Using InVEST to Model Coastal Blue Carbon in Port Susan Bay, Washington

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List of Abbreviations

AOI – area of interest

CBC – coastal blue carbon

CO_2-eq – carbon dioxide equivalents

GHG – greenhouse gases

LiDAR – Light Detection and Ranging

LULC – land use/land cover

MSA – marine stewardship area

PSB – Port Susan Bay

QAQC – quality control/quality assurance

SLAMM – Sea-Level Affecting Marshes Model

SLR – sea level rise

TNC – The Nature Conservancy

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1. Recommended Course of Action

The focus of this project was to work with The Nature Conservancy (TNC) to model the impact of sea level rise (SLR) on the Port Susan Bay (PSB) Preserve in the Stillaguamish River Estuary in Washington State. To model this impact we applied the InVEST coastal blue carbon (CBC) model, developed by the Natural Capital Project. This not only represents the first application of this model in the Puget Sound region, but is also the first documented case study of this model in the Pacific Northwest. TNC's primary purpose for proposing this project was to determine if this model's robustness and results could be supported within the scientific community for use as a strategic conservation tool.

The main goal of this project was to assess the utility of the InVEST CBC model to adequately account for carbon stocks, sequestration, and emissions under a 1m projected SLR and alternative land use/land cover (LULC) change scenarios in the PSB Preserve. The results from the model are compiled to document how climate change and SLR impact the ability of coastal habitats to sequester carbon over time. The intent is that these results will allow TNC to make informed, science-based strategic planning decisions that could be applied to shape future policy and land management decisions in the region, in addition to enable ways to measure the outcomes of these decisions. The model results could also be used to optimize funding opportunities for future research and habitat restoration projects.

Our objectives to achieve this goal were to 1) learn the inner workings of the CBC model, 2) communicate a thorough internal understanding of the model to TNC, and 3) document the CBC model results to enable TNC's assessment of this model's potential applicability across Puget Sound coastal ecosystems for use as a strategic conservation planning tool.

Our recommendations moving forward are to 1) devote additional time to researching model input parameters and re-running the CBC model for the PSB Preserve with best available data, 2) perform sensitivity analyses on model input parameters where a high level of uncertainty exists, 3) apply the CBC model to the Snohomish River Estuary to validate the CBC model results against the findings of Crooks et al. 2014, and 4) as funding is available, support the development and execution of blue carbon capacity monitoring plans at the Port Susan Bay Preserve.

If it is determined that the CBC model is able to defensibly analyze coastal habitat impacts from SLR, TNC would likely create a scope of work to expand this project and apply the model to multiple coastal areas within the Puget Sound. This would provide a regional analysis of the future potential of coastal habitats to sequester carbon in the face of climate change and the threat of SLR. We provide a detailed business case for project expansion at the end of this report.

2. Introduction

2.1. Problem Statement

Atmospheric concentrations of greenhouse gases (GHGs) (carbon dioxide, methane, and nitrous oxide) are at levels unprecedented in the last 800,000 years (IPCC 2013). Driven primarily by fossil fuel emissions and secondarily by net land use change emissions, carbon dioxide concentrations have increased by 40% since pre-industrial times (IPCC 2013). Of all GHG emissions, 44% is absorbed by the atmosphere, 26% by terrestrial forests and 30% by the oceans (Wilson 2012). 70% of long-term marine carbon storage occurs in vegetated coastal areas (Nellemann et al. 2009) yet it has been estimated that over 67% of coastal wetlands have been lost during human history (Gedan et al. 2009). Losing area in these ecosystems means releasing both the carbon that is already stored as well as losing the future potential to store more carbon. Both the carbon storage potential of these ecosystems and the risk of substantially increasing global GHG emissions by releasing these vast carbon reserves via land conversion or other disturbances to these systems has, until recent years, been relatively unappreciated (Pendleton 2012). The critical need to address the challenges of climate change has motivated a recent focus on the role that coastal ecosystems play in the carbon cycle.

'Blue carbon' refers to the carbon that is stored in the biomass and sediments of tidal marshes, mangroves and seagrass beds. These coastal ecosystems sequester substantial amounts of carbon per unit area; orders of magnitude greater than that which is stored in terrestrial forests on a per unit area basis (McCleod et al. 2011). Globally, tidal marsh, mangrove and seagrass bed ecosystems cover approximately 49 million hectares but it is estimated that, at current conversion rates, nearly 100% of mangroves and 30-40% of tidal marshes and seagrass beds could be lost in the next 100 years (Pendleton 2012).

SLR plays an important role in the natural cycle of tidal marshes by contributing to sediment delivery and the geologic development of tidal marshes (Gedan et al. 2009). As sea level rises, marshes respond with a process called accretion: the vertical growth of the marsh as organic and inorganic sediments are deposited onto the marsh during inundation as well as when salt marsh plants grow and decompose (Schuerch et al. 2012). The balance between the rate of SLR and that of accretion is critical to the persistence of tidal marshes. In the period 1901 to 2010, global mean sea level increased by 0.19m (IPCC 2013). The IPCC Fifth Assessment Report on Climate Change (IPCC 2013) reports that since the mid-19th century, the rate of SLR has been larger than the mean rate during the previous two millennia. As rates of SLR accelerate, the concern is that this rate will overtake that of the accretion and result in the loss of tidal marshes to submergence.

2.2. Project Goals, Objectives and Scope

The main goal of the this project is to assess the utility of the Natural Capital Project's InVEST CBC model to adequately account for carbon stocks, sequestration, and emissions under scenarios of SLR and LULC change in Port Susan Bay, Washington. The results produced by this modeling effort are presented herein with the objective of enabling TNC to assess the utility of the CBC model as a strategic conservation tool to aid in prioritizing habitat preservation and restoration. This project is at the forefront of blue carbon modeling work being done in Washington State and we are relying on existing and future blue carbon research, particularly in the Puget Sound, to inform, calibrate, and validate the InVEST CBC modeling efforts.

The deliverables of this project are 1) to provide TNC Washington Chapter with a thorough internal understanding of the CBC model, 2) compile a series of maps and summary tables to demonstrate what future projections of SLR in PSB Preserve look like, 3) provide a recommended course of action to TNC in regards to the usefulness and effectiveness of the InVEST CBC model after this initial phase of scenario modeling, 4) provide a literature database of recent blue carbon and salt marsh ecology resources, and 5) provide a data package of model input and output data as well as the custom ArcGIS Toolbox tools developed for this project.

2.3. Study Area

Our project study area is Port Susan Bay in the Stillaguamish River Estuary (hereafter, estuary) in northern Puget Sound, WA. Port Susan Bay is bounded by the Snohomish County shoreline on the east and by Camano Island to the north and west. The Stillaguamish River, draining approximately 700 square miles and discharging on average 3,700 cfs into Port Susan Bay annually, is the fifth largest tributary to Puget Sound (Heatwole 2006). The Stillaguamish River Estuary historically included 1,120 ha of estuarine emergent wetlands, 1,190 ha of shrub-scrub wetlands, and 2,010 ha of floodplain forests (Collins 2000). Over the 19th and 20th centuries these habitat areas were significantly reduced through diking and land conversion to agricultural use (Collins 2000). In 2001, The Nature Conservancy acquired a 4,122 acre property in the estuary known as the Port Susan Bay Preserve and works actively to monitor, restore and conserve the remaining estuary habitat. This preserve boundary serves as the focal area of our project (Figure 1).

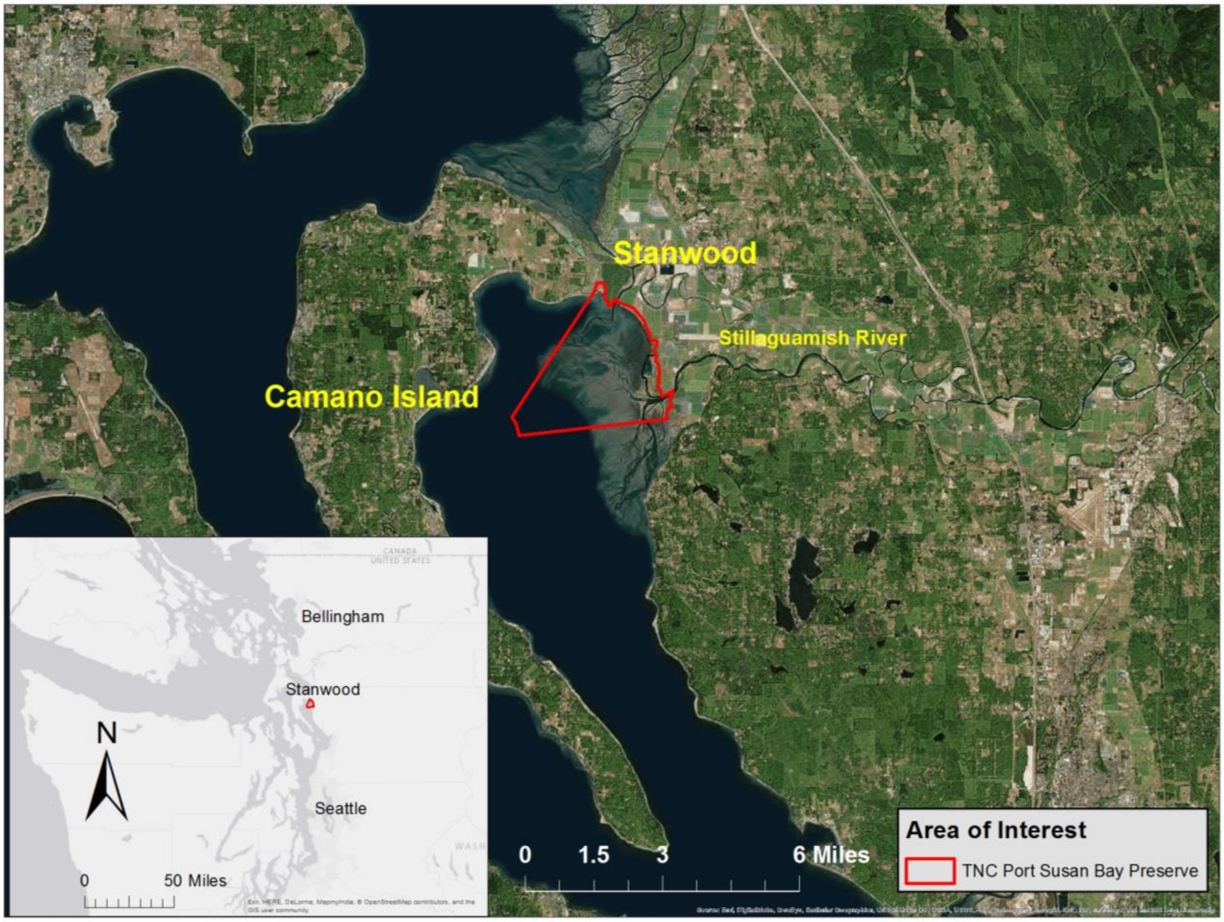

Figure 1 Port Susan Bay Preserve located in the Stillaguamish River Estuary near Stanwood, WA.

2.4. Social-Ecological System

The marshes, mudflats and tidally influenced channels of Port Susan Bay are well-recognized for their ecological importance; these habitats support thousands of birds, smelt, several at-risk salmon species, English sole and clams (TNC 2015). Port Susan Bay is part of Washington Audubon's Western Lowlands Important Bird Area and can support over 20,000 shorebirds within one season (Cullinan 2001). In addition to providing habitat for an array of species, salt marshes produce some of the most valued ecosystem services among natural environments including coastal protection, water purification, erosion control, habitat, food production, raw materials, recreation and carbon sequestration (Costanza et al. 1997; Barbier et al. 2011). Recently, in the face of intensifying global climate change, the carbon sequestration potential of salt marshes has gained increased recognition.

This coastal ecosystem, also referred to as "coastal fringe habitat", plays two very important roles in the global carbon cycle - carbon sequestration and carbon storage. Carbon sequestration is the process of capturing carbon dioxide from the atmosphere in biomass and soil carbon pools and is measured as a rate of carbon uptake per year. Carbon storage is the long-term confinement of carbon in plant materials and sediments and is measured as total weight of carbon stored. These ecosystems remove carbon dioxide (CO_2) from the atmosphere via photosynthesis, return some to the atmosphere through respiration and oxidation, and store the remaining carbon in two pools 1) living biomass (both aboveground and belowground vegetation) and 2) soil organic carbon (Figure 2). Because these intact ecosystems typically have mature vegetation that maintain a steady biomass, nearly all the sequestration ends up buried in the soil carbon pool (Murray et al. 2011). Coastal wetland ecosystems have the capability of storing large amounts of carbon for two reasons 1) their vegetation grows rapidly each year and sequesters large amounts of CO_2 in the process and 2) their soils are largely anaerobic (without oxygen) so carbon that gets incorporated into the soils decomposes very slowly and can persist for hundreds or even thousands of years.

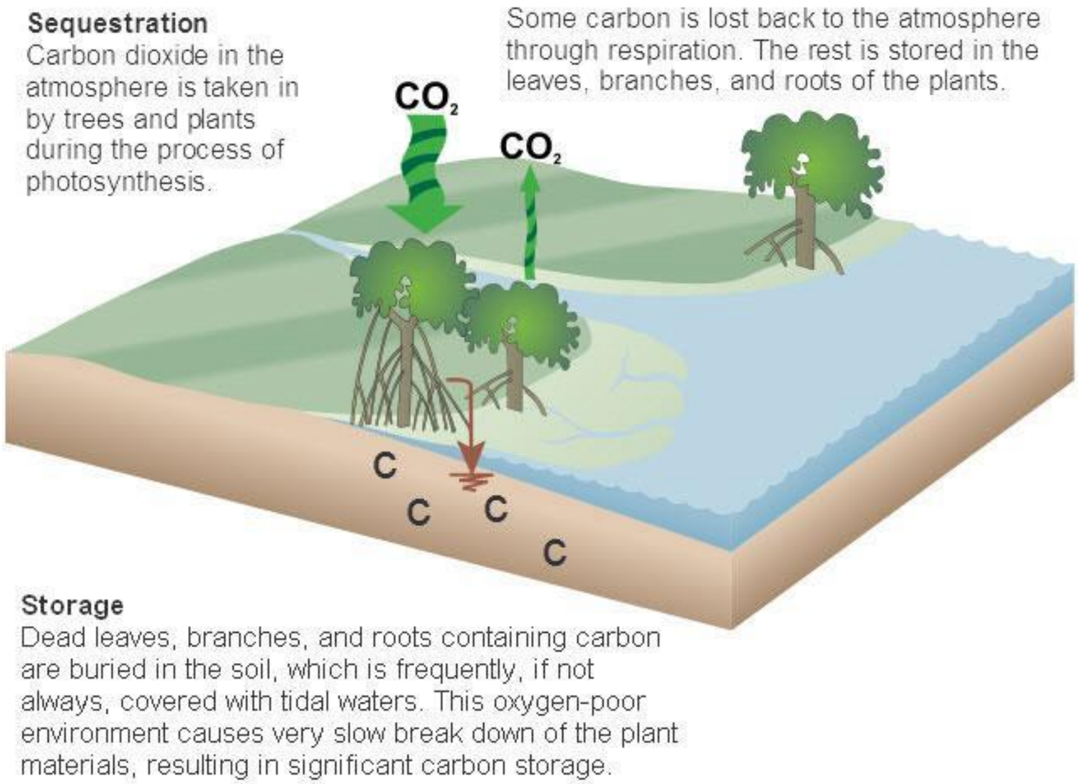

Figure 2 A diagram detailing the mechanisms by which carbon moves into and out of coastal wetlands (NOAA Habitat Conservation, http://www.habitat.noaa.gov/coastalcarbonsequestration.html)

The social-ecological systems table (Table 1) addresses the biophysical, economic, and social domains over different focal areas. The focal area incorporates PSB, while the Puget Sound is the scale above and the salt marsh area within PSB at the scale below. Coastal habitat areas (marshes) are the main theme throughout all the state planes. Identified within each domain is the importance of salt marshes concerning the ecology, economy, and social/cultural aspects of this region.

Table 1 Social-ecological system table featuring Port Susan Bay, Washington.

Scale	Biophysical	Economic	Social
Scale Above Focal Area: Puget Sound	**Sea level rise will have drastic impacts within the Puget Sound. Critical habitat loss will occur resulting in flora/fauna population and diversity decline, less ability of land cover to limit storm surge/impact, and disrupt ecosystem function. Additionally, the ability of these at risk habitat types to sequester carbon will greatly be diminished, resulting in a potential increase in carbon release before it reaches its half-life and also reducing the amount of habitat that could sequester carbon.**	**Storm size and damage will increase due to climate change and sea level rise. This is have a large impact on the economy resulting from property value decline, job loss and decreased revenue. With ecosystems and habitats in poor health, recreation and tourism will certainly decline. If carbon credits are incorporated into our economy, local/state jurisdictions may be responsible for payment due to loss of habitat to sequester carbon.**	**Puget Sound is rich in cultural and recreational opportunities, which are evident at all scales. Native Americans inhabited this region over 150 years ago with over 50 tribes. They used the water to navigate, fish, and transport goods. The hunted the upland areas to feed their family. In the modern day, this region is highly dependent on recreational and tourism opportunities. These range from boating/sailing, fishing, exploring, and enjoying the scenic beauty. Most of these cultural and recreational opportunities are threatened by sea level rise.**
Focal Area: Port Susan Bay	**Sea level rise in Port Susan Bay will result in a reduction in tidal flats and marshes. The loss of these habitats will result in a higher water temperature, decrease in water quality, and increase in sedimentation especially during storm events. This will have significant impacts on salmon populations and also impact bird populations that rely on this area for food and shelter. Additionally, carbon sequestration will decline.**	**Storm surge could destroy the diking system and in turn ruin productive farmland. The farm community will be largely impacted, resulting in job and revenue loss for the region. Estuary stream channels and vegetation (sea grass) will also be destroyed. This habitat loss will greatly impact fish, shellfish, and bird populations. Combined with the decline of recreation and tourism, sea level rise could be catastrophic to this area and region.**	
Scale Below Focal Area: Port Susan Bay Salt Marshes	**TNC Preserve will observe a significant decrease in amount of habitat, primarily as tidal flat and salt marshes. Water quality is will decrease while sedimentation and water temperature will increase. Salt marshes are one of the best habitat types when it comes to carbon sequestration in this region. With PSB salt marshes unable to migrate to higher elevations to compensate for sea level rise, the amount of carbon sequestration taking place at this scale will decline.**	**Salt marshes provide habitat for sea life, filter fresh water, and protect near shore areas from storm surges. With sea level rise coupled with the inability for the marshes to migrate, we will soon lose the benefits provided by the marshes. This will have a negative impact on the local economy ranging from reduced salmon populations, recreation/tourism opportunities, to property damage.**	

3. Design & Methods

3.1. InVEST Coastal Blue Carbon Model: How it Works

For this project we used the InVEST CBC model, version 3.0.1, to quantify the value of carbon storage and sequestration services provided by coastal ecosystems by analyzing changes in carbon storage over time in response to LULC changes and comparing this across alternative management scenarios. These LULC changes are then classified as accumulation or disturbance in the form of a transition matrix. This model produces spatially explicit outputs on net sequestration, net present value of avoided emissions, carbon stock and gain/loss information on the modeled landscape over time (Sharp et al. 2014). The CBC model can be used to analyze disturbances to vegetation caused by climate change and human activities, which is important for prioritizing conservation strategies and managing resources.

The CBC model is comprised of two separate tools: 1) the blue carbon pre-preprocessor and 2) the blue carbon calculator. The pre-processor tool creates a transition matrix that is the result of the changes in LULC over a user-defined time period. The blue carbon calculator quantifies carbon storage across the landscape by using LULC maps for multiple years and uses a simplified carbon cycle approach by summing the carbon stored in four carbon pools – above- and below-ground biomass, litter and soil – and the rate of annual carbon accumulation in the sediments and biomass. The CBC model tracks the carbon cycle through a bookkeeping-type approach and requires users to provide land cover maps of coastal ecosystems that store carbon (i.e., mangroves, seagrasses and salt marshes) (Sharp et al. 2014). If local carbon data values are unavailable, users can draw on the global database of values for carbon stocks and accumulation rates sourced from the peer-reviewed literature that is included in the model. Data from field studies or other local sources should be used instead of global values when available. In summary, the land cover maps represent changes in human use patterns in coastal areas or changes to sea level, and are used to estimate the amount of carbon loss (emissions) or gain (sequestration) over a specified period of time. The model then quantifies carbon storage across the land by summing the carbon stored in the four carbon pools mentioned above.

3.2. Preparing Data Inputs: LULC, Carbon Stocks, Transition Matrix and Default Values

The InVEST CBC model requires biophysical inputs including spatial and tabular data in the form of rasters and CSV files. Economic inputs are optional if the user is interested in modeling the monetary value of carbon sequestration. Global carbon values are included in the model as default data and should be replaced when local data is available. The required model inputs and data needs can be found in more detail in the InVEST CBC user manual (Sharp et al. 2014). Data inputs for the Port Susan Bay Preserve study site were acquired through a recent blue carbon study conducted in the Snohomish River Estuary (Crooks et al. 2014), extensive literature searches and the global default values provided by InVEST. When possible, we used the best available local data for our study area.

3.2.1. LULC Data: SLAMM

After consulting with TNC we settled on using data outputs from the Sea Level Affecting Marshes Model (SLAMM) developed by Warren Pinnacle Consulting Inc. (Clough and Larson 2010). This model simulates the dominant processes involved in wetland conversions and shoreline modification during long-term SLR. Map distributions of wetlands are produced and projected under conditions of accelerated SLR. Results are then summarized in tabular and graphical form (Clough and Larson 2010). In 2009, TNC funded work that applied SLAMM in Port Susan Bay, Washington. This application utilized 5x5 meter cells and was run on several remediation scenarios to examine changes in dike placement, flow regimes and potential marsh predation by snow geese that covered an area of approximately 35,000 hectares. SLAMM classified land cover into 23 habitat types, 14 of which are represented in our study area (Figure 3).

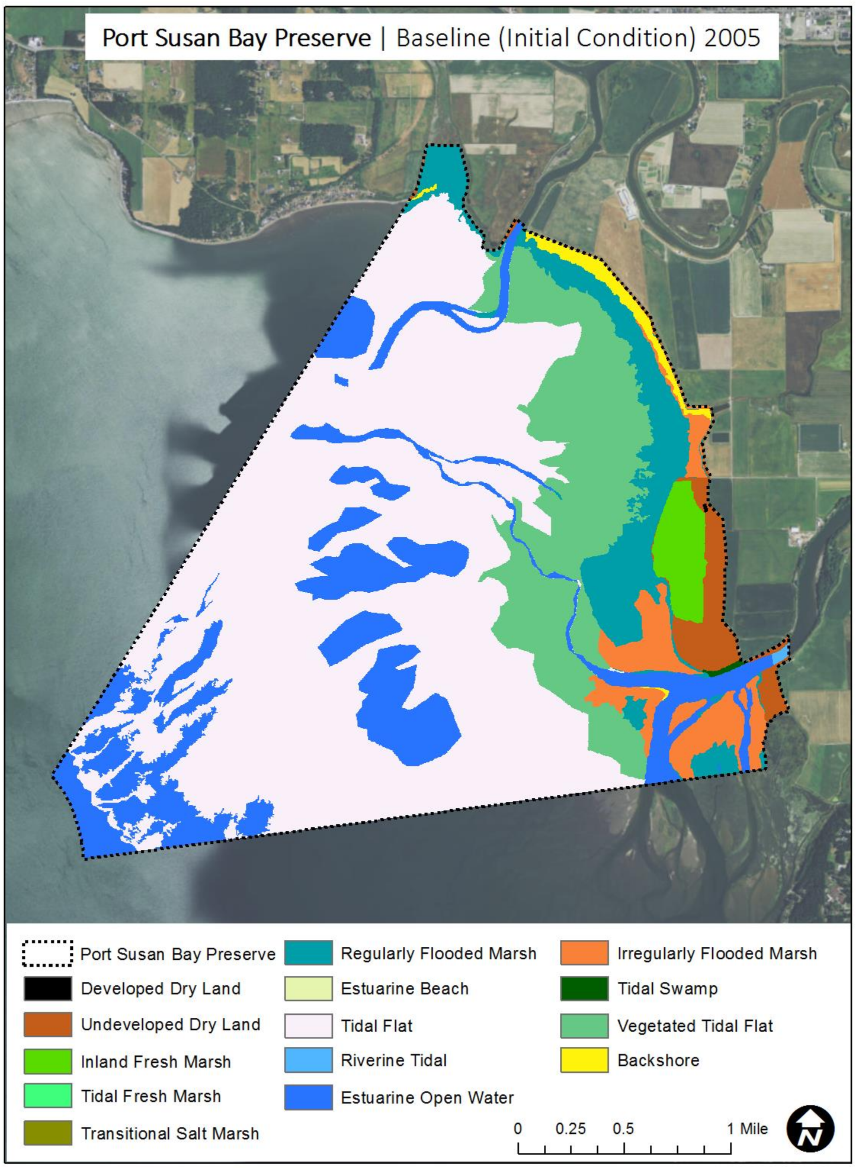

Figure 3 Port Susan Bay Preserve SLAMM land cover categories representing initial condition in 2005.

Scenarios

In Port Susan Bay, SLAMM was run using four SLR scenarios (0.34m, 0.59m, 1.0m and 1.75m), a baseline (current condition) scenario and five alternative management (remedial) scenarios. Each simulation was run for a time period spanning 2005 to 2100 to produce LULC maps for the years 2025, 2050, 2075 and 2100. The five remedial scenarios were Restoration 2, Restoration 3, Restoration 4, Snow Geese and Low Flow (refer to Clough and Larson 2010 for details of these scenarios).

Based on conservation priorities identified by TNC, we focused CBC modeling efforts on the 1m projected SLR scenario for the remedial baseline, snow geese, and restoration 2 (hereafter referred to as "restoration") scenarios. The baseline scenario is the initial LULC conditions from the year 2005. The snow geese scenario includes 240 acres of restored marsh based on existing TNC projects *and* assumes that snow geese will remove most of the low marsh zone within the next few years, effectively converting 85% of this habitat type into vegetated tidal flats. The restoration scenario includes the restoration of 240 acres of marsh based on existing TNC projects and is represented as the current LULC conditions minus a small area in the northern part of the estuary. All scenarios were run on the simulation period of 2005-2100. The primary reason for running both the snow geese and restoration scenarios was to isolate the benefits of restoration in the absence of compounding pressures (i.e., consumer control by snow geese and SLR). The presence of snow geese in the PSB Preserve is considered to negatively impact the marsh by reducing resilience due to pressure from both SLR and the overuse of a small amount of existing habitat by snow geese (Gedan 2009; Jamie Robertson TNC, personal communication, August 11, 2015). All three scenarios were run using a single set of parameters based on habitat conversions that were ranked on a high/medium/low scale (see Transition Matrix). Figure 4 presents the SLAMM input LULC maps by scenario. See Article I.Appendix 1 for the full page representations of SLAMM input LULC maps.

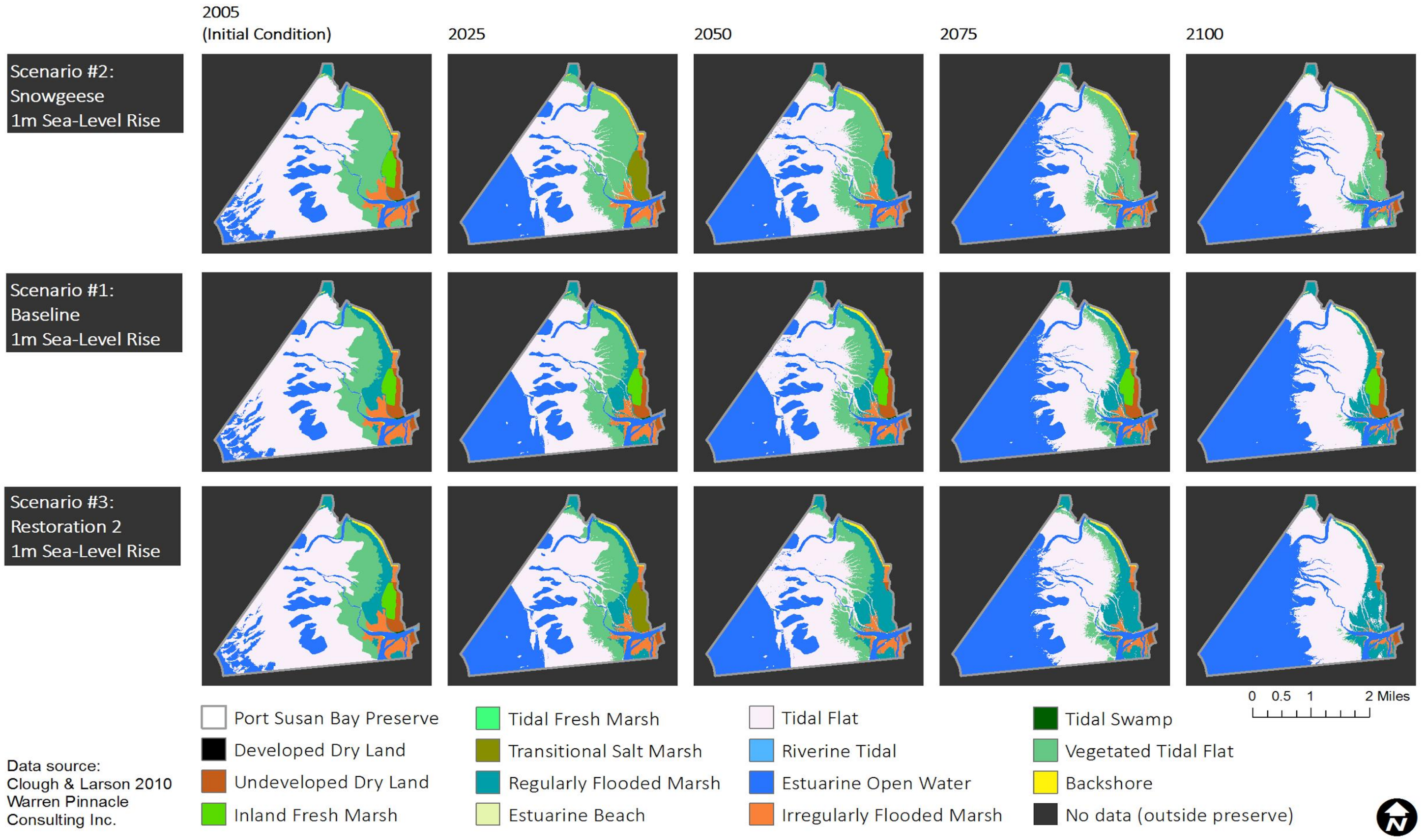

Figure 4 Side-by-side scenario and time step comparison of SLAMM input LULC maps (source data provided by Warren Pinnacle Consulting Inc.). See Article I.Appendix 1 for full-page maps of each scenario and time step.

Preparing SLAMM rasters

The CBC model requires two or more LULC maps representing current (t_1) and future (t_2) states of the land. These input rasters must meet the conditions specified in Table 2.

Table 2 CBC LULC map requirements and initial and final properties of the SLAMM rasters. Bold properties indicate a modification was necessary on the original SLAMM rasters.

CBC Model Condition	Initial Property	Final (Run-ready) Property
Matching projected coordinate systems	Undefined	**NAD 1983 HARN State Plane Washington North FIPS 4601 (Meters)**
Matching extents (top, left, right, bottom)	141477, 375776, 396061, 124042	141477, 375776, 396061, 124042
Matching cell size (X,Y)	5, 5	5, 5
NoData Value*	-9999	**256**

**National Capital Project developers recommended that this be a positive value greater than the highest LULC class value*

Three steps were performed to prepare the SLAMM rasters for input into the CBC model: 1) build raster attribute tables, 2) change the NoData value from -9999 to 256, and 3) define projection. Step 1 was not required to run the CBC model but was performed for quality assurance/quality control (QAQC) purposes and also to enable area calculations by LULC type. Step 2 was recommended by National Capital Project model developers. Step 3 was required in order to run the model; the SLAMM data was provided with an undefined spatial reference and through trial and error we identified NAD 1983 HARN State Plane Washington North FIPS 4601 (Meters) as the correct projection.

Scenario modeling often implies numerous input and output datasets – the SLAMM dataset was no exception. In total, the SLAMM data package included 120 potential input rasters for use by the CBC model: the baseline scenario and 5 remedial scenarios run against 4 sea-level rise scenarios with results output at 5 time steps. While we necessarily limited our analysis to the baseline, 2 remedial scenarios and 1 SLR scenario given available time, we anticipated the need for TNC to run these raster preparation steps multiple times if pursuing future work with the SLAMM data and CBC model. We created an ArcGIS ModelBuilder tool to enable batch preparation of SLAMM input rasters (Figure 5, Figure 6). A sample output log from running this tool in batch mode (Figure 7) to prepare the restoration scenario rasters is presented in Article I.Appendix 2.

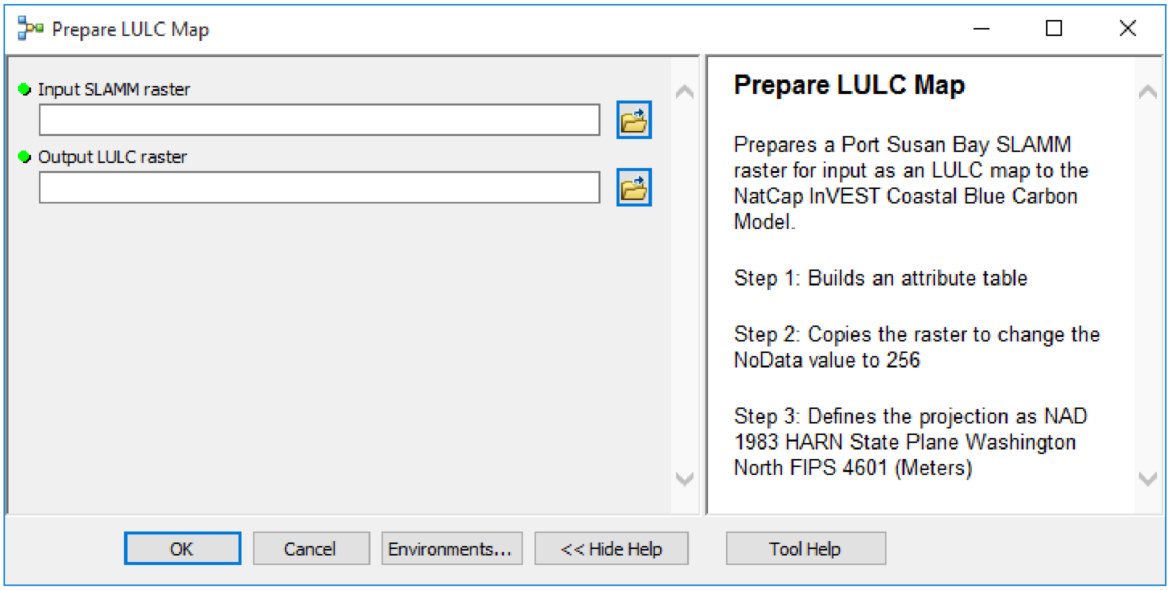

Figure 5 A custom-built ArcGIS tool for preparing SLAMM rasters as inputs to the InVEST Coastal Blue Carbon model.

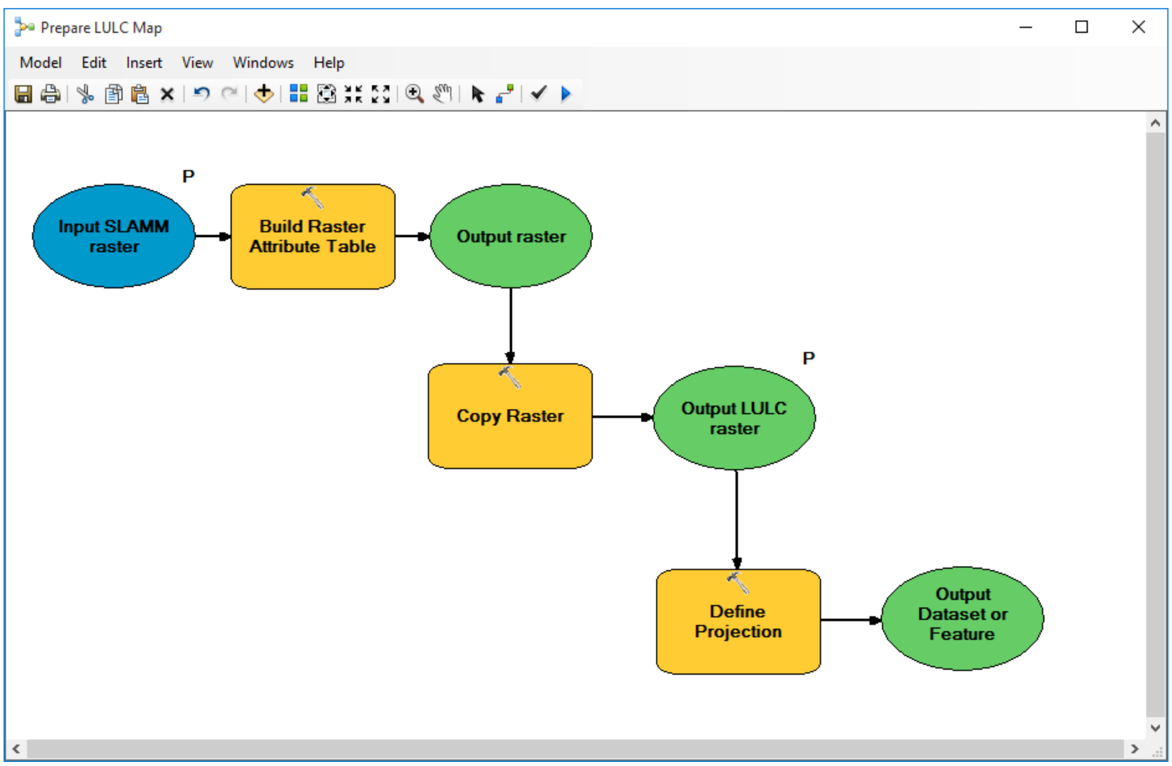

Figure 6 Model workflow for the Prepare LULC Map tool.

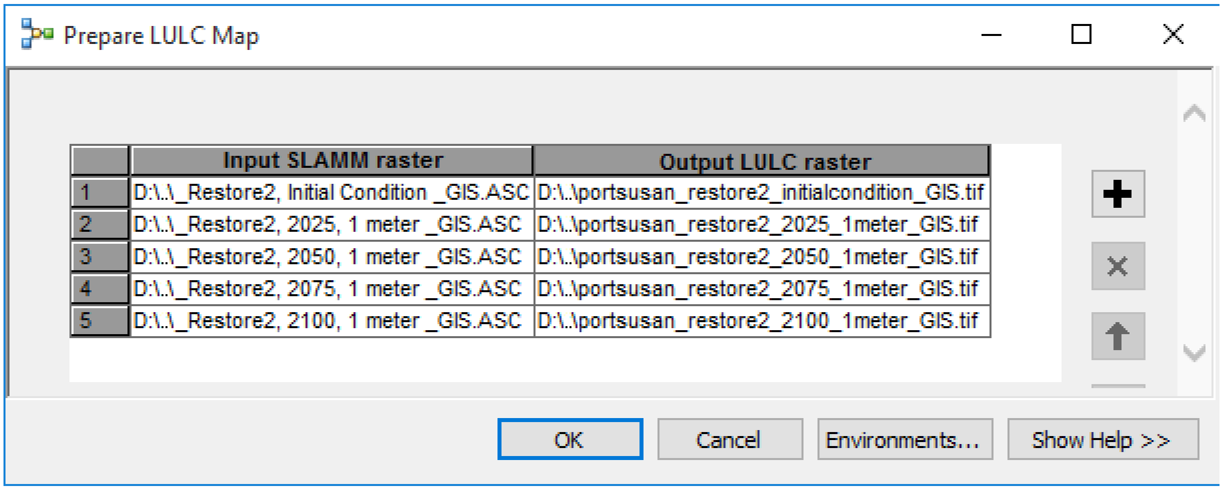

Figure 7 Batch interface of the Prepare LULC Map tool.

3.2.2. Carbon Data

User-defined input parameters for carbon data consist of carbon pool storage and accumulation rates, soil and biomass disturbance magnitude, and carbon decay rates. Both local and global values can be used for these inputs. Soil and biomass disturbance rates are the percentage of carbon that is lost as a result of the disturbance that occurs after LULC change. For example, higher impact disturbances will release 100% of the biomass and soil pools whereas a low impact disturbance might only cause the release of 50% of the biomass and 30% of the soil pool. These percentages are specified specific to vegetation types and come from an extensive literature review conducted by the Natural Capital Project (Sharp et al. 2014) and are available as default inputs. The user has the ability to modify inputs if they have better data available specific to their study area; in our case we used these default disturbance percentages. Carbon pool storage and accumulation rates are defined by the user based on each vegetation type that is classified in the SLAMM LULC raster. Local data was sourced from a recent blue carbon study conducted in the Snohomish River Estuary by Crooks et al. 2014. We chose to use the carbon data from a particular site in the estuary (Quilceda Marsh) as it was comparable to the PSB study area based on similar habitat types (estuarine emergent and estuarine shrub-scrub). In order to use these local values as input to the InVEST CBC model, we performed the conversion factors in Table 3. Global carbon pool input values were provided in the model as default values and sourced from peer-reviewed literature (Sharp et al. 2014). The carbon decay rate parameter is based on vegetation disturbance-specific to a 7.5 year carbon release rate and is based on a global literature review (Sharp et al. 2014).

Table 3 Conversion factors performed on local carbon data.

Carbon Pool	Original Value	Conversion Factor kg C/m^2	New Value	Conversion Factor Mg C/ha	New Value	Conversion Factor Mg CO2-eq/ha	Final Value Ready for InVEST CBC Input
Soil	7.17 kg C/m^2	none	None	x10	71.7 Mg C/ha	x3.67	263 Mg CO_2-eq/ha
Soil Accumulation Rate	110.2 g C/m^2/yr	x0.001	0.1102 kg C/m^2/yr	x10	1.102 Mg C/ha/yr	x3.67	4 Mg CO_2-eq/ha/yr

3.2.3. Transition Matrix

The transition matrix is the output table produced by the CBC pre-processor tool. The pre-processor tool compares the LULC input maps on a pixel by pixel basis and catalogs the entire set of LULC transitions that occur between t_1 and t_n. The result of the pre-processor tool is a matrix with the full list of LULC classes as rows and columns (Appendix 3). The inner cells of this matrix contain values of "None", "Accumulation" or "Disturbance". "None" indicates that the transition between LULC types did not occur across any of the LULC maps. "Accumulation" indicates that an LULC class with carbon storage potential persisted between time steps (for example, a salt marsh pixel that remains a salt marsh pixel across all time steps). "Disturbance" indicates that an LULC class with carbon storage potential was changed to a vegetated LULC class to a non-vegetated LULC class (for example, a salt marsh pixel that changes to developed dry land). This table must then be modified by the user before it can be input to the core CBC model. The user must change cells within the matrix containing the values "Disturbance" to either "Low Disturbance", "Medium Disturbance", or "High Disturbance" based on the intensity of impact on carbon for that specific LULC transition.

Table 4 presents the user-modified transition matrix table for the PSB Preserve model runs. An unformatted version of this table is available in Appendix 4.

Table 4 User-modified transition matrix table for the Port Susan Bay Preserve model runs.

	1 Developed Dry Land	2 Undeveloped Dry Land	3 Swamp	5 Inland Fresh Marsh	6 Tidal Fresh Marsh	7 Trans. Salt Marsh	8 Regularly Flooded Marsh	10 Estuarine Beach	11 Tidal Flat	15 Inland Open Water	16 Riverine Tidal	17 Estuarine Open Water	20 Irreg. Flooded Marsh	22 Inland Shore	23 Tidal Swamp	25 Vegetated Tidal Flat	26 Backshore
1 Developed Dry Land						Accumulation	Accumulation										
2 Undeveloped Dry Land						Accumulation	Accumulation									Accumulation	
3 Swamp						Accumulation	Accumulation						Accumulation				
5 Inland Fresh Marsh				Accumulation		Accumulation	Accumulation					Low Disturbance					
6 Tidal Fresh Marsh					Accumulation		Accumulation					Low Disturbance	Accumulation				
7 Trans. Salt Marsh						Accumulation	Accumulation		Medium Disturbance			Low Disturbance					
8 Regularly Flooded Marsh	High Disturbance	High Disturbance				Accumulation	Accumulation		Medium Disturbance			Low Disturbance	Accumulation			Accumulation	
10 Estuarine Beach																	
11 Tidal Flat							Accumulation									Accumulation	
15 Inland Open Water																	
16 Riverine Tidal																	
17 Estuarine Open Water																	
20 Irreg. Flooded Marsh							Accumulation		Medium Disturbance			Low Disturbance	Accumulation				
22 Inland Shore																	
23 Tidal Swamp							Accumulation						Accumulation				
25 Vegetated Tidal Flat									Medium Disturbance			Low Disturbance				Accumulation	
26 Backshore								Medium Disturbance				Low Disturbance					Accumulation

High Disturbance, Medium Disturbance, Low Disturbance, Accumulation, No Transition

We categorized conversion of vegetated classes to developed dry land and undeveloped dry land as high disturbance. Vegetated class conversion to estuarine beach and tidal flat were categorized as medium disturbance. Conversion from a vegetated class to estuarine open water was categorized as a low disturbance. The impact of inundation on soil carbon pools is not well understood. While it is understood that carbon accumulation potential is lost when marsh is converted to open water we assumed that soil carbon was left relatively undisturbed when covered with open water. Given that 95-99% of total carbon stocks in salt marshes are stored in the first 3 meters of soil (Murray et al. 2011), we categorized conversion to open water as a low disturbance. Tidal flats and estuarine beach land cover classes are subject to greater exposure to oxygen as land is inundated and exposed with the tides. Oxidation is a primary driver of soil carbon release and thus we categorized conversion to these classes as a medium disturbance relative to conversion to open water. Conversion to developed and undeveloped dry land implies a greater impact on the landscape either through physical disruption to the soil for land development or conversion of land to agricultural land via soil drainage and diking (Sharp et al. 2014, Pendleton et al. 2012). Marsh conversion to these classes was therefore categorized as a high disturbance relative to other land conversions.

Based on the biomass disturbance input parameters (see 3.2.2 Carbon Data), 50% of carbon stored in biomass will be released under a low or medium disturbance and 100% of the carbon stored in biomass will be released under a high disturbance. For soil disturbance input parameters, 30% of soil carbon will be released under a low disturbance and 100% will be released under a medium or high disturbance. All carbon releases occur over time according to the marsh-specific 7.5 year carbon decay rate (Sharp et al. 2014) specified in the half-life input table.

3.2.4. Valuation

We ran the valuation section of the model using the default inputs for the social cost of carbon option. This project's focus was concerned with the ability to sequester carbon with the threat of rising sea levels within the Puget Sound coastal areas, which is categorized as a social issue. The discount rate of 5% was applied because we believe this percentage will be closer to the real rate of interest over the time period used for this project. All defaults are based on a global literature review (Sharp et al. 2014).

3.3. Summarized Model Outputs

3.3.1. Available Model Outputs

The InVEST CBC model produces an output folder that contains shapefiles, summary reports and raster maps that are created from running both the pre-processor and the blue carbon calculator tools. The shapefile shows the extent of the SLAMM produced LULC maps. This area expands outside of TNC's preserve area and incorporates Port Susan Bay. The preprocessor report provides a summary table(s) of the LULC transitions from t_1 (2005) to t_5 (2100). The table displays the total area of each land cover type for the corresponding time period. This report also shows the amount of change in regard to the vegetation transition over our study period. For each transition, the tables display the amount of vegetation that has transitioned a LULC type called “other” to LULC type called “marsh”. The core model report provides a summary table(s) for every model input (.csv file) based on the LULC changes from t_1 to t_5. Additionally, a table is provided that displays the carbon gain/loss and net sequestration for each time period, which is also displayed as a raster file.

The output folder also contains raster maps for five different carbon outputs over the time periods t_1- t_5 which are gain, loss, sequestration, stock, and net present value (NPV). The gain raster displays the areas that have gained carbon for each time period while the loss raster displays the areas that have observed a decline in carbon storage. The sequestration maps show the net value (+/-) between the gain and loss rasters. Carbon stock raster maps are provided which display the total stock from the combined four pools (above-ground biomass, below-ground biomass, soil, and litter). Finally, a raster map showing NPV (in U.S. dollars) of carbon sequestered per pixel is included. It should be noted that the values for the previously mentioned rasters (excluding NPV) are in megagrams of CO_2-eq per pixel which is equal to metric tons of CO_2-eq per pixel.

Contained within the output folder is a subfolder called intermediate. This folder contains raster maps of carbon accumulation/disturbance and carbon stock for each vegetation type within the soil, biomass, and litter pools. As with the output folder, these raster maps show the results for the time periods t_1- t_5. In summary, these maps are more specific to the change in carbon amount within the each vegetation type for each carbon pool.

3.3.2. Analyzed Model Outputs

For this project, the focus was on analyzing three main outputs from the InVEST CBC model: net present value, carbon sequestration, and carbon stock rasters. The net present value output was chosen because it produced a monetary value based on the amount of carbon sequestered. Carbon sequestration outputs were used because the net amount of carbon sequestered or emitted at each pixel within the AOI was the primary focus. Stock outputs were used to show the total stock of carbon within the AOI. They are also a useful visual aid when comparing side by side with the previously mentioned outputs.

Processing Outputs

We created two ArcGIS ModelBuilder tools to enable batch processing of the CBC model output rasters. These are simple tools which execute a single geoprocessing tool each. The first tool, Clip Raster to PSB Preserve, clips a raster to the extent of the PSB Preserve (Figure 8, Figure 9). This tool executes the Extract by Mask tool on a specified input raster. This tool is pre-configured to use the PSB Preserve polygon as the mask. We created this tool because the original extent of the SLAMM LULC rasters covered an area greater than that of our AOI. We therefore wanted a method to batch process (clip) the SLAMM rasters to the PSB Preserve for display purposes.

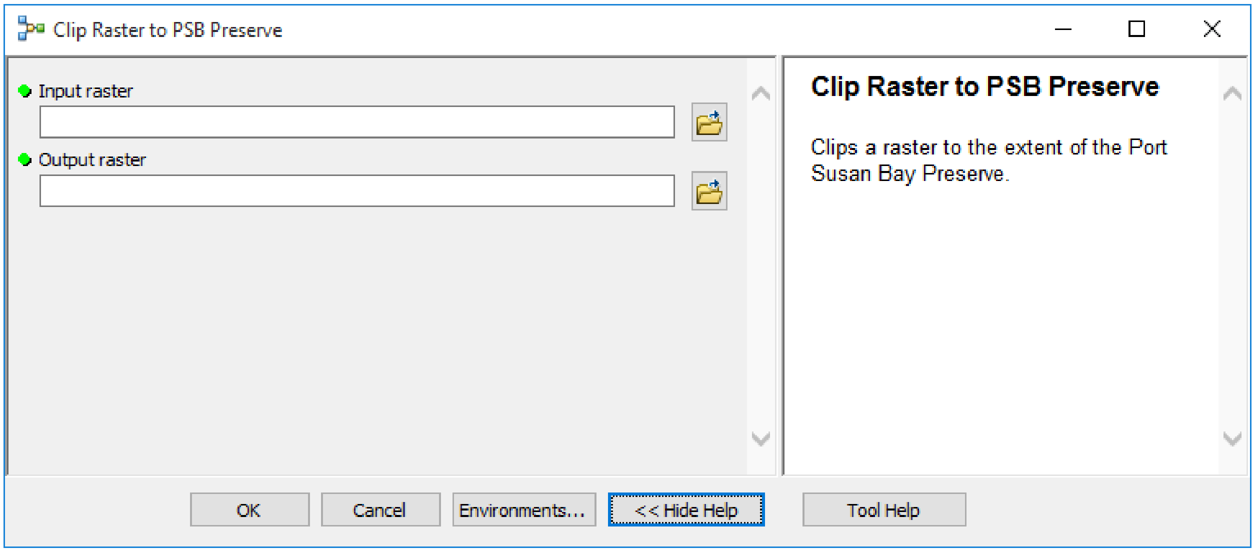

Figure 8 A custom-built ArcGIS tool for clipping rasters to the Port Susan Bay Preserve boundary.

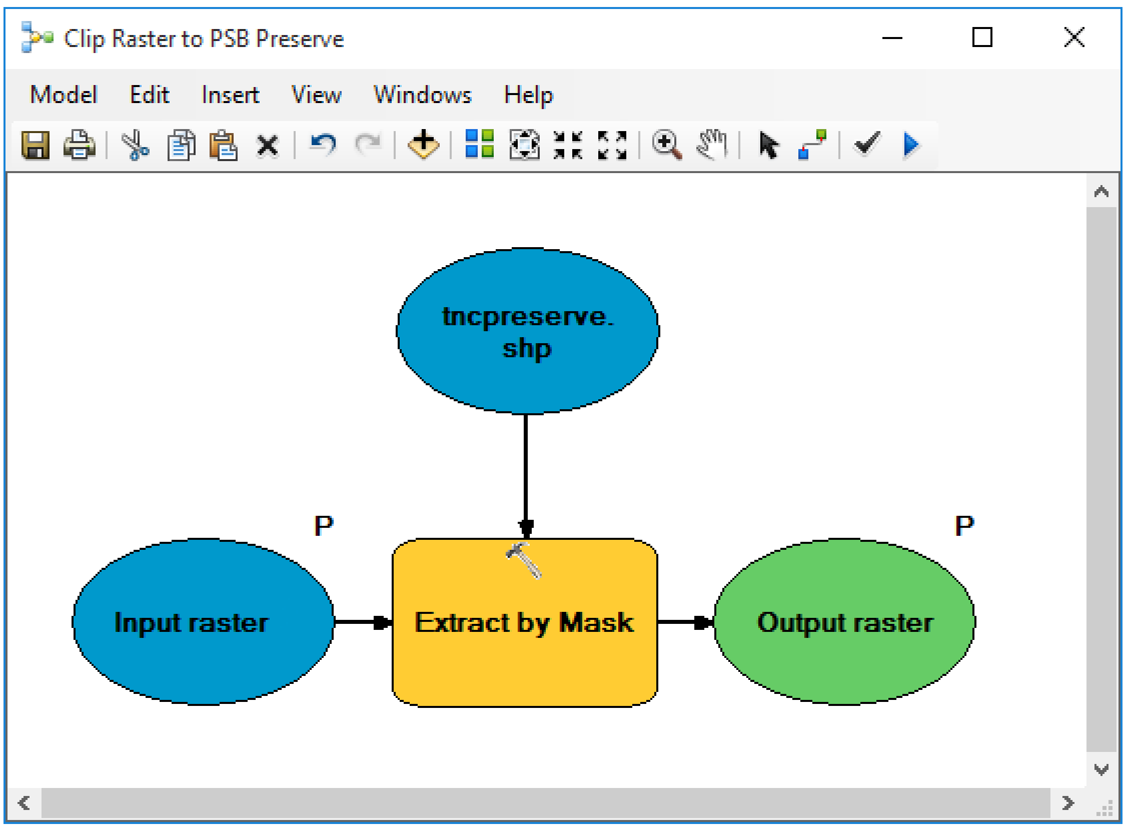

Figure 9 Model workflow for the Clip Raster to PSB Preserve tool.

The second tool, Summarize Output Raster, executes the Zonal Statistics as Table tool on a specified input raster (Figure 10, Figure 11). This tool is pre-configured to use the PSB Preserve polygon as the input zone. The purpose of this tool is to summarize the CBC output raster values within the specified zone of interest (preserve boundary). Like the Clip Raster to PSB Preserve tool, this tool should be executed in batch mode to maximize efficiency.

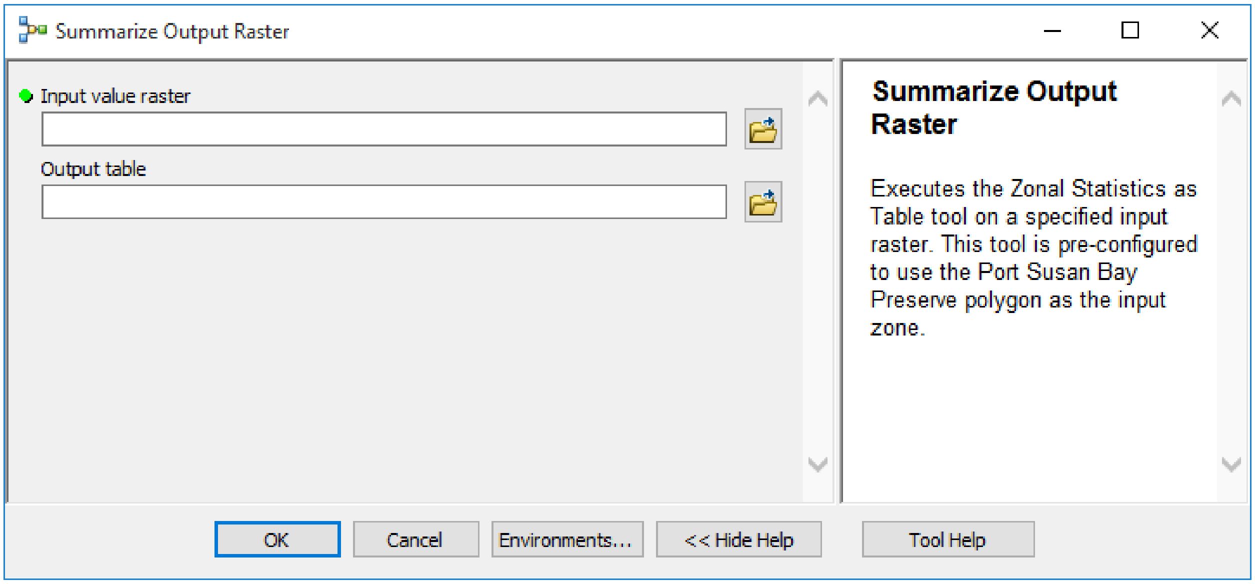

Figure 10 A custom-built ArcGIS tool for summarizing CBC output raster values within the Port Susan Bay Preserve boundary.

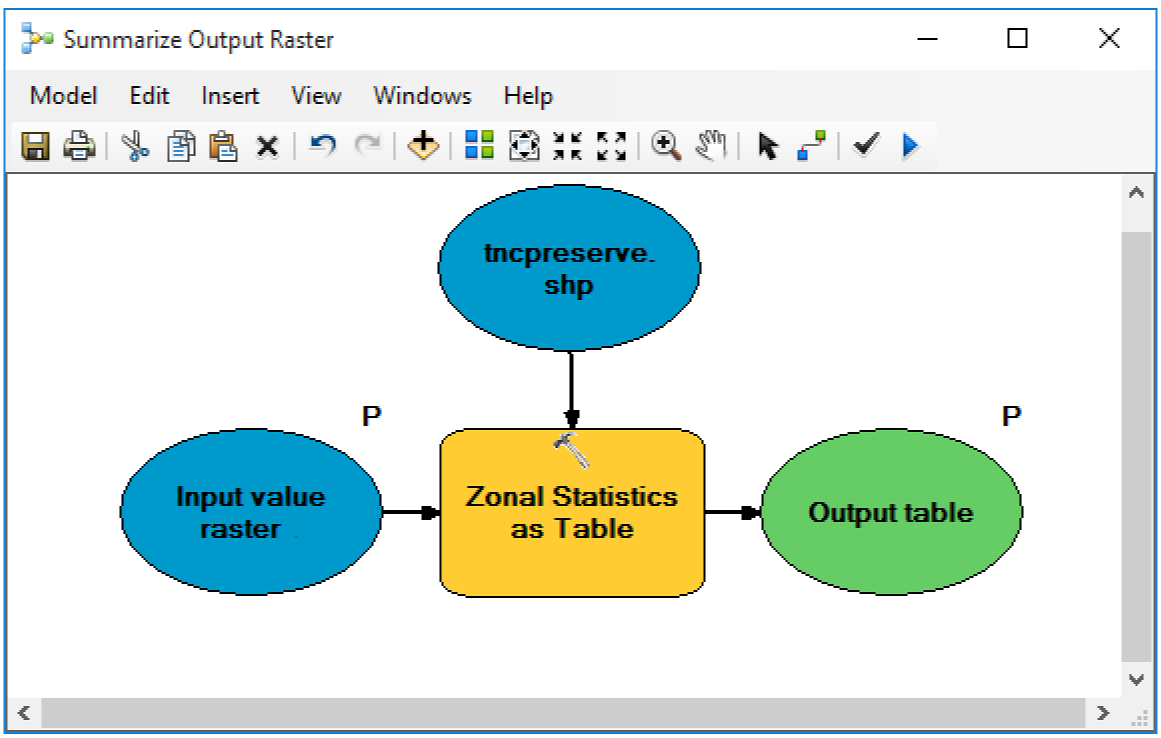

Figure 11 Model workflow for the Summarize Output Raster tool.

3.4. Literature Search

We compiled a repository of literature sources (many of which are referenced throughout this report) to leverage the time and effort we spent researching and collecting literature on the state of blue carbon science and salt marsh ecology. We created a file package with an HTML index file for easy access to these materials in the future (Figure 12).

Coastal Blue Carbon Literature Package

Barbier, Edward B., Sally D. Hacker, Chris Kennedy, Evamaria W. Koch, Adrian C. Stier, and Brian R. Silliman. "The value of estuarine and coastal ecosystem services." Ecological Monographs 81, no. 2 (2011): 169-193.

Clough, J. and E. Larson. "Application of SLAMM 6 to Port Susan Bay Including Remedial Alternatives, Final Report." The Nature Conservancy, WA. (2010)

Collins, B. "Mid -19th century stream channels and wetlands interpreted from archival sources of three north Puget Sound estuaries." Unpublished report to the Skagit River System Cooperative, La Conner, WA; Bullitt Foundation, Seattle, WA; and Skagit Watershed Council, Mt. Vernon , WA. (2000)

Figure 12 Index page of the coastal blue carbon literature package.

4. Results

4.1. InVEST Coastal Blue Carbon Model Outputs

We modeled the total amount of carbon (expressed as megagrams of carbon dioxide equivalents, Mg CO_2-eq) stored within the Port Susan Bay Preserve for 2005, 2025, 2050 and 2100 under three scenarios: current (baseline) conditions with 1m sea-level rise, restoration of 240 acres and snow geese grazing with 1m sea-level rise, and restoration of 240 acres with 1m sea-level rise. We configured the CBC model to account for carbon stored in three different pools 1) above ground biomass, 2) below ground biomass, and 3) soil. Results for stock (total amount of carbon in all 3 pools at a given time step), sequestration (net of accumulation and emissions) for each time period, and net present value (NPV) of carbon sequestered for each time period were summarized.

Of all the scenarios, the restoration scenario had the most carbon on the landscape (stock) at each time step and had a final stock of 187100 Mg CO_2-eq in year 2100 (Table 5). For sequestration (Table 6), all scenarios had a net gain between 2025 and 2050. The amount of carbon sequestered decreased for all scenarios between 2050 and 2075 (Figure 13). The snow geese scenario became a net emitter of carbon between 2050 and 2075. The baseline and restoration scenarios became net emitters of carbon between 2075 and 2100. In total, over the 95 modeled years, 46915 Mg CO_2-eq, 20133 Mg CO_2-eq and 54934 Mg CO_2-eq were sequestered by the baseline, snow geese, and restoration scenarios, respectively. When considering the net present value of avoided emissions in total for each scenario (Table 7), the restoration scenario yields the highest economic value for avoided emissions ($551,074) followed by the baseline scenario ($477,068) and then the snow geese scenario ($262,818). Figure 14 presents a side-by-side comparison of the sequestration and NPV outputs by scenario. Refer to Appendix 5, Appendix 6, and Appendix 7 for full-page maps of the sequestration, NPV and stock output maps by scenario and time period.

Table 5 Carbon stock totals (in Mg CO_2-eq) for each time step for the three scenarios of the Port Susan Bay Preserve.

Time Step	**Scenario #1: Baseline 1m**	**Scenario #2: Snow Geese 1m**	**Scenario #3: Restoration 1m**
2005 (t_1)	132166	107981	132166
2025 (t_2)	150729	119538	153313
2050 (t_3)	173497	133878	179364
2075 (t_4)	185122	133601	193945
2100 (t_5)	179082	128064	187100
Totals	**820596**	**623062**	**845888**

Table 6 Carbon sequestration (+) and emissions (-) (in Mg CO_2-eq) for each 25-year time period for the three scenarios of the Port Susan Bay Preserve.

Time Period	**Scenario #1: Baseline 1m**	**Scenario #2: Snow Geese 1m**	**Scenario #3: Restoration 1m**
2005-2025 (t_1-t_2)	18563	11557	21148
2025-2050 (t_2-t_3)	22767	14340	26050
2050-2075 (t_3-t_4)	11625	-227	14581
2075-2100 (t_4-t_5)	-6040	-5537	-6845
Totals	**46915**	**20133**	**54934**

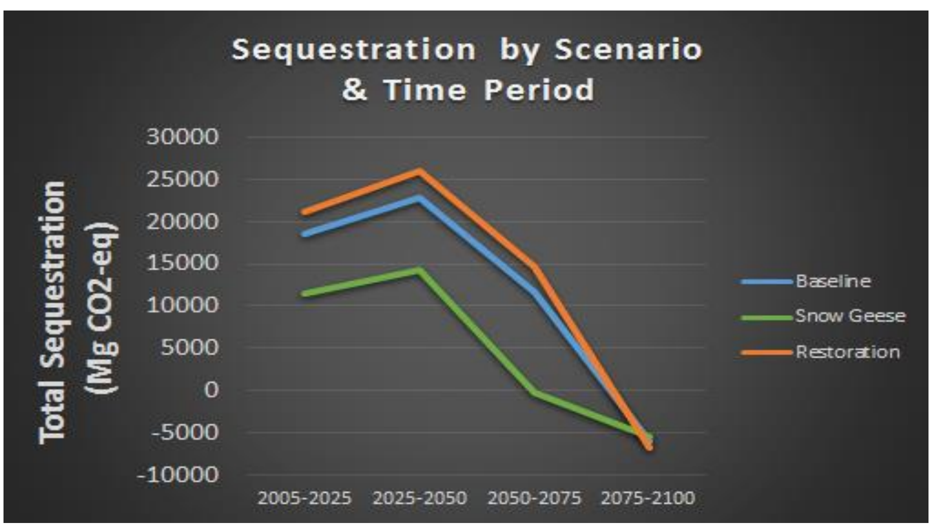

Figure 13 Net sequestration by scenario and time period.

Table 7 Net present value (in U.S. dollars) of avoided emissions for each 25-year time period for the three scenarios of the Port Susan Bay Preserve.

Time Period	Scenario #1: Baseline 1m	Scenario #2: Snow Geese 1m	Scenario #3: Restoration 1m
2005-2025 (t_1-t_2)	$236,813	$148,603	$269,215
2025-2050 (t_2-t_3)	$203,150	$127,285	$232,842
2050-2075 (t_3-t_4)	$54,327	$347	$68,212
2075-2100 (t_4-t_5)	-$17,223	-$13,417	-$19,195
Totals	**$477,068**	**$262,818**	**$551,074**

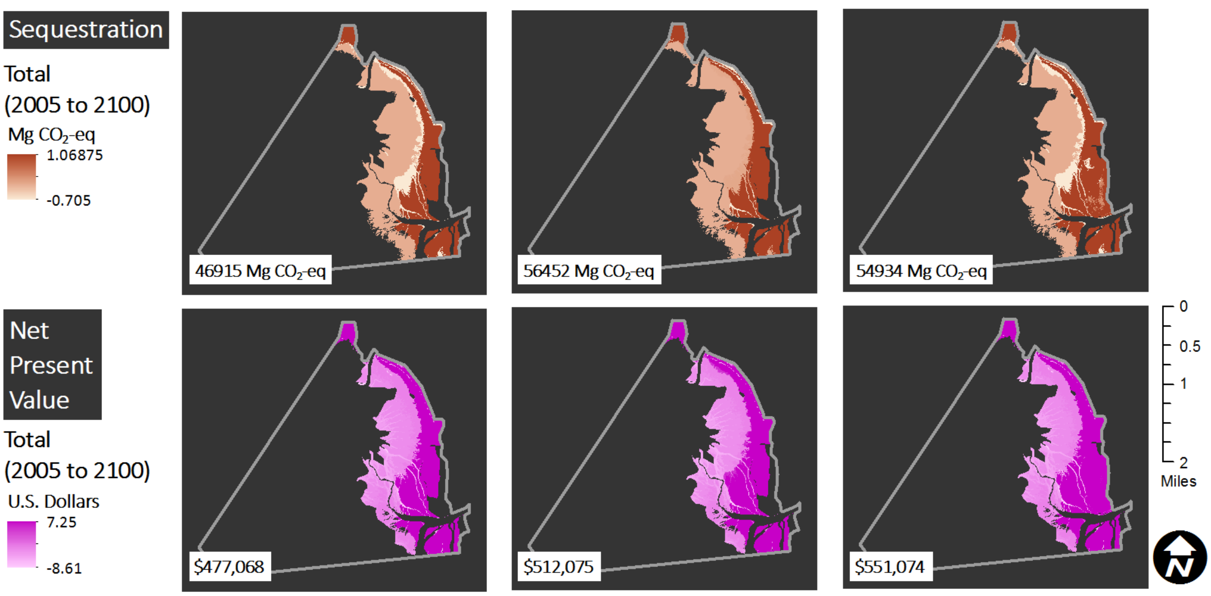

Figure 14 Scenario comparison of sequestration (total between 2005 and 2100) and net present value (total between 2005 and 2100) results within the Port Susan Bay Preserve boundary. Gray area on maps represents zero (within boundary) and no data (outside boundary).

5. Discussion

5.1. Major Findings Based on Scenario Comparison

We modeled three SLAMM 1m SLR scenarios that were identified as high priority by TNC including baseline, snow geese and restoration. Our results indicate that both snow geese and SLR are threats to the PSB Preserve and continue to have negative impacts on this coastal ecosystem through the modeled time period (2005-2100). We also found that restoration of degraded marsh habitat increased carbon sequestration. This indicates that continued restoration efforts are essential to PSB's ability to function as a carbon sink.

5.2. Limitations, Assumptions and Simplifications

In the absence of detailed knowledge on the carbon dynamics in coastal and marine systems, the InVEST CBC model takes an accounting approach and draws on published carbon stock datasets from neighboring coastlines. With the exception of the local data obtained from Crooks et al. 2014, carbon pool estimates, soil and biomass disturbance rates and carbon decay rates for Port Susan Bay habitat types were obtained from the most extensive and up-to-date published global datasets of carbon storage and accumulation rates compiled by the Natural Capital Project and partners at Duke University (Fourqurean et al. 2012; Silfeet et al. 2011). We classified disturbance magnitude using the transition matrix with some uncertainty due to general assumptions that are made by the user on what happens when LULC types are converted.

One of the main limitations of the SLAMM application in PSB was the accuracy of accretion rates. Recent data indicates that accretion rates may in fact be higher than what was applied in the SLAMM model for PSB. This would mean that the marsh may have more capacity to build resilience to keep pace with SLR.

5.3. Snow Geese Impact

Snow Geese are federally protected migratory game birds whose numbers have grown rapidly since the mid-twentieth century, likely due to warming conditions in arctic breeding grounds and a ban on hunting in the early 1900's (Cornell Lab of Ornithology 2015). Snow geese are voracious eaters (particularly during the early breeding season) that feed mainly in marsh habitats and may degrade habitat by grubbing vigorously for food and disturbing the vegetation and soil. Historically, salt marshes were thought to be controlled exclusively by physical forces such as temperature, salinity, and nutrients that regulated ecosystem productivity and structure (Gedan 2009). However, there is mounting evidence that human disturbances are triggering consumer control in salt marshes, often with catastrophic consequences (Bertness and Silliman 2008), such as what we see with the snow geese. Our results show this when comparing modeled scenario outcomes from the baseline and restoration scenarios to the snow geese scenario.

5.4. Sea-Level Rise Impact

Without the ability for the marsh in the PSB Preserve to migrate, due to diking and agricultural land use, a 1m SLR will result in the conversion of the marsh into tidal flat and open water over the next 95 years. Some SLR impacts may be mitigated by restoration efforts but eventually the marsh's ability to keep pace with SLR will fail according to the SLAMM model outputs. The expected acceleration of SLR will exacerbate the vulnerability of coastal habitats and will likely become a major threat to coastal ecosystems in the near future (Cazenave and Cozannet 2014).

5.5. Restoration Efforts Are Essential

Continued restoration efforts in the PSB Preserve are essential to its ability to function as a carbon sink and to support the plethora of flora and fauna that depend on this highly functioning coastal ecosystem. A restoration project at the PSB Preserve was previously completed in 2012, where 150 acres of tidal marsh were restored in the Stillaguamish River estuary (TNC 2015). This restoration projected consisted of the removal of an outer dike and the redesign of an inner dike in order to provide greater protection for neighboring farmlands during floods and improve the ability of fish caught in flood waters to return to the natural system. Upon completion of this restoration project native marsh habitats are in better condition, allowing juvenile Chinook salmon better access to restored rearing habitats and increasing the connectivity between the river and tidal areas. Expanding restoration efforts in the PSB Preserve will increase the resilience of the estuary to SLR by enabling marsh migration and healthier tidal wetlands.

5.6. Recommendations and Next Steps

With this being the first attempt at applying the InVEST CBC model to the PSB Preserve, we have identified several areas within this project that can be improved upon given more time and resources. In an effort to increase the completeness of this analysis it would be wise to run the CBC model on the remaining projected SLAMM SLR scenarios (0.34m, 0.59m, and 1.75m). Additionally, we recommend running the two additional restoration scenarios (Restoration 3 and Restoration 4) and the Low Flow scenario (refer to Clough and Larson 2010 for details of these scenarios). Figure 15 represents the PSB Preserve area with current and future restoration sites. The blue polygon (area a) is what was reported as the restoration scenario in this project. The pink and green polygons (b, c) are potential future dike restoration areas for which SLAMM data is available but we did not have time to run these scenarios. Therefore, we recommend running the future dike restoration scenarios through the CBC model as one of the next steps in this modeling effort.

Local carbon data is scarce and hard to find. Furthermore, when available it is not always collected or reported on in a standardized manner. For example, we were able to obtain local soil carbon data that was collected in our study area, but could not use it in this analysis due to unknown collection methods and units that were unusable as model inputs. Therefore it is important to increase and improve the collection of carbon data by implementing standardized carbon sampling programs. We concluded from the literature that the soil carbon pools and soil accumulation rates are the most significant sources when it comes to modeling blue carbon in salt marshes (Guannel et al. 2010, Reddy et al. 2015, Murray et al. 2011). In the first meter of sediments alone, soil organic carbon averages 917 t CO_2-eq/ha for salt marshes and is by far the biggest carbon pool for all coastal habitats. In relative terms, about 95% to 99% of total carbon stocks of salt marshes and seagrasses are stored in the soils beneath them, while in mangrove systems, 50% to 90% of the total carbon stock is in the soil carbon pool; the rest is in living biomass (Murray et al. 2011). Based on this information, it seems wise to focus sampling efforts on collecting soil carbon samples.

In summary, we have several recommendations for how TNC can move forward with the Port Susan Bay CBC modeling effort. These include 1) research and refine model input parameters and run all SLR and restoration scenarios, 2) perform sensitivity analyses on input parameters, 3) apply the InVEST CBC model to the Snohomish River Estuary for validation, and 4) develop blue carbon capacity monitoring plans in the Port Susan Bay Preserve.

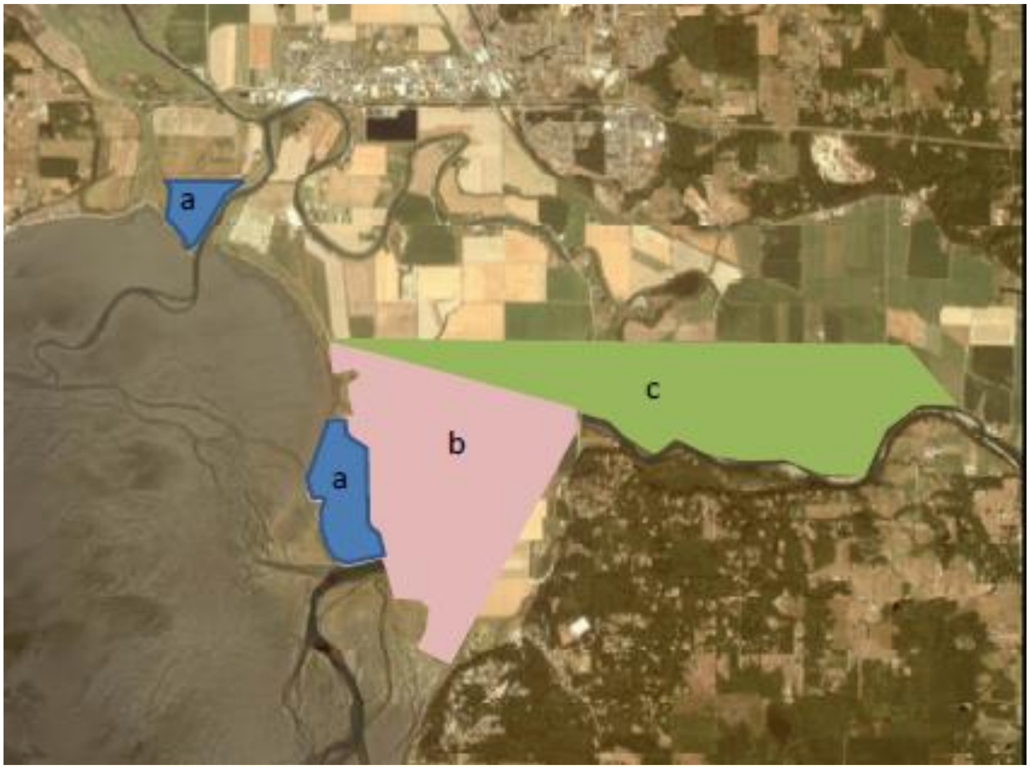

Figure 15 Port Susan Bay Preserve dike restoration map with current (blue polygon) and future (pink and green polygons) restoration sites (Clough and Larson 2010).

6. Business Case & Implementation Plan

The InVEST (CBC) model is used to analyze LULC changes overtime to determine the value of carbon and the ability of the coastal ecosystems to sequester carbon (Sharp et al. 2014). For the purposes of this project, we were using the CBC model to validate its effectiveness of using both local and global data to determine the impacts that Sea-Level Rise (SLR) has on the TNC preserve's ability to sequester carbon over time. If this project determines that the CBC model is an effective and valuable tool, TNC would expand the area of interest to all coastal habitats within the Puget Sound within the planning phase of the project. Further expansion of this project would be outside the footprint on TNC, but felt it was important to expand the scope of this plan given the importance of this issue. For the purpose of this project, the business plan incorporates the improvement programming and project implementation phases. Figure 16 below provides a conceptual workflow diagram of the three project phases - planning, implementation and improvement programming. In order to proceed with these additional phases, the assumption was made that SLR would have a large, negative impact on coastal habitats and would significantly reduce the amount of carbon sequestration taking place within Puget Sound.

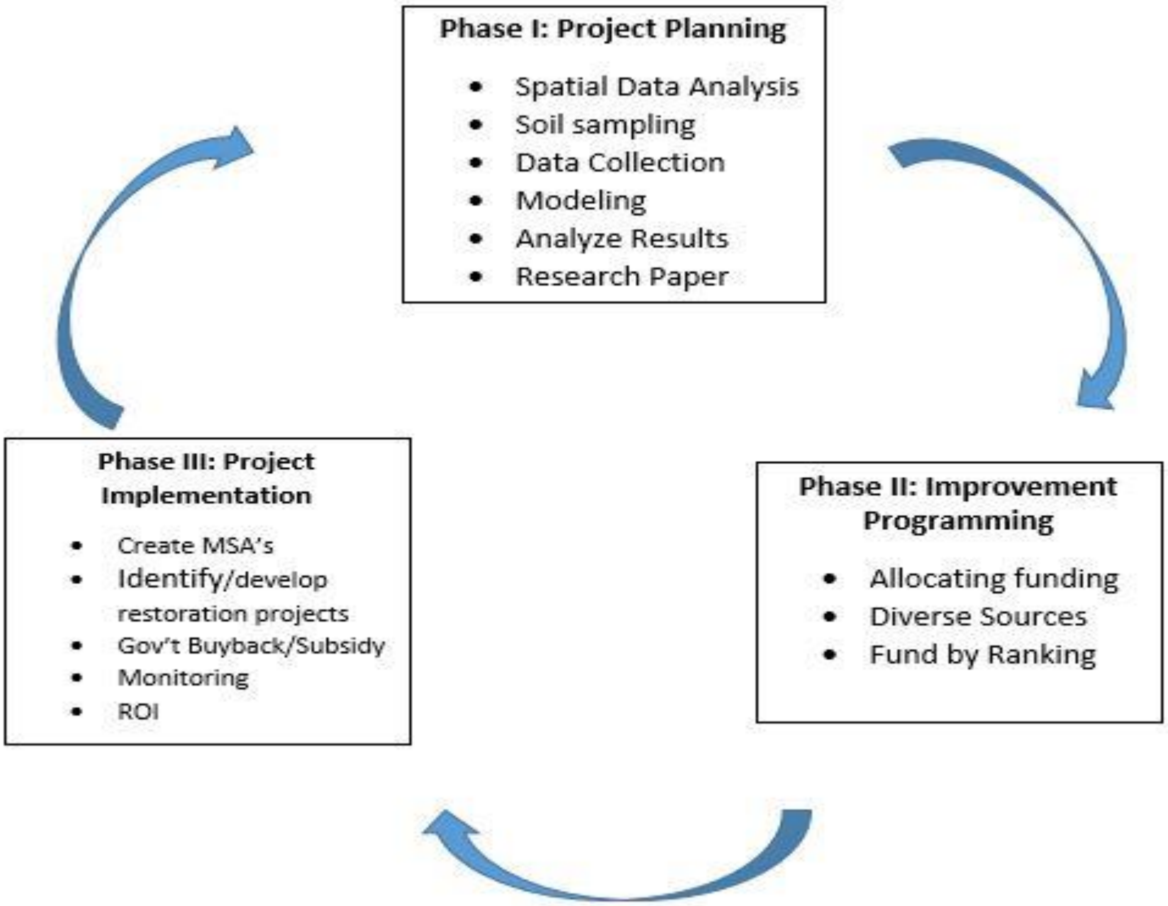

Figure 16 Conceptual workflow diagram of the PSB Preserve business plan representing the three phases of project: planning, improvement programming and project implementation.

6.1. Project Planning: Phase I

The planning phase of this business plan is a multi-step process that involves spatial data analysis, soil sampling, data collection and modeling. This phase is highly important because the results will determine if SLR impact on carbon sequestration will be great enough to warrant funding and implementation efforts. Spatial mapping of the AOI's, beginning with Port Susan Bay, within Puget Sound is the first step of this process. Using LiDAR (Light Detection and Ranging) technology will provide the highest quality of data. High resolution imagery can be used to accurately map the habitat types within each bay in the Puget Sound. For this analysis, LiDAR will substitute for manually surveying habitat types in which only minor ground-truthing will need to take place.

Following habitat mapping, collecting soil samples using a standardized sampling protocol within this large project area will be the next step. The soil samples will be used to determine how much carbon is stored in each pool (biomass, litter, and soil) within the AOI. Another important aspect of this project involves determining property ownership of both the habitat types within the bay and the land behind these areas. Identifying the parcel owners in the areas adjacent to the marsh area is relevant for land purchasing or subsidizing purposes, which will be addressed in the following phases.

Phase I is envisioned to be led by TNC but will require the collaboration of many partners, involving consulting firms, additional non-profit organizations, universities, local and state governments and volunteers. LiDAR surveying would be the first step of this phase, which will lay the groundwork for site and soil analysis. When the data has been compiled, the model inputs can be populated. These results can then be compiled and described in detail in a research paper. It is envisioned that this process will be completed within a two year time period.

Phase I will also include a detailed gap analysis to determine where the science on CBC modeling currently stands and where the existing knowledge gaps are. This analysis will be primarily based on model inputs that are difficult to obtain and a global literature review of the coastal blue carbon field. Results from this analysis will inform management teams on the kinds of sampling protocols that need to be incorporated into sampling and monitoring programs.

6.2. Improvement Programming: Phase II

Allocating funding for projects is difficult and usually comes from numerous sources. Local, state and the federal government are envisioned to be the main sources of funding for a project with a scope this large. Prior to receiving this funding, project sponsors are usually responsible for funding the initial planning and analysis that provides key information that would justify spending public money on a project. These sponsors would consist of non-profit organizations, universities, and private donors. Once the planning phase (phase I) of the project is complete, funding from governmental branches can commence in order to fund the implementation phase (phase III). It is expected that the federal government would be the largest contributor to this project given the role carbon plays in regards to climate change. Determining the amount of funding to implement a project of this scale is impossible given that the results of the analysis will be needed completed first. It is estimated that phase I funding will be acquired within the first year following the development of the project scope of work. Funding phase III will involving a more exhaustive process that may require three to five to procure.

6.3. Project Implementation: Phase III

The first step of the implementation process is to create Marine Stewardship Areas (MSA's) within all the bays that were selected in the planning stage. These are vital ecosystems for carbon sequestration in the region and will need protection from future human disturbance. The MSA's goals are to educate the public, protect marine habitats, manage resources, and conduct research to make more informed decisions (SJCMRC 2007). Following the creation of the MSA's, habitat restoration and enhancement projects will need to be developed. In coordination with these projects is the need to develop a governmental land buy back or subsidy program. With rising sea levels, marsh areas are being threatened and are at risk of disappearing. Prior to land development in these areas, marshes were able to migrate to higher areas to compensate for SLR. Due to modern land development in these areas, the marshes are longer able to migrate. Creating a program to buy or subsidize private undeveloped (i.e., open space) land will allow habitat restoration projects to convert open areas back to their natural state being estuarine emergent and scrub shrub wetlands (NOAA 2007).

The buyback program will be difficult to implement and also controversial. First, private citizens will not be willing to sell their land back to the government. Second, land prices, especially near water, are expensive and acquiring the funding to purchase land throughout the project area will be challenging. Additionally, all parcels adjacent to the water within a bay area will need to be purchased. Increasing the habitat area will not be successful unless the marshes are able to migrate throughout the entire bay and not just in small sections. An important point to make to landowners is with rising sea level and larger storms, the land adjacent to the bay is at risk of being exposed to salt water. This could have the potential to make this land unusable for agricultural purposes. Being able to sell this land at a premium price would be beneficial to current landowners. A potentially more viable and feasible option would be to create a subsidy program. This program would compensate landowners who convert portions of their property to wetland areas. This would allow them to maintain ownership of their land. Most landowners do not have the ability or means to convert their land into a wetland. With the help from non-profit organizations, landowners can work with these groups to accomplish this challenge.

Finally, a monitoring plan must be created to track the progress of the habitat restoration projects and carbon sequestration along with SLR. Monitoring fish, shellfish, plant, and bird populations within this region is important for tracking the tangible and intangible benefits of this project. Recording recreational and tourism activity within this region is valuable, especially in regards to justifying the cost of the project. As previously mentioned, the Puget Sound region is highly dependent on recreational and tourism as a revenue stream. Restoring ecosystems and habitats will certainly increase these opportunities. Lastly, monitoring the cost of storm damage in the future will be crucial. The greatest return on investment for this project will be placing a value on the ecosystem services that mitigate the damage caused by storms.

With a project this complex, at a large scale, and requiring massive funding (mostly public), an important question is: What is the expected return on investment? Over the last decade, we have seen larger than normal storms greatly damage coastal areas like New Orleans from Hurricane Katrina and the northeast coastline from Hurricane Sandy. The cost to repair these communities was in the hundreds of billions of dollars (Time 2012). Both these regions at one time had extensive wetland communities that could absorb the brunt of these storms and limit the impact on land (NWF 2008). Today, these areas have been converted into subdivisions and are no longer resilient to the impacts from large storms. At a smaller scale, similar conditions are apparent along the coastal areas of the Puget Sound. By restoring the natural habitat within these estuary and marsh areas while protecting pristine habitat from becoming degraded in the first place, the resilience of the region will be stronger. The ecosystems will be able to limit the amount of damage created from future storms. Therefore, the investment made today will pay for itself in the coming decades. Based on the restoration plan proposals developed by TNC for the Port Susan Bay area, we envision this massive plan to be fully implemented between thirty to fifty years.

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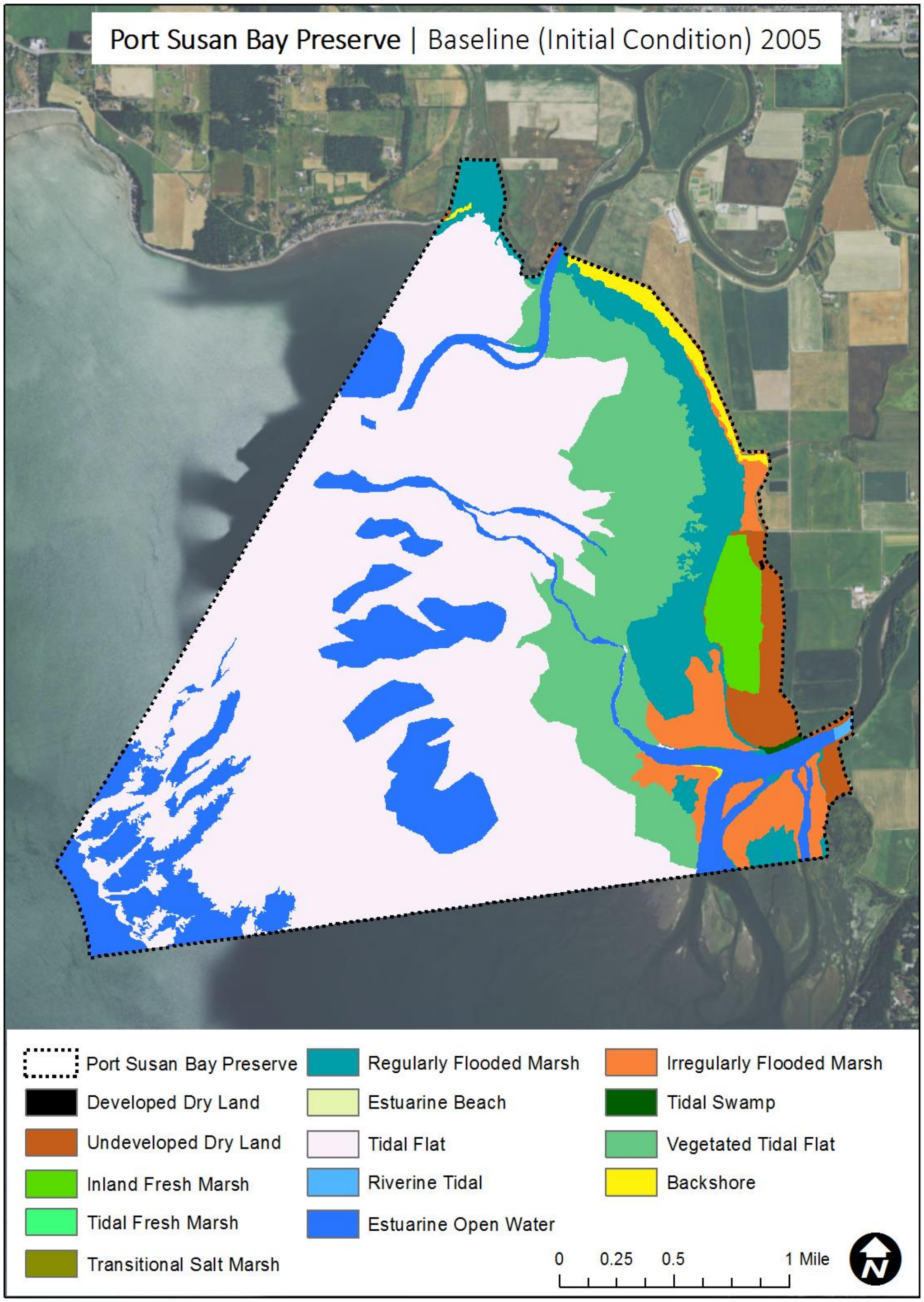
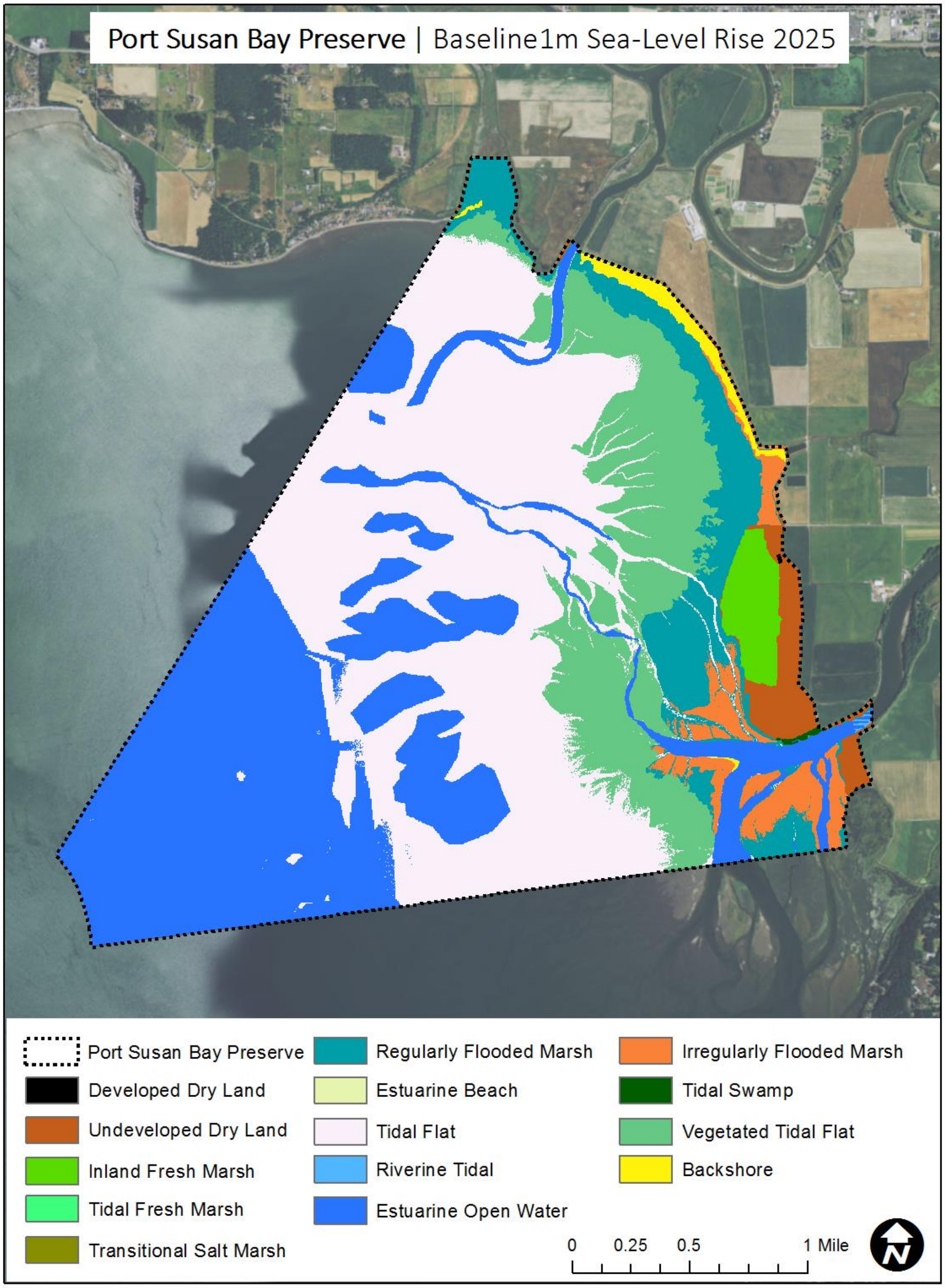
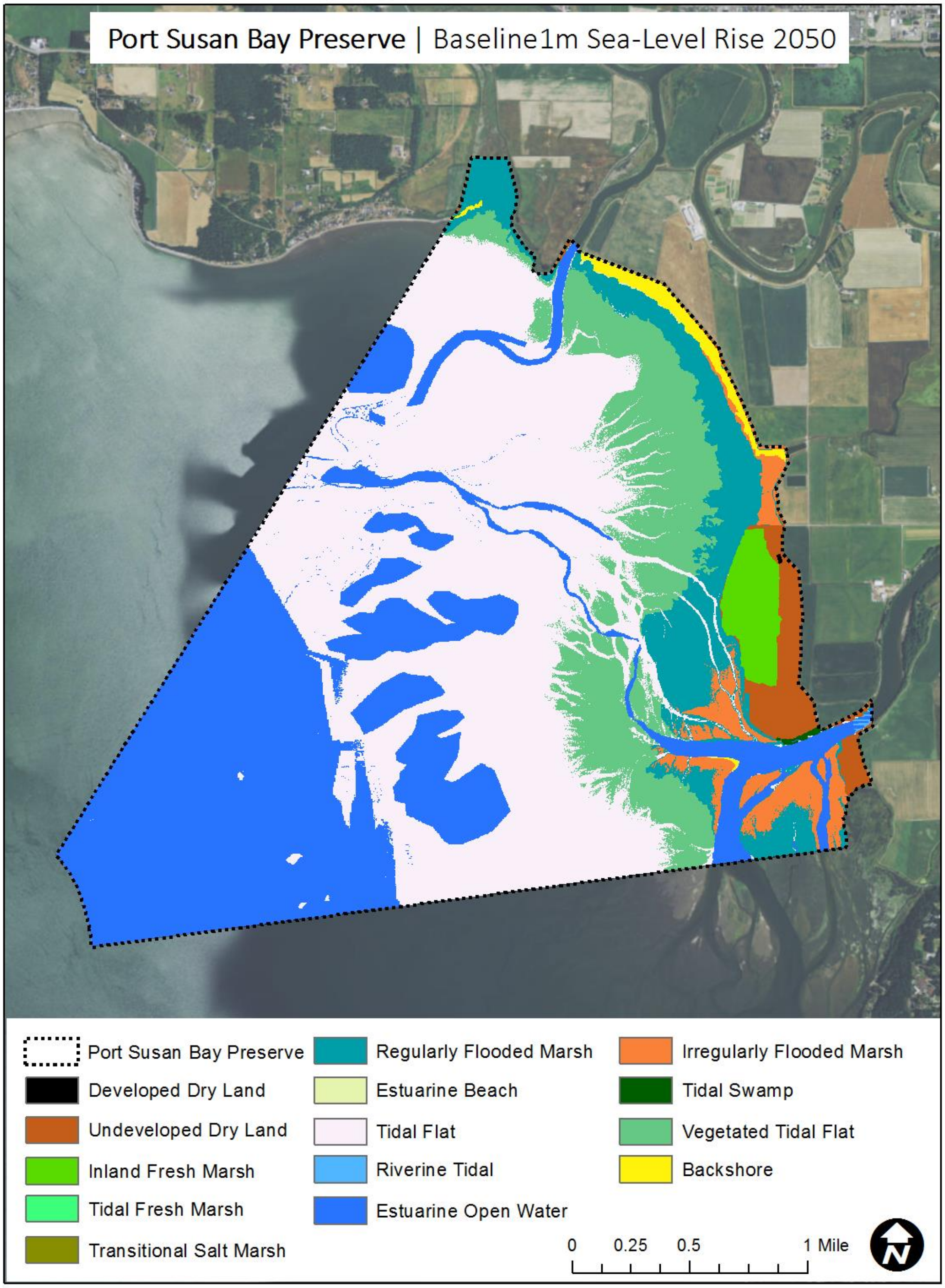
8. Appendices

Appendix 1 Full-page SLAMM input maps by scenario and time step





Port Susan Bay Preserve | Baseline1m Sea-Level Rise 2025
Port Susan Bay Preserve
Developed Dry Land
Undeveloped Dry Land
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Salt Marsh
Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
Riverine Tidal
Estuarine Open Water
Irregularly Flooded Marsh
Tidal Swamp
Vegetated Tidal Flat
Backshore
0 0.25 0.5 1 Mile
N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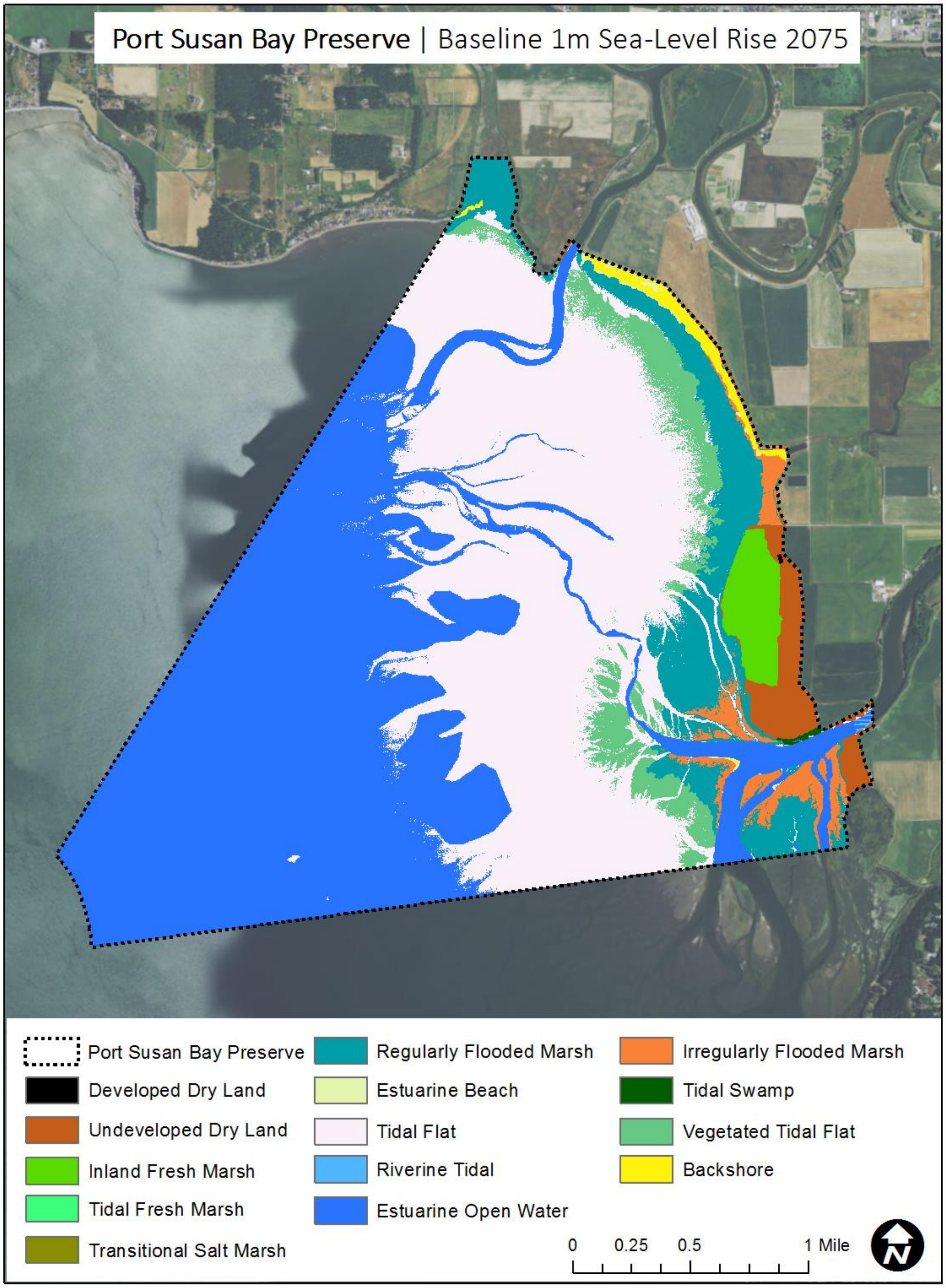
Port Susan Bay Preserve
Developed Dry Land
Undeveloped Dry Land
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Salt Marsh
Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
Riverine Tidal
Estuarine Open Water
Irregularly Flooded Marsh
Tidal Swamp
Vegetated Tidal Flat
Backshore
0 0.25 0.5 1 Mile
N



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Port Susan Bay Preserve
Developed Dry Land
Undeveloped Dry Land
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Salt Marsh
Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
Riverine Tidal
Estuarine Open Water
Irregularly Flooded Marsh
Tidal Swamp
Vegetated Tidal Flat
Backshore
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0.25
0.5
1 Mile
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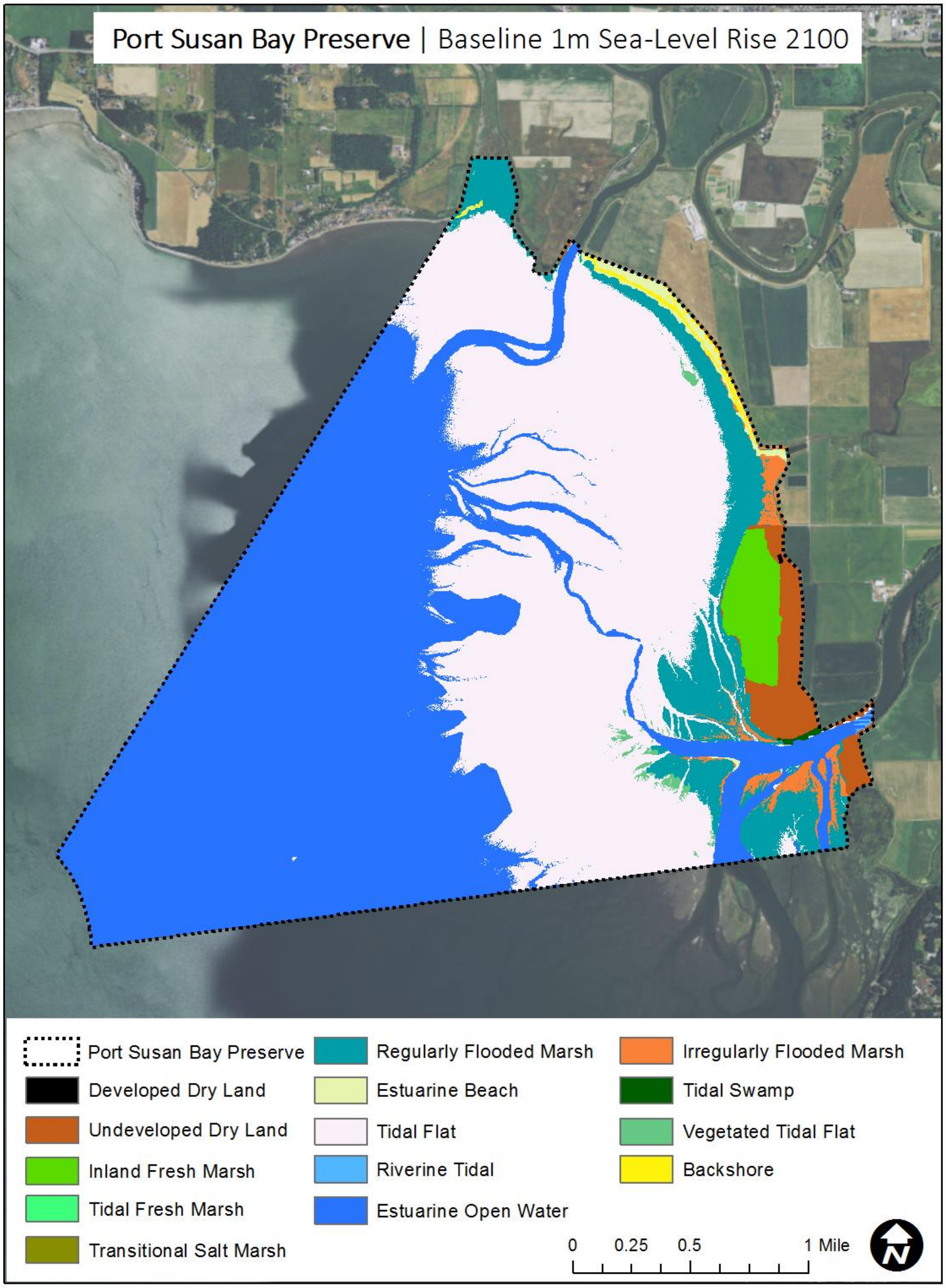
Port Susan Bay Preserve | Baseline 1m Sea-Level Rise 2100
Port Susan Bay Preserve
Developed Dry Land
Undeveloped Dry Land
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Salt Marsh
Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
Riverine Tidal
Estuarine Open Water
Irregularly Flooded Marsh
Tidal Swamp
Vegetated Tidal Flat
Backshore
0 0.25 0.5 1 Mile
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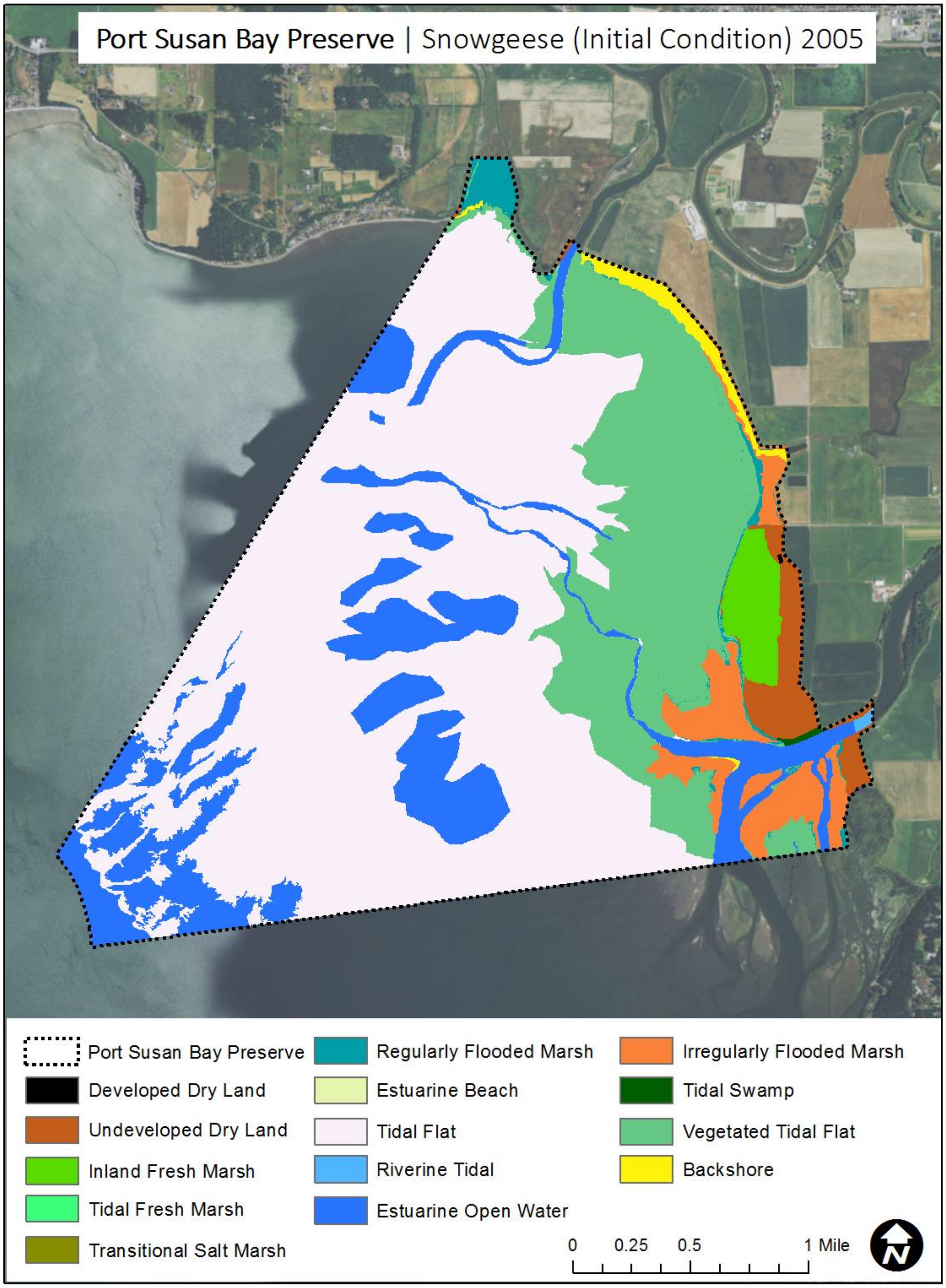
Port Susan Bay Preserve | Snowgeese (Initial Condition) 2005
Port Susan Bay Preserve
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Undeveloped Dry Land
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Salt Marsh
Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
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Backshore
0 0.25 0.5 1 Mile
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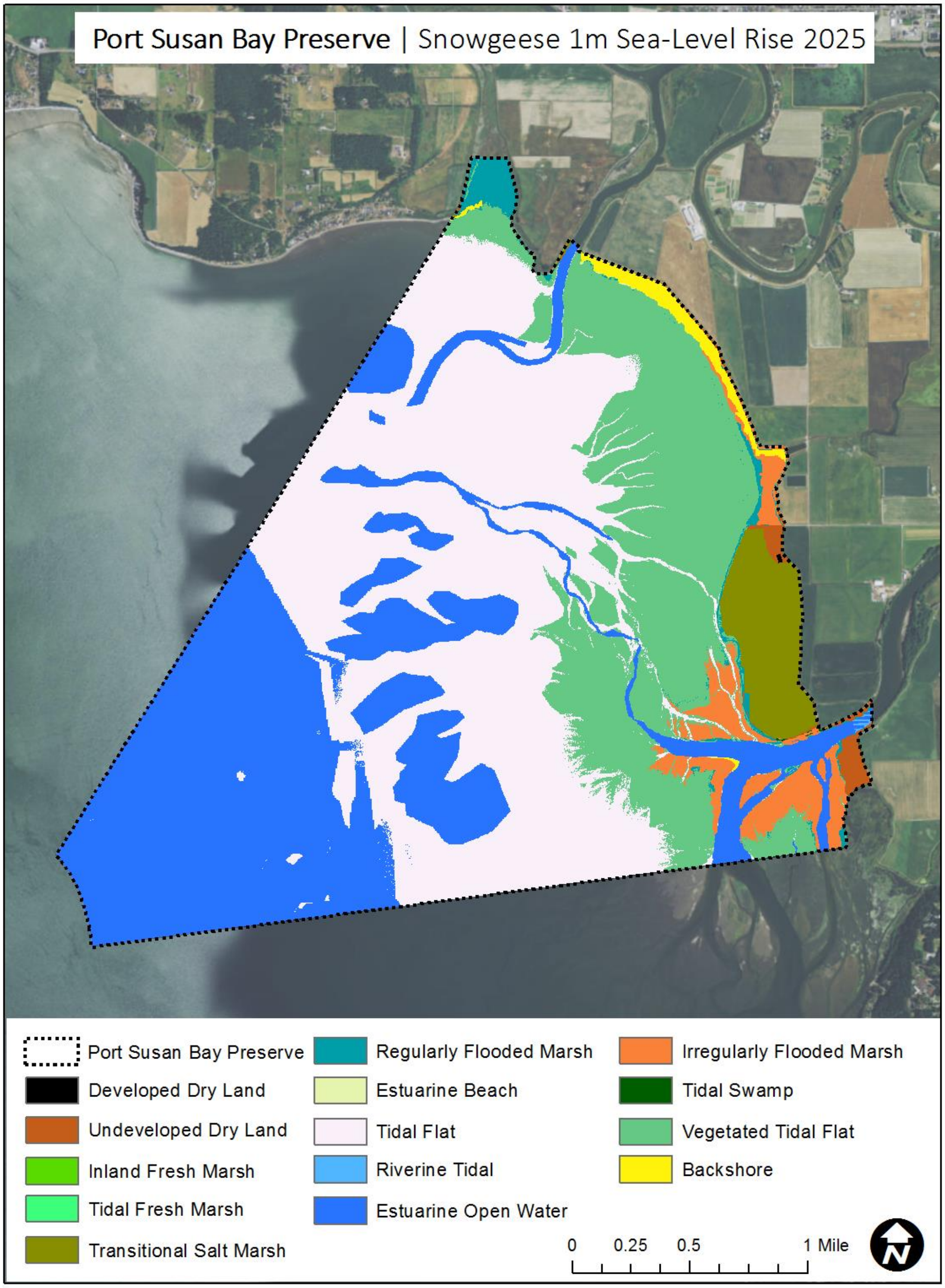

Port Susan Bay Preserve | Snowgeese 1m Sea-Level Rise 2025
Port Susan Bay Preserve
Developed Dry Land
Undeveloped Dry Land
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Salt Marsh
Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
Riverine Tidal
Estuarine Open Water
Irregularly Flooded Marsh
Tidal Swamp
Vegetated Tidal Flat
Backshore
0
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1 Mile
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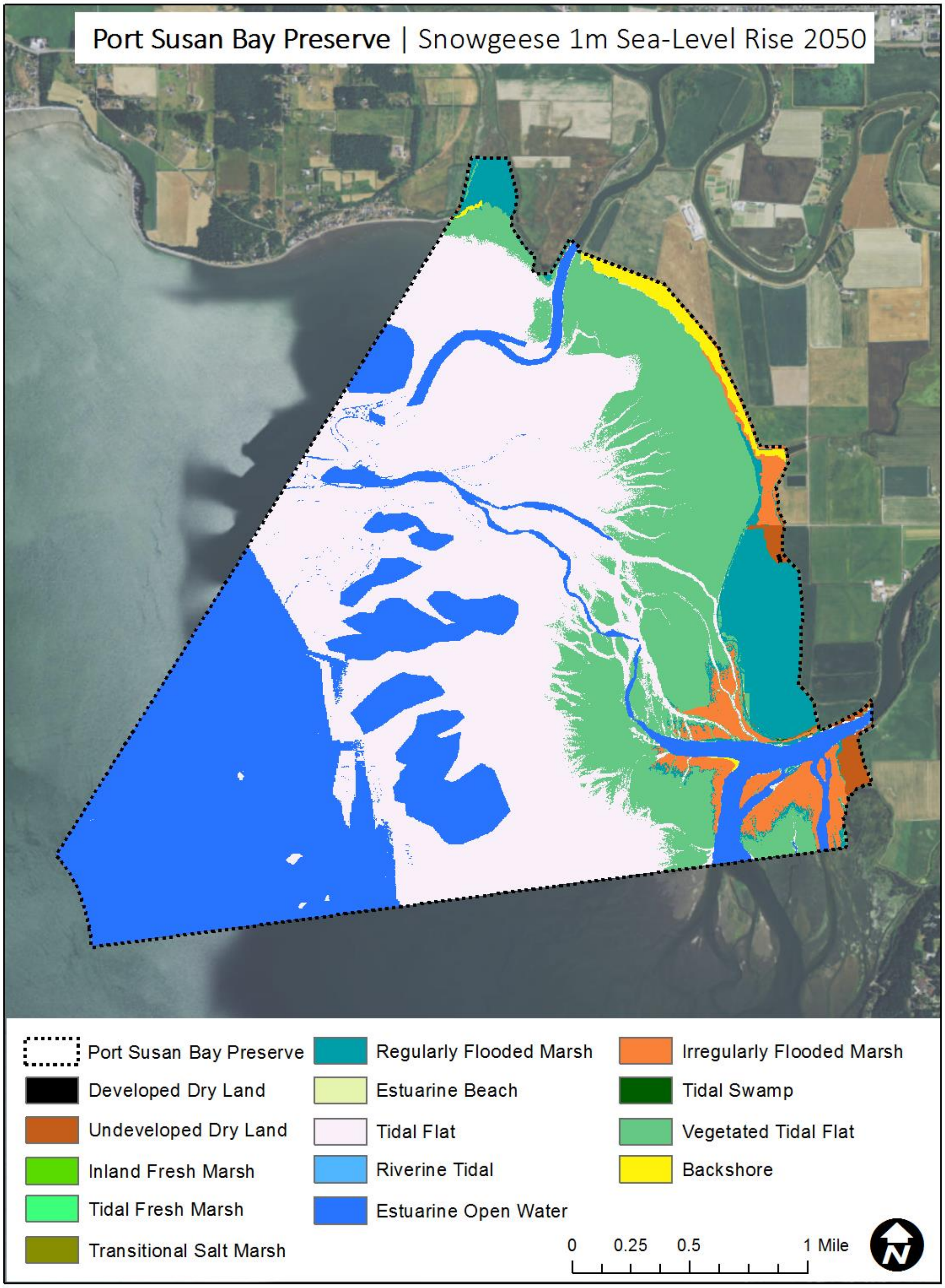

Port Susan Bay Preserve | Snowgeese 1m Sea-Level Rise 2050
Port Susan Bay Preserve
Developed Dry Land
Undeveloped Dry Land
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Salt Marsh
Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
Riverine Tidal
Estuarine Open Water
Irregularly Flooded Marsh
Tidal Swamp
Vegetated Tidal Flat
Backshore
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1 Mile
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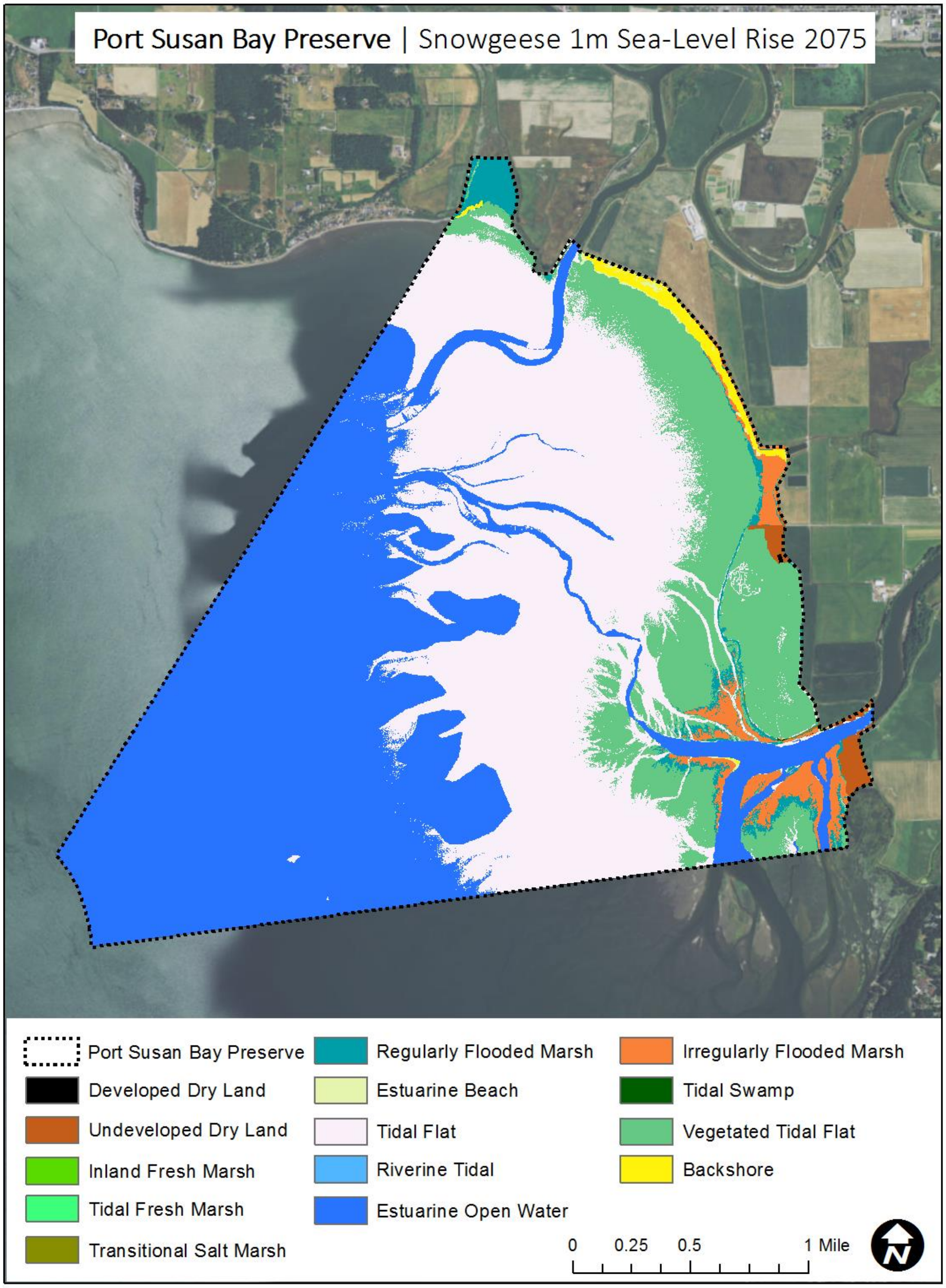
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Port Susan Bay Preserve
Developed Dry Land
Undeveloped Dry Land
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Salt Marsh
Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
Riverine Tidal
Estuarine Open Water
Irregularly Flooded Marsh
Tidal Swamp
Vegetated Tidal Flat
Backshore
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1 Mile
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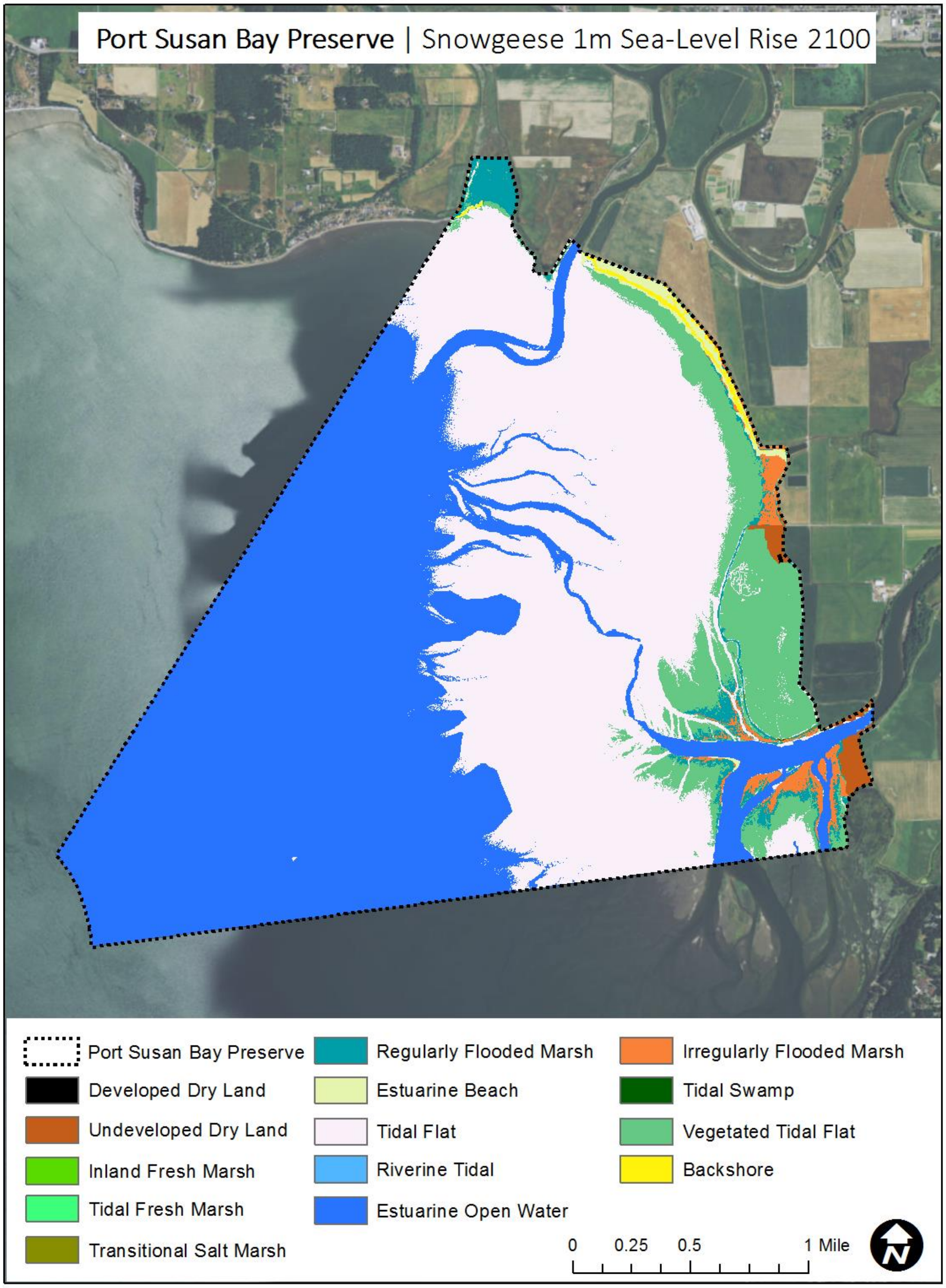
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Port Susan Bay Preserve
Developed Dry Land
Undeveloped Dry Land
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Salt Marsh
Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
Riverine Tidal
Estuarine Open Water
Irregularly Flooded Marsh
Tidal Swamp
Vegetated Tidal Flat
Backshore
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1 Mile
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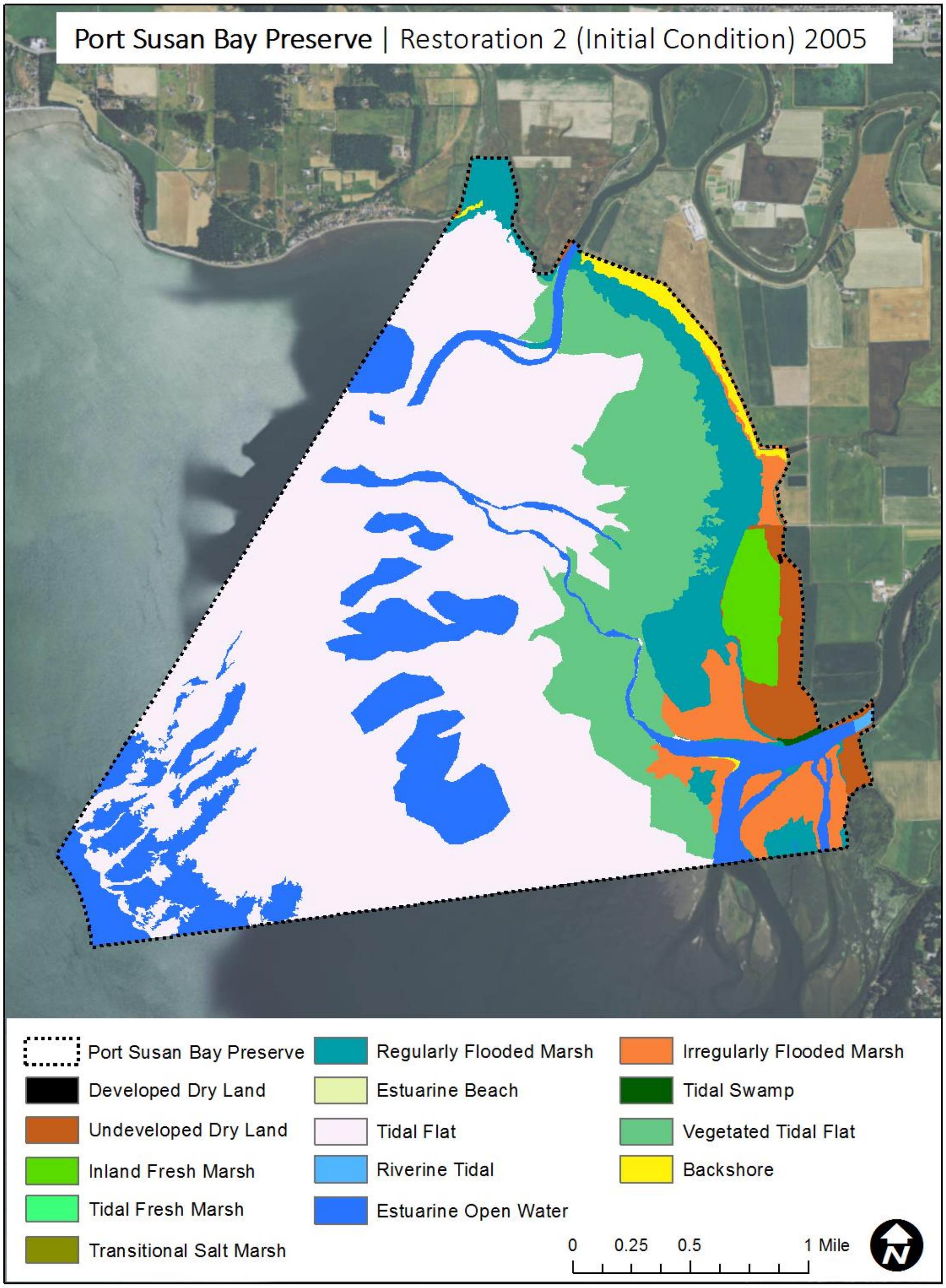
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Port Susan Bay Preserve
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Undeveloped Dry Land
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Salt Marsh
Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
Riverine Tidal
Estuarine Open Water
Irregularly Flooded Marsh
Tidal Swamp
Vegetated Tidal Flat
Backshore
0 0.25 0.5 1 Mile
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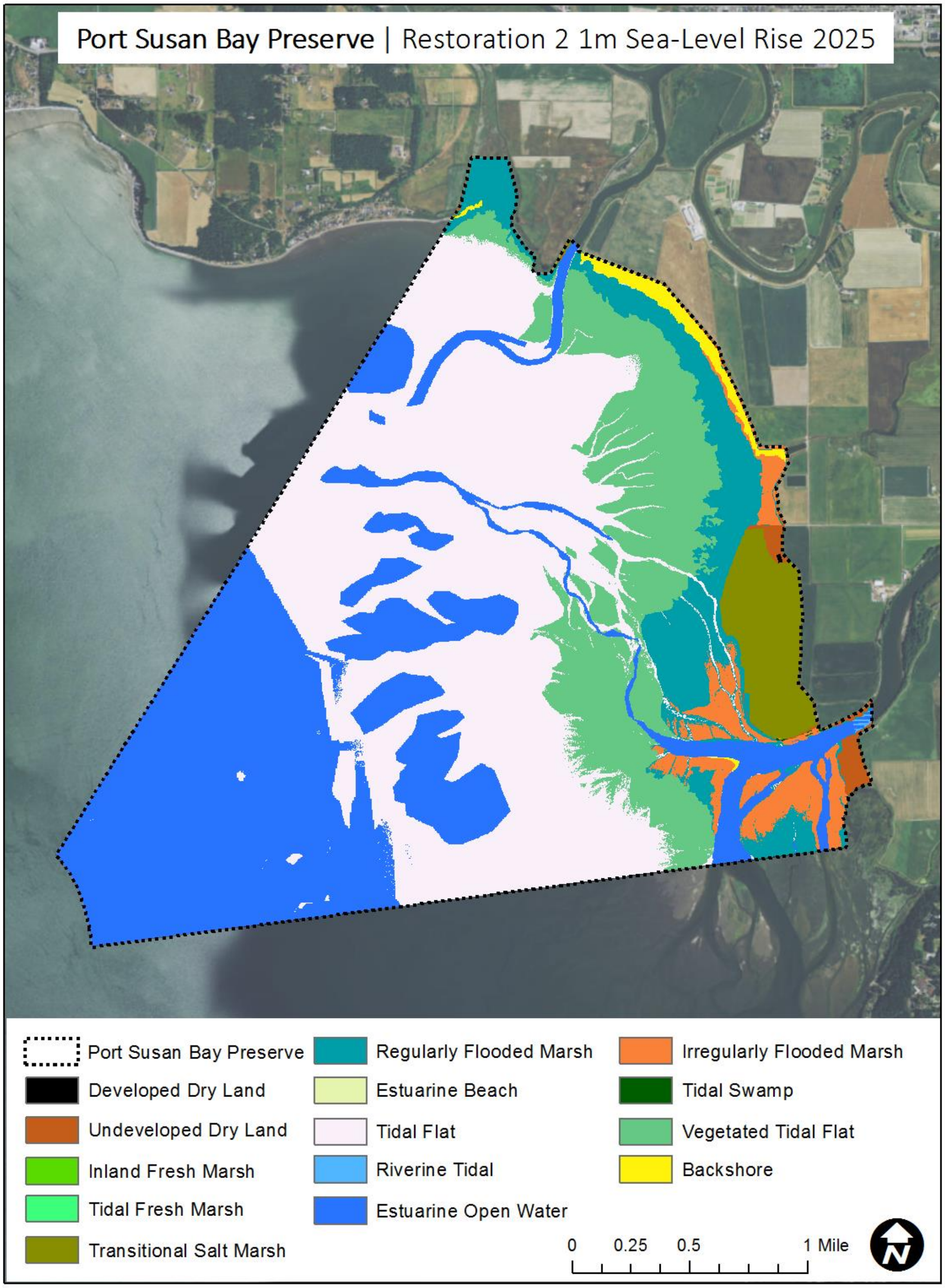

Port Susan Bay Preserve | Restoration 2 1m Sea-Level Rise 2025
Port Susan Bay Preserve
Developed Dry Land
Undeveloped Dry Land
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Salt Marsh
Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
Riverine Tidal
Estuarine Open Water
Irregularly Flooded Marsh
Tidal Swamp
Vegetated Tidal Flat
Backshore
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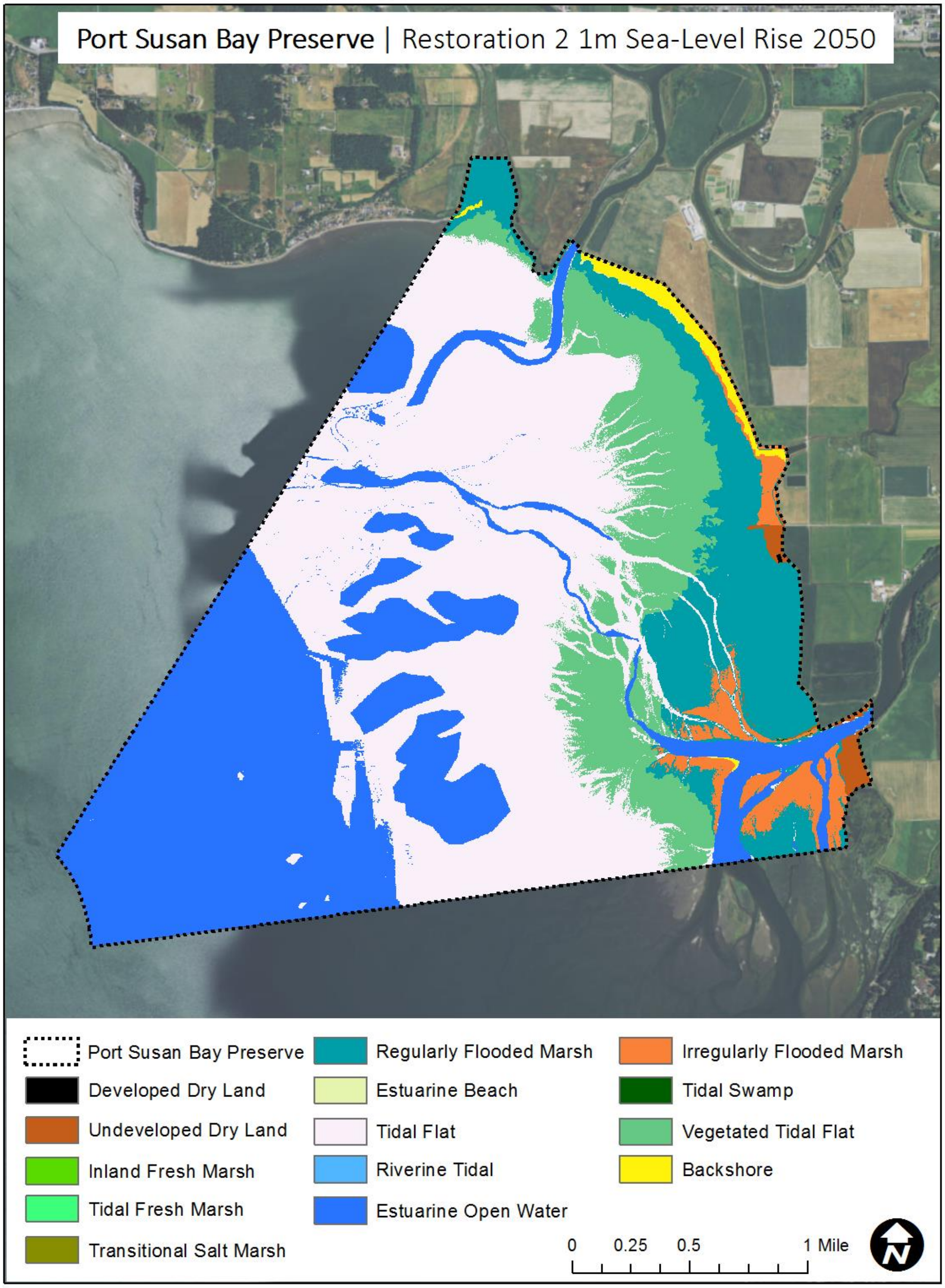
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Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
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Vegetated Tidal Flat
Backshore
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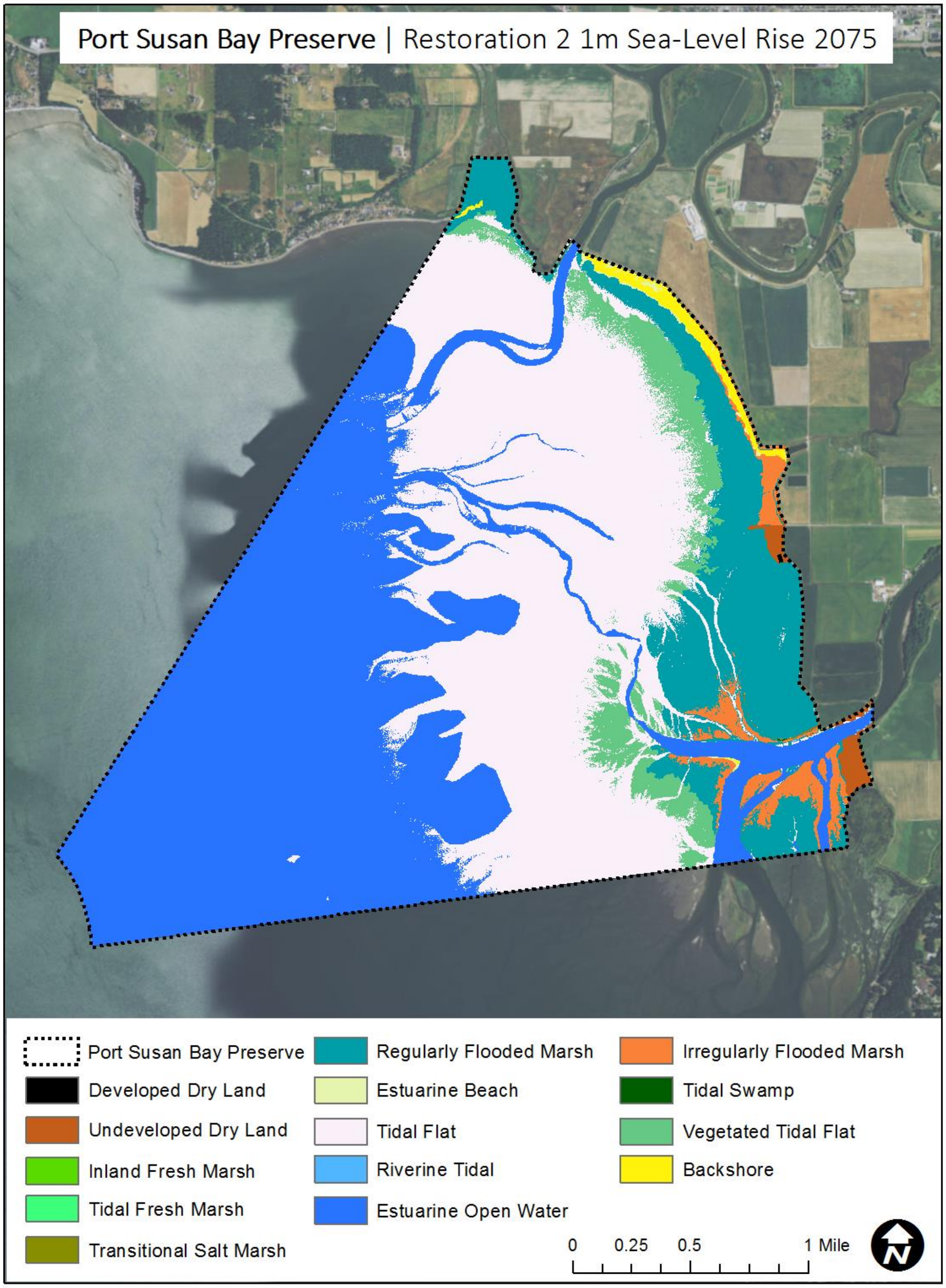
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Port Susan Bay Preserve
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Undeveloped Dry Land
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Salt Marsh
Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
Riverine Tidal
Estuarine Open Water
Irregularly Flooded Marsh
Tidal Swamp
Vegetated Tidal Flat
Backshore
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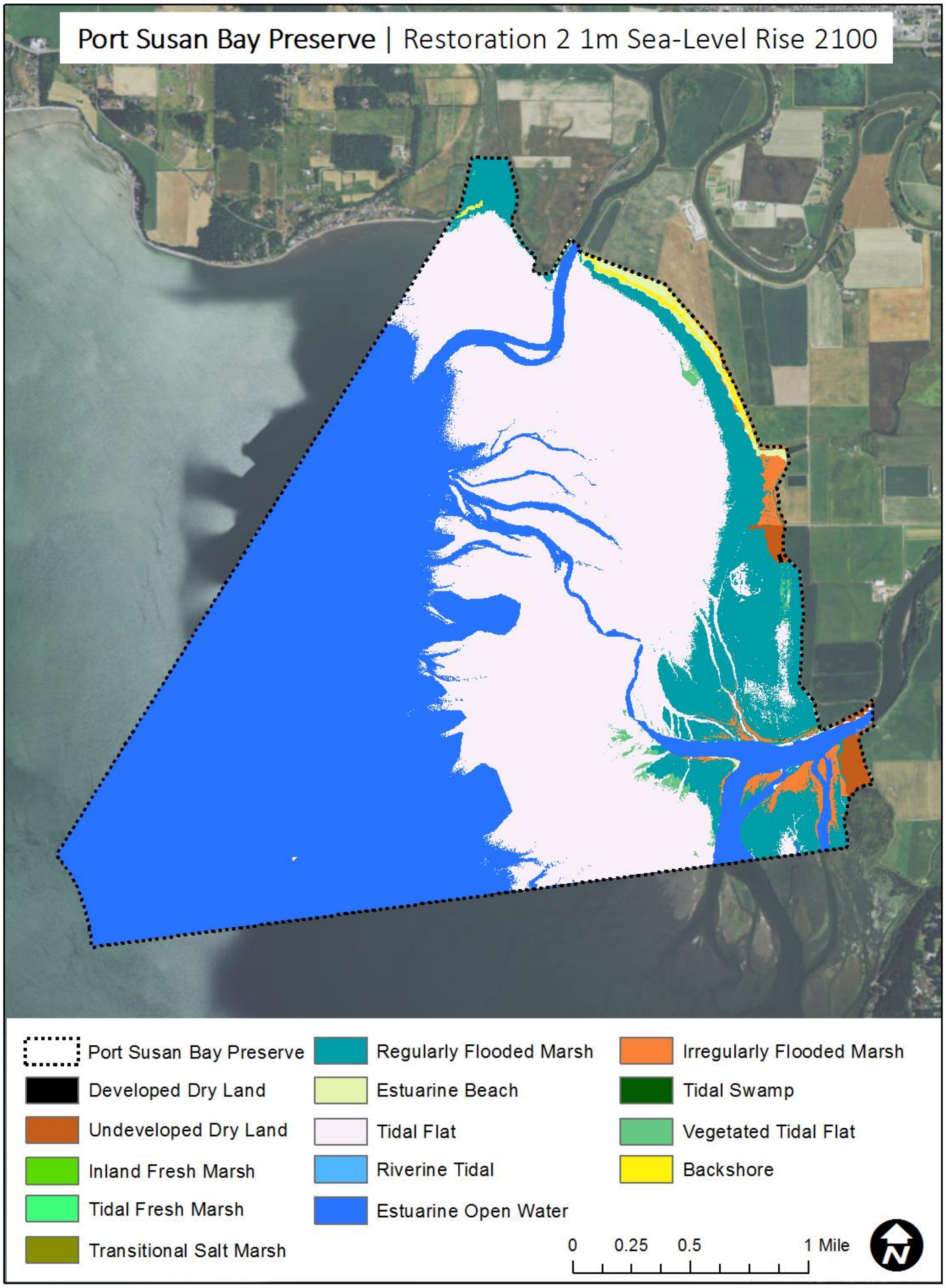
Port Susan Bay Preserve | Restoration 2 1m Sea-Level Rise 2100
Port Susan Bay Preserve
Developed Dry Land
Undeveloped Dry Land
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Salt Marsh
Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
Riverine Tidal
Estuarine Open Water
Irregularly Flooded Marsh
Tidal Swamp
Vegetated Tidal Flat
Backshore
0 0.25 0.5 1 Mile
N

Appendix 2 Output log from the Prepare LULC Map tool

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333333333],PARAMETER['Latitude_Of_Origin',47.0],UNIT['Meter',1.0]]
Executing (Define Projection): DefineProjection
D:\GISDATA\UWGIS\GEOG569\Model\input\SLAMM\Restore2NoData256\portsusan_restore2_2050_1meter_GIS.t
if
PROJCS['NAD_1983_HARN_StatePlane_Washington_North_FIPS_4601',GEOGCS['GCS_North_American_1983_HARN
',DATUM['D_North_American_1983_HARN',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenw
ich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Lambert_Conformal_Conic'],PARAMETER['Fal
se_Easting',500000.0],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-
120.8333333333333],PARAMETER['Standard_Parallel_1',47.5],PARAMETER['Standard_Parallel_2',48.73333
333333333],PARAMETER['Latitude_Of_Origin',47.0],UNIT['Meter',1.0]]
Executing (Define Projection): DefineProjection
D:\GISDATA\UWGIS\GEOG569\Model\input\SLAMM\Restore2NoData256\portsusan_restore2_2075_1meter_GIS.t
if
PROJCS['NAD_1983_HARN_StatePlane_Washington_North_FIPS_4601',GEOGCS['GCS_North_American_1983_HARN
',DATUM['D_North_American_1983_HARN',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenw
ich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Lambert_Conformal_Conic'],PARAMETER['Fal
se_Easting',500000.0],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-
120.8333333333333],PARAMETER['Standard_Parallel_1',47.5],PARAMETER['Standard_Parallel_2',48.73333
333333333],PARAMETER['Latitude_Of_Origin',47.0],UNIT['Meter',1.0]]
Executing (Define Projection): DefineProjection
D:\GISDATA\UWGIS\GEOG569\Model\input\SLAMM\Restore2NoData256\portsusan_restore2_2100_1meter_GIS.t
if
PROJCS['NAD_1983_HARN_StatePlane_Washington_North_FIPS_4601',GEOGCS['GCS_North_American_1983_HARN
',DATUM['D_North_American_1983_HARN',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenw
ich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Lambert_Conformal_Conic'],PARAMETER['Fal
se_Easting',500000.0],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-
120.8333333333333],PARAMETER['Standard_Parallel_1',47.5],PARAMETER['Standard_Parallel_2',48.73333
333333333],PARAMETER['Latitude_Of_Origin',47.0],UNIT['Meter',1.0]]
Succeeded at Sat Aug 15 12:55:18 2015 (Elapsed Time: 0.23 seconds)
Succeeded at Sat Aug 15 12:55:18 2015 (Elapsed Time: 44.12 seconds)
```

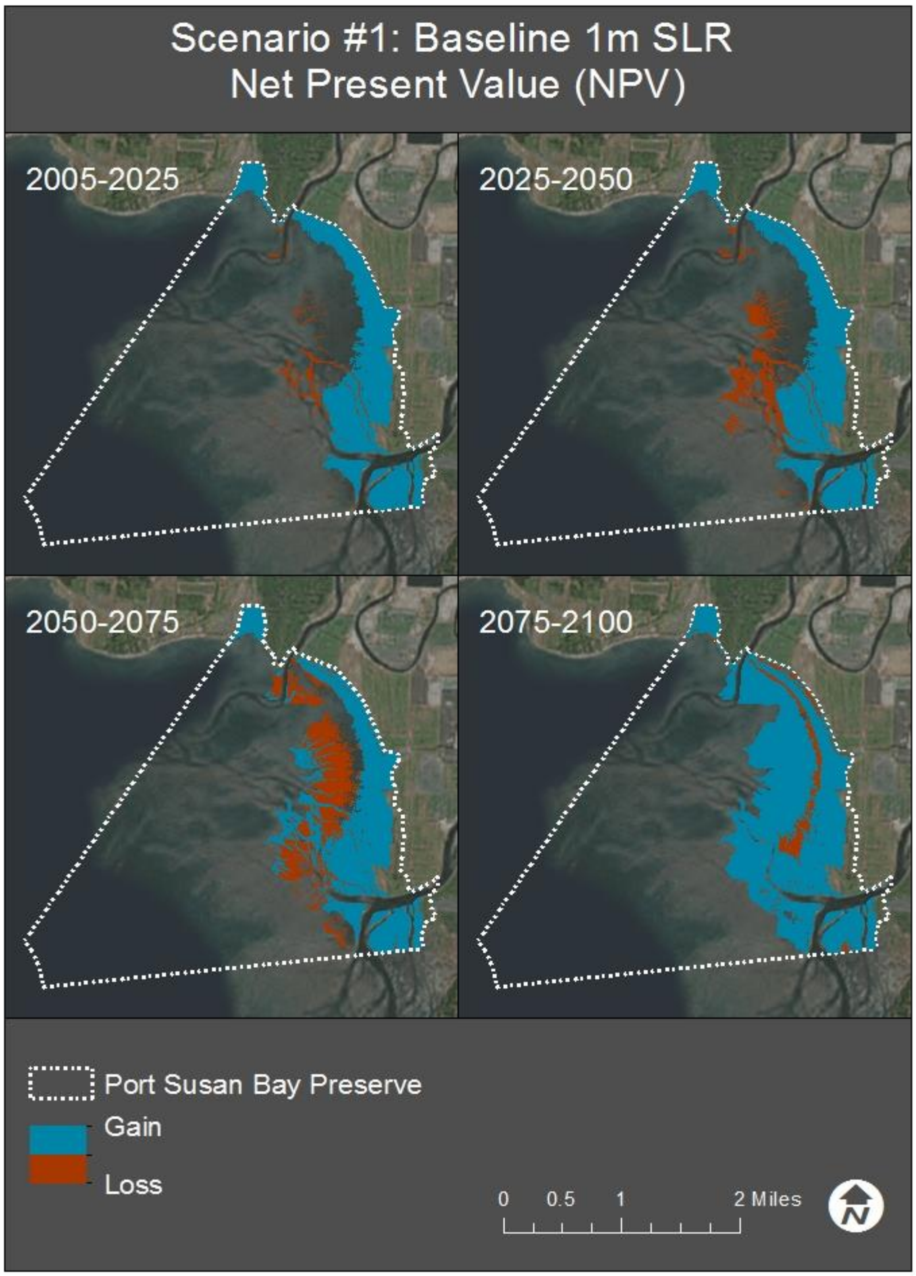
Appendix 3 Transition matrix as output from the CBC pre-processor tool

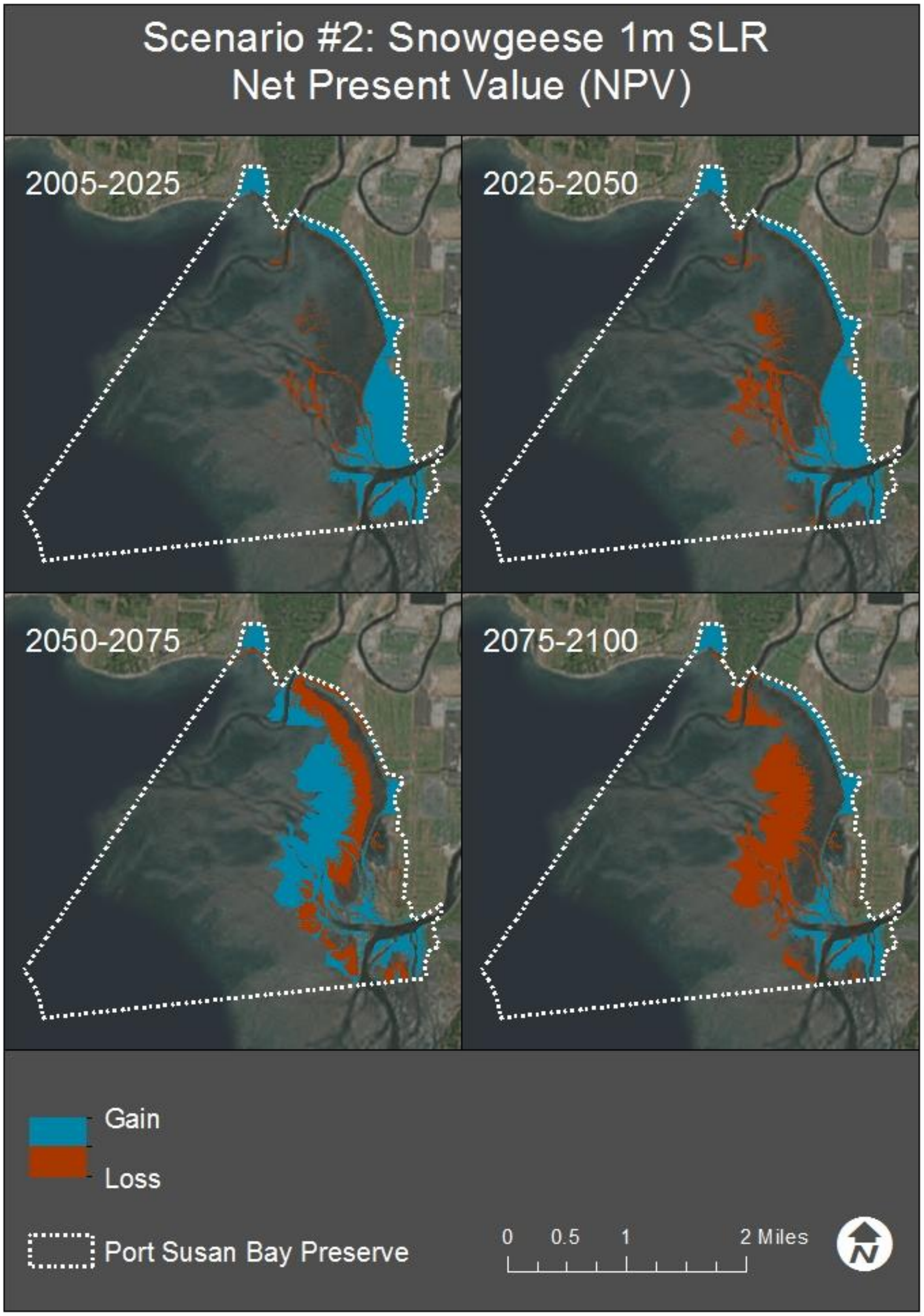
Id	Name	1	2	3	5	6	7	8	10	11	15	16	17	20	22	23	25	26
1	Developed Dry Land	None	None	None	None	None	Accumulation	Accumulation	None	None	None	None	None	None	None	None	None	None
2	Undeveloped Dry Land	None	None	None	None	None	Accumulation	Accumulation	None	None	None	None	None	None	None	None	Accumulation	None
3	Swamp	None	None	None	None	None	Accumulation	Accumulation	None	None	None	None	None	Accumulation	None	None	None	None
5	Inland Fresh Marsh	None	None	None	Accumulation	None	Accumulation	Accumulation	None	None	None	None	Disturbance	None	None	None	None	None
6	Tidal Fresh Marsh	None	None	None	None	Accumulation	None	Accumulation	None	None	None	None	Disturbance	Accumulation	None	None	None	None
7	Trans. Salt Marsh	None	None	None	None	None	Accumulation	Accumulation	None	Disturbance	None	None	Disturbance	None	None	None	None	None
8	Regularly Flooded Marsh	Disturbance	Disturbance	None	None	None	Accumulation	Accumulation	None	Disturbance	None	None	Disturbance	Accumulation	None	None	Accumulation	None
10	Estuarine Beach	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None
11	Tidal Flat	None	None	None	None	None	None	Accumulation	None	None	None	None	None	None	None	None	Accumulation	None
15	Inland Open Water	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None
16	Riverine Tidal	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None
17	Estuarine Open Water	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None
20	Irreg. Flooded Marsh	None	None	None	None	None	None	Accumulation	None	Disturbance	None	None	Disturbance	Accumulation	None	None	None	None
22	Inland Shore	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None
23	Tidal Swamp	None	None	None	None	None	None	Accumulation	None	None	None	None	None	Accumulation	None	None	None	None
25	Vegetated Tidal Flat	None	None	None	None	None	None	None	None	Disturbance	None	None	Disturbance	None	None	None	Accumulation	None
26	Backshore	None	None	None	None	None	None	None	Disturbance	None	None	None	Disturbance	None	None	None	None	Accumulation

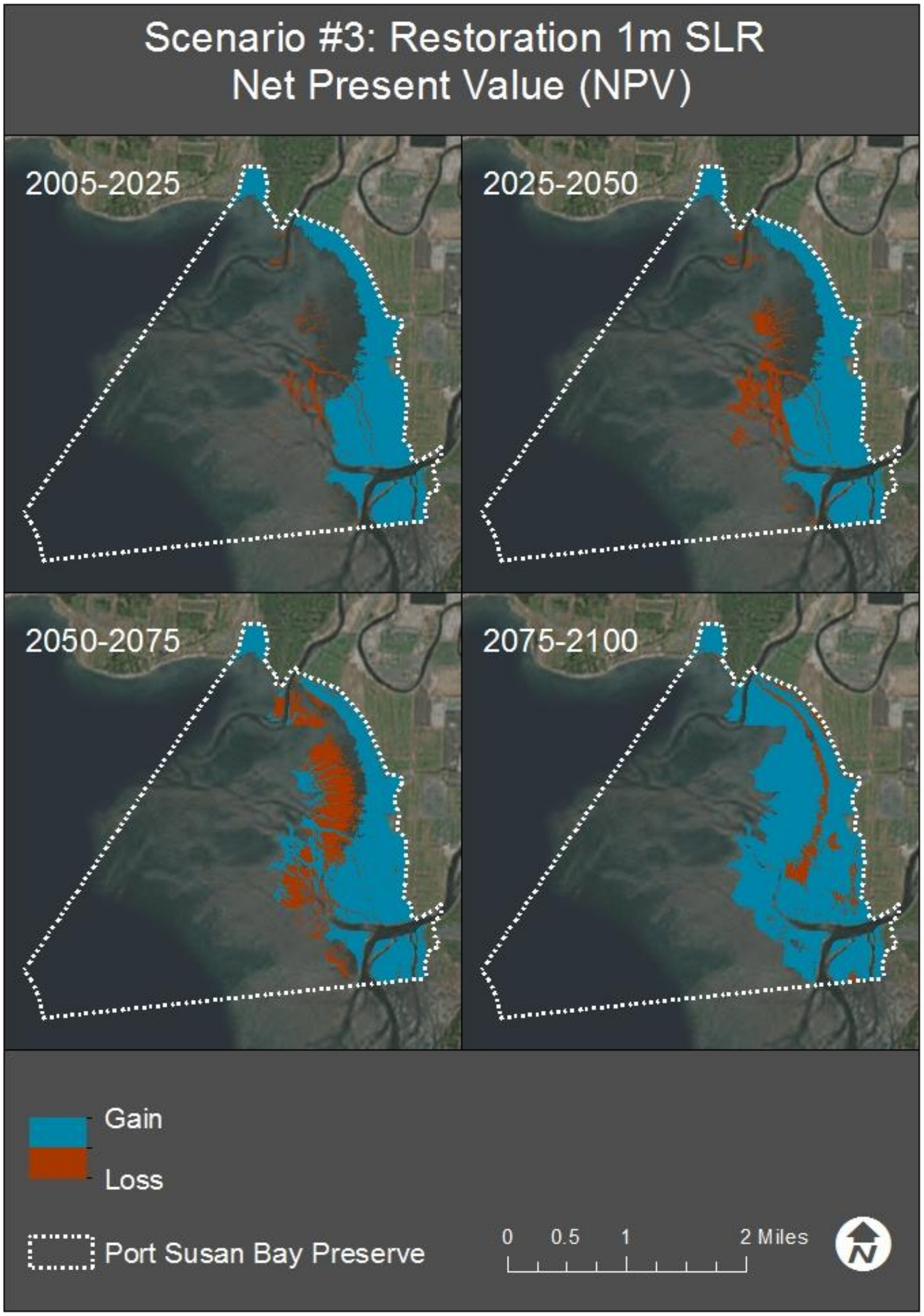
Appendix 4 User-modified transition matrix with disturbance magnitudes

Id	Name	1	2	3	5	6	7	8	10	11	15	16	17	20	22	23	25	26
1	Developed Dry Land	None	None	None	None	None	Accumulation	Accumulation	None	None	None	None	None	None	None	None	None	None
2	Undeveloped Dry Land	None	None	None	None	None	Accumulation	Accumulation	None	None	None	None	None	None	None	None	Accumulation	None
3	Swamp	None	None	None	None	None	Accumulation	Accumulation	None	None	None	None	None	Accumulation	None	None	None	None
5	Inland Fresh Marsh	None	None	None	Accumulation	None	Accumulation	Accumulation	None	None	None	None	Low Disturbance	None	None	None	None	None
6	Tidal Fresh Marsh	None	None	None	None	Accumulation	None	Accumulation	None	None	None	None	Low Disturbance	Accumulation	None	None	None	None
7	Trans. Salt Marsh	None	None	None	None	None	Accumulation	Accumulation	None	Medium Disturbance	None	None	Low Disturbance	None	None	None	None	None
8	Regularly Flooded Marsh	High Disturbance	High Disturbance	None	None	None	Accumulation	Accumulation	None	Medium Disturbance	None	None	Low Disturbance	Accumulation	None	None	Accumulation	None
10	Estuarine Beach	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None
11	Tidal Flat	None	None	None	None	None	None	Accumulation	None	None	None	None	None	None	None	None	Accumulation	None
15	Inland Open Water	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None
16	Riverine Tidal	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None
17	Estuarine Open Water	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None
20	Irreg. Flooded Marsh	None	None	None	None	None	None	Accumulation	None	Medium Disturbance	None	None	Low Disturbance	Accumulation	None	None	None	None
22	Inland Shore	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None
23	Tidal Swamp	None	None	None	None	None	None	Accumulation	None	None	None	None	None	Accumulation	None	None	None	None
25	Vegetated Tidal Flat	None	None	None	None	None	None	None	None	Medium Disturbance	None	None	Low Disturbance	None	None	None	Accumulation	None
26	Backshore	None	None	None	None	None	None	None	Medium Disturbance	None	None	None	Low Disturbance	None	None	None	None	Accumulation

Appendix 5 Full-page net present value (NPV) output maps by scenario for all time periods

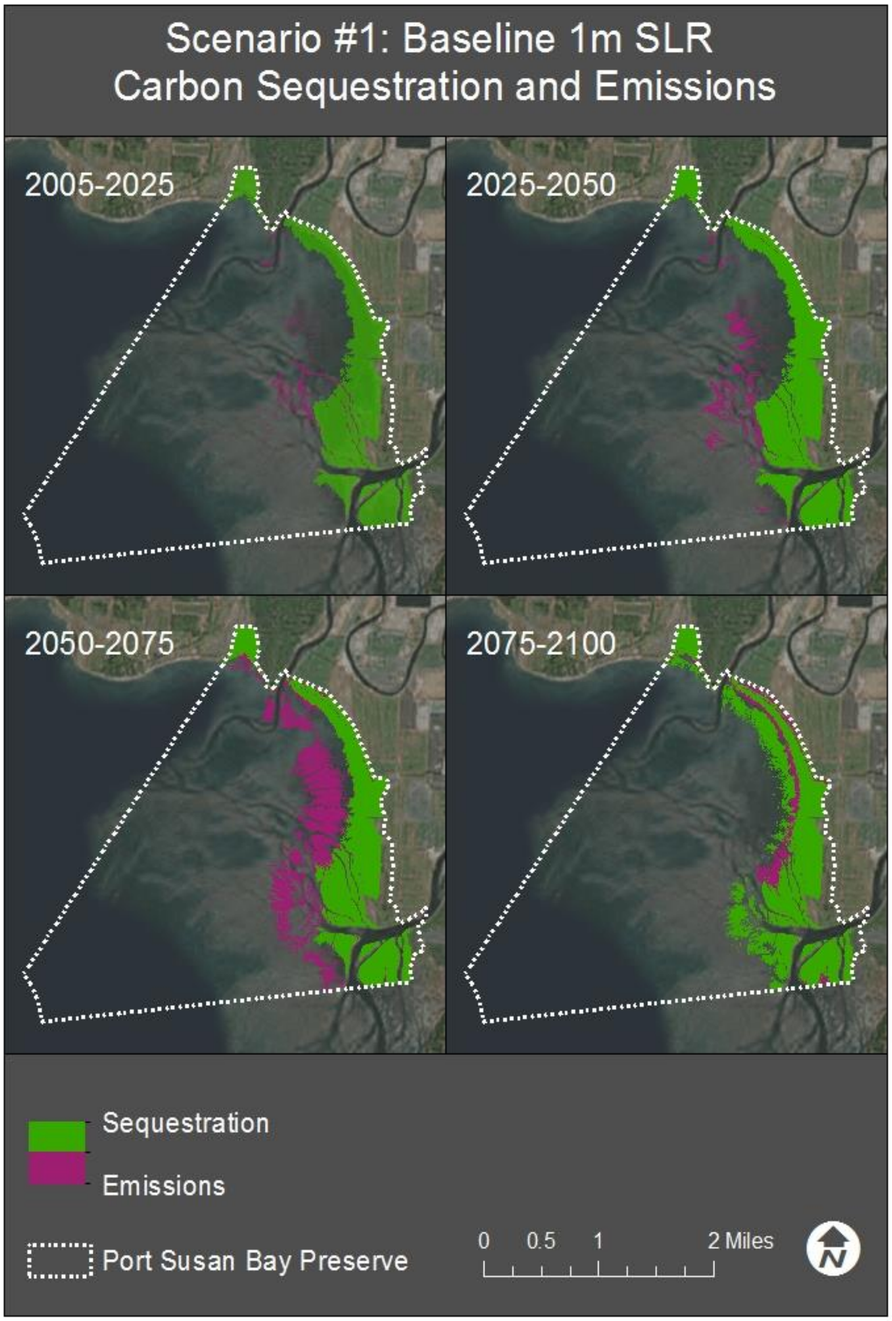


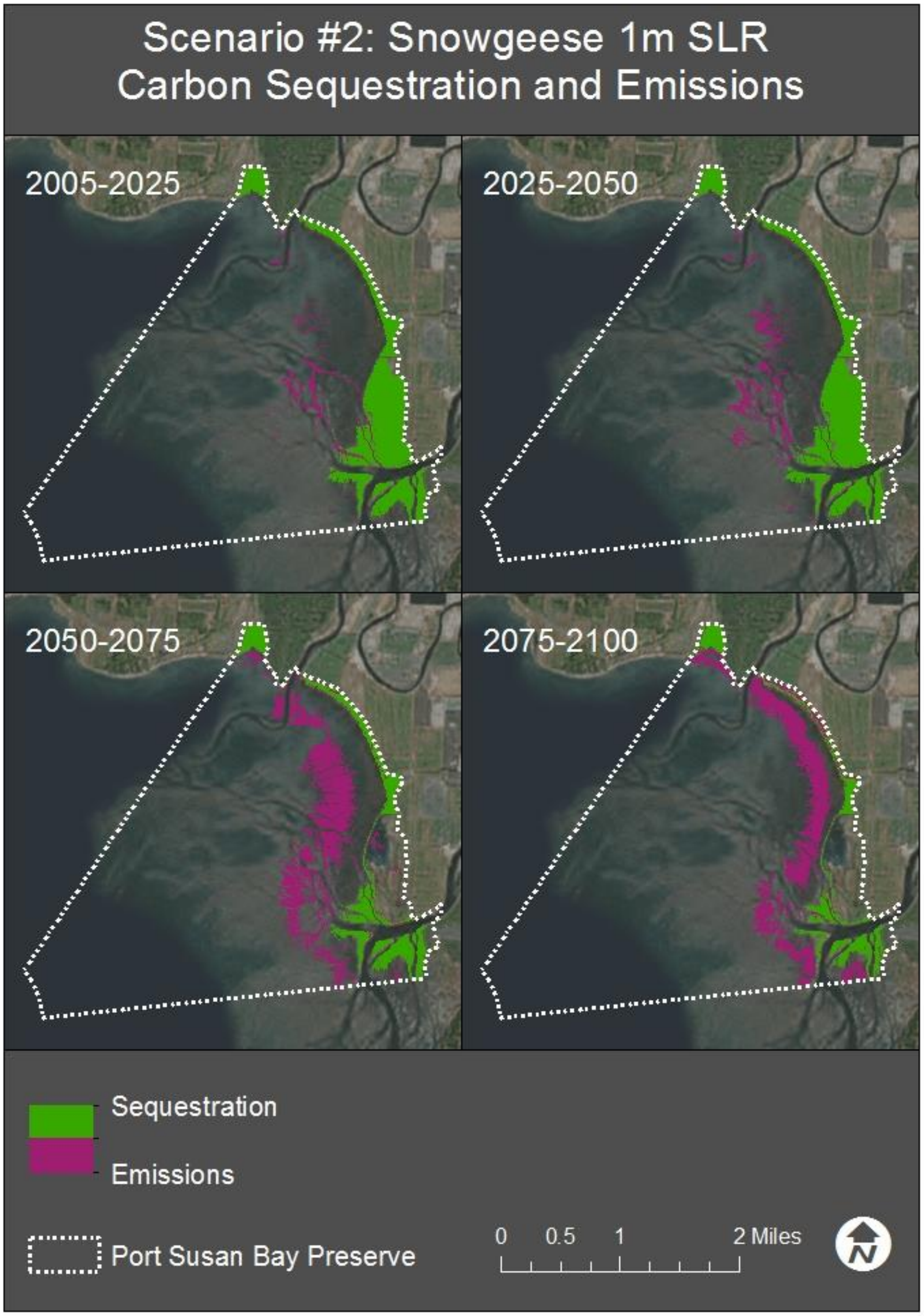

Scenario #2: Snowgeese 1m SLR
Net Present Value (NPV)
2005-2025
2025-2050
2050-2075
2075-2100
Gain
Loss
Port Susan Bay Preserve
0 0.5 1 2 Miles
N



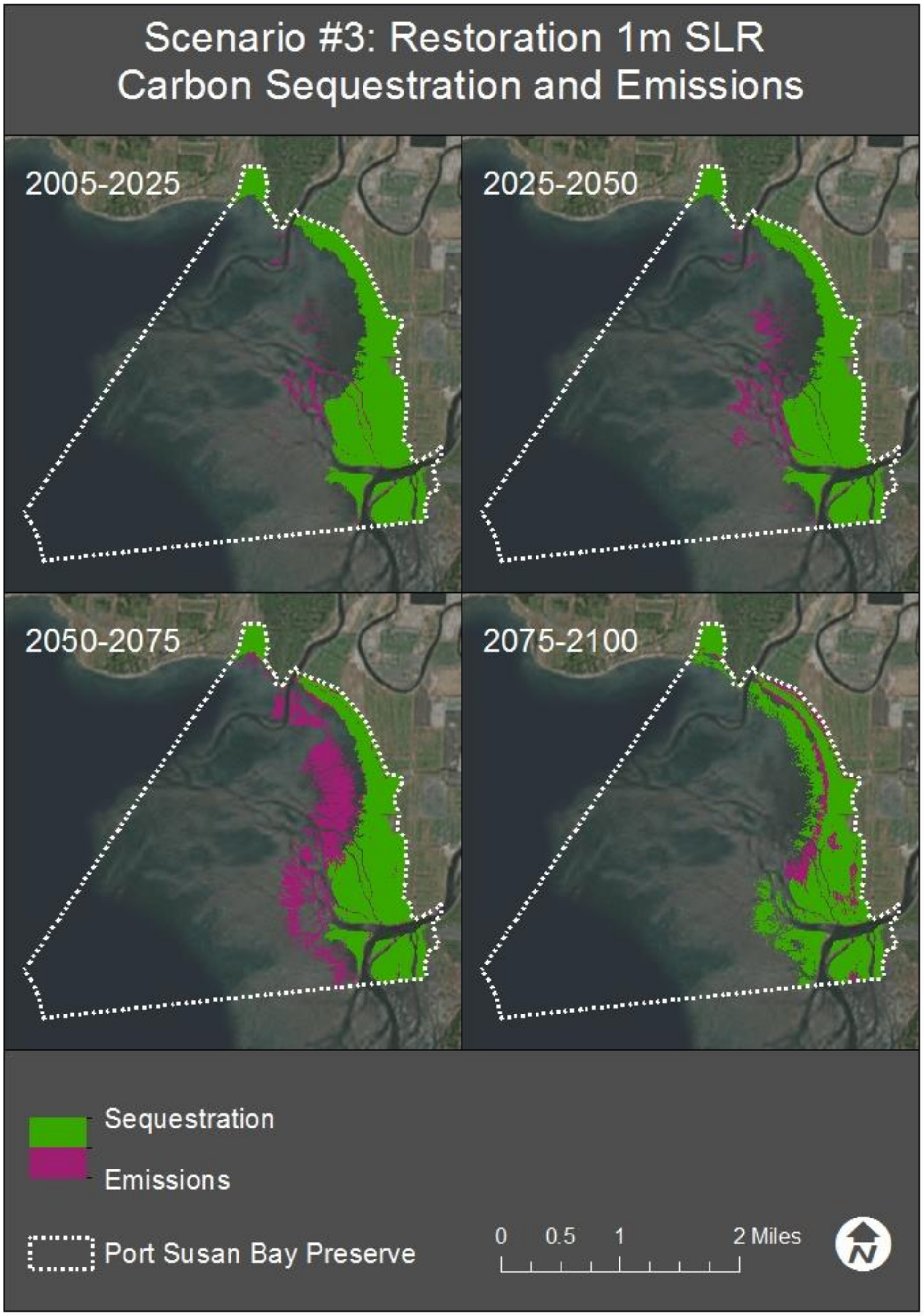
Scenario #3: Restoration 1m SLR
Net Present Value (NPV)
2005-2025
2025-2050
2050-2075
2075-2100
Gain
Loss
Port Susan Bay Preserve
0 0.5 1 2 Miles
N

Appendix 6 Full-page carbon sequestration and emissions output maps by scenario for all time periods



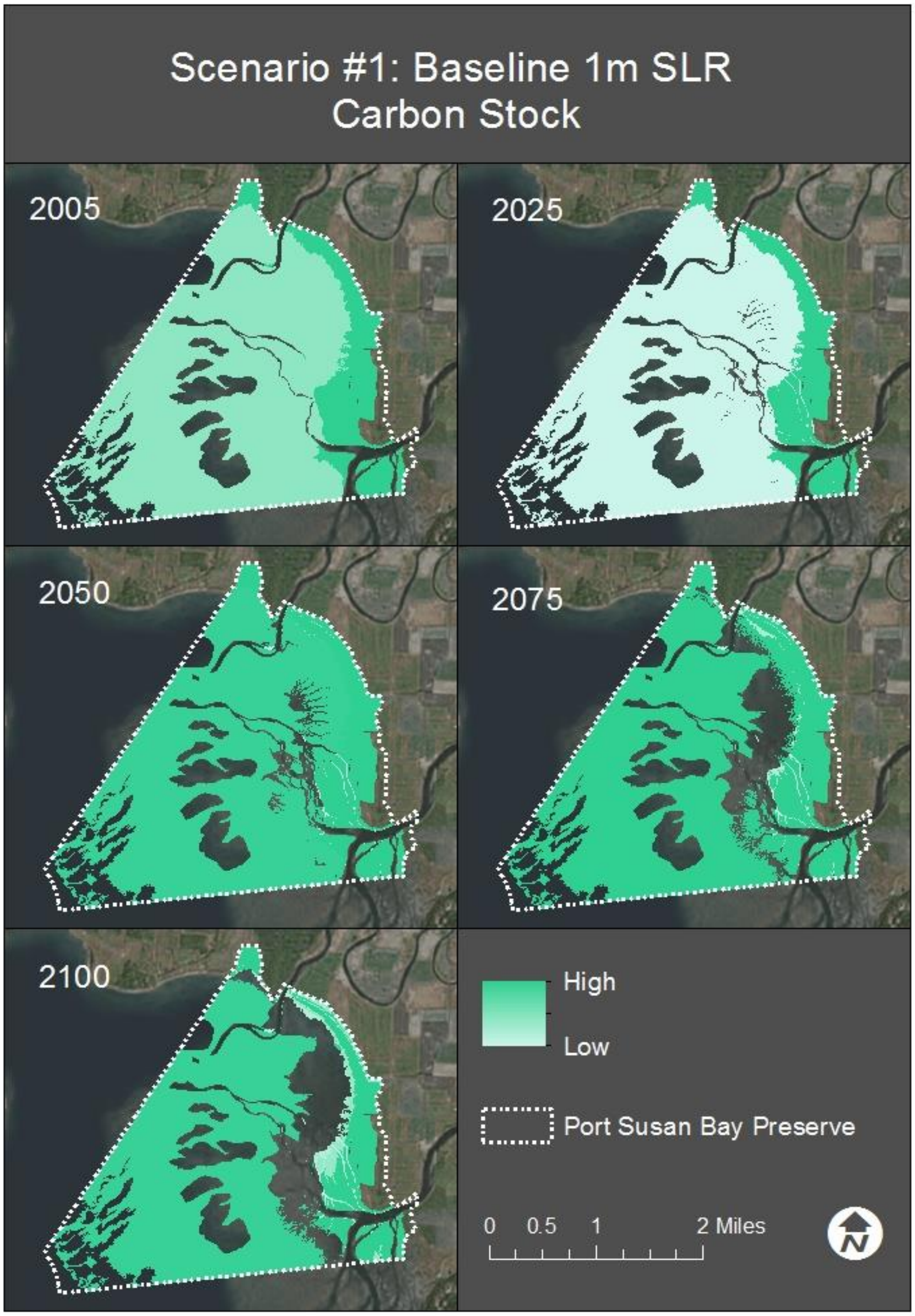


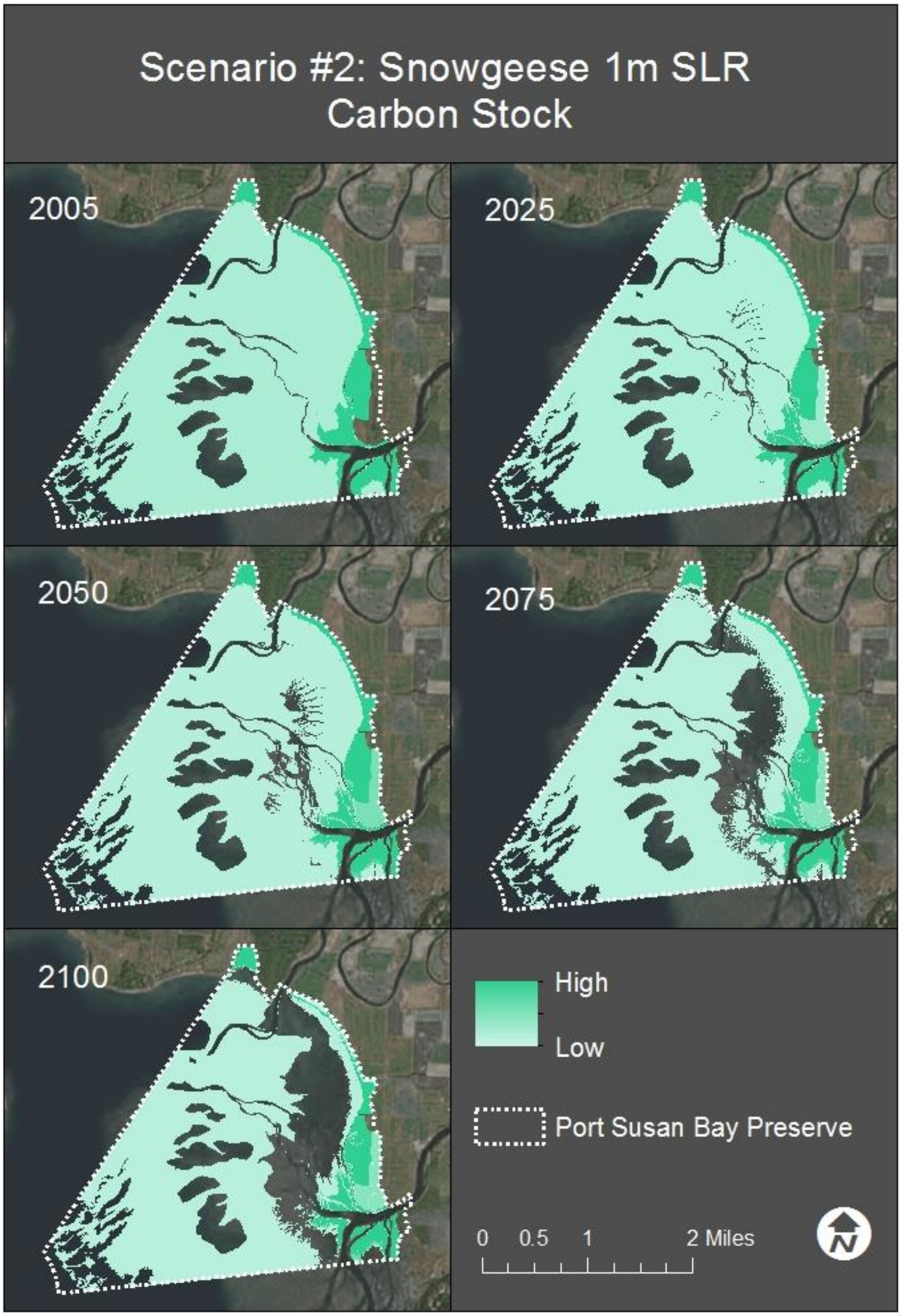
Scenario #2: Snowgeese 1m SLR
Carbon Sequestration and Emissions
2005-2025
2025-2050
2050-2075
2075-2100
Sequestration
Emissions
Port Susan Bay Preserve
0
0.5
1
2 Miles
N

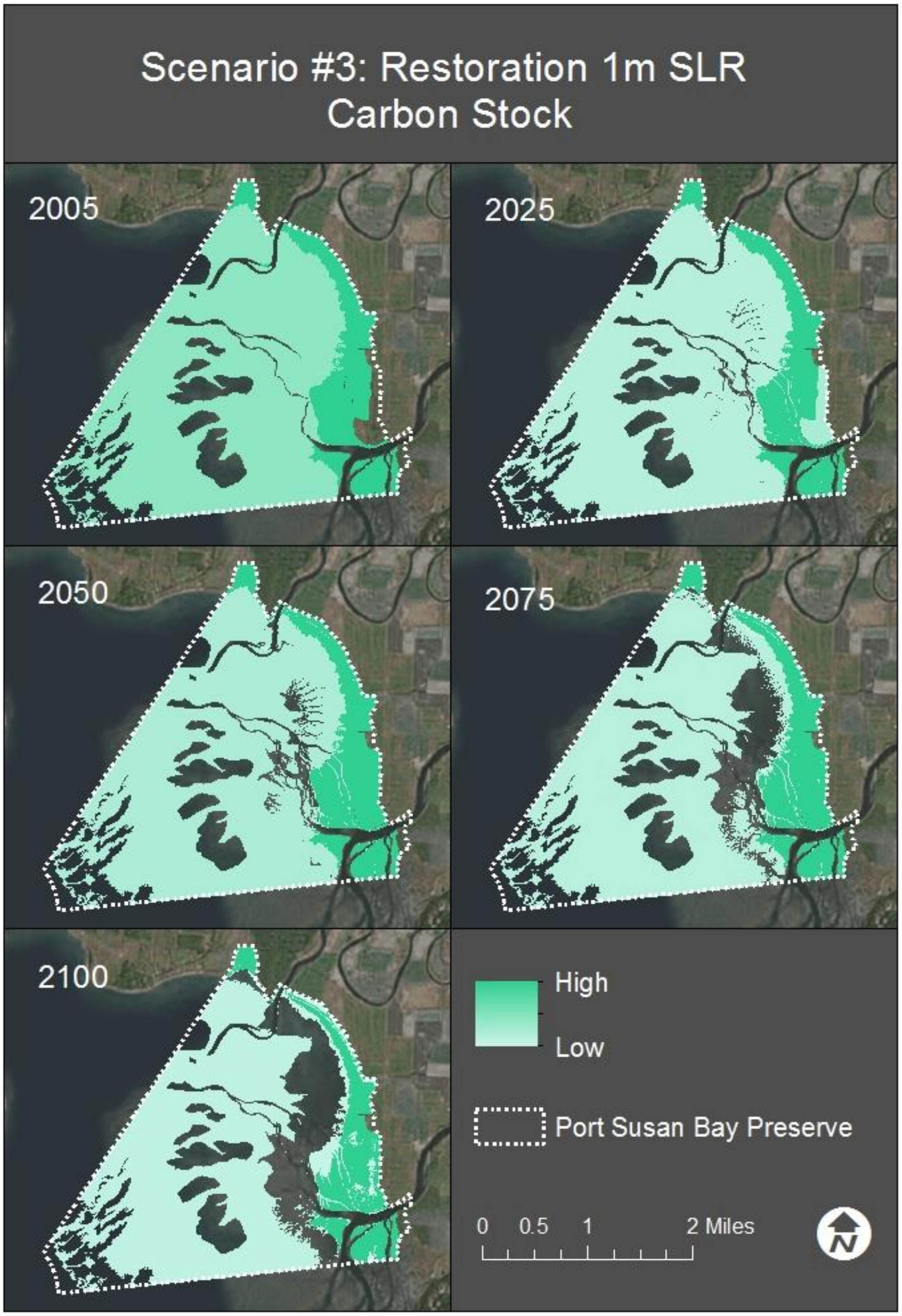


Scenario #3: Restoration 1m SLR
Carbon Sequestration and Emissions
2005-2025
2025-2050
2050-2075
2075-2100
Sequestration
Emissions
Port Susan Bay Preserve
0 0.5 1 2 Miles
N

Appendix 7 Full-page carbon stock output maps by scenario for all time periods




Scenario #2: Snowgeese 1m SLR
Carbon Stock
2005
2025
2050
2075
2100
High
Low
Port Susan Bay Preserve
0 0.5 1 2 Miles
N


Scenario #3: Restoration 1m SLR
Carbon Stock
2005
2025
2050
2075
2100
High
Low
Port Susan Bay Preserve
0
0.5
1
2 Miles
N