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Valuation of long-term coastal wetland changes in the U.S.

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ABSTRACT

Sea level rise threatens the coastal landscape, including coastal wetlands, which provide a unique natural habitat to a variety of animal and plant species as well as an array of ecosystem service flows of value to people. The economic valuation of potential changes in coastal wetland areas, while challenging, allows for a comparison with other types of economic impacts from climate change and enhances our understanding of the potential benefits of greenhouse gas mitigation. In this study, we estimate an ensemble of future changes in coastal wetland areas considering both sea level rise, future greenhouse gas emissions, and accretion rate uncertainty, using outputs from the National Ocean and Atmospheric (NOAA) marsh migration model. By the end of the century, total wetland losses range from 2.0 to 10.7 million acres across sea level rise scenarios. For Representative Concentration Pathway (RCP) 4.5 and RCP8.5, respectively, cummulative net wetland area loss is 1.8 and 2.4 million acres by 2050 and 3.5 and 5.2 million acres by 2100. We then estimate economic impacts with two distinct approaches: restoration cost and ecosystem services. The ecosystem services considered are limited by what can be reliably quantified—namely, coastal property protection from coastal flooding and carbon sequestration, the latter using a social cost of carbon approach. By the end of the century, annual restoration costs reach $1.5 and $3.1 billion for RCP 4.5 and RCP8.5, respectively. The lost ecosystem services, together, reach annual economic impacts that are much higher, reaching $2.5 billion for RCP4.5 and $6.1 billion for RCP8.5.

1. Introduction

Wetlands are dynamic, ecologically and economically significant systems that provide valuable benefits and support a variety of services including natural infrastructure protection (i.e., from coastal storms), reduced shoreline erosion from waves, improved water filtration and quality, fisheries, tourism, and recreation (Barbier et al. (2011). Wetlands also provide climate mitigation benefits by absorbing atmospheric carbon dioxide (Howard et al., 2017; USGCRP 2018). As a result, there is increasing concern about the impacts of climate change on wetlands, especially sea level rise (SLR), and the role wetlands play, along with other types of natural coastal infrastructure (e.g., dunes, barrier beaches, etc.), in providing protection from coastal hazards (Arkema et al., 2013; Barbier et al., 2013; Saleh and Weinstein 2016).

In the U.S. and elsewhere, attempts have been made to account for wetland losses in economic terms (e.g., Flight et al., 2012; Narayan et al., 2017; Gardner and Johnston 2020). Most attempts to value SLR-driven wetland losses have been conducted for relatively small areas, at the scale of approximately one U.S. county, owing in part to the need for site-specific data and information to assess physical and economic impacts. The implications of how these wetlands respond to rapid sea level changes are important not only because they provide ecosystems for a variety of unique plant and animal species, but also because of the services wetlands provide to human inhabitants, such as reducing storm surge damage by dampening wave action and surge velocities.

Sea-level rise (SLR) affects marsh viability in coastal areas through processes of landward migration of salt-marsh vegetation zones, submergence at lower elevations, and drowning of interior marshes (Wong et al., 2014). Marshes do gain elevation through accretion, reducing the impacts of the rising seas. As a result, marshes may gain area even as sea levels rise in certain locations, dependent on physical factors including the rate of sea level rise, topography, and other site characteristics.

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However, coastal properties are also vulnerable to sea level rise and episodic flooding from storm surge (Neumann et al., 2015, 2021; Dinan, 2017) and protecting these valuable properties with impeding structures like sea walls will likely obstruct marsh migration inland. Studies have also indicated that wetlands offer some protection for coastal properties against storm surge (Barbier et al., 2013; Boutwell and Westra 2016). Understanding how these factors interact is and will be an active area of research. For example, Holmquist et al. (2021) develops a meta-analysis of accretion rates, vertical resilience indices, and localized SLR across the country. They find that almost half of wetland areas, 43%–48%, are both vulnerable to vertical accretion deficits, due to rapid sea level rise compared to accretion rates, and restricted migration inland because of lateral barriers such as topography and development. Given the complex physical and biological factors that impact marsh migration as well as the importance of wetland areas, many efforts have turned to marsh migration models to quantitatively assess the impacts of sea level rise to coastal wetlands.

There are many different types of models and tools used to understand how coastal wetland areas may change in the future (see S2 in the Supplemental Material for more detail on marsh migration models). Probably the most widely used model in the U.S. is the Sea Level Affecting Marshes Model (SLAMM; Warren Pinnacle Consulting, 2016), an open-source geomorphic model maintained by Warren Pinnacle Consulting. SLAMM is a relatively complex model to run and typically evaluates study sites the size of planning areas like the coastal region of New York State (Clough et al., 2016) or in a specific river delta like the Liaohe Delta in China (Zhi et al., 2022).

The migration model available from National Oceanic and Atmospheric Administration's (NOAA) sea level rise viewer (NOAA 2021) includes output from a marsh migration model, originally designed as a simpler form of SLAMM, evaluated over the entirety of the coastal Contiguous United States (CONUS). The model uses the change extent in several tidal surfaces to drive the changes in wetland types that would occur under user defined sea level rise scenarios and rates of accretion. Tidal variation (modeled as four different tidal surfaces), elevation, boundary between upland area and wetland, and baseline wetland habitat are used as inputs to the model. Land area changes are triggered by changes in land conditions as sea levels rise, and how those correspond with the preferences of each wetland category (as defined by tidal surface transitions). These characteristics make NOAA's sea level rise viewer a good choice for the CONUS scale analysis presented here.

Estimation of physical impacts, such as area of wetland lost, is a critical output of this analysis, but monetization of physical impacts facilitates a comparison with economic impact results from other sectors (e.g., coastal property loss from sea level rise). Monetization also introduces an additional layer of uncertainty and rarely encompasses all types of impacts and harm. Generally, two types of approaches have been developed to monetize ecosystem impacts: restoration costs and value of existing ecosystem services – both are used here. Restoration costs are based on the cost to construct or repair habitat, usually on a per-acre basis. Ecosystem services are generally more difficult to quantify, as services are varied and often hard to enumerate, but represent a preferred measure by most analysts (Guerry et al., 2015). Some services (e.g., flood protection), can be quantified based on changes in damage frequency and severity of physical assets with quantifiable values. Others, such as recreational value, can be valued based on survey data on willingness-to-pay or stated preference, or through more conservative but easier calculations such as ticket prices for parks or revenue from tourism industries.

In 2007, the Environmental Law Institute (ELI) worked with the US Army Corps of Engineers (USACE) to develop restoration costs per-acre by USACE district across all wetland types based on restoration projects in fiscal year 2003 (Environmental Law Institute, 2007). High costs are associated with districts surrounding large coastal cities. For example, per-acre costs are over $100,000 in the Los Angeles, New York, Philadelphia, Sacramento, and San Francisco districts. Inland districts, districts with less urban area, or districts in the Gulf tend to have lower cost estimates. For example, the Pittsburgh district provides a per-acre restoration cost of $21,300; the Wilmington district: $19,050; and New Orleans: $23,150. These estimates are based on survey responses by staff in each USACE district.

Regarding ecosystem services, here we focus on monetization of two categories that have previously been shown to be important in this context: wetland flood protection value; and wetland greenhouse gas sequestration. In a review of 88 tropical storms and hurricanes hitting the United States between 1996 and 2016 along the Atlantic and Gulf Coasts, Sun and Carson (2020) find that coastal wetlands are associated with a statistically significant reduction in property damages from tropical storms and hurricanes. The authors find that the marginal value of wetlands is higher near coastal cities in the Northeast (e.g., near Boston, New York) and along the Gulf Coast east of New Orleans. The annual marginal value of wetlands can vary significantly – "from less than $800 to $100 million per km2, with an average of about $1.8 million and a median value of $91,000."

In addition to the potential of providing protection to property from coastal storms, wetlands have the potential to be an overall sink of greenhouse gases. Vegetated coastal wetlands hold dead organic carbon in the soils preserved against decomposition and so build large pools of sequestered carbon over time. They also emit methane, a GHG more potent than CO_2 but with a significantly shorter atmospheric lifetime, as the dead organic materials decompose, emitting a significant share of natural methane emissions; though anthropogenic sources of methane have recently overtaken natural emissions (Jackson et al., 2020). Sea level rise poses a particularly dire threat to the "blue carbon" stored by coastal wetlands in the soil when the sea sufficiently drowns the vegetation, as most of the carbon stored in the soil is lost to erosion. Also important to consider is that, as coastal wetlands migrate inland, they are able to store carbon in previously upland zones providing newly sequestered carbon pools.

The study described herein uses the NOAA marsh migration model outputs to develop coastal wetland areas losses across a portfolio of sea level rise scenarios for the entirety of the coastal Contiguous United States (CONUS). These wetland areas are valued with two approaches: restoration cost and ecosystem services - with the latter approach focused on two components: property protection from flooding and carbon sequestration. To the knowledge of the authors, this is the first study of this kind to develop valuations of coastal wetland area changes for the entire CONUS. Studies like this can help direct national policy and assist in our understanding of the economic impacts of climate change.

The analysis is part of a larger multi-sector modeling project to estimate climate change impacts in the United States, with evaluation of how risks can be reduced through greenhouse gas (GHG) mitigation and adaptation actions (EPA 2021). Improved understanding of the risks that inundation pose to coastal wetlands and the services they provide is important to ensure that these impacts are considered in broader analyses of climate policies.

2. Methods

Our approach first builds projections of coastal land area changes relying primarily on the NOAA marsh migration data at specified relative changes in sea level. Integrating local sea level rise projections with local accretion rates, NOAA marsh migration outputs are interpolated between the specified heights to solve annual changes in land areas. The results from this procedure are compared with SLAMM results for the Gulf Coast to understand model output differences. To understand how developed areas might respond to coastal flooding, we compare developed areas designated in the NOAA marsh migration output with adaptation responses simulated with the National Coastal Properties Model (NCPM). Finally, we estimate the economic impacts of wetland area changes using a restoration approach and two ecosystem service approaches—property protection and carbon sequestration.

2.1. NOAA marsh migration

The NOAA marsh migration model provides gridded land cover at a 10-m resolution for all three of the major coastlines in the U.S.: Gulf, Atlantic, and Pacific. It also provides 2–2.4-m outputs in the Pacific and Caribbean, where higher resolution initial land cover maps exist. The outputs are not based on a particular sea level rise projection and/or accretion rate. Instead, an estimate of the land area types for the coast is provided at half-foot increments of relative SLR from zero to 10 ft. This dataset allows flexibility for the user to select the output that most closely matches the most appropriate sea level rise projection and accretion rate. It is important to note that the dynamic effects of dikes and levees, or other hydraulic structures, are not considered in NOAA's model.

NOAA's marsh migration output was chosen for this study because it provided a consistent set of output layers available nationally. In addition, the flexible approach ensured that the necessary information corresponding to the specific amount of sea level rise, appropriate accretion rate, and time frame for each county would be available. As previously discussed, this modeling only accounts for these factors. Impacts from erosion, overwash, future storms, or other impacts are not factored into the outputs.

Because the NOAA outputs are created at half foot increments of potential sea level rise net impact, it should be noted that there could be a difference of up to one quarter of a foot between the available layers and the actual county specific value. This is addressed with an interpolation described in Section 2.4. In addition, because NOAA handles accretion as a flat value across all land types including wetland and upland areas in unison (in order to simplify the required modeling), it was necessary to utilize two of NOAA's layers for each county. One layer for wetland areas, where accretion estimates were included, that accounted for vertical movement of existing marshes and their ability to keep up with sea level rise in place. And a second layer for upland areas, where accretion was not included from the net sea level rise impacts, that more accurately accounted for the landward migration of future marsh area.

2.2. Sea leve rise projections

Changes in land types are driven by projections of changes in sea level from (Sweet et al., 2017) used in the Fourth National Climate Assessment Report (USGCRP 2018). These projections incorporate local factors into the six GMSL rise uncertainty scenarios (Kopp et al., 2014) including shifts in oceanic factors, changes in Earth's gravitational field and rotation, glacial rebound effects, and vertical land movement, among others. The Northeast Atlantic and Western Gulf Coasts are expected to experience higher rates of sea level rise than the global average for all scenarios and the Western Gulf in particular is likely to experience rapid rates of relative rise early in the century because of subsidence. In contrast, the Pacific Northwest projections are generally lower than the global average although it is higher for the Intermediate-High, High, and Extreme scenarios, which is also the case for all CONUS coastlines (Sweet et al., 2017).

The projections are available at a 1° grid spatial scale at for each decade starting in 2000 and ending in 2100. These are spatially aggregated to 302 coastal counties following prior CIRA coastal analysis (Neumann et al., 2021). The six uncertainty scenarios are Low (30 cm of GMSL rise by the end of the century), Intermediate-Low (50 cm), Intermediate (100 cm), Intermediate-High (150 cm), High (200 cm), and Extreme (250 cm). Using probability weights (available in EPA 2017) that sum to one, we approximate the effect of two greenhouse gas emissions scenarios on the net expectation of SLR by multiplying the six sea-level rise uncertainty scenarios by the weights and summing the product. The greenhouse gas emissions scenarios are consistent with radiative forcing associated with the Representative Concentration Pathways (RCP) 4.5 (moderate emissions) and 8.5 (higher emissions). The weights are higher for more likely scenarios (e.g., the Intermediate-Low and Intermediate scenarios) and lower for the Low and Extreme scenarios that have lower probabilities of occurrence.

2.3. Accretion

Accretion is the growth by deposition of suspended particles and plant material in areas with occasional or permanent flooding, effectively raising the ground level. This effect reduces SLR relative to the ground surface and varies substantially geographically and over time and is therefore essential in the understanding of SLR impacts on coastal wetlands. Accretion rates are difficult to define over a large area with diverse hydrologic, biologic, and geologic structures and compositions. In spite of these uncertainties, we know accretion rates vary geographically and a comprehensive literature review that covers, as much as possible, a variety of locations on all three coastlines, helps anchor a centralized estimate.

From the broad literature review of accretion rate sources, a set of analyses conducted by SLAMM developers (Warren Pinnacle, 2021) with 296 sites total, and the database developed in Holmquist et al. (2021) with 481 sites, were the most comprehensive. We also included accretion rates reported by Reed et al. (2006), 69 sites, and Cressman (2020), 15 sites, as described in Table 1.

Each source listed in Table 1 provides accretion rates that we then assign to their respective counties in CONUS. In many cases, the SLAMM reports use default accretion rates by vegetation type, employing site-specific observations or region-specific measurements based on other literature where available. Without a clear method for discerning the accuracy of each measurement within a county, we average accretion rates to provide a centralized approximate accretion rate per county, called the "medium accretion rate scenario." Using the average range of accretion rates for all counties with measurements available, we develop both a Low and High accretion rate scenario as well. These are the Medium accretion rate scenario values −2.5 mm/year and +2.5 mm/year, respectively. Counties without measured accretion rates are assigned accretion rates using the three nearest counties weighted by the inverse of the distance to the centroid of the coastline. Fig. 1 shows the accretion rate for the coastal counties for the Medium scenario. See Section S3 with Figs. S1, S2, and S3 in the Supplemental Material for more detail on the approach.

2.4. Interpolation of indexed runs to SLR scenarios

As mentioned, NOAA's model provides outputs at relative SLR heights from zero to ten feet at half foot increments. These heights represent the height of the sea relative to the ground surface. To build projections of land type changes, these indexed outputs are interpolated to match how this relative height changes in time, across SLR projections, and using an assumed accretion rate. First, these output raster files were disaggregated from state to county for 302 coastal counties, each of which are assigned sea level rise projections consistent with the

Table 1
Summary of sources for coastal accretion rates.

Source	Location	Description
Warren Pinnacle 2021	Gulf Coast, Connecticut, Virginia and National Wildlife Refuges	Accretion rates gathered for various projects implementing SLAMM
Reed et al. (2006)	Mid-Atlantic States (NY, NJ, DE, MD, VA)	Accretion rates gathered from various published sources
Cressman (2020)	15 National Estuarine Research Reserves in CONUS	Surface Elevation Tables (SETs) accretion rate measurements
Holmquist et al. (2021)	481 sites across CONUS	Database of Cesium-137 based estimates of accretion.

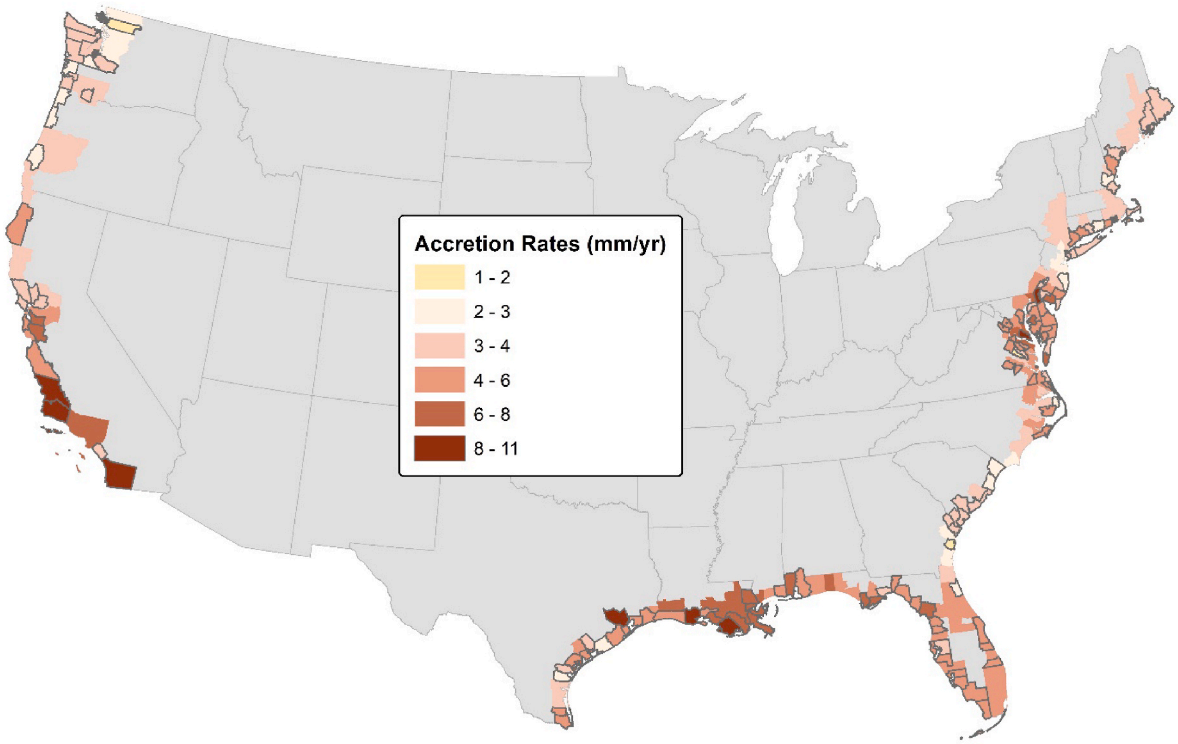

Fig. 1. Accretion rates for the medium scenario by county. Counties with borders include measured accretion rates and counties without borders were interpolated.

National Coastal Properties Model (NCPM; Neumann et al., 2015). Areas for each land type are calculated at the 11 relative height increments, zero to ten feet.

We then calculate relative sea level heights for each year and scenario using these projections and accretion rates from the three accretion rate scenarios described above as well as for a scenario without accretion to estimate land area changes in the uplands (see Section 2.1). The land areas for each county and the relative heights for each projection and accretion rate are then used to develop a land area for each county, sea level rise projection, and year from 2000 to 2100. To do this, we used a shape-preserving piecewise cubic interpolation, which includes some curvature but avoids oscillation errors in a flat progression often observed in spline approaches. The NOAA marsh migration output is bound by no relative rise (0 ft) and 10 ft, so the interpolation does not attempt to extrapolate beyond those bounds.

2.5. Comparison with SLAMM

In order to understand some of the limitations of the NOAA marsh migration model, we conduct a straightforward comparison with SLAMM wetland area outputs. SLAMM provides a point of comparison because the model has been used in many contexts, is well trusted, and model outputs from various projects are publicly available. The most comprehensive compilation of SLAMM outputs comes from a study along the Gulf Coast, which compiles past outputs at the site level with new modeled areas to fill in the gaps along the coast. This dataset provides an appropriate comparison since it is about the spatial scale of the regional analysis that follows and is focused on the region of the U.S. with the highest likelihood of changes in wetland area because of the aggressive local sea level rise projections, particularly in the western Gulf. Details about how this comparison was done including linking land categories can be found in Section S4 of the Supplemental Material.

2.6. Developed area comparison

In the NOAA marsh migration framework, developed areas are assumed to remain unchanged. While projecting changes in coastal development nationally through the end of the century is well outside the scope of this study, we can offer some insight from the output of the National Coastal Properties Model (NCPM; Neumann et al., 2015; 2021). The NCPM has been used for over a decade to assess coastal flooding damages to property and to simulate scenarios of varying levels of protection or retreat. While the NCPM operates on a different spatial scale (150m by 150m grid) and with various input, it can still provide insight into the likelihood of developed areas protecting or retreating. To this end, we compare the developed areas in the NOAA model output (NOAA 2021), and find out if those areas are more likely to retreat or protect with either hard structures like sea walls given the least-cost protection decision tree implemented in the NCPM. For this we use the intermediate-high sea level rise scenario, which reaches 150 cm of global mean sea level rise by the end of the century. This scenario reaches a GMSL higher than expected by the end of the century and so offers a larger inundated area with more properties evaluated for this particular assessment.

2.7. Valuation

The three valuation approaches included in this analysis are described below. First, we apply the restoration cost estimates from Environmental Law Institute (2007). While these estimates are based on restoration activity in 2003 and thus in need of update, these restoration costs are the most spatially comprehensive wetland valuation estimates available for the CONUS. For each of the 38 USACE districts (see Fig. S6), ELI provides estimated average low, middle, and high costs per acre. To estimate restoration costs associated with SLR, each coastal county is assigned to one of the 17 CONUS coastal USACE districts based on which district the majority of the county area is located in. While a range of restoration costs are available, we rely on the middle estimate for valuation to provide a magnitude of cost as a point of comparison across regions and scenarios.

The second valuation approach estimates the changes in coastal property damage that may occur as protective coastal wetland areas change. Sun and Carson (2020) estimates the avoided damages to coastal property by county per unit of area for each county on the Atlantic and Gulf Coasts. Unlike restoration costs, which are related to the annual loss or gain of wetland area, expected property damage is related to the cumulative loss or gain from the start of the simulation—e.g., a loss of one acre of coastal wetland in 2010 does not provide protection for all subsequent years.

For the third valuation approach, carbon sequestration, we use the methods employed in the EPA GHG Inventory for 1990–2019 (EPA 2021), which follows the procedures of the IPCC, particularly the wetlands supplement to the 2006 IPCC guidelines (IPCC et al., 2014). The sources and sinks included are listed below.

- **Land converted to coastal wetland:** includes above- and below-ground biomass carbon stock changes, changes in dead organic matter, soil carbon stock changes, and soil methane emissions
- **Coastal wetlands remaining coastal wetlands:** includes changes in above- and below-ground biomass as wetland types transition to other wetland types, soil carbon stock changes, and emissions of methane.
- **Loss of coastal wetlands to open water:** includes above- and below-ground biomass carbon stock losses, dead organic matter losses, and loss of soil carbon from erosion.

To estimate the differences attributable to sea level rise in particular, we develop a counterfactual scenario without sea level rise in which land areas remain constant. To estimate this and the land converted to coastal wetland sources and sinks, we integrated upland land cover categories (cropland, grassland, forests, and other upland), which are assumed to stay in place unless overtaken by marsh migration, from the NOAA Coastal Change Analysis Program (C-CAP)(NOAA, 2021b).

To value the sources and sinks of both carbon and methane, we use the most recent social cost of carbon estimates (IWG 2021). These are provided at 5-year increments from 2020 to 2050. Using the estimates with a 3% discount rate, we linearly interpolate between the 5-year increments but do not extrapolate after 2050, where costs remain constant out to 2100.

3. Results

3.1. Baseline

Although the analysis is conducted at the county level, results are grouped into coastal regions based on the regions used in the National Climate Assessment Reports, except that the Southeast region is divided into two: Gulf and Atlantic. Fig. 2 shows the county extent for the six regions of CONUS, as well as the land area composition, which includes five wetland types, unconsolidated shore, upland, and developed area.

Most of the wetland area (palustrine plus estuarine areas), is along the Atlantic (12 million acres) and Gulf Coasts (12 million acres) with only a small fraction in the Pacific (0.5 million acres). Estuarine wetlands contribute a similar share of total wetland areas for the three coasts—20% in the Atlantic, 22% in the Gulf, and 26% along the Pacific. The composition of Palustrine wetlands differ where in the Atlantic Coast, the majority of the wetland area is classified as Palustrine Forested Wetlands at about 60%, with 12% as Scrub/Shrub Palustrine, 7% Emergent Palustrine; the Gulf Coast has a slightly lower share of forested wetlands, at 52%, and Scrub/Shrub at 10% but a higher share of

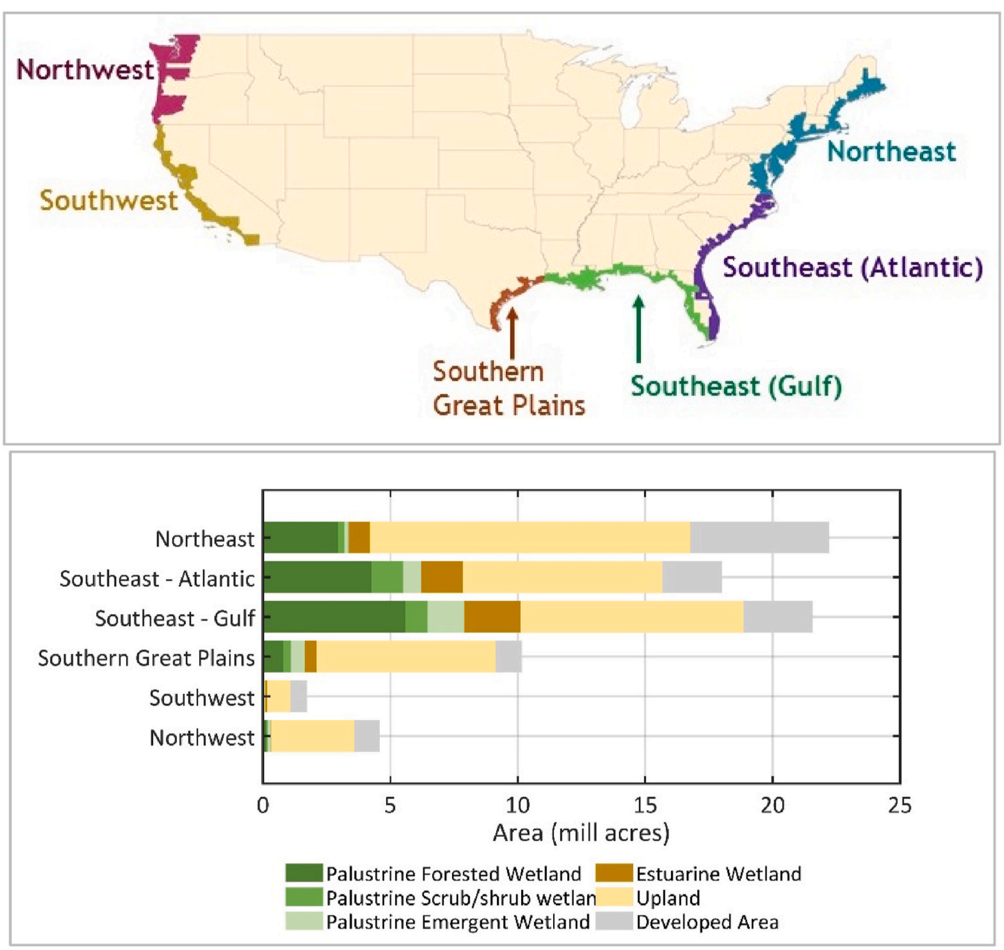

Fig. 2. Baseline regional land composition.

Emergent wetlands at 16%; and the Pacific has the lowest share of Forested wetlands of the three coasts at 26% but a larger share of Scrub/Shrub wetlands at 14% and Emergent wetlands at 34%. Developed areas include high, medium and low intensity development as well as developed open space and are largest in the Northeast, which is important because these areas are kept constant in the NOAA Marsh Migration model for all future years. For the remainder of the results section, we will focus on changes in the five wetland area types: three Palustrine types, Brackish/transitional, and Estuarine wetlands.

3.2. Changes in wetland areas

Total coastal wetland areas decrease CONUS-wide across all sea level rise scenarios and all accretion rates. Fig. 3 shows the total net wetland losses across sea level rise scenarios for the medium accretion rate. By the end of the century, total wetland losses range from 2.0 million acres for the Low sea level rise scenario to 10.7 million acres for the Extreme scenario. The results for RCP 4.5 and 8.5 are superimposed on Fig. 3, both of which fall within the range of the intermediate-low and the intermediate SLR scenarios. For RCP4.5 and RCP8.5, respectively, net wetland area loss is 1.8 and 2.4 million acres by 2050 and 3.5 and 5.2 million acres by 2100.

Cumulative net loss of wetland area in the Gulf for RCP4.5 and RCP8.5, respectively, is 1.69 and 2.17 million acres by 2050 and 2.89 and 4.05 million acres in 2090. Losses along the Atlantic are lower reaching 0.09 in 2050 and 0.22 million acres in 2090 for RCP4.5 and 0.14 in 2050 and 0.32 million acres in 2090 for RCP8.5. The Northwestern Coast, the only area in CONUS with sea level rise projections consistently lower than GMSL rise for the most likely scenarios, has a net gain of wetland area of about 36 and 38 thousand acres in 2090 for RCP4.5 and RCP8.5, respectively. Net wetland areas in the Southwest reduce by 34 and 72 thousand acres in 2050 and 0.13 and 0.33 million acres by 2090 for RCP4.5 and RCP8.5, respectively.

The rates of wetland area gain as marshes migrate inland and loss to unconsolidated shore and open water are relatively high in the 2030 era and decelerate through the 2050 era (see Fig. 4). The vast majority of these early loss rates occur in the Gulf Coast, where loss rates are high at lower levels of relative rise and decline rapidly from 0.5 ft to about 2.5 ft (see Fig. S7). For RCP4.5, gains in area continue to slow down through the end of the century but losses start to accelerate reaching a loss of about 40,000 acres per year by the 2090 era. In RCP8.5, wetland areas migrate inland slightly faster after 2050 in response to higher rates of sea level rise compared to RCP4.5 but this is counteracted by much faster rates of loss reaching about 110,000 acres per year by the 2090 era for the medium accretion scenario. Differences between the low and high accretion scenarios where the ranges decrease from the 2030 era to 2050—aside from RCP8.5 losses—and continue to increase in the latter half of the century.

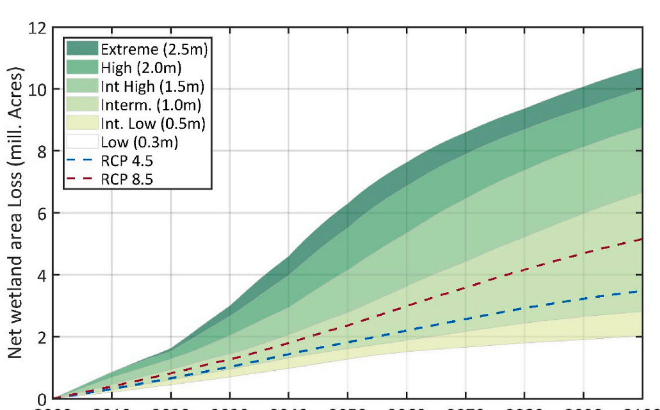

Fig. 3. Total net wetland area losses in CONUS by sea level rise scenario for the medium accretion rate scenario.

Overall, net losses are highest in the Gulf and lowest in the Pacific (see Fig. 5 for RCP4.5). The composition of the wetland area losses often follows the baseline composition. For example, losses in the two Atlantic regions are primarily composed of palustrine forested wetlands whereas the Gulf has a larger share of palustrine emergent wetland loss than the Atlantic. The loss of wetland area to the sea is related to the difference between the rate of sea level rise and the accretion rate as well as topography. Areas with higher local sea level rise, particularly areas where seal level rise rates are expected to accelerate over the century, are proportionally less sensitive to the accretion rate. For this reason, the Southeast-Gulf region where the difference between low and high accretion scenario is slightly less than double, is proportionally less sensitive to accretion rates than, for example, the two regions on the Pacific Coast.

3.3. Comparison with SLAMM

The analysis of the Gulf Coast using SLAMM was conducted from 2008 to 2013, which predates the 2016 C-CAP used in the NOAA marsh migration model. Because of this, the baselines of the two models differ although this is difficult to quantify because the two models use different model domains. Total wetland area is 11.3 million acres in the SLAMM domain and 12.2 million acres in the NOAA model domain. Likely the best point of comparison for the baseline is the Estuarine wetland areas, which are slightly higher for SLAMM at 2.9 million acres than for the NOAA model at 2.7 million acres (see Fig. S2 and Table S2) although these differences could be differences in wetland category attributions. Since the RCP4.5 and RCP8.5 probability-weighted results both fall between the Intermediate-Low (50 cm) and Intermediate (100 cm) scenarios, we use these for the comparison of wetland area changes. Total wetland area for the Intermediate-Low scenario using SLAMM by 2100 is 10.4 million acres compared to 9.6 million acres for the medium accretion rate scenario and 8.6 to 11.0 for the Low and High scenarios, respectively. For the Intermediate scenario, total areas are 8.7 million acres using SLAMM and 7.8 million acres for the medium accretion rate scenario and 7.4 to 8.4 million acres for the low and high scenarios, respectively. See Figs. S3 and S4 for more detail. These comparisons indicate that SLAMM estimates smaller wetland area losses that are closer to the area losses estimated with the high accretion rate scenario than the medium. There are many reasons for these differences including the way SLAMM accounts for accretion using a more dynamic process with accretion rates varying by wetland type.

3.4. Developed area comparison

Comparing developed areas indicated in the NOAA marsh migration output to the decisions simulated in the NCPM, we find that most of the areas set aside as a barrier to marsh migration in C-CAP are not valuable enough to warrant the cost of protection in all six coastal regions (see retreat in Fig. 6). Results from the NCPM are a definitive projection - there are many reasons to protect areas that are not captured with the least-cost approach implemented in the NCPM – but the NCPM results do consider existing property and structure value on these lands and suggest that more area for wetland migration might be available than suggested by the C-CAP developed land data. Also, as mentioned before, differences in input datasets, particularly topography, as well as differences in the spatial scale all lead to uncertainties in this assessment. It is also important to note that C-CAP designates the majority of developed area impacted by sea level rise inundation as “developed open space” and these are also kept constant in the NOAA marsh migration datasets. In spite of these differences, areas that do retreat inland may allow for additional coastal wetland migration depending on the state it is left in after the retreat. In contrast, areas that are armored may impede coastal wetland migration much further inland than the property area shown in Fig. 6 since even the natural areas further inland may remain dry as well.

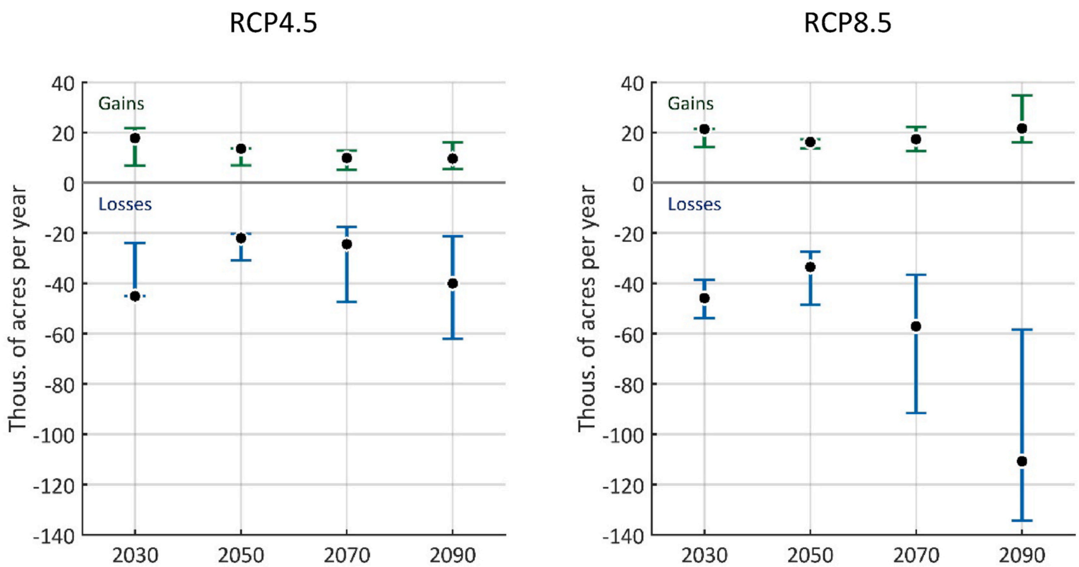

Fig. 4. Rates (thousands of acres per year) of loss to sea level rise and rates of gain through inland migration for both RCP4.5 and RCP8.5 and four eras (2030: 2020–2039, 2050: 2040–2059, 2070: 2060–2079, 2090: 2080–2099). Black dots show the rates for the medium accretion scenario and whiskers show the high and low accretion scenarios.

Properties that are elevated may behave as they are handled in the NOAA marsh migration dataset—without marsh migration on the property itself but without a migration barrier like a sea wall. It is important to note that Gardner and Johnston (2020) found that armoring is more often motivated by biophysical factors (e.g., erosion from high wave energy) and not as a method to prevent marsh migration onto property. They note that coastal properties typically had hard structures when they were located farther away or near smaller areas of salt marsh and not in areas well-suited for viable marsh migration.

3.5. Valuation

This section focuses on impacts measured by the three valuation approaches and provides a comparison for the two general approaches: restoration and ecosystem services. Fig. 7 shows annual economic impacts using a restoration approach and the loss of two ecosystem services: property protection and carbon sequestration. The range across the high and low accretion rates are also shown to indicate the uncertainty associated with accretion rates. Using the medium accretion rate, in 2050 era, restoration costs reach $1.5 and $2.5 billion a year for RCP4.5 and RCP8.5, respectively. Property protection and carbon sequestration are considerably lower in 2050, less than $1 billion a year except for carbon sequestration for RCP8.5, which reaches almost $1.3 billion a year. By the 2090 era, annual restoration impacts increase for RCP8.5 by $0.5 billion (23% of 2050 impacts) for the medium accretion rate scenario, but reduce slightly for RCP4.5 by about 3%. In contrast, both property protection and carbon sequestration impacts increase more substantially in the 2090 era. Property protection value losses increases 80% for RCP4.5 and more than doubles for RCP8.5 while carbon sequestration increase about 80% for RCP4.5 and 2.5 times for RCP8.5. The considerable increase in damages from lost carbon sequestration services under RCP8.5 is related to the rate of loss of salt marsh (see Fig. 4) wherein the sequestered carbon in the soil is lost to erosion. It is important to note that the impacts of property protection and carbon sequestration are both independent while the restoration approach is meant to be a comprehensive valuation alternative (albeit not the preferred alternative). In 2050, the sum of both the ecosystem services quantified is lower than the restoration approach but in 2090 ecosystem services are higher than restoration costs by 70% for RCP4.5 and 100% higher for RCP8.5. The range across the high and low accretion rate scenarios decreases for restoration costs from 2050 to 2090 but increases for both ecosystem service impacts and is particularly high for carbon sequestration in 2090.

For another comparison across valuation approaches, we calculate the cumulative economic impacts by region, discounting to 2020 using a 3% discount rate (see Table 2 for RCP4.5, medium accretion scenario and Section S6 in the Supplementary Material for the other scenarios). Since restoration costs and property protection impacts are both based on the net loss of wetland area, the highest impacts for those approaches is the region with the highest net loss—Southeast-Gulf. Similarly, the two regions on the Pacific have the lowest restoration costs and the Northwest, with a net gain in wetland area, has a small benefit. For carbon sequestration, impacts are highest in the Southeast-Atlantic, the region with the second highest net loss in wetland area. Carbon sequestration impacts are lower for the Southeast-Gulf than the Southeast-Atlantic in 2050 and actually decline when we consider the cumulative costs to the end of the century. This is because wetland area loss rates are particularly high earlier in the century and decline later in the century. Therefore, while soil carbon is lost early, the reduction in annual methane emissions from the loss of net wetland area accumulates through the end of century.

4. Discussion

Wetlands provide numerous valuable ecosystem services when they remain intact. For example, as a natural defense system against coastal hazards like erosion, flooding, and storm surge (Arkema et al., 2013), healthy wetlands are critical to both ecosystem and community resilience. Losses of wetlands currently in place to protect properties from coastal flooding may be the final prod that displaces coastal communities who do not have the financial means to protect or easily relocate. And the increases in GHG emissions from wetland losses to sea level rise, driven primarily by the loss of stored soil carbon sequestered by coastal wetlands that have been in place for many years, is itself a small-scale positive emissions feedback loop contributing to an already dangerous global circumstance.

Because this work was conducted as part of a larger multi-sector modeling project to estimate climate change impacts in the United States, the results are comparable to projected economic damages for other sectors. The projected end of century damages in this study ($1.5 - $6.1 billion annually depending on emission scenario and valuation metric) are similar in magnitude to estimated damages for other

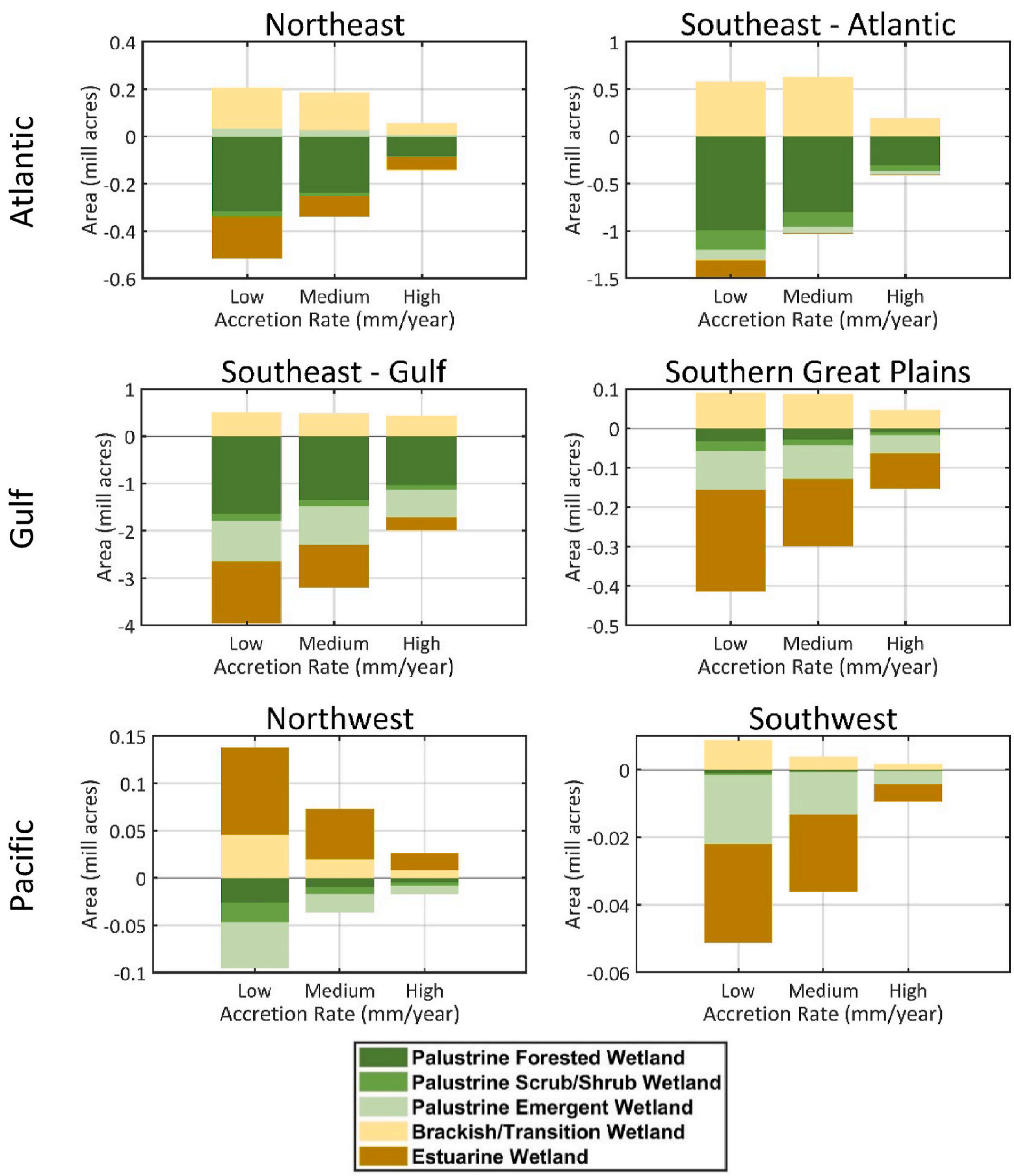

Fig. 5. Changes in net wetland area across the century by wetland type for the six regions for the three accretion rates under RCP 4.5, difference from 2000 to 2100. A positive value on the vertical axis represents a net gain in area while a negative value represents a net loss. Y-axes are not consistent across regions to allow for better visibility of specific wetland type composition changes.

ecosystem effects, such as freshwater recreational fishing and coral reef recreation, as well as damages from climate-driven changes in West Nile neuroinvasive disease (Martinich and Crimmins, 2019). But as noted below, the current study does not capture the full monetized value of changes in coastal wetlands. As the continuously evolving literature on wetland ecosystem service valuation progresses, the economic impact of wetland losses presented here could be readily updated or customized, reflecting site-specific conditions and mapping for wetland type, species habitat, contribution of wetland aesthetics to local property value, recreational value, or other beneficial service flows.

To reduce the impacts of climate change, communities can take different actions to improve resiliency by adopting nature-based solutions, including restoring and conserving coastal habitats, and enhancing natural infrastructure that mitigate waves and erosion (Fleming et al., 2018). Although this study offers a comprehensive understanding of wetland area changes in CONUS and potential economic implications that arise from the massive expected net losses in coastal wetland areas, the goal of this study is not to provide local- or project-level predictions or to offer the kinds of solutions and recommendations that require site-specific analysis. Instead, this work is in part an extension of the goals and intentions of NOAA's Sea Level Rise Viewer, a screening-level tool for evaluating some of the possible impacts and risks from sea level rise, with the potential to highlight regions that might be most at risk. This tool is provided to technical users as well as to those who may not have the necessary data or expertise to run more detailed analysis and is intended to help guide managers and policy makers in land use planning, understanding the risks of, for example, loss of habitat, potential for adaptation or restoration, and changes in the risk of flooding on coastal communities.

While this study focused on the impacts of climate change to marshes in the contiguous United States, this paper does present a methodological framework that could be applied to an international context. The general steps of identifying a suitable marsh migration model and economic valuation approaches with data relevant to a particular country or

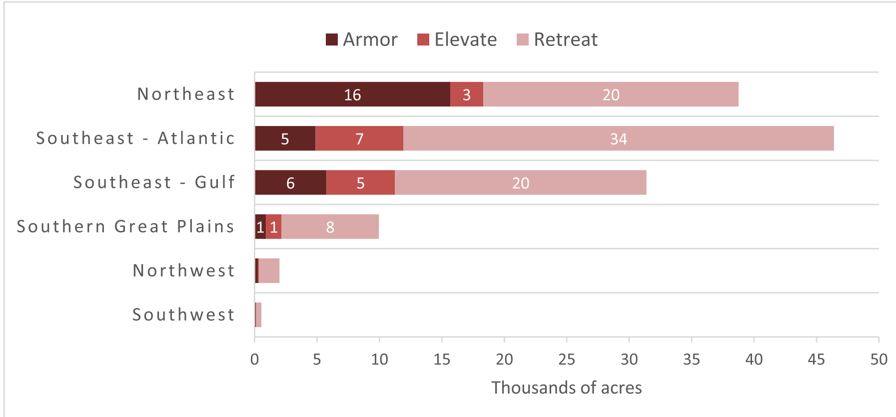

Fig. 6. NCPM decision outcomes for C-CAP designated developed areas.

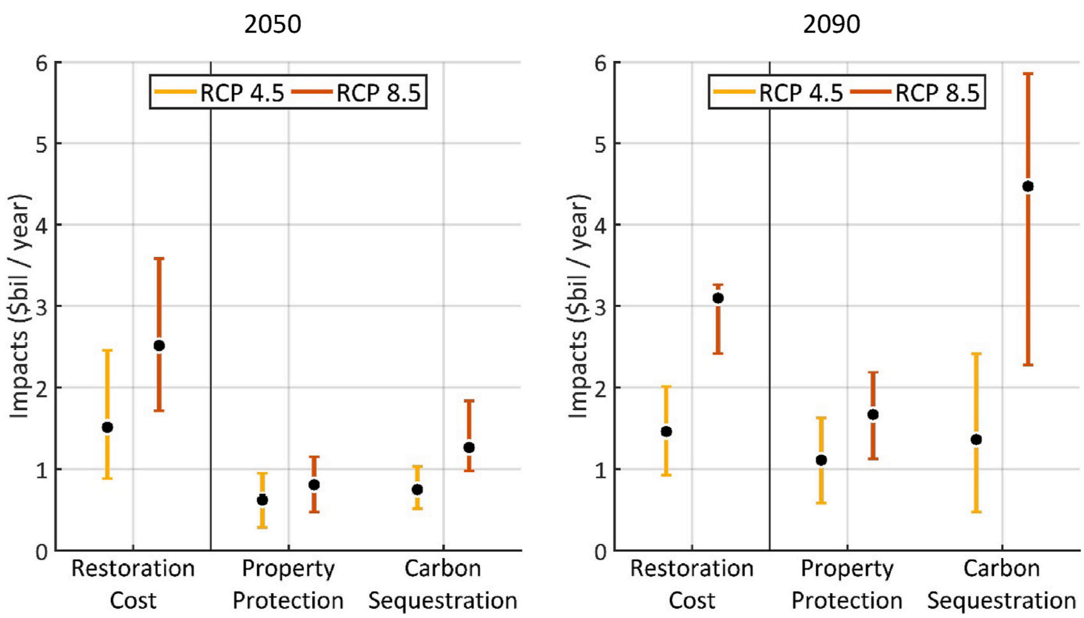

Fig. 7. Total CONUS economic impacts for the three valuation approaches (restoration, property protection, and carbon sequestration) for 2050 (2040–2059) and 2090 (2080–2099) and the two RCPs. Property protection and carbon sequestration are independent ecosystem service flows provided by intact wetlands, and so are additive within the ecosystem service flow valuation paradigm. Black dots show the impacts for the medium accretion scenario and whiskers show impacts for the high and low accretion scenarios.

Table 2
Total economic impacts (billions 2020 USD, at 3%) by coastal region for the medium accretion rate scenario and RCP4.5

Region	2020–2050			2020–2100		
	Restor-ation Cost	Ecosystem Services		Restor-ation Cost	Ecosystem Services	
		Property Protection	Carbon Seq.		Property Protection	Carbon Seq.
Northeast	$5.3	$2.2	$3.9	$8.3	$3.5	$8.3
Southeast - Atlantic	$3.3	$0.5	$11.0	$6.9	$1.2	$17.9
Southeast - Gulf	$47.9	$7.5	$5.6	$56.3	$13.5	$0.9
Southern Great Plains	$2.6	$0.9	$2.6	$3.8	$2.0	$4.9
Southwest	$2.2	$0.0	$0.4	$2.9	$0.0	$0.6
Northwest	-$1.0	$0.0	$0.2	-$1.3	$0.0	$0.6
Total	***$60.4***	***$11.0***	***$23.7***	***$77.0***	***$20.2***	***$33.2***

region and utilizing globally recognized sea level projections is broadly applicable and can be tailored to a specific study site. The methods presented here also connect the marsh migration analysis in NOAA's Sea Level Rise viewer with globally recognized SLR projections like the uncertainty ensemble developed in Kopp et al. (2014) and the CMIP-5 Representative Concentration Pathways. This allows for comparison across national-scale studies of a similar nature in other countries—e.g., Payo et al. (2016) in Bangladesh or Zhi et al. (2022) in China, among many others—as well as a starting point for either detailed project-level analysis or regional-scale studies in the United States—e.g., Clough et al.

(2016) for New York State or Bacopoulos et al. (2019) in Florida.

There are many limitations to work conducted at this scale. For example, while we capture county-to-county variation in expected accretion rates, we assume all types of coastal wetlands within a county exhibit the same accretion rates. Although the analysis does consider accretion rate uncertainty with low and high accretion rate scenarios, accretion rates can vary considerably within a county depending on local hydrologic conditions, soils, topography, physical plant characteristics, and others. Some of these factors can be captured with models of higher complexity but those models require extensive measurements and input datasets. The estimates of carbon sequestration by wetlands, and consequently greenhouse gas (GHG) emissions, is an active area of research. Coastal wetlands naturally exhibit both efficient carbon sequestration in the soil and produce significant methane emissions. These two competing factors as well as the uncertainty in estimating these GHG sinks and sources (Holmquist, 2018) has led some to question whether wetlands do provide an overall sink in GHGs (Rosentreter et al., 2021). Many of these limitations are better addressed at smaller spatial scales with more extensive, multi-year in situ measurements for model building and validation (e.g., RAE (2016) in Tampa, Florida) or more detailed modeling tools such as Bacopoulos et al. (2019), which uses Hydro-MEM to account for the potential for marsh destabilization in response to a sudden loss of marsh elevation. Future site-specific studies can also be used to corroborate the incremental, county-level property protection value estimated in Sun and Carson (2020).

Our work employs two alternative paradigms to estimate the value provided by existing marshes which are threatened by sea-level rise – yet both are limited and likely underestimate the full value of this resource. Consistent with the "natural capital" literature, we suggest that the preferred economic paradigm is an ecosystem service flow valuation approach (e.g., Guerry et al., 2015). Prior research has suggested that four aspects of marsh ecosystem service flow can be feasible for valuation, at least at regional to statewide spatial scales: carbon storage; inland flood control; water purification; and coastal storm protection (Flight et al., 2012) – we capture only two of these. Barbier (2013) provides a longer list of potentially monetizable wetlands services for three Louisiana case studies. Flight et al.'s application to Delaware suggests that water purification services might be as large as 50% of the value of carbon storage, suggesting substantial potential for a more comprehensive ecosystem valuation effort to results in a substantial increase in our estimates. Other research also suggests a positive effect of coastal wetlands on adjacent properties, which may capture the more difficult to estimate recreational, aesthetic, biodiversity, and habitat protection ecosystem values (e.g., Sander and Polasky 2009), but may also reflect at least a portion of flood protection benefits. Our national-scale approach reflects carbon storage and flood control benefits, and the latter only for the Atlantic and Gulf coasts, so likely omits other values of wetlands which either require site- and context-specificity to value, or are simply more difficult to estimate. In contrast, the restoration cost approach reflects the resources required to rebuild lost wetlands, which we argue can be interesting and informative for policy-makers – if, for example, a "no net loss" of wetland policy were to be adopted, the restoration cost approach provides a fiscal cost estimate to compensate for the wetland loss implied by climate change. However, without a legal mechanism for establishing a responsible party to replace wetlands lost to SLR, it does not provide a reasonable estimate of lost value or even avoided costs of replacing ecosystem services. Research suggests that restoration efforts to date address only a fraction of wetlands lost in the U.S. (Gittman et al., 2019). In either paradigm, our valuation results should not be interpreted as a total value for wetlands lost, nor should an average per-acre value be inferred across space, owing to variation in both flood protection and carbon sequestration values by location and wetland type. In addition, it is important to note that valuation reflects scenarios of changes from wetlands to other land types, so it reflects net rather than gross values of coastal wetland loss.

Future enhancements to this approach, for application in the US and elsewhere to generate more reliable estimates of the loss of wetlands and wetland service flows attributable to climate change, should focus in two areas. First, the reduced form approach required for a CONUS-scale analysis of wetland losses cannot fully reflect the complex dynamics of wetland response to elevated sea level. As research progresses on site- and project-specific studies of wetland sensitivity, insight from that work should be generalized for application in CONUS-scale studies and tools such as those applied here. Second, there remains substantial work to more comprehensively value the service flows that derive from coastal wetlands, from ecosystem flows with connections to market activity such as recreation, angling, and hunting, to more fully nonmarket categories such as spiritual and cultural values. Progress in these two areas can elevate the consideration of risks to coastal wetlands from climate change in multiple locations and policy making contexts, including our understanding of the benefits of mitigating climate change through reduced greenhouse gas emissions that achieve more moderate outcomes for future sea level rise.

Data availability statement

All data used in this analysis are described in detail in S1 of the Supplemental Material. Some or all data, models, or code generated or used during the study will be posted to EPA's Environmental Dataset Gateway upon publication. Some or all data, models, or code used during the study were provided by a third party. Direct requests for these materials may be made to the provider as indicated in the Acknowledgements.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2022.106248.

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