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LIMNOLOGY AND OCEANOGRAPHY
Letters

ASLO
Open Access

Limnology and Oceanography Letters 2022

doi: 10.1002/lol2.10230

LETTER

Reconciling models and measurements of marsh vulnerability to sea level rise

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Scientific Significance Statement

Accelerating sea level rise (SLR) and declining sediment supplies threaten coastal ecosystems around the globe. Coastal marshes are among the most valuable and vulnerable systems because they often must build vertically to avoid submergence by SLR. The fate of marshes under SLR is hotly debated: field measurements suggest imminent marsh submergence, whereas models predict survival at SLR rates exceeding 10 mm yr^{-1}. Here, we present novel measurements of suspended sediment concentrations and vertical accretion and a meta-analysis of measurements around the world to quantify the limits of wetland survival. We show that variability in two simple parameters (suspended sediment supply and tidal range) largely explains global patterns of wetland vulnerability and that numerical models and field measurements are not incongruous.

Abstract

Tidal marsh survival in the face of sea level rise (SLR) and declining sediment supply often depends on the ability of marshes to build soil vertically. However, numerical models typically predict survival under rates of SLR that far exceed field-based measurements of vertical accretion. Here, we combine novel measurements from seven U.S. Atlantic Coast marshes and data from 70 additional marshes from around the world to illustrate that—over continental scales—70% of variability in marsh accretion rates can be explained by suspended sediment concentratin (SSC) and spring tidal range (TR). Apparent discrepancies between models and measurements can be explained by differing responses in high marshes and low marshes, the latter of which accretes faster for a given SSC and TR. Together these results help bridge the gap between models and measurements, and reinforce the paradigm that sediment supply is the key determinant of wetland vulnerability at continental scales.

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Associate editor: Iris E. Hendriks

Author Contribution Statement: DJC led the manuscript effort, conducted the field work, and wrote the paper. MLK, GG, and DJC came up with the research question and designed the study approach. CGS analyzed and interpreted radioisotope data. MS conducted global-scale modeling. ST contributed to interpretation of the results. All authors participated in the editing process.

Data Availability Statement: Data are available in the Environmental Data Initiative at https://doi.org/10.6073/pasta/d3a96e0db54f4c66899e82e6641ab42b, http://doi.org/10.6073/pasta/79384be16d78e0d559b32d04ad567818, https://doi.org/10.6073/pasta/a886dc23d15dff38d0e31499d5a69f27, https://doi.org/10.6073/pasta/f1c1e6b2fd092c50fbe46dbe98b516cd, https://www.sciencebase.gov/catalog/item/6196be81d34eb622f691acbc

Additional Supporting Information may be found in the online version of this article.

Accelerating rates of sea level rise (SLR) threaten coastal landforms and ecosystems (Kirwan and Megonigal 2013). Wetlands build soil elevation by trapping allochthonous sediment and accumulating organic matter, which are processes that tend to increase under accelerating rates of SLR (Kirwan and Megonigal 2013). However, sediment delivery to the coast has significantly declined in many regions of the world (Wang et al. 2011; Weston 2014), meaning that wetlands are potentially receiving less allochthonous material to build soils at ever faster rates. Indeed, observations of wetland loss today (Crosby et al. 2016; Morris et al. 2016; Jankowski et al. 2017) and in the stratigraphic record (Saintilan et al. 2020; Törnqvist et al. 2020) indicate that there are limits to wetland accretion that must be quantified to predict how coastal ecosystems will respond to global change.

Wetland vulnerability is best characterized through spatially explicit metrics that incorporate both vertical and lateral responses (Marani et al., 2007; Kirwan et al. 2016; Ganju et al. 2017; Mariotti 2020; Holmquist et al. 2021). However, the maximum possible rate of vertical accretion commonly defines a threshold for wetland survival, beyond which SLR leads to wetland drowning. Estimates for threshold rates of SLR differ widely, especially between projections from numerical simulation models and empirical measurements. Numerical models often predict stability under relatively high future rates of SLR (e.g., 10–50 mm yr^{-1}; Kirwan et al. 2016; Schuerch et al. 2018), whereas contemporary field measurements suggest vulnerability at rates of SLR observed even today (<5 mm yr^{-1}; Jankowski et al. 2017; Morris et al. 2016; Crosby et al. 2016). Modeled threshold rates depend strongly on sediment supply and tidal range (TR, Kirwan and Guntenspergen 2010), suggesting that discrepancies between models and observations may partially be related to variability within and between marshes. However, under conditions that can be found on the U.S. Atlantic Coast estuaries (spring TR = 1 m; suspended sediment concentration = 30 mg L^{-1}), measurements of organic and inorganic contributions to soil accretion suggest drowning under SLR rates greater than $\sim$5 mm yr^{-1} (Morris et al. 2016), while an ensemble of numerical models predicts a threshold SLR rate twice as high (Kirwan and Guntenspergen 2010).

There are inherent advantages and disadvantages to using models and empirical measurements to predict the maximum rate of SLR that existing marshes can persst in place. Numerical models typically focus on basic feedbacks between inundation and sediment transport that allow projections of elevation building through time in response to changing environmental conditions (Fagherazzi et al. 2012; Kirwan et al. 2016). Yet, models are inherent simplifications of real-world process that often rely on basic treatment of vegetation, nonvolumetric sediment budgets, lack of spatial resolution, and sensitivity to poorly constrained parameters such as the concentration and settling velocity of suspended sediment (Wiberg et al. 2020; Törnqvist et al. 2021). Field measurements directly measure rates of vertical accretion influenced by a more complete suite of processes (DeLaune et al. 1978; Jankowski et al. 2017; Parkinson et al. 2017), but can be difficult to apply to other sites. Furthermore, accretion rates tend to increase with flooding depth and duration (Friedrichs and Perry 2001; Temmerman et al. 2003), making it difficult to project measurements based on current or historical conditions into a future characterized by faster SLR rates (Kirwan et al. 2016). Sediment records covering multiple millennia offer evidence of how wetlands responded to SLR rates faster than present rates (Horton et al. 2018; Saintilan et al. 2020; Törnqvist et al. 2020), but it remains unknown how other differences (e.g., atmospheric CO_2 concentrations) may have affected marsh response in the past.

Here, we attempt to bridge the gap between numerical models and field measurements by developing an empirical model of salt marsh vulnerability in the vertical dimension based on novel field measurements and a global meta-analysis of accretion and suspended sediment concentration (SSC). Our work finds that vertical accretion is fundamentally tied to SSC and spring TR, and that perceived differences between models and measurements can partially be explained by the difference between marsh elevation loss relative to sea level and marsh drowning.

Drivers of Vertical Accretion

We directly measured SSC and vertical accretion in seven tidal marshes spanning the eastern coast of the United States and one on the eastern coast of Australia (Fig. 1). In contrast to the traditional approach of quantifying SSC using bottle sampling (Christiansen et al. 2000; Leonard and Reed 2002; Wang et al. 2011; Moskalski and Sommerfield 2012; Ensign et al. 2017; Poirier et al. 2017), we measured SSC via optical back-scatter sensors every 15 min over seasonal to annual time scales and on the marsh platform rather than relying on discontinuous or channel-based measurements. Four of these sites were located within extremely low elevation, youthful marshes, evidenced by recent expansion or recovery from disturbance (labeled sites in Fig. 1B; Supporting Information S1; Coleman and Kirwan 2018, 2020, 2021a, 2021b). We selected low marshes as they are thought to have local maximum rates of vertical accretion because of a negative feedback between inundation, plant productivity, and sediment deposition (Kirwan et al. 2016; Morris et al. 2016). Therefore, maximum accretion rates measured in low marshes are considered here to represent the maximum SLR rates that marshes could keep up with by sediment accretion. To complement these measurements, we compiled vertical accretion and SSC data from the literature for 70 additional tidal marshes around the

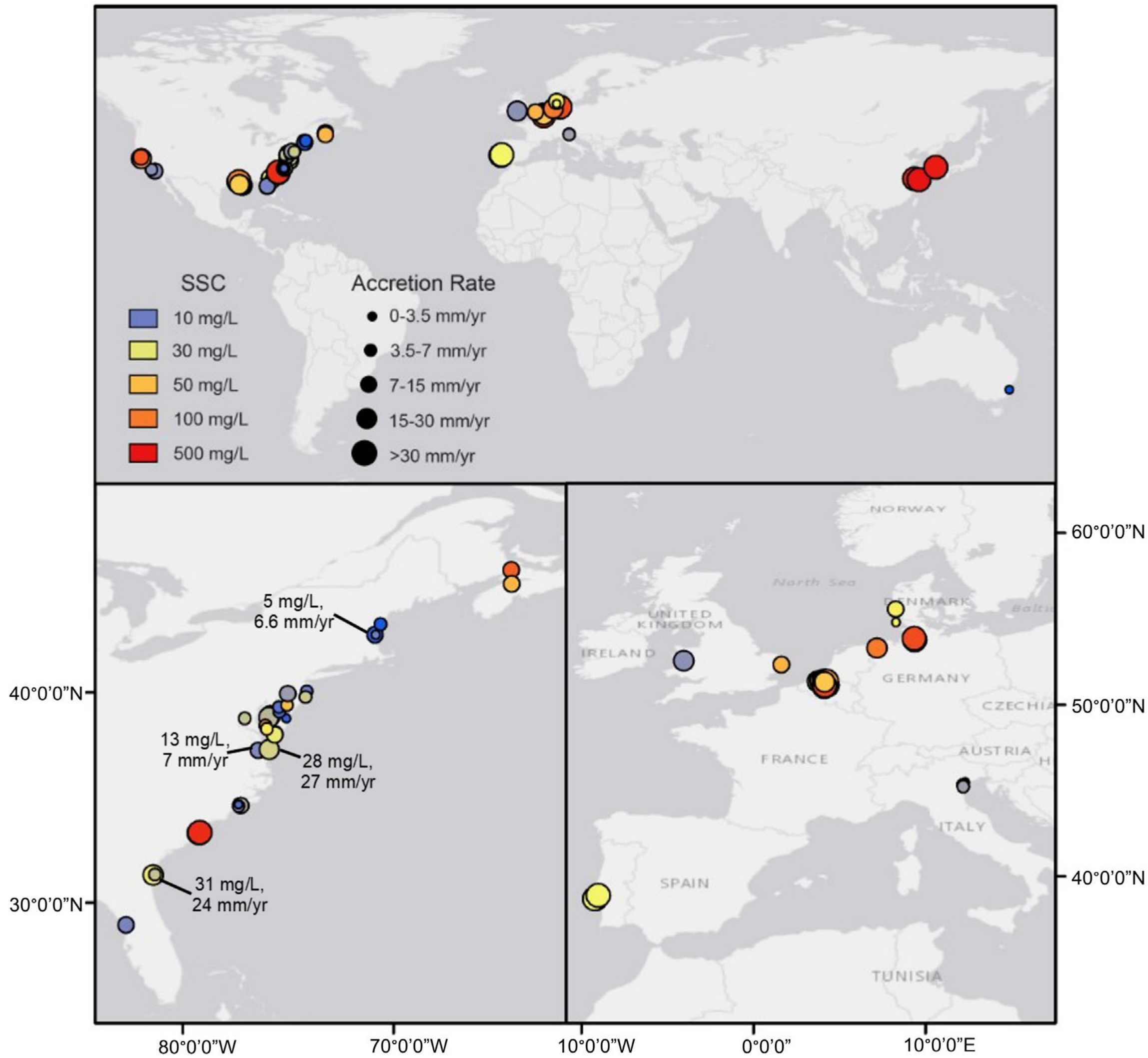


Fig 1. (**A**) Site map showing SSC and accretion rates of sites used in the meta-analysis. Warmer colors indicate higher SSC and reference values are displayed in the legend. Size of the circle represents accretion rate, with larger circles indicating greater accretion rates. (**B**) Magnified view of the east coast of North America with labels indicating SSC and accretion rate for the four low marsh monitoring sites and (**C**) Western Europe.

world, with the greatest concentration of sites in Europe (25 sites) and North America (47 sites; Fig. 1). In contrast to our direct field measurements, these sites varied widely in marsh elevation, TR, vegetation type, and the methodology used to measure accretion and SSC (Supporting Information Table S1). Therefore, our analyses include marshes across a wide range of environmental gradients; SSC ranged from approximately 5–30 mg L^{-1} and TR from 1.1 to 3.6 m in low marsh monitored sites, whereas the meta-analysis sites encompassed a wider variety of SSC (0.5–358 mg L^{-1}) and TR (0.3–12 m).

Combining measurements and literature data, we found that accretion rate is significantly related to SSC*TR (robust linear regression, $R^2 = 0.73$, $p < 0.001$; Fig. 2a). We determined a simple empirical model to describe this relationship (Supporting Information S2), defined as,

$$\text{Accretion} = C_1 * \text{SSC} * \text{TR}. \quad (1)$$

This equation is analogous to accretion rate (mm yr^{-1}) having a fixed proportional relationship (C_1 in mm L m^{-1} mg^{-1} yr^{-1}) to the sediment suspended (mg L^{-1}) in the flooding waters (m). We calculated $C_1 = 0.2212 \pm 0.008$ ($\pm$ SE) for all sites excluding five outliers (Supporting Information S2), which can be subdivided between $C_1 = 0.1624 \pm 0.0134$ for high marsh sites and $C_1 = 0.2250 \pm 0.0114$ for low marsh sites. The higher value of C_1 for low marshes is consistent with observations that frequently flooded marshes have higher rates of accretion

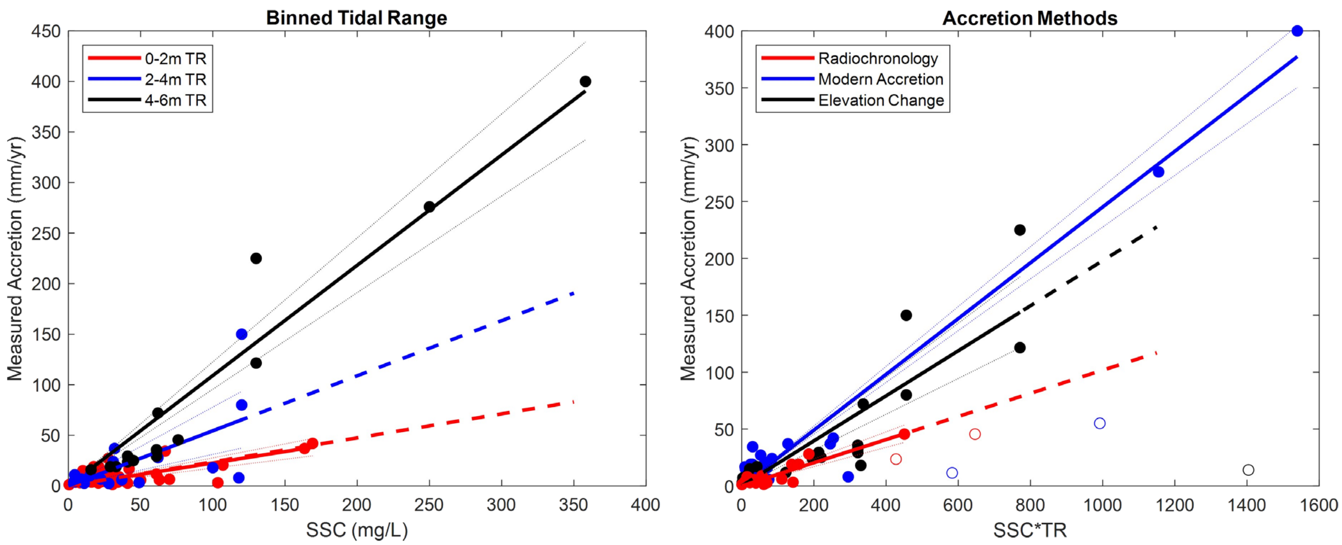


Fig 2. (**A**) Measured accretion rate is linearly positively related to suspended sediment concentration for a given tidal range (red $R^2 = 0.54$, blue $R^2 = 0.40$, black $R^2 = 0.91$). (**B**) Relationship between accretion, SSC, and TR is dependent on methodology, with radiochronology (red, $R^2 = 0.80$) having a significantly lower slope than modern accretion (blue, $R^2 = 0.96$) or elevation change (black, $R^2 = 0.72$). Dashed lines indicate data extrapolation and empty circles indicate the outliers removed from the fit.

(Fagherazzi et al. 2012; Kirwan et al. 2016). Furthermore, C_1 calculated for only the four low marsh sites that we directly measured is even larger, $C_1 = 0.3535 \pm 0.0587$, supporting our assumption that these extremely low marshes would have local maximum accretion rates. Interestingly, we found no significant difference between modern sedimentation measurements ($C_1 = 0.2452 \pm 0.009$) and modern elevation change measurements ($C_1 = 0.1980 \pm 0.019$). This suggests that shallow subsidence did not play a major and consistent role in the relationship between SSC * TR and accretion over regional-continental gradients, despite its potential impact at the site-specific level (Cahoon et al. 2006). Accretion rates derived from both short-term measurements and long-term radiochronology were linearly correlated with SSC * TR, though the slope from measurements that integrated over long time periods (decades-centuries) ($C_1 = 0.1014 \pm 0.008$) was less than that observed using modern accretion measurements (Fig. 2b). This difference could be attributed to either accretion rates that are accelerating in parallel with SLR (Kirwan and Temmerman 2009; Kolker et al. 2010) and/or the long-term effect of compaction and organic matter decomposition that are not fully expressed in short-term measurements (Breithaupt et al. 2018; Törnqvist et al. 2020).

Conceptual and numerical models often emphasize the role of mineral sediment supply in determining marsh vulnerability to SLR (Reed 1995; Mudd et al. 2004; FitzGerald et al. 2008; Kirwan and Guntenspergen 2010; Fagherazzi et al. 2012; Kirwan and Megonigal 2013), though attempts to demonstrate this in the field have been inconsistent. For example, many field studies do not find a relationship between average SSC and marsh accretion rates within a single study site (*see* Murphy and Voulgaris 2006; D'Alpaos and Marani 2016; Poirier et al. 2017; Palinkas and Engelhardt 2018; Duvall et al. 2019). Similarly, a relationship between TR and accretion rates is inconsistent (Kirwan and Guntenspergen 2010), with studies finding a positive relationship (Harrison and Bloom 1977; Stevenson et al. 1986), but others finding a negative relationship (Chmura and Hung 2004) or none at all (Cahoon et al. 2006; French 2006). In contrast, robust linear regression with all 77 of our marsh sites indicates that over 70% of the variability in accretion is explained by terms that directly relate to sediment deposition, that is, SSC and TR ($R^2 = 0.73$, $p < 0.001$; Fig. 2a). We suggest that the definitive role of physical processes becomes apparent only by considering SSC and TR together, and at regional to global spatial scales that encompass wider gradients in SSC and TR. Together, our results demonstrate the primary importance of sedimentation and support assumptions of numerical models that aim to predict accretion rates based largely on physical processes (Fagherazzi et al. 2012).

Nevertheless, our work also illustrates substantial variability in accretion rates that cannot be explained by physical factors such as SSC and TR alone. Our empirical model predicts accretion rates that are more than twice as high as measured rates in many locations. For example, the empirical model predicts that marshes in the German Wadden Sea (SSC = 34 mg L^{-1}, TR = 2 m; Schuerch et al. 2013) should have accretion rates of ~15 mm yr^{-1}, whereas measured rates are only 3.5 mm yr^{-1} (Schuerch et al. 2012). As discussed in the next section, we attribute this type of discrepancy to variability in the sampling locations on the marsh platform, where low marshes and those close to channels have higher accretion rates than high elevation marshes far from channels (this study; Friedrichs and Perry 2001; Temmerman et al. 2003). Variability in predicted accretion rates may also be attributed to the role of organic accretion, which is more important for vertical accretion than inorganic sedimentation under certain conditions (Turner et al. 2002; Morris et al. 2016). Dominance of organic accretion could explain measured rates that exceed predicted rates, especially in low SSC and TR environments (Fig. 2a).

Our focus on vertical accretion and SSC represents a common, but imperfect, approach to assessing wetland vulnerability. Volumetric sediment fluxes are potentially better metrics of wetland vulnerability, and its dependence on sediment supply, because they account for spatial gradients within marshes and the source of suspended sediment (Ganju et al. 2017; Törnqvist et al. 2021). SSC is a poor predicter of marsh vulnerability and sediment supply in systems where sediment cannot reach the interior of marshes (Coleman et al. 2020; Duran Vinent et al. 2021) and in systems with significant resuspension and edge erosion (Ganju et al. 2013). Nevertheless, volumetric sediment fluxes tend to increase consistently with SSC in a variety of U.S. marshes, suggesting the metrics are tightly linked (Ganju et al. 2017). Moreover, SSC and vertical accretion are the most widely reported field-based metrics, and form the basis for most numerical models (Fagherazzi et al. 2012). Despite the limitations noted above, our simplistic model represents a fundamental relationship between easily measured parameters (SSC and TR) and a physical process strongly associated with marsh survival (vertical accretion). Therefore, our work provides empirical support to the paradigm that autochthonous sediment availability drives wetland elevation change at the regional-global scale, while emphasizing that marsh vulnerability at any particular location will be influenced by a number of other factors that cannot be predicted with simple numerical models.

Comparison with numerical models

To understand potential differences between field measurements and numerical models, we used a previously published ensemble of five numerical models (Kirwan and Guntenspergen 2010) to predict the threshold rate of SLR that each marsh in our data set could survive given its site-specific SSC and TR. Following Schuerch et al. (2018), the ensemble model results can be summarized as,

$$\text{Threshold SLR} = a * \text{SSC} * \text{TR}^b + c, \tag{2}$$

where the constants a, b, and c equal 0.292, 0.915, and 1.5, respectively. The ensemble model indicates threshold SLR rates increase linearly with SSC for a given TR (Kirwan and Guntenspergen 2010), which is consistent with our empirical model. However, linear regression demonstrates that the ensemble model predicts threshold SLR rates that are higher than measured accretion rates when all high marshes are included (i.e., slope $m = 0.57$, $R^2 = 0.68$, $p < 0.001$ where $m = 1$ would indicate modeled threshold rates equivalent to measured accretion rates) (Fig. 3a). The analog comparison using only marshes reported as low elevation ($n = 41$) reveals that measured accretion rates in low elevation marshes are nearly identical to modeled threshold rates of SLR for a given SSC and TR (Fig. 3b; $m = 0.92$, $R^2 = 0.89$, $p < 0.001$).

These results illustrate a fundamental link between marsh elevation and vulnerability that may help reconcile field-based measurements of marsh accretion with numerical models of marsh survival. For example, a previous meta-analysis found that approximately 75% of marsh locations were accreting at rates less than the 7.4 mm yr^{-1} rate of SLR projected under the IPCC RCP6.0 scenario and concluded that those marshes would not survive (Crosby et al. 2016). These types of observations inspire concern that numerical models overestimate accretion rates compared to what has been measured, and therefore underestimate marsh vulnerability to SLR (Jankowski et al. 2017; Parkinson et al. 2017). Indeed, we find that across our global network of sites, 40% (31 of 77) of accretion measurements are less than 7.4 mm yr^{-1}. Yet measured accretion rates are not themselves an indicator of the threshold rate for marsh survival because accretion rates tend to increase with flooding depth and duration (Friedrichs and Perry 2001; Temmerman et al. 2003; Kirwan et al. 2016).

While a low marsh plant community that loses elevation relative to sea level is at risk of drowning, a high marsh plant community that loses elevation is at risk of first converting into a low marsh community, assuming this ecological transition is possible in the given system. This represents a key distinction, where *maintaining* elevation means that high marshes can persist as high marshes and *surviving* means that low marshes will not drown. When we restrict our analysis to low marsh sites, we find that less than 15% (6 of 41) of locations have accretion rates less than 7.4 mm yr^{-1}, and importantly, that measured low marsh accretion rates are similar to threshold rates of SLR predicted by numerical models for a given SSC and TR (Fig. 3b). These results are consistent with observations of increased marsh inundation under current SLR rates, evidenced by shifts toward more flood tolerant vegetation (Donnelly and Bertness 2001; Raposa et al. 2017), despite relatively few locations with extensive marsh drowning (Kirwan et al. 2016). Thus, our empirical analysis is consistent with numerical models that predict relatively high threshold SLR for marsh survival (i.e., low marsh accretion keeping pace with SLR), albeit with significant geomorphic and ecological changes.

Global analysis of critical SSC

We applied our empirical regression model (Eq. 1) to assess global tidal marsh vulnerability with the global Dynamic

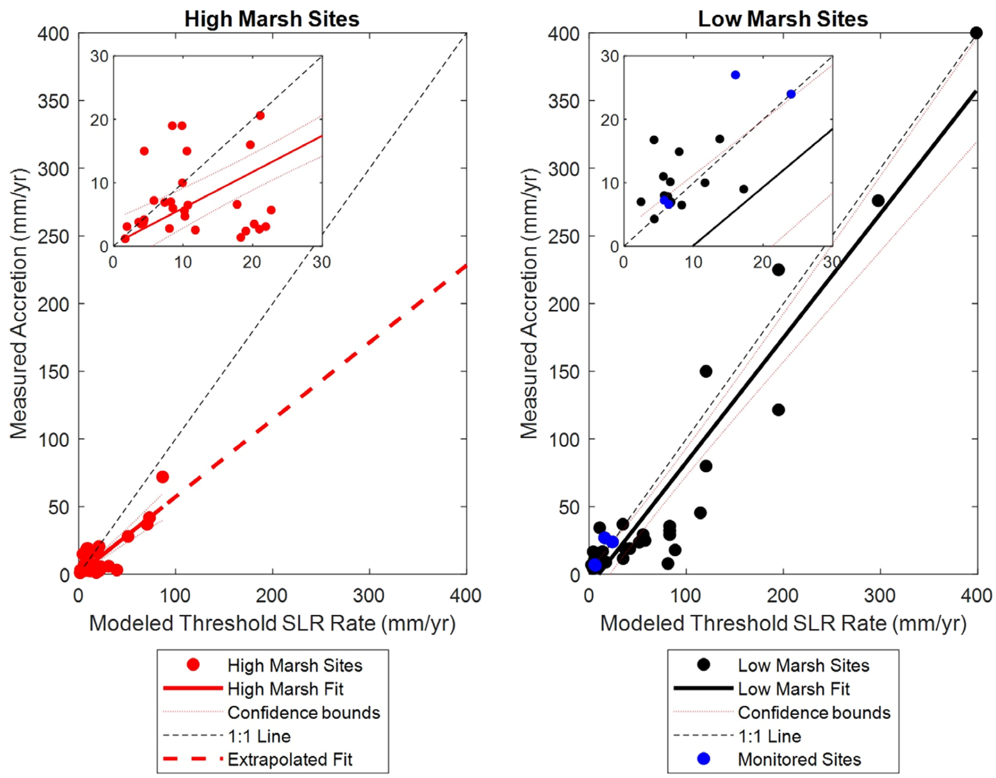
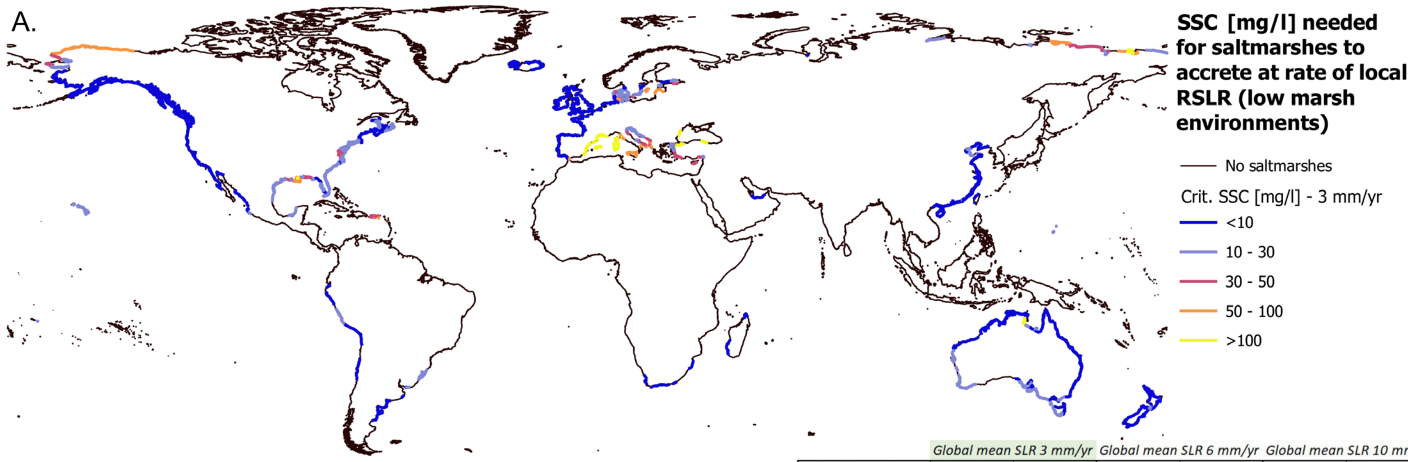


Fig 3. (**A**) Comparison of observed accretion rate with threshold SLR determined from the ensemble model for high marsh sites ($R^2 = 0.67$, $p < 0.01$). (**B**) Comparison of observed accretion rate with threshold SLR determined from the ensemble model for only sites that were reported as low marsh ($R^2 = 0.89$, $p < 0.01$). Blue points represent the four low marsh monitoring sites, and the insets are a magnified view of 0–30 mm yr^{-1}.

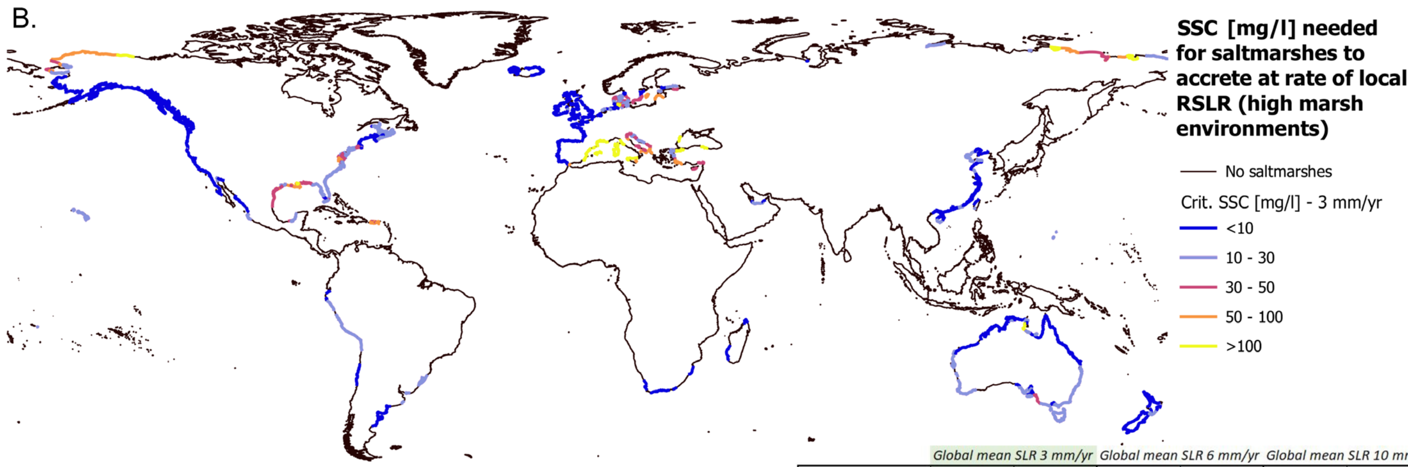
Interactive Vulnerability Assessment (DIVA) database of TR, SSC, and local relative SLR rates for coastal segments that contain marshes around the world (Spencer et al. 2016; Schuerch et al. 2018). We considered the critical SSC (SSC_{crit}) needed for marsh accretion, based on DIVA TR and relative SLR data (Eq. 1), and our empirical model coefficients that predict marsh accretion under these physical parameters. We calculated the SSC that would be required to produce accretion rates equal to the current RSLR rate using both empirical model coefficients, $C_1 = 0.1624$ (calculated from high marshes) and $C_1 = 0.2250$ (calculated from low marshes). We assume that the lower empirical model coefficient ($C_1 = 0.1624$) results in a SSC_{crit} required for the marsh to *maintain* its current elevation distribution of high and low marsh relative to SLR. Below this SSC_{crit}, high marshes become more inundated and are subject to vegetation shifts (i.e., shift toward more flood tolerant species). In contrast, we assume the higher coefficient ($C_1 = 0.2250$) predicts the SSC_{crit} for marshes to *survive* SLR, below which the entire marsh will drown (i.e., convert to open water). If a system has a SSC below the SSC_{crit} for maintenance of elevation but higher than the SSC_{crit} for survival, we would expect any high marsh to convert to low marsh and then for the low marsh to persist into the future.

Evaluation of SSC_{crit} reveals three distinct behaviors related to the maintenance of current marsh elevation and the long-term survival of marshes (Fig. 4). First, there are locations where SSC exceeds both the SSC_{crit} required to maintain elevation and the $SSC_{crit}$to survive SLR. This behavior is illustrated by marshes in Great Britain, where high TRs and low relative SLR rates lead to SSC_{crit} of less than 10 mg L^{-1}. Estimated SSC in this region are at least four times greater than the predicted critical concentrations, and many locations have recently experienced substantial marsh expansion (Ladd et al. 2019). A second behavior is when sediment supply is insufficient to maintain elevation or to survive. The low TR of western Mediterranean marshes results in SSC_{crit} greater than 100 mg L^{-1} under both empirical model conditions. Previous work indicates low SSC in the region and large-scale wetland loss that is consistent with our empirical model predictions (Ibáñez et al. 2010; Day et al. 2011). Finally, the vulnerability mapping reveals a number of locations where SSC is likely lower than the SSC_{crit} to maintain relative elevation, but higher than the SSC_{crit} required to survive. This behavior is consistent with marshes in the Northeastern United States, where accretion deficits are ultimately leading to increasing dominance of flood tolerant vegetation (Donnelly and Bertness 2001; Raposa et al. 2017), but marshes are surviving



SSCcrit = RSLR / (0.2250 x Spring Tidal Range)

Crit. SSC range [mg/l]		Global mean SLR 3 mm/yr: Global area [km2]	Fraction [%]	Global mean SLR 6 mm/yr: Global area [km2]	Fraction [%]	Global mean SLR 10 mm/yr: Global area [km2]	Fraction [%]
-394	10	27,486	50	16,138	30	6,207	11
10	30	13,167	24	18,315	34	9,341	17
30	50	6,279	11	10,533	19	7,835	14
50	100	6,302	12	5,736	10	7,916	14
100	27828	1,428	3	3,940	7	23,363	43



SSCcrit = RSLR / (0.1624 x Spring Tidal Range)

Crit. SSC range [mg/l]		Global mean SLR 3 mm/yr: Global area [km2]	Fraction [%]	Global mean SLR 6 mm/yr: Global area [km2]	Fraction [%]	Global mean SLR 10 mm/yr: Global area [km2]	Fraction [%]
-546	10	24,569	45	12,970	24	1,571	3
10	30	10,930	20	15,560	28	10,903	20
30	50	7,734	14	6,438	12	6,029	11
50	100	9,283	17	11,560	21	8,683	16
100	38555	2,146	4	8,134	15	27,477	50

Fig 4. (**A**) World map indicating critical suspended sediment concentration (SSCcrit) needed for (**A**) low marshes to survive, or not drown and (**B**) high marshes to maintain current elevation. Colored segments indicate coastlines where marshes are found.

SLR because accretion rates accelerate with inundation duration (Kolker et al. 2010; Wilson et al. 2014).

To explore the effect of SLR on marsh vulnerability, we calculated the percentage of global marsh area that would require SSC greater than a reference value under different scenarios of accelerated SLR. Like our previous analyses, we consider both the SSC_{crit} needed to maintain marshes at their current elevation, and the SSC_{crit} needed for marshes to survive. We use 30 mg L^{-1} as a reference value as the median SSC of our data set is 33 mg L^{-1} and the average SSC for U.S. coastal rivers is 30.3 mg L^{-1} (Weston 2014). We find that approximately 35% of global marsh area requires SSC > 30 mg L^{-1} to maintain elevation under the current rate of eustatic SLR (3 mm yr^{-1}), and that the percentage increases to 77% at SLR rates of 10 mm yr^{-1} (Fig. 4a). However, to survive current SLR (3 mm yr^{-1}) only 26% of global marsh area requires SSC > 30 mg L^{-1}, increasing to 71% at high rates of SLR (10 mm yr^{-1}) (Fig. 4b). This suggests there may be considerable marsh area that can survive current SLR by converting from high marsh to low marsh (i.e., not maintaining elevation). This area decreases at higher SLR, where marsh survival requires substantially higher SSC. While many other factors (e.g., organic accretion, shallow subsidence) influence local marsh survival, measured accretion rates in low marshes are consistent with modeled threshold rates of SLR for a given TR and SSC (Fig. 3b). Together, these results help bridge the gap between numerical models and field measurements, and suggest that threshold rates of SLR can be predicted primarily by physical factors at the regional to global scale.

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Acknowledgments

This work was funded by the U.S. Geological Survey Land Change Science Climate R&D Program. Additional funding was provided through The National Science Foundation (NSF) Graduate Research Fellowship Program, NSF LTER #1832221, NSF EAR-CAREER #1654374, NSF EAR-GLD #1529245, and NSF OCE-SEES #1426981. GRG acknowledges support from the U.S. Geological Survey Ecosystems Mission Area. The authors would like to thank the many researchers who provided valuable data, including W. Wagner, D. von Proosdij, C. Lovelock, K. Rogers, C. Ladd, and J. Raw. We would also like to thank J. Green, D. Walters, J. Himmelstein, D. Nicks, R. Walker, T. Messershmidt, N. Schieder, and the staff of the PIE LTER, GCE LTER, VCR LTER, and CB NERR for their assistance in data collection. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. This is contribution no. 4061 of the Virginia Institute of Marine Science.

Submitted 06 May 2021
Revised 16 November 2021
Accepted 17 November 2021