

RESEARCH ARTICLE

Sea level rise drives carbon and habitat loss in the U.S. mid-Atlantic coastal zone

Katie Warnell^{1*}, Lydia Olander², Carolyn Currin³

1 Nicholas Institute for Environmental Policy Solutions, Duke University, Durham, North Carolina, United States of America, **2** National Ecosystem Services Partnership, Nicholas Institute for Environmental Policy Solutions, Nicholas School of the Environment, Duke University, Durham, North Carolina, United States of America, **3** NOAA National Ocean Service National Centers for Coastal Ocean Science (Retired), Beaufort, North Carolina, United States of America

* katie.warnell@duke.edu

Abstract

Coastal marshes and seagrass beds store millions of tons of carbon in their sediments and sequester carbon at higher per-area rates than most terrestrial ecosystems. There is substantial interest in this “blue carbon” as a carbon mitigation strategy, despite the major threat that sea level rise (SLR) poses to these habitats. Many projections of habitat and carbon change with SLR emphasize the potential for inland marsh migration and increased rates of marsh carbon sequestration, but do not consider carbon fluxes associated with habitat conversion. We integrated existing data and models to develop a spatial model for predicting habitat and carbon changes due to SLR in six mid-Atlantic U.S. states likely to face coastal habitat loss over the next century due to low tidal ranges and sediment supply. Our primary model projection, using an intermediate SLR scenario (1.2 m SLR by 2104), predicts loss of 83% of existing coastal marshes and 26% of existing seagrasses in the study area. In addition, 270,000 hectares of forest and forested wetlands in low-lying coastal areas will convert to coastal marshes. These SLR-driven habitat changes cause the study area to shift from a carbon sink to a source in our primary model projection. Given the many uncertainties about the habitat and carbon changes represented in our model, we also identified the parameters and assumptions that most strongly affected the model results to inform future research needs. These included: land availability for inland marsh migration, the baseline extent and location of coastal marshes, proportion of stored carbon emitted from lost habitats (coastal marsh sediments or terrestrial biomass carbon), and methane emissions from freshwater habitats. The study area switched from a net carbon sink to a net carbon source under SLR for all but three model runs; in those runs, net carbon sequestration declined by 57–99%.

OPEN ACCESS

Citation: Warnell K, Olander L, Currin C (2022) Sea level rise drives carbon and habitat loss in the U.S. mid-Atlantic coastal zone. *PLOS Clim* 1(6): e0000044. <https://doi.org/10.1371/journal.pclm.0000044>

Editor: Ming Li, University of Maryland Center for Environmental Science, UNITED STATES

Received: December 6, 2021

Accepted: May 16, 2022

Published: June 23, 2022

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Data Availability Statement: All data are available in the manuscript, [Supporting Information](#) files, or the Duke Research Data Repository (<https://doi.org/10.7924/r4cr5zc7v>).

Funding: KW and LO received funding from the United States Climate Alliance Grant Program for Natural and Working Lands Research, made possible by a grant from the Doris Duke Charitable Foundation and administered by American Forests. The project described in this publication was also supported by Grant or Cooperative Agreement No. G17AC00204 from the United States Geological

1. Introduction

Coastal wetland habitats, including saline marshes and seagrasses, provide many valuable ecosystem services, including serving as nursery areas for commercially and recreationally harvested fish species, providing habitat for coastal birds, improving water quality, and buffering shorelines from storms and erosion [1–4]. In the last decade, these habitats have also been

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Competing interests: The authors have declared that no competing interests exist.

increasingly recognized for their large stores of “blue carbon” and high rates of carbon sequestration [5–9]. The majority of the blue carbon in coastal marshes and seagrass beds is stored in the underlying sediments, where it can be locked away for hundreds to thousands of years [10,11]. Given the long lifetime of CO₂ emitted to the atmosphere, wetland C sequestration must persist for at least a century to be considered effective climate mitigation [12,13].

The carbon density in salt marsh sediments exhibits a normal distribution, and the average value has been used to estimate marsh carbon stock in the conterminous US (CONUS) at 2,640 million metric tons CO₂ equivalent (MMT CO₂e) [14]. Carbon storage in North American tidal wetland systems has been estimated to be 5,170 MMT CO₂e, while carbon storage in seagrass beds has been estimated at 447 MMT CO₂e [15]. Coastal wetlands in the conterminous U.S. removed 4.8 MMT CO₂e from the atmosphere in 2019 [16]. There is additional potential for reducing carbon emissions via restoration; Fargione et al. [17] estimated that tidal wetland restoration to reduce methane emissions of “freshened” (less saline) marshes in the U.S. could avoid emissions of 12 MMT CO₂e/year based on models by Kroeger et al. [18].

Due to the high rate of carbon sequestration in coastal wetlands compared to many terrestrial habitats, enhancing blue carbon through coastal habitat protection and restoration has been discussed as a substantial contribution toward reducing net greenhouse gas emissions [19–21]. However, these essential carbon sequestration and storage functions are dependent on the long-term survival of coastal marshes and seagrasses [22]. While there are many threats to coastal habitats, including water pollution and human development, sea level rise is likely to be the most significant and widespread stressor over the next century. Global assessments have projected major changes in salt marsh extent and location due to sea level rise, with losses of over 50% possible if marshes do not have sufficient space to migrate inland with sea level rise [23,24]. While potential seagrass losses under climate change have not been quantified at large scales, seagrasses are sensitive to many environmental factors expected to be influenced by climate change, such as temperature, salinity, and especially water depth, which limits light availability [25,26].

Moderate- to high-resolution models have been used to assess the vulnerability of coastal marshes to sea level rise and identify locations where marsh restoration or conservation projects are likely to persist [27–30]. These projections range from no change in coastal marsh area to significant coastal marsh loss, depending on the rate of sea level rise, marsh elevation, and opportunity for inland marsh migration. Depending on the specific model used, some of these estimates do not fully account for the ability of coastal marshes to vertically accrete along with sea level rise, and therefore overestimate marsh loss [27,31,32]. Inland marsh migration plays a key role in determining future marsh extent; each of the three sea level rise scenarios modeled by Schuerch et al. [24] had the potential to either increase or decrease the total area of coastal wetlands globally, depending on the availability of inland areas for marsh migration.

Coastal marsh changes driven by sea level rise have major implications for carbon stocks and fluxes. Conversion between habitat types can cause carbon emissions and changes in sequestration rates, while increases in vertical accretion or biomass due to SLR can increase carbon sequestration in coastal marshes [10,33,34]. Studies on the changes in the carbon stocks and accumulation in these coastal wetlands and other habitats find a range of expected shifts in carbon, depending on the geographic and temporal scale of the analysis and the specific habitat changes addressed. A national-scale analysis based on observed wetland losses in the contiguous United States estimated that 6.6 MMT CO₂e is emitted annually due to coastal marsh loss, but emphasized the large uncertainties associated with those losses [15]. Other studies have focused on the effects of individual processes on carbon emissions and accumulation. An examination of aerobic decomposition of eroded marsh sediment estimated that 0.06 MMT CO₂e/year may be released via this process in the conterminous US [35]. Studies of

carbon export associated with barrier island rollover and salt marsh erosion in North Carolina demonstrated that marshes may already be net carbon sources [36,37]. However, the ability of salt marshes to accrete vertically in response to sea level rise may result in a positive relationship between sea level rise and marsh carbon sequestration, potentially leading to an increase in total carbon sequestration with sea level rise even as coastal marsh area declines [5,10,34,38,39].

Recent work in the “ghost forests” created as coastal marshes migrate inland have found large declines in aboveground carbon associated with tree mortality [40], suggesting that forest conversion to coastal marsh may cause large net carbon emissions due to biomass mortality that will not be offset by increased soil carbon sequestration in the new marshes unless they persist for hundreds of years [41]. However, other assessments of changes in carbon accumulation in coastal habitats due to sea level rise have focused on current intertidal and subtidal wetlands, and do not include these forest carbon changes [5,34].

To fully understand the cumulative implications of SLR on our coastal habitats and their potential contributions to greenhouse gas reduction efforts, we applied an integrated approach that encompasses the carbon implications of the major habitat transitions happening across the coastal landscape over the next century. Coastal marsh that persists or migrates inland may sequester more carbon in response to SLR, but how much marsh will persist and migrate [34]? What will happen to the carbon in drowned or eroded marsh, and in the habitats that are replaced by migrating marsh [35,42]? What is the impact of these habitat transitions on the coastal carbon balance? Our study aims to estimate the net effect of these changes across six eastern states, integrating results from previous research and existing models to provide a comprehensive view of habitat and carbon effects due to sea level rise. The results of this work include (1) predictions of habitat changes on the coastal plain of the mid-Atlantic US, (2) implications for carbon storage and emissions, and (3) identification of key research questions that can improve our understanding of these impending coastal transitions.

Decision-makers at the local, state, and national levels in the United States have begun to consider the effects of sea level rise on communities and ecosystems, as well as recognize the importance of natural habitats’ carbon storage in their greenhouse gas emissions budgets [43–45]. To incorporate these issues into relevant planning efforts, spatially explicit information about current and future blue carbon stocks and fluxes, accounting for habitat response to sea level rise, is required. To do this, studies will need to take more integrative approaches at a landscape scale. The model presented in this paper was developed in collaboration with state agency staff and other partners working on coastal management in the six mid-Atlantic states to understand landscape scale coastal transitions with sea level rise. This work was informed by their on-the-ground experience; the primary model projection presented in this paper was adapted using state-specific assumptions and sea level rise scenarios to produce data layers and results that each state could use (see state-specific products, [46]).

2. Methods

2.1 Study area

The analysis was conducted for the coastal areas of six U.S. states along the Atlantic coast: New York, New Jersey, Delaware, Maryland, Virginia, and North Carolina. The geographic extent for spatial analysis was set by the combination of the current extent of coastal marshes and sea-grass beds (see section 3.2.2) with the area with potential to support inland migration of coastal marsh for the selected sea level rise scenario, which we call the transition zone (see section 3.2.6). The distance inland for the analysis varied from 1 to 12 km across the states.

2.2 Data sources and preparation

All input data sources were resampled or converted to 30-meter rasters and projected to the USA Contiguous Albers Equal Area Conic USGS coordinate system using the ArcGIS Pro resample tool (for raster datasets) or polygon to raster tool (for polygon datasets). To reduce error associated with resampling, projection, and conversion [47], nearest neighbor resampling was used for categorical data (such as habitat type) and bilinear resampling for continuous data (such as elevation).

2.2.1 Sea level rise projection. The intermediate sea level rise projection used for this analysis estimates 1.2 meters (4 feet) of sea level rise in the study area in the year 2104 (mean for all points within the study area with SLR projections), relative to a 2010 baseline [48]. Timesteps for intermediate years between 2010 and 2104 correspond with a 0.15-meter (0.5-foot) increase in sea level rise elevation, so that timesteps are shorter in the latter part of the study period (Table A in [S1 Text](#)).

2.2.2 Coastal habitat and elevation data. Baseline coastal marsh and seagrass extent and location were identified using the best available data source for each state, as identified by state partners (Table B in [S1 Text](#)). These were primarily state-specific datasets developed for coastal habitat management purposes; data from the National Wetlands Inventory was used when state-specific datasets were not available (Table B in [S1 Text](#)). Coastal marsh elevation and seagrass depth were extracted from NOAA 1/9 arc-second bathymetric-topographic elevations [49] and converted to mean low water (coastal marsh) and mean higher high water (seagrass) using NOAA's VDatum software [50]. The NOAA bathymetric-topographic elevation dataset is a combination of lidar-based elevation datasets; while there is uncertainty associated with elevation data, particularly in marsh areas if the lidar does not penetrate the vegetation [51], NOAA does not perform accuracy assessment on the data, so this uncertainty could not be quantified.

2.2.3 Salinity. Salinity of coastal marshes drives methane emission from these habitats [52], with lower salinity typically found further inland. Comprehensive spatially explicit salinity datasets were available for New Jersey, Virginia, and Maryland [53,54]. Salinity rasters were created 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 [53]. To reduce the effect of uncertainty in the interpolated salinity rasters, they were used to classify coastal marsh habitats into three salinity categories: low (< 5 psu), moderate (5–18 psu), and high (>18 psu).

2.2.4 Tidal range. Tidal range was estimated by converting NOAA bathymetric-topographic elevations [49] to mean high water (MHW) and mean low water (MLW) using VDatum software [50], and subtracting MLW from MHW.

2.2.5 Suspended sediment. Suspended sediment concentration was estimated as the long-term average of monthly aggregated sediment concentrations from the GlobColour total suspended matter dataset [55].

2.2.6 Transition zone. The geographic area that could potentially convert to coastal marsh under the 1.2 m by 2104 sea level rise scenario, called the transition zone, was identified from NOAA's sea level rise marsh migration datasets [56], which are available at 0.15-meter (0.5-foot) increments of sea level rise from 0.15 m to 3.05 m (0.5' to 10'), following the method in [57]. A series of adjustments to this transition zone were made to create the "adjusted transition zone" used in the primary model projection. The adjusted transition zone excludes developed areas (other than "open space", which is land that is in a developed setting but more than 80% vegetated) and existing coastal marsh. The adjusted transition zone only includes areas that are spatially contiguous with either existing coastal marsh or projected future marsh areas

in the transition zone for the preceding SLR elevation. This ensures that there is a pathway for coastal marsh to migrate from its existing extent into the adjusted transition zone and excludes any isolated areas within the transition zone that are not likely to be colonized by coastal marsh. Areas where development is projected to occur in the future, identified using the Integrated Climate and Land Use Scenarios (ICLUS) v2 projections [58], and existing agricultural land (based on C-CAP 2016 [59]) were removed from the adjusted transition zone, as were areas that are spatially connected to existing coastal marsh areas only through areas projected to be developed in the future or existing agricultural land.

2.2.7 Potential coastal marsh creation and restoration areas. We also identified areas where coastal marsh could be created or restored by hydrologically connecting or reconnecting open water and freshwater wetlands to tidal flows, in order to expand future salt marsh and reduce methane emissions associated with freshwater habitats [18]. We combined a tide settings dataset [60], which represents the probability that an area is subtidal or intertidal (and therefore potential salt marsh) based on elevation and tidal range, with information on wetland and water body type from the National Wetlands Inventory and C-CAP [59,61]. All areas with tide settings values greater than 0.5 (predicted to be intertidal or subtidal habitats) that are not flowing (lotic) open water were considered to be areas where coastal marsh could occur. We excluded existing coastal marshes, developed land, agricultural land, forests, and woody wetlands from the areas where coastal marsh could occur to identify areas with potential for coastal marsh restoration or creation. This left open water and freshwater emergent herbaceous wetlands as areas that could be hydrologically connected to create or restore coastal marsh. The tidal settings dataset was not available for North Carolina, so in that state, wetland areas classified as impoundments in the National Wetland Inventory [61] that are less than 5 meters in elevation were considered to have potential for coastal marsh creation or restoration. To avoid including isolated pixels, we removed patches less than 10 acres in size from the final layer.

2.3 Habitat model

Spatial representations of change in blue carbon habitats—tidal brackish and saline coastal marsh and seagrass—due to sea level rise were created by starting with the current extent of these habitats and creating maps for each model timestep based on the major processes expected to create change due to sea level rise. These processes include erosion, drowning due to SLR, and inland migration for coastal marshes, and depth-dependent loss for seagrass.

Many of the processes represented in the habitat projection models described below continue to be studied and refined [24,34,35,62–65], and input dataset limitations contribute additional uncertainty [14,22,66]. Our primary model projection represents a reasonable estimate of the habitat changes likely to occur due to sea level rise, based on information from published literature, predictive models, and expert opinion. The primary model projection results are used as the central estimate to which we compare the results of a sensitivity analysis (see section 3.5) that includes all substantial uncertainties and assumptions.

2.3.1 Horizontal erosion of coastal marshes. We estimate the rate of horizontal change (centimeters/year) in coastal marsh from the size of the water body associated with coastal marsh areas (a proxy for fetch and wave energy, which are linearly correlated with erosion rate [67]) and tidal range (see supplementary materials, S1.2 for details).

2.3.2 Potential sediment accretion of coastal marshes with sea level rise. Marshes' ability to keep up with sea level rise through sediment accretion is strongly determined by the availability of suspended sediment in the water and the tidal range that carries the sediment onto the marsh [31]. The maximum potential sediment accretion rate for coastal marshes was

calculated following the method by Schuerch et al. [24] based on tidal range and suspended sediment availability (see supplementary materials, S1.3 for details). At each time step, coastal marsh pixels below mean low water because they were not able to keep up with sea level rise through sediment accretion were classified as drowned.

2.3.3 Inland migration of coastal marshes. When creating the habitat map for each time step, all areas of the adjusted transition zone (see section 3.2.6) for the relevant sea level rise elevation were classified as new migrated coastal marsh. Given the absence of information from the literature about the expected salinity distribution of migrated marsh, the primary model projection assumed that the current salinity distribution of coastal marshes would remain constant. New migrated coastal marsh pixels were randomly assigned a salinity value (low, moderate, or high) in the same proportion as the existing coastal marshes in the state. If a new migrated coastal marsh pixel was no longer part of the transition zone for a subsequent time step, it was assumed to have drowned due to additional SLR and was classified as lost migrated marsh.

2.3.4 Seagrass loss. Seagrass loss due to sea level rise was projected based on the maximum depth at which the seagrass beds currently grow in each of the six states. Light availability decreases with depth, making depth an important limiting factor for seagrasses [68,69]. We estimated the maximum depth at which seagrasses can grow as the first percentile of the current depth distribution of seagrass beds in each state (-2.3 meters for NC, -2.4 meters for MD, NJ, and VA, and -3.9 meters for NY). As sea level rises, the depth at which the existing seagrass beds are growing increases. When the depth of seagrass beds exceeds the maximum depth for the state, the seagrass is considered lost.

2.4 Carbon accounting

Carbon stocks and fluxes were estimated for the 1.2 m sea level rise scenario and a no sea level rise scenario to assess the effect of sea level rise on carbon (an additional SLR scenario was modeled in the sensitivity analysis; see section 3.5 for details). Each of the habitat types present in the study area at the beginning of the analysis period has associated carbon stocks and annual carbon fluxes (sequestration and/or emissions), as does each new habitat created by sea level rise. There are also carbon fluxes associated with habitat conversion. Carbon fluxes included in the analysis are summarized in Fig 1. Data and calculations for each carbon flux are described below.

2.4.1 Baseline carbon stocks and accumulation rates in blue carbon habitats. Estimates for current carbon stocks and accumulation rates by coastal marsh and seagrass were derived from published field measurements in those ecosystems. For seagrass, carbon stock was set at 198.2 metric tons CO₂e/hectare using the mean value for carbon stocks in temperate Western Atlantic eelgrass meadows [70]. Carbon accumulation by seagrass (Fig 1, flux 1) was set at 1.8 metric tons CO₂e/hectare/year using a global estimate of carbon burial rate by seagrasses [71]. This likely overestimates carbon accumulation by seagrasses in the study area, which does not contain some of the seagrass species with higher carbon accumulation rates [72]. Previous research has found little evidence for increased methane emissions by seagrass in lower-salinity areas, so all seagrass areas were assigned the same carbon accumulation rate [73].

For coastal marsh, which includes high (≥ 18 psu), moderate (5–18 psu), and low salinity (<5 psu) marshes, carbon stock was set at 737.2 metric tons CO₂e/hectare, and carbon accumulation by high-salinity marsh was set at 3.85 metric tons CO₂e/hectare/year (Fig 1, flux 2). These are the mean values of a compilation of field measurements obtained from the Coastal Carbon Atlas [74] of sediment carbon storage and sequestration in coastal marshes in the study area (see supplementary materials S1.4 for full list of field measurement sources). To

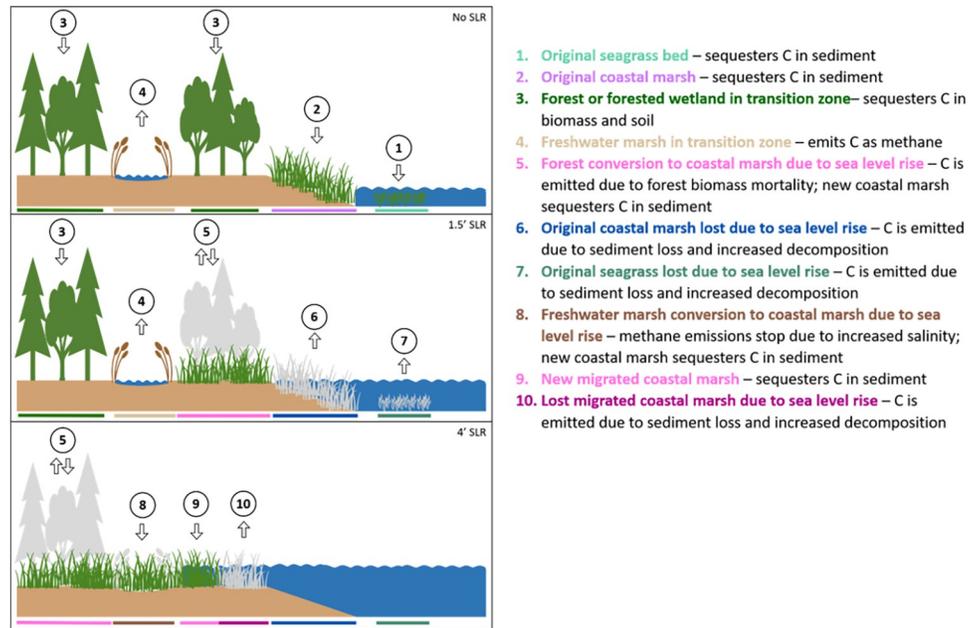


Fig 1. Carbon fluxes (sequestration and emissions) associated with coastal habitats and habitat changes due to sea level rise.

<https://doi.org/10.1371/journal.pclm.0000044.g001>

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 [7,52,75]. New marshes in the transition zone accumulate carbon at the same rate as existing marshes, depending on their salinity class.

2.4.2 Carbon sequestration by vertically accreting marshes. Sea level rise drives marsh elevation accretion by enhancing delivery of suspended sediment by tidal flooding. Marshes are able to keep up with sea level rise by vertically accreting at the same or higher rate as sea level rise; these marshes accumulate carbon at a higher rate than the background carbon accumulation rate for coastal marsh (see section 3.4.1) due to the additional sedimentation and increase in sediment volume [34,38,39]:

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

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/cm³; this is the mean value from the Coastal Carbon Atlas dataset for the study area ([74]; supplementary materials S1.4).

2.4.3 Carbon emissions from lost marshes and seagrass bed. When marshes or seagrass beds drown or erode, they stop accumulating carbon. In addition, a portion of the underlying sediment moves into the estuary, and some of the carbon stored in the sediment is emitted to the atmosphere (Fig 1, fluxes 6 and 7). There is high uncertainty about the amount of stored carbon that is emitted; 25% was set as a best estimate by the state partners based on their experience and literature [35,42]. Carbon released from sediment due to marsh or seagrass loss was assumed to follow an exponential decay function with a half-life of 10 years. A recent field study estimated carbon loss from eroded marsh sediment in the U.S. at 7–24% per year, depending on temperature [35], so a total loss of 25% may be conservative.

2.4.4 Baseline carbon stocks and fluxes in transition zone habitats. The transition zone into which coastal marshes may migrate due to sea level rise is currently occupied by a variety of habitats with associated carbon stocks and fluxes. In the no-SLR scenario, the carbon fluxes from these habitats continue for the entire analysis period. In the SLR scenario, the carbon fluxes from the transition zone habitats continue until they convert to coastal wetlands due to sea level rise, at which point some of their carbon is emitted (see section 3.4.5).

We included baseline carbon stocks and carbon fluxes prior to marsh conversion for forests, wetlands, shrub-scrub, grasslands, and agricultural land. Carbon stocks include biomass (aboveground and belowground) in forests, scrub-shrub, grasslands, and forested and scrub-shrub wetlands, and soil carbon in all of these habitats plus agricultural land and palustrine emergent wetlands (see supplementary materials, S1.5 Tables S3 and S5-6 in [S1 Text](#) for details). Carbon fluxes include biomass carbon sequestration in forests, forested wetlands, and scrub-shrub wetlands; soil carbon sequestration in forests, agricultural land, palustrine emergent wetlands, scrub-shrub wetlands, and forested wetlands; and methane emissions from open water and all wetland types (see supplementary materials, S1.5 Tables S4 and S7-S8 in [S1 Text](#) for details). We did not account for carbon stocks or fluxes for open space developed areas (cleared areas with little vegetation other than grass), or barren land, as they are assumed to be negligible relative to the vegetated land cover types.

2.4.5 Carbon fluxes associated with transition zone habitat conversions. When the transition zone converts to salt marsh due to sea level rise, there are several effects on carbon fluxes. Carbon sequestration by the original habitats is replaced by carbon sequestration from the new coastal marsh habitat, as described in section 3.4.1 ([Fig 1](#), flux 9). Existing carbon stocks in aboveground biomass (e.g., trees) associated with the original habitat type are lost as the vegetation dies and decays ([Fig 1](#), flux 5); existing carbon stocks in soil are assumed to remain intact during the conversion to coastal marsh [[41](#)]. The primary model projection assumes that 100% of aboveground biomass carbon is lost due to the conversion to marsh, following an exponential decay function with a half-life of 10 years. Recent studies have found aboveground biomass carbon decreases associated with conversion to marsh of more than 95% [[40,41](#)]. Methane emissions from wetland and open water areas that convert to marsh decline due to increased salinity from sea level rise, depending on the salinity class to which the migrated marsh is assigned ([Fig 1](#), flux 8). When migrated coastal marsh is lost due to additional sea level rise, we assume that a portion of its stored sediment carbon is emitted ([Fig 1](#), flux 10), using the same methods as for lost original coastal marsh (see section 3.4.3).

2.4.6 Coastal blue carbon model runs. The blue carbon model consists of two components: the InVEST Coastal Blue Carbon model [[76](#)] was used to estimate carbon stocks and fluxes in blue carbon habitats (coastal marsh and seagrass), including new migrated marshes. We developed a separate spatial model to account for the carbon fluxes in the transition zone (described in sections 3.4.4 and 3.4.5). To generate our primary model projection results, these blue carbon models were run twice: once for a no-SLR scenario assuming no changes to any habitats (salt marsh, seagrass, or habitats in the transition zone), and once for the SLR scenario with the projected habitat changes. No SLR is not a realistic future scenario (SLR is already occurring within the study area) [[77](#)]; including it allowed us to assess the effect of SLR on carbon flux by comparing the total carbon flux from the study area (coastal blue carbon habitats and transition zone) with and without the SLR-driven habitat changes. All model runs cover the time period from the baseline year (2010) to 20 years beyond the final future habitat raster (2124). This additional time allows for carbon effects from any habitat changes during the final time interval.

2.5 Sensitivity analysis

Many of the processes in the habitat projection and carbon models are not yet fully understood, and the datasets used are imperfect, contributing additional uncertainty via measurement error (e.g., elevation dataset based on lidar), omission of temporal variation in parameters (e.g., salinity, suspended sediment), classification error (e.g., habitat data), variation in data source dates across the study area (e.g., habitat data, salinity data), and the inherent uncertainty of predicting future changes (e.g., SLR projections, availability of the transition zone for marsh migration). To evaluate the impacts of the uncertainties in model input variables and process parameters on the model results, we performed a sensitivity analysis in which input dataset values, model parameters, and assumptions were varied from the primary model projection (Table 1; for additional description of sources of uncertainty and detail on methods to create variations for sensitivity analysis, see supplementary materials S1.3). Model variations that resulted in changes to habitat projections of at least 10% were included in the blue carbon sensitivity analysis, along with model variations that directly affected carbon calculations. For the blue carbon sensitivity analysis, each model variation was run for a no-SLR and a SLR scenario to allow us to assess the effect of SLR on net carbon flux.

3. Results

3.1 Future habitat projections—primary model projection

At baseline, the study area includes about 371,000 hectares of coastal marsh, 134,000 hectares of seagrass, and 463,000 hectares in the transition SLR zone. Based on increased water depth due to

Table 1. Data and model variations tested in the sensitivity analysis.

Name	Data, parameter, or assumption in primary model projection	Model variations tested in sensitivity analysis
Horizontal erosion rate	Estimated based on water body size and tidal range	Primary model projection estimate -50% Primary model projection estimate +100%
Sediment concentration	GlobColour dataset	Primary model projection dataset +20% Primary model projection dataset -20%
Potential vertical accretion rate	Estimated based on sediment concentration and tidal range	Primary model projection estimate +6 mm/year
Migrated marsh salinity	Randomly assigned using state-level proportions	Randomly assigned based on HUC8-level proportions
Transition zone availability for marsh migration	Exclude projected future development and agricultural land; all other TZ habitats available for marsh migration	Include projected future development Include agricultural land Include both projected future development and agricultural land Exclude forests
Seagrass loss	Depth-dependent	No loss Constant 4% annual loss
SLR scenario	Intermediate (1.2 m by 2104)	Intermediate-low (0.6 m by 2107)
Coastal marsh extent	Identified using state-selected data sources	Identified using C-CAP land cover
Salinity	Estimated based on interpolated water quality data	Primary model projection parameter +20% Primary model projection parameter -20%
Salinity shift during analysis period due to SLR	None	50% of low- and moderate-salinity habitats shift to next higher salinity class in 2039 50% of low- and moderate-salinity habitats shift to next higher salinity class in 2062
Carbon emission from lost coastal marsh and seagrass	25% of total soil carbon stock emitted over long term (exponential decay with 10-year half-life)	Primary model projection parameter +100% Primary model projection parameter -60%
Methane emissions from freshwater habitats	Median estimate from Holmquist et al. 2018 [14]	Low estimate from Holmquist et al. 2018 [14] High estimate from Holmquist et al. 2018 [14]
Aboveground biomass carbon emissions due to forest conversion to marsh	100% of aboveground biomass carbon emitted over long term (exponential decay with 10-year half-life)	Primary model projection parameter -25% Primary model projection parameter -75%

<https://doi.org/10.1371/journal.pclm.0000044.t001>

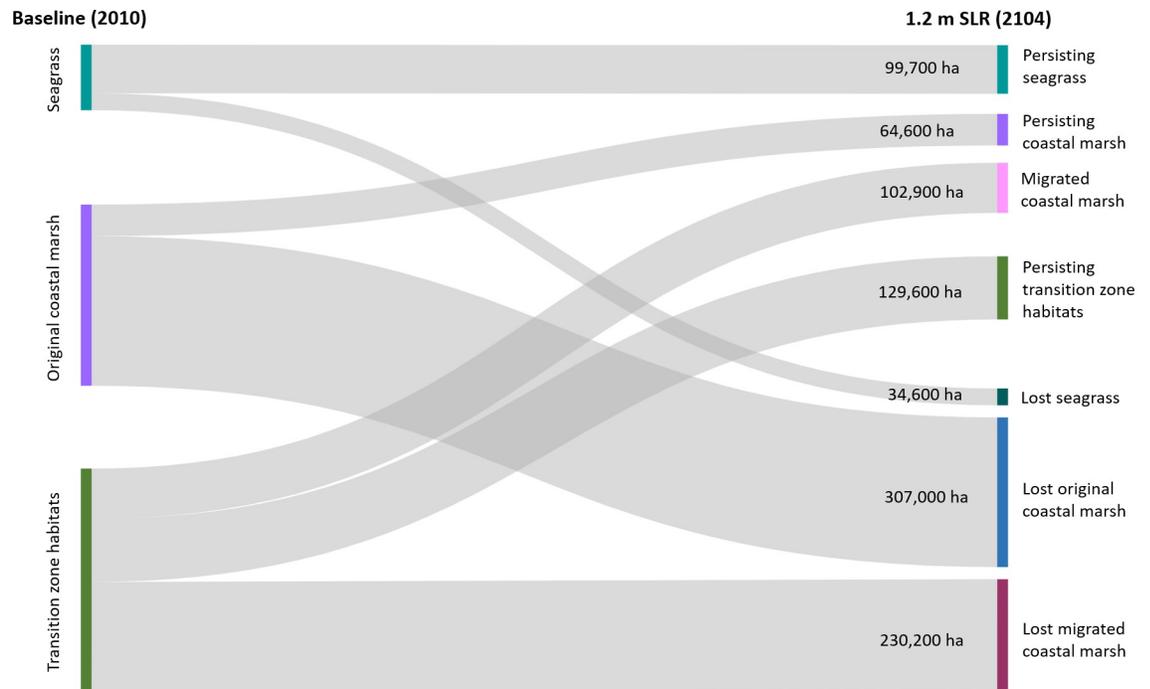


Fig 2. Baseline (no SLR) and primary model projection projected coastal habitat (1.2 m of sea level rise by 2104) in the study area. See Fig A-F in [S2 Text](#) for state-level diagrams.

<https://doi.org/10.1371/journal.pclm.0000044.g002>

sea level rise, approximately 35,000 hectares of seagrass in the study area are projected to be lost under the primary model projection, which assumes 1.2 m of sea level rise by 2104 (Fig 2). Seagrass loss within individual states ranged from 2% to 68%. Coastal marshes in the study area are vulnerable to sea level rise, with 307,000 hectares of coastal marsh loss projected to occur under the primary model projection SLR scenario (Figs 2 and 3A). Coastal marsh loss within individual states ranged from 42% (Delaware) to 98% (Maryland, North Carolina). Approximately 333,000 hectares of the transition zone is projected to convert to marsh during the analysis period, but only 31% of this migrated marsh is projected to persist to 2104 under the 1.2 m sea level rise scenario (Fig 3C). As of 2104, migrated marsh offsets 34% of original coastal marsh loss in the study area; within individual states, this ranged from 13% (New York) to 56% (Delaware). About 17,000 hectares of freshwater wetlands and water bodies were identified as having potential for coastal marsh restoration or creation via hydrologic connection; only 2,000 hectares (12%) were hydrologically connected due to sea level rise by the end of the analysis period. State-level habitat projection results are included in the supplementary materials (S2).

As marsh migrates inland, it replaces existing ecosystems. In the primary model projection, which excludes both agricultural land and projected future development from being available for marsh migration, the majority of habitats lost due to marsh migration are forested areas, including both forested wetlands and upland forests (Fig 3B). Non-forested freshwater wetlands are the next most common original habitat to convert to marsh; grassland, barren land, and open space developed areas make up a smaller proportion in most states.

Net coastal marsh loss or gain is driven by the loss of existing coastal marsh and the creation of new coastal marsh through inland migration. This leads to initial gains in total coastal marsh area with sea level rise as the rate of loss lags behind the rate of inland migration (Fig 4). The rate of marsh migration slows in the 2040s due to decreased availability of land for

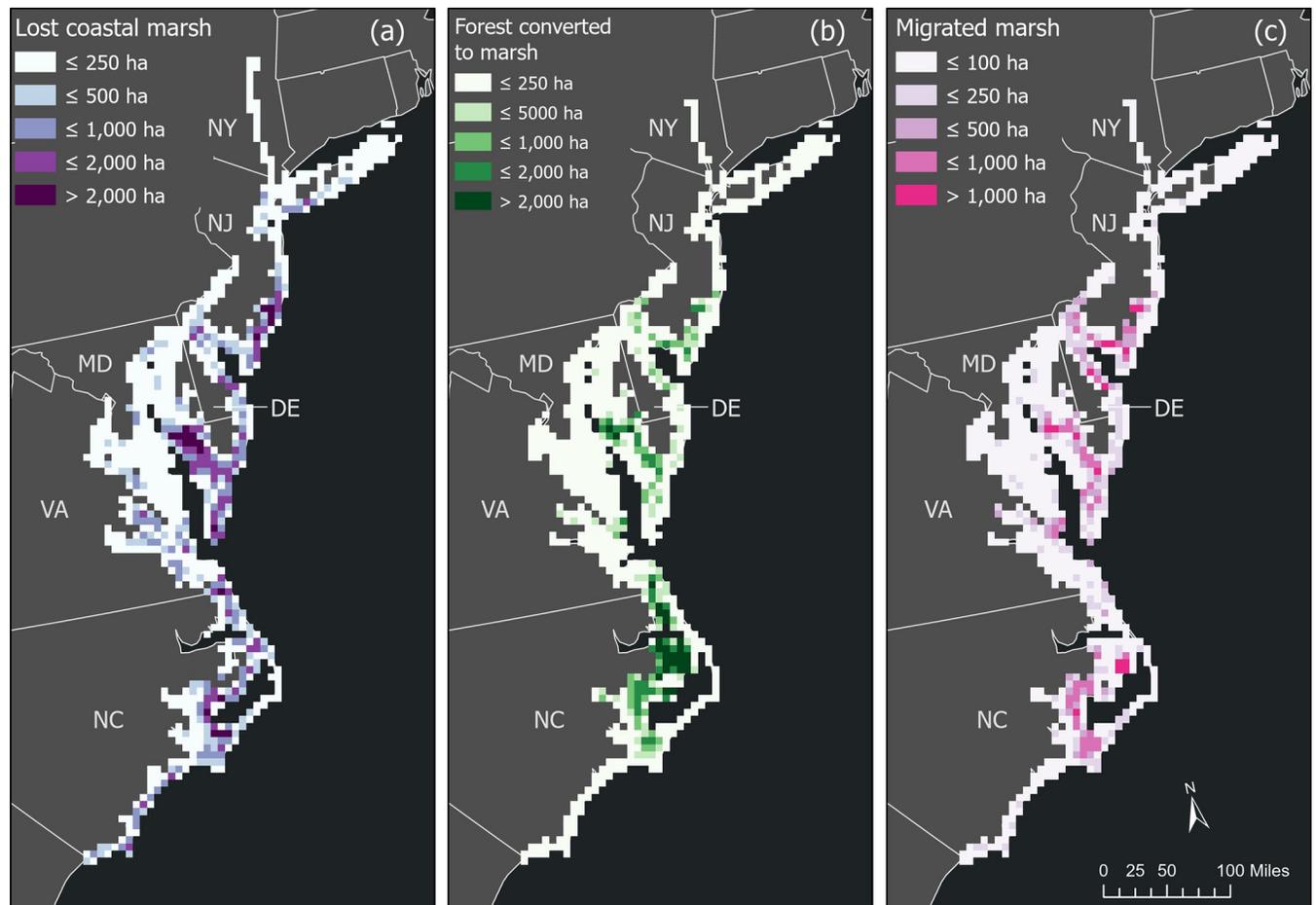


Fig 3. Spatial distribution of (a) projected coastal marsh loss given 1.2 m SLR through 2104, (b) projected forest conversion to coastal marsh, including both wetland and upland forests, given 1.2 m SLR through 2104, and (c) projected migrated marsh present in 2104, given 1.2 m SLR. Made with Natural Earth (<http://www.naturalearthdata.com/about/terms-of-use/>).

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migration. 0.6 meters (2 feet) of sea level rise by 2062 is a threshold after which there is significant decline in total coastal marsh area (persisting original coastal marsh plus new migrated marsh) from baseline; holding sea level rise below this threshold would avoid major coastal marsh losses in the study area.

Existing coastal marshes in the study area have low estimated sediment accretion rates due to their location in areas with low tidal range and relatively low sediment concentrations (Table 2).

None of the marshes in our primary model projection were able to keep up with sea level rise, which reaches rates of up to 16.9 mm/year in the later part of the analysis period. There are about 1,500 hectares of marsh, all in Delaware and New Jersey, that are estimated to be capable of accreting at a rate of about 12 mm/year, and therefore can keep up with sea level rise until about 2050, when SLR exceeds 13 mm/year. Once SLR exceeds that rate, only coastal marshes at a sufficiently high elevation are able to survive.

3.1.1 Sensitivity analysis results for habitat modeling. Given the numerous assumptions and uncertainties in the primary model projection and results described above, we assessed the influence of each uncertainty and assumption on the projected future habitat maps. Several of the model variations that we evaluated—adjusting the sediment concentration input dataset

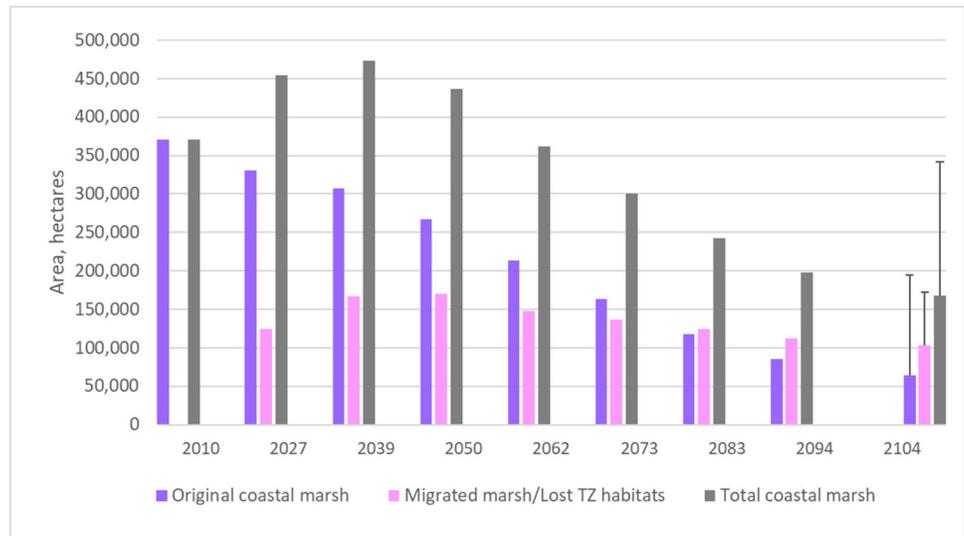


Fig 4. Projected coastal marsh changes over time across six eastern states for the primary model projection. The large, low-elevation coastal plain provides an extensive area for inland marsh migration during the first half of the century, but additional sea level rise causes the loss of migrated marsh after 2050. Error bars represent the minimum and maximum projected area of each habitat type in 2104 among the model variations included in the sensitivity analysis.

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by +/- 20%, adding 6 mm/year to the estimated potential vertical accretion rate, and adjusting the estimated horizontal erosion rate by -50% and +100%—affected the projected future habitat areas by less than 2%, so were not further analyzed. The rest of the model variations tested in the sensitivity analysis had the potential for greater effects on the projected future habitats; these included areas available for coastal marsh migration, SLR scenario, salinity of original coastal marsh, salinity shift with SLR, salinity of migrated coastal marshes, use of alternative coastal marsh datasets, and loss of seagrasses. Thus, the habitat model was rerun for each of these variations individually to assess its effect. State-level sensitivity analysis results are included in S9-S14 Tables in [S1 Text\(Supplementary Materials\)](#).

Area available for coastal marsh migration: In comparison to the primary model projection, which had 333,000 ha of marsh migration over the analysis period, allowing marsh migration into agricultural lands increased the total area available for marsh migration by 92,000 hectares, while allowing migration into areas projected to be developed in the future increased total area available for marsh migration by 41,600 hectares. An additional 36,500 hectares is currently agricultural and projected to be developed, or is connected to existing coastal marsh through those areas. Therefore, it only becomes available for marsh migration if those areas are allowed to transition to coastal marsh.

Table 2. Percentage of existing coastal marshes in the study area by their suspended sediment concentration and tidal range. Most marshes are in areas with low sediment availability and low tidal range, which limits their potential rates of sediment accretion and thus their ability to keep up with sea level rise.

		Sediment concentration (mg/L)					
		<5	5–10	10–15	15–20	20–25	25–30
Tidal range (m)	< 0.5	19.2%	26.3%	3.3%	6.5%	4.0%	1.6%
	0.5–1	6.6%	5.4%	3.8%	1.6%	0.4%	0%
	1–1.5	4.6%	2.9%	0.4%	0.3%	0%	0%
	1.5–2	0.9%	0%	0.1%	0.5%	0.9%	0.3%
	2–2.5	0.2%	0%	0%	0%	0%	0%

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Sea level rise scenario: Using a lower SLR scenario (0.6 m SLR by 2107) resulted in significantly more original coastal marsh surviving to the end of the analysis period (194,300 vs. 64,600 ha). Less of the transition zone converted to marsh with lower SLR (259,700 ha vs. 333,100 ha), but more migrated marsh is projected to exist at the end of the analysis period (147,500 ha vs 102,900 ha). A substantial area of migrated marsh is lost in the 1.2 m SLR scenario which is maintained in the lower 0.6 m scenario.

Salinity of original coastal marsh: Adjusting the salinity raster used in the primary model projection by +/-20% changed the salinity class of 11–13% of coastal marshes in the baseline year. Increasing the estimated salinity values by 20% resulted in a 32% increase in marshes in the high salinity class at baseline and in 2104 (1.2 m SLR). Decreasing the estimated salinity values by 20% resulted in a 25% reduction in marshes in the high salinity class at baseline, and a 27% reduction in persisting marshes in the high salinity class in 2104 (1.2 m SLR).

Marsh salinity shift with sea level rise: When salinity classes defined in the primary model projection are shifted to the next highest class (low salinity to moderate salinity and moderate salinity to high salinity) in 2039 for 50% of marshes, to reflect the potential effect of increased saltwater intrusion and inundation, 24,400 hectares of coastal marsh are in a higher salinity class at the end of the analysis period. Whether this shift takes place in 2039 or 2062 does not change the final salinity class distribution of persisting marsh, but the earlier shift means that more coastal marsh is in a higher salinity class for a longer time period, which has implications for net carbon sequestration.

Migrated marsh salinity: When salinity classes of migrated marsh were defined based on the proportion of existing marshes in each salinity class within the HUC8 watershed, rather than the state, about 7% of migrated marsh existing in 2104 (1.2m SLR) changed salinity class relative to the primary model projection. Overall, there was a decrease in high-salinity migrated marsh and an increase in low- and moderate-salinity migrated marsh when using HUC8 salinity proportions compared to state-level proportions.

Alternative coastal marsh datasets: The Coastal Change Analysis Program (C-CAP) (used for the national inventory) identified 431,000 hectares of coastal marsh at baseline, 59,700 hectares more than the state-selected habitat data used in the primary model projection. This change in baseline extent translated to about 3,600 more hectares of coastal marsh persisting until 2104 (1.2 m SLR).

Seagrass loss: Seagrass extent in 2104 with 1.2 m sea level rise is 99,700 hectares under the primary model projection with depth-dependent seagrass decline. This is an intermediate estimate compared to an alternative with no seagrass losses occur due to sea level rise (134,300 hectares with 1.2 m SLR) and with seagrass area declining at a constant annual rate of 4% (3,100 hectares with 1.2 m SLR).

All of the variations tested as part of the habitat sensitivity analysis also influence the carbon results; those effects are shown in section 4.2.1. The later (2062) marsh salinity shift was not included in the carbon sensitivity analysis since it affected a relatively small amount of marsh due to substantial marsh losses projected to occur by 2062.

3.2 Coastal blue carbon

Coastal marshes and seagrass in the study area currently store about 301 million metric tons CO₂e and sequester an additional 1.1 million metric tons each year. Freshwater wetland and terrestrial habitats (e.g., forests, shrubland, grassland) in the transition zone currently store about 446.9 million metric tons CO₂e and sequester 732,000 metric tons annually. Together, these sequestration rates offset about 0.3% of gross GHG emissions from the six states in the study area (based on the 2019 U.S. National Greenhouse Gas Inventory) [78] and would add

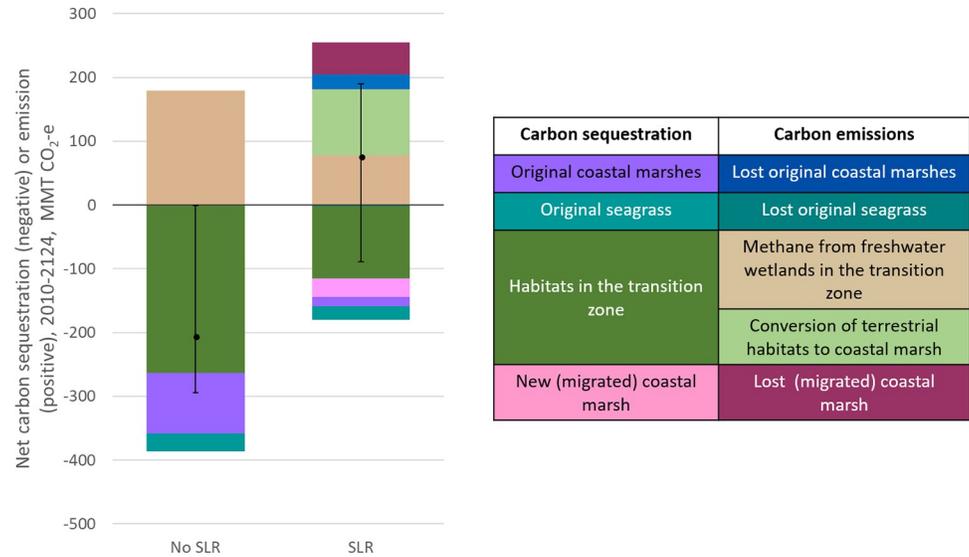


Fig 5. Net carbon fluxes—carbon sequestration (negative) and emissions (positive) for the study area (including the original extent of seagrass and coastal marsh plus transition zone) through 2124, comparing no sea level rise with projected habitat changes due to 1.2-meter sea level rise by 2104. Black points represent total net carbon flux (emissions minus sequestration); error bars are the maximum and minimum projected carbon fluxes among the variations included in the sensitivity analysis (see section 4.2.1 for details). For state-level results, see Fig G-L in S2 Text.

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up to an additional 207.3 million metric tons of stored carbon by 2124 if there were no changes to coastal marshes, seagrasses, or habitats within the transition zone and carbon sequestration continued. However, the projected changes in habitat extent due to sea level rise (from the primary model projection) are estimated to cause the study area to switch to a net source of carbon, emitting 74.6 million metric tons CO₂e (Fig 5) when estimated over the same period. These total emissions over the 114-year analysis period are approximately equal to 12% of the gross GHG emissions from the six states in the study area in 2019 (the average annual emissions over the analysis period are about equal to 0.1% of the 2019 gross GHG emissions) [78].

While there are several carbon flux processes operating in the study area under both the no-SLR and intermediate SLR scenarios, the high projected carbon emissions under the SLR scenario are primarily due to carbon emissions from (1) decomposition of all aboveground terrestrial biomass in the transition zone as it converts to marsh, (2) reduced carbon sequestration by lost original coastal marshes and terrestrial habitats in the transition zone, and (3) microbial decomposition of marsh sediments in the migration space when they are fully inundated and lost due to sea level rise (25% total loss following exponential decay with a 10-year half-life). Methane emissions from freshwater habitats are reduced due to sea level rise as coastal marsh migrates inland and increases salinity levels. The areas identified as having potential for coastal marsh restoration or creation via hydrologic connection make up a small proportion of the total freshwater habitats in the study area. These restorable areas were projected to release 25.7 MMT CO₂e as methane in the no-SLR scenario (through 2124). In the SLR scenario, about 12% of these areas convert to higher-salinity coastal marsh by 2104 due to SLR, dramatically reducing their methane emissions. The remaining 88% release 24 MMT CO₂e. These may be opportunities for restoration, but some are likely in use for other purposes or not ecologically suitable for restoration.

The annual carbon flux in the study area shifts from net sequestration to net emissions over the analysis period, tracking the habitat changes that drive the carbon fluxes (Fig 6). Between

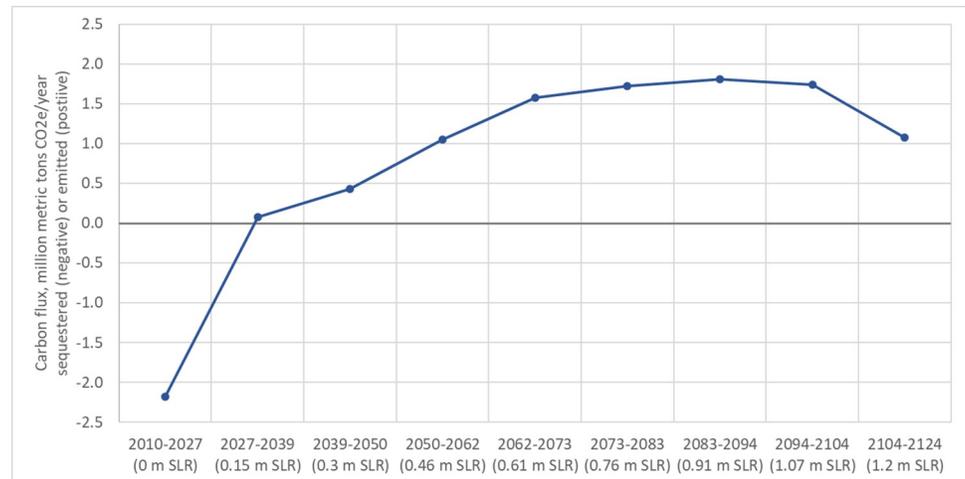


Fig 6. Annual carbon flux (MMT CO₂e/year) sequestered (negative) or emitted (positive) by the study area over time for primary model projection, as habitats change due to sea level rise. See Fig G-L in [S2 Text](#) for state-specific results.

<https://doi.org/10.1371/journal.pclm.0000044.g006>

2010 and 2027, the study area sequesters 2.2 million metric tons CO₂e/year; in the 2027–2039 time step (0.15 m SLR), it switches to a net source, emitting 0.08 million metric tons CO₂e/year. Carbon emissions continue to increase until 2083, when they begin to decline as the rate of habitat loss slows. This pattern is driven by the large transition zone areas where marsh migration occurs when SLR reaches low elevations (0.6 m or less). At the end of the analysis period used in our model (1.2 m SLR in 2104), the habitats present in the study area are sequestering about 0.75 MMT CO₂e per year (not accounting for ongoing carbon emissions from habitat conversion). This is approximately 34% of the estimated annual carbon sequestration at baseline, because much of the area that was originally carbon-sequestering habitat (whether coastal marsh, seagrass, freshwater wetlands, or terrestrial forest) has converted to open water by that point.

3.2.1 Sensitivity analysis results for carbon modeling. The carbon estimates are highly sensitive to the assumptions and data used in the model, with many tested variations causing deviations of greater than 20% from the primary model projection results. (State-level results are included in Table G in [S2 Text](#)). However, SLR was projected to cause a net increase in carbon emissions from the study area over the next century for the primary model projection and all of the tested variations ([Fig 7](#)). The study area was projected to become a net carbon source due to SLR for all but three of the tested variations: no marsh migration into forests, 25% biomass carbon emitted during transition zone conversion to marsh (rather than 100% in the primary model projection), and the intermediate-low SLR scenario ([Fig 8](#)). Each of these variations still resulted in substantial reduction in net carbon sequestration relative to no SLR (by 57%, 99%, and 77%, respectively).

Several of the sensitivity analysis variations have different effects (in terms of direction of change from the primary model projection) on the additional net carbon emissions due to SLR ([Fig 7](#)) and the total net carbon flux under SLR ([Fig 8](#)). For example, the high methane emissions from freshwater wetlands variation results in the second-greatest net carbon emissions under SLR of all tested variations ([Fig 8](#)), but the additional net carbon emissions due to SLR for this variation are the second-lowest of all tested variations. This is because these variations influence net carbon flux without SLR as well as with SLR. In the no-SLR scenario for the high methane emissions from freshwater wetlands variation, freshwater wetlands in the

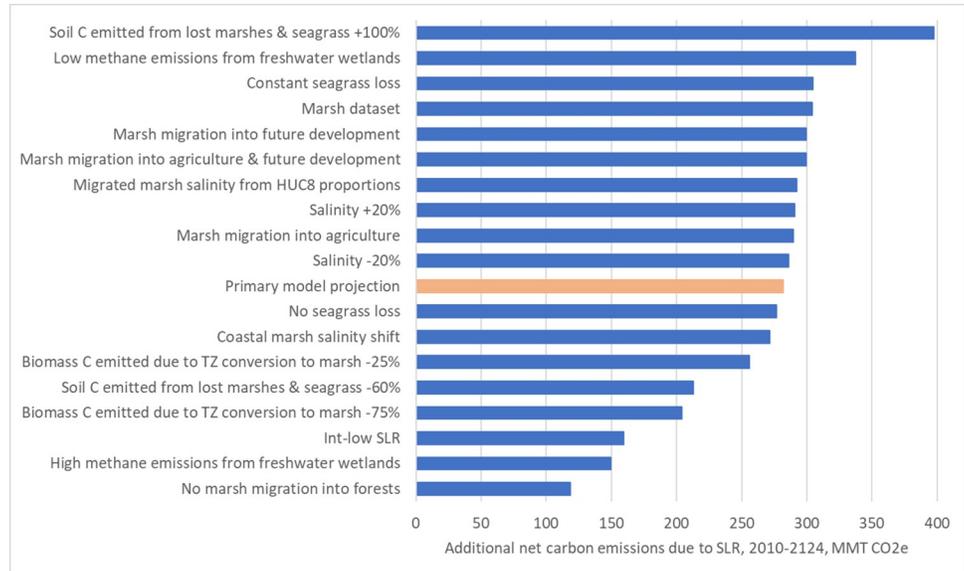


Fig 7. Additional net carbon emissions due to SLR (difference between net C flux with SLR and net C flux without SLR), MMT CO₂e, 2010–2124. Results for the variations tested in the sensitivity analysis are shown in blue bars; the results from the primary model projection are shown in an orange bar for comparison.

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transition zone emit many tons of methane over the entire analysis period. In the SLR scenario, saltwater intrusion and inland marsh migration cut methane production from freshwater wetlands. Therefore, the high methane emissions from freshwater wetlands variation increases the beneficial effect of SLR in reducing methane emissions from freshwater habitats relative to the median methane emissions used in the primary model projection, and reduces the difference between net carbon flux with and without SLR compared to the primary model projection. The reverse effect occurs for the low methane emissions from freshwater wetlands

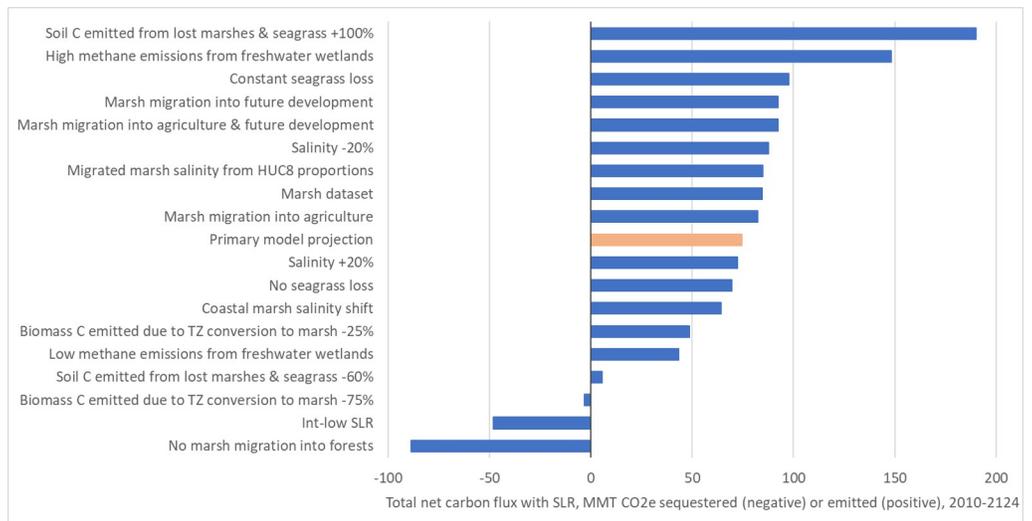


Fig 8. Sensitivity analysis of modeled net carbon flux with SLR to input parameters and assumptions (blue bars), at the regional scale (totals across all states in the study area), compared to the primary model projection results (orange bar). Percent changes in the variation descriptions (e.g., Salinity +20%) are relative to the parameters used in the primary model projection. State-level results available in supplementary materials (Table G in S2 Text).

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variation. Other model variations that influence net carbon flux with and without SLR are the two salinity variations (+20% and -20%) and using the C-CAP dataset to identify coastal marshes.

4. Discussion

4.1 Consequences of SLR-driven habitat conversions on carbon emissions

Our model of SLR-driven habitat conversions in mid-Atlantic states projects widespread loss of existing coastal marshes and inland marsh migration into other habitat types such as upland and wetland forests. It also predicts the loss of about 26% of existing seagrass beds in the study area by the end of the century due to reduced light attenuation with higher sea level in estuaries. These extensive habitat changes will result in carbon emissions, likely causing the coastal zone in the study area to switch from a carbon sink to a carbon source. Only three of the variations, using alternate values of model parameters, tested in our sensitivity analysis resulted in the study area remaining a carbon sink under SLR: no marsh migration into forested areas, 25% vs. 100% emission of biomass carbon from transition zone conversion to coastal marsh, and the intermediate-low vs. intermediate SLR scenario. Preventing marsh migration into forested areas entirely is not feasible; there are extensive low-elevation forests along the coast in the study area, and saltwater intrusion is already causing tree mortality and creating “ghost forests” in the region [40,79]. While the amount of biomass carbon emissions associated with forest loss is uncertain, and 25% emission is possible, studies available so far are much closer to the 100% emission used in our primary model projection [40,41]. Limiting SLR to the intermediate-low scenario depends on global carbon emissions over the coming decades, but the measured rate of SLR at some tidal gauges in the study area has already approached or exceeded the SLR rate in the intermediate-low scenario (5.6–6.6 mm/year) [77].

Even if loss of existing coastal marshes could be reduced through targeted restoration and facilitation of inland marsh migration, the conversion of forested wetlands and upland forests to coastal marsh will release millions of tons of carbon currently stored in tree biomass. Our landscape-scale carbon model shows that the shift from sink to carbon source is dominated by the loss and decomposition of forested habitats, which have large aboveground biomass carbon stocks. These habitat transitions and biomass carbon emissions begin to occur at very low sea level rise elevations (< 0.3 m) and continue throughout the analysis period as additional habitat within the transition zone is replaced by coastal marsh. In fact, the loss of coastal forests is already underway [40,79]. Our results suggest that efforts to incorporate blue carbon (through management of existing and migrating coastal marsh and salt marsh) as a carbon mitigation strategy in the mid-Atlantic coast at a landscape scale are unlikely to succeed into the next century. Current Verified Carbon Standard methodology requires that credits for restored or created marshes can only be allocated if the project significantly reduces carbon loss or enhances carbon sequestration over a 100-year period [13,80]. This may not be feasible in many parts of the study area where existing marshes are highly vulnerable to SLR and inland migration is likely to cause carbon emissions.

In the second half of our analysis period, habitat conversion in the transition zone slows because smaller areas of land are available for marsh migration as sea level rise approaches 1.2 m. This is driven by the topography of the coastal plain in the study area and will vary by location. The reduced rate of habitat change also slows the carbon emissions from the study area toward the end of the analysis period, which are in large part generated by decomposition following habitat conversion. Generally, if the rate of habitat conversion slows either due to topography or because sea level rise itself slows, habitats in the coastal zone would stabilize and the area could again become a net carbon sink.

4.2 Management options to reduce carbon emissions

The fundamental results of our model—significant loss of coastal habitat and carbon—are unlikely to change unless one or more of the key drivers (sea level rise, coastal marsh elevation, or forest conversion to marsh and subsequent biomass carbon emissions) is altered.

Reducing the rate of SLR, as we tested in our sensitivity analysis, results in less habitat conversion (both in terms of coastal marsh and seagrass loss and inland habitats converting to coastal marsh) and therefore lower carbon emissions, but net carbon sequestration within the study area still decreased by 77% for the analysis period under the intermediate-low SLR scenario (0.6 m SLR by 2107). Long-term records of sea level rise at tidal gauges in the study area show SLR of 4.13 mm/year on average, reaching up to 6.05 mm/year [77]. These SLR rates are calculated over long time periods (going back to 1944 on average, and 1856 in one case); as SLR has been increasing in recent decades, the long-term average likely underestimates current rates of SLR in this area. Therefore, SLR rates in the intermediate-low scenario (5.6–6.6 mm/year) are already being exceeded in some parts of the study area; the intermediate SLR scenario used in the primary model projection represents a 3–4x increase over the long-term SLR rates. Reducing greenhouse gas emissions and limiting climate change is the only way to keep SLR (and its effects on coastal habitats and carbon fluxes) as low as possible. A recent NOAA report estimated that if global temperature change reaches 1.5°C by 2100, the probability of exceeding the intermediate-low SLR scenario is 37%, and the probability of exceeding the intermediate scenario used in our primary model projection is <1% [81]. If global temperature change reaches 3°C, those probabilities increase to 82% and 5%, respectively.

Management options to reduce habitat changes and carbon emissions due to sea level rise are limited. Restoring marsh by adding sediment (e.g., creating marsh islands, thin layer placement, etc.) to build up degraded marshes or create new marsh areas can increase marsh elevation via increasing biomass and accretion rates [82], but such efforts are time-consuming (and costly) and have not yet been implemented at broad scales [83]. The biggest drivers of carbon emissions in our analysis are biomass mortality (loss of inland coastal forests and coastal marshes) and methane emissions from freshwater habitats, so methods for controlling those carbon losses would be particularly helpful. It may be possible to slow inland marsh migration to reduce carbon emissions associated with biomass mortality in terrestrial habitats. In some parts of the mid-Atlantic, steps such as building berms and removing salt water via pumping have already been implemented to keep agricultural land in production and protect developed areas from flooding. For example, a six-foot-tall berm around the town of Swan Quarter, NC, protects 11,000 acres of valuable farmland as well as the town [84]. While these measures are expensive, they could be implemented to protect particularly high-carbon areas like forests at risk of mortality due to sea level rise. Reducing decomposition of aboveground biomass in forests that do convert to marshes may be possible through actions such as burial of trees or preemptive harvest (similar to salvage harvest following hurricane damage, e.g. [85]), but these ideas have not been tested and would have their own ecological impacts.

Methanogenesis from low-salinity habitats is highly variable and not well understood, so increased research may illuminate new management options [66]. Even with these uncertainties, it has been shown that restoring saline tidal flows to impounded coastal areas where salinity has been reduced has significant potential for reducing methane emissions. A 2017 analysis of opportunities for restoring impounded wetlands on the U.S. Atlantic coast extrapolated from known impounded wetlands to estimate that 27% of tidal wetlands on the Atlantic coast were impounded and freshened [18]. This would equate to 100,000 ha in our study area, much more than the 17,000 ha we identified as areas of potential coastal marsh that are currently freshwater habitats (see section 3.2.7). If half of the potentially restorable areas we identified

were restored and their methane emissions eliminated, our model projects that carbon emissions through 2124 would decline by 17%. The effect on carbon emissions would be significantly greater if there is a larger area with potential for restoration, as Kroeger et al. suggest [18]. However, many of these freshwater habitats are managed for uses such as waterfowl habitat or are privately owned and may not be available for restoration.

4.3 Comparison to other models

Comparing our modeled habitat and carbon changes to field observations and other models helps to assess whether our results are reasonable and where simplifications and data limitations may be affecting our conclusions. The predicted loss of 83% of current coastal marshes and total coastal marsh decline (accounting for inland marsh migration) of 45% in the study area by 2104 is in line with projected losses from several other models for U.S. coastal marshes, although models differ in their spatial extent, predicted SLR, time frame, and parameterization of key variables. On the Georgia coast, which has a higher tide range and greater sediment supply than our study area, sea level rise of 52 cm and 82 cm by 2100 was projected to cause salt marsh area to decline by 20% and 45%, respectively [27]. An analysis for two watersheds in the Chesapeake Bay region projected 7.3%-23% coastal marsh loss given 62.2 cm SLR by 2070, and 60–90% loss given 124.3 cm SLR by 2070 [86]. Given the vulnerability of existing coastal marshes in our study area due to their low elevations, sediment supply, and tidal range, and the higher SLR scenario we used (except for the >120 cm by 2070 scenario used in one of the Chesapeake Bay models), our slightly greater projected losses seem reasonable. A recent national-scale analysis of coastal wetlands' ability to respond to sea level rise vertically (through sediment accretion) and laterally (through inland migration) identified our study area as having low vertical resilience (vertical accretion rate less than the relative SLR rate for the vast majority of coastal wetlands) for an RCP4.5 SLR scenario, which projects 7.8 mm/year of RSLR in our study area through 2100 [65]. This rate of sea level rise is lower than the 1.2 m SLR by 2104 scenario used in our primary model projection, which reaches rates of more than 16 mm/year. As part of this work, Holmquist et al. developed an equation for estimating sediment accretion potential based on tidal range and relative sea level rise [65] that estimates that marshes need a tidal range of at least 2 meters to keep up with SLR of 8.2 mm/year, and a tidal range of 1.5 meters to keep up with SLR of 6.4 mm/year. 99.8% of marshes in our study area experience tidal range of less than 2 meters, and 97% experience tidal range of less than 1.5 meters, so they are not likely to keep up with these rates of SLR, which are lower than the intermediate SLR scenario used in our primary model projection and similar to the intermediate-low SLR scenario tested in the sensitivity analysis. While the specific sediment accretion rates estimated by Holmquist et al. are higher than those used in our model (given identical conditions) in most cases (see Fig B in [S3 Text](#) for a comparison), their analysis aligns with our conclusion that most coastal marshes in our study area are unlikely to keep up with SLR.

Recent and historical observations also support the widespread potential for inland marsh migration projected by our model. In North Carolina, 15% of unmanaged public lands in the Albemarle-Pamlico Peninsula transitioned from coastal forest to ghost forest (an intermediate step prior to conversion to coastal marsh) between 2001 and 2014 [40]. A similar analysis of the Alligator Wildlife Refuge (which is part of the Albemarle-Pamlico Peninsula) found that 11% of forest in the refuge transitioned to ghost forest between 1985 and 2019, with more than 4,000 hectares of ghost forest forming between 2011 and 2012 (after several stressors including a multi-year drought and a hurricane) [79]. Comparison of nineteenth-century maps to current photographs show that about one-third of present-day marsh in the Chesapeake Bay was created by inland migration over the last 150 years [87].

Several recent studies have connected coastal marshes' vulnerability to SLR with their status as a carbon sink or source. An assessment of seven sediment-rich Louisiana marshes found that two marshes were already carbon sources, and four of the remaining five would become carbon sources within the next 80 years due to loss of carbon from drowned and eroded marshes [34]. Extrapolating measured accretion and carbon accumulation rates for wetlands in the Albemarle-Pamlico peninsula in North Carolina estimated that carbon sequestration by those wetlands would decline by 35% (for 25 cm SLR) to 88% (for 100 cm SLR) without accounting for inland migration of coastal wetlands [88]. With migration included, carbon sequestration declines were smaller (2% and 23% under the 25 cm and 100 cm SLR scenarios), but these estimates did not account for reduced biomass carbon sequestration in areas that convert from forests to marshes, or carbon emissions resulting from tree mortality in those areas, some of the largest carbon losses in our model.

4.4 Uncertainties and research needs

Our sensitivity analysis enabled the identification of major uncertainties and research needs that, if addressed, would improve our ability to estimate habitat and carbon changes at broad spatial scales.

The major uncertainties related to future habitat changes were assumptions about (1) the areas available for inland marsh migration, (2) salinity of existing and future marsh habitats, and (3) marshes' ability to keep up with sea level rise through vertical accretion. Future rates of SLR, which are inherently uncertain and have a large effect on projected habitat changes, are already the subject of intensive research and are not discussed further here. Our decision to exclude agricultural land and areas likely to be developed in the future from areas available for marsh migration may have caused us to underestimate future coastal marsh extent. Additional information about the options land managers have to slow or prevent marsh migration, and how effective these options will be in different areas, would help to inform these assumptions. The total amount of marsh migration will partly depend on policies and decisions about the trade-offs between protecting existing land uses (or options for future development) and allowing or promoting marsh migration. In addition, many of the relevant landscape features that prevent or facilitate marsh migration (e.g., roadside berms, agricultural ditches) occur at finer scales than the 30-m resolution used for this analysis. Higher-resolution input datasets, particularly elevation data, and finer-scale modeling would allow for improved understanding of where marsh migration is likely to occur, and where topographic barriers may prevent it.

Salinity is another key uncertainty; most available salinity data is for estuaries adjacent to marshes rather than within the marshes themselves. While porewater in marshes may have higher salinity than the adjacent estuary due to evaporation, groundwater inflows can also decrease marsh salinity relative to nearby waterways [89–91]. When we increased the interpolated salinity values used in our primary model projection by 20% as part of the sensitivity analysis, there was a 32% increase in marshes in the high-salinity class in the baseline year, and carbon emissions under the sea level rise scenario were reduced by about 3%. We were unable to project future salinity changes in estuaries or marshes due to the complex dynamics affecting salinity.

When considering marshes' ability to keep up with sea level rise through accretion, some of the uncertainties and simplifications in the model made our projections of marsh loss and carbon emissions more conservative (projecting less habitat change and carbon emissions): the lidar-based marsh elevation data was not corrected for aboveground biomass and therefore likely overestimated the original marsh elevation by 10 to 20 centimeters [51], and we did not include local subsidence data that could increase the relative rate of sea level rise in certain

locations [48]. In addition, the modeled sediment accretion does not consider the position of the marsh in the tidal frame, or distance from marsh edge, which can be important determinants of suspended sediment supply and sediment accretion [30,38,92,93]. In particular, this likely led to overestimation of sediment accretion for marshes high in the tidal frame, which are inundated less frequently [92]. Other uncertainties made our projections less conservative (projecting greater habitat change and carbon emissions): the simplified sediment accretion equation did not account for belowground biomass growth [94,95] or the potential for eroded sediment from the marsh edge to increase elevation in the marsh interior [63]; there are no sufficiently large datasets with the required accuracy to refine the sediment accretion equation at this scale. In North Carolina and Virginia, our modeled accretion rates vary significantly from measured accretion rates for coastal marshes in certain locations (see Fig A in S3 Text), suggesting that the additional factors not included in the simple sediment accretion equation play a large role [94,96–98]. Our model also neglected the potential for increased carbon dioxide concentrations and temperatures to increase vegetation growth rates [99–101], nor did it include the potential for surface elevation increase in the freshwater tidal migration space [102].

Our primary model projection's projection of seagrass change does not include seagrass colonization of newly-inundated, shallow areas with sea level rise, nor the ability of seagrass to accrete sediments [103]. These effects may be limited given that seagrass is highly sensitive to other environmental conditions including water quality, temperature, and physical disturbance, that are influenced by climate change and other human actions. In particular, turbidity and pollution are likely to increase as terrestrial areas flood due to SLR. Recent measurements have detected annual rates of seagrass decline that, if they continue, would result in almost total loss in the study area by the end of the century [104]. This amount of seagrass loss would increase carbon emissions under sea level rise by about 31% relative to our primary model projection. The potential for exacerbation of existing stressors due to climate change, and for shifting geographic distributions of seagrass species [25,105], makes projections of future seagrass extent and location highly uncertain; more research in this area is needed.

While all of the uncertainties related to habitat changes also affect carbon, the two variables that lead to the greatest uncertainty in our projected carbon fluxes are (1) methane emissions from freshwater wetlands and (2) carbon emissions associated with habitat losses (both biomass carbon emissions from forest loss and soil carbon emissions from coastal habitat loss). Using a high-end estimate for methane emissions, rather than the median estimate used in the primary model projection, almost entirely eliminated the study area's carbon sequestration even in the no-SLR scenario. The low-end methane emissions estimate, in contrast, increased carbon sequestration in the no-SLR scenario by 42%. Freshwater methane emissions are highly variable and therefore difficult to predict across large areas [66]; they also have significant implications for the status of the coastal zone as a carbon sink or source both now and in the future. Greater confidence in coastal blue carbon estimates will require an improved understanding of the factors driving methane emissions that can be incorporated into models.

In our primary model projection, we assumed that 100% of the carbon in the aboveground terrestrial biomass is lost when converting to salt marsh. When this assumption is changed to 25% and 75% of carbon lost, the net estimated carbon emissions in the sea level rise scenario are reduced by 35% and 104% relative to the primary model projection results, respectively. While an increasing amount of research is focused on improving estimates of carbon emissions from decomposing ghost forests created by saltwater intrusion and from eroded marsh sediments [35,40,41], additional work in a broader range of geographic areas and environmental conditions is needed. Without a better understanding of coastal carbon emissions from loss

and decomposition of these coastal habitats, it will be difficult to refine coastal blue carbon models in low-lying regions where coastal habitats are migrating inland.

4.5 Conclusion

Conserving and enhancing blue carbon in coastal habitats has been discussed as a promising carbon mitigation strategy [20,21], although our estimate of current annual carbon sequestration by coastal zone habitats (including seagrass, coastal marshes, and low-elevation upland habitats) is just 0.3% of gross greenhouse gas emissions from the six states included in the study area [78]. Several studies have predicted increasing carbon accumulation over the coming decades, even with coastal marsh area loss due to SLR [5,34,38,39]. While a short-term increase in tidal wetland carbon accumulation may occur, in our study area we project that over a century, the loss and decomposition of forest biomass caused by the inland migration of marshes will more than offset this, causing the coastal area to convert to a carbon source. Therefore, the coastal zone is unlikely to be a reliable or significant carbon sink into the next century, and blue carbon cannot be relied upon as a mitigation strategy without additional adaptive management actions.

Coastal habitats are valuable for many reasons other than carbon sequestration, including protecting coastal areas from flooding and erosion, enhancing water quality, and providing habitat for commercially and recreationally significant wildlife species [1–4]. Efforts to conserve or create new habitat areas will enhance these values and may also provide some carbon benefit by increasing carbon sequestration and minimizing emissions. Many coastal states are already beginning to use some of the products of this modeling work in their climate mitigation and coastal management planning. The spatially explicit modeling of coastal change and coastal carbon can be used to inform selection of coastal areas for future research and monitoring and to prioritize areas for conservation and restoration projects. For example, North Carolina is including information about projected marsh loss with sea level rise, inland marsh migration, and current and future blue carbon stocks in its updated Coastal Habitat Protection Plan. There is also potential for this work to inform the standardized incorporation of blue carbon into state greenhouse gas inventories; currently, the EPA tool that many states use for their greenhouse gas inventories does not include blue carbon [106]. Given the likelihood of significant changes to both coastal habitats and blue carbon in the coming decades, and the growing attention to these issues at all levels, addressing the research and data gaps identified in this paper to provide reliable information for coastal decision-makers is critical.

Supporting information

S1 Text. Table A. Sea level rise elevation and rate for timesteps in the analysis. Table B. Data sources for existing salt marsh and seagrass extent and location. Table C. Carbon stocks for original habitat types in the transition zone. Table D. Carbon fluxes (annual sequestration or emissions rates) for original habitat types in the transition zone. Table E. Biomass carbon stocks for grassland and shrub/scrub from Sleeter et al. 2018. Table F. Soil carbon stocks for forests, grassland, and shrub/scrub from Sleeter et al. 2018. Table G. Annual carbon sequestration (MT CO₂e/ha/year) in live biomass by forest type and age class. Table H. Wetland methane emissions estimates from Holmquist et al. 2019. (DOCX)

S2 Text. Fig A-F. Projected coastal habitat changes under 1.2 m SLR by 2104 from the primary model projection. See main text Fig 2 for the regional results. Note that the scale of each state-level figure is independent (bars of equal widths in two state diagrams do not necessarily

represent the same area). Fig G-L. Projected net carbon fluxes—carbon sequestration (negative) and emissions (positive) for each state in the study area through 2124, comparing no sea level rise with projected habitat changes due to 1.2-m SLR by 2104. Points represent total net carbon flux (emissions minus sequestration); error bars are the maximum and minimum projected carbon fluxes among the variations included in the sensitivity analysis (see section 4.2.1 for details). Fig M-R. Annual carbon flux (MMT CO₂e/year) sequestered (negative) or emitted (positive) by each state in the study area over time as habitats change due to SLR, for the primary model projection. Tables A-F. Sensitivity of habitat change results due to changes in initial conditions or model parameters at the state level. Table G. Sensitivity of carbon flux results due to changes in initial conditions or model parameters at the state level, by state. (DOCX)

S3 Text. Fig A. Comparison of measured vertical accretion rates in North Carolina and Virginia coastal marshes with estimated sediment accretion rates using the equation from Schuerch et al. 2018 [24]. This suggests that the Schuerch equation may be underestimating accretion rates in some marshes by about 6 mm/year, and was used to inform sensitivity analysis related to the accretion rate (see S1.3.1). Fig B. Comparison of estimated accretion rates from Schuerch et al. 2018 [24] (used in this paper) with Holmquist et al. 2021 [24]. (DOCX)

Acknowledgments

Thanks to the following partners from each state in the study area for their guidance and feedback on method development and interim results: from North Carolina, Lora Eddy (The Nature Conservancy—NC), Stacey Feken (Albemarle-Pamlico National Estuary Partnership), and Sarah Spiegler (NC Sea Grant); from Virginia, Molly Mitchell (Virginia Institute of Marine Science), Ann Phillips (Virginia Office of the Governor), Mark Luckenbach (Virginia Institute of Marine Science), Tom Allen (Old Dominion University), Elizabeth Spach (Virginia Office of the Governor), and Benjamin Nettleton (Virginia Office of the Governor); from Maryland, Elliott Campbell (MD Department of Natural Resources), Nicole Carlozo (MD Department of Natural Resources), Jason Dubow (MD Department of Planning), Susan Payne (MD Department of Agriculture), and Deborah Herr Cornwell (MD Department of Planning); from Delaware, Mark Biddle, Kari St. Laurent, and Jennifer DeMooy (all DE Department of Natural Resources and Environmental Control); from New Jersey, Becky Hill, Metthea Yepsen, David DuMont, Elizabeth Semple, and Ruth Foster (all NJ Department of Environmental Protection); and from New York, Riobart Breen and Willow Eyres (both NY Department of Environmental Conservation). Thanks also to Nate Herold (NOAA), Kevin Kroeger (USGS), James Holmquist (Smithsonian Environmental Research Center), Mark Schuerch (University of Lincoln), Analie Barnett (The Nature Conservancy), Joe Fargione (The Nature Conservancy), Benjamin Sleeter (USGS), and Stephen Ogle (Colorado State University) for sharing their expertise and data.

Author Contributions

Conceptualization: Katie Warnell, Lydia Olander.

Data curation: Katie Warnell.

Formal analysis: Katie Warnell.

Funding acquisition: Katie Warnell, Lydia Olander.

Methodology: Katie Warnell, Lydia Olander, Carolyn Currin.

Project administration: Katie Warnell.

Supervision: Lydia Olander, Carolyn Currin.

Writing – original draft: Katie Warnell.

Writing – review & editing: Lydia Olander, Carolyn Currin.

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