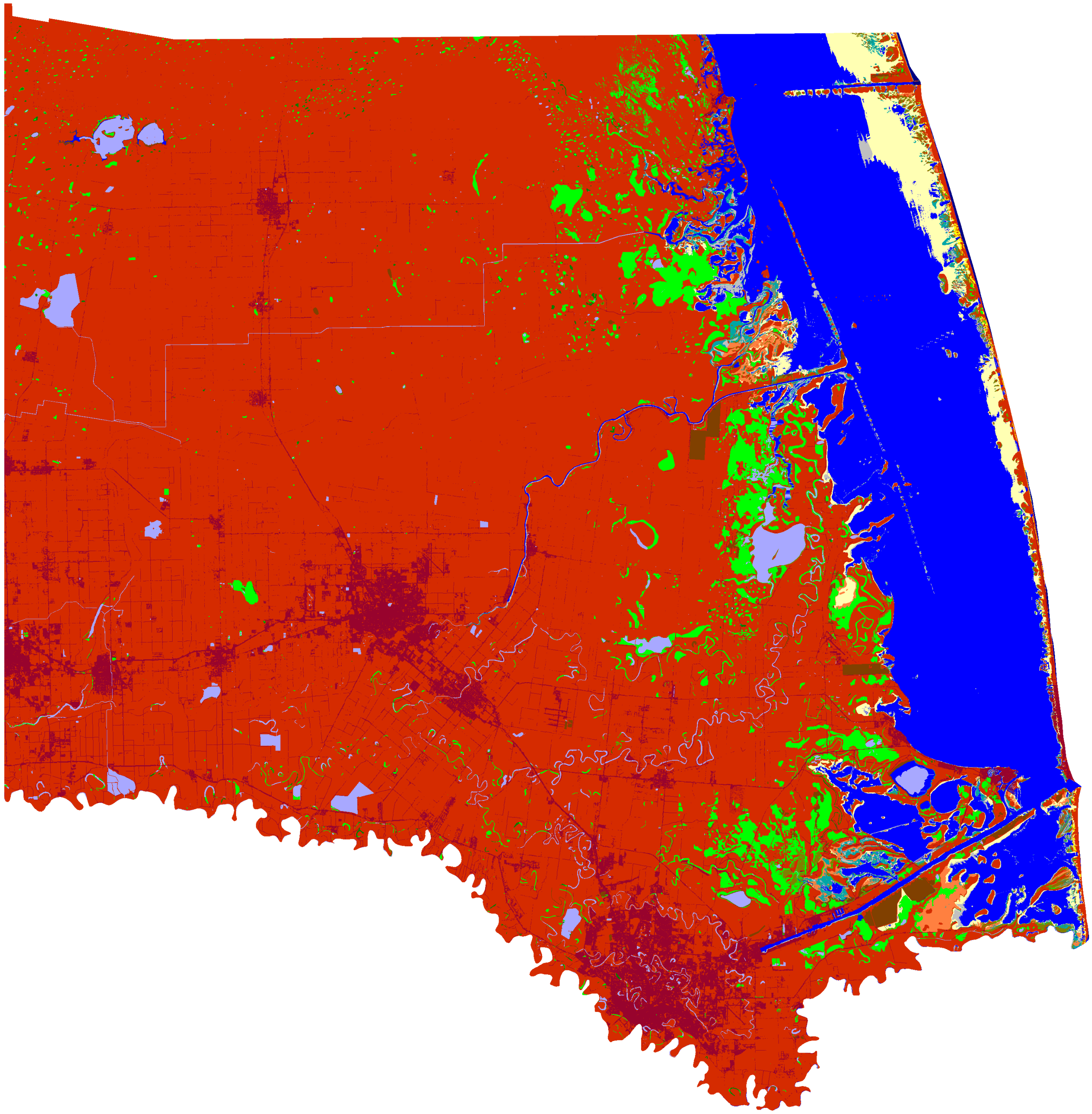
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	949491	942303	936809	924664	908578
	Estuarine Open Water	135285	160503	212550	241777	255205
	Developed Dry Land	76152	75849	75574	74736	73753
	Estuarine Beach	64720	50697	24938	5920	3414
	Inland Fresh Marsh	48753	48565	47704	46225	43084
	Tidal Flat	35343	26745	7431	8107	7740
	Inland Open Water	24336	24305	23656	22355	21889
	Irregularly Flooded Marsh	11027	9406	6114	3869	1978
	Inland Shore	7568	6905	6692	6102	4591
	Regularly Flooded Marsh	2412	6114	7925	7823	14048
	Swamp	1280	1280	1280	1277	1266
	Open Ocean	838	917	1006	1419	2580
	Riverine Tidal	735	340	326	308	288
	Transitional Salt Marsh	315	4246	5572	12187	18828
	Ocean Beach	199	281	878	1687	1214
	Tidal Fresh Marsh	5	3	2	2	1
	Total (incl. water)	**1358458**	**1358458**	**1358458**	**1358458**	**1358458**



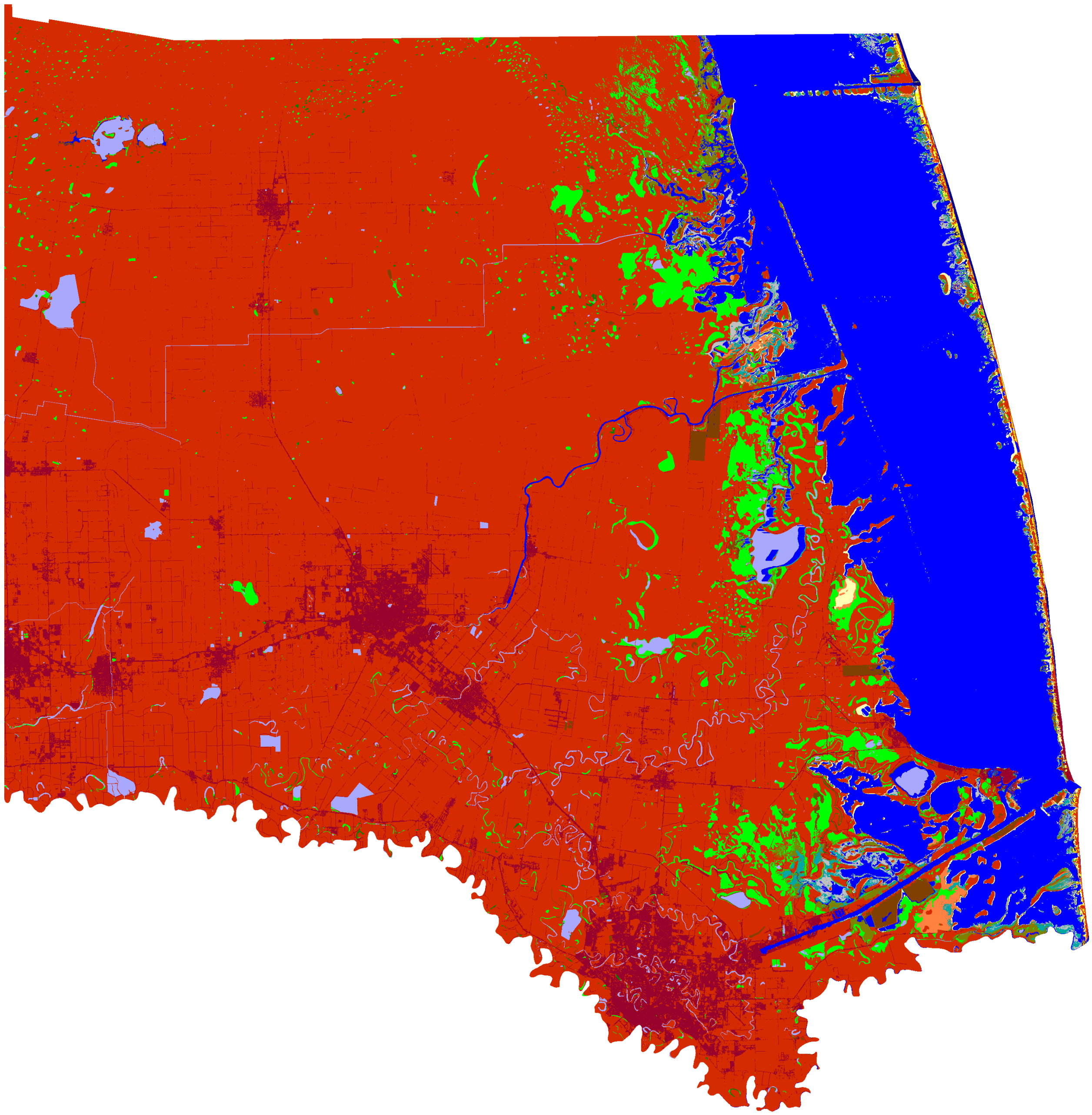
Lower Rio Grande Valley NWR, Initial Condition



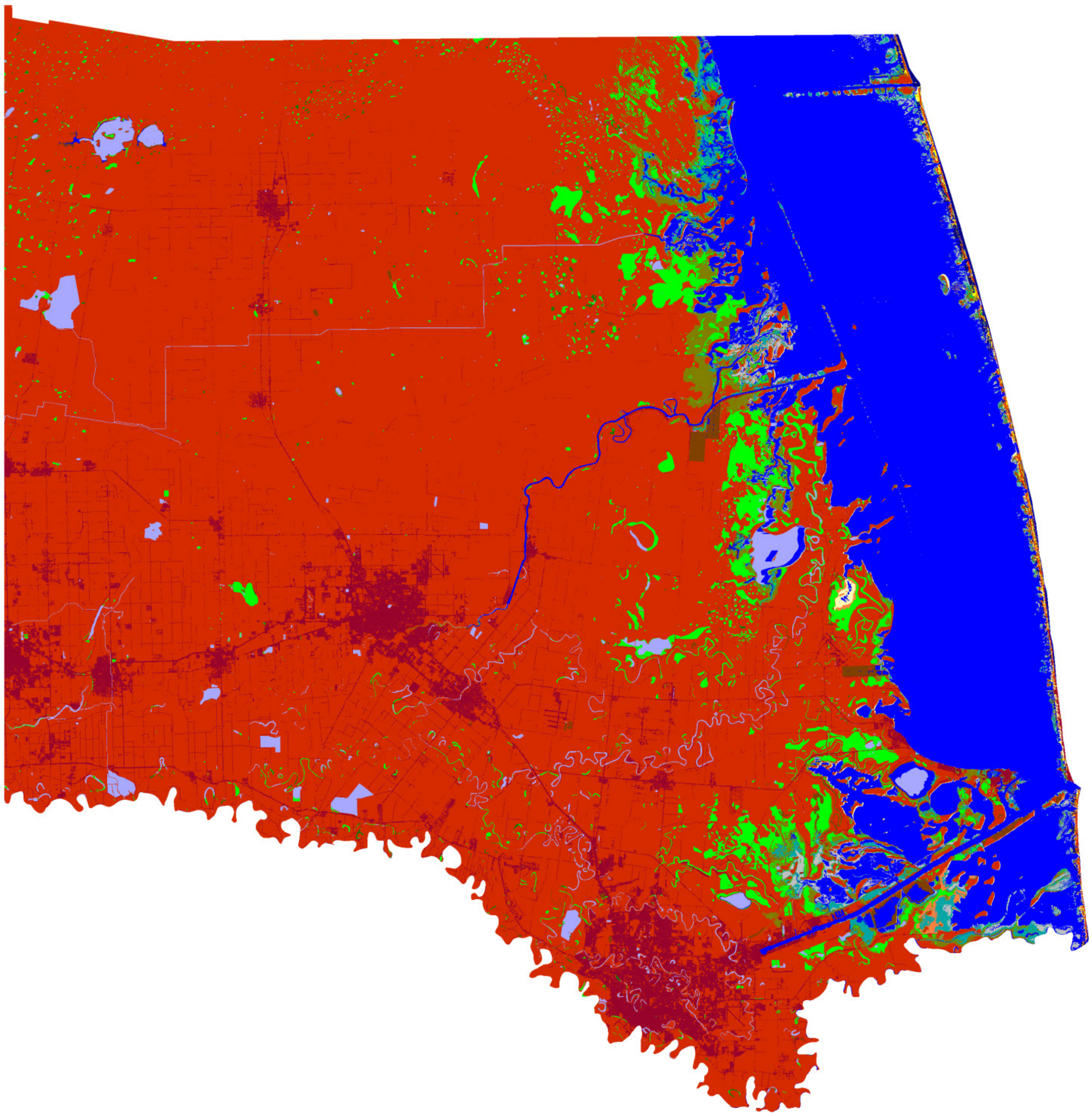
Lower Rio Grande Valley NWR, 2025, 1.5 m SLR



Lower Rio Grande Valley NWR, 2050, 1.5 m SLR



Lower Rio Grande Valley NWR, 2075, 1.5 m SLR

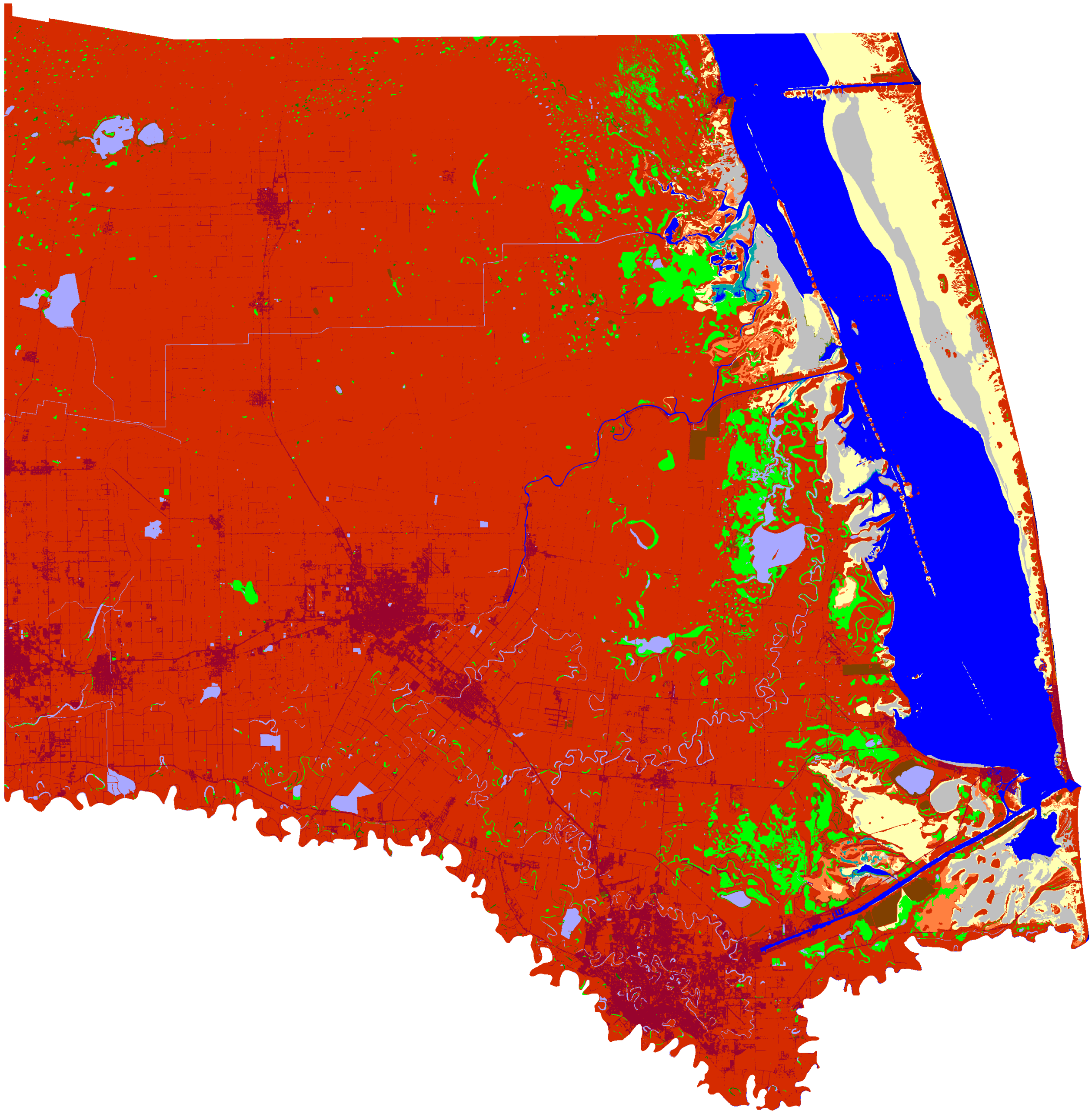


Lower Rio Grande Valley NWR, 2100, 1.5 m SLR

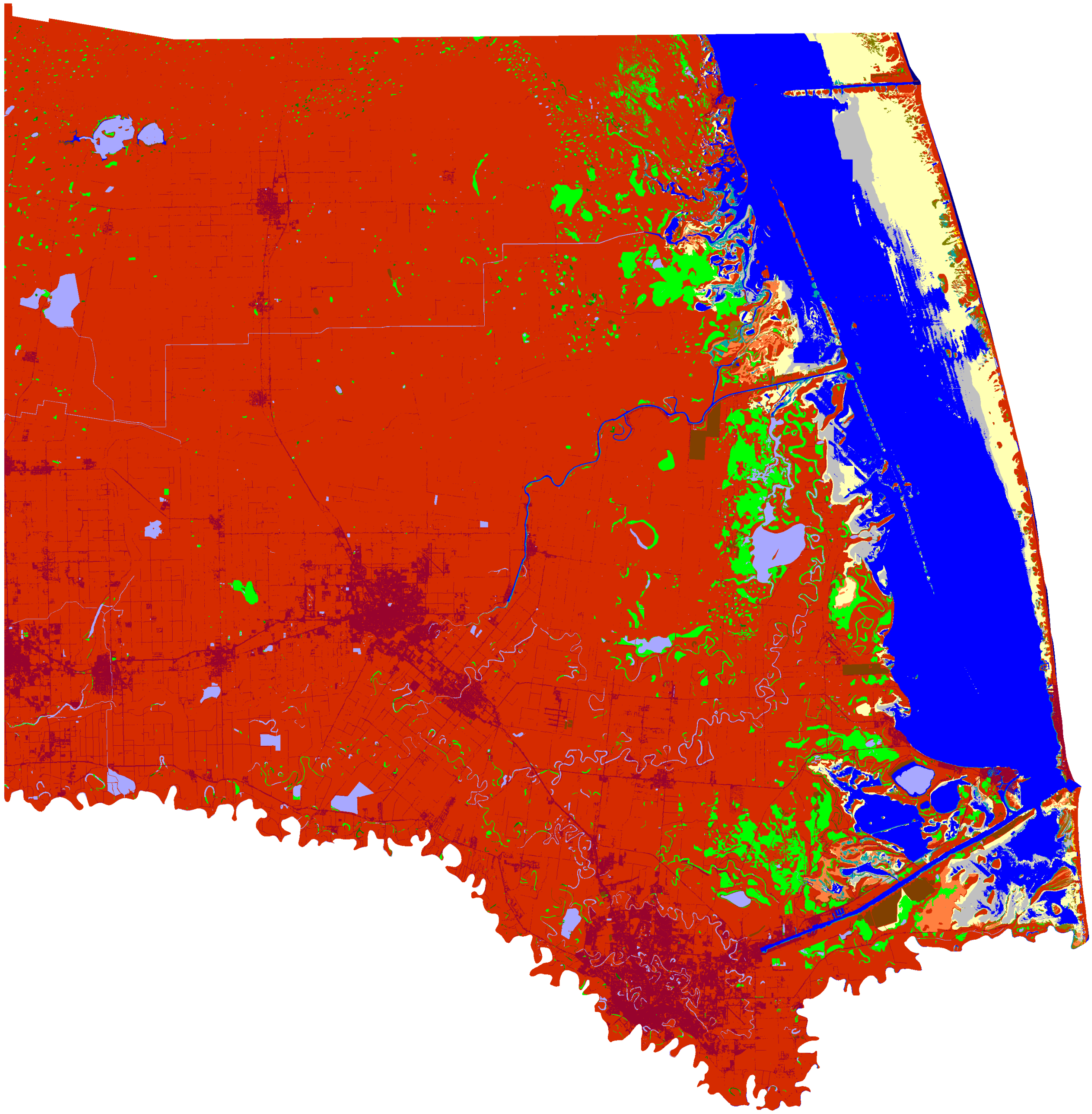
Lower Rio Grande Valley NWR
2 m eustatic SLR by 2100

Results in Acres

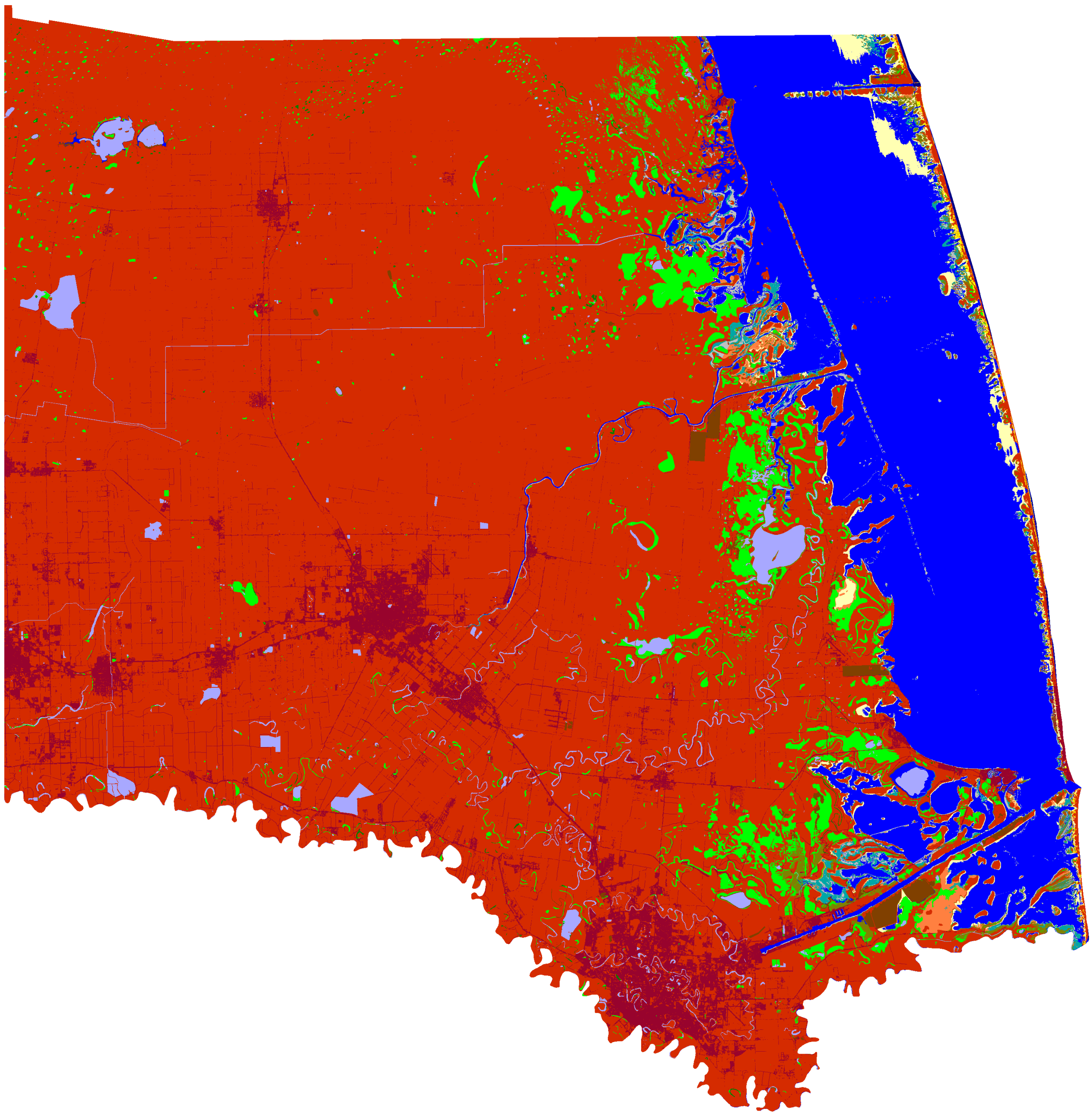
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	949491	941270	933293	913766	887286
	Estuarine Open Water	135285	175607	227914	247833	261465
	Developed Dry Land	76152	75811	75309	74071	72550
	Estuarine Beach	64720	43769	12202	4131	1995
	Inland Fresh Marsh	48753	48479	46790	43107	31394
	Tidal Flat	35343	19231	7585	8376	10528
	Inland Open Water	24336	24303	23517	22150	21540
	Irregularly Flooded Marsh	11027	8388	4669	2169	572
	Inland Shore	7568	6851	6556	4996	3607
	Regularly Flooded Marsh	2412	7250	8374	10798	23607
	Swamp	1280	1280	1280	1270	1233
	Open Ocean	838	950	1093	2087	3338
	Riverine Tidal	735	339	322	298	264
	Transitional Salt Marsh	315	4584	8327	22052	38465
	Ocean Beach	199	345	1226	1351	613
	Tidal Fresh Marsh	5	2	2	1	1
	Total (incl. water)	**1358458**	**1358458**	**1358458**	**1358458**	**1358458**



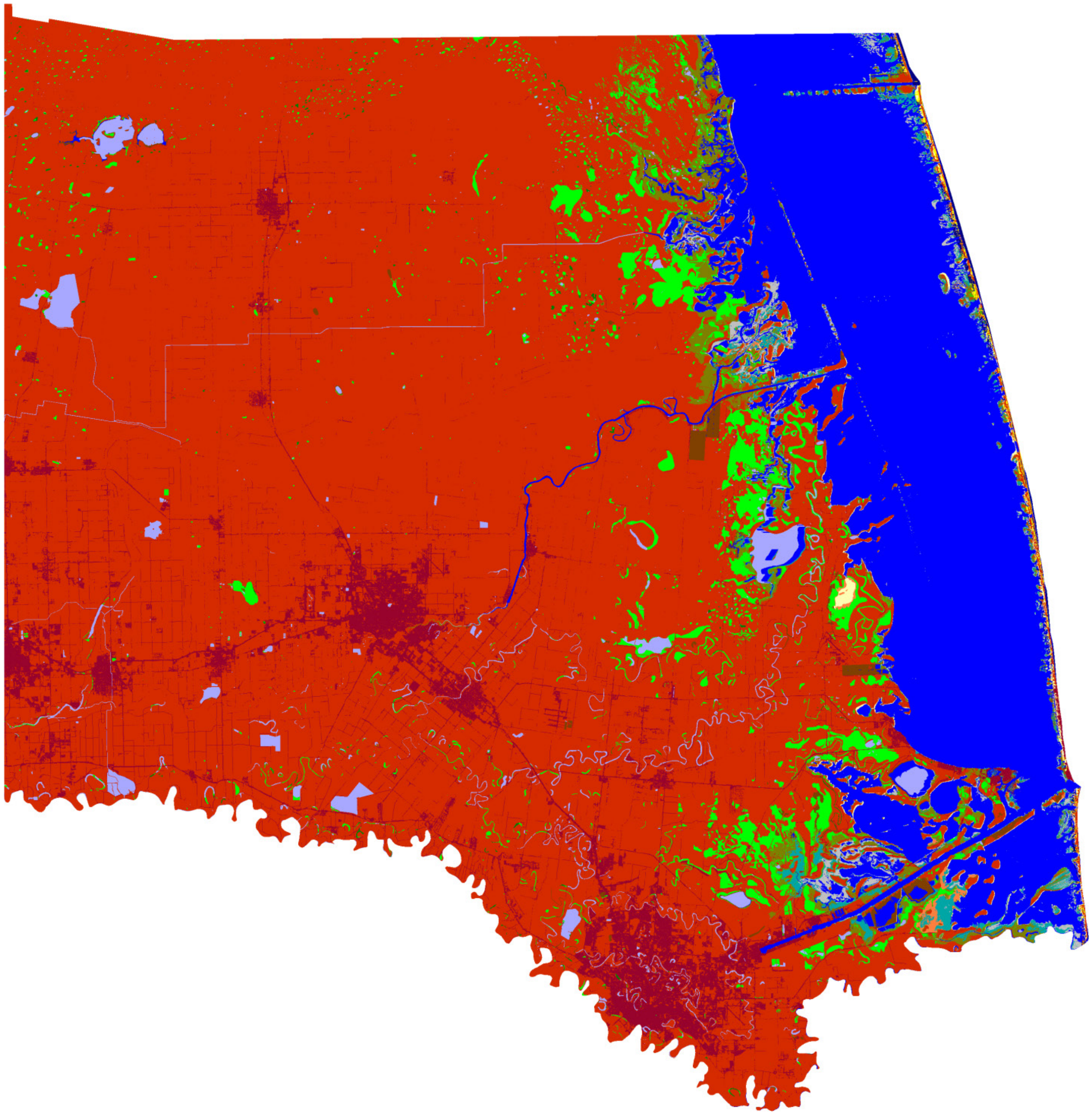
Lower Rio Grande Valley NWR, Initial Condition



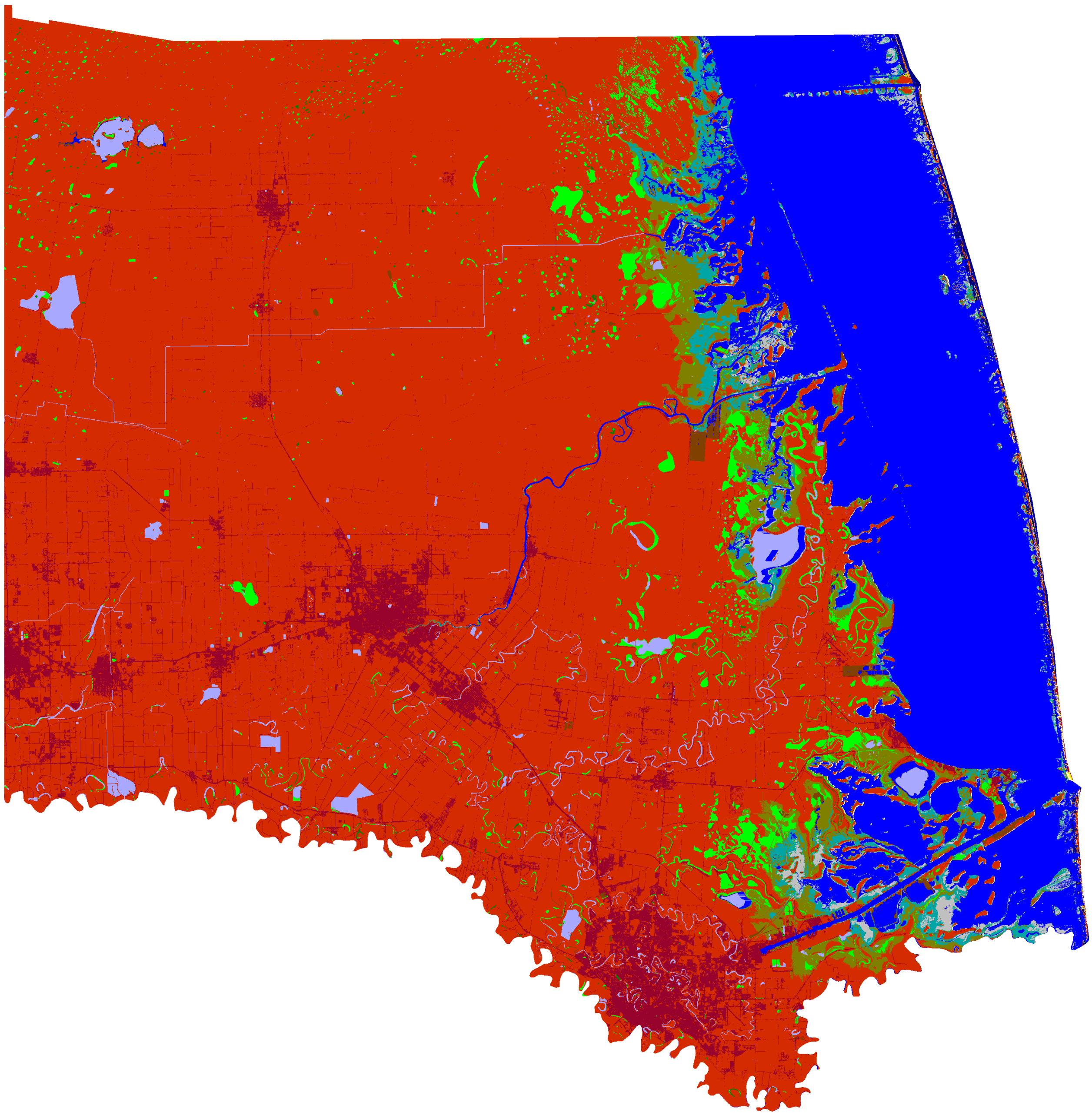
Lower Rio Grande Valley NWR, 2025, 2 m SLR



Lower Rio Grande Valley NWR, 2050, 2 m SLR



Lower Rio Grande Valley NWR, 2075, 2 m SLR



Lower Rio Grande Valley NWR, 2100, 2 m SLR

Discussion

Model results for Lower Rio Grande NWR indicate that overall the refuge is relatively resilient to the SLR scenarios examined. The majority of the study area is located at elevations that preclude effects from SLR by 2100 (e.g., more than 70% of the study area is dry land with elevation above 2 m).

As expected, the most heavily affected areas are the coastal boundaries. By 2100, a large portion of these areas are predicted to be inundated under each SLR scenario examined. Between 44% and 97% of the beaches on the Intracoastal Waterway are predicted to be lost. Other wetland cover classes in this part of the refuge, although they currently represent a small fractional coverage of the overall refuge, are also predicted to undergo large changes. A considerable portion of the irregularly-flooded marshes will be lost and converted to regularly-flooded marshes given SLR above 0.69 m by 2100. Inland-fresh marshes and swamps are predicted to be resilient due to high elevations and higher dry-lands located between these wetlands and the ocean.

In addition to the land-cover changes cited above, model predictions under higher rates of SLR suggest that the protective functions of the barrier islands will be largely compromised.

Local accretion data were taken from available literature and applied to the entire study area. However, more specific measurements of accretion rates within the refuge could provide better predictions of marsh losses in the future.

Most of the study area was covered by high-vertical-resolution LiDAR data; however some areas were covered by older NED data (Figure 6). In these non-LiDAR areas, model results are subject to considerable uncertainty as wetland elevations were estimated based on the local tide range.

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