Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Bandon Marsh 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.

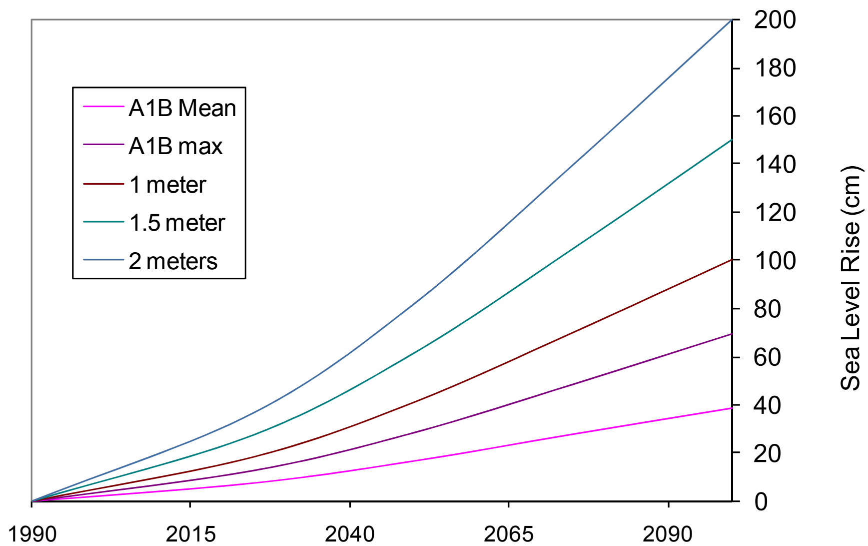
Sea Level Rise Scenarios

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 Oregon DOGAMI (Department of Geology and Mineral Industries) and is based on high-resolution LiDAR with a 2008 photo date (Figure 1).

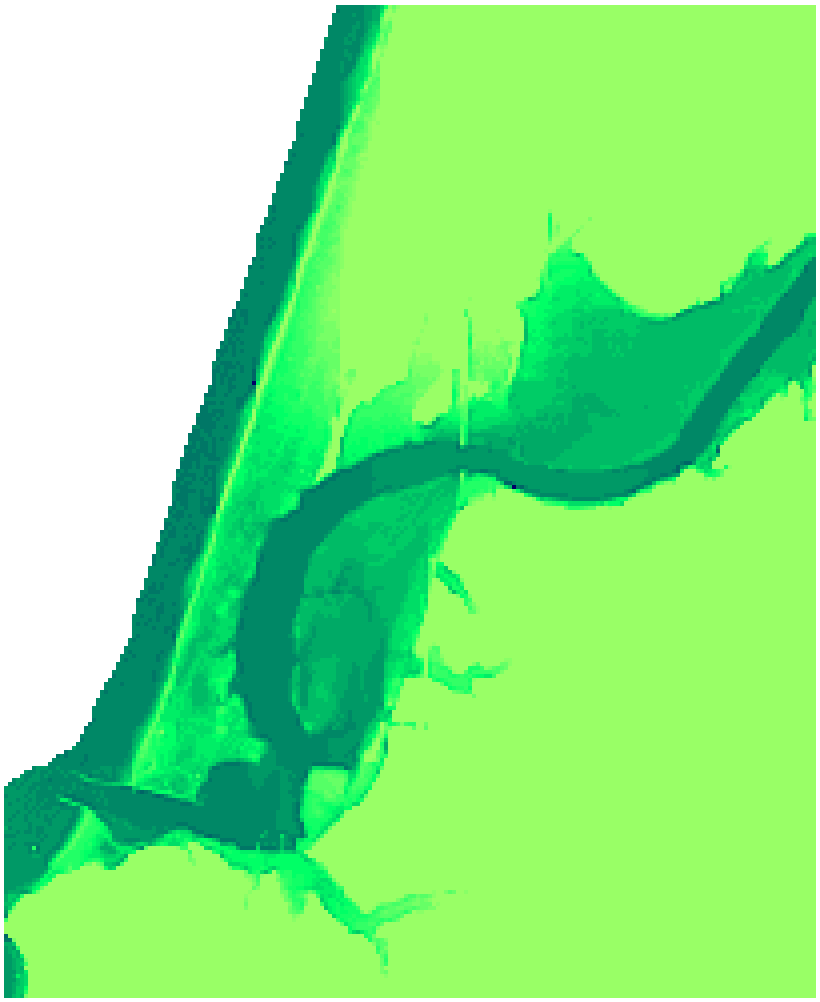


Figure 1: Elevation map of the NWR created using SLAMM.

The wetlands layer for the study area was produced by the Oregon Wetlands Program and is based on a 1982 photo date. Converting the NWI survey into 30 meter cells indicates that the approximately one thousand acre refuge (approved acquisition boundary including water) is composed of primarily the following categories:

Inland Fresh Marsh	39.6%
Saltmarsh	16.2%
Tidal Flat	11.8%
Undev. Dry Land	10.8%
Swamp	8.7%
Brackish Marsh	7.8%
Estuarine Open Water	2.7%

Nearly all of the refuge inland fresh marsh is impounded – nearly half the refuge – according to the wetland layer produced by Oregon Wetlands Program (Figure 2).

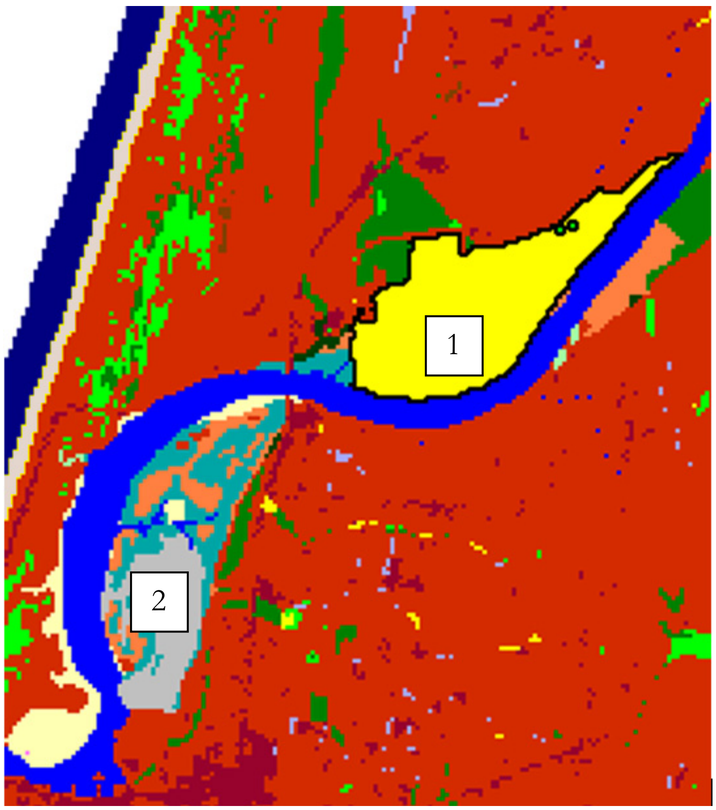


Figure 2: Diked areas are shown in yellow. Ni-les'tun Unit [1] and Bandon Marsh Unit [2].

Several changes were made to the wetland and dike data layers. To produce a comprehensive dike map, the dike layer from the State of Oregon was combined with that from the National Wetland Inventory. This change led to the impoundment of all of the inland fresh marsh in the Ni-les'tun Unit (Figure 2).

The historic trend for sea level rise was estimated at 1.29 mm/year using the nearest NOAA gage with SLR data (9432780, Charleston, OR). The rate of sea level rise for this refuge is slightly lower than the global average for the last 100 years (approximately 1.7 mm/year) suggesting regional isostatic rebound.

The tide range was estimated at 2.162 meters (great diurnal range or GT) using NOAA tide gage (9432373, Bandon, Coquille River, OR) (Figure 3).

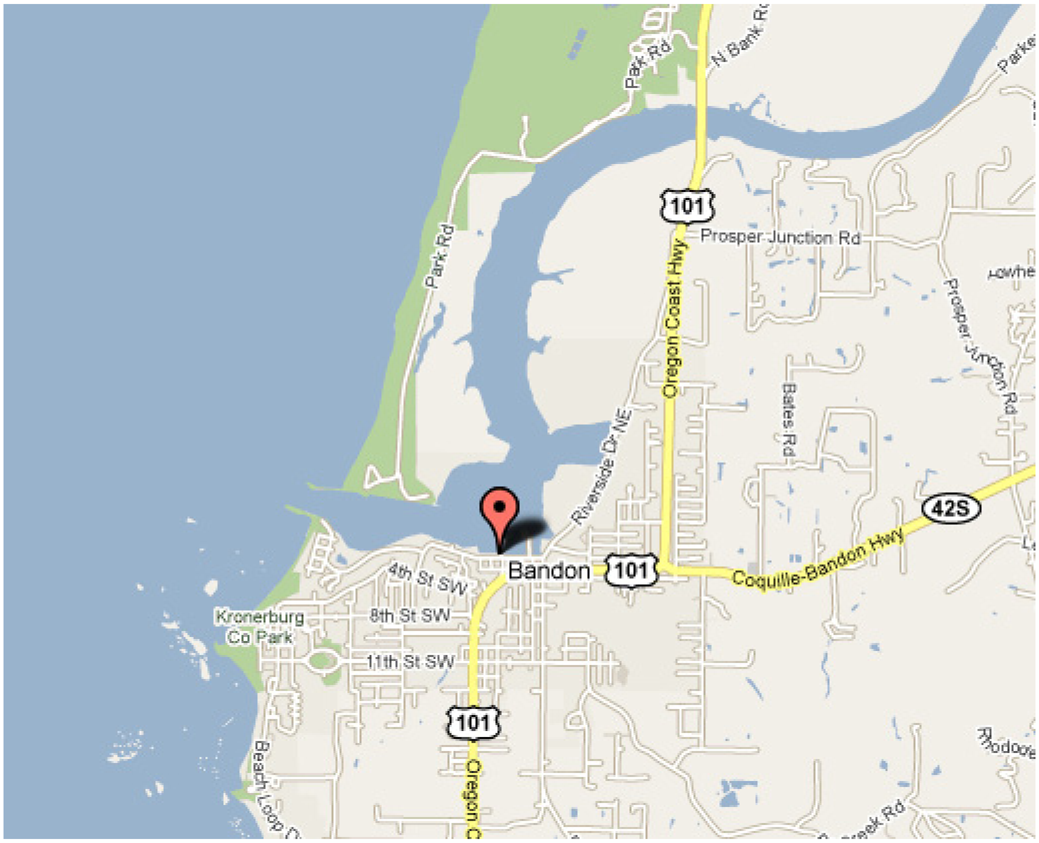


Figure 3: NOAA Gage Relevant to the Study Area.

Marsh accretion was set to 3 mm/year based on an accretion study performed in Salmon River (Thom, 1992). No site-specific accretion data were available for this site, but this value is close to regional average of 3.8 mm/year for the Pacific Northwest also described by Thom (1992).

Marsh erosion values were set to 0 meters/year based on a report of the Ni-les'tun Unit of the refuge (USFWS, 2009). According to the report, the estuary is low energy environment where erosion effects are minimal.

The MTL to NAVD88 correction was derived using the NOAA VDATUM product. The value of 1.12 meter was used based on the average values from several locations ranging from 1.11 meters to around 1.13.

Modeled U.S. Fish and Wildlife Service refuge boundaries for California are based on Approved Acquisition Boundaries as published on the FWS National Wildlife Refuge Data and Metadata website. The cell-size used for this analysis was 30 meter by 30 meter cells. Note that the SLAMM model will track partial conversion of cells based on elevation and slope.

Erin Stockenberg and Khem So, both of Oregon USFWS, each helped us in our data and parameterization search. Our contacts were not aware of any local accretion or erosion studies beyond the papers cited above.

SUMMARY OF SLAMM INPUT PARAMETERS FOR BANDON MARSH NWR

Parameter	Global
Description	Bandon Marsh
NWI Photo Date (YYYY)	1982
DEM Date (YYYY)	2008
Direction Offshore [n,s,e,w]	West
Historic Trend (mm/yr)	1.29
MTL-NAVD88 (m)	1.12
GT Great Diurnal Tide Range (m)	2.162
Salt Elev. (m above MTL)	1.513
Marsh Erosion (horz. m /yr)	0
Swamp Erosion (horz. m /yr)	0
T.Flat Erosion (horz. m /yr)	0
Reg. Flood Marsh Accr (mm/yr)	3
Irreg. Flood Marsh Accr (mm/yr)	3
Tidal Fresh Marsh Accr (mm/yr)	3
Beach Sed. Rate (mm/yr)	0.5
Freq. Overwash (years)	0
Use Elev Pre-processor [True,False]	FALSE

Results

The SLAMM simulation for Bandon Marsh NWR predicts only moderate effects of sea level rise (SLR) in scenarios under one meter (eustatic SLR by 2100). At one meter of SLR and above, results become more severe.

The refuge's "inland fresh marsh" fares well across all sea level rise scenarios because nearly all of it is diked. (Within SLAMM, dikes are assumed to be maintained against up-to 2 meters of SLR.)

Regularly flooded (salt) marshes fare well through the 1-meter scenario, after which inundation leads to nearly half of the salt marsh being lost. Salt marsh is actually predicted to increase under the one meter scenario due to the regular inundation of irregularly flooded (high) marshes.

Bandon Marsh NWR is predicted to lose between 19% and 92% of its swamp by 2100 depending on the SLR scenario utilized.

SLR by 2100 (m)	**0.39**	**0.69**	**1**	**1.5**	**2**
Inland Fresh Marsh	0%	0%	0%	0%	2%
Saltmarsh	1%	-4%	-31%	17%	44%
Undev. Dry Land	34%	42%	49%	54%	56%
Swamp	19%	38%	57%	78%	92%
Brackish Marsh	5%	13%	65%	90%	98%

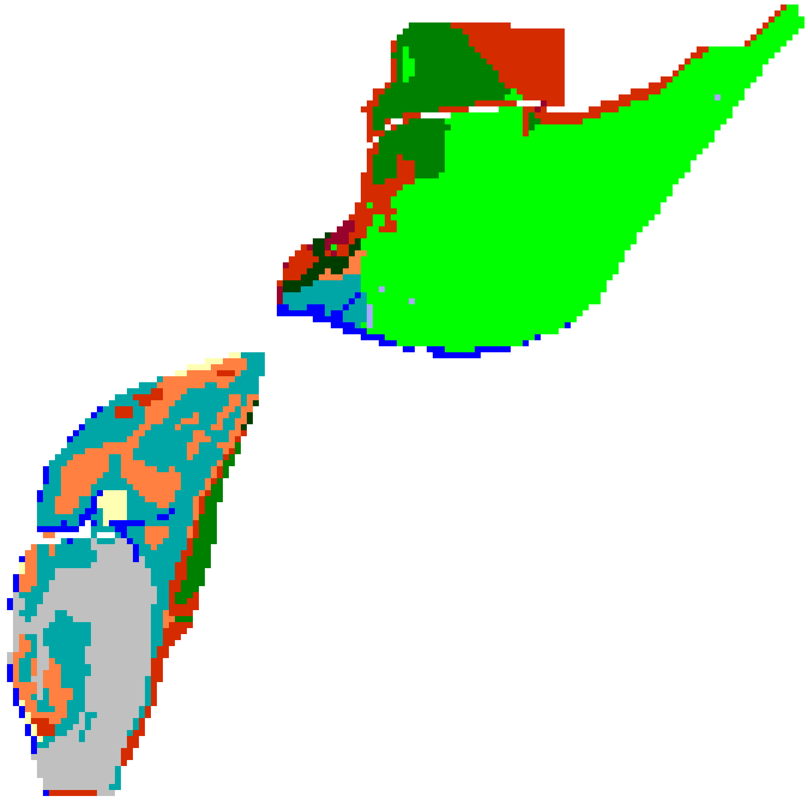
Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

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

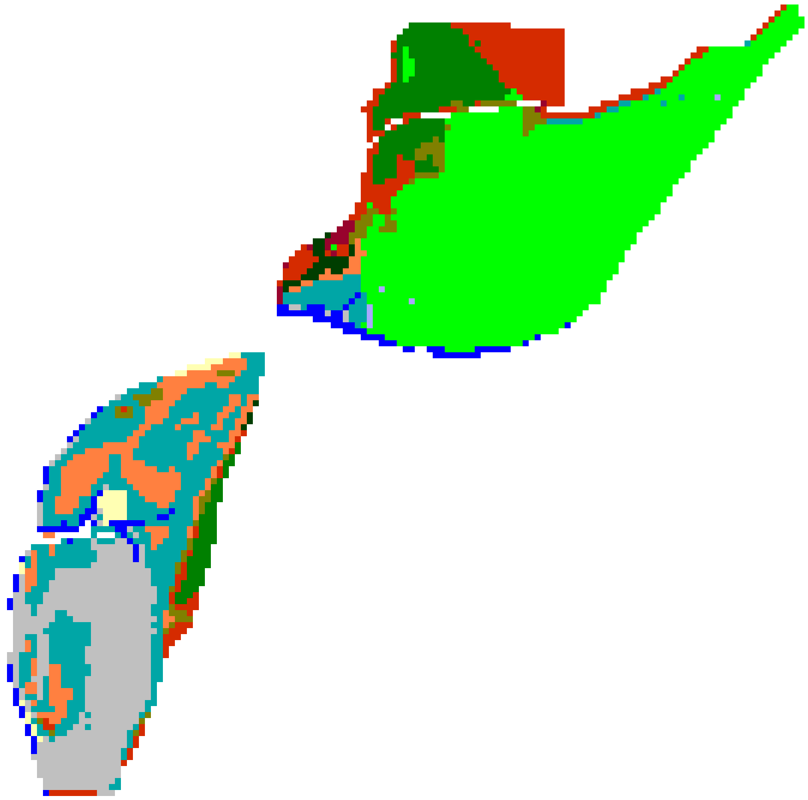
Bandon Marsh NWR
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

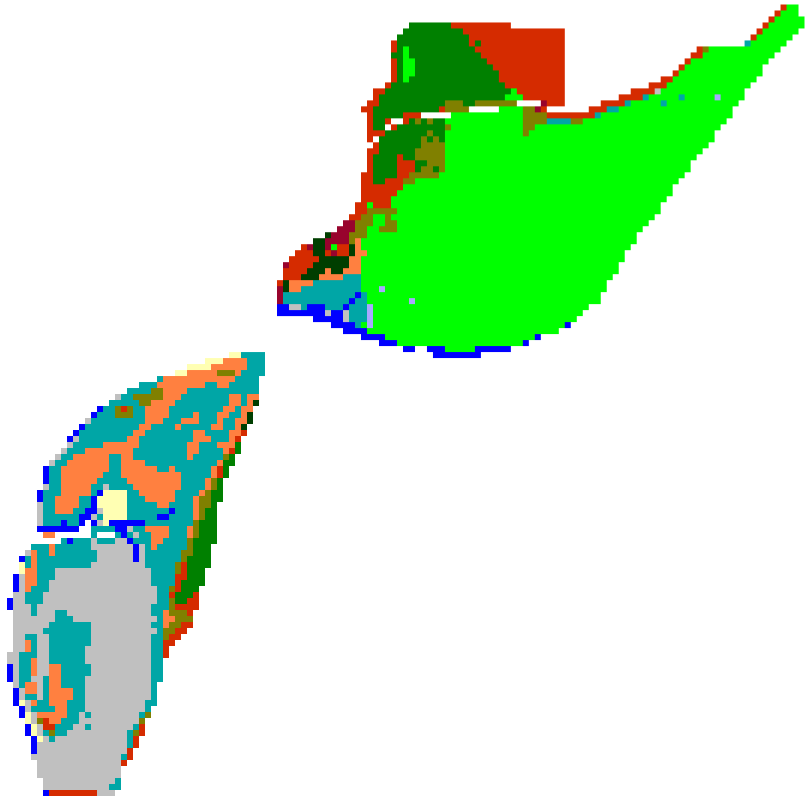
	Initial	2025	2050	2075	2100
Inland Fresh Marsh	400.1	399.6	399.6	399.6	399.6
Saltmarsh	163.2	162.7	161.3	161.5	162.1
Tidal Flat	119.0	134.6	135.9	136.0	135.9
Undev. Dry Land	108.5	80.4	77.7	74.3	71.7
Swamp	87.4	80.0	77.5	73.9	70.8
Brackish Marsh	78.5	73.3	73.5	73.9	74.2
Estuarine Open Water	27.6	27.8	27.9	28.1	28.4
Estuarine Beach	9.3	9.3	9.3	9.3	9.3
Tidal Swamp	9.3	7.5	7.3	7.0	6.6
Dev. Dry Land	4.7	4.5	4.5	4.5	4.5
Inland Open Water	1.6	1.6	1.6	1.6	1.6
Trans. Salt Marsh	0.0	27.7	32.9	39.6	44.6
Total (incl. water)	**1009.2**	**1009.2**	**1009.2**	**1009.2**	**1009.2**



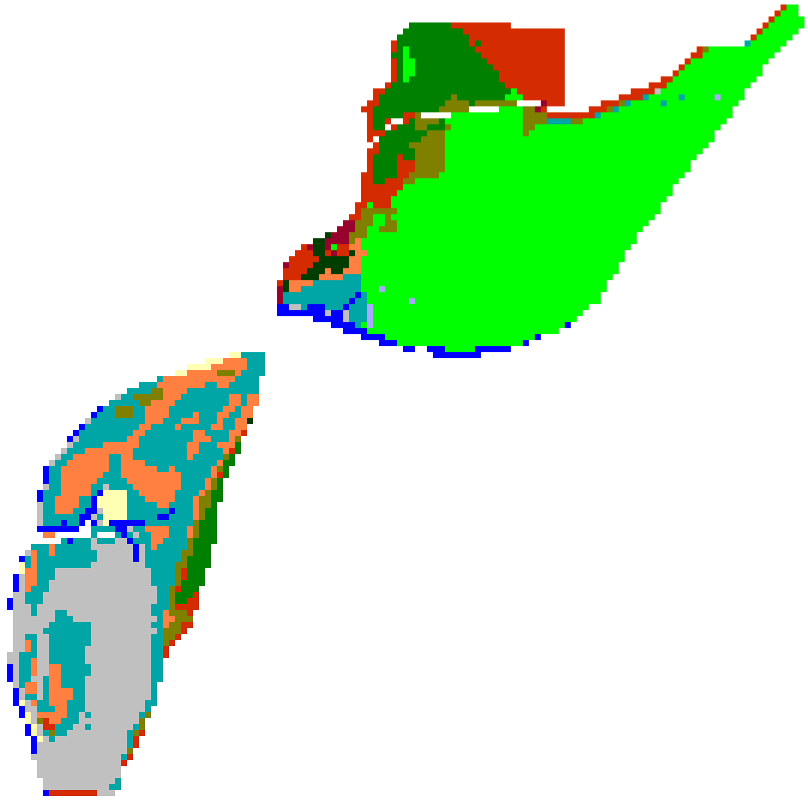
Bandon Marsh NWR, Initial Condition



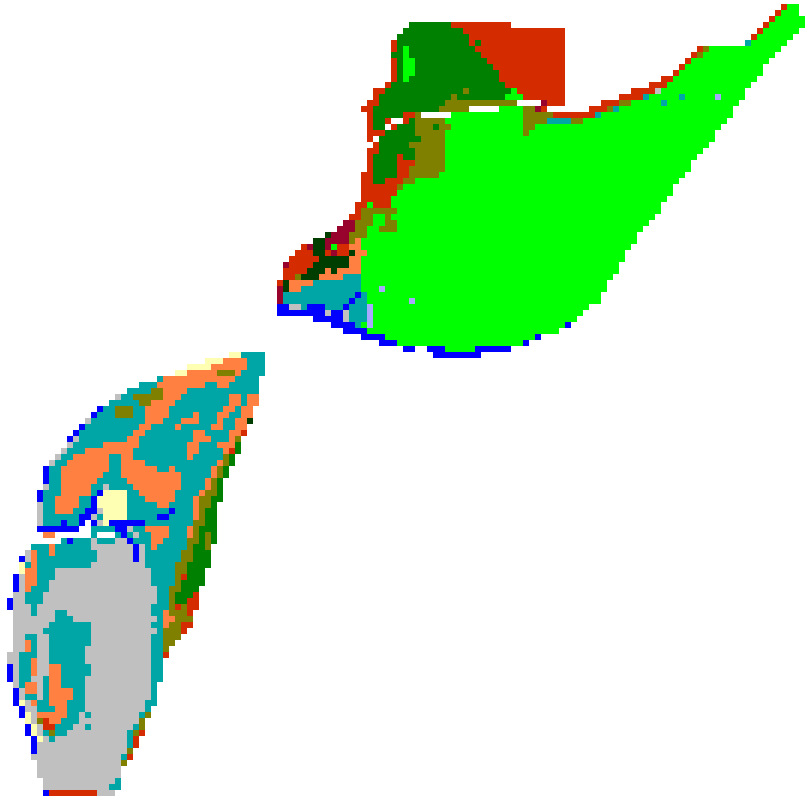
Bandon Marsh NWR, 2025, Scenario A1B Mean



Bandon Marsh NWR, 2050, Scenario A1B Mean



Bandon Marsh NWR, 2075, Scenario A1B Mean

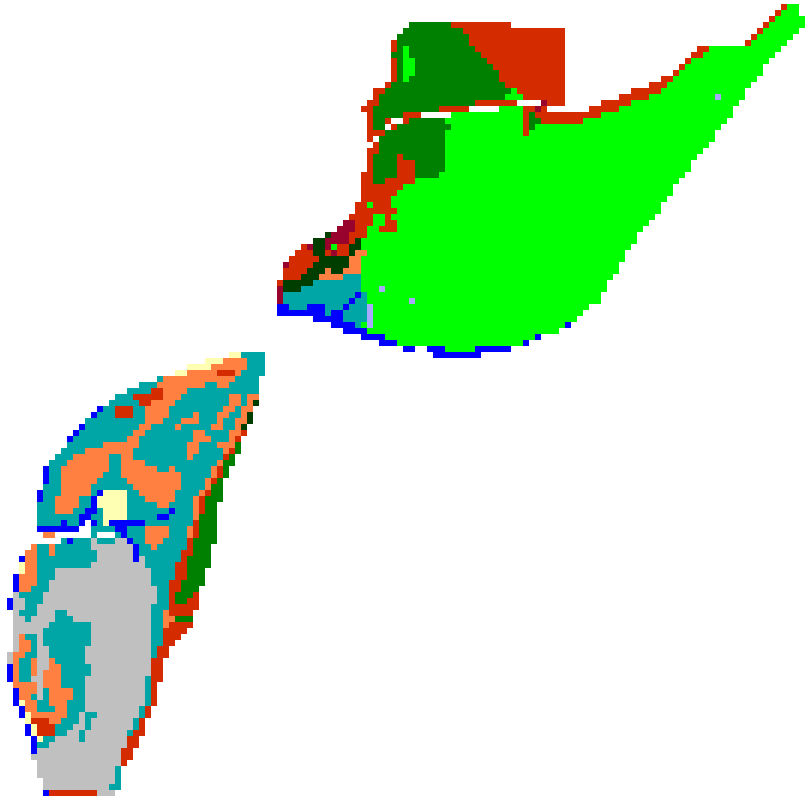


Bandon Marsh NWR, 2100, Scenario A1B Mean

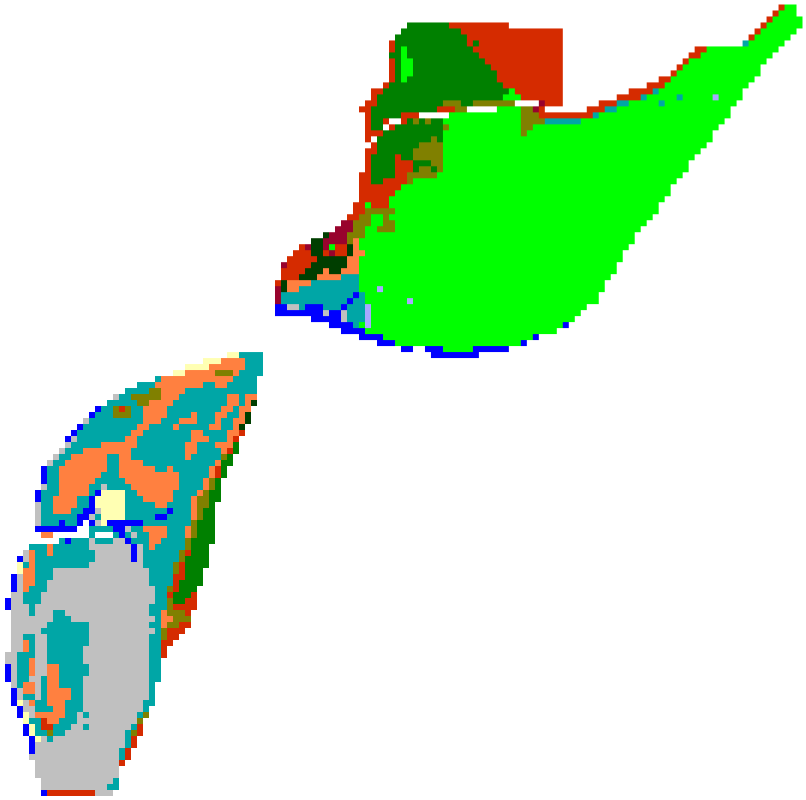
Bandon Marsh NWR
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

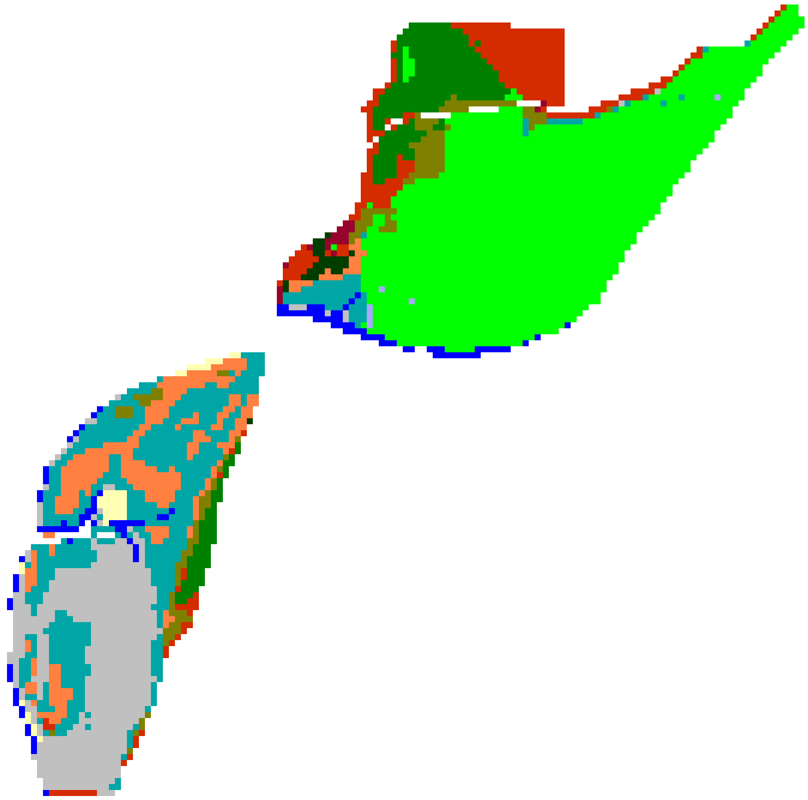
	Initial	2025	2050	2075	2100
Inland Fresh Marsh	400.1	399.6	399.6	399.6	399.5
Saltmarsh	163.2	163.6	161.6	163.3	169.9
Tidal Flat	119.0	134.8	139.8	144.5	132.3
Undev. Dry Land	108.5	78.7	73.8	68.7	62.5
Swamp	87.4	78.4	73.1	65.5	54.2
Brackish Marsh	78.5	73.5	73.0	71.7	68.0
Estuarine Open Water	27.6	27.9	28.2	30.1	49.8
Estuarine Beach	9.3	9.3	9.3	8.9	7.8
Tidal Swamp	9.3	7.3	6.8	5.3	3.2
Dev. Dry Land	4.7	4.5	4.5	4.4	4.3
Inland Open Water	1.6	1.6	1.6	1.6	1.6
Trans. Salt Marsh	0.0	29.9	37.8	45.5	56.1
Total (incl. water)	**1009.2**	**1009.2**	**1009.2**	**1009.2**	**1009.2**



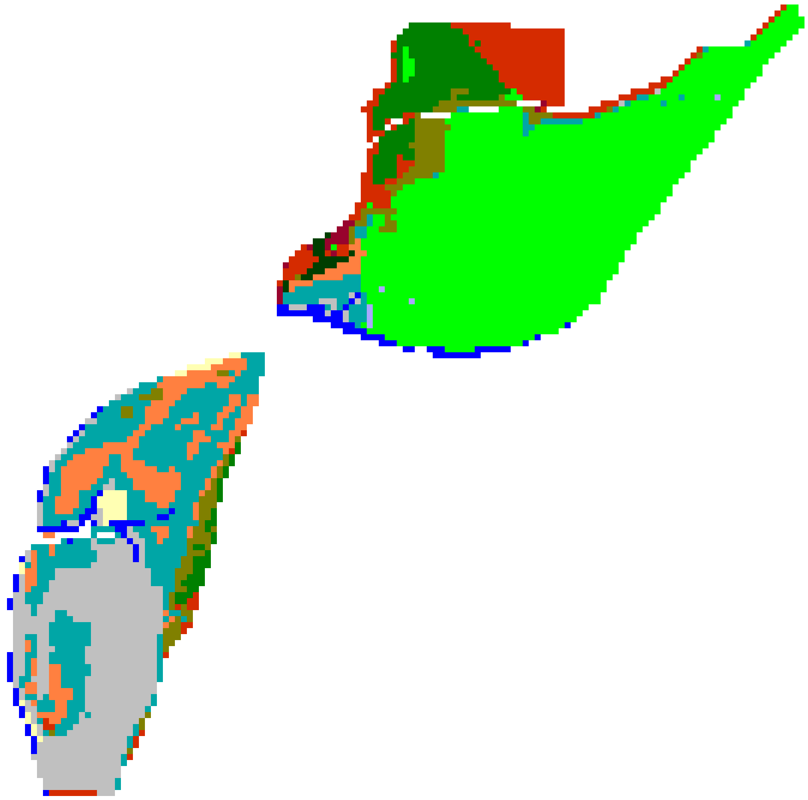
Bandon Marsh NWR, Initial Condition



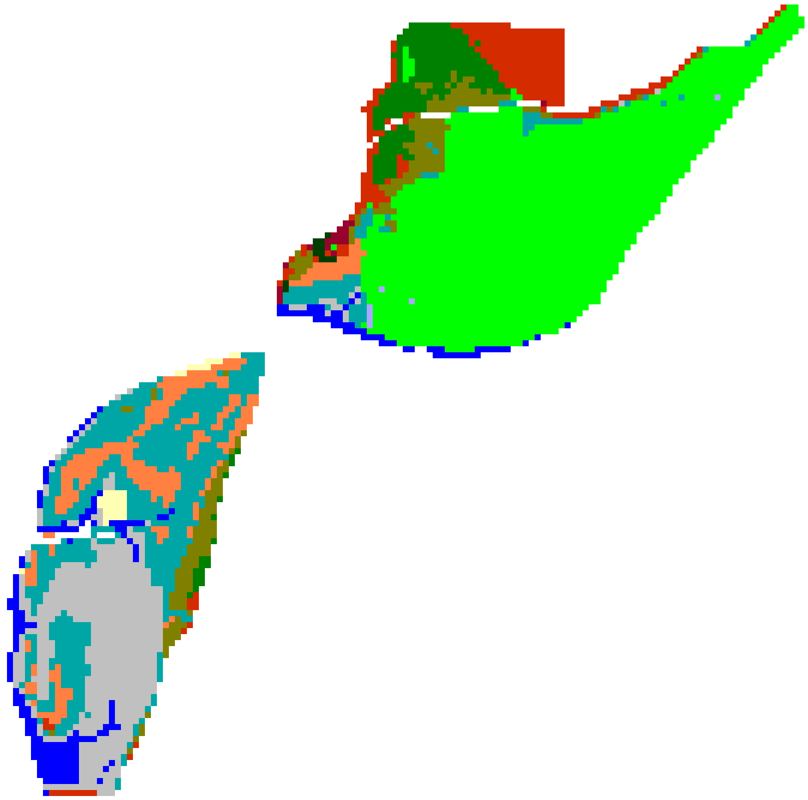
Bandon Marsh NWR, 2025, Scenario A1B Maximum



Bandon Marsh NWR, 2050, Scenario A1B Maximum



Bandon Marsh NWR, 2075, Scenario A1B Maximum

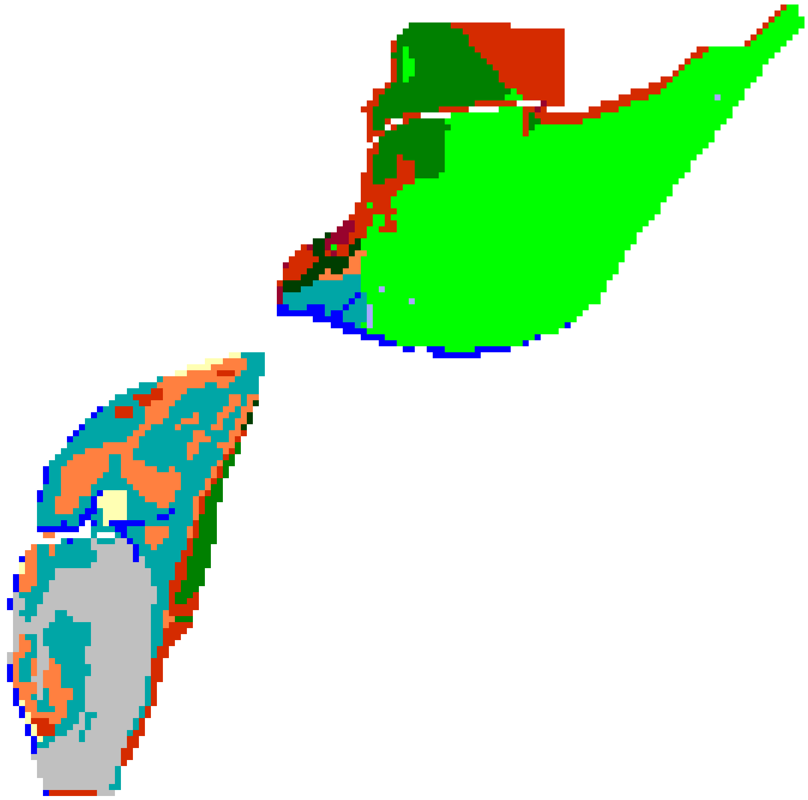


Bandon Marsh NWR, 2100, Scenario A1B Maximum

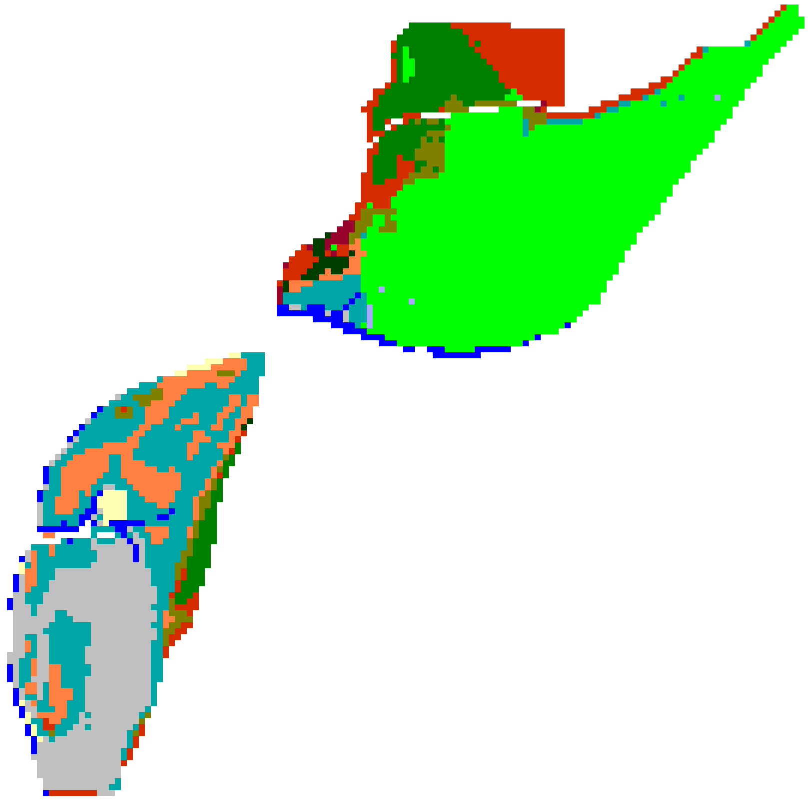
Bandon Marsh NWR
1 Meter Eustatic SLR by 2100

Results in Acres

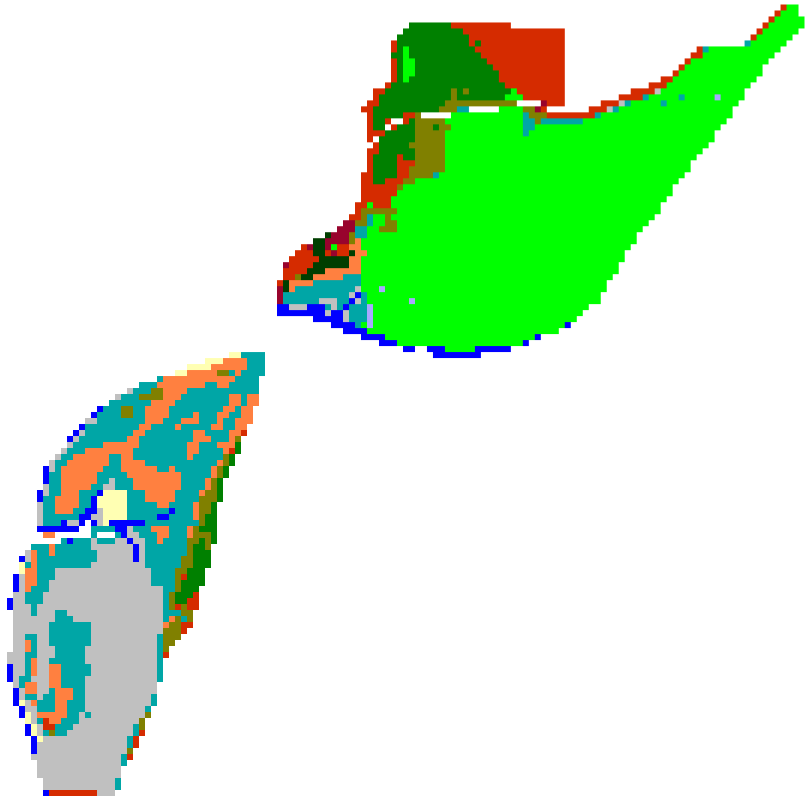
	Initial	2025	2050	2075	2100
Inland Fresh Marsh	400.1	399.6	399.6	399.4	399.2
Saltmarsh	163.2	163.6	163.5	180.0	213.9
Tidal Flat	119.0	137.3	146.1	137.5	128.3
Undev. Dry Land	108.5	76.8	70.7	62.2	55.9
Swamp	87.4	76.3	68.6	53.1	37.3
Brackish Marsh	78.5	73.0	70.9	59.6	27.8
Estuarine Open Water	27.6	28.0	29.0	51.9	83.9
Estuarine Beach	9.3	9.3	9.1	7.7	6.9
Tidal Swamp	9.3	7.1	5.7	2.8	1.7
Dev. Dry Land	4.7	4.5	4.4	4.3	3.9
Inland Open Water	1.6	1.6	1.6	1.6	1.6
Trans. Salt Marsh	0.0	32.2	39.8	49.0	48.9
Total (incl. water)	**1009.2**	**1009.2**	**1009.2**	**1009.2**	**1009.2**



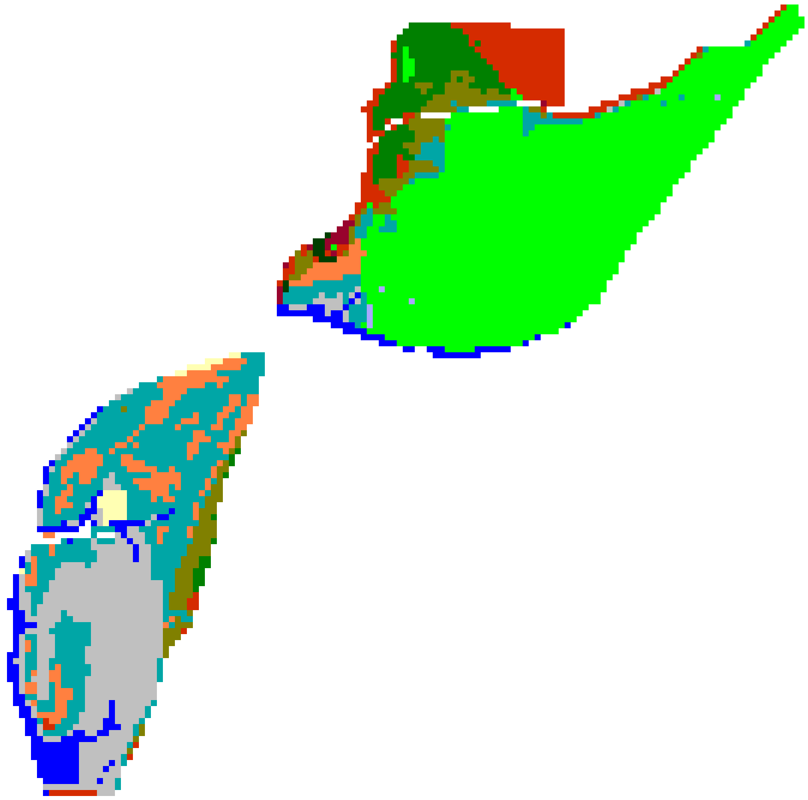
Bandon Marsh NWR, Initial Condition



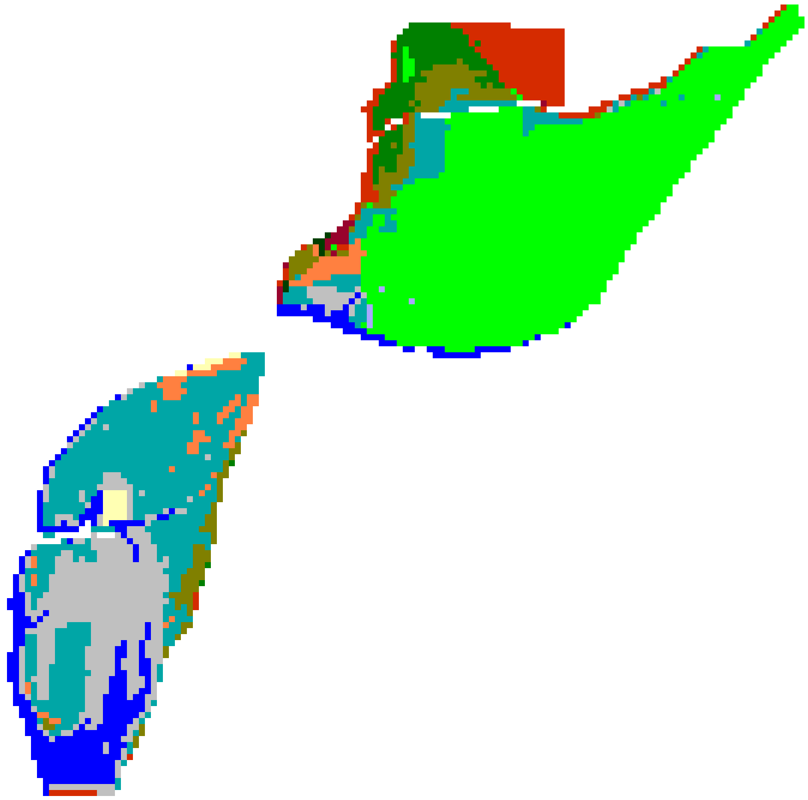
Bandon Marsh NWR, 2025, 1 meter



Bandon Marsh NWR, 2050, 1 meter



Bandon Marsh NWR, 2075, 1 meter

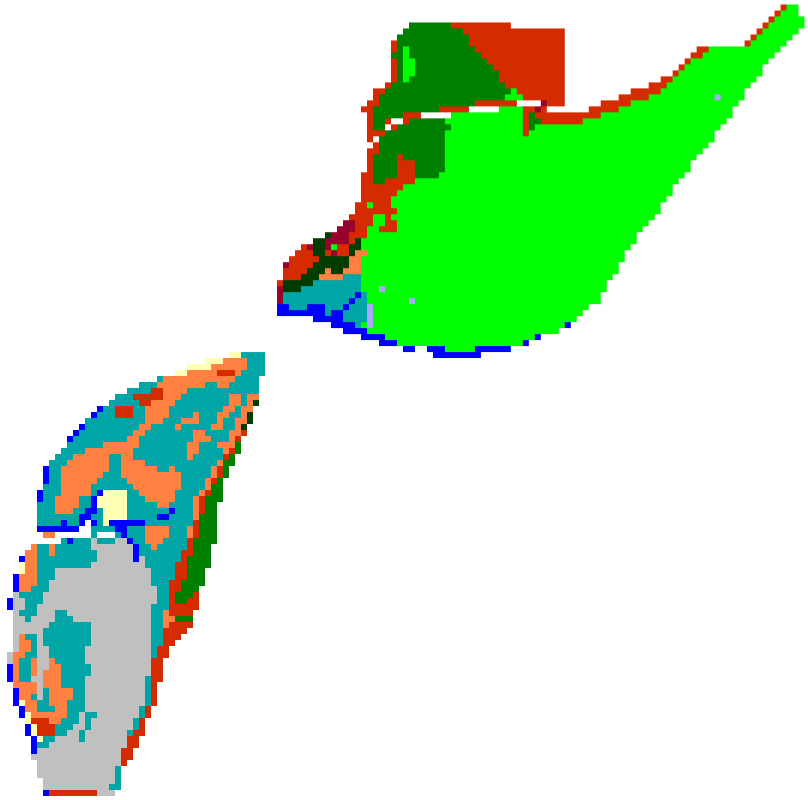


Bandon Marsh NWR, 2100, 1 meter

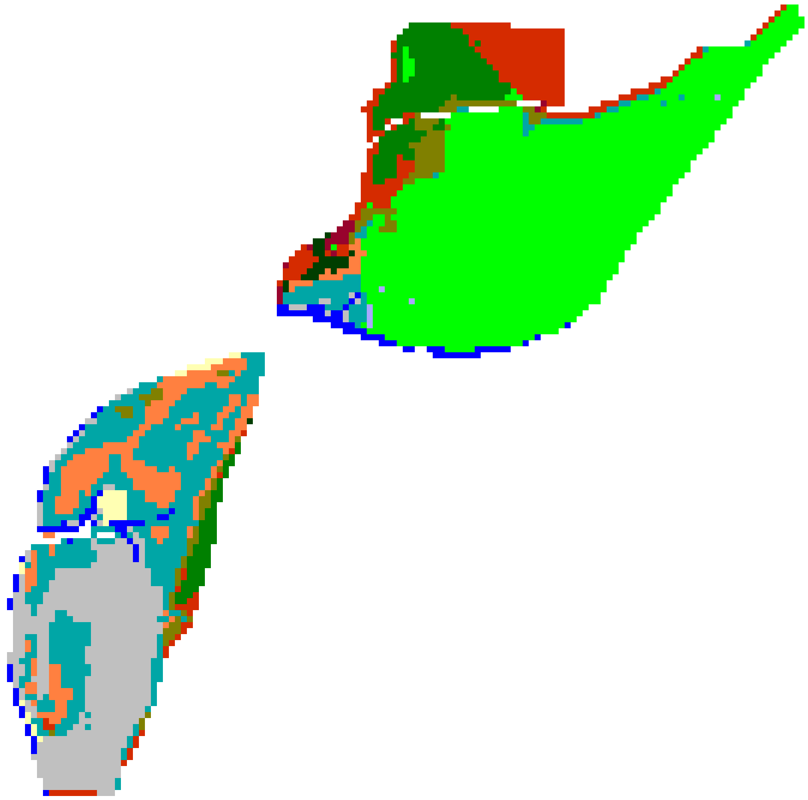
Bandon Marsh NWR
1.5 Meters Eustatic SLR by 2100

Results in Acres

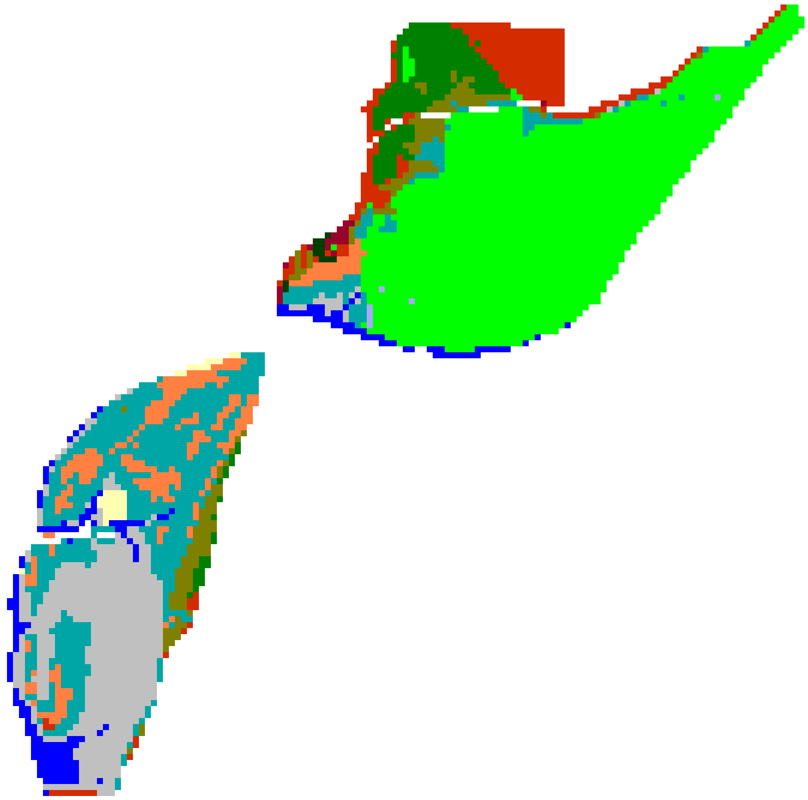
	Initial	2025	2050	2075	2100
Inland Fresh Marsh	400.1	399.6	399.4	399.1	398.6
Saltmarsh	163.2	164.8	180.0	208.3	136.3
Tidal Flat	119.0	141.5	144.2	144.7	199.3
Undev. Dry Land	108.5	73.8	64.4	54.9	49.8
Swamp	87.4	72.8	56.6	34.0	18.9
Brackish Marsh	78.5	71.5	59.0	20.4	8.1
Estuarine Open Water	27.6	28.2	45.4	91.3	162.9
Estuarine Beach	9.3	9.3	7.9	6.7	2.5
Tidal Swamp	9.3	6.6	3.3	1.5	0.8
Dev. Dry Land	4.7	4.5	4.4	3.8	3.3
Inland Open Water	1.6	1.6	1.6	1.6	1.6
Trans. Salt Marsh	0.0	35.1	43.1	42.9	27.1
Total (incl. water)	**1009.2**	**1009.2**	**1009.2**	**1009.2**	**1009.2**



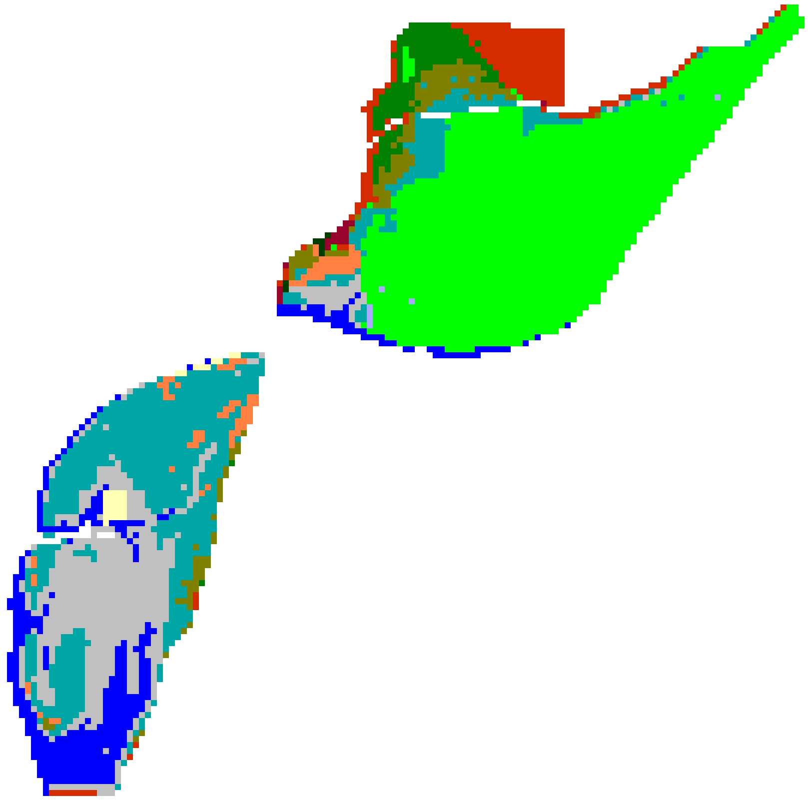
Bandon Marsh NWR, Initial Condition



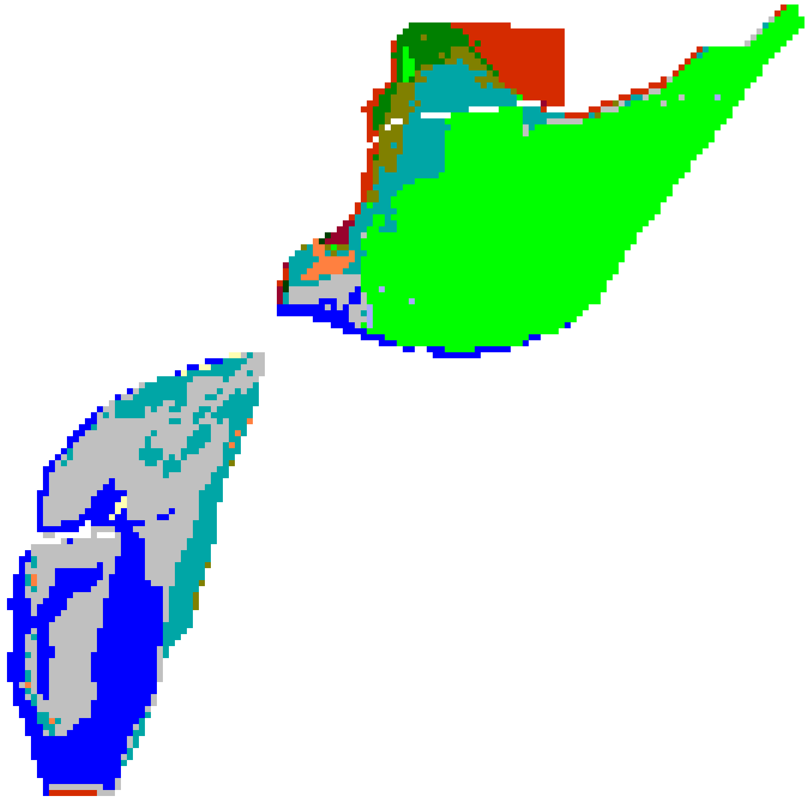
Bandon Marsh NWR, 2025, 1.5 meter



Bandon Marsh NWR, 2050, 1.5 meter



Bandon Marsh NWR, 2075, 1.5 meter

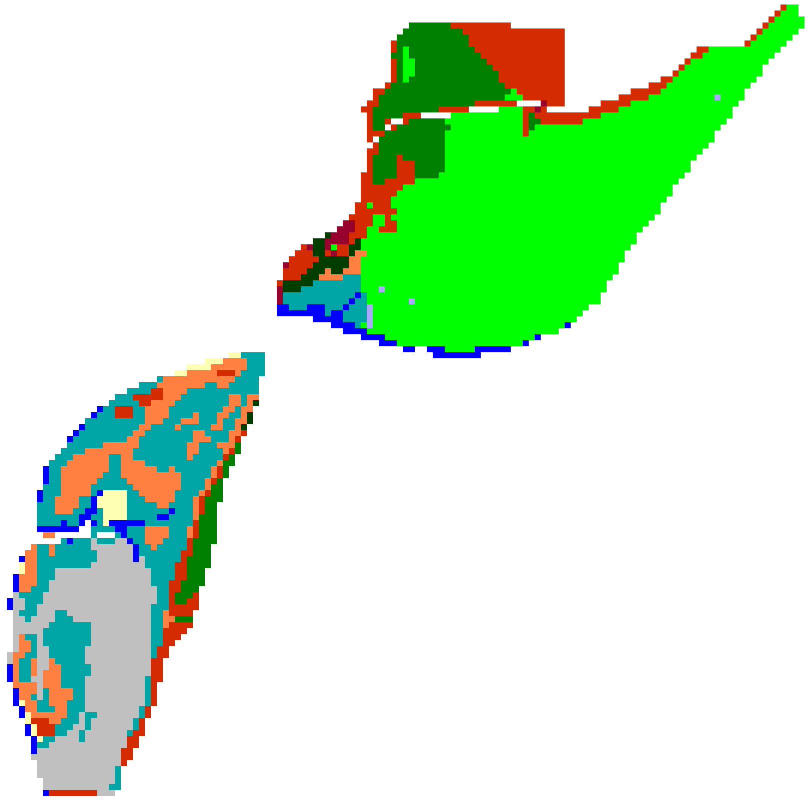


Bandon Marsh NWR, 2100, 1.5 meter

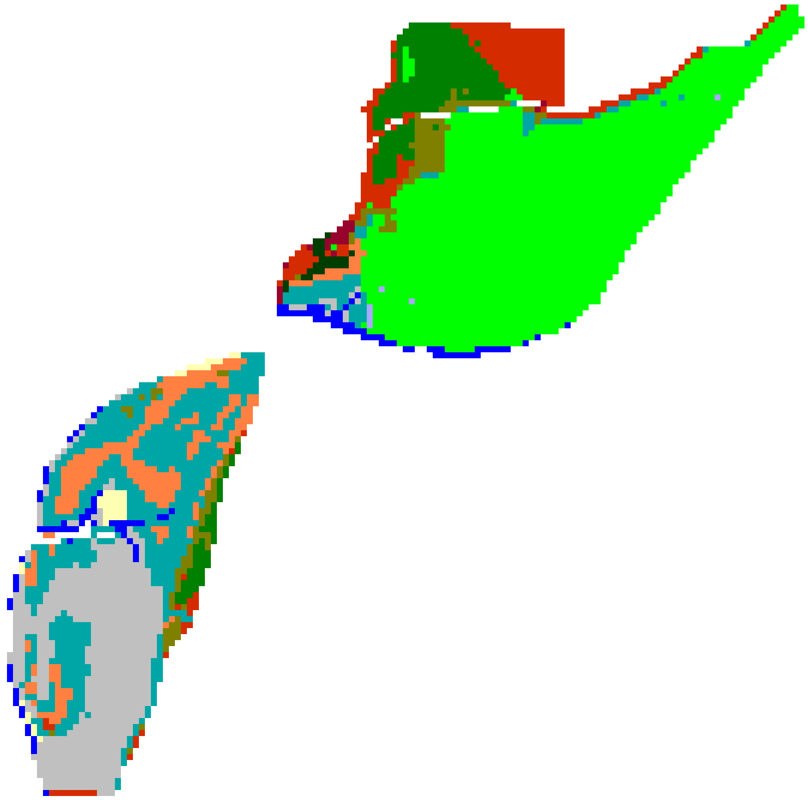
Bandon Marsh NWR
2 Meters Eustatic SLR by 2100

Results in Acres

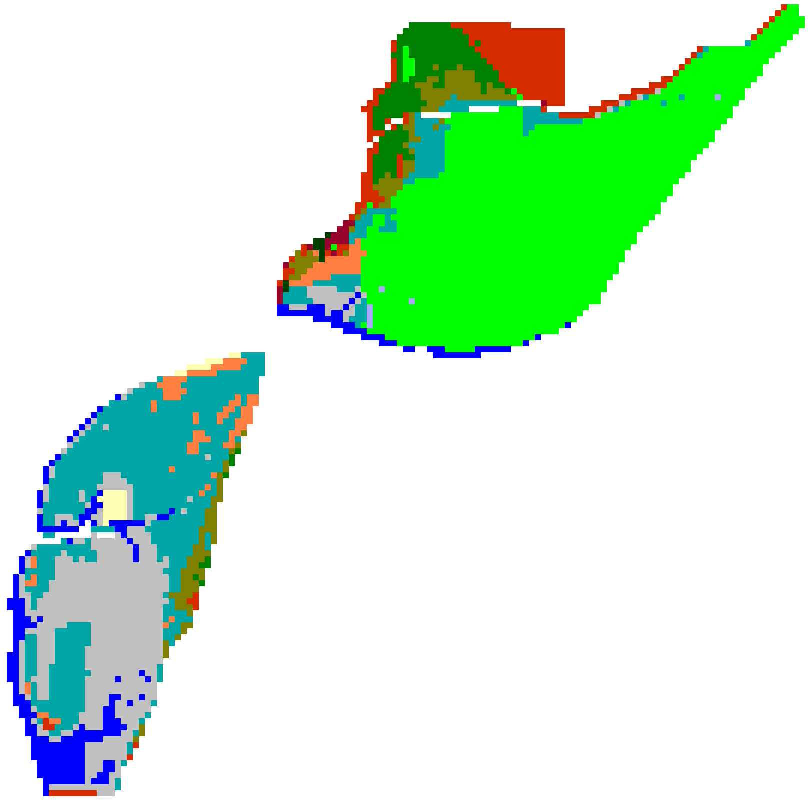
	Initial	2025	2050	2075	2100
Inland Fresh Marsh	400.1	399.6	399.2	398.7	392.4
Saltmarsh	163.2	168.1	208.8	128.9	91.2
Tidal Flat	119.0	145.5	148.7	202.4	219.0
Undev. Dry Land	108.5	71.5	59.6	50.6	48.2
Swamp	87.4	69.4	45.2	21.5	7.3
Brackish Marsh	78.5	69.2	27.9	8.5	1.6
Estuarine Open Water	27.6	28.7	62.0	155.0	226.3
Estuarine Beach	9.3	9.2	7.2	3.2	0.4
Tidal Swamp	9.3	5.8	2.1	0.8	0.5
Dev. Dry Land	4.7	4.5	4.2	3.4	2.6
Inland Open Water	1.6	1.6	1.6	1.6	1.6
Trans. Salt Marsh	0.0	36.2	42.6	34.6	18.2
Total (incl. water)	**1009.2**	**1009.2**	**1009.2**	**1009.2**	**1009.2**



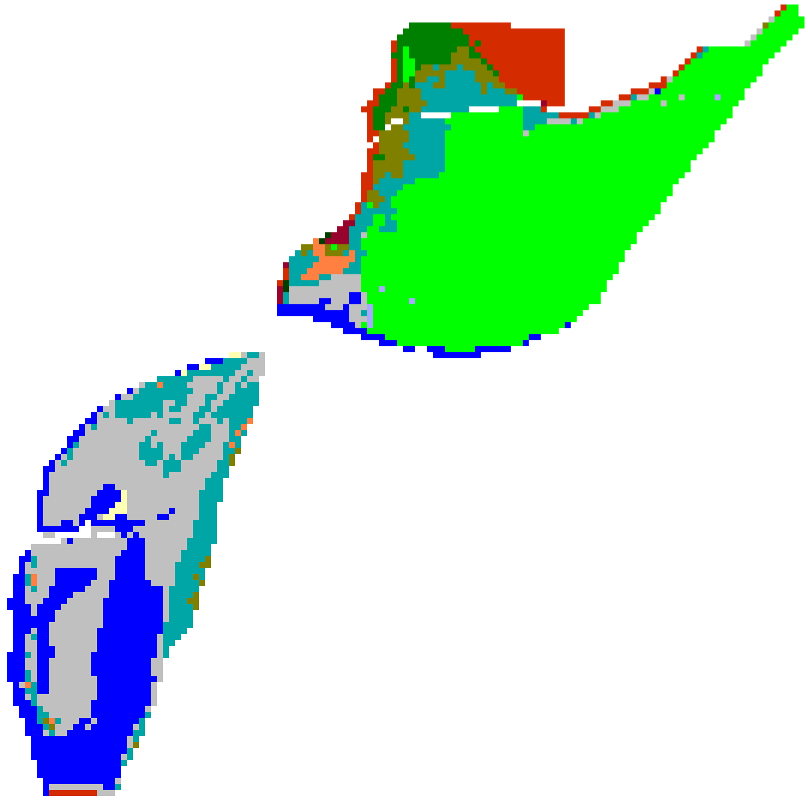
Bandon Marsh NWR, Initial Condition



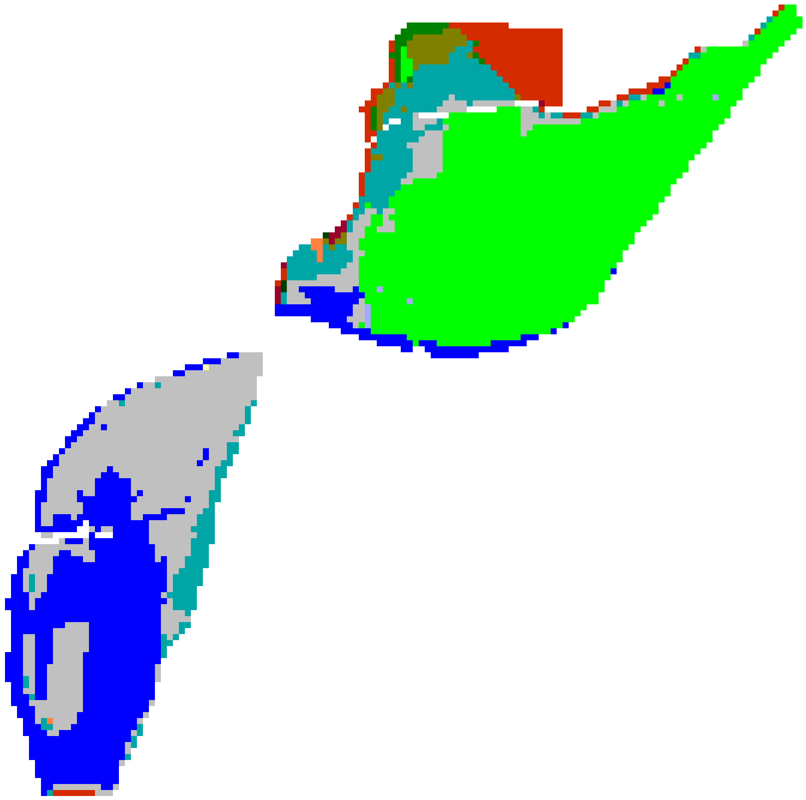
Bandon Marsh NWR, 2025, 2 meters



Bandon Marsh NWR, 2050, 2 meters



Bandon Marsh NWR, 2075, 2 meters



Bandon Marsh NWR, 2100, 2 meters

Discussion

This SLAMM simulation indicates that the marshes of Bandon Marsh NWR may be fairly resilient to SLR up until one meter of eustatic SLR by 2100. In the one-meter scenario, high marsh starts to convert to regularly flooded salt marsh. In scenarios beyond one meter of SLR (by 2100) much of the marshes convert to tidal flats and open water.

No local marsh accretion data were available for this site so accretion was modeled using a rough regional average. Data about sediment trapping and marsh accretion at this site could reduce model uncertainty to some degree.

This simulation also couples an elevation data set from 2008 with a wetlands cover layer from 1982. This can be the cause of additional model uncertainty, especially if substantive land-cover changes have occurred since the wetlands photo date.

Nearly all of the swamp in the refuge is located in the Ni-les'tun Unit of Bandon Marsh NWR (Figure 2). This swamp is located behind a large swath of impounded inland fresh marsh. There is an undiked region west of the inland fresh marsh capable of allowing some saltwater intrusion into the swamps. However, the semi-protected location of these swamps suggests an overall "muted" tidal input. This potential reduction in tide range due to impoundment location means that SLAMM results for swamp loss in Bandon Marsh may be overstated. On the other hand, as SLR scenarios increase, the extent of such "muting" will likely be reduced. SLAMM is not a hydrodynamic model and is not capable of estimating tidal ranges based on water flows and dike locations.

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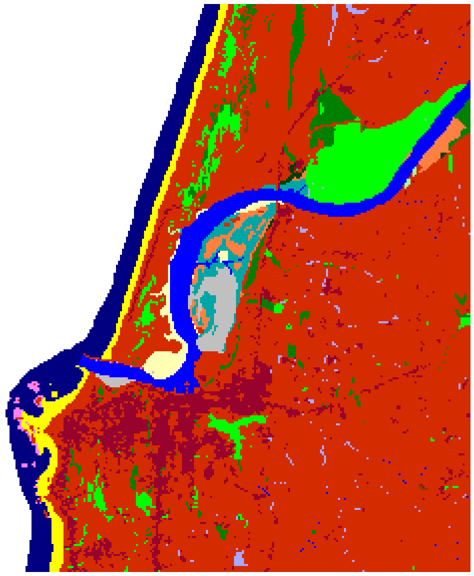
Appendix A: Contextual Results

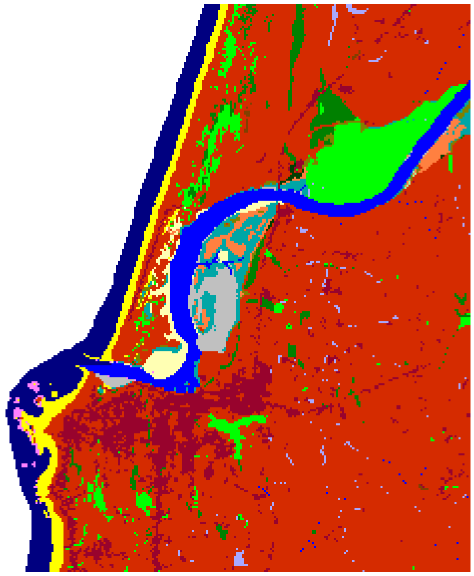
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

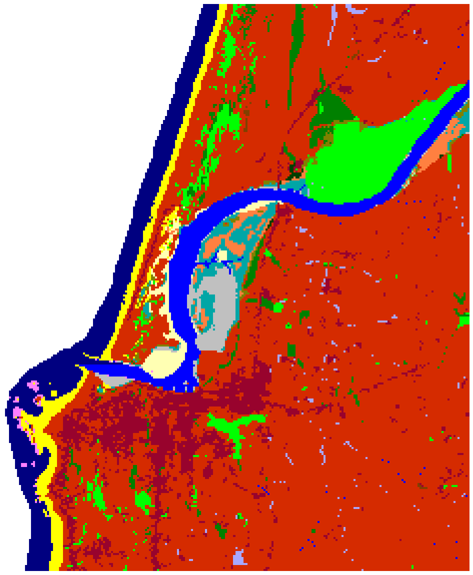
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



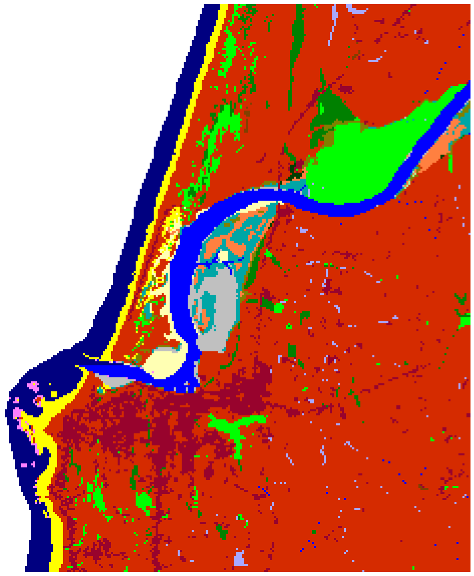
Bandon Marsh NWR, Initial Condition



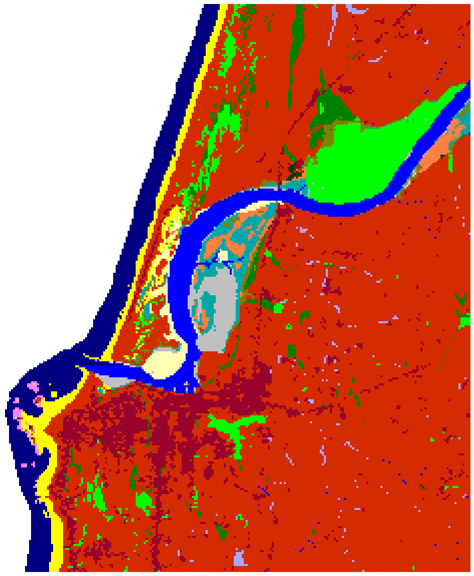
Bandon Marsh NWR, 2025, Scenario A1B Mean



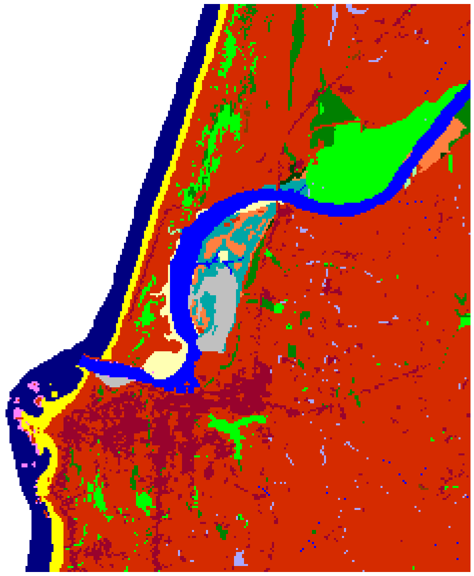
Bandon Marsh NWR, 2050, Scenario A1B Mean



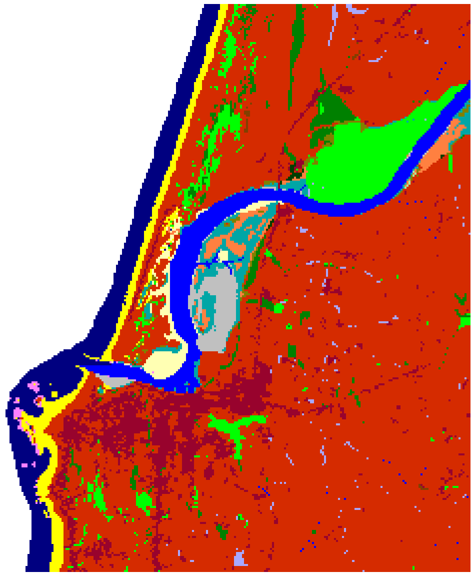
Bandon Marsh NWR, 2075, Scenario A1B Mean



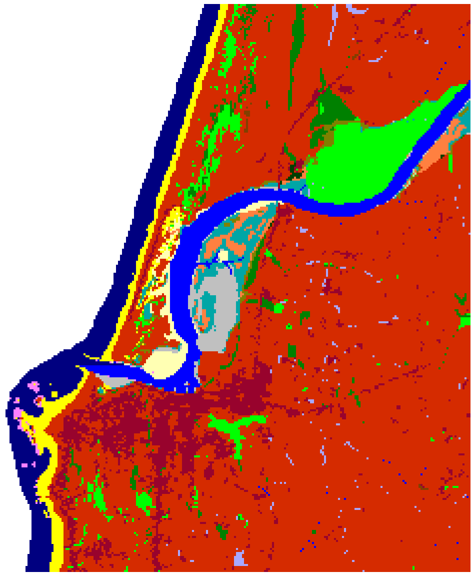
Bandon Marsh NWR, 2100, Scenario A1B Mean



Bandon Marsh NWR, Initial Condition



Bandon Marsh NWR, 2025, Scenario A1B Maximum



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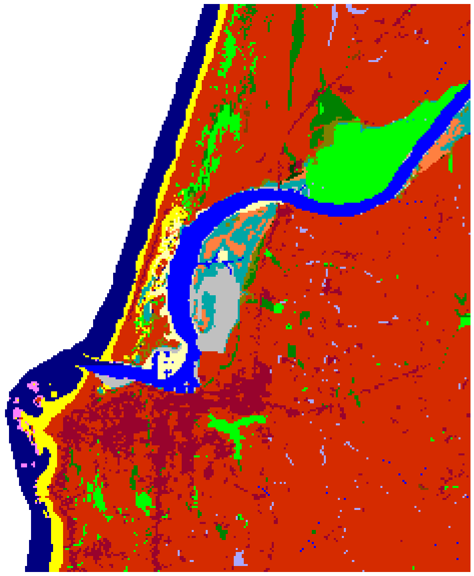
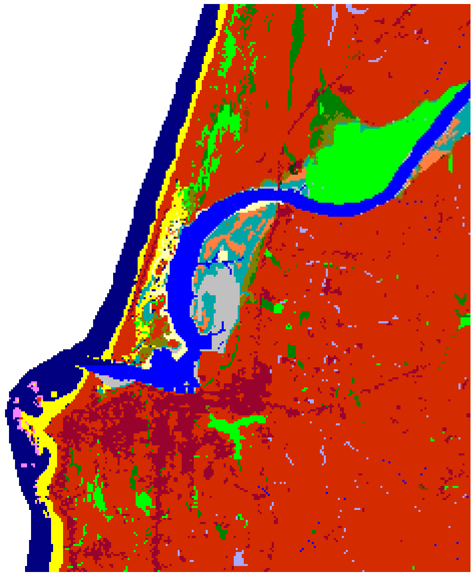
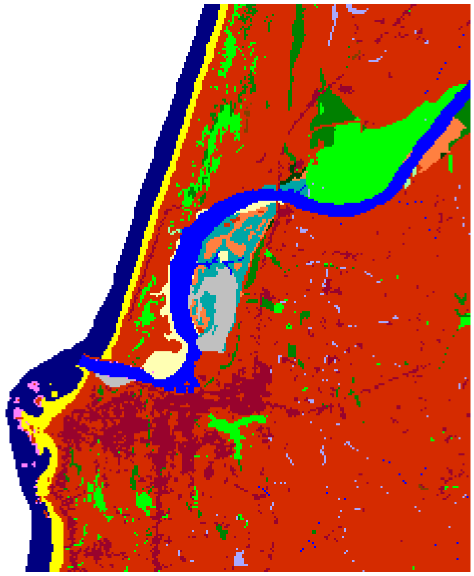


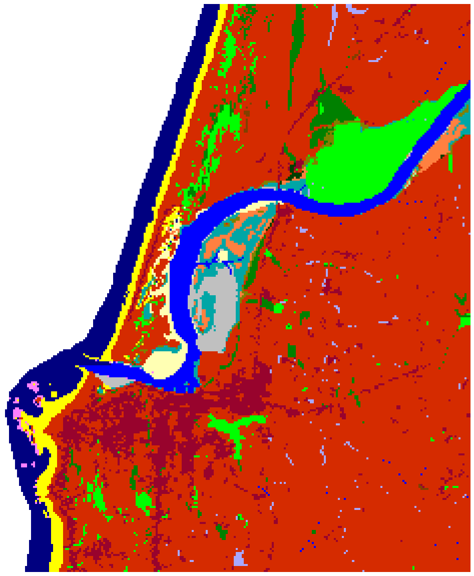
Bandon Marsh NWR, 2075, Scenario A1B Maximum



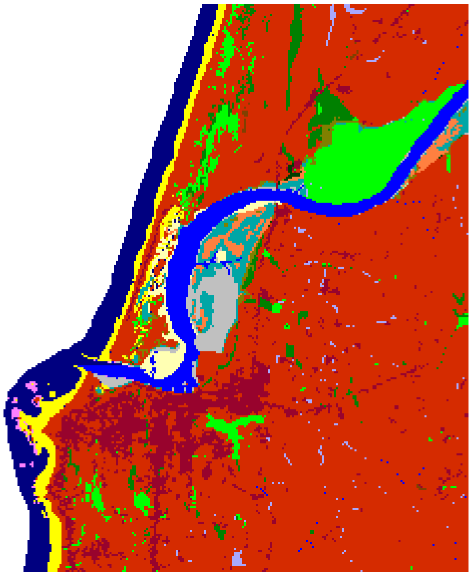
Bandon Marsh NWR, 2100, Scenario A1B Maximum



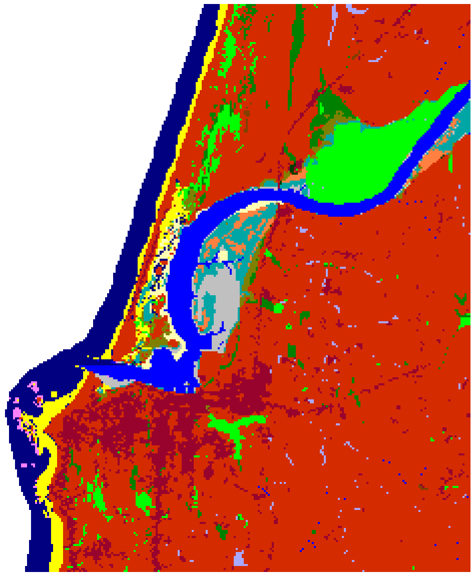
Bandon Marsh NWR, Initial Condition



Bandon Marsh NWR, 2025, 1 meter



Bandon Marsh NWR, 2050, 1 meter



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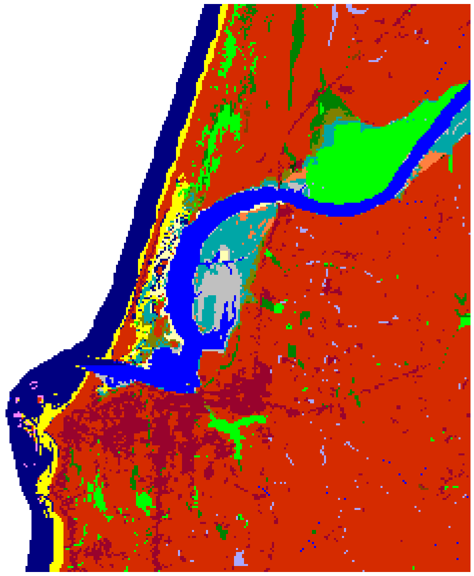
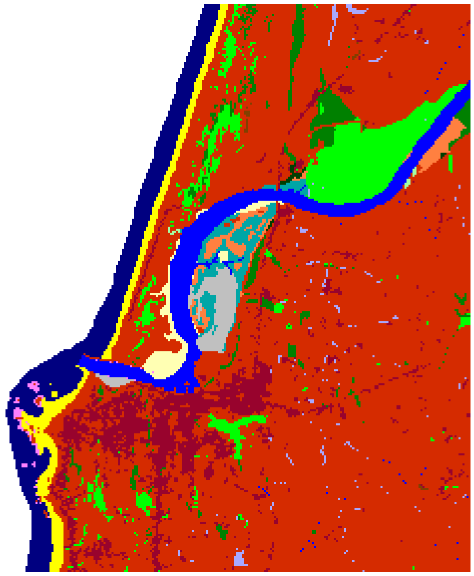
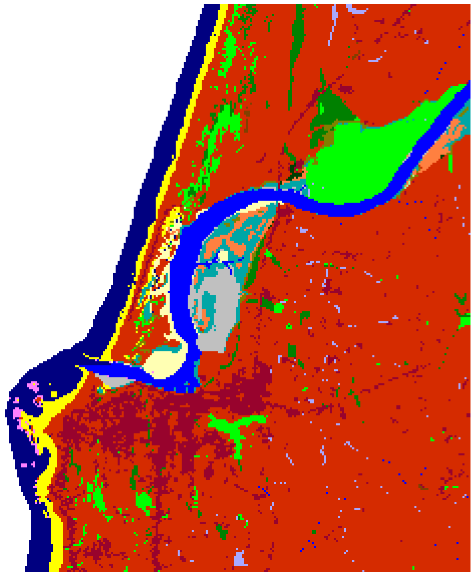


Bandon Marsh NWR, 2100, 1 meter



Bandon Marsh NWR, Initial Condition



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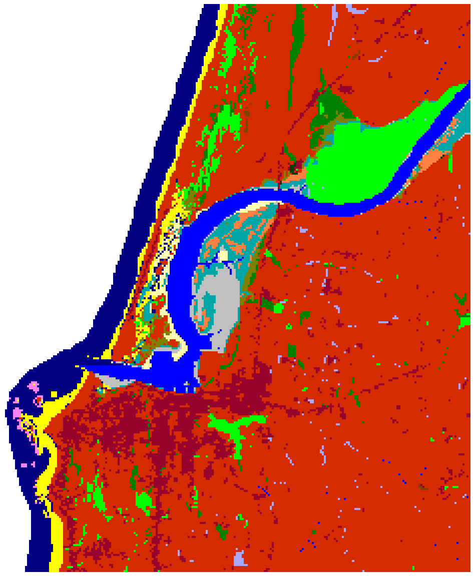
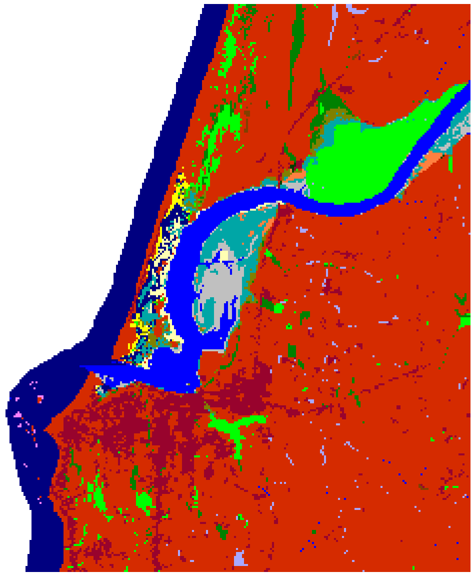


Bandon Marsh NWR, 2050, 1.5 meter



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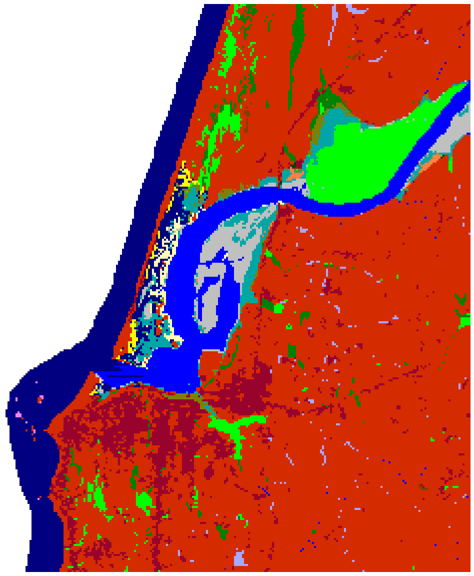

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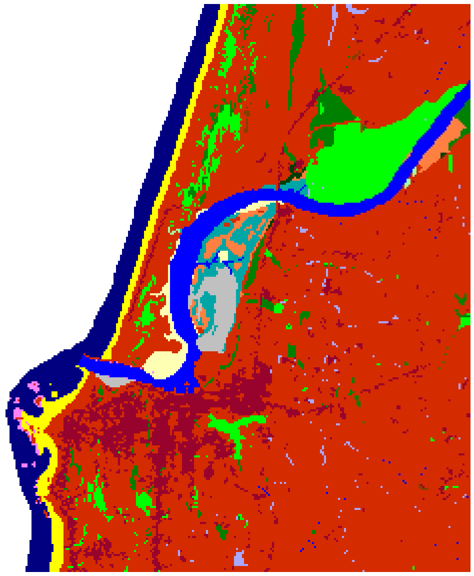
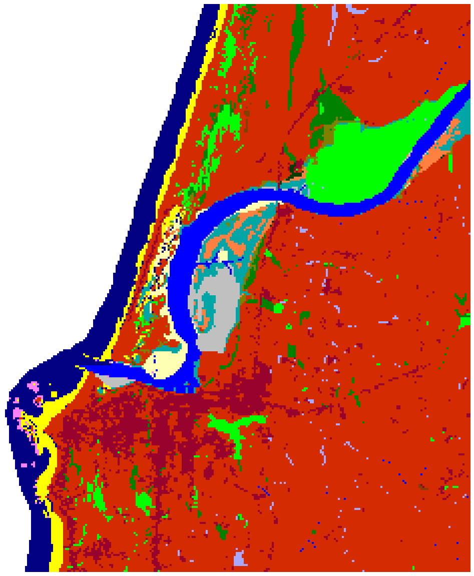
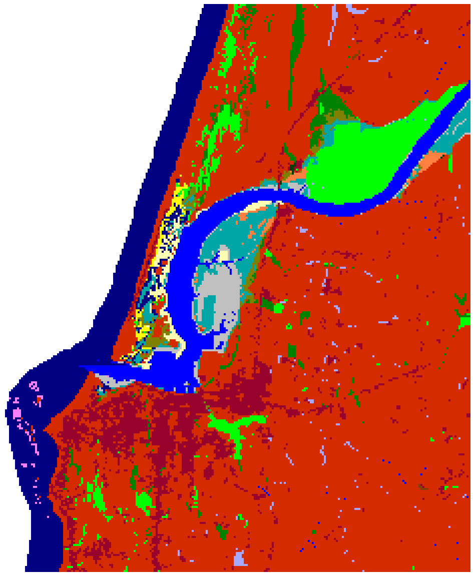
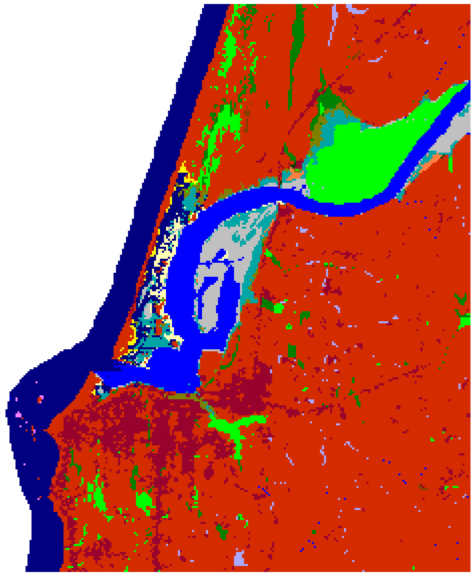


Bandon Marsh NWR, Initial Condition


Bandon Marsh NWR, 2025, 2 meter



Bandon Marsh NWR, 2050, 2 meter



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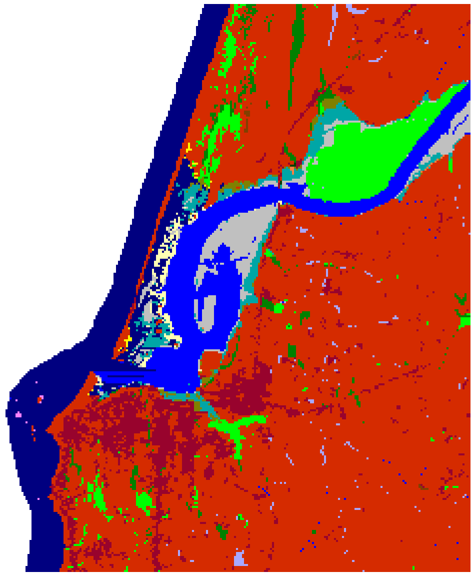

Bandon Marsh NWR, 2100, 2 meter