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

Ellen R. Herbert[1], Lisamarie Windham-Myers[2] and Matthew L. Kirwan[1*]

[1]Virginia Institute of Marine Sciences, College of William & Mary, Gloucester Point, VA 23062

[2] U.S. Geological Survey, Menlo Park, CA 94024

*Corresponding author: Matthew L. Kirwan, Virginia Institute of Marine Sciences, P.O. Box 1346 Gloucester Point, VA 23062; 804-684-7054; kirwan@vims.edu

*Lead Contact: Matthew L. Kirwan, Virginia Institute of Marine Sciences, P.O. Box 1346 Gloucester Point, VA 23062; 804-684-7054; kirwan@vims.edu

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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 feedbacks between climate and carbon cycling influence the ability of ecosystems to absorb and store carbon. Models and empirical observations in marine, peatland, and terrestrial systems point to a positive carbon-climate feedback, where 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 feedbacks 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[13,14,15]. Instead, model[16] and experimental results[8] suggest 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 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 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.

META-ANALYSIS OF NORTH AMERICAN CARBON ACCUMULATION RATES

To examine the drivers of CAR, we compiled a dataset of 372 CAR measurements in wetlands from across the continental United States (mangroves and marshes)[15] and 131 additional salt and brackish marshes across coastal Louisiana (Louisiana Coastwide Reference Monitoring System, CRMS)[33] (*see Experimental Procedures, Fig. 1, Table S1*). For the U.S. nited States dataset, we collated data on carbon accumulation (CAR, soil accretion rate, soil carbon density) and environmental parameters (RSLR, tide range, mean annual temperature, precipitation) directly from Wang et al[15]. For the Louisiana dataset, we started with 274 CRMS sites[27], filtered the data to isolate salt and brackish marshes, leaving us with a total of 131 saline and brackish marsh locations in our analysis. Soil accretion rates 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 (CAR) responded to physical (e.g. RSLR, accretion) and/or climatic (e.g. temperature) drivers (*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 (<1m soil depth) as measured by physical marker horizons (i.e. accumulated above ceramic tiles or feldspar layers), permanent benchmarks, radioisotope or radiocarbon dating. Short-term (<50 year) CAR measurements include labile C 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 (<1m)[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, $R^2 = 0.42$, RMSE = 123.7), but the trend was driven mostly by sites in the Lower Mississippi region with RSLR rates > 5 mm yr^{-1} (*Fig. 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 datapoints. 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) (*Fig. 2B, 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 (*Fig. S1 & Table S2*). Eighty percent of the variation between CAR and RSLR was explained by the increase in vertical soil accretion rate (SAR) under increased RSLR (*Fig. 3A, Fig. 3B, Table S3*). Regional variation in soil carbon density was not significantly correlated with RSLR (*Fig. 3C*). The inclusion of a carbon density x RSLR interaction in a mixed model showed similar power in predicting CAR ($R^2 = 0.45$, RMSE = 124) compared to 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. *Fig. 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 (*Fig. S2*). Mean annual temperature (MAT) and mean annual precipitation (MAP) were not correlated with CAR when averaged at regional scales (n=7 regions, $p<0.05$, *Fig. S2a,c*). 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 (*Fig. S2b,d*), but RMSE was high for both climate variables and they explained only 2-3% of the variance in the data, respectively. Further, 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[13-15,39]. 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[34,40-42], calling into question the stability of the coastal carbon sink under accelerated SLR [29,31,32,43,44]. 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, Fig. S3*), where net change reflects the balance between carbon accumulating in surviving marshes and carbon lost due to marsh drowning and erosion (*Experimental Procedures*).

We find that land loss and carbon accumulation both increase with the rate of RSLR (*Fig. 4A & 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 6 of the 7 coastal Louisiana basins examined (*Fig. 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 yr^{-1} in the 7 basins studied (Table 1). Nevertheless, negative and neutral carbon budgets in 2 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, sediment 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[45]. This could result in an overestimate of CAR, particularly in Louisiana basins where the measurement period is less than 1 decade and decomposition is likely incomplete. However, we note that the average CAR (272 +/- 47 g m^{-2} yr^{-1}) from Wang's Lower Mississippi region[15], where 43 of 47 measurements are based on long-term radiochronology, is well within the range of CAR (149-591 g m^{-2} yr^{-1}) from short-term marker horizons in the same region (Table S1; 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[44,46,47]. 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 (<1m), so that CAR estimates correspond to similar depths and timescales as the soil eroded in submerging marshes[29,35]. Finally, we acknowledge that sedimentation rate data were used to calculate both CAR (i.e. sediment 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} yr^{-1} in the

Sabine/Calcasieu and Mermentau basins to 532 g m^{-2} yr^{-1} in the Barataria and Breton Sound basins, associated with RSLR rates that increase from 6.0 mm yr^{-1} at Sabine Pass to 9.1 mm yr^{-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 U.S. (Fig. 1), and regardless of whether short-term, Louisiana measurements are included in the analysis (Fig. S1; 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[48] and field[28] results from other locations that show 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 (Fig. 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[46,49,50]. 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 feedbacks, and the amplification of global warming [6,7,51]. 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[16,21,29,32,43,52,53]. 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 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:** None
- **Data and code availability:** Carbon accumulation rates and supporting information (e.g. soil accretion rate, carbon density, and climate information) for each wetland location are available through the journal website, and as a published dataset: Kirwan, M., E. Herbert, and L. Windham-Myers. 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.

Data compilation. Data for coastal wetland carbon accumulation rates (CAR) were compiled from a synthesis of continental U.S. measurements by Wang et al. (n=372)[15] and data from the Louisiana Coastwide Reference Monitoring System[33] (n=274) (CRMS). Carbon accumulation rates (g C m^{-2} yr^{-1}), soil accretion rates (cm yr^{-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 soil accretion rates 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 reestablishment 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 24cm of soil reported at each CRMS site, and an empirical relationship between organic matter and carbon content[54]. CAR (g C m^{-2} yr^{-1}) was then calculated by multiplying the soil carbon density (g C cm^{-3}) by the soil accretion rates (cm yr^{-1}), using the same methodological criteria established by Ouyang and Lee[14] and references therein.

Estimates of SAR and RSLR rates were taken directly from the continental U.S.[15] and Louisiana[27] datasets, and methods used to derive them differ substantially. The continental U.S. 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 continental U.S. 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, RSLR[45,55]. Nevertheless, observed relationships between CAR and RSLR are consistent between the U.S. 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 Continental United States (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 40mm yr^{-1} was applied to remove 3 high estimates, and to focus the analysis on more representative cases of RSLR (n=128). For these final datasets of carbon accumulation rates (CAR), we used ordinary least-squares regression to analyze the interactions between individual independent variables (RSLR, mean annual temperature, mean annual precipitation, tidal range) on the dependent variables (CAR, soil accretion rate, and soil C 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 C density, mean annual temperature, and mean annual precipitation on C accumulation rate.

Estimates of the carbon balance for coastal Louisiana. We followed the basic approach of DeLaune and White[29], Theuerkaf et al.[31] to estimate annual change in the coastal Louisiana soil C balance (ΔC) within each of 7 coastal basins (Table 1, *Fig. 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 Louisana Coastal Protection and Resotration Authority coastal basin boundaries[33] (Fig. S3). Basin-averaged RSLR (mm yr^{-1}), soil carbon density (gC m^3, $SOCD_{basin}$) and CAR (gC m^{-2} yr^{-1}, CAR_{basin}) were calculated using the points within the basin. Carbon gain was estimated by multiplying the basin-averaged carbon accumulation rate (CAR_{basin}) by the cumulative saline marsh (salt and brackish marsh) area in each basin (A_{basin}) based on 2007 vegetation maps[56] (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 yr^{-1}) estimated by Couvillion et al.[57] or the years 1985-2010 (includes effects of hurricane activity) and basin-averaged soil carbon density ($SOCD_{basin}$; gC m^{-3}) assuming the depth of soil lost (*d*) is 1 m (35). ΔC was estimated as the annual gain from accumulation on surviving marshes minus annual losses from marsh erosion and drowning as:

$$\Delta C_{basin} = (A_{basin} \times CAR_{basin}) - (\Delta A_{basin} \times SOCD_{basin} \times d)$$

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:

$$t = \frac{Saline\ marsh\ area - \frac{Annual\ carbon\ loss}{Carbon\ accumulation\ rate}}{Annual\ land\ loss}$$

using the basin-averaged values in Table 1. This approach is overly simplistic because it assumes that neither the carbon accumulation rate 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[58]. 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 basinwide 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 1m depth is consistent with protocols for assessing vulnerable carbon[36,59] and is within the range of depths of previously eroded marsh area observed in Louisiana, generally 0.6 - 1.5 m [29,35,60-61] . At the same time, our estimates may underestimate carbon gain because the land loss data include marshes of all types, whereas our basinwide 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 6 of the 7 coastal basins is robust.

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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.

Additional information

The authors declare no competing financial interests. The complete dataset used in the analysis has been uploaded as a supplemental spreadsheet.

References

1. Friedlingstein P (2015) Carbon cycle feedbacks and future climate change. Philos Trans R Soc A Math Phys Eng Sci, 1–22.
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(540), 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 CO2. Front Ecol Environ 9(10), 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 Commun11 2458. 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(1549), 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(3), 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 CO2. Proc Natl Acad Sci USA, 116(43), 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(7081), 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(17), 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. Global Biogeochem.Cycles 17, 111117(4). doi:10.1029/2002GB001917.

14. Ouyang X., and Lee S.Y. (2014) Updated estimates of carbon accumulation rates in coastal marsh sediments. Biogeosciences 11(18), 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, 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(7417), 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, geormorphic, 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(10):2869–2877.

19. Redfield, A.C. (1972) Development of a New England Salt Marsh. Ecol Monogr 42(2), 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. Recarbonization of the Biosphere, eds Lal R, Lorenz K, Hüttl RF, Schneide BU, von Braun J (Springer Netherlands), 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. 10.1038/s41586-019-0951-7.

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, ISSN 0272-7714 https://doi.org/10.1016/j.ecss.2018.11.003.

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 https://doi.org/10.1038/s41598-019-40855-5

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. Earth, Environmental, and

Marine Sciences Faculty Publications and Presentations. 30.

27. Jankowski, K.L., Törnqvist, T.E., and Fernandes, A.M. (2017) Assessing the vulnerability of Louisiana's coastal wetlands to present-day rates of relative sea-level rise. Nat Commun DOI: 10.10.

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. 10.1038/ncomms14156

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(1–2), 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(2), 313–324. https://doi.org/10.1007/s13157-016-0871-3

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. 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. doi:10.1890/070219

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(4), 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, Oak Ridge, Tennessee, USA

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 millenia. J. Geophs. Res. 124, 2945-2957. doi.org/10.1029/2019JG005207.

38. Choi, Y., and Wang, Y. (2004) Dynamics of carbon sequestration in a coastal wetland using radiocarbon measurements. Global Biogeochem Cycles 18(4), 1–12.

39. 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., & Hartley, S. B. (2018). Climate and plant controls on soil organic matter in coastal wetlands. Global Change

Biology, 24(11), 5361–5379. https://doi.org/10.1111/gcb.14376

40. 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. doi:10.1016/j.ecss.2016.10.001.

41. 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 (7722), 231–234. https://doi.org/10.1038/s41586-018-0476-5

42. 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, 1–8.

43. 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(2), 186–194.

44. 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. 10.1038/s41561-019-0435-2.

45. 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).

46. 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.

47. 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. Science of The Total Environment, 633, 391-398. doi:10.1016/j.scitotenv.2018.03.120.

48. Mariotti, G., and Carr, J. (2014). Dual role of salt marsh retreat: Long-term loss and short-term resilience. Water Resour Res 50(4). doi:10.1002/2013WR014676.

49. 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(6), 2498-2512.

50. 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. doi:10.1002/lno.11475

51. 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.

52. 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.

53. 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.

54. 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.

55. Keogh, M., and Törnqvist, T. (2019). Measuring rates of present-day relative sea-level rise in low-elevation coastal zones: A critical evaluation. Ocean Science. 15, 61-73. 10.5194/os-15-61-2019.

56. Sasser, C.E, Visser, J.M., Mouton, E., Linscombe, J., and Hartley, S.B. (2008) Vegetation Types in Coastal Louisiana in 2007: U.S. Geological Survey Open-File Report 2008-1224, 1 sheet, scale 1:550,000.

57. 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: U.S. Geological Survey Scientific Investigations Map 3164, scale 1:265,000.

58. 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. Geophysical Research Letters 38, doi:10.1029/2011GL049458.

59. IPCC 2014 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands ed T Hiraishi (Bracknell: IPCC).

60. 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 and Shelf Science 226, 106289. doi:10.1016/j.ecss.2019.106289.

61. Valentine, K. and Mariotti, G., 2019. Wind-driven water level fluctuations drive marsh edge erosion variability in microtidal coastal bays. Continental Shelf Research 176, 76-89.

Figure captions

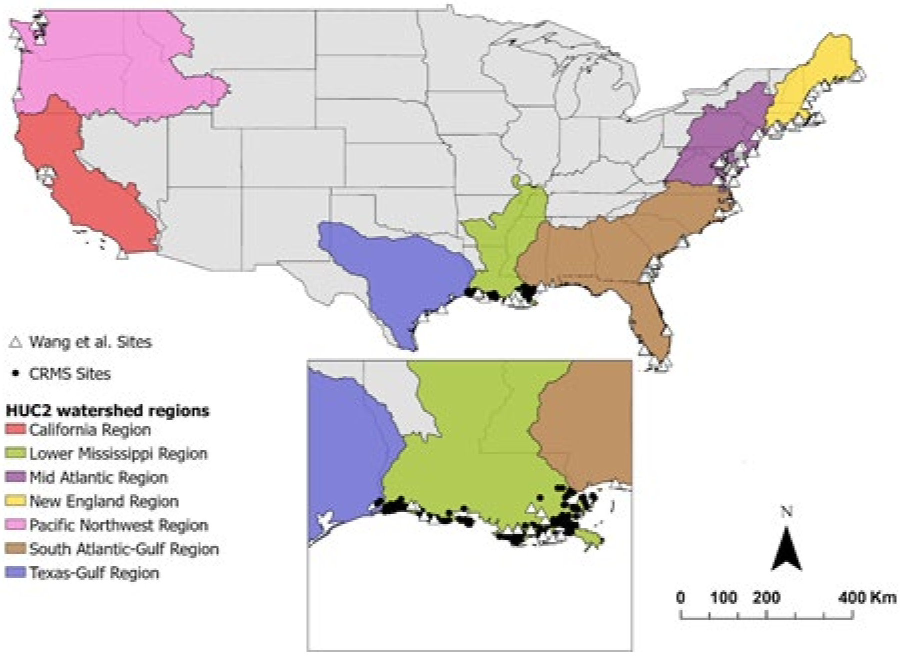

Fig. 1. Location of all carbon accumulation rate measurements used in the meta-analysis. Triangles represent measurement locations summarized in Wang et al. [15], black circles represent Louisiana Coastal Reference Monitoring System locations summarized in Jankowski et al.[27]. Regional boundaries follow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

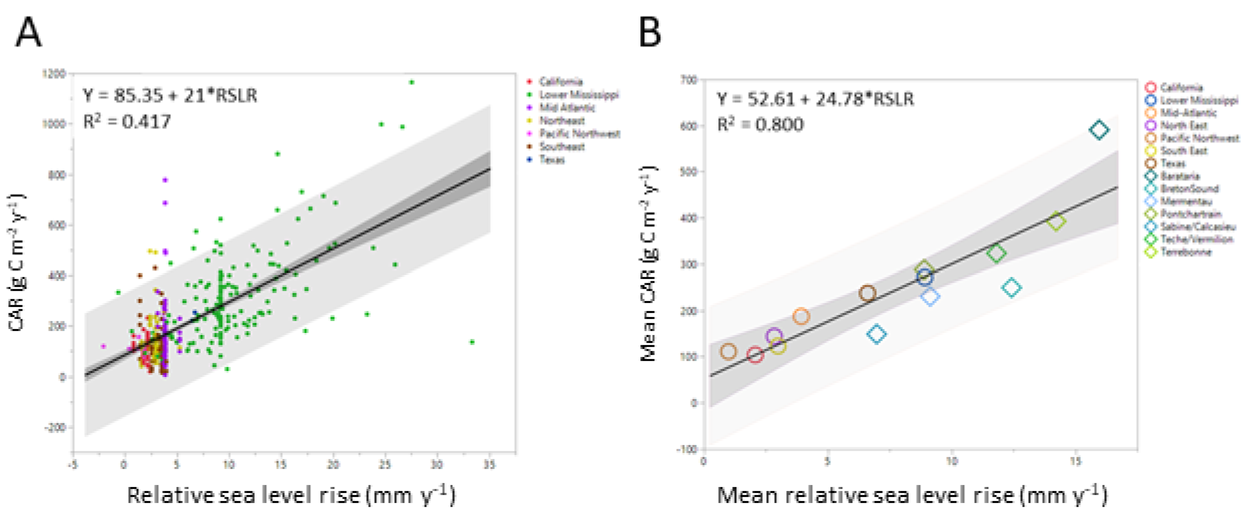

Fig. 2. Relationships between rates of carbon accumulation (CAR) and relative sea level rise (RSLR). In Figure 2A, each point represents an individual wetland (n=408) paired with the closest tide gauge record. RMSE: 123.7; $F(1,407) = 291.10$, $P < 0.0001$. In Figure 2B, all datapoints within a region are averaged to a mean value for both CAR and for RSLR. RMSE: 61.29; $F(1,12) = 48.03$, $P < 0.0001$. Climatic regions (n=7) from Wang et al.[15] are in colored circles, in coordination with Figure 1. Louisiana Basins (n=7) are displayed in a range of green diamonds. The two levels of grey shading illustrate the 95% confidence limit and the 95% prediction limit, respectively.

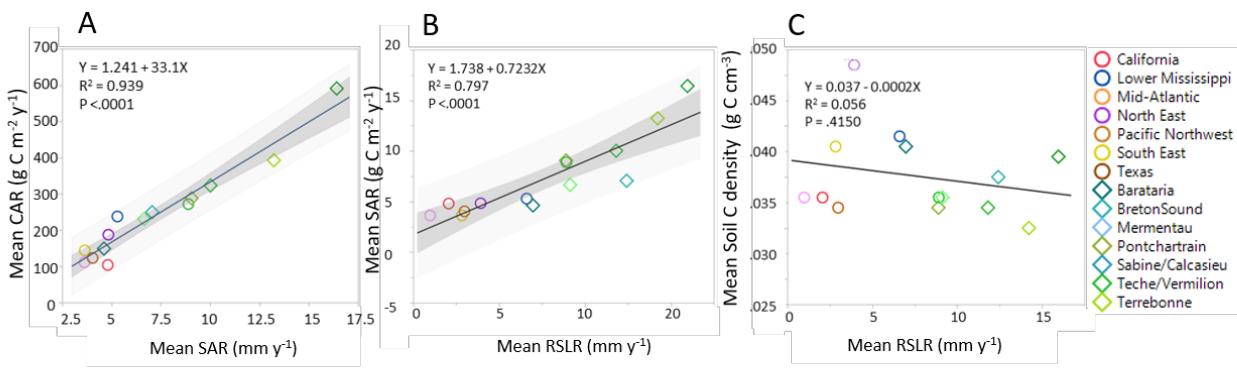

Fig. 3 Components of regional carbon accumulation rates. (A) Mean carbon accumulation rate (CAR) and soil accretion rate (SAR); RMSE = 33.87; $F(1,12) = 184.56$, $P < 0.0001$. (B) Soil accretion rate and relative sea level rise rate (RSLR); RMSE = 1.80; $F(1,12) = 47.19$, $P < 0.0001$. (C) soil carbon density (Cdens) and local RSLR; non-significant. Watershed-based regions from Wang et al 2019 are represented with 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 grey shading, which illustrate the 95% confidence limit and the 95% prediction limit, respectively.

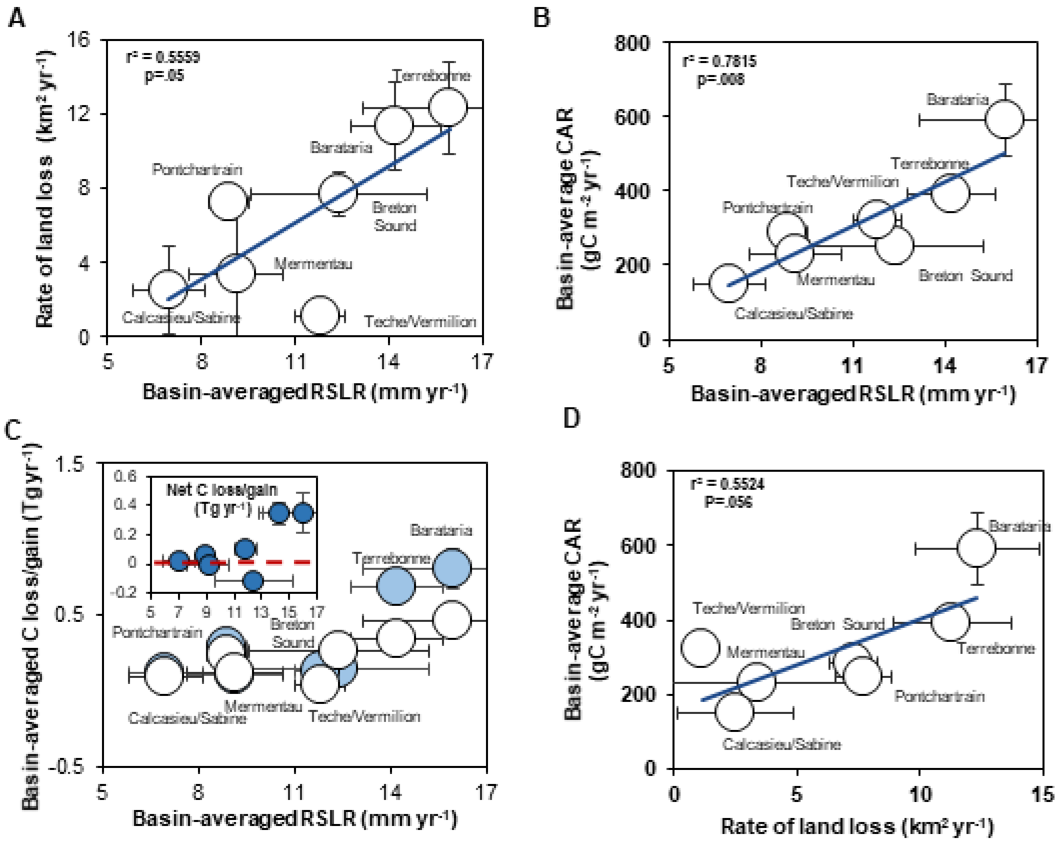

Fig. 4 Landscape carbon budgets for 7 coastal Louisiana basins shown in Figure S3. (A) The relationship between the basin-averaged RSLR rate (mm yr^{-1}) calculated from Jankowski et al. [27] and the rate of land loss (km^2 yr^{-1}) from 1985-2010 calculated by Couvillion et al[57]. (B) The relationship between the basin-averaged RSLR rate and the basin-average carbon accumulation rate (gC m^{-2} yr^{-1}) calculated in this study (Table 1). (C) Comparison of annualized basin-averaged carbon loss (white ○) and carbon gain (light blue ○). The inset is the net annual change in marsh carbon (dark blue ○), where the red line indicates no net change, positive numbers are net gains and negative numbers are net losses. (D) Relationship between basin-average carbon accumulation and land loss. In all cases, error bars = 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.[57]

Table 1. Calculations used to estimate annual change in Louisiana carbon pools due to marsh loss and increased CAR. Carbon gain was estimated by multiplying the basin-averaged carbon accumulation rate by the cumulative saline (salt and brackish marsh) marsh area in each basin based on 2007 vegetation maps (Sasser et al.[56] ; available at https://cims.coastal.louisiana.gov/). Carbon loss was estimated for one year as the annual area of land lost from 1985-2010 by Couvillion et al.[57] assuming a 1 meter deep soil column (following DeLaune and White[29]) and the basin-average 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: $t = \frac{Saline\ marsh\ area - \frac{Annual\ carbon\ loss}{Carbon\ accumulation\ rate}}{Annual\ land\ loss}$, assuming that neither the carbon accumulation rate nor the land loss rate changes through time.

Basin	**N**	**Basin-averaged RSLR (mm yr^{-1})**	**Vertical accum. rate (mm yr^{-1})**	**Carbon accum. rate (gC m^{-2} yr^{-1})**	**Saline Marsh Area (km^2)**	***Annual carbon accum. (TgC yr^{-1})***	**Annual land loss (km^2 yr^{-1})**	**Soil C density (gC m^{-3})**	***Annual carbon loss (TgC yr^{-1})***	***Net C Balance (TgC yr^{-1})***	***Time until carbon source (yr)***
Pontchartrain	19	8.9	9.1	288.1	1018	*0.29*	7.28	31800	*0.23*	*0.06*	*29*
Breton Sound	6	12.4	7.1	249.9	606	*0.15*	7.72	34694	*0.27*	*-0.12*	*N/A*
Barataria	29	16.0	16.4	590.7	1369	*0.81*	12.33	36937	*0.46*	*0.35*	*49*
Terrebonne	32	14.2	13.2	392.7	1754	*0.69*	11.32	30467	*0.34*	*0.34*	*77*
Teche/Vermilion	12	11.8	10.0	323.4	428	*0.14*	1.17	32152	*0.04*	*0.10*	*267*
Mermentau	16	9.1	6.7	230.9	483	*0.11*	3.37	33348	*0.11*	*-0.001*	*N/A*
Sabine/Calcasieu	17	7.0	4.6	149.1	796	*0.12*	2.51	38143	*0.10*	*0.02*	*61*