Prioritizing wetlands for carbon and resilience

Future coastal habitat and blue carbon modeling: Background and methods

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Background

The InVEST coastal blue carbon model (Sharp et al. 2018) estimates the amount of carbon stored in coastal habitats at set time points and the amount of carbon sequestered by those habitats over time. It also calculates carbon emitted due to disturbance or conversion of those habitats. It has been used previously for watershed-scale analyses (Richmond et al. 2015); no previous state- or national-level analyses using this model were found.

We developed a Python model to project changes to coastal habitats due to sea level rise; future coastal habitat maps were used as inputs for the InVEST coastal blue carbon model to assess carbon storage in salt marsh and seagrass habitats in the study area, how much additional carbon would be expected to accumulate if those habitats persisted undisturbed for a period of time, and how carbon fluxes from marshes might change due to sea level rise. Seagrass habitat extent and location were assumed to remain constant with sea level rise. While seagrasses will likely be affected by climate change through changes to light availability, water quality, and temperature (some of which are influenced by sea level rise), the variety of interacting factors make it difficult to predict whether and how seagrass in a particular area will be affected by sea level rise (Short and Neckles 1999). In contrast, marshes are very sensitive to inundation, and there has been a large amount of research on changes to marsh habitats due to sea level rise.

We also identified potentially restorable salt marsh and assessed the potential for “hands-off” restoration via reconnection of tidal flows due to sea level rise. Some of these areas were salt marsh in the past and become less saline following tidal disconnection due to a road, berm, or other barrier; others are natural freshwater marshes. In both cases, the low salinity makes these areas likely sources of methane, a potent greenhouse gas (Kroeger et al. 2017). Sea level rise is thought to increase salinity and reduce methane emissions when it reaches these areas. Restoring these areas to salt marsh also presents opportunities for restoration projects with carbon mitigation benefits (Fargione et al. 2018).

Model inputs and parameters

Key model inputs are maps representing the spatial distribution of blue carbon habitats at different time points and tables with information about the amount of carbon stored in each habitat type, the rate at which the habitat type sequesters additional carbon, and the impact of disturbance on carbon stored in the habitat.

Future spatial distribution of blue carbon habitats

Spatial representations of blue carbon habitats at different time points were created by starting with the current extent of blue carbon habitats and identifying where marshes are likely to drown, erode, accrete vertically, and migrate horizontally at set time points for several sea level rise scenarios. To create the future habitat map for a given SLR scenario and time point, several processes that cause changes to existing marsh and potentially restorable marsh are applied in succession: erosion, drowning or accretion due to SLR, and inland migration, as described in the following sections (Figure 1).

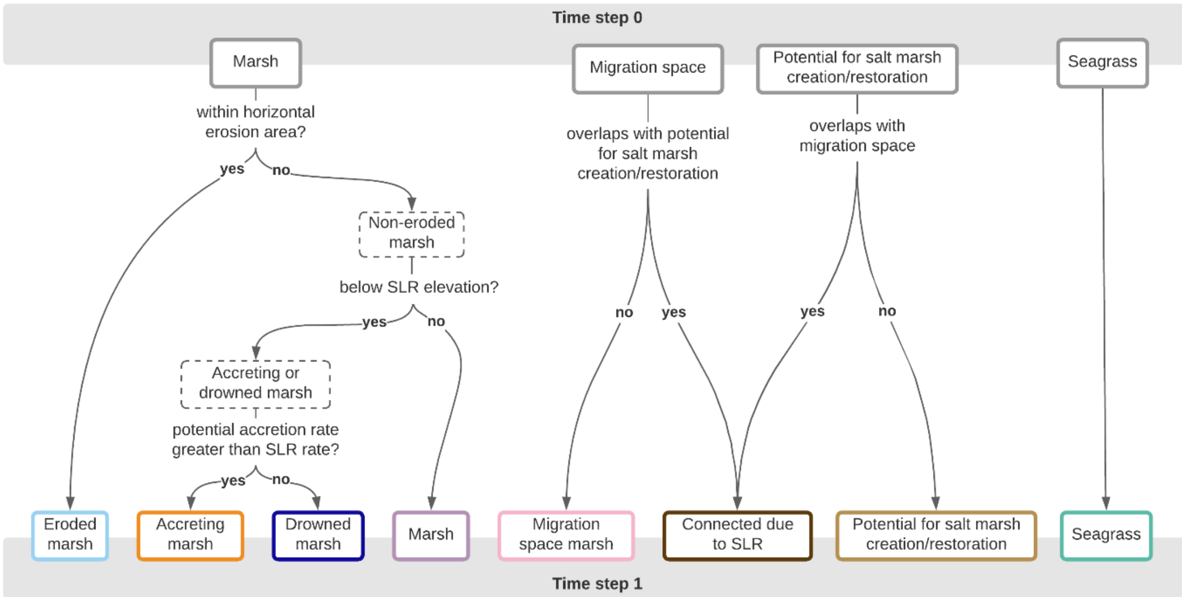

Figure 1: Process for creating future coastal habitat maps. For each time step, existing marsh is classified as eroded, accreting, drowned, or persisting marsh depending on the criteria shown in the flowchart. Accreting and persisting marsh areas are used as the marsh input for the next time step. Migration space for the SLR elevation associated with the timestep is overlaid with the potential for salt marsh creation/restoration layer; areas of overlap are classified as connected due to sea level rise, while non-overlapping migration space is migration space marsh, and non-overlapping potential for salt marsh creation/restoration remains unchanged as an input for the next time step. Seagrass extent is assumed to remain constant.

Sea level rise scenarios

A separate set of sea level rise scenarios was used for each state to align with the scenarios they currently use (formally or informally) in planning (Table 1). In addition, one common sea level rise scenario, the intermediate scenario from Sweet et al. 2017 (corresponding to 1-m global sea level rise by 2100), was used for a regional analysis to allow for cross-state comparison and use of the results.

Table 1. Sea level rise scenarios and sources for each state.

State	SLR scenarios	Source
Delaware	RCP 8.5, 17th and 83rd percentiles	Callahan et al. 2017
Maryland	RCP 2.6, RCP 4.5, and RCP 8.5, all 50th percentile	Boesch et al. 2018
New Jersey	Moderate emissions scenario, 83% chance of exceedance and 17% chance of exceedance	Kopp et al. 2019
New York	25th, 50th, and 75th percentiles	New York State Climate Change Regulatory Revisions 2016
North Carolina	Intermediate-low and intermediate scenarios	Sweet et al. 2017
Virginia	Intermediate and intermediate-high scenarios	Sweet et al. 2017

Some states' sea level rise projections are available at the state level, while other states have a set of projections for different locations within the state. The Sweet et al. 2017 projections are available for multiple locations within the six-state study area, including at tidal gauges and points on a one-degree grid. Whenever multiple projections for a scenario and time point were available, the mean of all projections within the state (or study area, for the regional analysis) was used.

All sea level rise projections were converted to a common vertical datum (MHHW) and baseline year (2010). Because the data used to delineate migration space was available for half-foot increments of sea level rise from this baseline, the sea level rise projections were interpolated to identify the years during which sea level rise was projected to reach the next half-foot increment. For example, the Sweet et al. intermediate scenario projects sea level rise to reach 0.3' in 2020 and 0.63' in 2030. After interpolating to align with half-foot increments, these projections are 0.5' in 2027 and 1' in 2039.

For each sea level rise scenario, a future habitat raster was created for each year in which projected sea level rise reached a new half-foot increment. For each state, a common end year near the end of the century was selected to use across the sea level rise scenarios to facilitate comparing results over the same time period. One constraint on the end year is the maximum sea level rise represented in the migration space dataset (10'); if sea level rise was projected to exceed 10' by the end of the century, an earlier end year was chosen. When there was no year in common among the sea level rise scenarios for a state, the earliest year of those in consideration was chosen and used for all scenarios. This results in a slight overestimate of sea level rise near the end of the century for the other scenarios, but generally end years for each sea level rise scenario were within 5 years of each other.

Existing coastal habitat extent and salinity

Existing marsh and seagrass extent and location were identified using the same data source from the coastal vulnerability analysis (Table 2). Marsh elevation was extracted from NOAA bathymetric-topographic elevations converted to MHHW using NOAA's VDatum software (CIRES 2014).

Table 2. Marsh and seagrass data sources for each state.

State	Marsh data source(s)	Seagrass data source(s)
Delaware	State of Delaware updated version of NWI (2019, provided by Mark Biddle)	None found
Maryland	National Wetland Inventory (US FWS 2019), Maryland wetlands (MD DNR 2019)	2018 Chesapeake Bay SAV Coverage (MD iMap, DNR, VIMS 2018)
New Jersey	Land Use/Land Cover of New Jersey 2015 (NJDEP Bureau of GIS 2019)	Seagrasses (NOAA Office for Coastal Management 2020)
New York	National Wetland Inventory (US FWS 2019), Hudson River Tidal Wetlands Inventory (NY DEC 2014)	Seagrasses (NOAA Office for Coastal Management 2020), Statewide Seagrass map, (NYS Dept. of Environmental Conservation 2018)

North Carolina	National Wetland Inventory (US FWS 2019)	SAV 2012-2014 mapping (NC DMF 2019), National Wetland Inventory (US FWS 2019)
Virginia	VIMS Tidal Marsh Inventory (Berman et al. 2016)	2018 Chesapeake Bay SAV coverage (MD iMap, DNR, VIMS 2018) and National Wetland Inventory (US FWS 2019)

Salinity is a key driver of methane emissions from coastal habitats; since methane is a potent greenhouse gas, this determines whether coastal habitats are net carbon sinks or sources of carbon emissions. Therefore, it was important to classify coastal habitats by salinity. Comprehensive spatial salinity datasets were available for the coastal areas of New Jersey, Virginia, and Maryland (Lathrop 2015, VIMS 2017). We created salinity rasters for North Carolina, Delaware, and New York by interpolating from point measurements of water salinity obtained from the National Water Quality Portal following the method used to create the New Jersey salinity dataset (Lathrop 2015). Final salinity rasters were overlaid with marsh and seagrass habitats to classify them into three salinity categories: low (< 5 psu), moderate (5-18 psu), and high (>18 psu).

Horizontal marsh erosion

Horizontal erosion of marshes is a significant cause of marsh loss in the study area and is influenced by many factors, including marsh condition, wave energy, boat wakes, sediment availability, shoreline composition, and tidal dynamics (Cowart et al. 2010). We estimate the horizontal change rate (feet/year) from the size of the water body associated with the marsh (a proxy for fetch and wave energy, which have been found to correlate with erosion rates, e.g., Schwimmer 2001) and tidal range (difference between MHW and MLW), calibrated using approximately 8,000 measurements of shoreline change rates in marshes from Virginia, Maryland, New Jersey, and New York (Offerman 2015, Knippler and Sylvia 2016a, Knippler and Sylvia 2016b, Defne 2017, VIMS 2019, Welk 2019):

$$Marsh\ horizontal\ change\ rate\ = -.798 - \left(.0008 * \sqrt{A_{WB}}\right) + \ .129 * TR + (.0025 * TR * \left(\sqrt{A_{WB}}\right))$$

in which A_{WB} is the area of the water body (acres) and TR is the tidal range (meters). Because the shoreline change rate dataset was so noisy, this equation predicts relatively low erosion rates (negative horizontal rates of change), ranging from approximately 0.4 to 0.9 feet/year over the multistate study area. Despite its weak predictive power, varying predicted erosion rates based on water body area and tidal rate is an improvement over using the mean measured erosion rate and helps to capture the overall expected magnitude of marsh loss due to erosion (e.g., Cowart et al. 2011). It does not identify specific areas that are very vulnerable to erosion.

At each time step in the model, the horizontal change rate for each marsh pixel is calculated using the equation above. For all marsh pixels, the total horizontal erosion since the previous time step is calculated by multiplying the horizontal change rate by the number of years since the previous time step. Then, the cumulative amount of horizontal erosion from the beginning of the analysis period is updated (for the first time step, the cumulative erosion is equal to erosion in that time step; for later time steps, cumulative erosion is the sum of erosion in all earlier time steps and erosion in that time step). The distance from each marsh pixel to the adjacent water body is compared to the cumulative amount of horizontal erosion that has occurred since the beginning of the analysis period. All marsh pixels closer to the water body than the cumulative amount of horizontal erosion that has occurred are considered eroded. For example, if the cumulative horizontal erosion is 150’, all marsh pixels less than 150’ from the adjacent water body are considered eroded.

The area of the adjacent water bodies and distance from marsh pixels to those water bodies are updated at each time step. This allows changes due to sea level rise (marsh drowning, water body expansion) to influence marsh erosion rates.

Maximum vertical accretion with sea level rise

The maximum vertical accretion rate for coastal areas was calculated following the method in Schuerch et al. 2018 based on tidal range (difference between MHW and MLW) and suspended sediment availability, both of which have a positive relationship with accretion rate. Tidal range was estimated by converting NOAA bathymetric-topographic elevations to MHW and MLW using NOAA’s VDatum software and subtracting MLW from MHW. Suspended sediment concentration was estimated as the long-term average of monthly aggregated sediment concentrations from the GlobColour total suspended matter dataset, which is derived from satellite imagery. The maximum possible vertical accretion rate for each pixel in the study area was estimated as follows:

$$Maximum\ vertical\ accretion\ (mm/year) = \left(\frac{1}{3.42}\right) * TR^{0.915} * SS - 1.5$$

in which *TR* is the tidal range (meters) and *SS* is the suspended sediment concentration (mg/liter). The other parameters in the equation were set by Schuerch et al. (2018) using data and models by Kirwan et al. 2010.

Potential for salt marsh creation/restoration through hydrologic connection

Some wetland and open water areas along the coast are potentially suitable for salt marsh creation or restoration, given their elevation and tides, but are currently low-salinity marsh or open bodies of freshwater. Some of these areas were historically salt marsh, but were cut off from tidal flows by a road, berm, or other barrier; or purposely disconnected to create impoundments (Kroeger et al. 2017). Others are natural freshwater wetlands where salinity is low due to groundwater inflows. In both cases, the low salinity in these areas makes them potential sources of methane.

To identify areas where salt marsh could be created or restored, we combined a potential salt marsh dataset (McGarigal et al. 2018) with information from the National Wetlands Inventory (US FWS 2019). From the DSL tidal settings data, all pixels with values greater than 0.5 were considered to be potential salt marsh or wetter. Areas of flowing (lotic) open water (open water identified from the 2016 NLCD, lotic water bodies identified from NWI) were excluded from potential salt marsh areas (these included estuaries and rivers). The DSL dataset is not available for North Carolina, so potential for salt marsh creation or restoration in that state was based on the NWI and elevation. All wetlands classified as impoundments in the NWI that are less than 5 meters in elevation were considered to have potential for salt marsh creation or restoration. We were not able to identify specific barriers to flow or to differentiate between historic salt marshes lost due to tidal disconnection and natural freshwater marshes.

Using land cover (NLCD 2016, USGS 2019), we excluded developed land, agricultural areas, forests, and woody wetlands from the potential for salt marsh creation or restoration layer. We also excluded existing salt marshes. This leaves open water and freshwater emergent herbaceous wetlands as areas with potential for salt marsh creation or restoration that could reduce methane emissions. Finally, we removed patches less than 10 acres in size from the final layer, to avoid including isolated pixels.

Migration space

Migration space was created from NOAA's 2019 sea level rise marsh migration datasets, which are available at half-foot increments of sea level rise from 0.5' to 10', following the method in Anderson & Barnett 2019. For a given sea level rise elevation, all areas that convert from non-tidal habitats in the baseline scenario to tidal habitats and do not overlap with developed areas (from CCAP 2016, NOAA 2020) are considered potential migration space. The migration space layers were updated to exclude overlap with existing tidal habitats, and only migration space areas that are spatially contiguous with either existing tidal habitats or migration space for the preceding SLR elevation were included in the final migration space layers.

Areas where development is projected to occur in the future were removed from the final migration space layers using the Integrated Climate and Land Use Scenarios (ICLUS) v2 projections (US EPA 2016), which project land use and land cover at decadal intervals through 2100 based on shared socioeconomic pathways. When creating the future habitat raster, the ICLUS development projection for the year closest to the year being modeled was selected, and all pixels classified as high-density exurban or more developed (including urban, suburban, commercial, industrial, institutional, and transportation) were removed from the migration space available at that time point.

The migration space was overlaid with the potentially restorable salt marsh layer; migration space overlapping with potentially restorable salt marsh was classified as restored salt marsh due to sea level rise, while all other migration space was classified as new marsh in the migration space. New marsh pixels in the migration space were randomly assigned a salinity value (low, moderate, or high) in the same proportion as the current marshes in the state. For example, if 40% of existing marshes in a state are in high-salinity areas, 40% of the new marsh in the migration space is assumed to be high-salinity.

Carbon storage, accumulation, and emission parameters

Baseline carbon storage and accumulation rates

Estimates for carbon storage and accumulation rates by salt marsh and seagrass were derived from existing field measurements in those ecosystems. For each habitat type, initial carbon storage was assumed to be constant across salinity classes, but carbon accumulation rates varied by salinity class.

For seagrass, carbon storage was set at 198.2 metric tons CO_2e/hectare using the mean value for carbon stocks in temperate Western Atlantic eelgrass meadows from Rohr et al. 2018. Carbon accumulation by high-salinity seagrass (>18 psu) was set at 1.8 metric tons CO_2e/hectare/year using a global estimate of carbon burial rate by seagrasses (Siikamaki et al. 2012). Previous research estimated that seagrass in lower-salinity areas have methane emissions approximately equal to their carbon sequestration rates (Pendleton et al. 2012), so the low- and moderate-salinity seagrass was assigned a carbon accumulation rate of zero.

For salt marsh, carbon storage was set at 737.2 metric tons CO_2e/hectare, the mean value of a compilation of field measurements obtained from the Coastal Carbon Atlas of sediment carbon storage in saline and brackish marshes in the study area (see appendix I for full list of field measurement sources). Carbon accumulation by high-salinity salt marsh (>18 psu) was set at 3.85 metric tons CO_2e/hectare/year, the mean value of a compilation of field measurements from the study area obtained from the Coastal Carbon Atlas (see appendix I). This is a conservative rate; two global estimates of salt marsh carbon accumulation (McLeod et al. 2011; Ouyang and Lee 2014) and one estimate for the conterminous United States (Chmura et al. 2003) range from 8–8.98 metric tons CO_2e/hectare/year. To compensate for increased methane emissions from moderate- and low-salinity marshes, the carbon accumulation rate for moderate-salinity marshes was set to 48% of the value for high-salinity marshes, and the carbon accumulation for low-salinity marshes was set to zero (Poffernbarger et al. 2011, Chmura et al. 2003).

Marshes in the migration space accumulate carbon at the same rate as existing marshes, depending on their salinity class.

Areas with potential for salt marsh creation or restoration do not have associated carbon storage or accumulation rates. They do not influence the carbon storage or sequestration calculated by the model unless they are connected by sea level rise, at which point they accumulate carbon at a rate equal to the expected methane emissions reduction from the conversion, 24.7 metric tons CO2-e/ha/year (Fargione et al. 2018).

Carbon accumulation by vertically accreting marshes

When marshes accrete vertically due to sea level rise, they accumulate carbon more quickly (Kirwan and Mudd 2012, Gonneea et al. 2019). The amount of carbon accumulated depends on the rate of vertical accretion and the carbon density of the accumulated sediment:

$$C_{acc} = Acc_v * OC_s$$

in which Acc_v is the vertical accretion rate (cm/year) and OC_s is the organic carbon density in the sediment. Organic carbon density was set to 0.328 grams C/m^3; this is the mean value from the Coastal Carbon Atlas dataset for the study area (see appendix I for full list of field data sources). Vertical accretion rate (equal to sea level rise rate, for marshes that can keep up), and therefore additional carbon accumulation, varies by sea level rise scenario and time period. For example, for the intermediate Sweet et al. 2017 scenario:

Time period(s)	Vertical accretion rate (equal to SLR rate), cm/yr	Carbon accumulation, grams C/m^2/year	Carbon accumulation, metric tons CO_2e/hectare/year
2010-2030	.762	0.0245	9.17
2040-2100	1.524	0.05	18.34
2100-2120	.762	0.0245	9.17

These carbon accumulation estimates are for high-salinity marshes; as described above, moderate-salinity marshes' accumulation rates were set to 48% of high-salinity marshes, and low-salinity marshes had zero carbon accumulation.

Carbon emissions from drowned marshes

When marshes drown due to sea level rise, they stop accumulating carbon, and some portion of their stored carbon is released. There is high uncertainty about the amount of stored carbon that is emitted; 25-50% was set as a best estimate by the North Carolina Natural and Working Lands group based on their experience and literature (Pendleton et al. 2012). Due to this uncertainty, each sea level rise scenario was modeled twice, once assuming that 25% of stored carbon is released following marsh drowning, and once assuming that 50% of stored carbon is released.

Carbon emissions from eroded marshes

Eroded marshes stop accumulating carbon, and some portion of their stored carbon is released as sediment erodes. However, research suggests that much of this sediment (and carbon) is captured by nearby marshes. This prevents the carbon from being emitted to the atmosphere, and the additional sediment supply can support marsh accretion, ultimately increasing the resilience and carbon sequestration potential of those marshes (Kirwan et al. 2016). Our model does not redistribute sediment or carbon from eroded marshes, but to account for the lower potential for carbon emissions from eroded marshes in comparison to drowned marshes, the model was run with 10% and 25% of stored carbon released following erosion.

Model runs and outputs

Model runs for each sea level rise scenario cover the time period from the baseline year (2010) to 20 years beyond the final future habitat raster. This additional time allows for the release of carbon from any marsh area lost during the final time interval. Carbon released due to marsh drowning or erosion was assumed to follow an exponential decay function with a half-life of 10 years.

Model outputs include rasters of carbon stocks at each modeled time point (specific time points vary by sea level rise scenario, as described above); carbon accumulation, carbon emissions, and net carbon sequestration (accumulation minus emissions) for each time period (between subsequent time points), and total net carbon sequestration for the entire analysis period. All raster outputs are in units of million metric tons CO_2e/hectare. These results were used to calculate total carbon stocks and fluxes (accumulation, emissions, and net sequestration) for each sea level rise scenario and time point by state, in million metric tons CO_2e.

Model caveats and limitations

Spatial datasets

Coastal blue carbon habitats: There is wide variation in the temporal and geographic coverage of marsh and seagrass data, with known data gaps in some areas. For example, the EPA is in the process of developing SAV data for the Delaware Bay, but that dataset is not yet available. Some states have more recent and comprehensive data than others. Despite known limitations of the National Wetlands Inventory, in particular the age of underlying datasets, it was used to fill gaps in other datasets where necessary. The spatial resolution of most of these datasets and the model (30-m) does not capture small-scale marsh topography (e.g., channels) that influence many of the processes described in the model.

Suspended sediment data: This is an older dataset (long-term average of monthly data from 2002 to 2012) and may not reflect recent changes to sediment availability. Its coarse spatial resolution (4 km) also obscures local sediment sources such as river inlets.

Modeled processes

Vertical accretion: This model uses a simple algorithm for determining marshes' ability to accrete vertically with sea level rise. It does not incorporate sediment supplied by marsh erosion, barrier island overwash, and aeolian transport of dune sand. These are difficult to estimate due to their episodic nature and lack of data. Their exclusion may result in underestimating the potential for vertical accretion.

Marsh migration: The areas available for marsh migration in the model were identified based on the NOAA datasets, updated to exclude current and projected developed land, as described above. As sea level elevations continue to increase, some areas are no longer suitable for marsh migration and are not included in the migration space layers, these migration space marshes are then designated as drowned marshes. We could not assess the potential for migration space marshes to vertically accrete and avoid drowning, because the data inputs used to estimate accretion ability (tidal range and suspended sediment) are not available over land where the migration areas are located.

Marsh erosion: The horizontal erosion rates used to identify eroded marshes are calculated from a simple equation based on water body size and tidal range that does not take into account many other factors that influence erosion, often on a local scale (e.g., sediment inflows, boat wakes). In addition, the spatial resolution of the model (30 m) means that very low erosion rates may not influence the future habitat maps; the cumulative amount of horizontal erosion must be at least 15 m (the mean distance between a marsh pixel and an adjacent body of water) over the analysis period to create eroded marsh in the future habitat maps.

Potential for salt marsh creation or restoration: This layer includes both historic salt marshes lost due to tidal disconnection and naturally occurring freshwater marshes; it does not differentiate between those two classes. While both may emit methane due to low salinity, disconnected salt marshes are a likely target for restoration, while managers likely want to preserve naturally occurring freshwater marshes for their habitat and other values, especially if they are a rare habitat type in the coastal area. The layer may also include impoundments that are being used for another purpose, such as providing drinking water, and so are not candidates for salt marsh creation or restoration.

Carbon emissions from drowned and eroded marshes: As discussed above, there is uncertainty about the fate of carbon stored in marshes when they drown or erode. Drowned marshes are likely to release a fraction of their carbon, but current estimates span a wide range (Pendleton et al. 2012). Eroded marshes can contribute sediment to nearby marshes, which may prevent carbon emissions and increase the accretion capability of those marshes, but some sediment is likely lost and releases its carbon.

Sea level rise: Sea level rise is projected to vary spatially, but available projections of sea level rise elevation are only available for certain locations (often tidal gauges) and do not fully reflect the potential geographic variation in sea level rise elevations. In addition, the model applies one sea level rise elevation across each modeled state for each time point; no intra-state variation in sea level rise is included. For the regional sea level rise scenario, one sea level rise elevation for each time point is used across the entire study area.

Processes not included in the model

Salinity changes: The model does not include potential shifts in salinity over time due to sea level rise due to the many complex and interacting factors that influence salinity (hydrodynamics, new inlets, freshwater inflows). Salinity changes may influence carbon fluxes from marshes (e.g., reduced methane fluxes from freshwater marshes that become more saline), but literature has shown different methane flux responses to saltwater intrusion into tidal freshwater marshes, so this effect is uncertain (Weston et al. 2014).

Local vertical land movement: While vertical land movement is included as a factor in many of the localized and regionalized sea level rise projections, subsidence occurs at very local scales due to factors such as groundwater and fossil fuel withdrawals (Karegar et al. 2016). Fine-scale vertical land movement is not captured in the model and may result in underestimation of marsh vulnerability to sea level rise in places with high local subsidence rates.

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Appendix I: Salt marsh carbon field measurement sources from Coastal Carbon Atlas

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