Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Egmont Key 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 (Park et al. 1991).

In an effort to plan for and potentially mitigate the effects of sea-level rise on the U.S. National Wildlife Refuge System (Refuge System), the U. S. Fish and Wildlife Service (FWS) uses a variety of analytical approaches, most notably the SLAMM model. FWS conducts some SLAMM analysis in-house and, more commonly, contracts the application of the SLAMM model. In most cases Refuge System SLAMM analyses are designed to assist in the development of comprehensive conservation plans (CCPs), land acquisition plans, habitat management plans, and other land and resource 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. Accretion feedbacks were applied in this simulation.
- 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, 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 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

Some SLAMM 6 predictions are obtained using SLR estimates from the Special Report on Emissions Scenarios (SRES) published by the Intergovernmental Panel on Climate Change (IPCC). All IPCC scenarios describe futures that are generally more affluent than today and span a wide range of future levels of economic activity, with gross world product rising to 10 times today's values by 2100 in the lowest, to 26-fold in the highest scenarios (IPCC 2007). Among the IPCC families of scenarios, two approaches were used, one that made harmonized assumptions about global population, economic growth, and final energy use, and those with an alternative approach to quantification. This is important to keep in mind as not all of the IPCC scenarios share common assumptions regarding the driving forces of climate change.

In this model application, the A1B scenario mean and maximum predictions are applied. Important assumptions were made in this scenario: reduction in the dispersion of income levels across economies (i.e. economic convergence), capacity building, increased cultural and social interactions among nations, and a substantial reduction in regional differences in per capita income, primarily from the economic growth of nations with increasing income (Nakicenovic et al. 2000). In addition, 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. Given today's global economic and political climate, as well as environmental and ecological constraints, these may not be feasible assumptions for the future.

In particular, the A1B scenario assumes that energy sources will be balanced across all sources, with an increase in use of renewable energy sources coupled with a reduced reliance on fossil fuels (Nakicenovic et al. 2000). Given this A1B scenario, the IPCC WGI Fourth Assessment Report (IPCC 2007) suggests a likely range of 0.21 m to 0.48 m of SLR by 2090-2099 "excluding future rapid dynamical changes in ice flow." The IPCC-produced 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. However, other scientists using the same set of economic growth scenarios have produced much higher estimates of SLR as discussed below.

Recent literature (Chen et al. 2006; Monaghan et al. 2006) indicates that eustatic sea-level rise is progressing more rapidly than was previously assumed. This underestimation may be due to the dynamic changes in ice flow omitted within the IPCC report's calculations, and a consequence of overestimating the possibilities for future reductions in greenhouse gas emissions while concurrently striving for economic growth.

A recent paper in the journal *Science* (Rahmstorf 2007) suggests that, taking into account possible model error, a feasible range of 50 to 140 cm by 2100. 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.

The variability of SLR predictions presented in the scientific literature illustrates the significant amount of uncertainty in estimating future SLR. Much of the uncertainty may be due to the unknown future of the drivers climate change, such as fossil fuel consumption and the scale of human enterprise. In order to account for these uncertainties, and to better reflect these uncertainties as well as recently published peer-reviewed measurements and projections of SLR as noted above, SLAMM was run not only assuming A1B-mean and A1B-maximum SLR scenarios, but also for 1 m, 1.5 m, and 2 m of eustatic SLR by the year 2100 as shown in Figure 1.

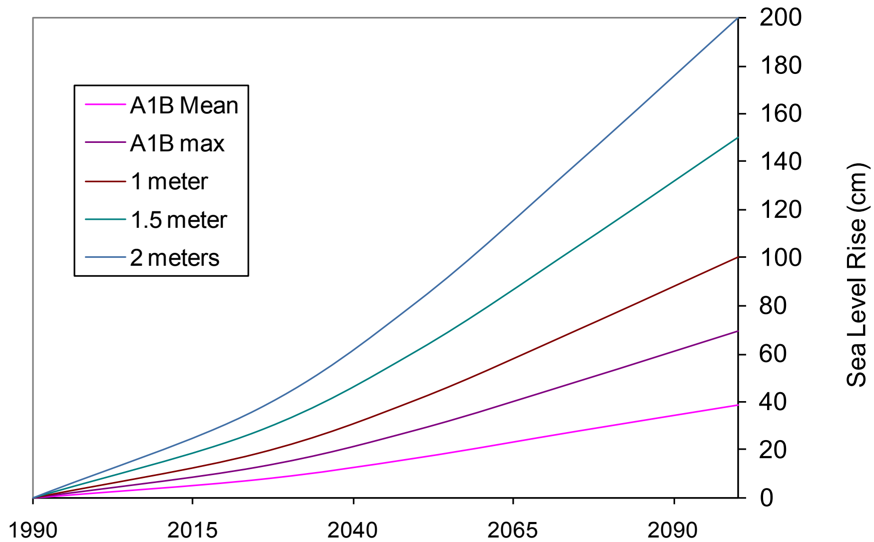


Figure 1. Summary of SLR scenarios utilized.

Data Sources and Methods

Wetland layer. Figure 2 shows the most recent available wetland layer obtained from a National Wetlands Inventory (NWI) photo dated 2009. Converting the NWI survey into 5 m x 5 m cells indicated that the approximately 331 acre Egmont Key NWR (approved acquisition boundary including water) is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Undeveloped Dry Land	196	59
	Open Ocean	109	33
	Ocean Beach	23	7
	Developed Dry Land	3	<1
	Total (incl. water)	**331**	**100**

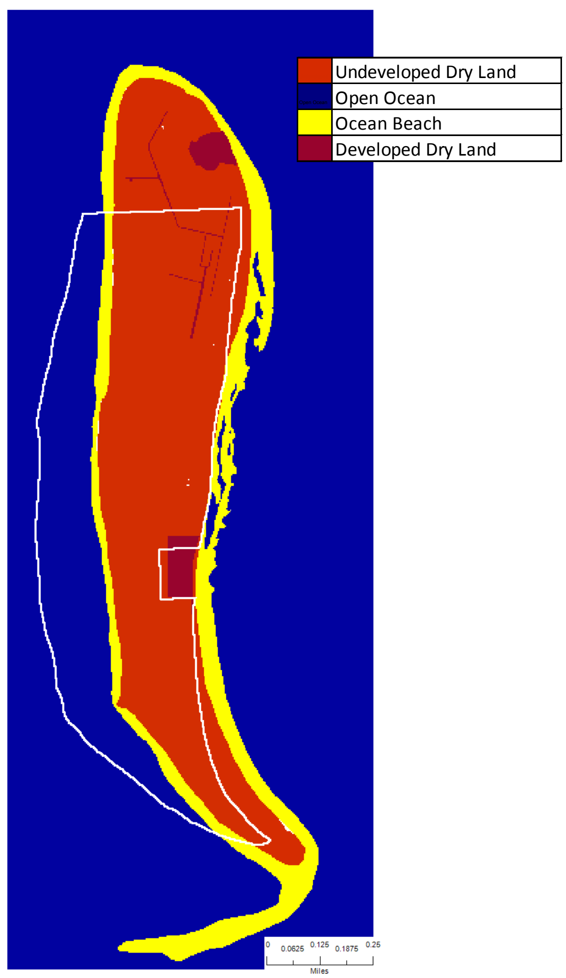


Figure 2. 2009 NWI coverage of the study area. Refuge boundaries are indicated in white.

Elevation Data. The refuge area is covered US Army Corps of Engineers LiDAR data collected in 2010. However, this LiDAR data layer does not contain elevation information for some of the surrounding beaches, as shown in Figure 3. For beaches lacking elevation data, elevations were identified using the elevation pre-processor module of SLAMM. This module estimates elevations for wetlands as a function of the local tide range (Clough et al. 2010). Because of this estimation, beach-loss predictions are more uncertain than dry-land loss predictions.

Figure 3. Location of LiDAR. Approved acquisition boundaries shown in red.

Dikes and Impoundments. According to the National Wetland Inventory, there are no dikes or impoundments in the island.

Model Timesteps. Model forecast data was output for years 2025, 2050, 2075 and 2100 with the initial condition date set to 2009 (the most recent wetland data available).

Historic sea-level rise rates. he historic trend for relative sea-level rise was estimated at 2.4 mm/year based on long term trends measured at nearby NOAA gauge stations in St. Petersburg, Florida (#8726520, period of record:1947-2006) and at Clearwater Beach (#8726724, 1973-2006), as shown in Figure 4. This historical trend is higher than the global average for the last 100 years (approximately 1.7 mm/year) indicating that local sea-level rise in this region is somewhat greater than eustatic sea-level rise.

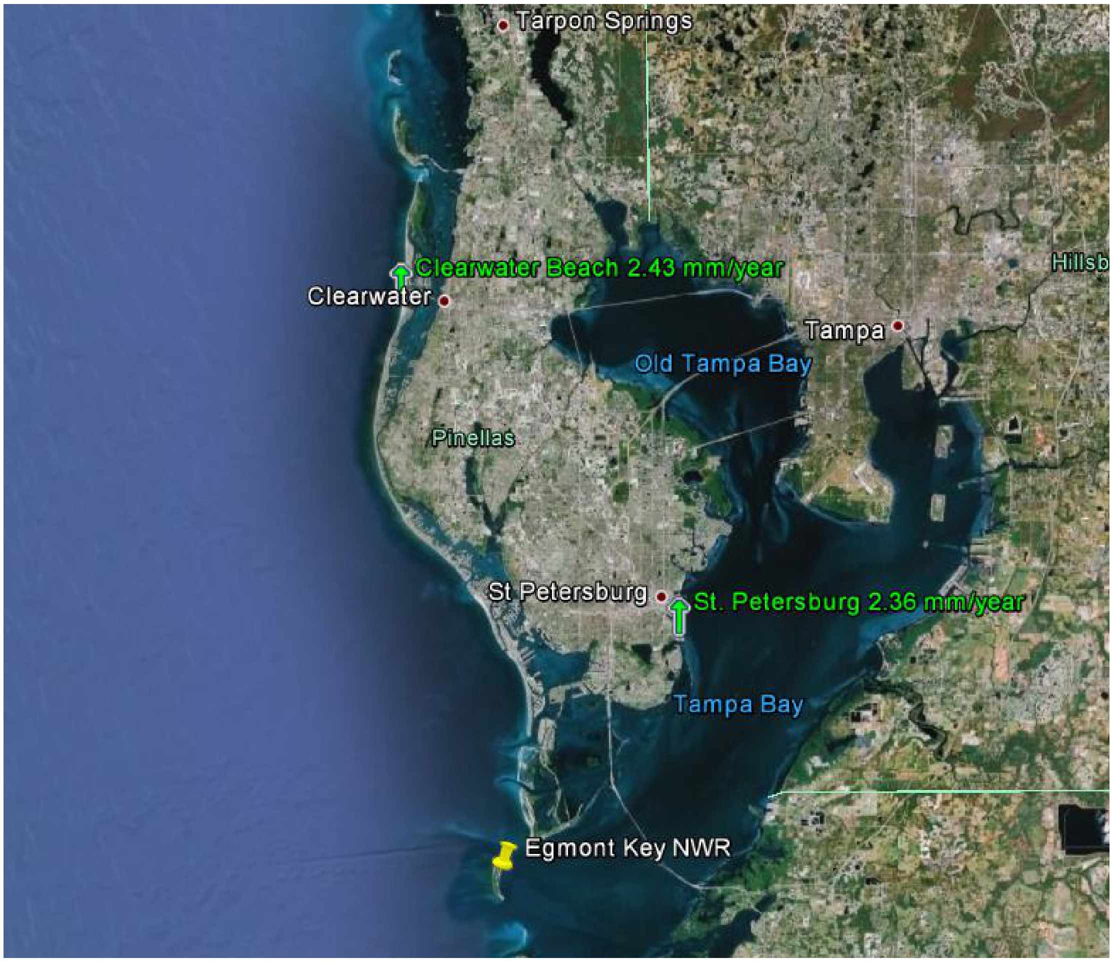


Figure 4. Historic average sea-level trends in the area around Egmont Key NWR.

Tide Ranges. The great diurnal range (GT) measured at the Egmont Key NOAA gauge station (#8726347) is 0.66 m. Other gauge stations in the vicinity have similar GT as shown in Figure 5.

Figure 5. Great diurnal tide ranges (GT) in meters observed at the NOAA gauge stations located in the area around Egmont Key NWR.

Salt elevation. This parameter within SLAMM designates the boundary between wet lands and dry lands or saline wetlands and fresh water wetlands. For this application, salt elevation was estimated at 1.5 Half Tide Units (HTU).

Accretion rates. Parameters pertaining to marshes (i.e. accretion rates and erosion rates) are not relevant to this site as there were no non-beach wetlands identified based on the National Wetlands Inventory, nor are any wetlands predicted to appear. Default values are therefore used, though the model will not be sensitive to those choices.

Erosion rates. No site-specific studies of horizontal erosion rates were located for this analysis. Tidal flat erosion rates were set to 0.5 horizontal meters per year based on the effects of wave action.

This is a default model value that has been used in previous SLAMM applications to the gulf coast of Florida.

Elevation correction. MTL to NAVD88 correction was determined using the available datum at the Egmont Key NOAA gauge station (#8726347), which suggested a correction value of - 0.14 m. Other gauge stations in the vicinity suggested similar correction values, as shown in Figure 6.

Figure 6. Spatial variability of MTL to NAVD88 correction estimates in the area around Egmont Key NWR.

Parameter summary. Equal input parameters were applied to the entire island. However, five different subsites were identified, depending on the direction offshore, as shown in Figure 7

Figure 7. Input subsites (S1-S5) for model application.

The parameters assigned to each subsite are presented in Table 1. The cell size used for this analysis is 5 m by 5 m. The connectivity module of SLAMM was used in this model application in order to ensure dry land only converts to wetland if there is an unimpeded path from open water to the dry land in question.

Table 1. Summary of SLAMM input parameters for Egmont Key NWR.

Parameter	S1/S2/S3/S4/S5
NWI Photo Date (YYYY)	2009
DEM Date (YYYY)	2010
Direction Offshore [n,s,e,w]	W/N/E/S/N
Historic Trend (mm/yr)	2.4
MTL-NAVD88 (m)	-0.138
GT Great Diurnal Tide Range (m)	0.66
Salt Elev. (m above MTL)	0.5
Marsh Erosion (horz. m /yr)	2
Swamp Erosion (horz. m /yr)	1
T.Flat Erosion (horz. m /yr)	0.5
Reg.-Flood Marsh Accr (mm/yr)	1.9
Irreg.-Flood Marsh Accr (mm/yr)	4.3
Tidal-Fresh Marsh Accr (mm/yr)	4.8
Inland-Fresh Marsh Accr (mm/yr)	4
Mangrove Accr (mm/yr)	7
Tidal Swamp Accr (mm/yr)	1
Swamp Accretion (mm/yr)	0.3
Beach Sed. Rate (mm/yr)	0.5
Freq. Overwash (years)	0
Use Elev Pre-processor [True,False]	TRUE

Overwash. The barrier-island overwash model was not used in this application of SLAMM, meaning that the effects of large storms are ignored. Model results may be considered to be conservative for this reason (i.e. they represent the result of long-term SLR, but not hurricanes or other large storms). The SLAMM barrier-island overwash model is subject to great uncertainty due to lack of knowledge about the timing, size, and direction of large storms. Additionally, due to the spatial simplicity of the SLAMM overwash model, it tends to produce streaky output maps at cell resolutions of less than 30 meters. As this site was run with 5-meter cell sizes, the model was not considered appropriate for this application.

Results

Table 2 presents the predicted losses for each land cover type by 2100 within the total approved acquisition boundary of Egmont Key NWR for each of the five SLR scenarios examined. For this simulation the land-cover losses are calculated in comparison to the 2009 NWI wetland layer.

Table 2. Predicted loss rates of land categories by 2100 given simulated scenarios of eustatic SLR at Savannah 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	196	2%	46%	70%	89%	96%
Developed Dry Land	3	0%	40%	83%	98%	100%

Results of SLAMM simulations suggest Egmont Key will be severely affected by increases in sea level given all but the most conservative SLR scenario. Overall, simulations predict much of the refuge will convert to beach and open water. Due to its low elevation distribution, dry land is predicted to be increasingly lost with almost a total loss under the 2 m SLR scenario. Ocean beach is predicted to initially increase its coverage, increasing to 141 acres under the 1 m SLR scenario, while for higher SLR rates ocean-beach gains are less pronounced.

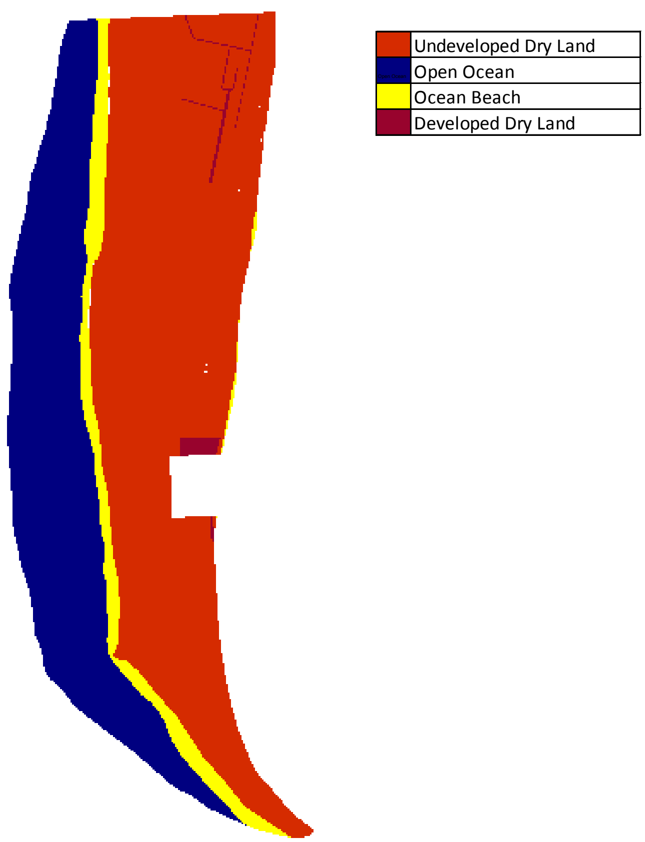
Table 3. Predicted land cover by 2100 given simulated scenarios of eustatic SLR at Egmont Key NWR.

Land cover category	Initial coverage (acres)	Land cover by 2100 for different SLR scenarios (acres)				
		0.39 m	0.69 m	1 m	1.5 m	2 m
Open Ocean	109	122	128	132	199	280
Ocean Beach	23	14	96	141	110	44

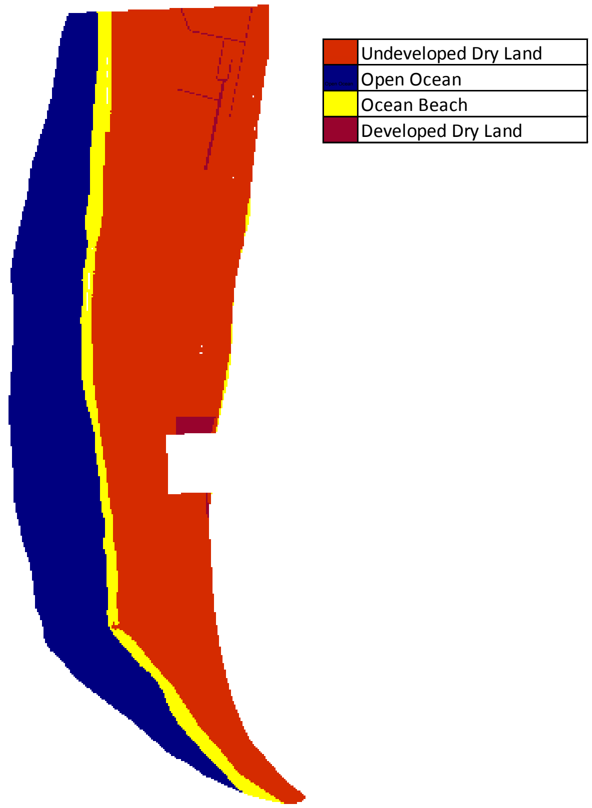
Egmont Key NWR
IPCC Scenario A1B-Mean, 0.39 m eustatic SLR by 2100

Results in Acres

		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	196	194	193	193	192
	Open Ocean	109	112	115	118	122
	Ocean Beach	23	23	20	17	14
	Developed Dry Land	3	3	3	3	3
	Total (incl. water)	**331**	**331**	**331**	**331**	**331**



Egmont Key NWR, Initial Condition.



Egmont Key NWR, 2025, Scenario A1B Mean, 0.39 m SLR by 2100.

Egmont Key NWR, 2050, Scenario A1B Mean, 0.39 m SLR by 2100.

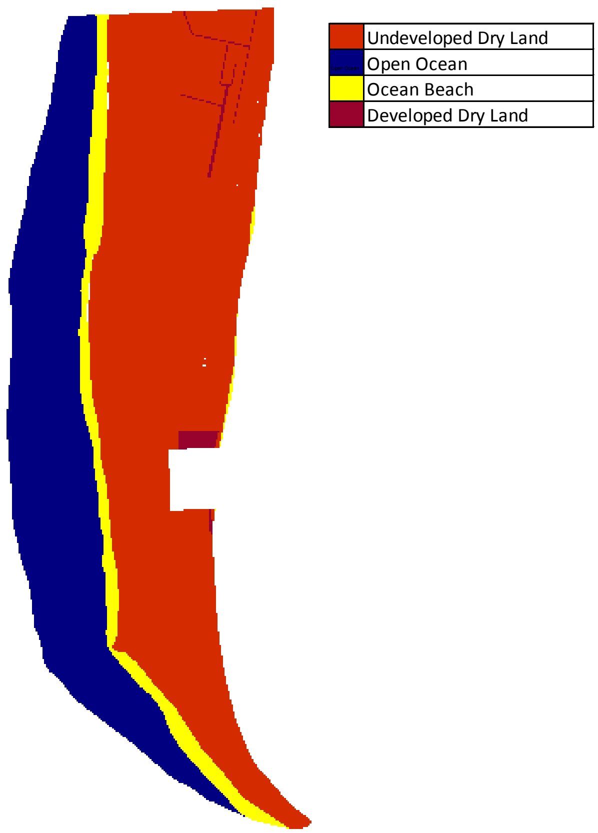
Egmont Key NWR, 2075, Scenario A1B Mean, 0.39 m SLR by 2100.

Egmont Key NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.

Egmont Key NWR
IPCC Scenario A1B-Max, 0.69 m eustatic SLR by 2100

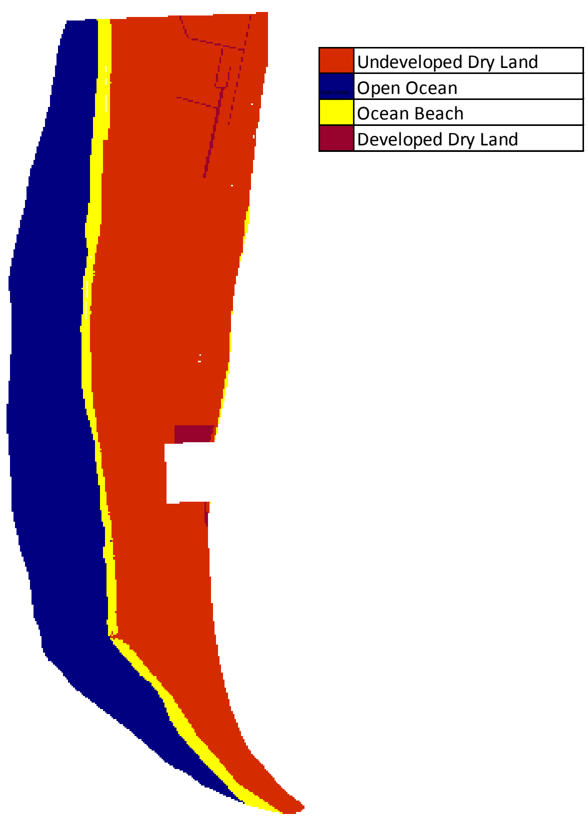
Results in Acres

		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	196	194	193	166	105
	Open Ocean	109	112	115	121	127
	Ocean Beach	23	23	20	42	96
	Developed Dry Land	3	3	3	2	2
	Total (incl. water)	**331**	**331**	**331**	**331**	**331**

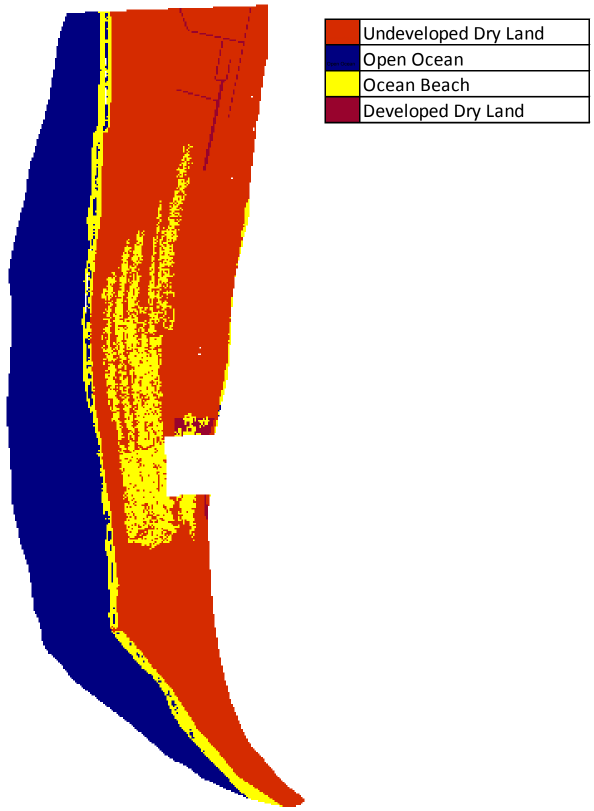


Egmont Key NWR, Initial Condition.

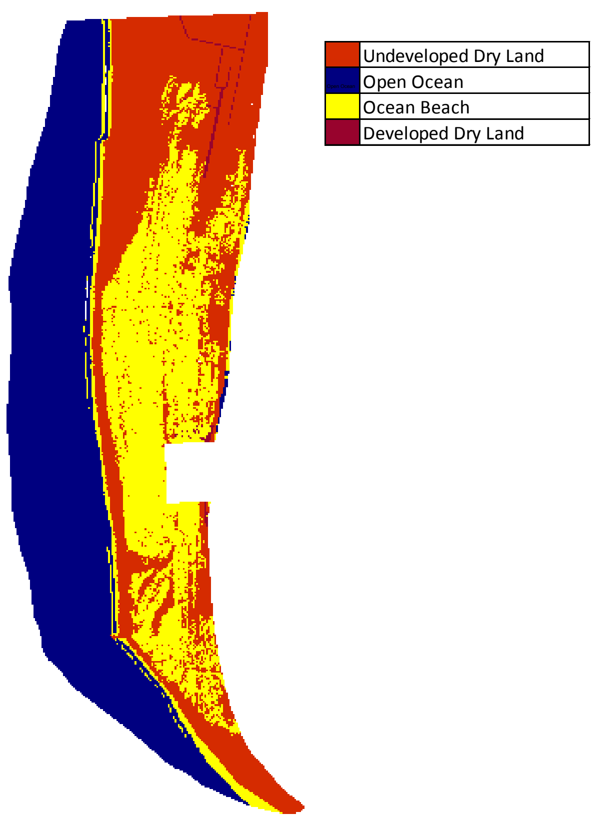
Egmont Key NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



Egmont Key NWR, 2050, Scenario A1B Maximum, 0.69 m SLR by 2100.



Egmont Key NWR, 2075, Scenario A1B Maximum, 0.69 m SLR by 2100.

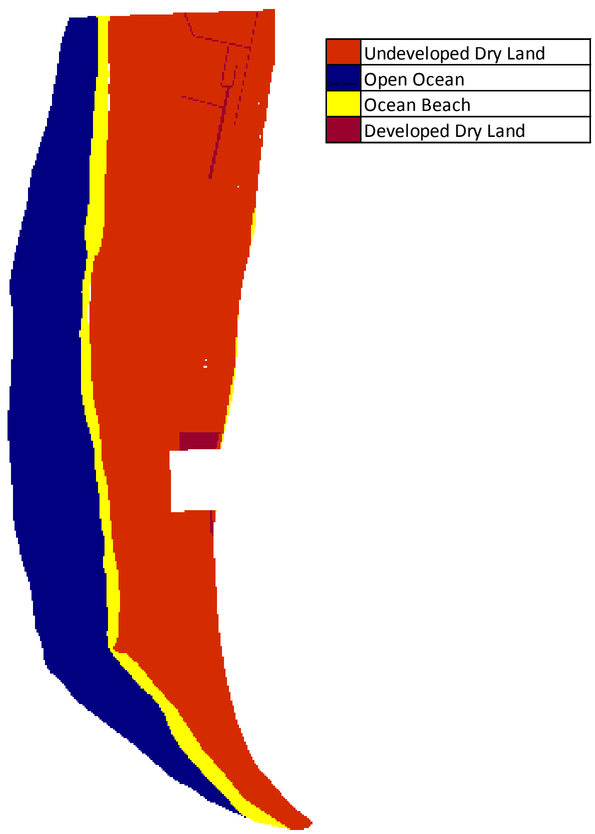


Egmont Key NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.

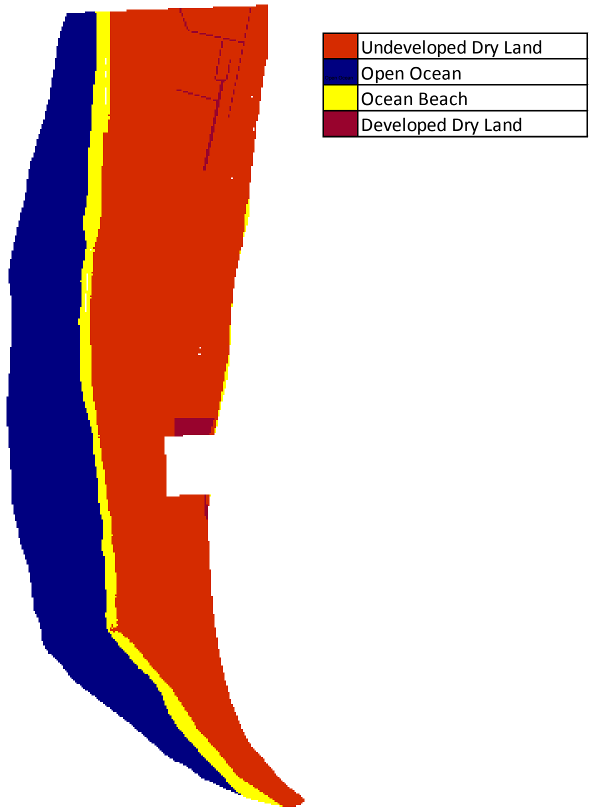
Egmont Key NWR
1 m eustatic SLR by 2100

Results in Acres

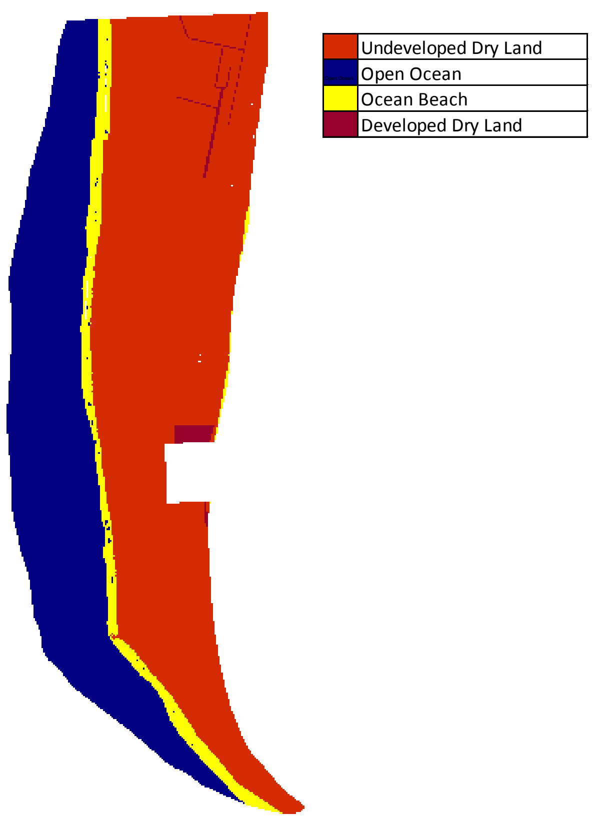
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	196	193	193	116	58
	Open Ocean	109	112	116	125	131
	Ocean Beach	23	23	20	88	141
	Developed Dry Land	3	3	3	2	1
	Total (incl. water)	**331**	**331**	**331**	**331**	**331**



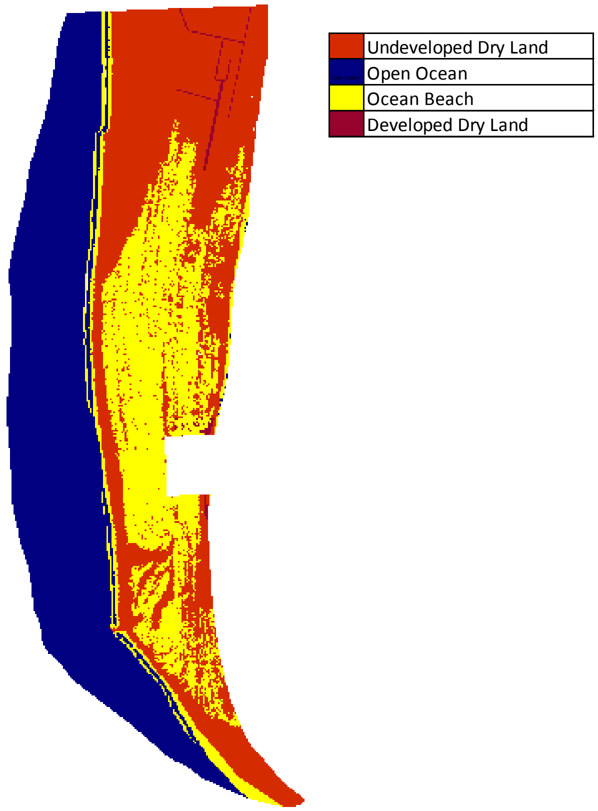
Egmont Key NWR, Initial Condition.



Egmont Key NWR, 2025, 1 m SLR by 2100.



Egmont Key NWR, 2050, 1 m SLR by 2100.



Egmont Key NWR, 2075, 1 m SLR by 2100.

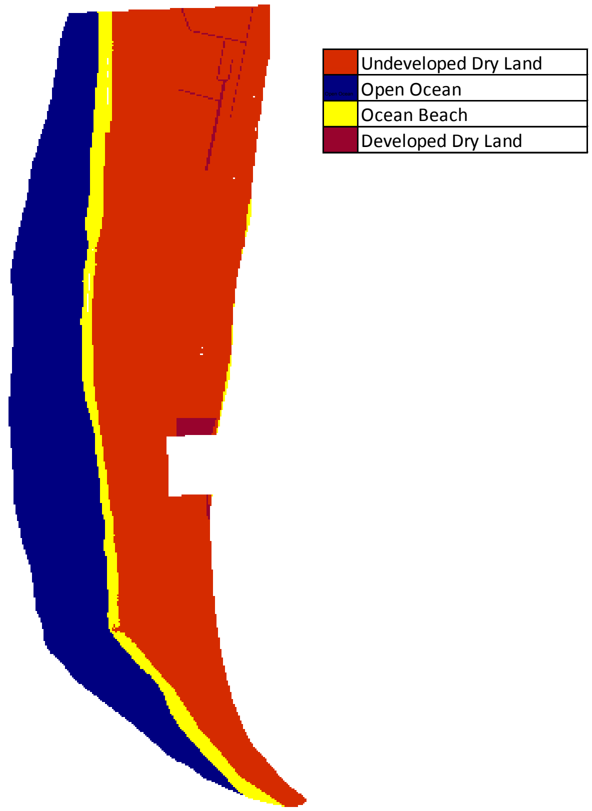
Egmont Key NWR, 2100, 1 m SLR by 2100.

Egmont Key NWR
1.5 m eustatic SLR by 2100

Results in Acres

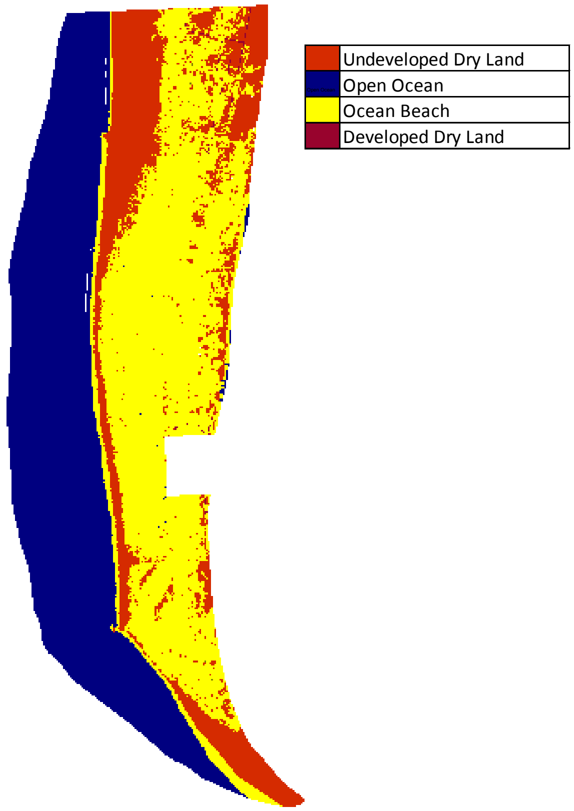
		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	196	193	156	61	22
	Open Ocean	109	112	121	131	199
	Ocean Beach	23	23	52	139	110
	Developed Dry Land	3	3	2	1	0
	Total (incl. water)	**331**	**331**	**331**	**331**	**331**

Egmont Key NWR, Initial Condition.

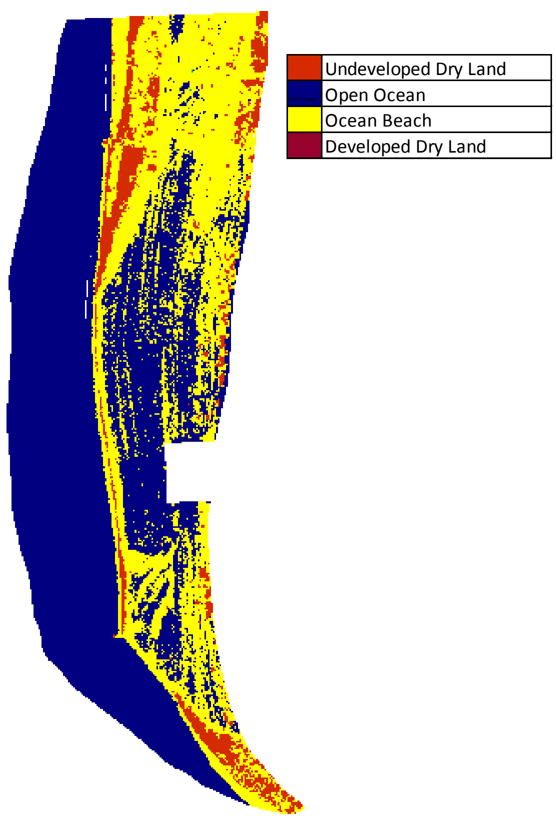


Egmont Key NWR, 2025, 1.5 m SLR by 2100.

Egmont Key NWR, 2050, 1.5 m SLR by 2100.



Egmont Key NWR, 2075, 1.5 m SLR by 2100.

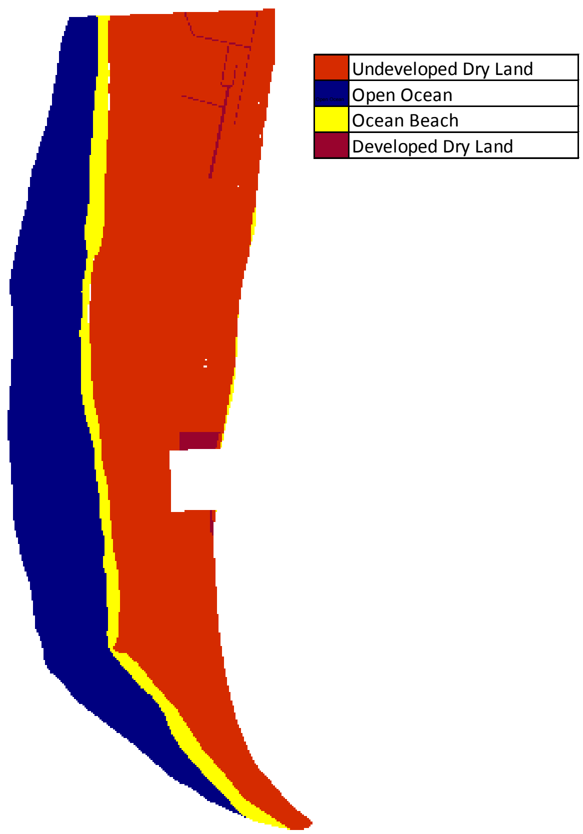


Egmont Key NWR, 2100, 1.5 m SLR by 2100.

Egmont Key NWR
2 m eustatic SLR by 2100

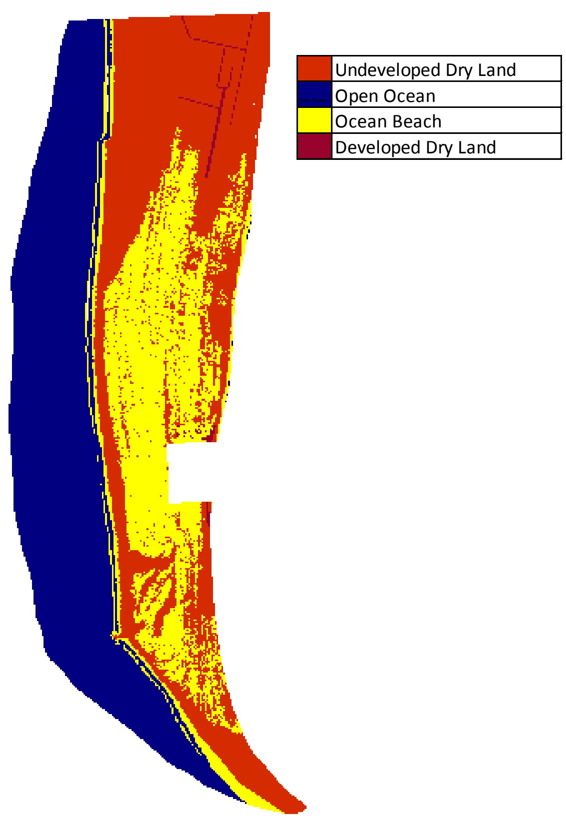
Results in Acres

		Initial	2025	2050	2075	2100
	Undeveloped Dry Land	196	193	115	32	8
	Open Ocean	109	112	125	155	280
	Ocean Beach	23	23	88	144	44
	Developed Dry Land	3	3	2	0	0
	Total (incl. water)	**331**	**331**	**331**	**331**	**331**



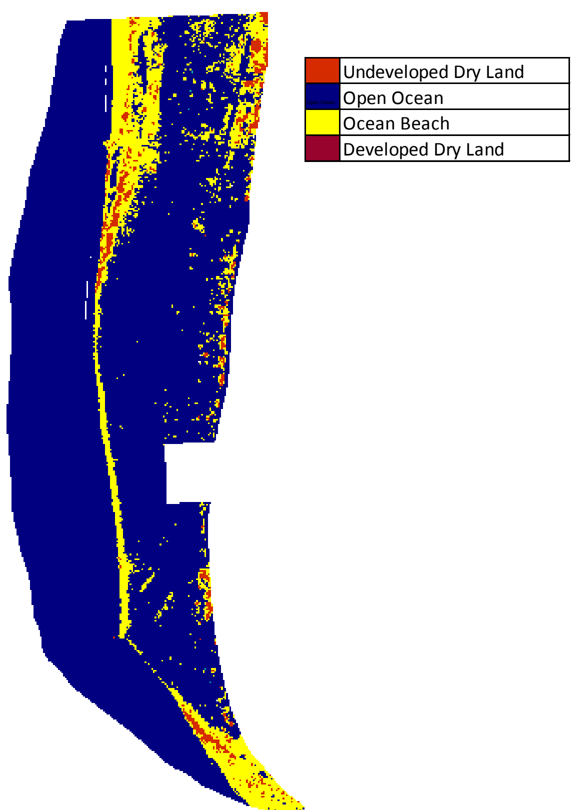
Egmont Key NWR, Initial Condition.

Egmont Key NWR, 2025, 2 m SLR by 2100.



Egmont Key NWR, 2050, 2 m SLR by 2100.

Egmont Key NWR, 2075, 2 m SLR by 2100.



Egmont Key NWR, 2100, 2 m SLR by 2100.

Discussion

SLAMM simulations indicate future SLR, coupled with low elevations, will cause severe land losses in Egmont Key NWR given all but the most conservative SLR scenario examined. Any scenarios with over 0.5 m of SLR by 2100 resulted in at least 45 percent of dry land being lost, converting to ocean beach and open water.

Several caveats should be noted when interpreting the results of these SLAMM simulations. First of all, the lack of elevation data for portions of the beaches and the consequent use of the preprocessor introduce a high degree of uncertainty on the elevations of these beaches that may affect the predicted timing of inundation. In addition, this model application does not estimate the potential losses that may occur based on large storms. While the effects of storms on wetlands are difficult to predict, they can have profound repercussions for this type of habitat.

This SLAMM simulation utilized the best available data layers and parameter inputs; however, these data and the conceptual model continue to have uncertainties that should be kept in mind when interpreting model results. Perhaps most importantly, the extent of future sea-level rise is unknown, as are the drivers of climate change used by scientists when projecting SLR rates. Future levels of economic activity, fuel type (e.g., fossil or renewable, etc.), fuel consumption, and greenhouse gas emissions are unknown and estimates of these driving variables are speculative. To account for these uncertainties, results presented here investigated effects for a wide range of possible sea-level rise scenarios, from a more conservative rise (0.39 m by 2100) to a more accelerated process (2 m by 2100). More in general, to better support managers and decision-makers, the results presented here could be studied as a function of input-data uncertainty to provide a range of possible outcomes and their likelihood.

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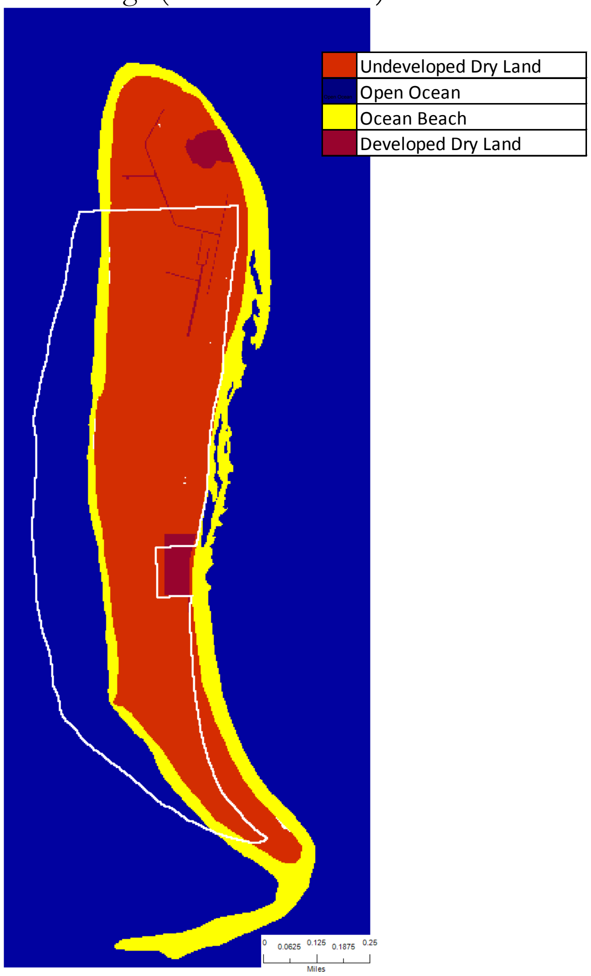
Appendix A: Contextual Results

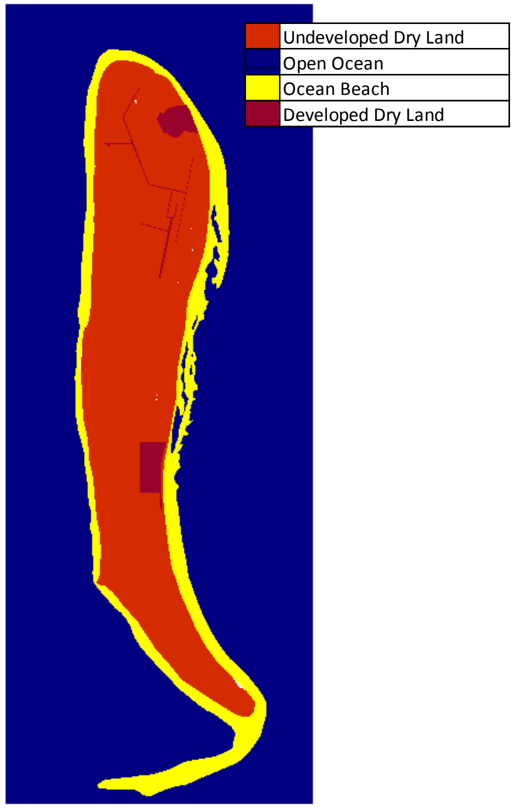
The SLAMM model takes into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated dry lands will convert to marshes or ocean beach depending on their proximity to open ocean (Clough et al. 2010).

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

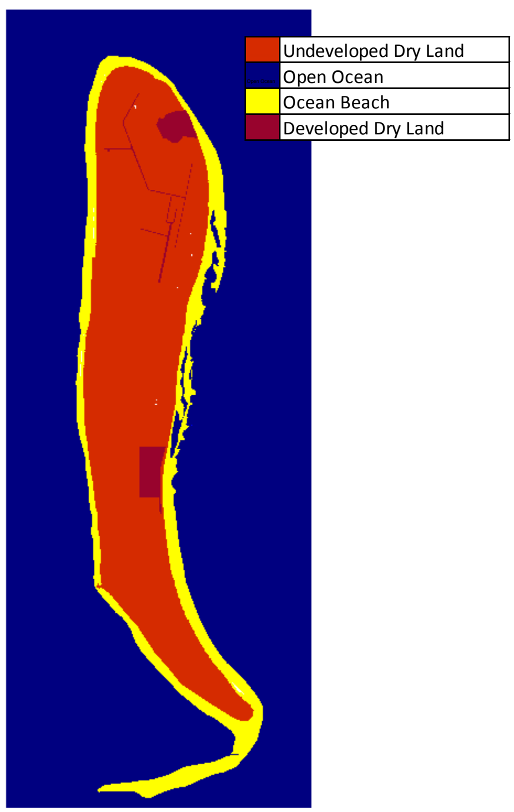
- Results were closely examined within USFWS refuges but not as closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort was made to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

Egmont Key National Wildlife Refuge (outlined in white) within simulation context.

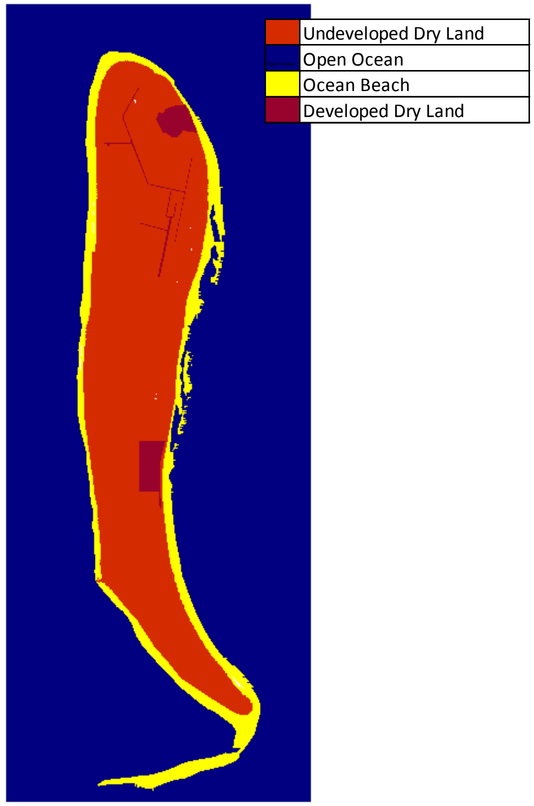




Egmont Key NWR, Initial Condition.

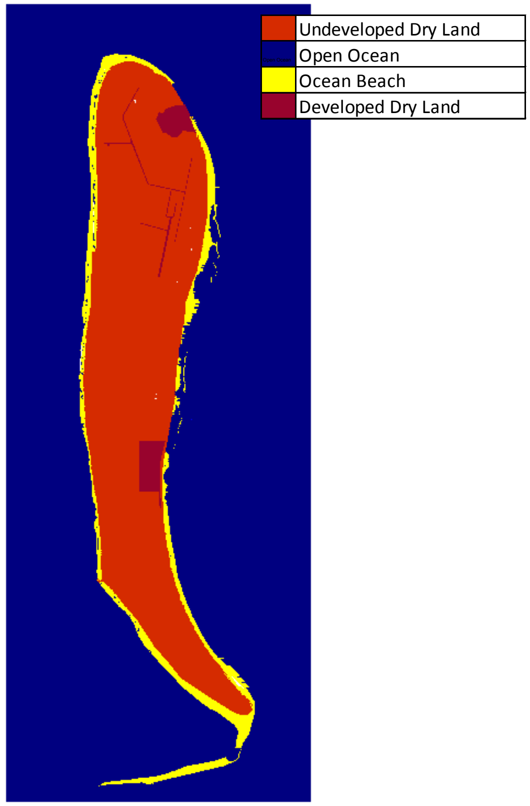


Egmont Key NWR, 2025, Scenario A1B Mean, 0.39 m SLR by 2100.

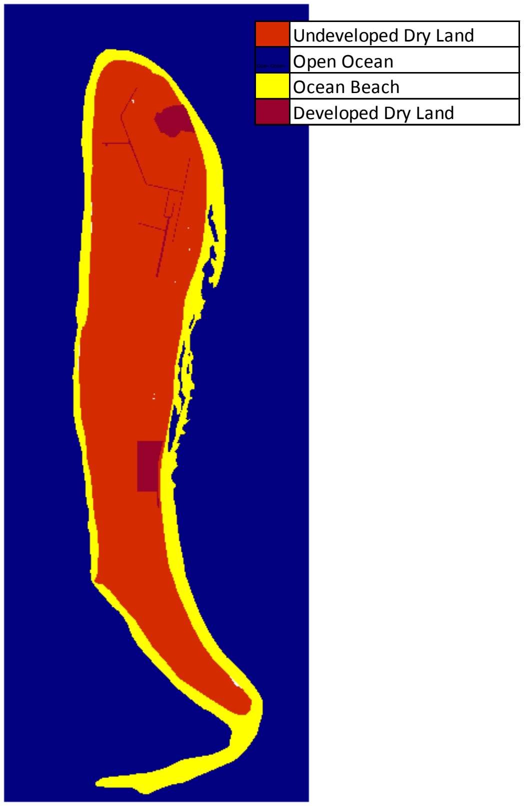


Egmont Key NWR, 2050, Scenario A1B Mean, 0.39 m SLR by 2100.

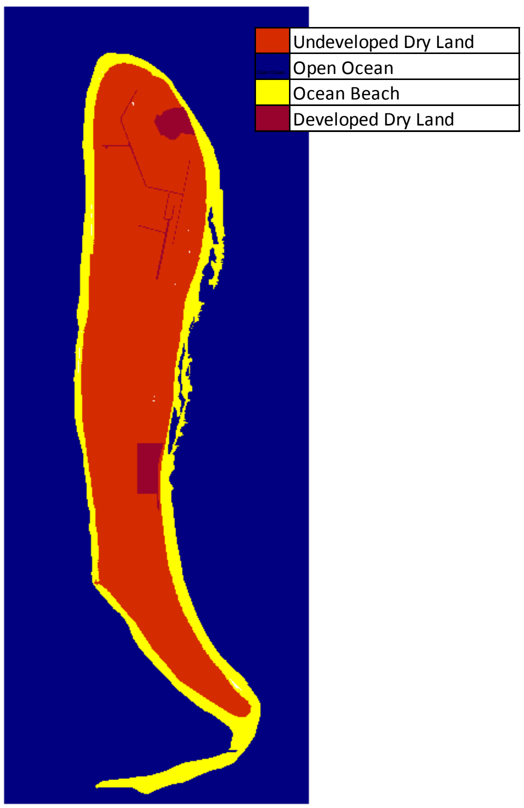
Egmont Key NWR, 2075, Scenario A1B Mean, 0.39 m SLR by 2100.



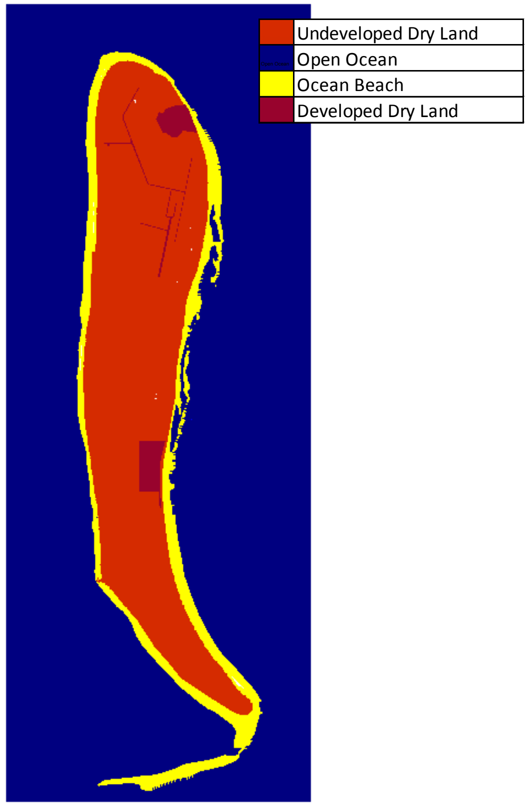
Egmont Key NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.



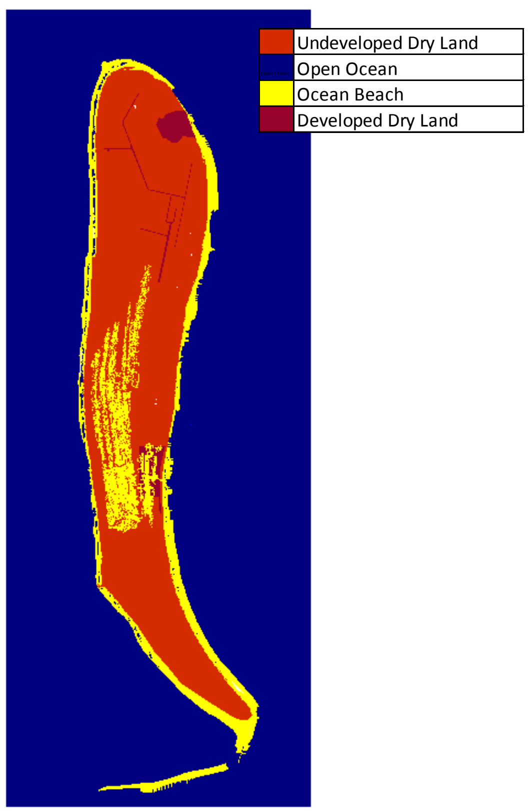
Egmont Key NWR, Initial Condition.



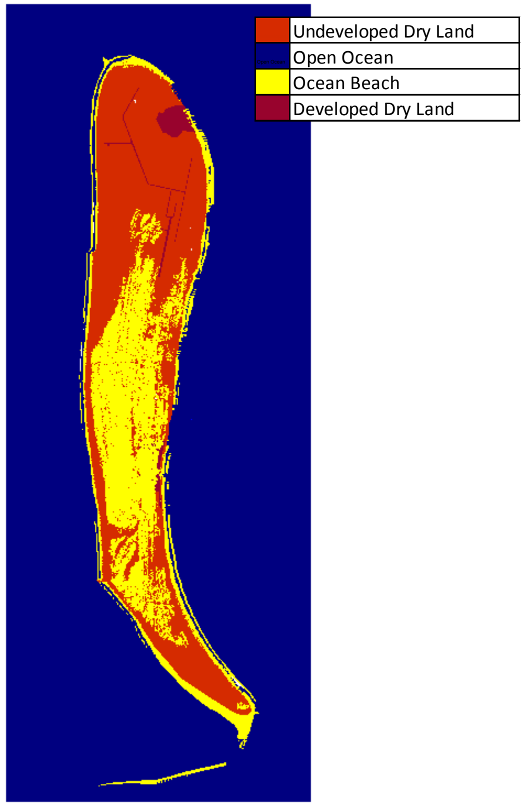
Egmont Key NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



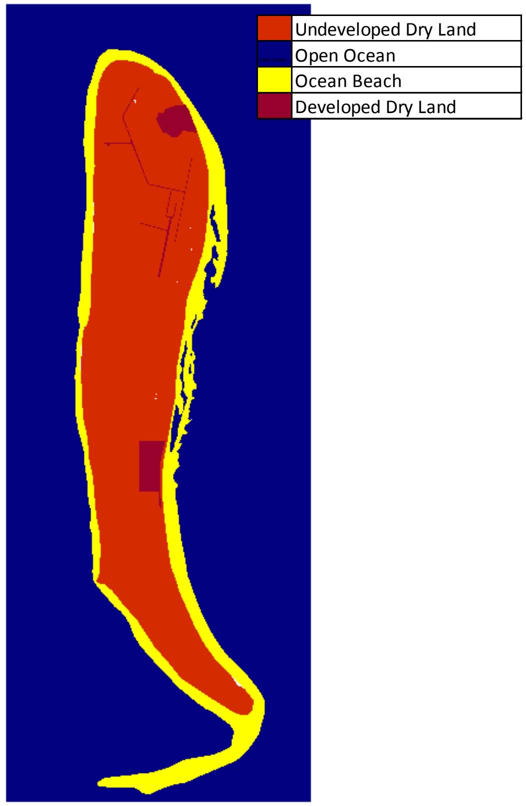
Egmont Key NWR, 2050, Scenario A1B Maximum, 0.69 m SLR by 2100.



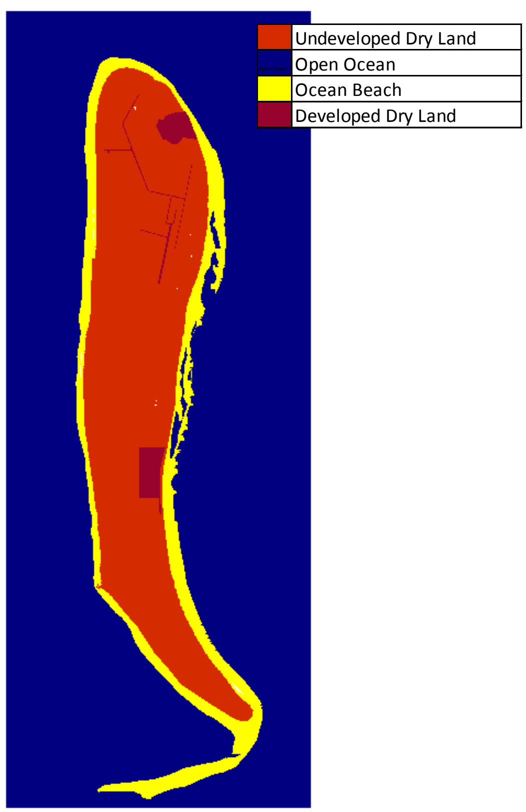
Egmont Key NWR, 2075, Scenario A1B Maximum, 0.69 m SLR by 2100.



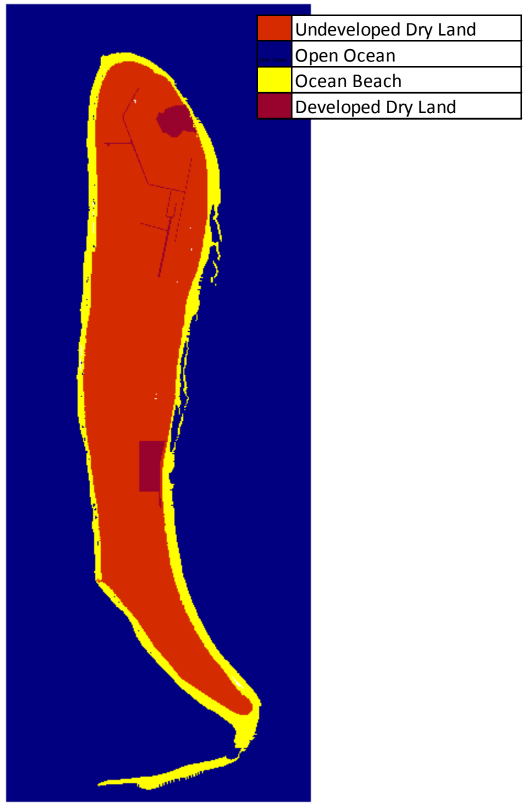
Egmont Key NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.



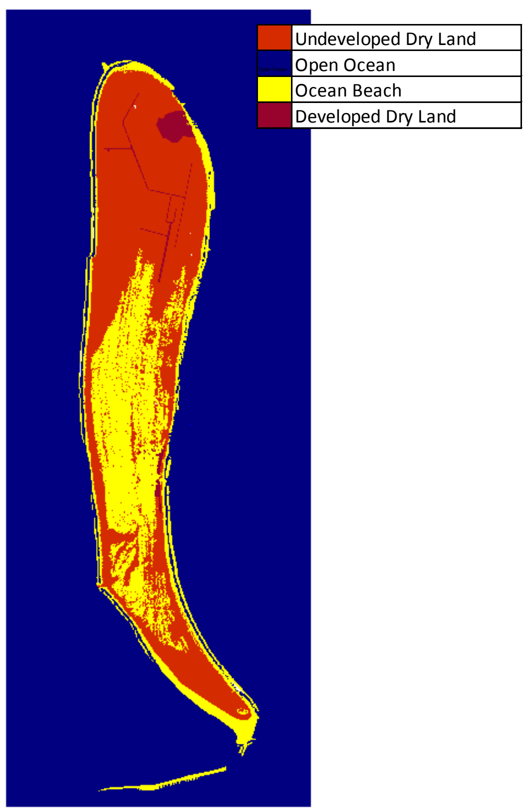
Egmont Key NWR, Initial Condition.



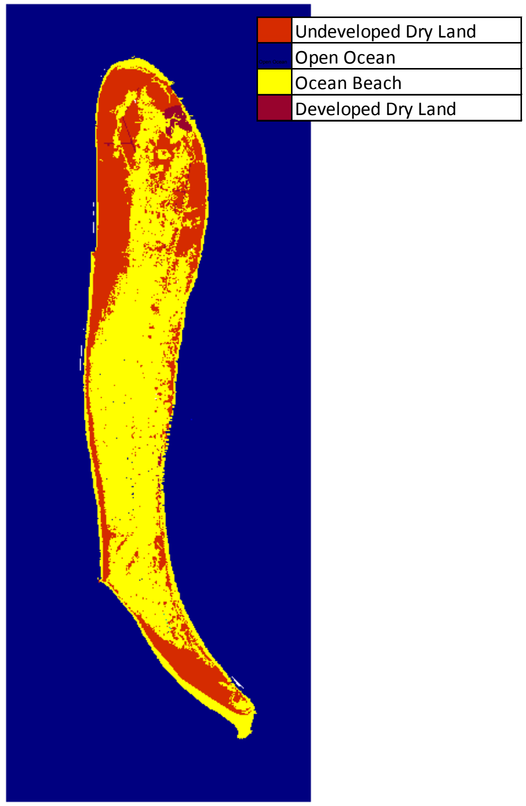
Egmont Key NWR, 2025, 1 m SLR by 2100.



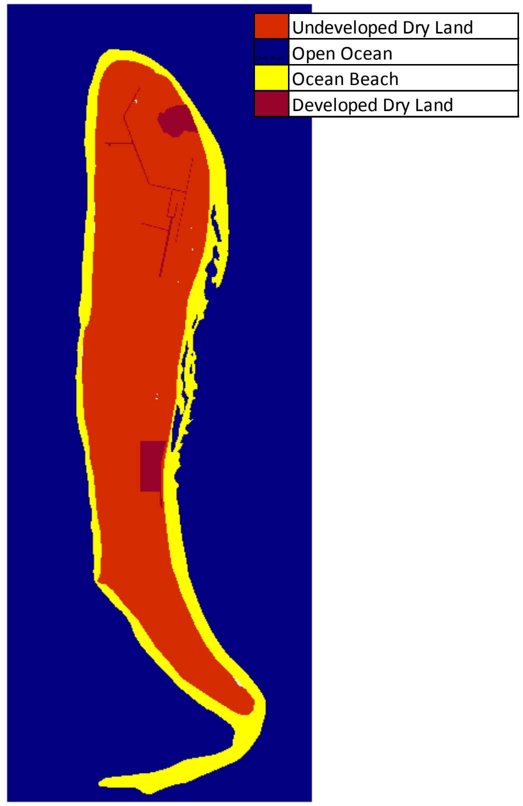
Egmont Key NWR, 2050, 1 m SLR by 2100.



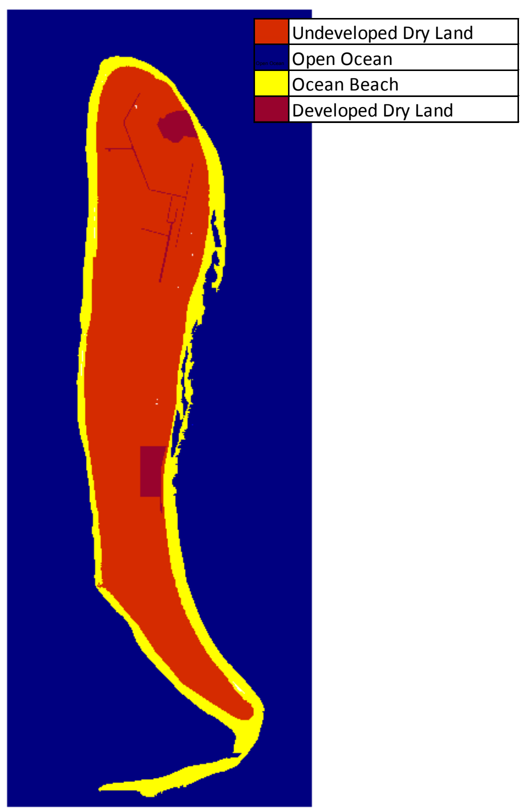
Egmont Key NWR, 2075, 1 m SLR by 2100..



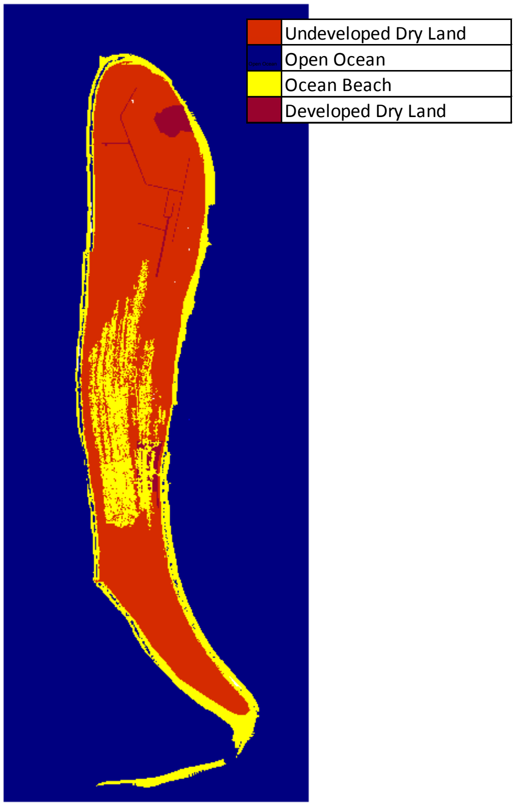
Egmont Key NWR, 2100, 1 m SLR by 2100.



Egmont Key NWR, Initial Condition.



Egmont Key NWR, 2025, 1.5 m SLR by 2100.



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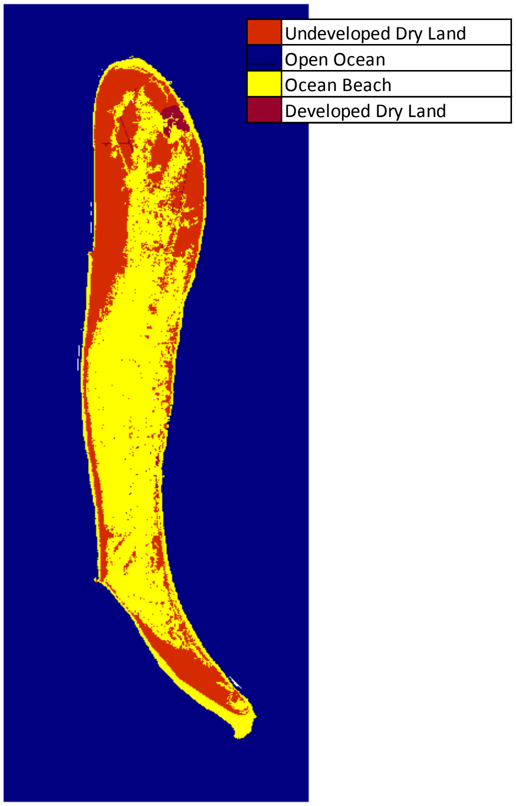

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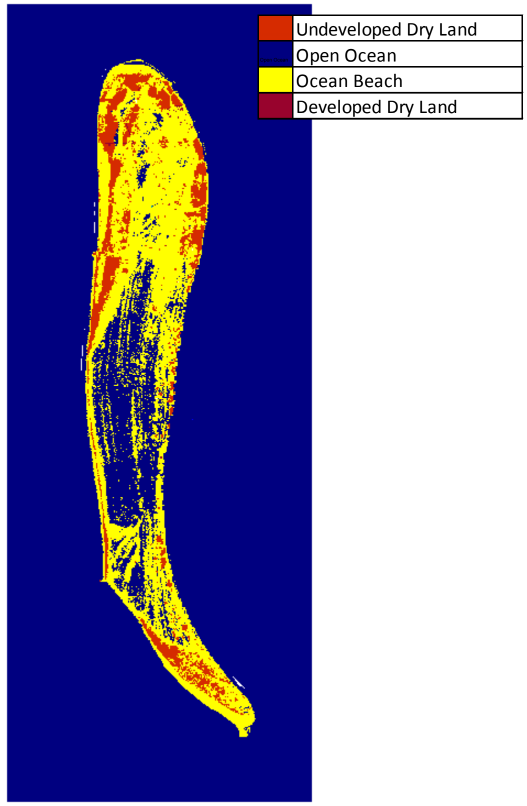

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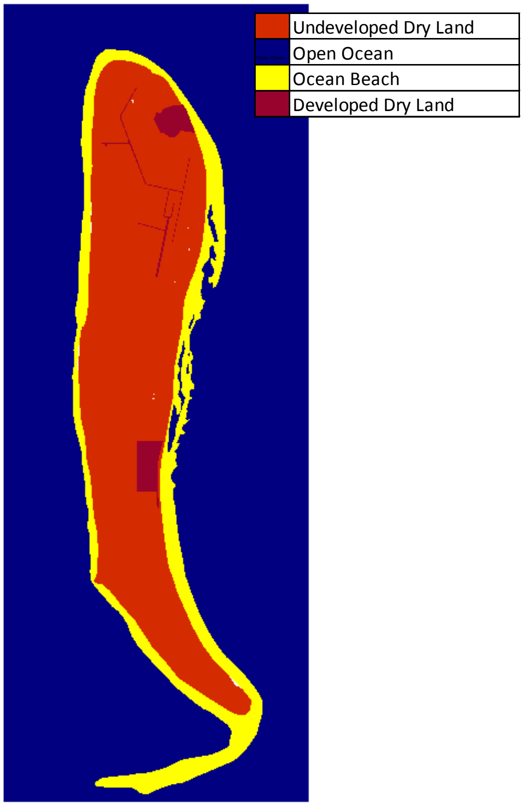

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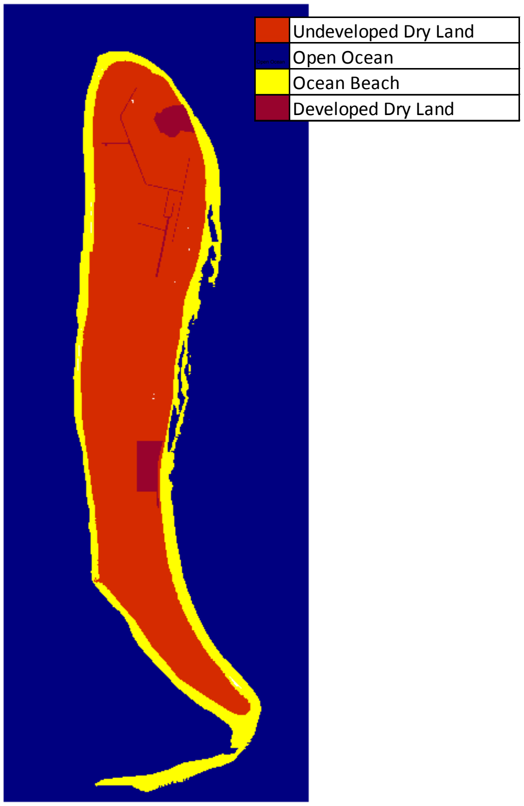
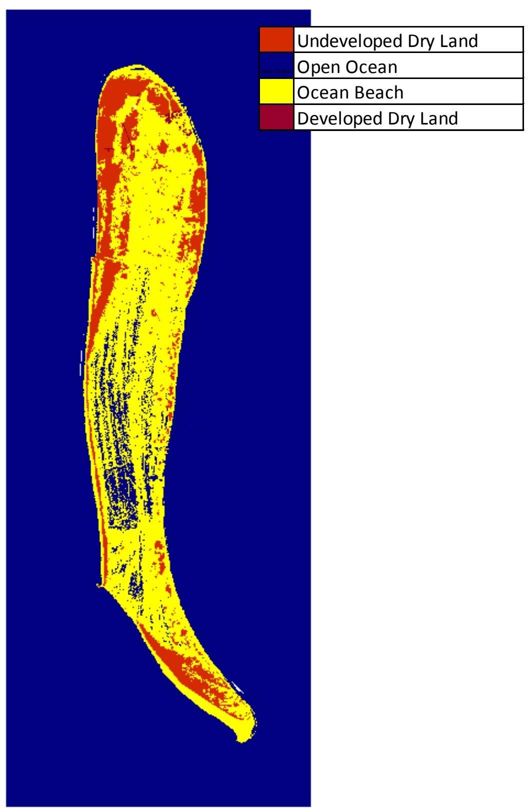


Egmont Key NWR, 2025, 2 m SLR by 2100.

Egmont Key NWR, 2050, 2 m SLR by 2100.



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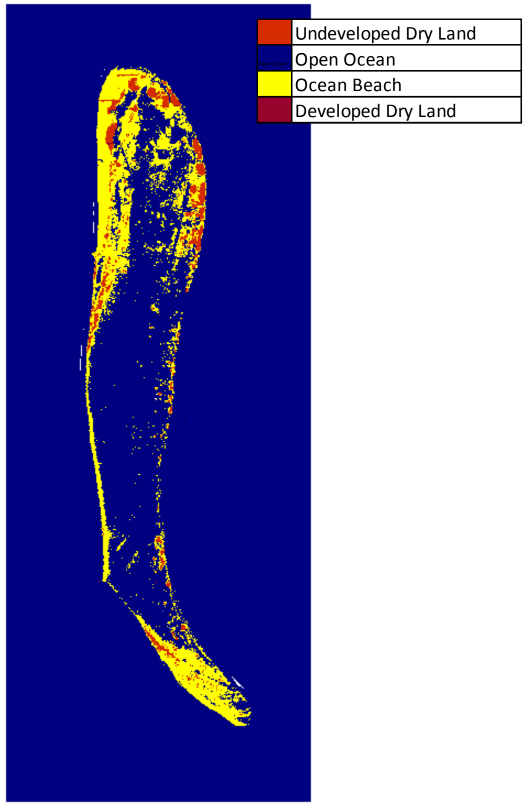

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