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Sea-level rise enhances carbon accumulation in United States tidal wetlands

Highlights

- Relative sea-level rise is the dominant driver of coastal wetland carbon accumulation
- Balances between soil growth and erosion determine landscape-scale carbon budgets
- Even submerging marshes sequester carbon at rates that increase with sea-level rise

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In brief

Coastal wetlands accumulate soil carbon more efficiently than terrestrial systems, but sea-level rise potentially threatens the persistence of this prominent carbon sink. Here, we combine a published dataset of 372 soil carbon accumulation rates from across the United States with new analysis of 131 sites in coastal Louisiana and find that the rate of relative sea-level rise explains 80% of regional variation in carbon accumulation. Our results suggest a strong negative carbon-climate feedback for coastal marshes.

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Sea-level rise enhances carbon accumulation in United States tidal wetlands

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SCIENCE FOR SOCIETY Coastal wetlands are well-known hotspots for carbon sequestration. However, they are vulnerable to sea-level rise, and there is concern that this important carbon sink may weaken under climate change. We synthesized 503 measurements of soil carbon accumulation rates from coastal wetlands across the United States and show that carbon accumulation rates are positively correlated with local rates of sea-level rise. We then examined the rapidly submerging Louisiana coast to investigate the balance between carbon loss in eroding marshes and carbon gain in surviving marshes. We find that carbon accumulation rates are generally fastest in portions of Louisiana where rates of sea-level rise and land loss are highest, allowing a net carbon sink to persist. Although erosion will eventually lead to net carbon loss, our results suggest a strong negative carbon-climate feedback for coastal marshes, where even submerging marshes sequester carbon at rates that increase with sea-level rise.

SUMMARY

Coastal wetlands accumulate soil carbon more efficiently than terrestrial systems, but sea-level rise potentially threatens the persistence of this prominent carbon sink. Here, we combine a published dataset of 372 soil carbon accumulation rates from across the United States with new analysis of 131 sites in coastal Louisiana and find that the rate of relative sea-level rise (RSLR) explains 80% of regional variation in carbon accumulation. A carbon mass balance for the rapidly submerging Louisiana coast demonstrates that carbon accumulation rates in surviving marshes increase with RSLR and currently exceed the rate of carbon loss due to marsh drowning and erosion. Although continued erosion will eventually lead to net carbon loss, our results suggest a strong negative carbon-climate feedback for coastal marshes, where even submerging marshes sequester carbon at rates that increase with RSLR.

INTRODUCTION

There is a growing effort to understand how feedback between climate and carbon cycling influences the ability of ecosystems to absorb and store carbon. Models and empirical observations in marine, peatland, and terrestrial systems point to positive carbon-climate feedback whereby warming reduces the capacity of ecosystems to accumulate carbon and thus amplifies global warming.[1,2] Recent observations that coastal wetlands accumulate soil carbon 10–100 times faster per unit area than upland ecosystems has led to increased interest in the potential role of these marshes in climate mitigation,[3] yet research exploring carbon-climate feedback in coastal wetlands remains in its infancy.[4] The metabolic theory of ecology predicts that respiration should be more sensitive to climate warming than photosynthesis,[5] consistent with many terrestrial systems where warming results in a net decrease in ecosystem carbon accumulation rate (CAR).[6,7] In coastal wetlands, there is an optimal temperature for productivity,[8,9] and small increases in temperature typically lead to enhanced plant growth.[8] The anaerobic conditions in marsh soils are predicted to limit the temperature sensitivity of soil respiration.[10,11] Field studies of marshes across latitudinal gradients suggest that the temperature sensitivity of primary productivity is greater than that of decomposition, leading to predictions that warming will enhance CAR.[12] However, there does not appear to be a strong relationship between marsh CAR and mean annual temperature at the global scale.[13–15] Instead, model[16] and experimental results[8] suggest that the effect of temperature is modulated by factors such as dominant vegetation species, nitrogen availability, and hydrology.

Soil carbon is the dominant pool of carbon in coastal wetlands.[3] Coastal wetland soil carbon accumulation is tied to

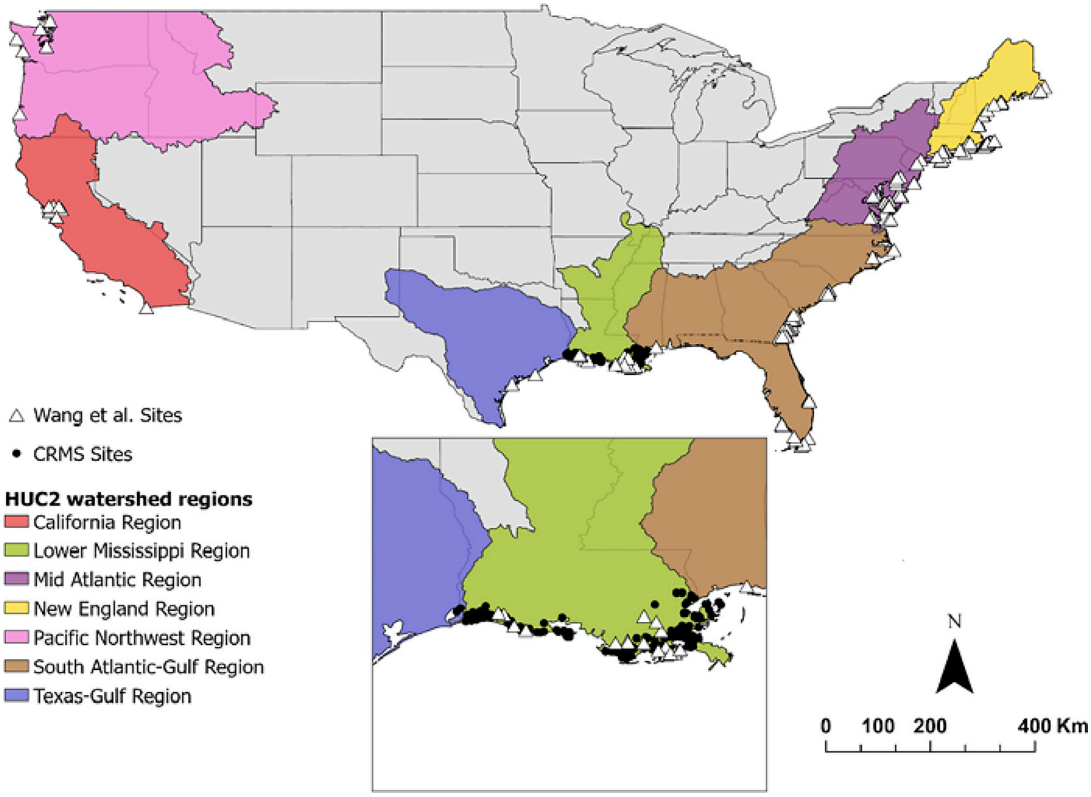

Figure 1. Location of carbon accumulation rate measurements used in the meta-analysis
Triangles represent measurement locations summarized in Wang et al.,[15] and black circles represent Louisiana Coastal Reference Monitoring System locations summarized in Jankowski et al.[27] Regional boundaries follow US Geological Survey HUC2 watersheds, as in Wang et al.[15]

a well-characterized set of ecogeomorphic feedbacks, where plant growth is stimulated by increased flooding up to some threshold, so that a moderate increase in relative sea-level rise (RSLR) is predicted to be accompanied by an increase in organic matter accumulation, mineral sediment deposition, and vertical soil growth.[17–19] These feedbacks lead to model-based predictions that CAR should be enhanced at higher rates of SLR.[16,20,21] Field-based studies show that carbon accumulation is generally higher in places with higher RSLR[15,22] and that CAR has increased in parallel with the historical acceleration in RSLR.[23] However, these point-based studies cannot address the feedbacks that control the spatial extent and distribution of wetlands.[24] Coastal wetlands are vulnerable to RSLR and human activity,[25–28] potentially leading to widespread erosion and drowning of this important carbon sink.[29–32] Here, we explore the link between CAR and RSLR in coastal wetlands across the continental United States (CONUS), and use higher-resolution observations from the Louisiana coast to determine how the balance between wetland size and carbon accumulation impact the net carbon balance across a rapidly submerging coastal landscape.

RESULTS AND DISCUSSION

Meta-analysis of North American CARs

To examine the drivers of CAR, we compiled a dataset of 372 CAR measurements in wetlands from across the CONUS (mangroves and marshes)[15] and 131 additional salt and brackish marshes across coastal Louisiana (Louisiana Coastwide Reference Monitoring System [CRMS])[33] (see experimental procedures, Figure 1, and Table S1). For the United States dataset, we collated data on carbon accumulation (CAR, soil accretion rate [SAR], and soil carbon density) and environmental parameters (RSLR, tide range, mean annual temperature, and precipitation) directly from Wang et al.[15] For the Louisiana dataset, we started with 274 CRMS sites[27] and filtered the data to isolate salt and brackish marshes, leaving us with a total of 131 saline and brackish marsh locations in our analysis. SARs and estimates of RSLR for the CRMS sites were taken directly from Jankowski et al.[27] We compiled measurements of organic content and bulk density of marsh soil using publicly available data,[33] and calculated CAR for each of the CRMS sites following established methods.[14,15,34] The combined database featured 503 measurements of carbon accumulation, spanning broad gradients in mean annual temperature, tide range, and dominant vegetation.

We used a simple regression approach to examine the extent to which and the scale at which tidal wetland soil carbon accumulation (i.e., CAR) responded to physical (e.g., RSLR, accretion) and/or climatic (e.g., temperature) drivers (see experimental procedures). We use the term carbon accumulation as it has commonly been used in coastal wetland literature[13,14,30] to describe the accumulation of soil carbon in surficial sediments (<1 m soil depth) as measured by physical marker horizons

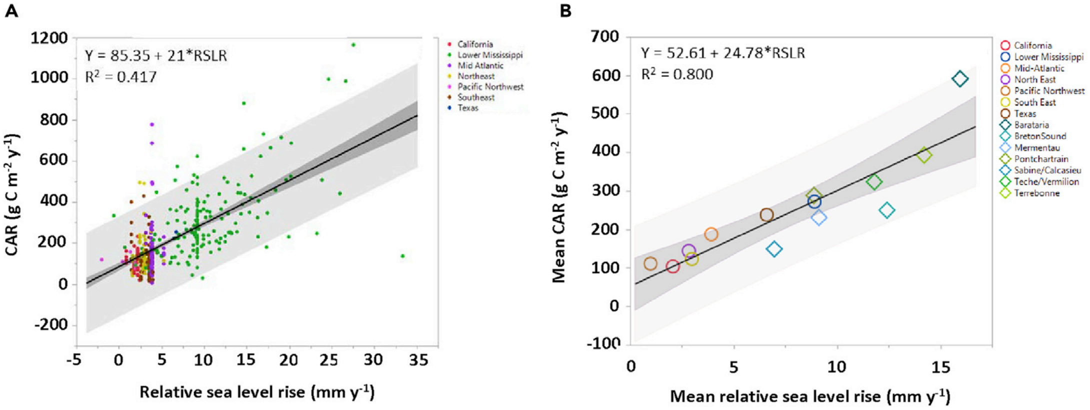

Figure 2. Relationships between rates of carbon accumulation and relative sea-level rise

(A) Each point represents an individual wetland (n = 408) paired with the closest tide gauge record. Root-mean-square error (RMSE) = 123.7; F(1,407) = 291.10, $p < 0.0001$.

(B) All data points within a region are averaged to a mean value for both carbon accumulation rate (CAR) and relative sea-level rise rate (RSLR). RMSE = 61.29; F(1,12) = 48.03, $p < 0.0001$. Climatic regions (n = 7) from Wang et al.[15] are shown as colored circles, in coordination with Figure 1. Louisiana basins (n = 7) are displayed in a range of green diamonds. The two levels of gray shading illustrate the 95% confidence limit and the 95% prediction limit, respectively.

(i.e., accumulated above ceramic tiles or feldspar layers), permanent benchmarks, and radioisotope or radiocarbon dating. Short-term (<50 years) CAR measurements include labile carbon that will decay with time and cannot be equated with the long-term carbon burial or sequestration. Nevertheless, short-term CAR measurements are useful because they correspond entirely to the period of accelerated RSLR (i.e., not averaged over periods of slow RSLR) and correspond to the depths of erosion typically observed in submerging salt marshes (<1 m).[31,35]

Relationships between CAR and RSLR were generally weak across individual sites and within regions. CAR was significantly correlated with RSLR among all individual sites with estimates of both CAR and RSLR (n = 408, $R^2 = 0.42$, root-mean-square error [RMSE] = 123.7), but the trend was driven mostly by sites in the Lower Mississippi region with RSLR rates >5 mm year^{-1} (Figure 2A). When assessed within regions, CAR-RSLR relationships were insignificant in all coastal regions except for the Lower Mississippi region (n = 171, $R^2 = 0.32$, RMSE = 147.51) (Table S2). Statistical models for CAR using RSLR within regions had lower predictability than across regions (Table S2), likely due to subregional variation in RSLR that is not captured with a limited number of tide gauges, and lower statistical power associated with having fewer CAR data points. Moreover, factors other than RSLR (i.e., sediment supply, vegetation type, marsh platform elevation) may drive variability in CAR in regions with a narrow range of RSLR rates or very low rates of RSLR.

In contrast to weak or insignificant relationships across sites and within regions, RSLR was a strong driver of CAR when both variables were averaged over contiguous coastal regions. RSLR explained 80% of the regional variation in CAR (R^2 = 0.80, RMSE = 62.8) (Figure 2B and Table S2). A strong relationship between regional CAR and SLR persisted even when the high rates of RSLR in the Louisiana Gulf Coast were omitted (Figure S1 and Table S2). Eighty percent of the variation between CAR and RSLR was explained by the increase in vertical SAR under increased RSLR (Figures 3A and 3B; Table S3). Regional variation in soil carbon density was not significantly correlated with RSLR (Figure 3C). The inclusion of a carbon density × RSLR interaction in a mixed model showed similar power in predicting CAR ($R^2 = 0.45$, RMSE = 124) compared with the least-squared model based on RSLR alone ($R^2 = 0.42$, RMSE = 124) (Table S2).

Together, these results suggest that the increase in CAR under elevated RSLR is primarily a product of increased vertical accretion (i.e., an increase in soil volume). A strong link between CAR, vertical accretion, and RSLR is consistent with a well-known ecogeomorphic feedback between flooding and increased sediment deposition,[17,18] a meta-analysis showing little spatial variability in carbon density across the United States,[36] and long-term data from sediment cores that show CAR has accelerated over time.[23,37] As we discuss in the next section, a positive relationship between RSLR and CAR could potentially be explained by allochthonous carbon deposition, where fast RSLR leads to marsh erosion and enhanced deposition of eroded carbon onto surviving marsh (i.e., Figure 4). Alternatively, rapid vertical accretion has been suggested to enhance the preservation of organic matter by accelerating the advection of material below the surface soil layers where decomposition is most intense.[16,20,38] However, more efficient carbon preservation would be expected to lead to higher soil carbon densities in places with rapid vertical accretion, which is inconsistent with our findings. Therefore, we suggest that the relationship is driven primarily by increases in soil volume rather than increases in the concentration of carbon in the soil.

Least-square models indicate that climatic variables had little influence on soil CAR (Figure S2). Mean annual temperature (MAT) and mean annual precipitation (MAP) were not correlated with CAR when averaged at regional scales (n = 7 regions, $p < 0.05$, Figures S2A and S2C). When individual site level data (n = 408) were included, statistical models showed a correlation between CAR, MAT, and MAP that was driven primarily by high CAR in the warm and wet Lower Mississippi Delta region (Figures S2B and S2D), but RMSE was high for both climate variables and they explained only 2%–3% of the variance in the data,

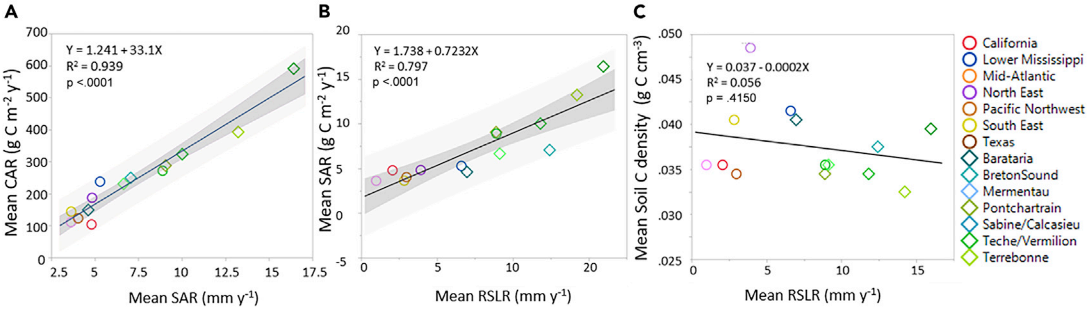

Figure 3. Components of regional carbon accumulation rates

(A) Mean carbon accumulation rate (CAR) and soil accretion rate (SAR). RMSE = 33.87; F(1,12) = 184.56, $p < 0.0001$.

(B) SAR and relative sea-levle rise rate (RSLR). RMSE = 1.80; F(1,12) = 47.19, $p < 0.0001$.

(C) Soil carbon density (C_{dens}) and local RSLR: non-significant.

Watershed-based regions from Wang et al.[15] are shown as colored circles, in coordination with Figure 1. Louisiana basins are displayed in a range of green diamonds. Significance is noted by the two levels of gray shading, which illustrate the 95% confidence limit and the 95% prediction limit, respectively.

respectively. Furthermore, mixed models including all physical, biotic, and climatic drivers showed no improved prediction with inclusion of these terms. These findings are consistent with other meta-analyses that show little relationship between temperature and CAR.[13–15,40] Together, these studies offer important empirical support for modeling that suggests that the direct effect of increased temperature on CAR will be more subtle than the effect of warming-driven RSLR on CAR.[16]

Landscape-averaged carbon balances in submerging marshes

While a high rate of RSLR drives enhanced CAR, RSLR may also enhance marsh drowning and loss,[34,41–43] calling into question the stability of the coastal carbon sink under accelerated rise in sea level.[29,31,32,44,45] To determine whether enhanced CAR in surviving marshes can offset significant carbon losses from declining marsh area, we estimated net changes in marsh soil carbon across the saline and brackish marshes of the Louisiana coast, where rates of RSLR and land-loss rates are among the highest in the world. We used a simple mass-balance approach to estimate annual net change in marsh soil carbon averaged across the seven coastal Louisiana basins with brackish and saline marshes (Table 1 and Figure S3), where net change reflects the balance between carbon accumulating in surviving marshes and carbon lost due to marsh drowning and erosion (see experimental procedures).

We find that land loss and carbon accumulation both increase with the rate of RSLR (Figures 4A and 4B). Accounting for changes in land area, marsh carbon accumulation in current wetlands equals or exceeds carbon lost to drowning and erosion, leading to net neutral or positive carbon accumulation in six of the seven coastal Louisiana basins examined (Figure 4C). Breton Sound, with a high rate of land loss and low current wetland area, was the only basin where annual rates of carbon loss substantially exceeded rates of carbon accumulation. Overall, we calculate that the combined effect of land loss and carbon accumulation in current wetlands is a net carbon sink of 0.7 Tg C year^{-1} in the seven basins studied (Table 1). Nevertheless, negative and neutral carbon budgets in two basins with relatively small marsh area suggest that there are limits to landscape carbon accumulation, so that future land loss will eventually lead to a transition from a net sink to a net source of carbon. Simple linear extrapolation of land loss and basin-averaged CAR suggest that these basins will transition from a net sink to a net source of carbon over decades to centuries (Table 1). While our results are consistent with previous work that identifies marsh size as a critical determinant of landscape-averaged carbon balances,[29,31] previous landscape-scale carbon estimates do not consider the effect of spatially or temporally variable RSLR on carbon accumulation in surviving marshes, leading to the conclusion that Louisiana marshes are not gaining carbon on the whole.[29] Our results therefore uniquely suggest that marsh carbon accumulation in surviving marshland responds dynamically to RSLR and can temporarily outpace carbon lost to drowning and erosion, even when marshes are in the process of submerging.

There are several important limitations to our approach that should be considered when interpreting these results. First, soil accretion rates and CAR depend on the depth and time period over which they are averaged, so that accumulation rates are typically slower when averaged over longer periods of time.[47] This could result in an overestimate of CAR, particularly in Louisiana basins where the measurement period is less than one decade and decomposition is likely incomplete. However, we note that the average CAR (272 ± 47 g m^{-2} year^{-1}) from the Lower Mississippi region in Wang et al.,[15] where 43 of 47 measurements are based on long-term radiochronology, is well within the range of CAR (149–591 g m^{-2} year^{-1}) from short-term marker horizons in the same region (Table S1 and Figure S1). Second, the fate of eroded carbon is poorly constrained because it contains a mix of labile and refractory carbon that may be deposited in a fundamentally different environment.[45,48,49] Therefore, carbon eroded from the marsh does not necessarily translate to a loss of carbon overall, suggesting that the landscape budgets could be conservative. Although these limitations cannot be fully evaluated, we have been careful to include studies of CAR only from relatively young, near-surface sediments (<1 m), so that CAR estimates correspond to similar depths and timescales as the soil eroded in submerging marshes.[29,35] Finally, we

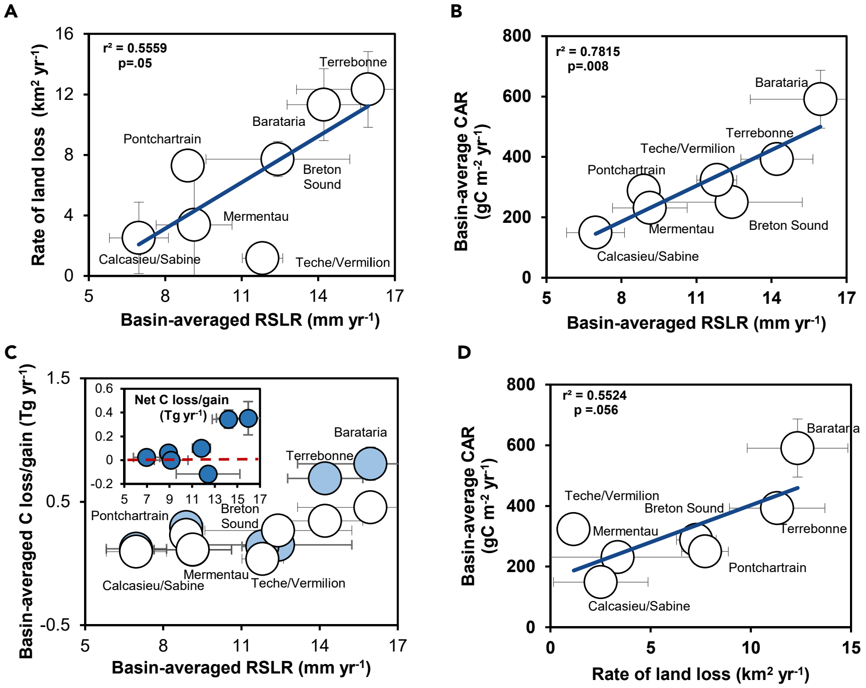

Figure 4. Landscape carbon budgets for seven coastal Louisiana basins shown in Figure S3

(A) Relationship between the basin-averaged relative sea-level rise (RSLR) rate (mm year^{-1}) calculated from Jankowski et al.[27] and the rate of land loss (km^2 year^{-1}) from 1985 to 2010 calculated by Couvillion et al.[39]

(B) Relationship between the basin-averaged RSLR rate and the basin-averaged carbon accumulation rate (CAR) (g C m^{-2} year^{-1}) calculated in this study (Table 1).

(C) Comparison of annualized basin-averaged carbon loss (white circles) and carbon gain (light-blue circles). The inset is the net annual change in marsh carbon (dark-blue circles), where the red line indicates no net change, positive numbers are net gains, and negative numbers are net losses.

(D) Relationship between basin-averaged carbon accumulation and land loss.

In all cases, error bars represent the standard error of the mean or, in the case of land-loss rate, standard error of the regression coefficient as estimated by Couvillion et al.[39]

acknowledge that sedimentation-rate data were used to calculate both CAR (i.e., soil accretion rate) and RSLR (i.e., shallow subsidence rate) in the Louisiana CRMS dataset, which could result in a spurious correlation between CAR and RSLR. Although tide gauge data alone is too limited to quantitatively test a relationship between CAR and RSLR across the Louisiana coast, spatial gradients in CAR generally follow gradients in RSLR observed in tide gauges (i.e., the average CAR increases from 189 g m^{-2} year^{-1} in the Sabine/Calcasieu and Mermentau basins to 532 g m^{-2} year^{-1} in the Barataria and Breton Sound basins, associated with RSLR rates that increase from 6.0 mm year^{-1} at Sabine Pass to 9.1 mm year^{-1} at Grand Isle; Table S1, https://tidesandcurrents.noaa.gov/sltrends/). Moreover, we note that CAR is strongly correlated with RSLR across multiple coastal regions of the United States (Figure 1), and regardless of whether they are short-term, Louisiana measurements are included in the analysis (Figure S1 and Table S2). Nevertheless, our results are best interpreted as short-term (i.e., decadal) approximations of landscape-scale CAR rather than long-term estimates of carbon sequestration.

While there is currently insufficient data to understand how SLR-driven increases in CAR will influence the carbon balance of coastal marshes outside Louisiana, our observations are consistent with model[50] and field[28] results from other locations showing that sediment accretion increases in surviving marshes even as marsh shorelines retreat. Deposition of eroded carbon on the surviving marshland may help explain high rates of CAR in coastal Louisiana, and is supported by a correlation between CAR and land-loss rates (Figure 4D). Tight correlation between CAR and land-loss rates in coastal Louisiana suggests that a significant proportion of the carbon accumulation is allochthonous material from marine sources or that some carbon is recaptured from eroding marshes themselves.[48,51,52] While our study suggests that the coastal saline marsh carbon sink grows stronger with accelerating SLR, at least temporarily, more work is needed to understand the origin and sink and source dynamics of coastal marsh carbon.

Conclusions and implications

In terrestrial ecosystems, the direct effects of warming are predicted to enhance carbon respiration to a greater degree than fixation, resulting in reduced CAR, positive carbon-climate feedback, and the amplification of global warming.[6,7,53] In contrast, our results suggest that in coastal wetlands there is no clear link between elevated temperature and CAR, and that RSLR is instead the dominant driver of CAR in coastal wetlands today. The fate of coastal wetlands under rapid future SLR is hotly debated and is an important determinant of the magnitude and direction of coastal carbon budgets.[16,21,29,32,44,54,55] Nevertheless, our analysis of the rapidly submerging Louisiana coast indicates that the magnitude of enhanced CAR in remaining marshland is currently large enough to counterbalance the effects of substantial marsh loss. Thus, our work suggests that the link between RSLR and CAR is strong enough to imply that a negative carbon-climate feedback may persist, at least temporarily, even as marshes deteriorate and occupy smaller areas.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Matthew L. Kirwan (kirwan@vims.edu).

Materials availability

This study did not generate new unique materials.

Table 1. Calculations used to estimate annual change in Louisiana carbon pools due to marsh loss and increased CAR

Basin	n	Basin-averaged RSLR (mm year^{-1})	Vertical accumulation rate (mm year^{-1})	Carbon accumulation rate (g C m^{-2} year^{-1})	Saline marsh area (km^2)	Annual carbon accumulation (Tg C year^{-1})	Annual land loss (km^2 year^{-1})	Soil carbon density (g C m^{-3})	Annual carbon loss (Tg C year^{-1})	Net carbon balance (Tg C year^{-1})	Time until carbon source (years)
Pontchartrain	19	8.9	9.1	288.1	1,018	0.29	7.28	31,800	0.23	0.06	29
Breton Sound	6	12.4	7.1	249.9	606	0.15	7.72	34,694	0.27	−0.12	NA
Barataria	29	16.0	16.4	590.7	1,369	0.81	12.33	36,937	0.46	0.35	49
Terrebonne	32	14.2	13.2	392.7	1,754	0.69	11.32	30,467	0.34	0.34	77
Teche/Vermilion	12	11.8	10.0	323.4	428	0.14	1.17	32,152	0.04	0.10	267
Mermentau	16	9.1	6.7	230.9	483	0.11	3.37	33,348	0.11	−0.001	NA
Sabine/Calcasieu	17	7.0	4.6	149.1	796	0.12	2.51	38,143	0.10	0.02	61

Carbon gain was estimated by multiplying the basin-averaged CAR by the cumulative saline (salt and brackish marsh) marsh area in each basin based on 2007 vegetation maps (Sasser et al.;[46] available at https://cims.coastal.louisiana.gov/). Carbon loss for one year was estimated as the annual area of land lost from 1985 to 2010 by Couvillion et al.[39] assuming a 1-m-deep soil column (following DeLaune and White)[29] and the basin-averaged soil carbon density for saline marsh. The time until each basin switches from a net sink to a net source of carbon was estimated as $t = \frac{\text{saline marsh area} - \frac{\text{annual carbon loss}}{\text{CAR}}}{\text{annual land loss}}$, assuming that neither the CAR nor the land-loss rate changes through time. NA indicates basin is already a net source of carbon, and therefore no time has been calcuated.

Data and code availability

Carbon accumulation rates and supporting information (e.g., soil accumulation rates, carbon density, and climate information) for each wetland location are available through the journal website and as a published dataset.[56]

Data compilation

Data for coastal wetland CARs were compiled from a synthesis of CONUS measurements by Wang et al.[15] (n = 372) and data from the Louisiana Coastwide Reference Monitoring System[33] (CRMS) (n = 274). CARs (g C m^{-2} year^{-1}), SARs (cm year^{-1}), and soil carbon density (g C cm^{-3}) were available directly from the Wang et al.[15] dataset. For the Louisiana CRMS sites, we started with a dataset of 274 SARs and RSLR rates synthesized by Jankowski et al.[27] These sites were selected by Jankowski et al. to include continuous records of at least 5 years without re-establishment due to damage, and for which the record was continuous above a single undisturbed sediment marker horizon. We filtered their dataset to include only saline and brackish marsh sites, resulting in a total of 131 CRMS sites in our analysis. Soil carbon density (g C cm^{-3}) was calculated using the average organic content and bulk density of the upper 24 cm of soil reported at each CRMS site, and an empirical relationship between organic matter and carbon content.[57] CAR (g C m^{-2} year^{-1}) was then calculated by multiplying the soil carbon density (g C cm^{-3}) by the SARs (cm year^{-1}), using the same methodological criteria established by Ouyang and Lee[14] and references therein.

Estimates of SARs and RSLR rates were taken directly from the CONUS[15] and Louisiana[27] datasets, and methods used to derive them differ substantially. The CONUS dataset includes estimates of SAR from a variety of sources, but is dominated by ^{137}Cs and ^{210}Pb dated sediment cores that yield decadal to century timescale rates.[15] Estimates of SAR in the Louisiana dataset come entirely from measurements of sediment accumulating above a feldspar marker horizon in the last 5–10 years.[27] RSLR rates in the CONUS dataset were derived from long-term tide gauge data spanning the most recent 60 years.[15] RSLR rates in the Louisiana dataset were derived from short-term measurements of shallow subsidence at each site, spatially interpolated estimates of deep subsidence, and a constant rate of eustatic sea-level rise derived from satellite altimetry.[27] These different approaches would be expected to lead to important differences in reported SAR, CAR, and RSLR.[47,58] Nevertheless, observed relationships between CAR and RSLR are consistent between the United States and Louisiana datasets, suggesting that the link between CAR and RSLR is strong enough to emerge above differences in timescale and methods.

Statistical analysis

All statistical analyses were performed in JMP 14.3 (2018; SAS Institute, Cary, NC). Data were analyzed for the CONUS regions alone,[15] (n = 372 individual CAR measurements), for the Louisiana CRMS sites alone[33] (n = 131 measurements), and for both datasets together (n = 503). For the CRMS data, a cutoff of 40 mm year^{-1} was applied to remove three high estimates and to focus the analysis on more representative cases of RSLR (n = 128). For these final datasets of CARs, we used ordinary least-squares regression to analyze the interactions between individual independent variables (RSLR, MAT, MAP, and tidal range) on the dependent variables (CAR, SAR, and soil carbon density) as well as the relationship between soil accretion (independent) and carbon accumulation (dependent) rates. After independent analysis illustrated the dominant role of RSLR on CAR, we then used a forward stepwise linear regression to explore the influence of the combination of RSLR with carbon density, MAT, and MAP on CAR.

Estimates of the carbon balance for coastal Louisiana

We followed the basic approach of DeLaune and White[29] and Theuerkaf et al.[31] to estimate annual change in the coastal Louisiana soil carbon balance (ΔC) within each of seven coastal basins (Table 1 and Figure S3) that contain CRMS data for salt and brackish marshes (the other two basins, the Atchafalaya and Birds-Foot/Mississippi Delta basins, are dominated by freshwater flows). Unlike previous budgets,[24,29,31] our budget specifically examined the role of RSLR on CAR and spatially variable land-loss rates. Basin location for each CRMS point was assigned using ArcGIS 10.3 by overlaying the Louisiana Coastal Protection and Restoration Authority coastal basin boundaries[33] (Figure S3). Basin-averaged RSLR (mm year^{-1}), soil carbon density (g C m^3, SOCD$_{basin}$) and CAR (g C m^{-2} year^{-1}, CAR$_{basin}$) were calculated using the points within the basin. Carbon gain was estimated by multiplying the basin-averaged CAR (CAR$_{basin}$) by the cumulative saline marsh (salt and brackish marsh) area in each basin (A_{basin}) based on 2007 vegetation maps[46] (available as GIS layer at https://cims.coastal.louisiana.gov/).[33] Carbon losses are the product of the annual change in marsh area (ΔA_{basin}; km^2 year^{-1}) estimated by Couvillion et al.[39] or the years 1985–2010 (includes effects of hurricane activity) and basin-averaged soil carbon density (SOCD$_{basin}$; g C m^{-3}) assuming the depth of soil lost (d) is 1 m.[31,35] ΔC was estimated as the annual gain from accumulation on surviving marshes minus annual losses from marsh erosion and drowning as

$$\Delta C_{basin} = (A_{basin} \times \mathrm{CAR}_{basin}) - (\Delta A_{basin} \times \mathrm{SOCD}_{basin} \times d).$$

Because continued land loss would eventually lead to a net loss of marsh carbon accumulation, we also calculated the number of years (t) required for each basin to transition from a net sink to a net source of carbon,

$$t = \frac{\text{saline marsh area} - \frac{\text{annual carbon loss}}{\text{CAR}}}{\text{annual land loss}},$$

using the basin-averaged values in Table 1. This approach is overly simplistic because it assumes that neither the CAR nor the land-loss rate changes through time. In reality, CAR is a dynamic function of RSLR, and land-loss rates are declining through time in response to declining rates of RSLR associated with slower deep subsidence and decreased oil production.[59] Therefore, we use these timescale estimates simply to highlight the potential future vulnerability of the Louisiana landscape carbon budget as wetlands continue to erode and submerge.

These basin-wide carbon budget calculations are sensitive to the depth of carbon eroded, which is poorly constrained in both coastal Louisiana and in continental assessments of coastal carbon vulnerability.[36] However, a loss of soil carbon to 1 m depth is consistent with protocols for assessing vulnerable carbon[36,60] and is within the range of depths of previously eroded marsh area observed in Louisiana, generally 0.6–1.5 m.[29,35,61,62] At the same time, our estimates may underestimate carbon gain because the land-loss data include marshes of all types, whereas our basin-wide calculations of carbon accumulation only include the area occupied by saline and brackish marshes, which represent only about 48% of marshes in the studied basins. These assumptions suggest that the net carbon budgets we report may be conservative, and that the positive or neutral carbon balance we report for six of the seven coastal basins is robust.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.02.011.

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AUTHOR CONTRIBUTIONS

E.R.H., L.W.-M., and M.L.K. designed the study, compiled data, and wrote the manuscript. L.W.-M. performed the statistical analyses, and E.R.H. and M.L.K. constructed the landscape carbon budgets.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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REFERENCES

1. Friedlingstein, P. (2015). Carbon cycle feedbacks and future climate change. Philos. Trans. R. Soc. A *373*, https://doi.org/10.1098/rsta.2014.0421.
2. Crowther, T., Todd-Brown, K., Rowe, C., Wieder, W., Carey, J., Machmuller, M., Snoek, B., Fang, S., Zhou, G., Allison, S., et al. (2016). Quantifying global soil C losses in response to warming. Nature *104*, 104–108.
3. Mcleod, E., Chmura, G.L., Bouillon, S., Salm, R., Björk, M., Duarte, C.M., Lovelock, C.E., Schlesinger, W.H., and Silliman, B.R. (2011). A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO$_2$. Front. Ecol. Environ. *9*, 552–560.
4. Ward, N., Megonigal, P., Bond-Lamberty, B., Bailey, V., Butman, D., Canuel, E., Diefenderfer, H., Ganju, N., Goñi, M., Graham, E., et al. (2020). Representing the function and sensitivity of coastal interfaces in Earth system models. Nat. Commun. *11*, 2458, https://doi.org/10.1038/s41467-020-16236-2.
5. Yvon-Durocher, G., Jones, J.I., Trimmer, M., Woodward, G., and Montoya, J.M. (2010). Warming alters the metabolic balance of ecosystems. Philos. Trans. R. Soc. Lond. B Biol. Sci. *365*, 2117–2126.
6. Lu, M., Zhou, X., Yang, Q., Li, H., Luo, Y., Fang, C., Chen, J., Yang, X., and Li, B. (2013). Responses of ecosystem carbon cycle to experimental warming: a meta-analysis. Ecology *94*, 726–738.
7. Schuur, E., McGuire, A.D., Schädel, C., Grosse, G., Harden, J., Hayes, D.J., Hugelius, G., Koven, C., Kuhry, P., Lawrence, D., et al. (2015). Climate change and the permafrost carbon feedback. Nature *2015*, 171–179.
8. Noyce, G.L., Kirwan, M.L., Rich, R.L., and Megonigal, J.P. (2019). Asynchronous nitrogen supply and demand produce nonlinear plant allocation responses to warming and elevated CO$_2$. Proc. Natl. Acad. Sci. U S A *116*, 21623–21628.
9. Liu, W., Chen, X., Strong, D.R., Pennings, S.C., Kirwan, M.L., Chen, X., and Zhang, Y. (2020). Climate and geographic adaptation drive latitudinal clines in biomass of a widespread saltmarsh plant in its native and introduced ranges. Limnol. Oceanogr. *65*, 1399–1409.
10. Davidson, E.A., and Janssens, I.A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature *440*, 165–173.
11. Wilson, R.M., Hopple, A.M., Tfaily, M.M., Sebestyen, S.D., Schadt, C.W., Pfeifer-Meister, L., Medvedeff, C., McFarlane, K.J., Kostka, J.E., Kolton, M., et al. (2016). Stability of peatland carbon to rising temperatures. Nat. Commun *7*, 13723–13733.
12. Kirwan, M.L., Guntenspergen, G.R., and Langley, J.A. (2014). Temperature sensitivity of organic-matter decay in tidal marshes. Biogeosciences *11*, 4801–4808.
13. Chmura, G.L., Anisfeld, S.C., Cahoon, D.R., and Lynch, J.C. (2003). Global carbon sequestration in tidal , saline wetland soils. Glob. Biogeochem.Cycles *17*, https://doi.org/10.1029/2002GB001917.

14. Ouyang, X., and Lee, S.Y. (2014). Updated estimates of carbon accumulation rates in coastal marsh sediments. Biogeosciences *11*, 5057–5071.

15. Wang, F., Lu, X., Sanders, C., and Tang, J. (2019). Tidal wetland resilience to sea level rise increases their carbon sequestration capacity in United States. Nat. Commun. *10*, https://doi.org/10.1038/s41467-019-13294-z.

16. Kirwan, M.L., and Mudd, S.M. (2012). Response of salt-marsh carbon accumulation to climate change. Nature *489*, 550–553.

17. Fagherazzi, S., Kirwan, M.L., Mudd, S.M., Guntenspergen, G.R., Temmerman, S., D'Alpaos, A., van de Koppel, J.M., Rybczyk, E.R., Craft, C., and Clough, J. (2012). Numerical models of salt marsh evolution: ecological, geomorphic, and climatic factors. Rev. Geophys. *50*, RG1002.

18. Morris, J.T., Sundareshwar, P.V., Nietch, C.T., Kjerve, B., and Cahoon, D.R. (2002). Responses of coastal wetlands to rising sea level. Ecology *83*, 2869–2877.

19. Redfield, A.C. (1972). Development of a New England salt marsh. Ecol. Monogr. *42*, 201–237.

20. Mudd, S.M., Howell, S.M., and Morris, J.T.((2009). Impact of dynamic feedbacks between sedimentation, sea-level rise, and biomass production on near-surface marsh stratigraphy and carbon accumulation. Estuar Coast Shelf Sci. *82* (3), 377–389.

21. Morris, J.T., Edwards, J., Crooks, S., and Reyes, E. (2012). Assessment of carbon sequestration potential in coastal wetlands. In Recarbonization of the Biosphere, R. Lal, K. Lorenz, R.F. Hüttl, B.U. Schneide, and J. von Braun, eds. (Springer), pp. 517–530.

22. Rogers, K., Kelleway, J., Saintilan, N., Megonigal, P., Adams, J., Holmquist, J., Lu, M., Schile-Beers, L., Zawadzki, A., Mazumder, D., and Woodroffe, C. (2019). Wetland carbon storage controlled by millennial-scale variation in relative sea-level rise. Nature *567*, 91–95.

23. Gonneea, M.E., Maio, C.V., Kroeger, K.D., Hawkes, A.D., Mora, J., Sullivan, R., Madsen, S., Buzard, R.M., Cahill, N., and Donnelly, J.P. (2019). Salt marsh ecosystem restructuring enhances elevation resilience and carbon storage during accelerating relative sea-level rise. Estuar Coast Shelf Sci. *217*, 56–68.

24. Braun, K.N., Theuerkauf, E.J., Masterson, A.L., Curry, B.B., and Horton, D.E. (2019). Modeling organic carbon loss from a rapidly eroding freshwater coastal wetland. Sci. Rep. *9*, 4204.

25. Kirwan, M.L., and Megonigal, J.P. (2013). Tidal wetland stability in the face of human impacts and sea-level rise. Nature *504*, 53–60.

26. Törnqvist, T.E., Jankowski, K.L., Li, Y.X., and Gonzalez, J.L. (2020). Tipping points of mississippi delta marshes due to accelerated sea-level rise. Sci. Adv. *6*, https://doi.org/10.1126/sciadv.aaz5512.

27. Jankowski, K.L., Törnqvist, T.E., and Fernandes, A.M. (2017). Vulnerability of Louisiana's coastal wetlands to present-day rates of relative sea-level rise. Nat. Commun. *8*, 14792.

28. Ganju, N., Defne, Z., Kirwan, M., Fagherazzi, S., D'Alpaos, A., and Carniello, L. (2017). Spatially integrative metrics reveal hidden vulnerability of microtidal salt marshes. Nat. Commun. *8*, 14156.

29. DeLaune, R.D., and White, J.R. (2012). Will coastal wetlands continue to sequester carbon in response to an increase in global sea level?: a case study of the rapidly subsiding Mississippi river deltaic plain. Clim. Change *110* (2), 297–314.

30. Baustian, M.M., Stagg, C.L., Perry, C.L., Moss, L.C., Carruthers, T.J.B., and Allison, M. (2017). Relationships between salinity and short-term soil carbon accumulation rates from marsh types across a landscape in the Mississippi river Delta. Wetlands *37*, 313–324.

31. Theuerkauf, E.J., Stephens, J.D., Ridge, J.T., Fodrie, F.J., and Rodriguez, A.B. (2015). Carbon export from fringing saltmarsh shoreline erosion overwhelms carbon storage across a critical width threshold. Estuar Coast Shelf Sci. *164*, 367–378.

32. Saintilan, N., Khan, N., Ashe, E., Kelleway, J., Rogers, K., Woodroffe, C., and Horton, B. (2020). Thresholds of mangrove survival under rapid sea level rise. Science *368*, 1118–1121, https://doi.org/10.1126/science.aba2656.

33. Coastal Protection and Restoration Authority (2019). LA Coastwide Reference Monitoring System Soil and Vegetation Data. https://lacoast.gov/crms2/home.aspx.

34. Craft, C., Clough, J., Ehman, J., Joye, S., Park, R., Pennings, S., Guo, H., and Machmuller, M. (2009). Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. Front. Ecol. Environ. *7*, 73–78.

35. Wilson, C.A., and Allison, M.A. (2008). An equilibrium profile model for retreating marsh shorelines in southeast Louisiana. Estuar Coast Shelf Sci. *80*, 483–494.

36. Holmquist, J.R., Windham-Myers, L., Bernal, B., Byrd, K.B., Crooks, S., Gonneea, M.E., Herold, N., Knox, S.H., Kroeger, K., Mccombs, J., et al. (2019). Coastal Wetland Elevation and Carbon Flux Inventory with Uncertainty, USA, 2006-2011 (ORNL DAAC).

37. McTigue, N., Davis, J., Rodriguez, A.B., McKee, B., Atencio, A., and Currin, C. (2019). Sea level rise explains changing carbon accumulation rates in a salt marsh over the past two millennia. J. Geophs. Res. *124*, 2945–2957.

38. Choi, Y., and Wang, Y. (2004). Dynamics of carbon sequestration in a coastal wetland using radiocarbon measurements. Glob. Biogeochem Cycles *18*, https://doi.org/10.1029/2004GB002261.

39. Couvillion, B.R., Barras, J.A., Steyer, G.D., Sleavin, W., Fischer, M., Beck, H., Trahan, N., Griffin, B., and Heckman, D. (2011). Land Area Change in Coastal Louisiana from 1932 to 2010: US Geological Survey Scientific Investigations Map 3164, Scale 1:265,000 (USGS).

40. Osland, M.J., Gabler, C.A., Grace, J.B., Day, R.H., McCoy, M.L., McLeod, J.L., From, A.S., Enwright, N.M., Feher, L.C., Stagg, C.L., and Hartley, S.B. (2018). Climate and plant controls on soil organic matter in coastal wetlands. Glob. Change Biol. *24*, 5361–5379.

41. Unger, V., Elsey-Quirk, T., Sommerfield, C., and Velinsky, D. (2016). Stability of organic carbon accumulating in Spartina alterniflora-dominated salt marshes of the mid-Atlantic U.S. Estuar. Coast Shelf Sci. *182 pt A*, 179–189.

42. Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M.L., Wolff, C., Lincke, D., McOwen, C.J., Pickering, M.D., Reef, R., Vafeidis, A.T., et al. (2018). Future response of global coastal wetlands to sea-level rise. Nature *561*, 231–234.

43. Kirwan, M.L., Walters, D.C., Reay, W., and Carr, J.A. (2016). Sea level driven marsh expansion in a coupled model of marsh erosion and migration. Geophys. Res. Lett. *43*, 4366–4373.

44. Hopkinson, C.S., Cai, W.J., and Hu, X. (2012). Carbon sequestration in wetland dominated coastal systems-a global sink of rapidly diminishing magnitude. Curr. Opin. Environ. Sustain. *4*, 186–194.

45. Spivak, A., Sanderman, J., Bowen, J., Canuel, E., and Hopkinson, C. (2019). Global-change controls on soil-carbon accumulation and loss in coastal vegetated ecosystems. Nat. Geosci. *12*, 685–692.

46. Sasser, C.E., Visser, J.M., Mouton, E., Linscombe, J., and Hartley, S.B. (2008). Vegetation Types in Coastal Louisiana in 2007: US Geological Survey Open-File Report 2008-1224, 1 Sheet, Scale 1:550,000 (USGS).

47. Breithaupt, J.L., Smoak, J.M., Byrne, R.H., Waters, M.N., Moyer, R.P., and Sanders, C.J. (2018). Avoiding timescale bias in assessments of coastal wetland vertical change. Limnol. Oceanogr. *63* (S1), S477–S495.

48. Hopkinson, C.S., Morris, J.T., Fagherazzi, S., Wollheim, W.M., and Raymond, P.A. (2018). Lateral marsh edge erosion as a source of sediments for vertical marsh accretion. J. Geophys. Res. Biogeosci. *123*, 2444–2465.

49. Leorri, E., Zimmerman, A.R., Mitra, S., Christian, R.R., Fatela, F., and Mallinson, D.J. (2018). Refractory organic matter in coastal salt marshes—effect on C sequestration calculations. Sci. Total Environ. *633*, 391–398.

50. Mariotti, G., and Carr, J. (2014). Dual role of salt marsh retreat: long-term loss and short-term resilience. Water Resour. Res. *50*, https://doi.org/10.1002/2013WR014676.

51. Van de Broek, M., Vandendriessche, C., Poppelmonde, D., Merckx, R., Temmerman, S., and Govers, G. (2018). Long-term organic carbon sequestration in tidal marsh sediments is dominated by old-aged allochthonous inputs in a macrotidal estuary. Glob. Chang Biol. *24*, 2498–2512.

52. Mariotti, G., Elsey-Quirk, T., Bruno, G., and Valentine, K. (2020). Mud-associated organic matter and its direct and indirect role in marsh organic matter accumulation and vertical accretion. Limnol. Oceanogr. *65*, 2627–2641.

53. Friedlingstein, P., Cox, P., Betts, R., Bopp, L., Von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., and Fung, I. (2006). Climate-carbon cycle feedback analysis: results from the C4MIP model intercomparison. J. Clim. *19*, 3337–3353.

54. Chmura, G.L. (2013). What do we need to assess the sustainability of the tidal salt marsh carbon sink? Ocean Coast Manag. *83*, 25–31.

55. Hill, T.D., and Anisfeld, S.C. (2015). Coastal wetland response to sea level rise in Connecticut and New York. Estuar Coast Shelf Sci. *163*, 185–193.

56. Kirwan, M., Herbert, E., and Windham-Myers, L. (2021). Synthesis of sea level rise and carbon accumulation rates in United States tidal wetlands ver 3. Environmental Data Initiative. https://doi.org/10.6073/pasta/a05eda62baa46677a6b1e8540ebab5a9.

57. Craft, C.B., Seneca, E.D., and Broome, S.W. (1991). Loss on ignition and Kjeldahl digestion for estimating organic carbon and total nitrogen in estuarine marsh soils: calibration with dry combustion. Estuaries *14*, 175.

58. Keogh, M., and Törnqvist, T. (2019). Measuring rates of present-day relative sea-level rise in low-elevation coastal zones: a critical evaluation. Ocean Sci. *15*, 61–73.

59. Kolker, A.S., Allison, M.A., and Hameed, S. (2011). An evaluation of subsidence rates and sea-level variability in the northern Gulf of Mexico. Geophys. Res. Lett. *38*, https://doi.org/10.1029/2011GL049458.

60. Hiraishi T. Krug T. Tanabe K. Srivastava N. Bassansuren J. Fukuda M. Troxler T.G. 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands ed (IPCC).

61. Sapkota, Y., and White, J.R. (2019). Marsh edge erosion and associated carbon dynamics in coastal Louisiana: a proxy for future wetland-dominated coastlines world-wide. Estuarine. Coastal Shelf Sci. *226*, 106289.

62. Valentine, K., and Mariotti, G. (2019). Wind-driven water level fluctuations drive marsh edge erosion variability in microtidal coastal bays. Continental Shelf Res. *176*, 76–89.