Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to National Key Deer National Wildlife Refuge

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). Sea level is predicted to increase by 30 cm to 100 cm by 2100 based on the International Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) (Meehl et al. 2007). Rising sea level may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat migration as salt marshes transgress landward and replace tidal freshwater and brackish marsh (Park et al. 1991).

In an effort to address the potential effects of sea level rise on United States national wildlife refuges, the U. S. Fish and Wildlife Service contracted the application of the SLAMM model for most Region 4 refuges. This analysis is designed to assist in the production of comprehensive conservation plans (CCPs) for each refuge. A CCP is a document that provides a framework for guiding refuge management decisions. All refuges are required by law to complete a CCP by 2012.

Model Summary

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

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

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

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

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

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

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

Model results presented in this report were produced using SLAMM version 5.0.1 which was released in early 2008 based on only minor refinements to the original SLAMM 5.0 model. Specifically, the accretion rates for swamps were modified based on additional literature review. For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 5.0.1 technical documentation (Clough and Park, 2008). This document is available at http://warrenpinnacle.com/prof/SLAMM

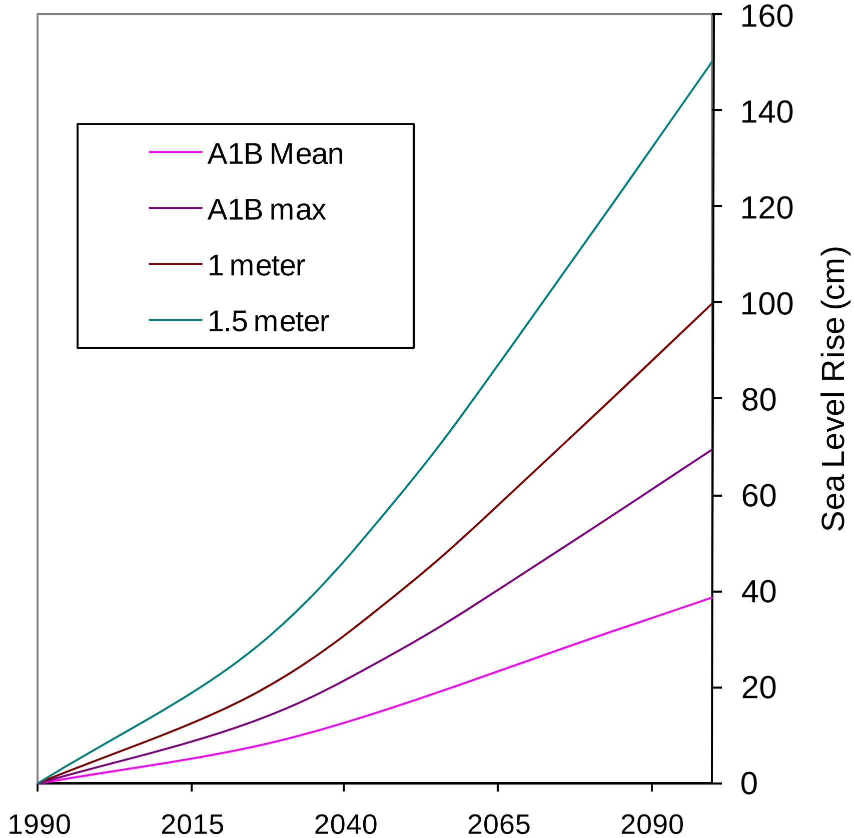
Sea-Level Rise Scenarios

The primary set of eustatic (global) sea level rise scenarios used within SLAMM was derived from the work of the Intergovernmental Panel on Climate Change (IPCC 2001). SLAMM 5 was run using the following IPCC and fixed-rate scenarios:

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

Recent literature (Chen et al., 2006, Monaghan et al., 2006) indicates that the eustatic rise in sea levels is progressing more rapidly than was previously assumed, perhaps due to 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. To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 meter, 1½ meters of eustatic sea-level rise by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 1).

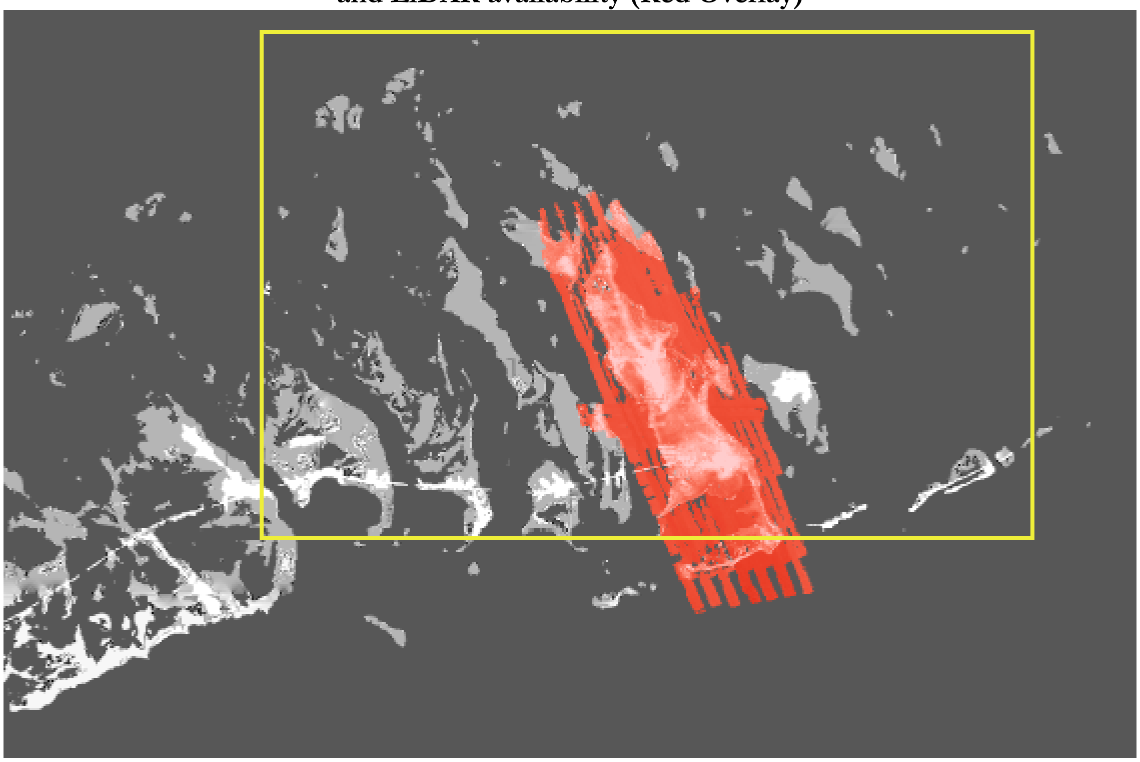
Figure 1: Summary of SLR Scenarios Utilized



Methods and Data Sources

LIDAR data are available for a limited portion of the National Key Deer NWR approved acquisition boundary as shown below. These data were made available thanks to the Nature Conservancy as derived from a 2007 survey performed by Florida International University. Areas in which LIDAR are not available were assigned elevations based on the National Elevation Dataset (NED). An examination of the metadata for the NED indicates that these data were derived from a 1972 survey with contour intervals of five feet. The process of creating a digital elevation map (DEM) from a contour map does interpolate between contour lines but there is considerable uncertainty in this process. Model results within areas not covered by LIDAR data should be considered subject to more uncertainty.

Figure 2: National Key Deer Approved Acquisition Boundary (Yellow Rectangle) and LiDAR availability (Red Overlay)

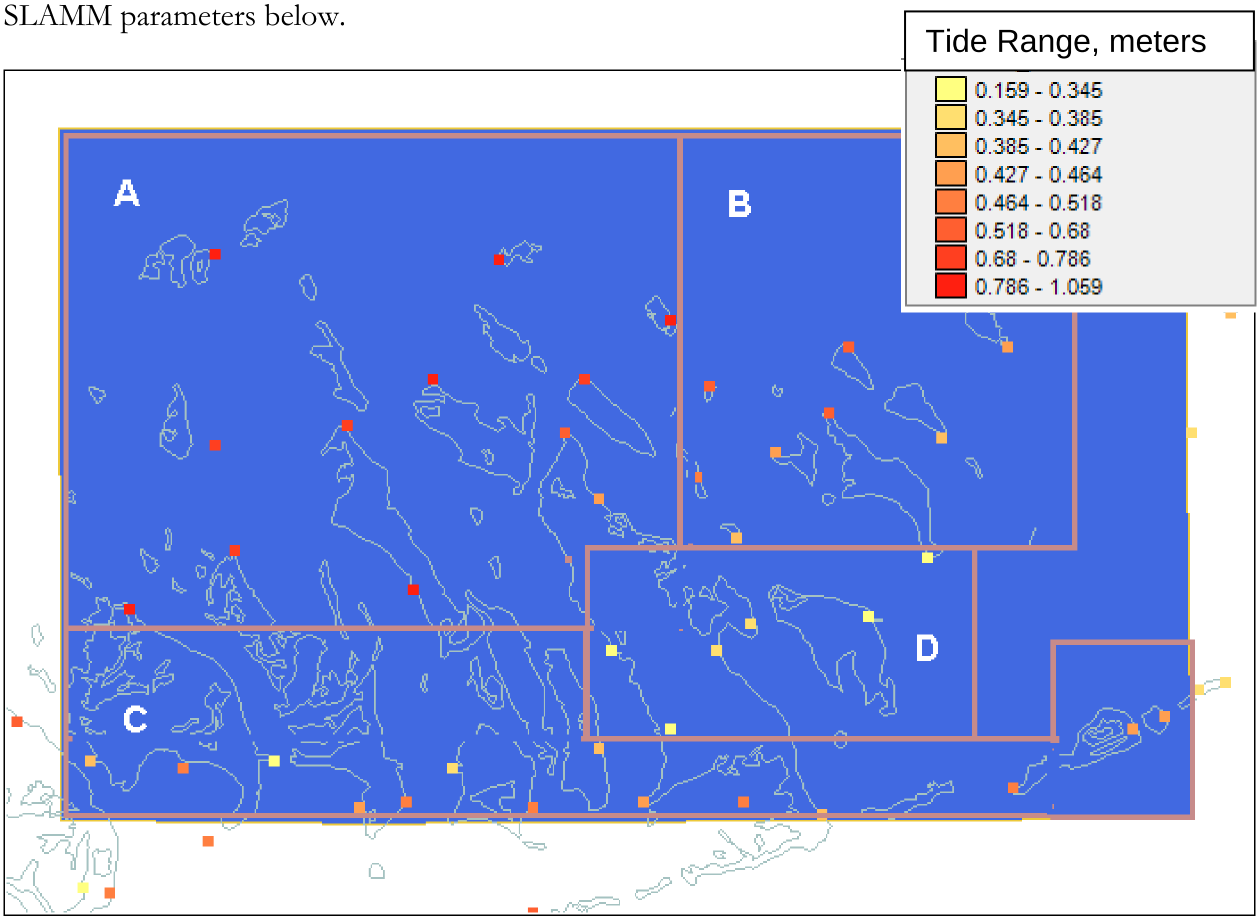


The National Wetlands Inventory (NWI) for National Key Deer is based on a photo date of 1986; this date represents the initial condition for this modeling analysis. The NWI survey, when converted to 30 meter cells, suggests that the approximately 138,000 acre refuge (approved acquisition boundary) is composed primarily of open water, scrub lands (transitional salt marsh), dry land, tidal flats, and mangrove forests.

Estuarine Open Water	56.4%
Open Ocean	21.6%
Trans. Salt Marsh	8.7%
Dry Land	6.3%
Tidal Flat	4.7%
Mangrove	1.8%
Brackish Marsh	0.2%
Ocean Beach	0.2%

At this site, the historic trend for Sea Level Rise was estimated at 2.51 mm/year based on long-term trends measured at Key West, Florida (NOAA station 8724580) and Vaca Key, Florida (8723970).

As shown in the figure below, the oceanic tide range was variable across the National Key Deer NWR approved acquisition boundary. For this reason, the site was split into four sub-sites (A-D) each with a unique tidal range. Derived tidal ranges for these sub-sites are shown in the table of SLAMM parameters below.



NOAA Stations used to gather tide data for National Key Deer and sub-sites A through D used in modeling. (Blue Area is Approved Acquisition Boundary)

Within SLAMM, mangrove accretion rates are estimated to be 7mm/year based on Cahoon et al. 1999.

Modeled U.S. Fish and Wildlife Service refuge boundaries are based on Approved Acquisition Boundaries as received from Kimberly Eldridge, lead cartographer with U.S. Fish and Wildlife Service, and are current as of June, 2008.

The cell-size used for this analysis was 30 meter by 30 meter cells. However, the SLAMM model does track partial conversion of cells based on elevation and slope.

According to the NWI survey, no diked wetlands occur within National Key Deer NWR.

Refuge manager Anne Morkill was extremely helpful in identifying LiDAR data used in this modeling as well as providing additional technical contacts and maps of the site.

SLAMM INPUT PARAMETERS FOR NATIONAL KEY DEER

Site	**Nat. Key Deer A**	**NKD B**	**NKD C**	**NKD D**
NED Source Date (yyyy)	1972	1972	1972	1972
NWI_photo_date (yyyy)	1986	1986	1986	1986
Direction_OffShore (N|S|E|W)	N	N	S	S
Historic_trend (mm/yr)	2.51	2.51	2.51	2.51
NAVD88_correction (MTL-NAVD88 in meters)	-0.2303	-0.2415	-0.2526	-0.234
Water Depth (m below MLW- N/A)	2	2	2	2
TideRangeOcean (meters: MHHW-MLLW)	0.782	0.514	0.438	0.342
TideRangeInland (meters)	0.782	0.514	0.438	0.342
Mean High Water Spring (m above MTL)	0.520	0.342	0.291	0.227
MHSW Inland (m above MTL)	0.520	0.342	0.291	0.227
Marsh Erosion (horz meters/year)	1.8	1.8	1.8	1.8
Swamp Erosion (horz meters/year)	1	1	1	1
TFlat Erosion (horz meters/year) [from 0.5]	2	2	2	2
Salt marsh vertical accretion (mm/yr) Final	3.9	3.9	3.9	3.9
Brackish March vert. accretion (mm/yr) Final	4.7	4.7	4.7	4.7
Tidal Fresh vertical accretion (mm/yr) Final	5.9	5.9	5.9	5.9
Beach/T.Flat Sedimentation Rate (mm/yr)	0.5	0.5	0.5	0.5
Frequency of Large Storms (yr/washover)	25	25	25	25
Use Elevation Preprocessor for Wetlands	NON LIDAR AREAS	NON LIDAR	NON LIDAR	NON LIDAR

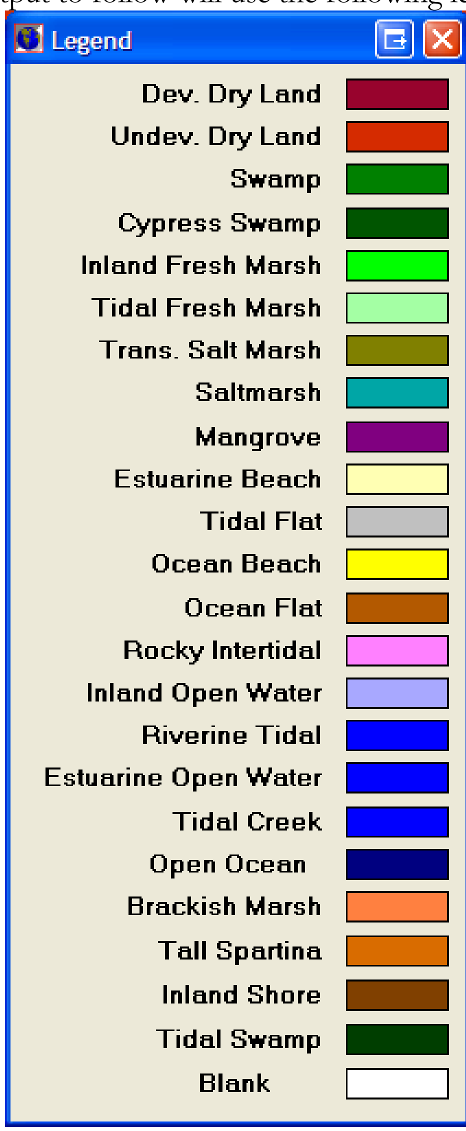
Results

The table below summarizes year 2100 results for the primary land categories in National Key Deer NWR:

SLR by 2100 (m)	0.39	0.69	1	1.5
Trans. Salt Marsh	11%	97%	99%	100%
Dry Land	64%	80%	92%	98%
Tidal Flat	68%	92%	95%	99%
Mangrove	-172%	-617%	-555%	27%
Brackish Marsh	7%	79%	96%	100%
All Beach	-132%	-84%	-69%	30%

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

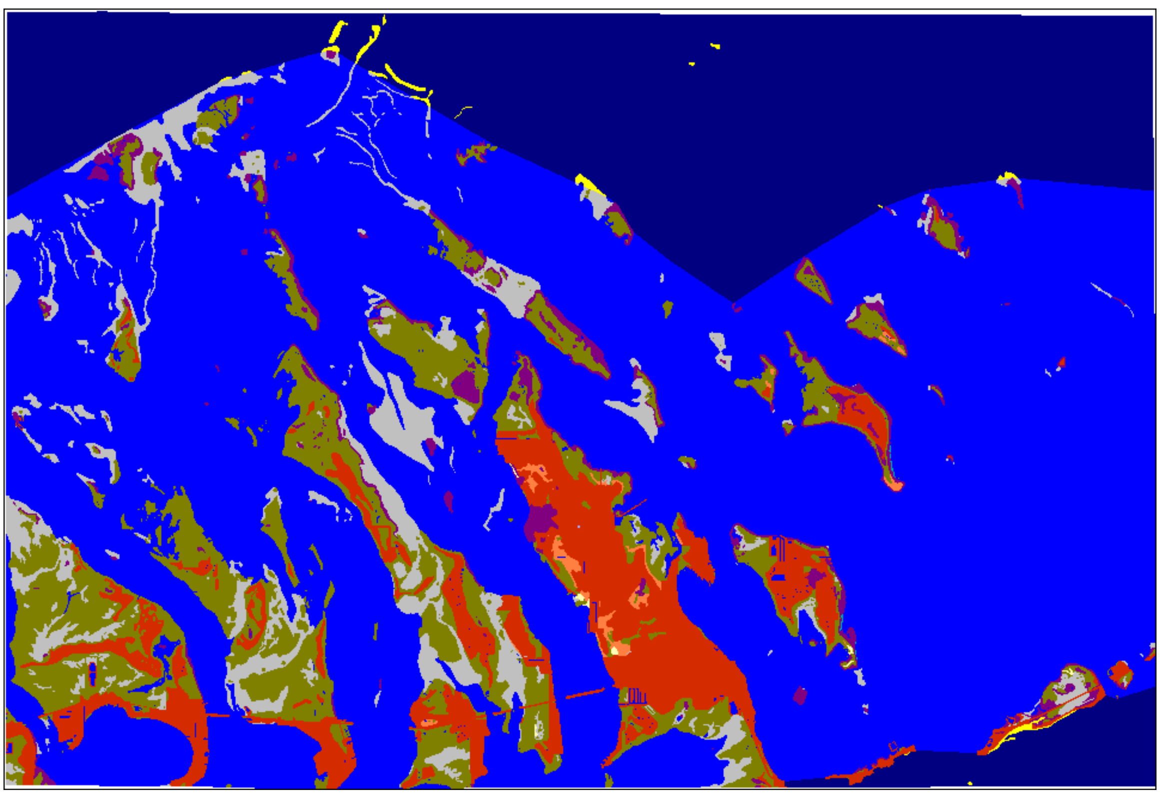
Maps of SLAMM input and output to follow will use the following legend:



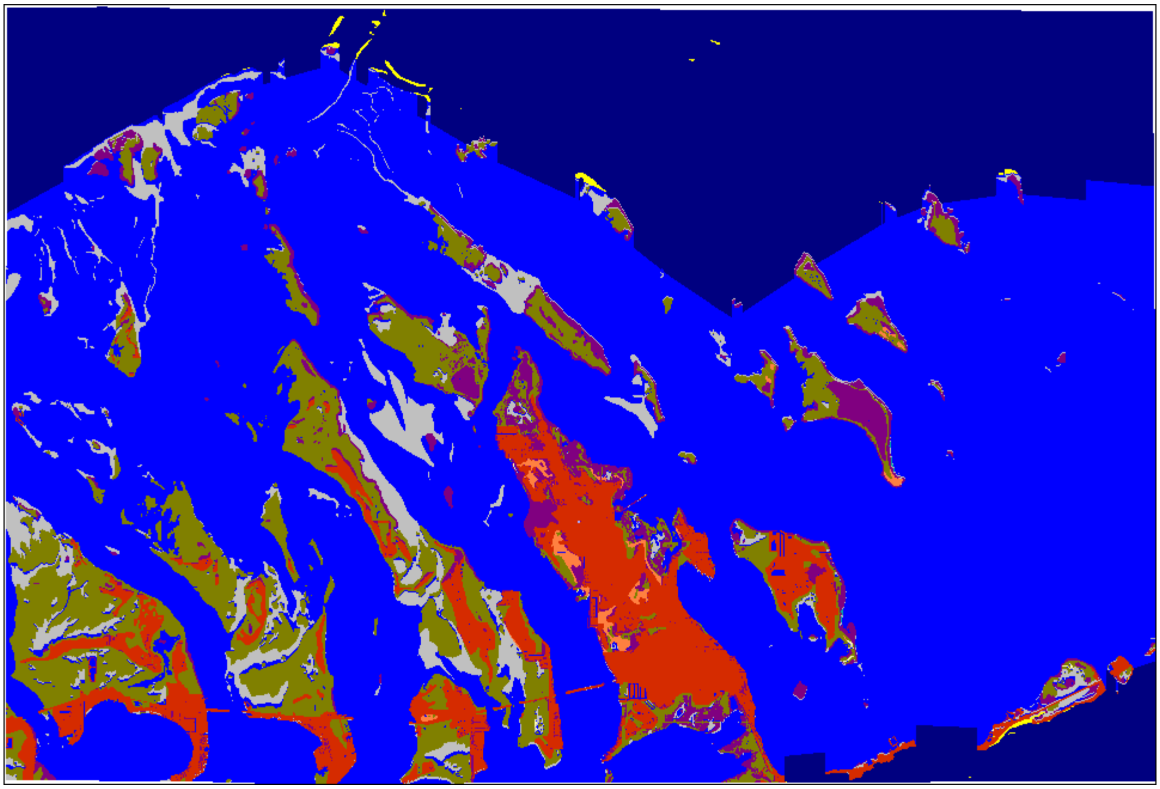
National Key Deer
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

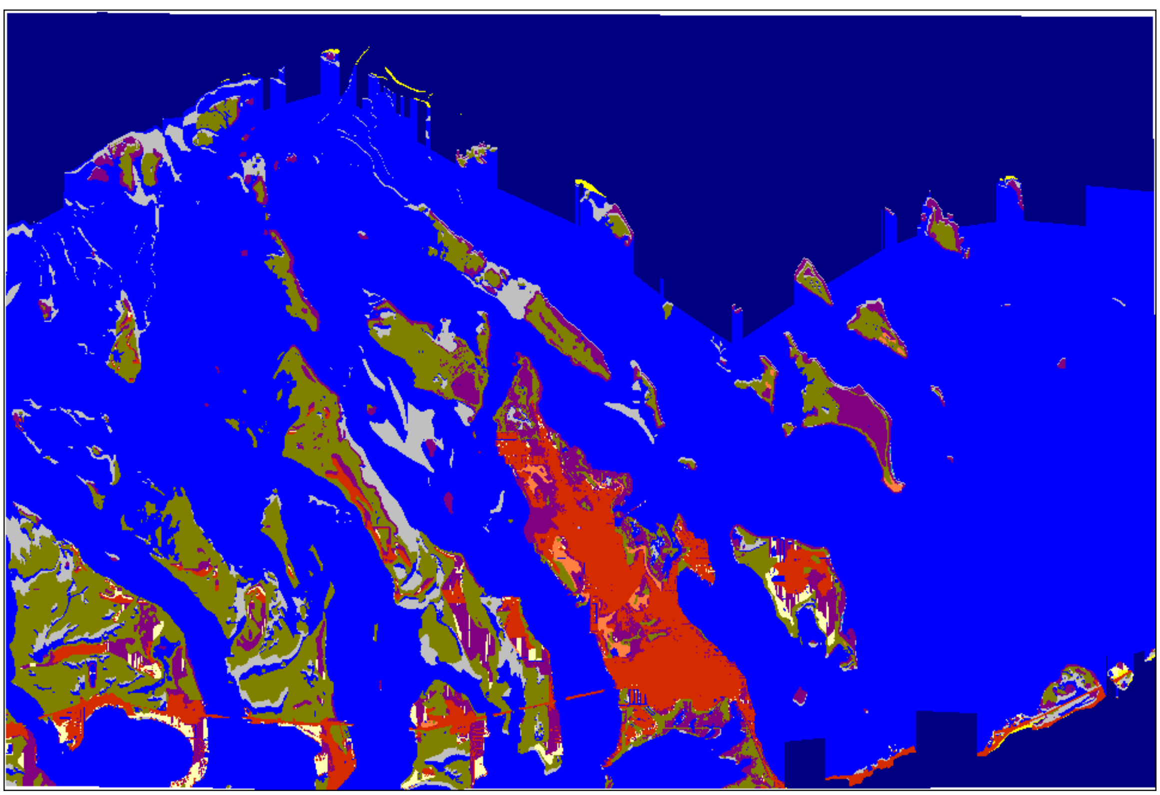
	Initial	2025	2050	2075	2100
Estuarine Open Water	77843.4	77070.1	76355.3	75993.9	74795.3
Open Ocean	29879.3	32523.6	34903.8	37061.5	39521.5
Trans. Salt Marsh	11997.7	11126.8	11022.6	10880.6	10718.1
Dry Land	8729.2	7586.6	5085.9	4157.1	3150.9
Tidal Flat	6503.0	5166.3	3854.9	2332.1	2063.1
Mangrove	2491.5	4083.0	5565.4	6159.1	6789.2
Brackish Marsh	334.0	320.6	320.1	315.8	311.6
Ocean Beach	232.4	160.0	100.7	50.8	32.0
Estuarine Beach	36.3	14.7	845.1	1104.3	675.1
Saltmarsh	12.0	7.3	5.1	3.7	2.0
Inland Open Water	0.9	0.9	0.9	0.9	0.9
Total (incl. water)	**138059.7**	**138059.7**	**138059.7**	**138059.7**	**138059.7**



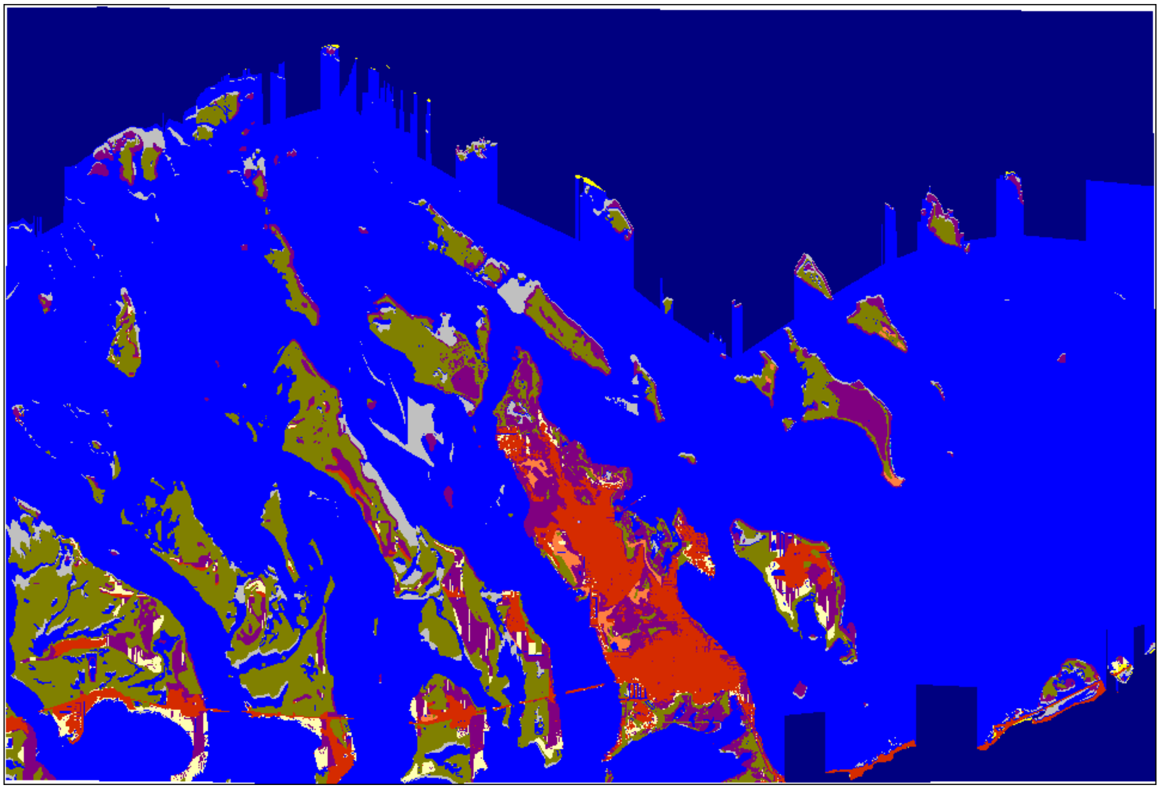
National Key Deer NWR, Initial Condition



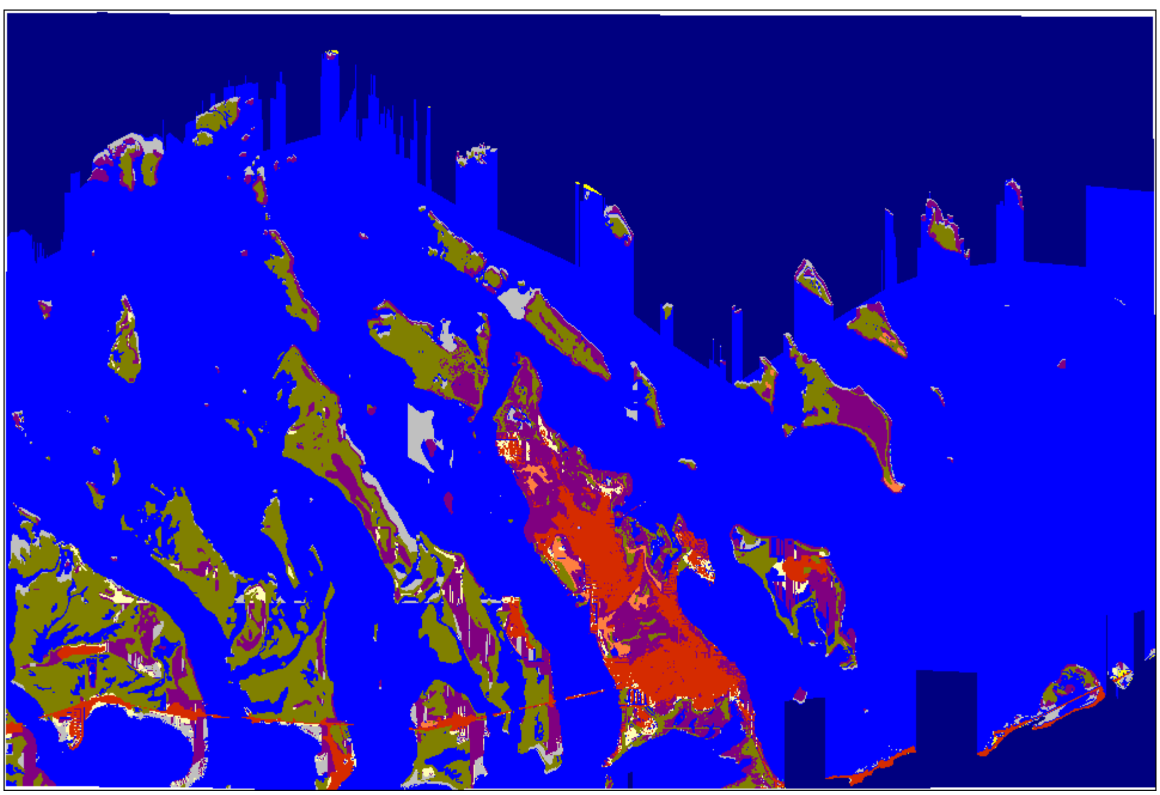
National Key Deer NWR, 2025, Scenario A1B Mean



National Key Deer NWR, 2050, Scenario A1B Mean



National Key Deer NWR, 2075, Scenario A1B Mean

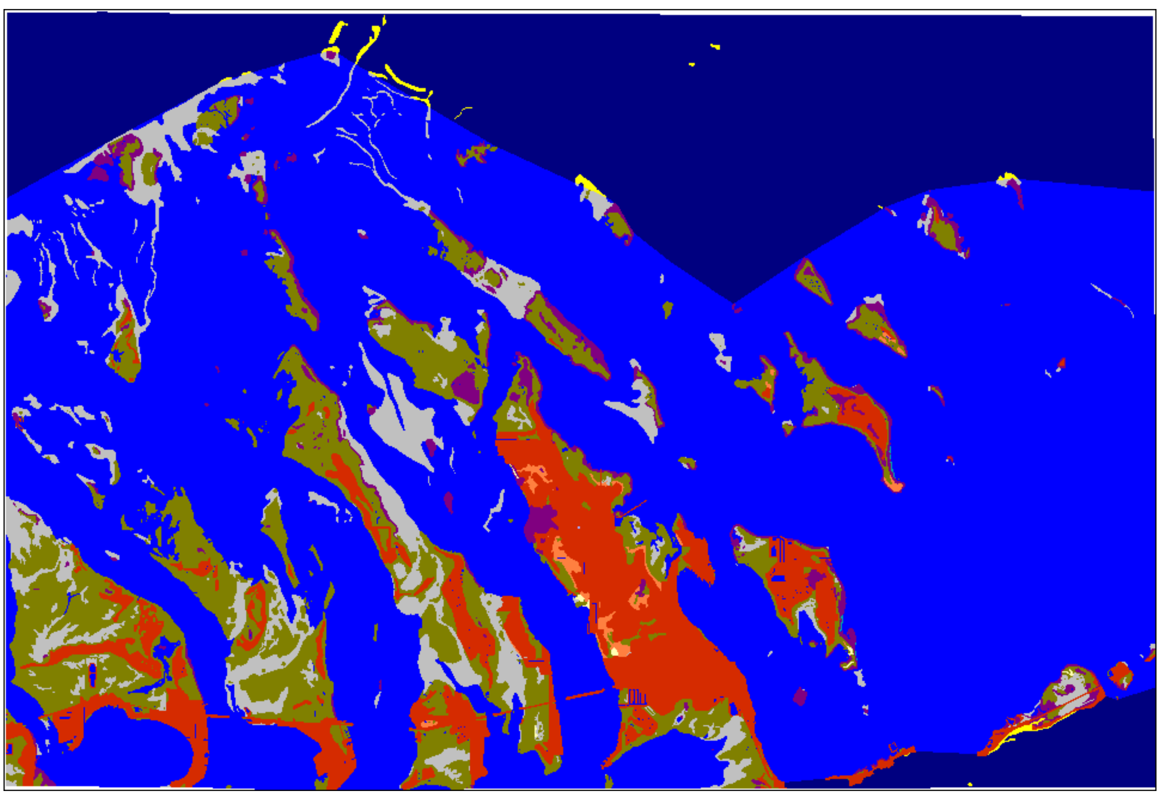


National Key Deer NWR, 2100, Scenario A1B Mean

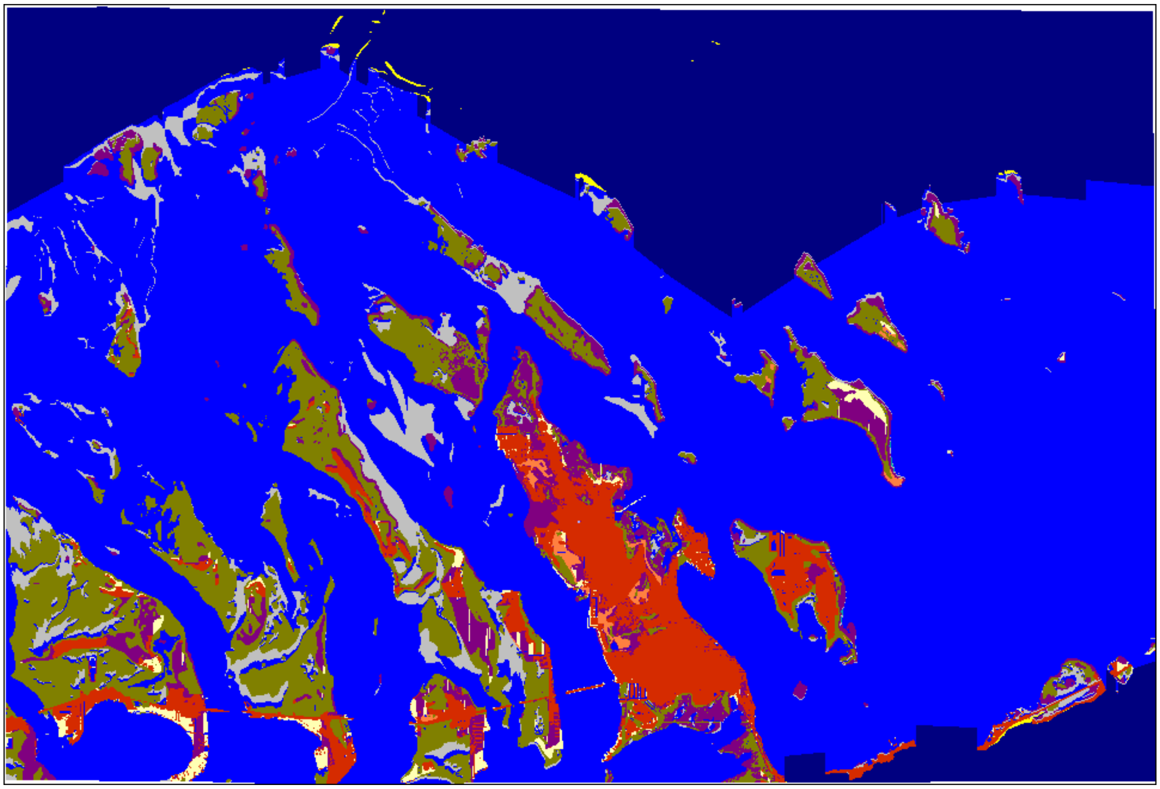
National Key Deer
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

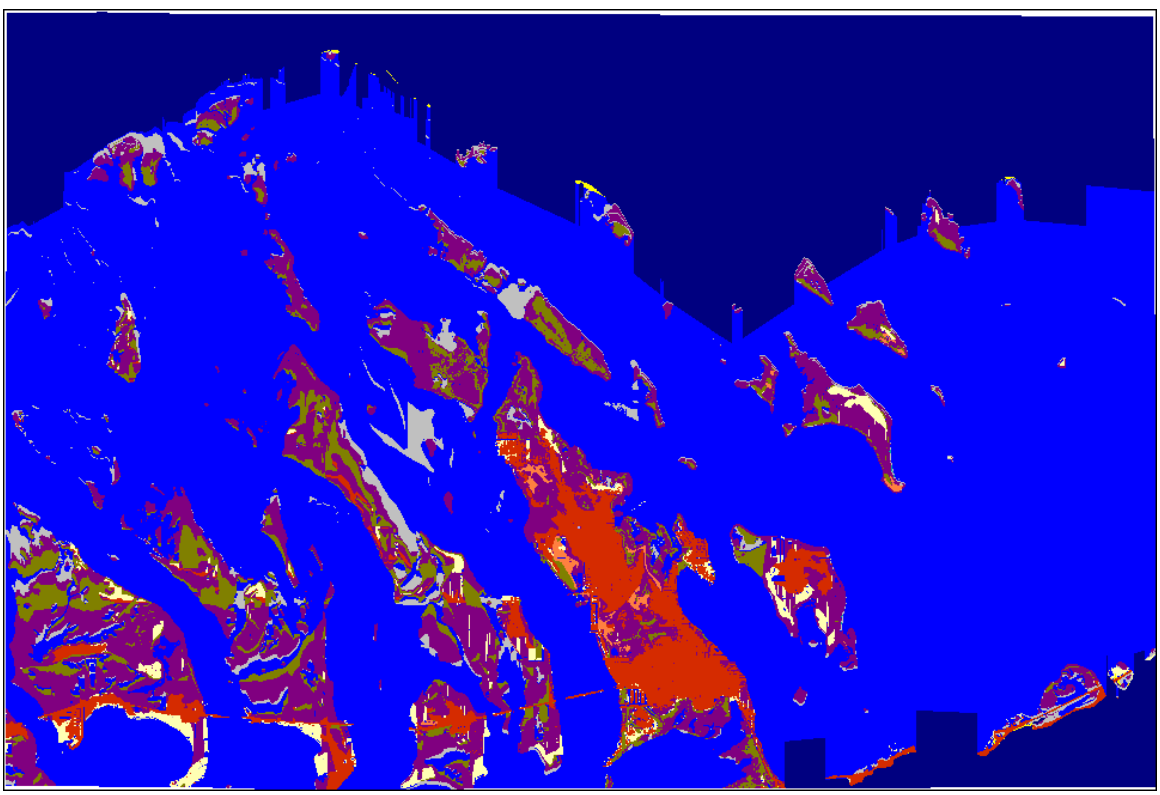
	Initial	2025	2050	2075	2100
Estuarine Open Water	77843.4	77787.9	77851.8	77803.3	76619.8
Open Ocean	29879.3	32566.5	35032.4	37583.7	40347.1
Trans. Salt Marsh	11997.7	10930.7	3948.1	732.8	371.4
Dry Land	8729.2	5877.2	4283.5	2830.2	1727.4
Tidal Flat	6503.0	4457.1	2413.5	1216.3	508.9
Mangrove	2491.5	5082.8	12912.7	16993.2	17852.5
Brackish Marsh	334.0	307.4	257.2	152.9	69.7
Ocean Beach	232.4	120.4	45.0	15.7	3.5
Estuarine Beach	36.3	921.7	1311.0	730.3	558.3
Saltmarsh	12.0	6.9	3.6	0.4	0.2
Inland Open Water	0.9	0.9	0.9	0.9	0.9
Total (incl. water)	**138059.7**	**138059.7**	**138059.7**	**138059.7**	**138059.7**



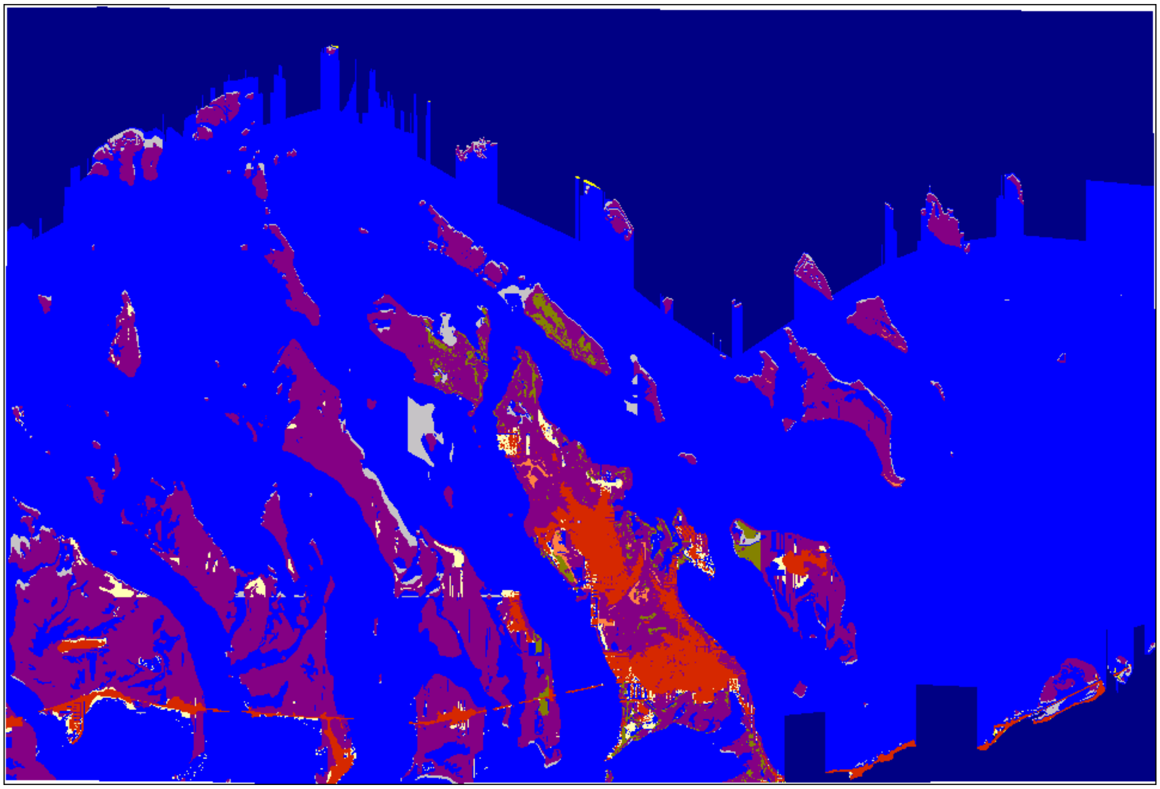
National Key Deer NWR, Initial Condition Scenario A1B Maximum



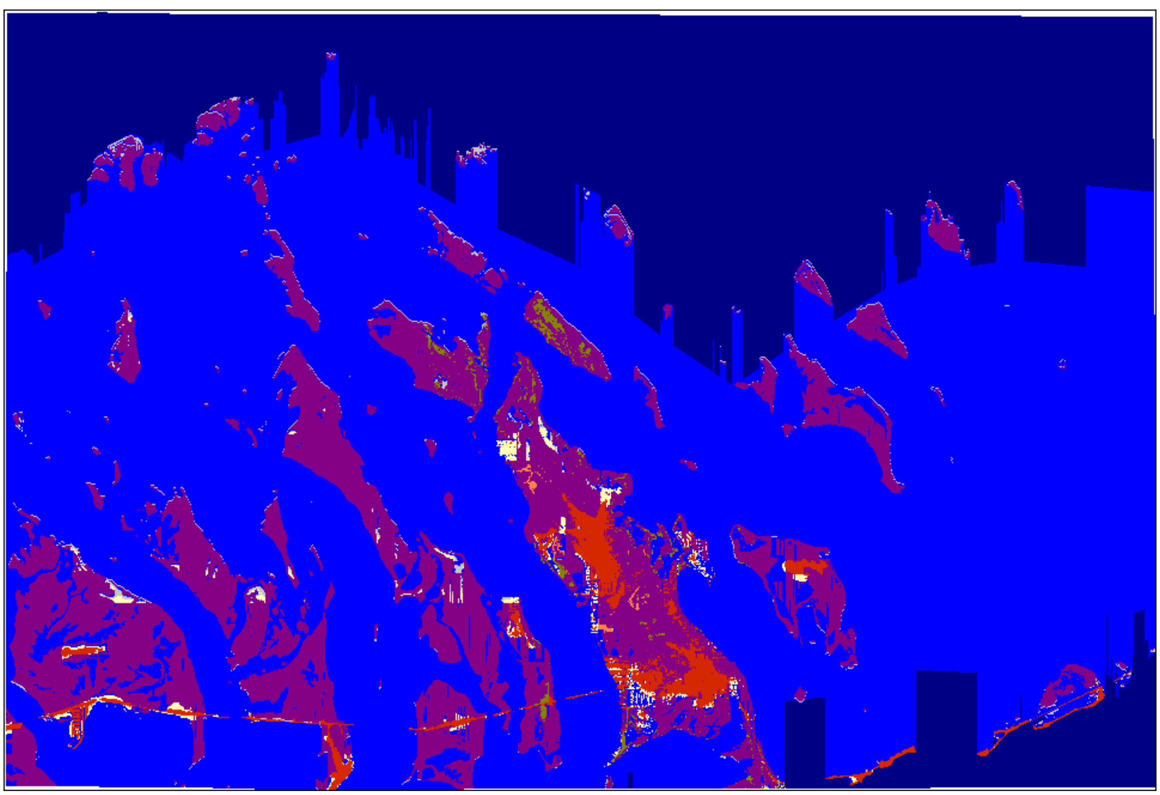
National Key Deer NWR, 2025, Scenario A1B Maximum



National Key Deer NWR, 2050, Scenario A1B Maximum



National Key Deer NWR, 2075, Scenario A1B Maximum

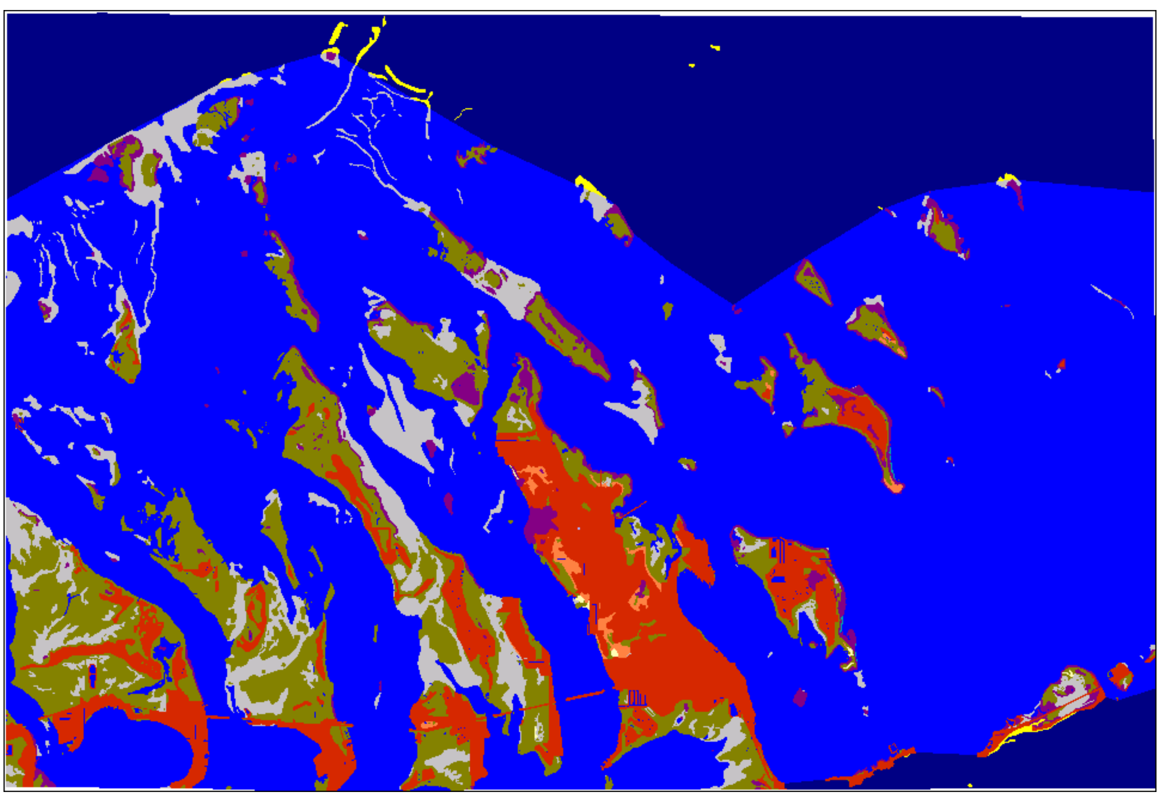


National Key Deer NWR, 2100, Scenario A1B Maximum

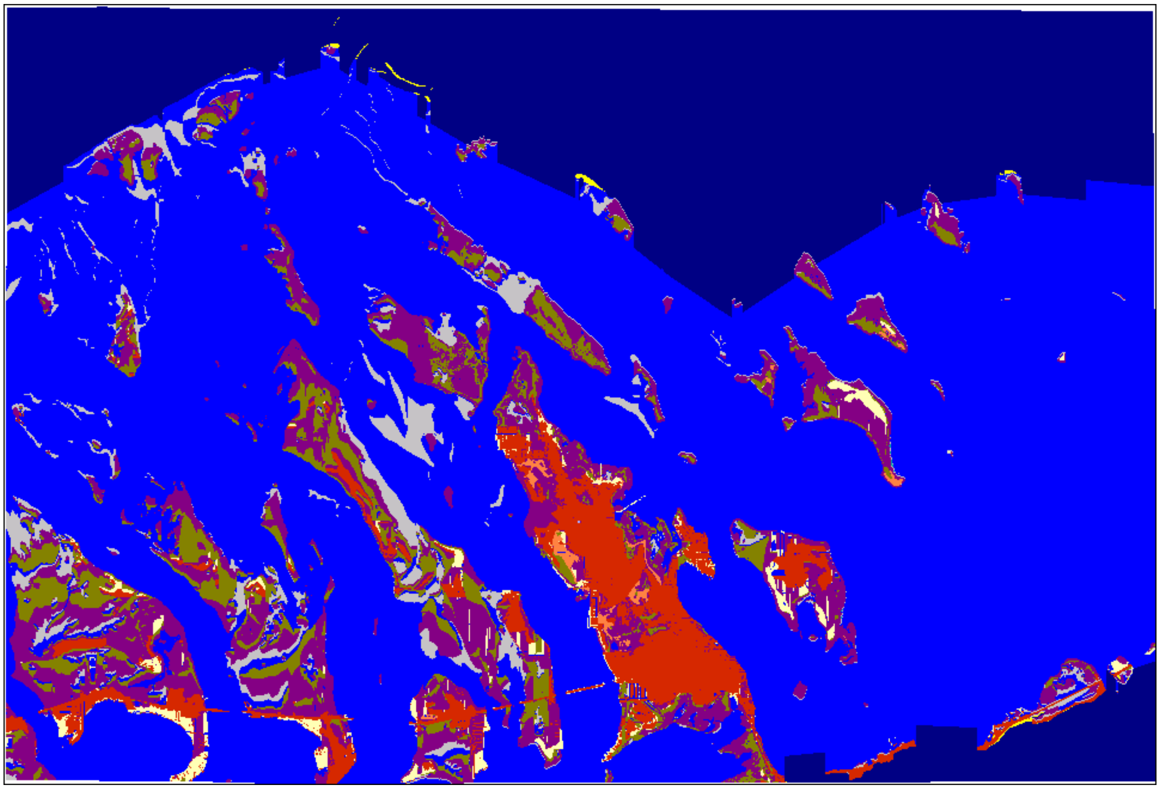
National Key Deer
1 Meter Eustatic SLR by 2100

Results in Acres

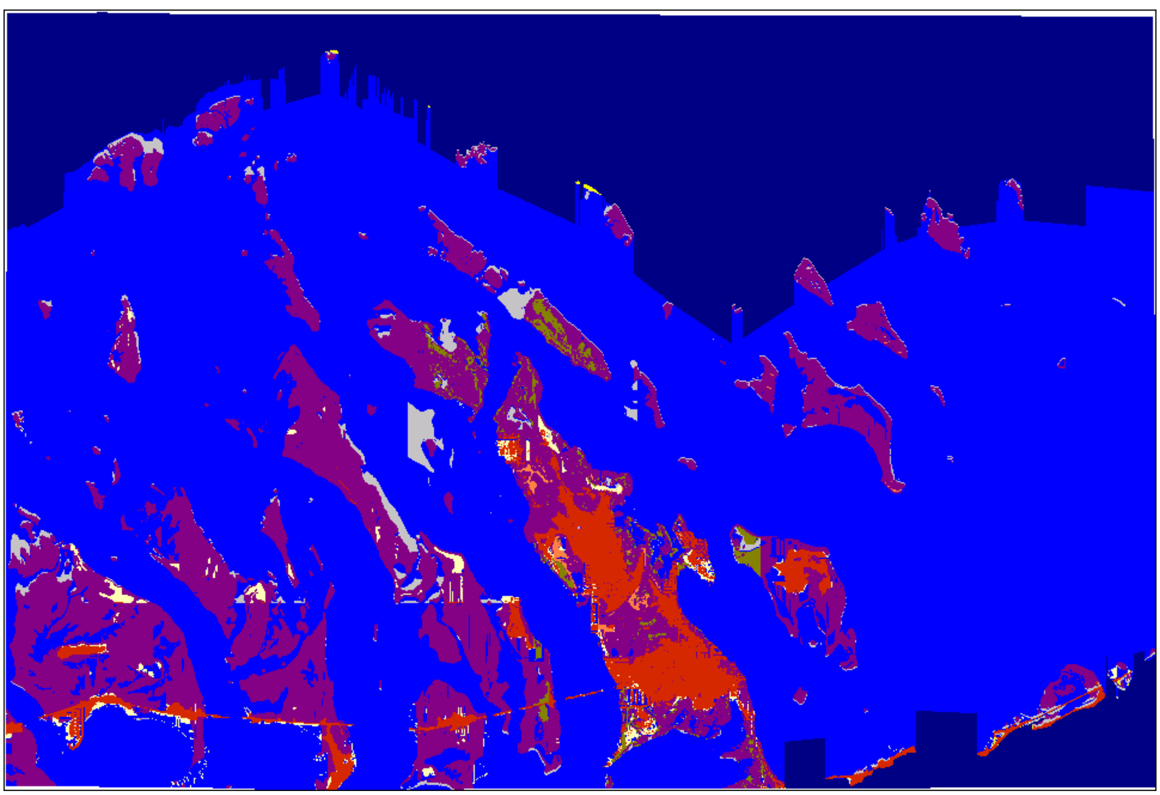
	Initial	2025	2050	2075	2100
Estuarine Open Water	77843.4	78568.5	79617.1	78924.6	79220.5
Open Ocean	29879.3	32605.3	35191.6	38076.2	40888.2
Trans. Salt Marsh	11997.7	4900.5	686.1	254.3	119.3
Dry Land	8729.2	5142.3	3389.1	1820.1	655.4
Tidal Flat	6503.0	3633.3	1413.7	417.9	325.3
Mangrove	2491.5	11686.7	16901.8	17862.4	16323.0
Brackish Marsh	334.0	264.9	138.2	35.9	12.6
Ocean Beach	232.4	83.6	21.4	4.4	4.3
Estuarine Beach	36.3	1169.1	699.3	662.8	511.1
Saltmarsh	12.0	4.7	0.6	0.2	0.0
Inland Open Water	0.9	0.9	0.9	0.9	0.0
Total (incl. water)	**138059.7**	**138059.7**	**138059.7**	**138059.7**	**138059.7**



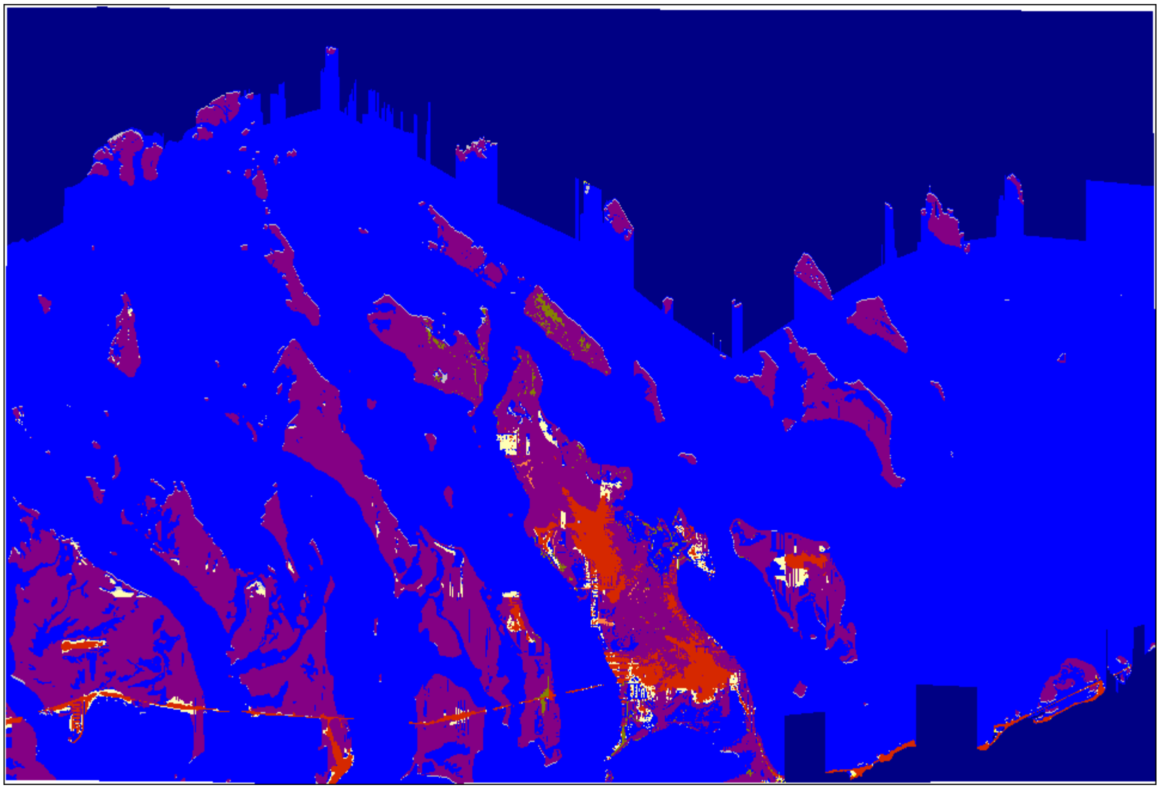
National Key Deer NWR, Initial Condition



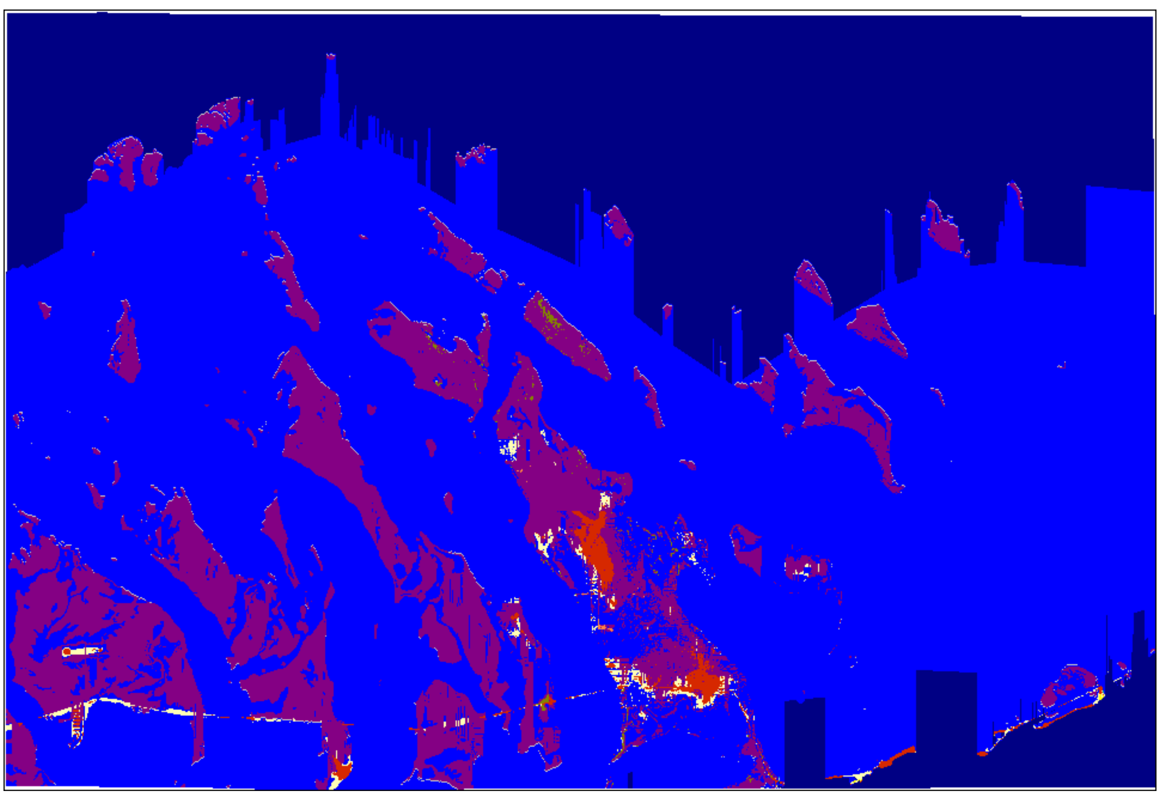
National Key Deer NWR, 2025, 1 meter eustatic SLR by 2100



National Key Deer NWR, 2050, 1 meter eustatic SLR by 2100



National Key Deer NWR, 2075, 1 meter eustatic SLR by 2100

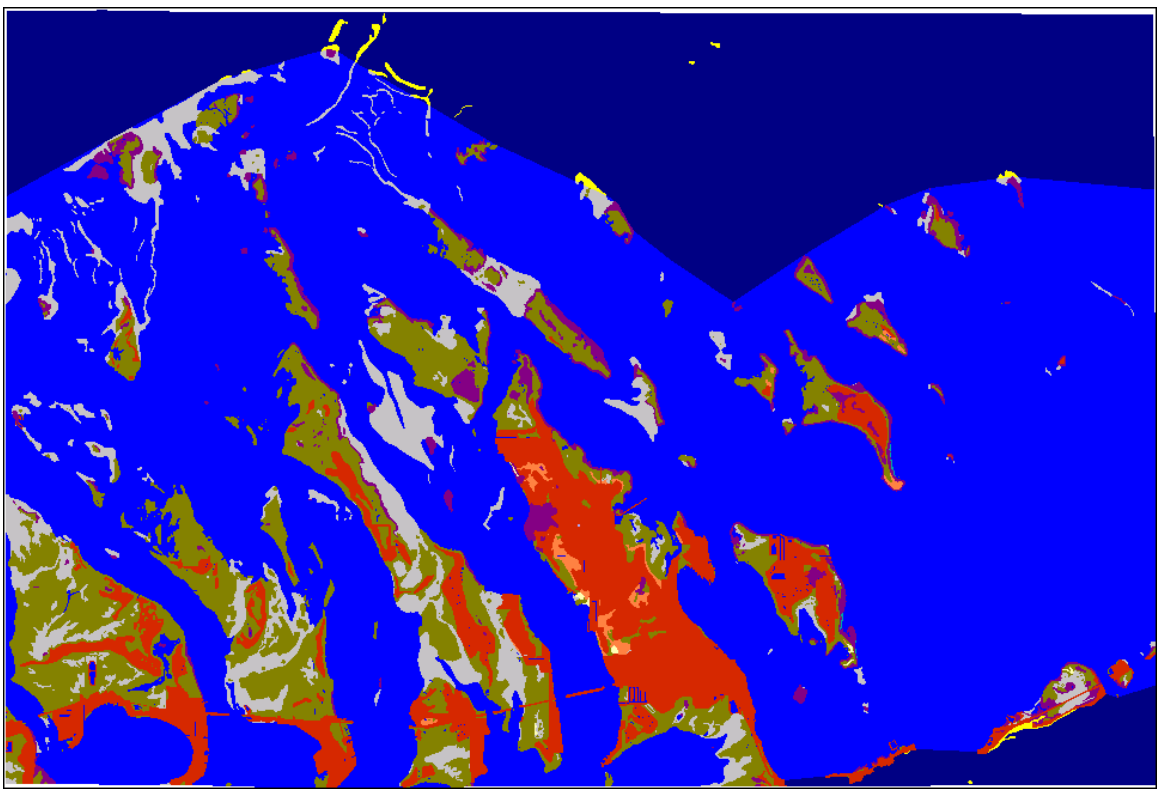


National Key Deer NWR, 2100, 1 meter eustatic SLR by 2100

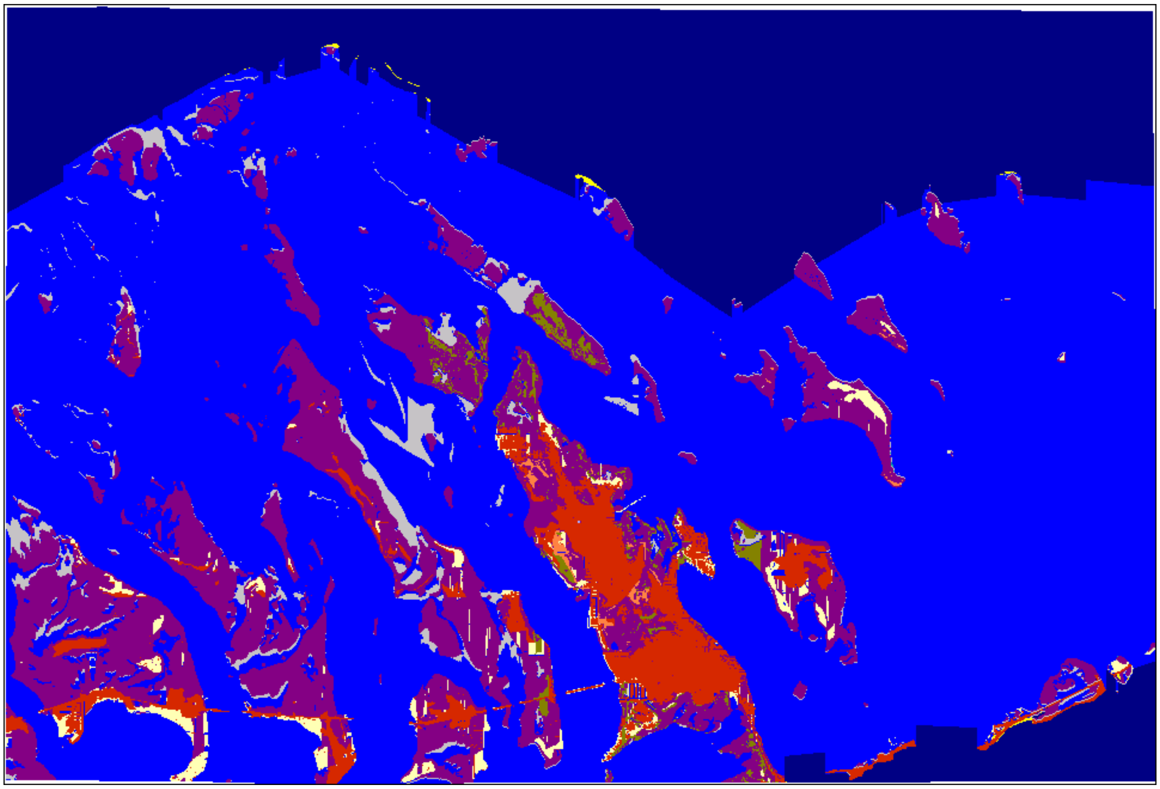
National Key Deer
1.5 Meters Eustatic SLR by 2100

Results in Acres

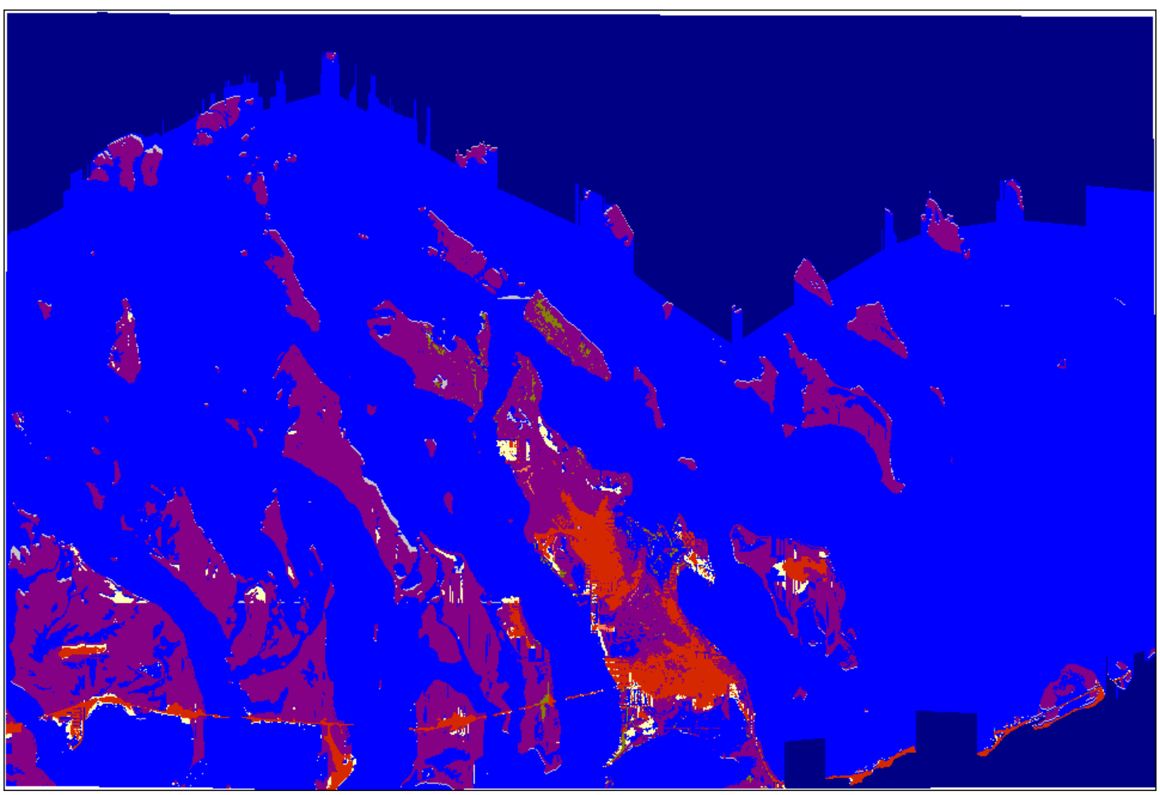
	Initial	2025	2050	2075	2100
Estuarine Open Water	77843.4	79728.6	81134.4	89173.9	94204.5
Open Ocean	29879.3	32645.3	35485.7	38438.4	41580.1
Trans. Salt Marsh	11997.7	809.7	248.8	74.9	23.8
Dry Land	8729.2	4499.6	2369.9	613.7	142.6
Tidal Flat	6503.0	2427.3	505.5	199.6	66.8
Mangrove	2491.5	16376.3	17583.1	8794.6	1829.5
Brackish Marsh	334.0	174.3	34.3	2.4	0.0
Ocean Beach	232.4	47.0	0.5	4.4	0.1
Estuarine Beach	36.3	1348.5	696.8	757.3	212.3
Saltmarsh	12.0	2.2	0.0	0.0	0.0
Inland Open Water	0.9	0.9	0.9	0.4	0.0
Total (incl. water)	**138059.7**	**138059.7**	**138059.7**	**138059.7**	**138059.7**



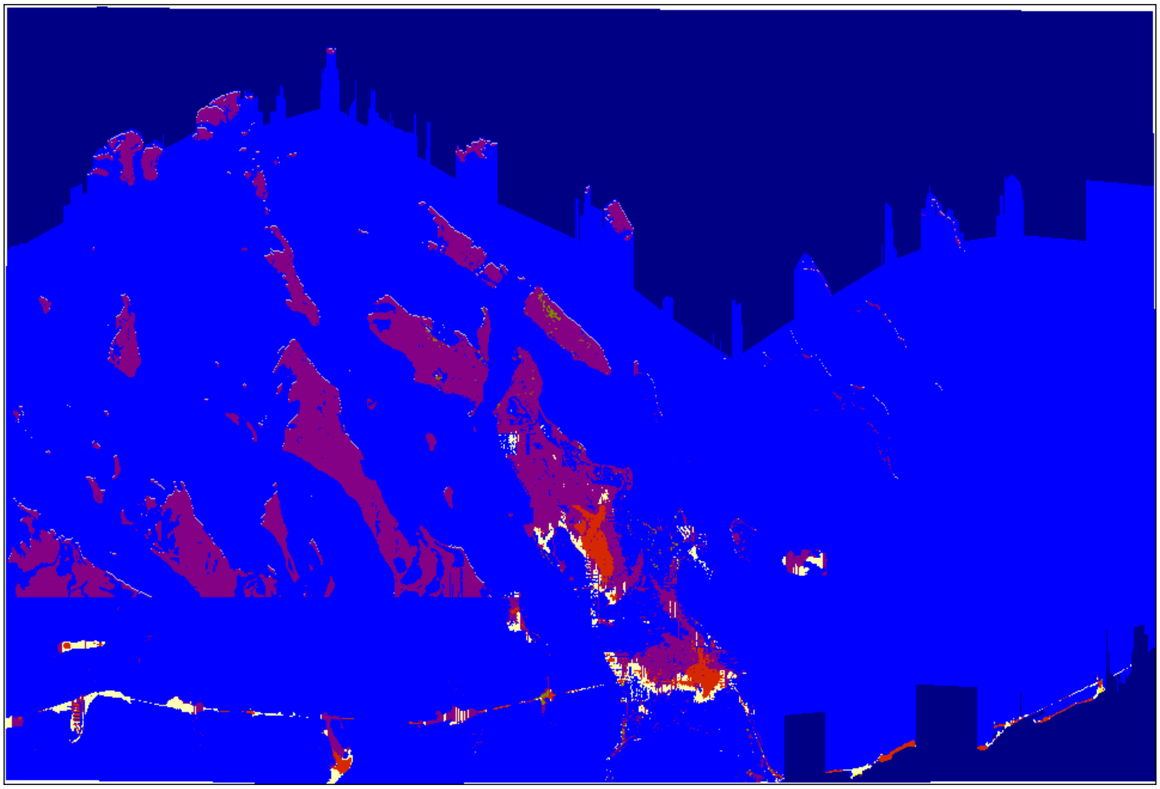
National Key Deer NWR, Initial Condition



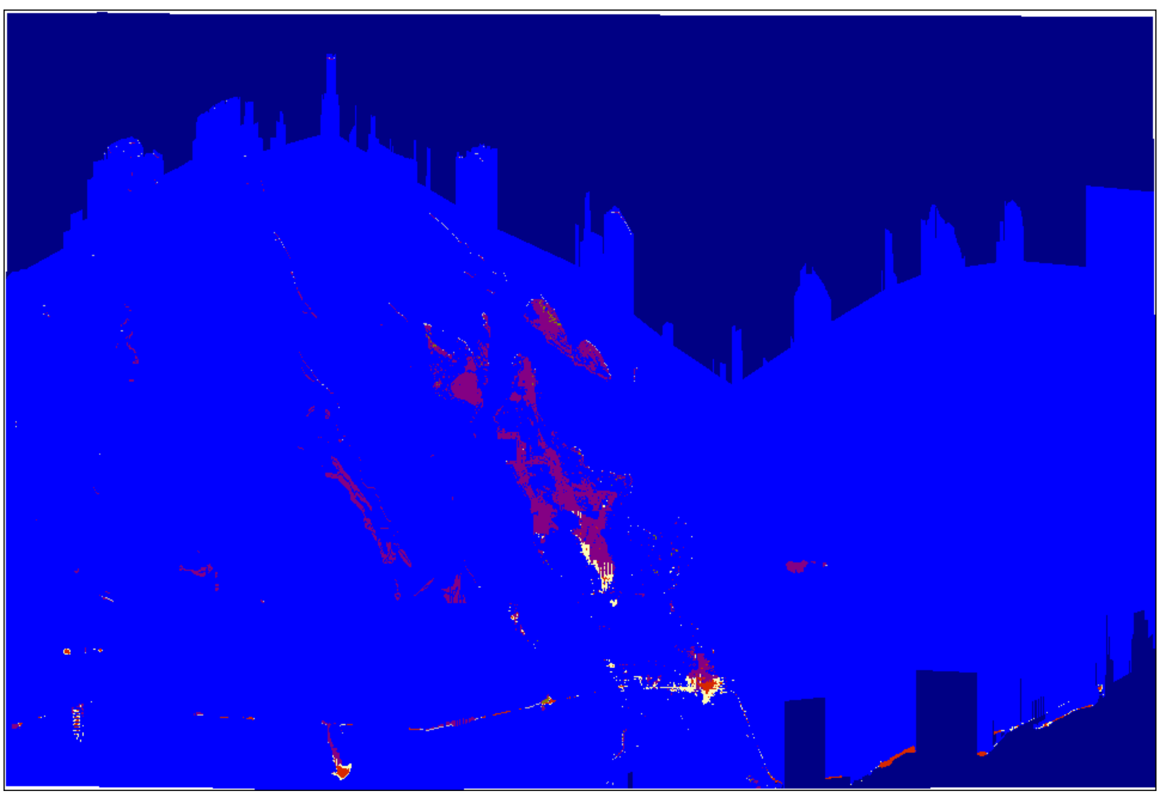
National Key Deer NWR, 2025, 1.5 meters eustatic SLR by 2100



National Key Deer NWR, 2050, 1.5 meters eustatic SLR by 2100



National Key Deer NWR, 2075, 1.5 meters eustatic SLR by 2100



National Key Deer NWR, 2100, 1.5 meters eustatic SLR by 2100

Discussion:

The scrub-shrub habitat that comprises much of the National Key Deer refuge is predicted to be at considerable risk under higher rates of sea level rise. Most of this habitat is predicted to convert to mangrove forest (under all but the most conservative sea level rise scenario run).

Dry land at this site is also predicted to be vulnerable. Interestingly, in the portion of the map with LiDAR coverage, dry land loss rates are lower. However, under higher rates of sea level rise, these LIDAR-surveyed dry lands are lost as well. Dry-land loss rates may be overpredicted in portions of the map that are not covered with LiDAR data due to uncertainty in elevation data. Given that these lands are generally located under the five foot contour interval, though, the model's prediction of vulnerability seems common sense. To produce a more precise prediction of the extent of dry lands lost under moderate scenarios of sea level rise, a more complete LiDAR coverage would be required.

Mangroves are predicted to thrive at this site, inhabiting submerged dry lands and scrub-shrub lands until the highest scenarios of SLR at which point they start to lose some acreage as well.

Beaches are predicted to increase under lower rates of sea level rise, as dry lands are converted, but decrease under the highest rates of predicted sea level rise.

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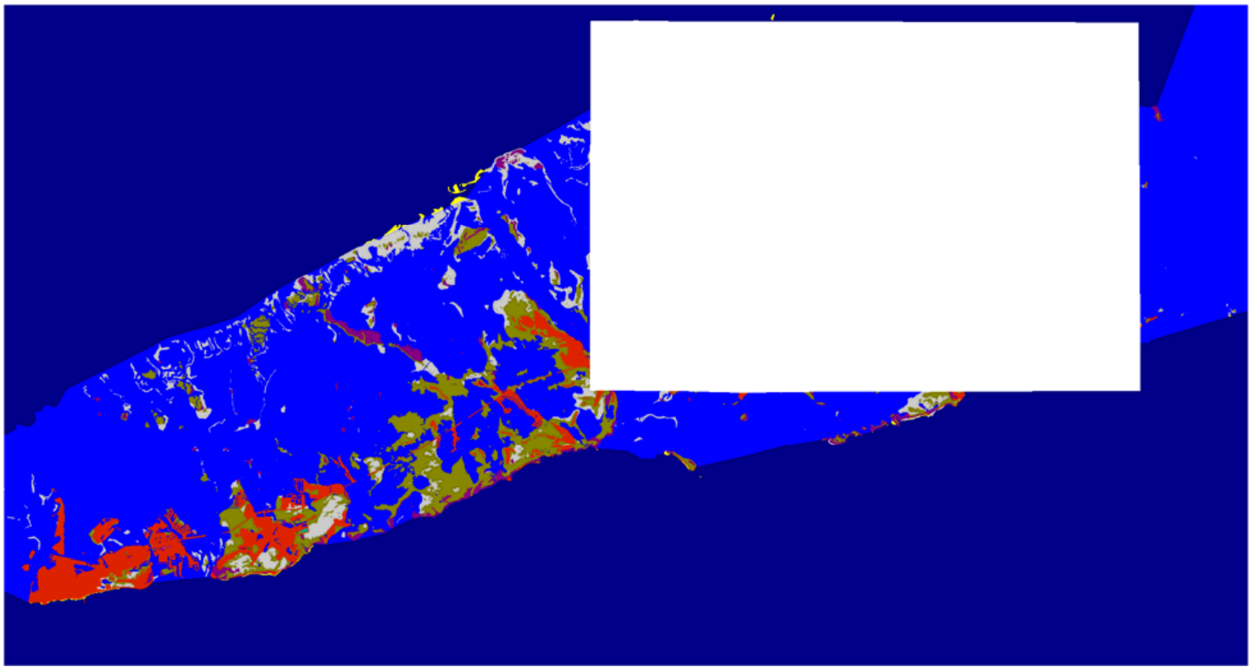
Appendix A: Contextual Results

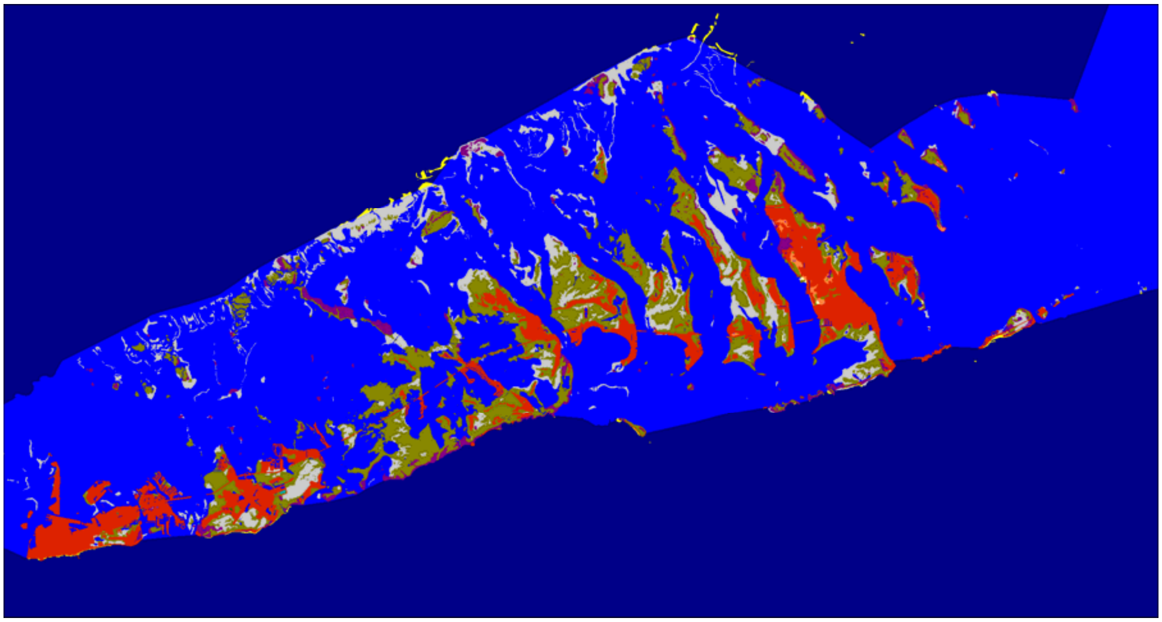
The SLAMM model does take into account the Context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated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

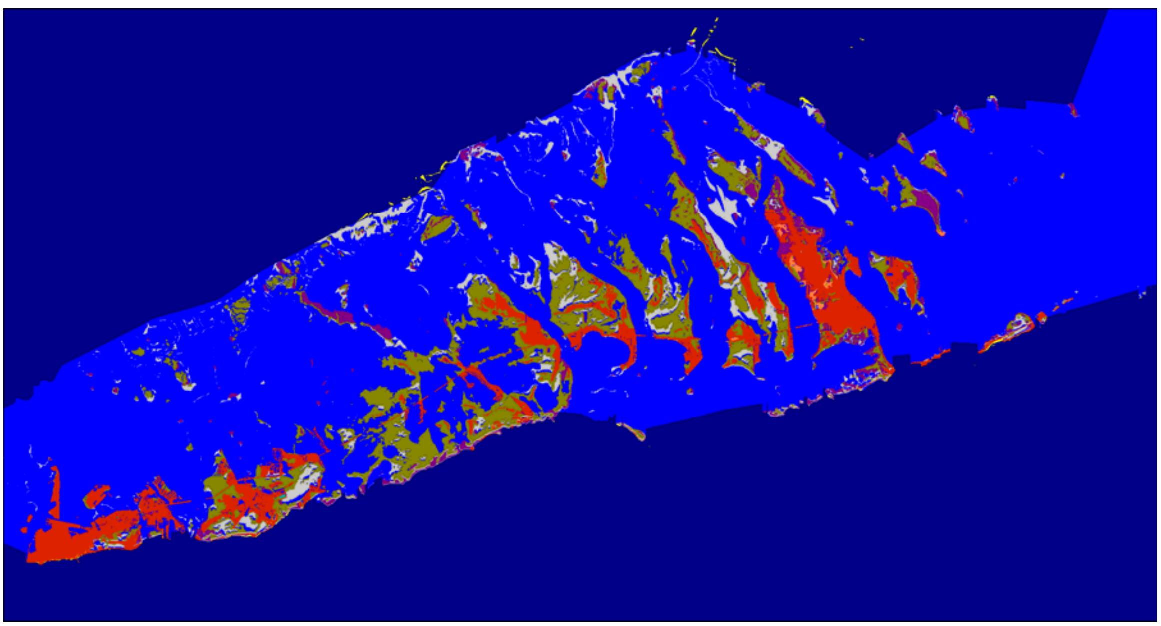
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort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



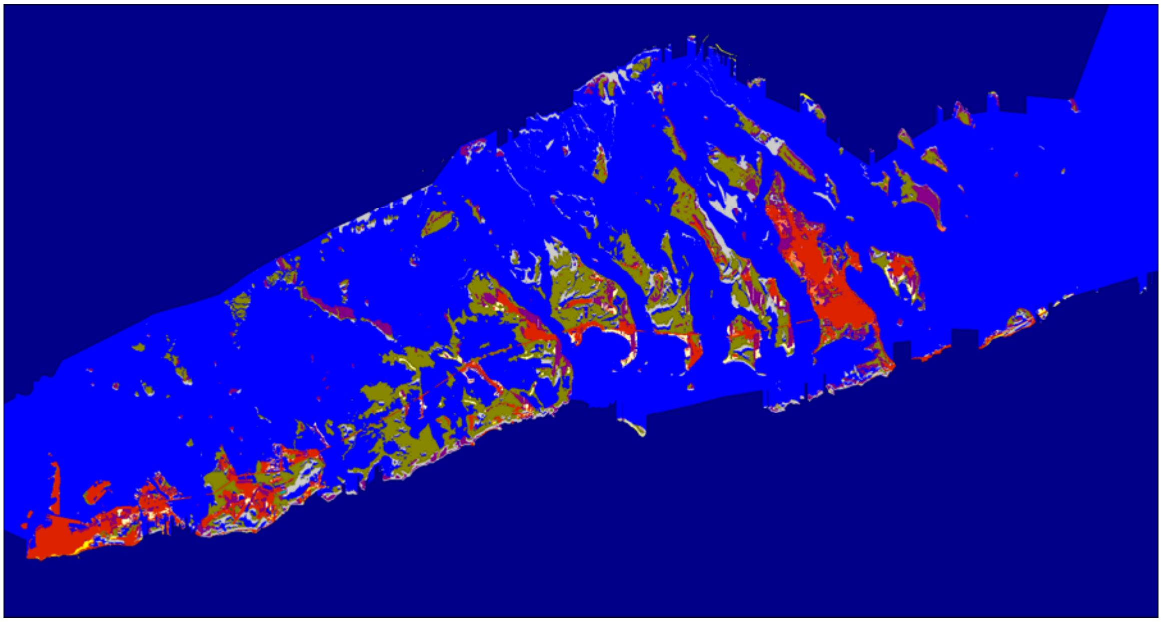
National Key Deer NWR (white rectangle) within Contextual simulation



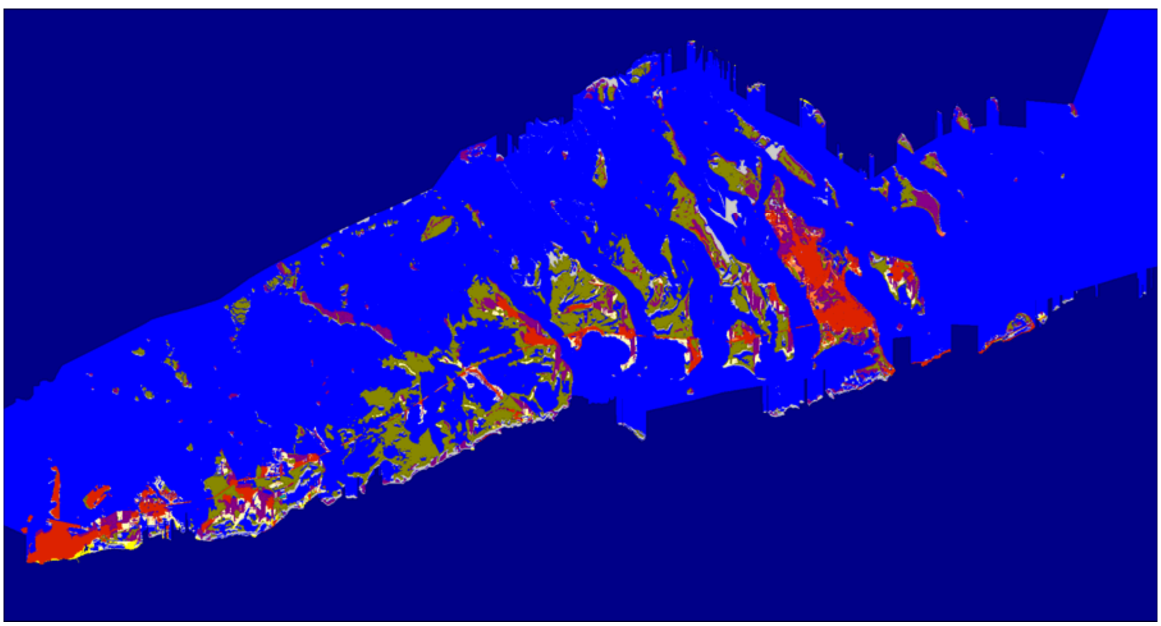
National Key Deer Context, Initial Condition Scenario A1B Mean



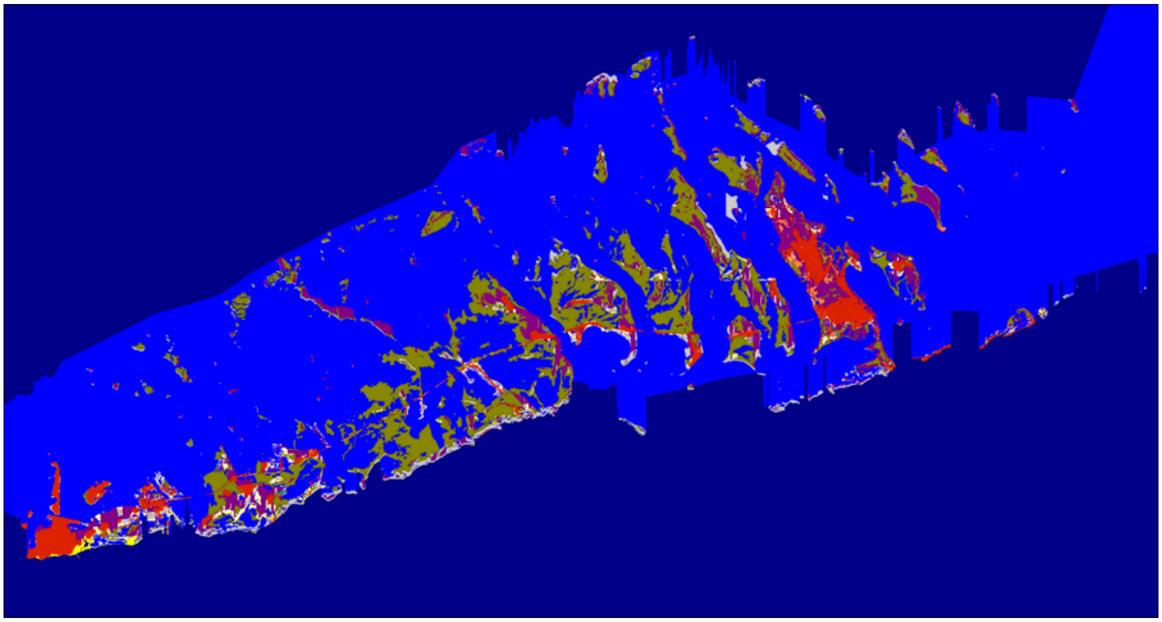
National Key Deer Context, 2025, Scenario A1B Mean



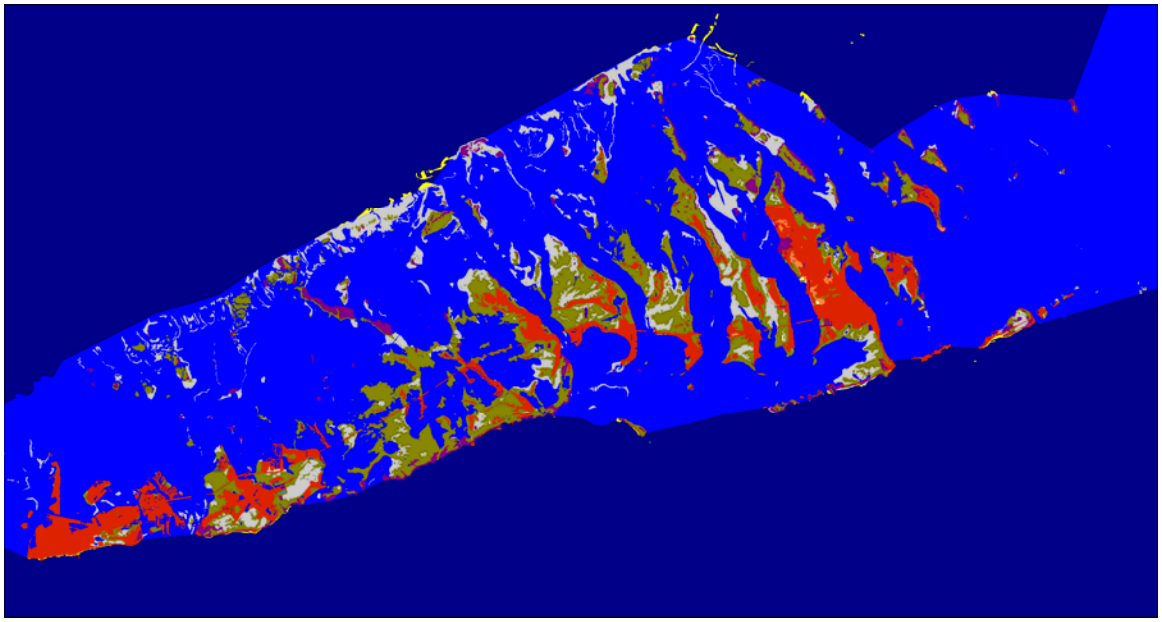
National Key Deer Context, 2050, Scenario A1B Mean



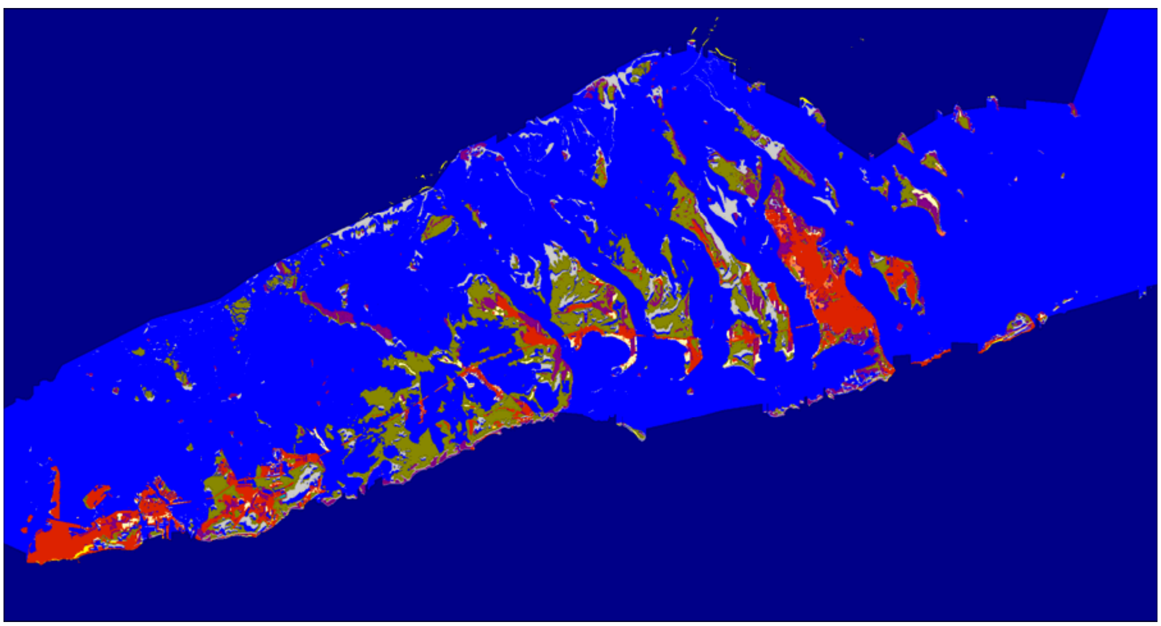
National Key Deer Context, 2075, Scenario A1B Mean



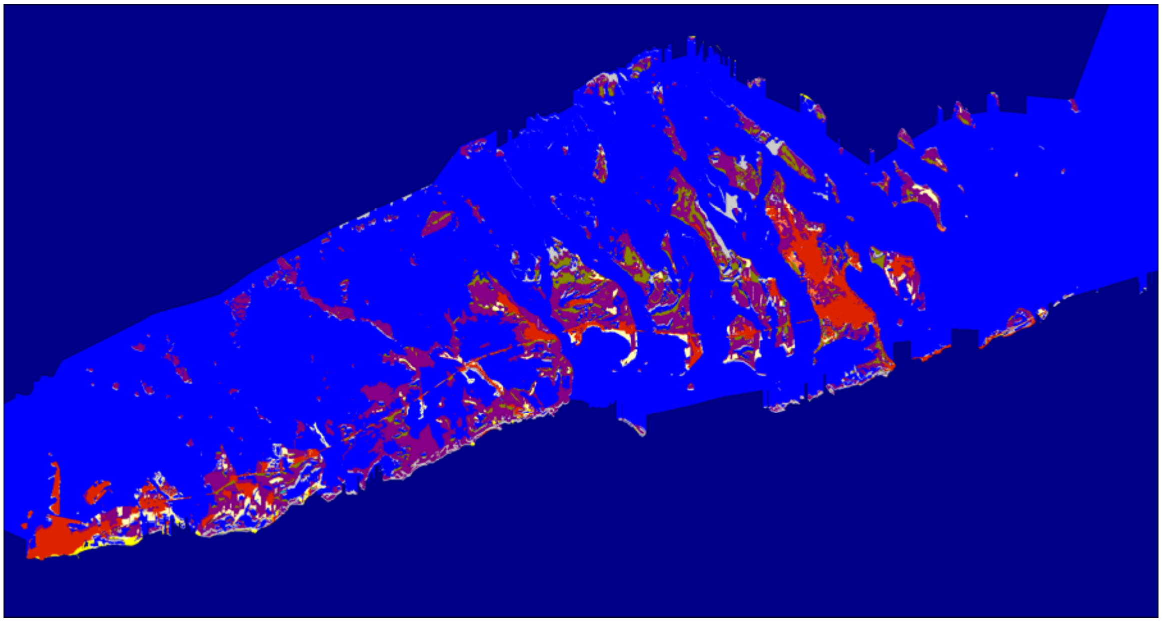
National Key Deer Context, 2100, Scenario A1B Mean



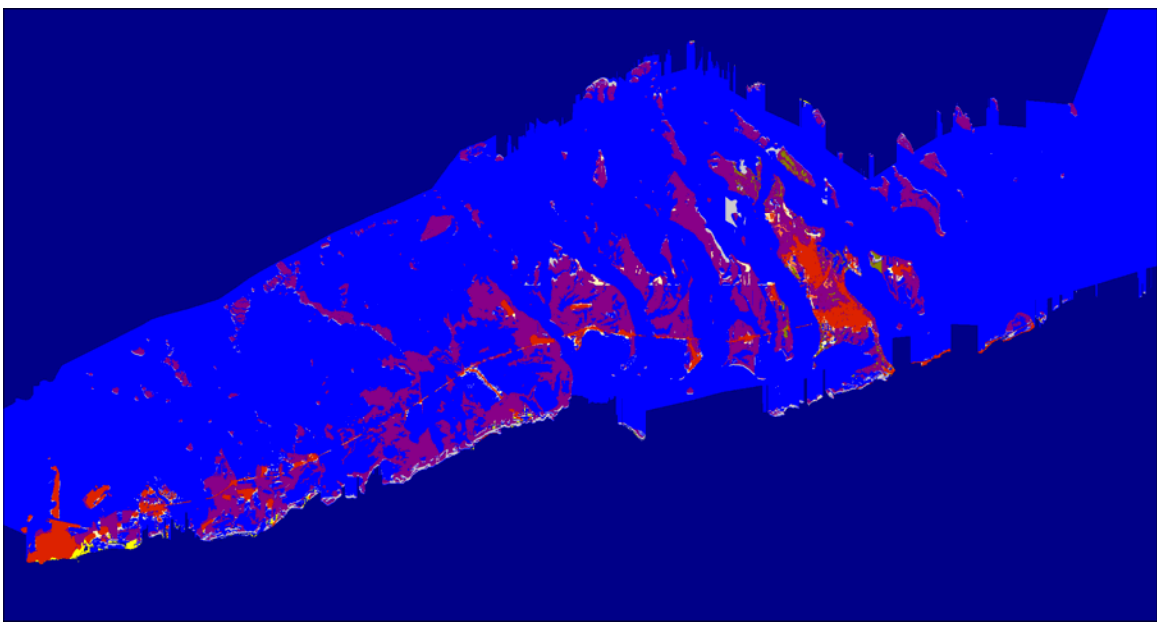
National Key Deer Context, Initial Condition Scenario A1B Maximum



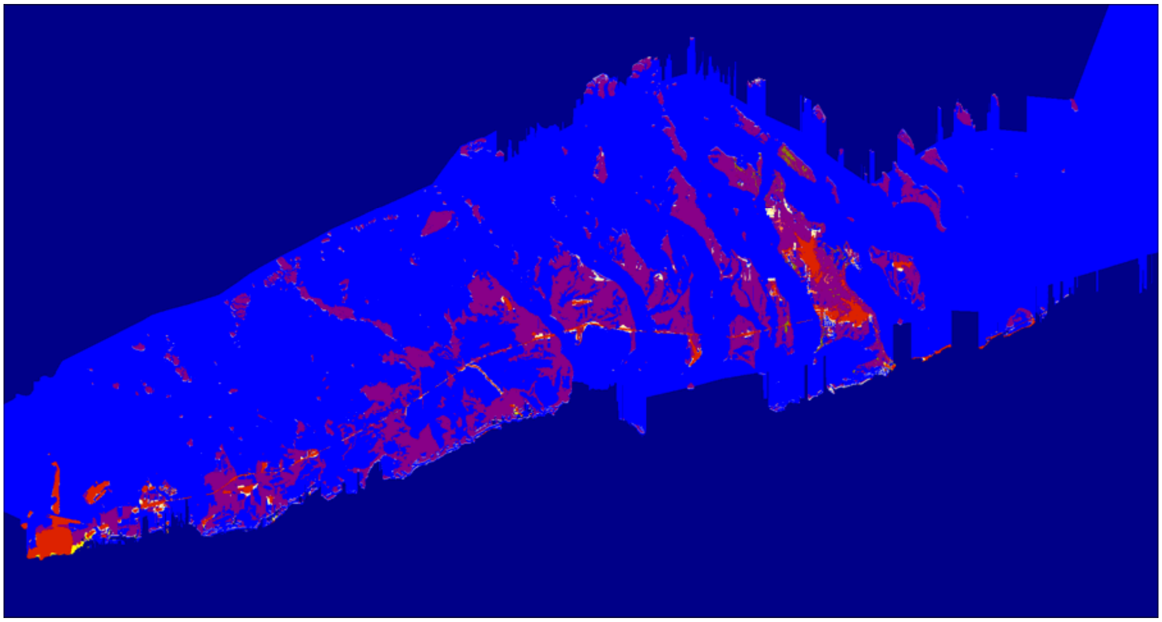
National Key Deer Context, 2025, Scenario A1B Maximum



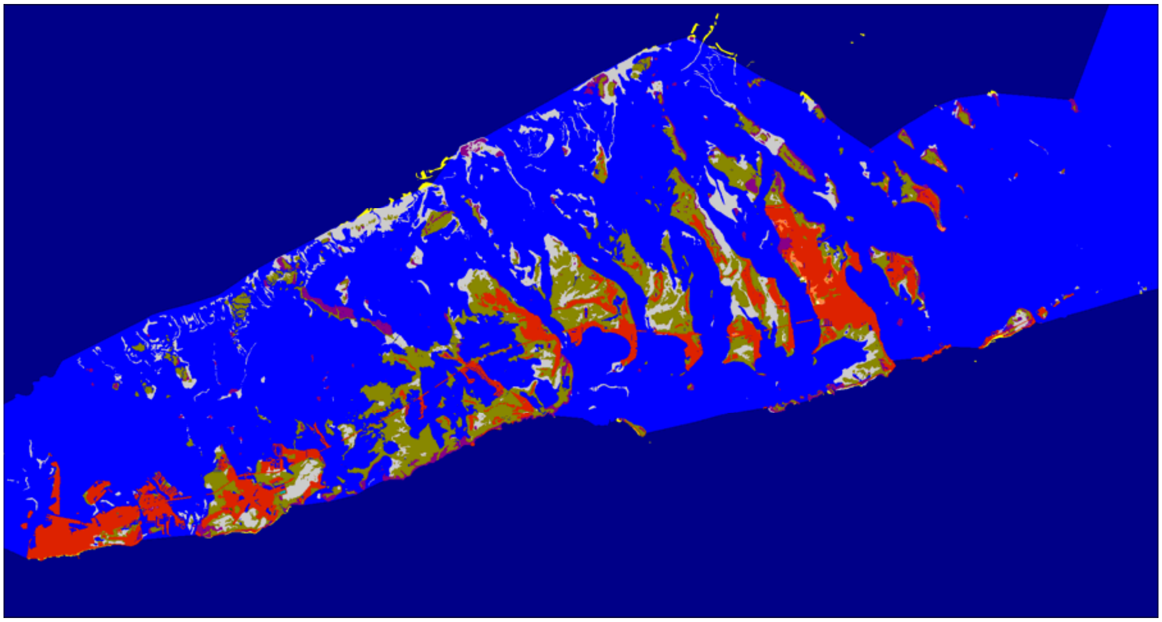
National Key Deer Context, 2050, Scenario A1B Maximum



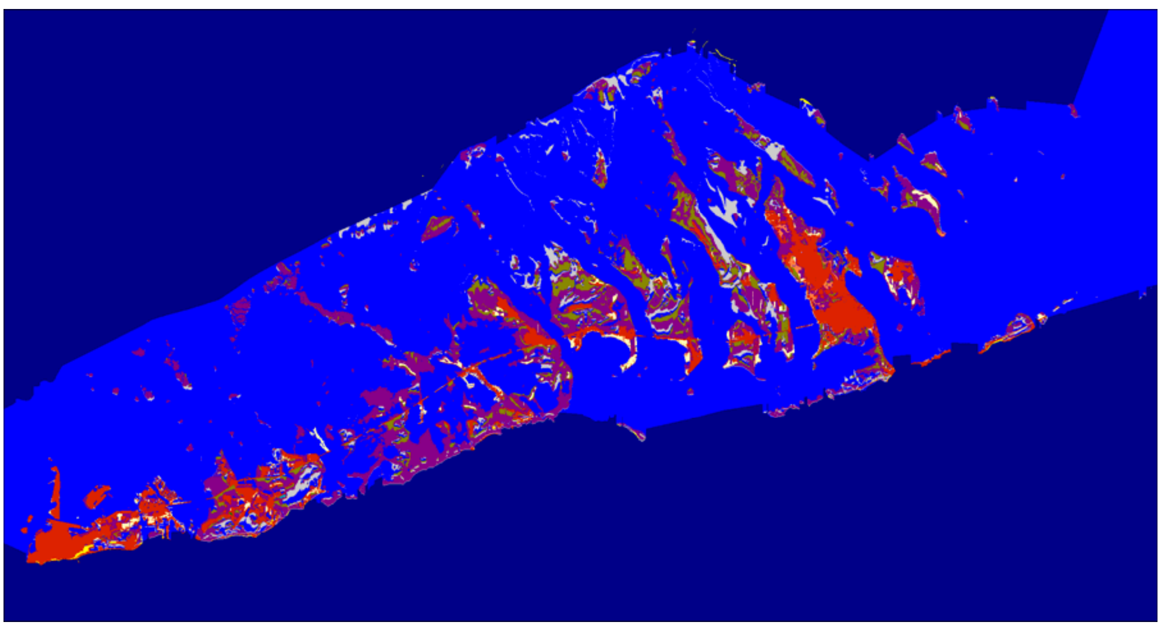
National Key Deer Context, 2075, Scenario A1B Maximum



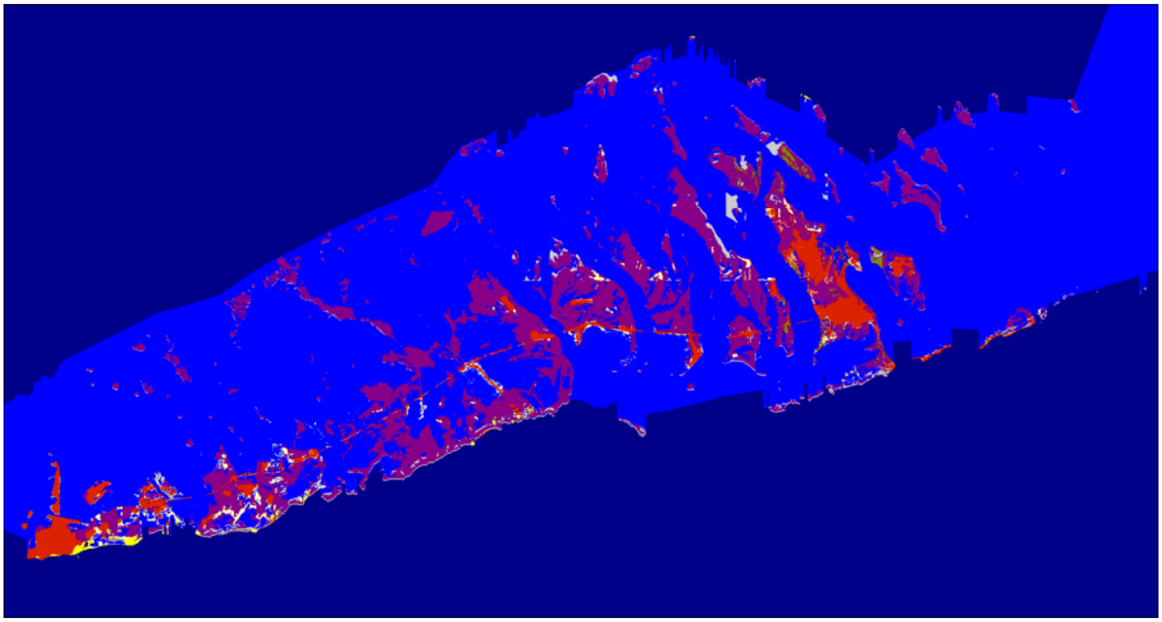
National Key Deer Context, 2100, Scenario A1B Maximum



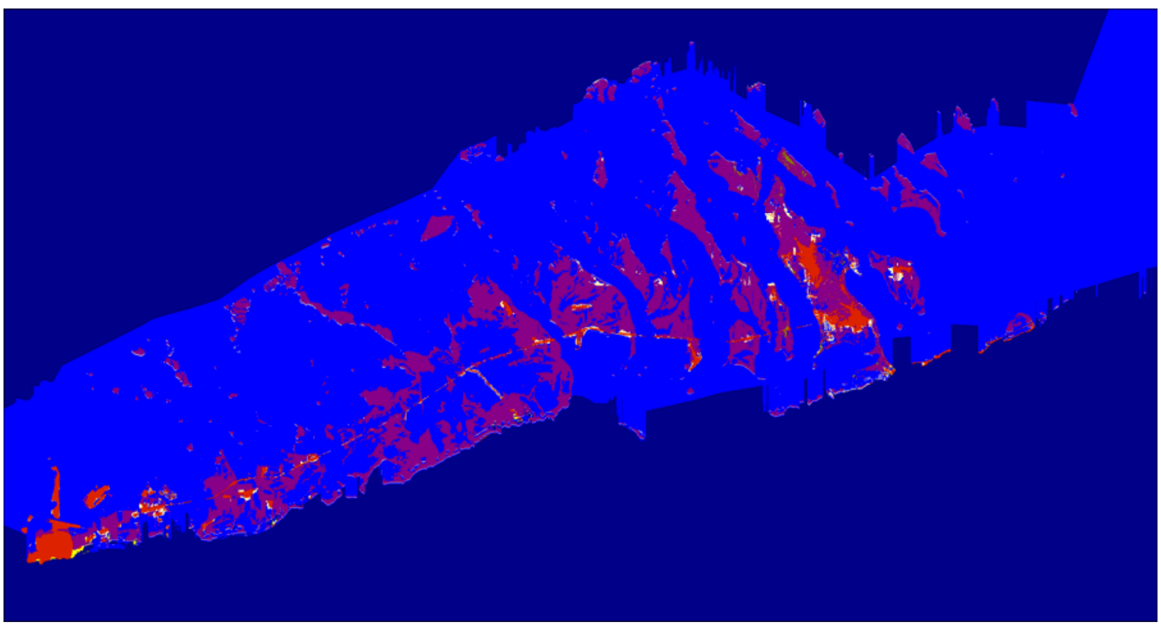
National Key Deer Context, Initial Condition



National Key Deer Context, 2025, 1 meter eustatic SLR by 2100



National Key Deer Context, 2050, 1 meter eustatic SLR by 2100



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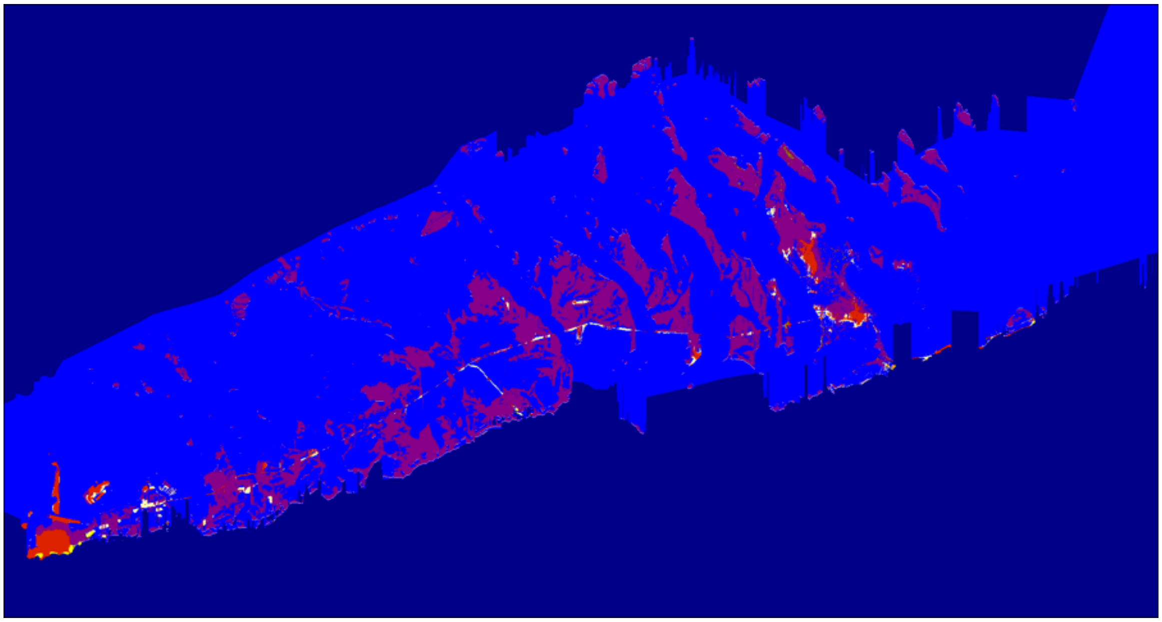
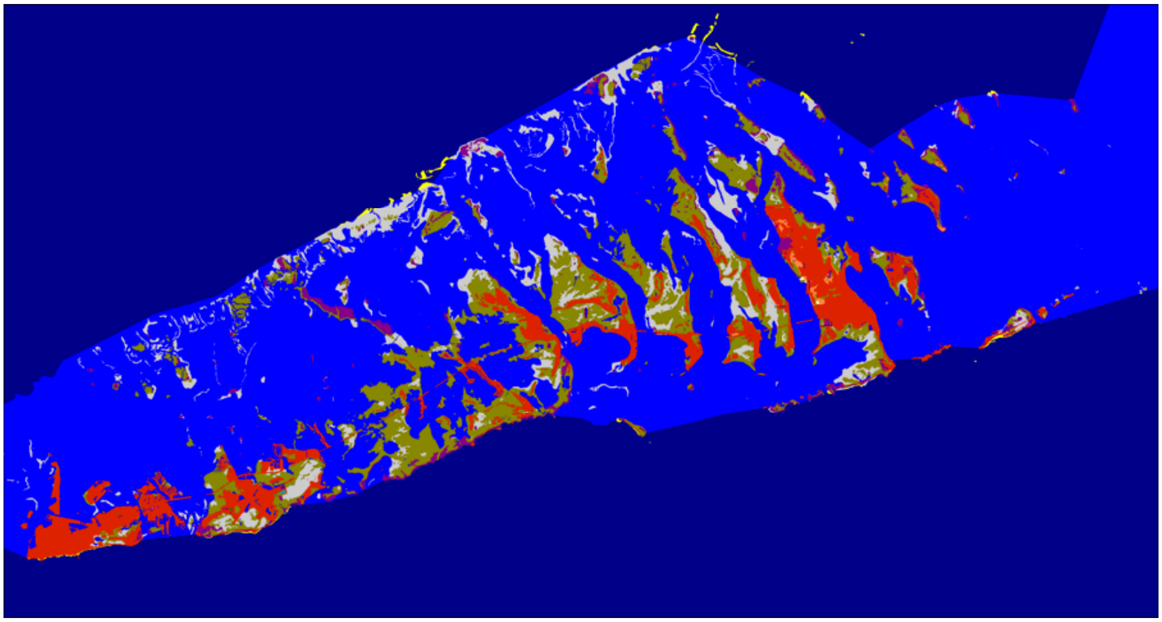
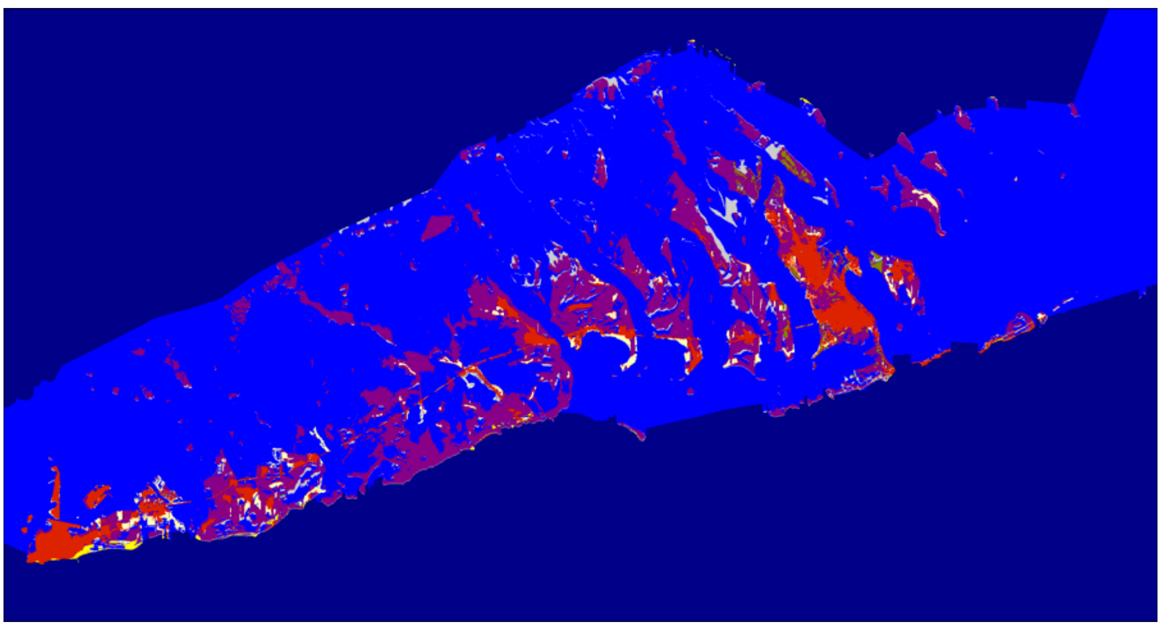


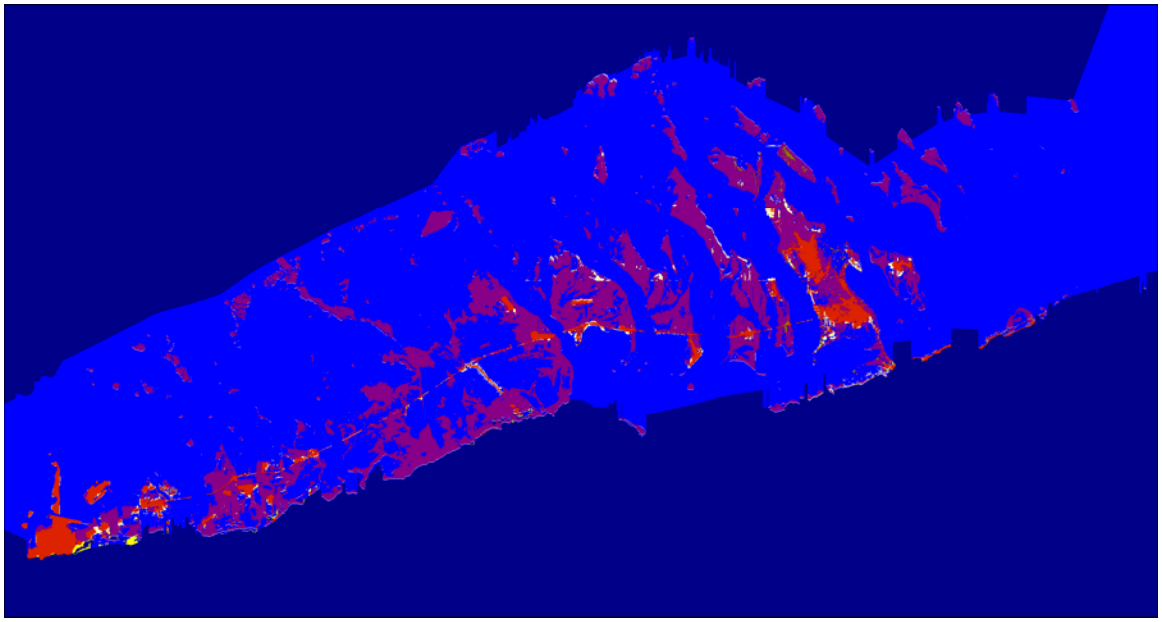
National Key Deer Context, 2100, 1 meter eustatic SLR by 2100



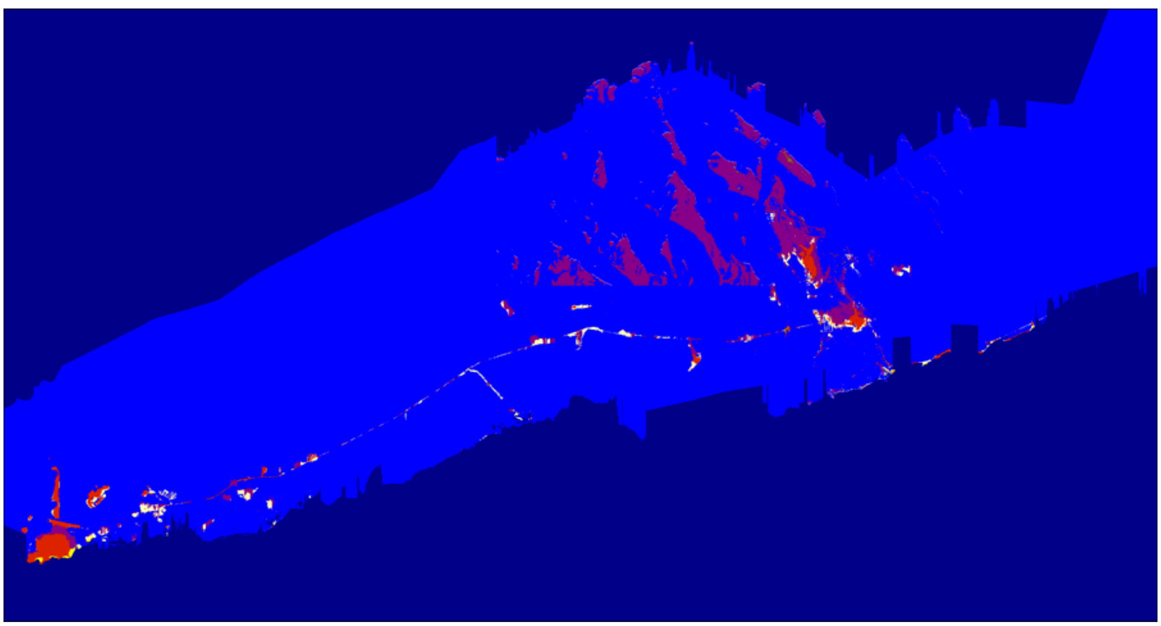
National Key Deer Context, Initial Condition



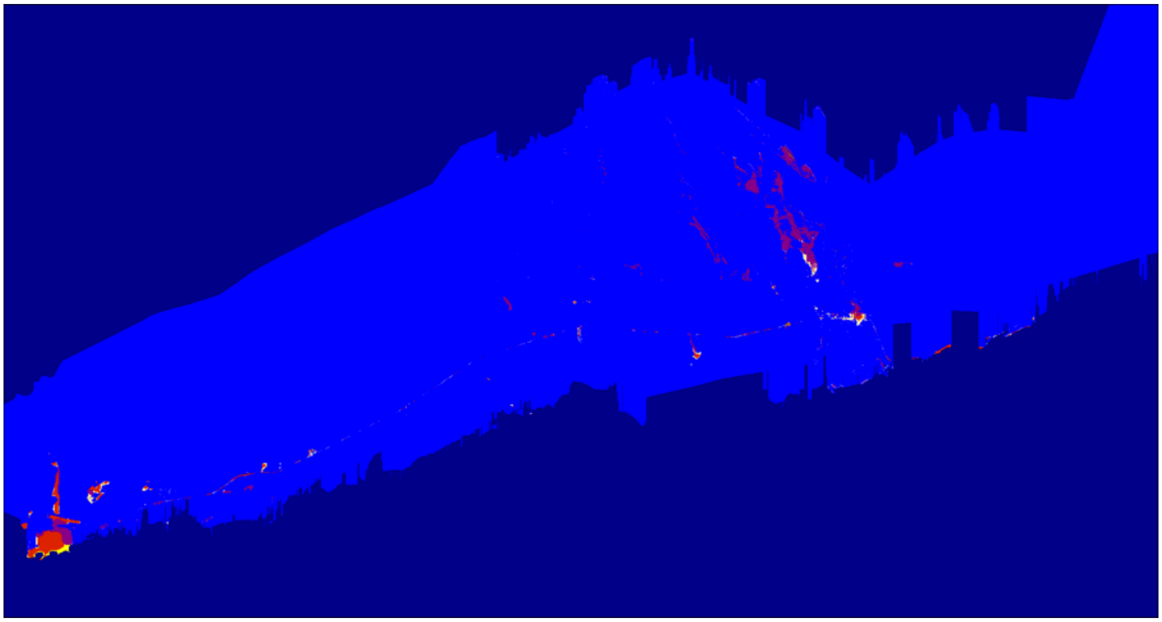
National Key Deer Context, 2025 1.5 Meters Eustatic by 2100



National Key Deer Context, 2050 1.5 Meters Eustatic by 2100



National Key Deer Context, 2075 1.5 Meters Eustatic by 2100



National Key Deer Context, 2100 1.5 Meters Eustatic by 2100