COASTAL ECOLOGY

Constraints on the adjustment of tidal marshes to accelerating sea level rise

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Much uncertainty exists about the vulnerability of valuable tidal marsh ecosystems to relative sea level rise. Previous assessments of resilience to sea level rise, to which marshes can adjust by sediment accretion and elevation gain, revealed contrasting results, depending on contemporary or Holocene geological data. By analyzing globally distributed contemporary data, we found that marsh sediment accretion increases in parity with sea level rise, seemingly confirming previously claimed marsh resilience. However, subsidence of the substrate shows a nonlinear increase with accretion. As a result, marsh elevation gain is constrained in relation to sea level rise, and deficits emerge that are consistent with Holocene observations of tidal marsh vulnerability.

Tidal marshes are among the most vulnerable of the world's ecosystems. Throughout human civilization, tidal marshes have been reclaimed for agriculture and settlement, and the pace of loss has accelerated in concert with burgeoning coastal populations on all inhabited continents over the past century (*1*, *2*). To this pressure has been added the threat of accelerating sea level rise. Because tidal marshes occur within tightly defined elevation ranges relative to mean sea level, they are sentinel ecosystems at the forefront of coastal climate change impact. Potential tidal marsh loss with sea level rise threatens a range of ecosystem services valued at US ~$27 trillion per year (*3*), extending to fisheries production, recreation, cultural heritage, coastal protection, water quality enhancement, and carbon sequestration.

Sea level rise can lead to marsh loss through marsh edge erosion, conversion to mudflats, encroachment of mangrove forests where they occupy lower tidal position, and/or the expansion of internal ponds and channels, with all mechanisms enhanced by the loss of marsh surface elevation relative to mean tide level (*4*). The fate of tidal marshes under accelerating sea level rise will be determined not only by opportunities for landward marsh migration (*5*) but also by the capacity of tidal marshes to gain elevation through vertical accretion of mineral sediment and organic matter (*6*). Biophysical feedbacks between sea level rise and the vertical development of marsh substrates reduce the risk of loss occurring through conversion to unvegetated mudflats or open water (*7*).

Modeling based on observations from US East Coast organic marshes (*8*) and UK minerogenic marshes (*9*) has suggested that an equilibrium may emerge among the position of a marsh within the tidal frame, plant productivity, root mass development, sedimentation, and the elevation of the marsh in response to mean sea level (Fig. 1). This equilibrium may be sustained under low rates of relative sea level rise (RSLR), the combination of vertical land movement and sea level change. How widely these controls and their upper limits operate across marsh sites globally has been a crucial and disputed question in the regional- to global-scale modeling of tidal marsh responses to projected rates of RSLR under climate change (*5*, *7*, *10*). At present, observations of contemporary marsh accretion suggest that marshes can adjust to rates of RSLR of >10 mm year^{-1} (*7*, *11*, *12*). However, the Holocene marsh record suggests that adjustment is highly unlikely (90% probability) at RSLR exceeding 7 mm year^{-1} for UK tidal marshes (*13*) and tropical mangroves (*10*), and 3 to 5 mm year^{-1} for marshes in the Gulf of Mexico (*14*). Here, we report on contemporary tidal marsh elevation gain in relation to RSLR, testing the importance of environmental conditions in mediating these responses.

Several factors may influence the efficacy of tidal marsh vertical adjustment to sea level rise, but their relative contributions to explaining observed regional to global variability in marsh responses remain poorly elucidated. Globally, tidal range in marshes can vary from a few centimeters to 16 m, and this variability will influence the susceptibility of marshes to drowning, particularly where the tidal range is low relative to the projected RSLR (*12*, *15*). The position within the tidal frame influences the depth and duration of inundation and the deposition of sediment, but it also influences mineral and organic accretion responses of the marsh vegetation occurring at these specific positions (*8*, *9*). Tidal hydrodynamics and river discharge contribute to sediment delivery and accumulation (*15*), and these may be modified by flow control structures (*16*). Plant productivity is influenced by climate (precipitation and temperature), salinity, nutrients (*17*), atmospheric CO$_2$, and vegetation composition, which in turn influence soil organic carbon accumulation and decomposition. The rate of RSLR varies between coastlines and continents, and millennial-scale variability in RSLR may also control soil organic content, which may increase with sea level rise when conditions are favorable (*18*). Sampling at regional to global scales across hydrogeomorphic settings and biogeographic regions can clarify the relative importance of these factors and determine the consistency of feedbacks facilitating marsh adjustment to RSLR.

Accurate measurements of tidal marsh vertical adjustment in relation to sea level require a fixed benchmark against which elevation gain or loss can be measured. To this end, the surface elevation table–marker horizon (SET-MH) method has been developed as a global standard (*19*) for monitoring tidal marsh responses to RSLR (Fig. 1). A rod is driven into the marsh to form a stable benchmark against which elevation change can be measured. Vertical accretion (the surface accumulation of inorganic sediment, organic sediment, and living roots) is also measured at most sites above an artificial marker horizon (typically white feldspar, clay, or sand) introduced at the time of the first measurements against the

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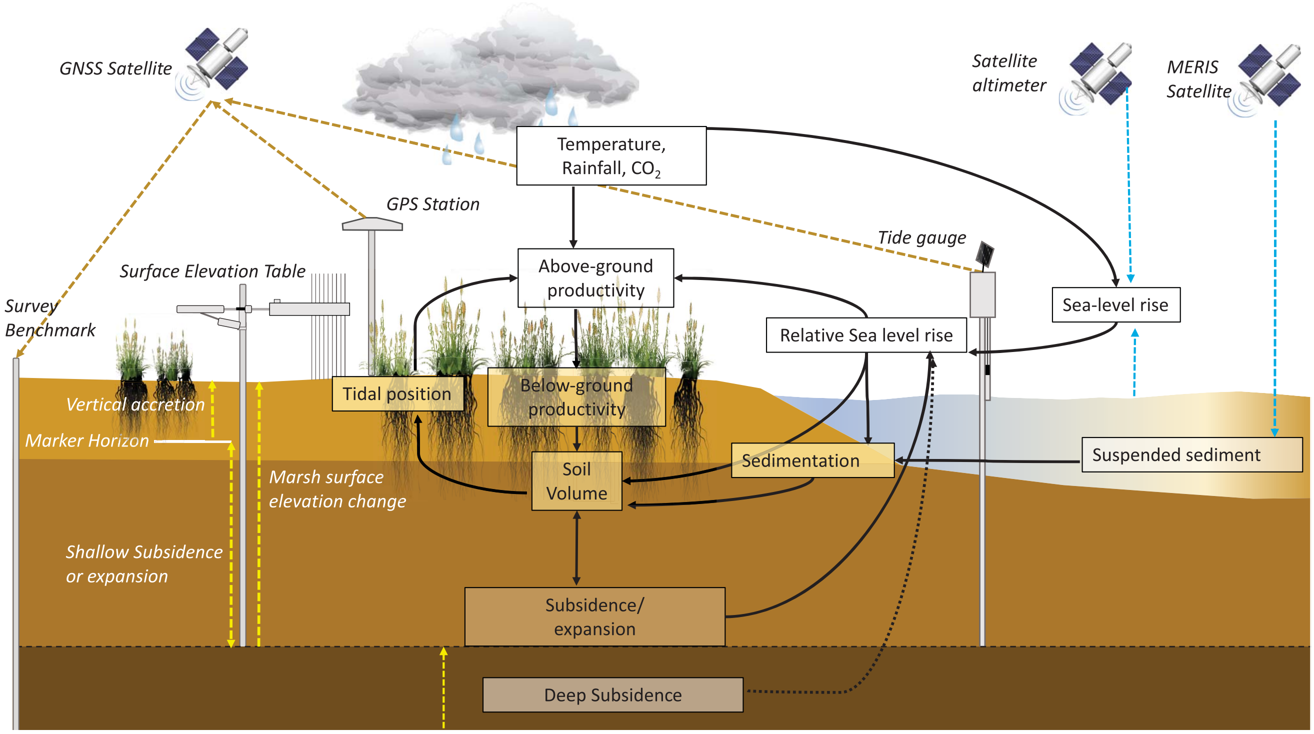

Fig. 1. Processes influencing marsh surface elevation and their measurement using the surface elevation table–marker horizon (SET-MH) monitoring station. Feedbacks among sea level rise, vertical accretion, and elevation gain are conceptualized as driving marsh substrates toward an equilibrium elevation within the tidal frame, facilitated by inputs of mineral and organic matter. The SET-MH method measures soil elevation relative to a benchmark (to which the portable component of the SET is attached), while a tide gauge records the combined effect of changes in sea level and land movement occurring below the survey benchmark rod, to which the gauge is routinely leveled. This combined recording of eustatic sea level (ocean volume) change and deep land movement is termed relative sea level rise (RSLR) and does not include processes measured by the SET-MH method. GNSS, Global Navigation Satellite System; MERIS, Medium Resolution Imaging Spectrometer.

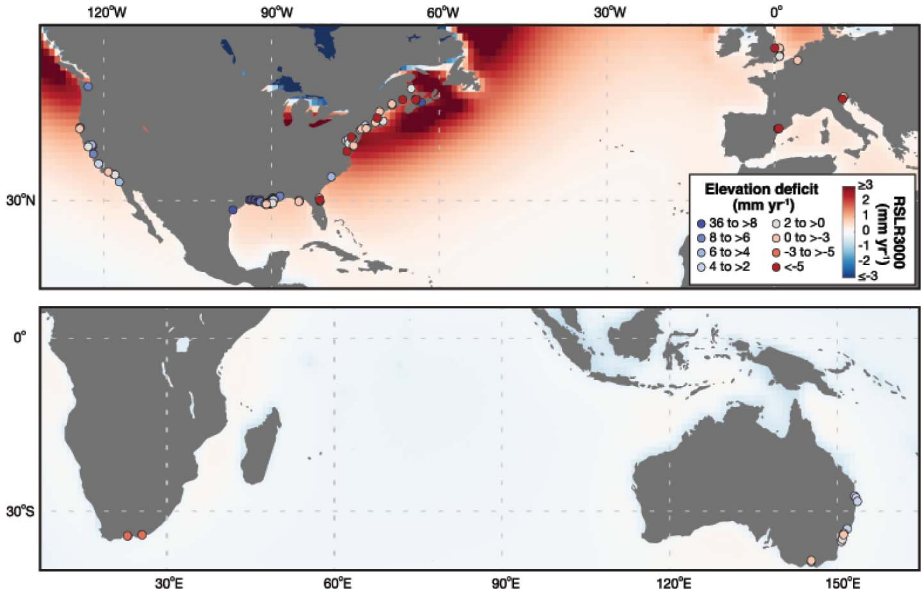

Fig. 2. Distribution of tidal marsh SET-MH monitoring stations used in the analyses, and deficit between elevation gain and contemporaneous local RSLR. Deficits are assigned positive numbers. The background of late Holocene (0 to 3000 years B.P.) RSLR is derived from glacio-isostatic modeling (*20*).

benchmark (*20*). Data from SET-MH stations have informed models of marsh resilience to RSLR (*7*, *12*), global projections of tidal marsh and mangrove change in the coming century (*5*, *21*, *22*), and the influence of vertical accretion on carbon sequestration (*23*, *24*).

We analyzed tidal marsh elevation adjustment in relation to RSLR from SET-MH monitoring stations that met our criteria of emergent tidal marsh vegetation, sufficient length of record (>3 years), and exclusion from hydrological or experimental manipulation. The resulting network of 477 tidal marsh SET-MH stations, across 97 sites, forms clusters in regions with distinct hydrogeomorphic histories and tidal and biogeographic characteristics thought to be important to marsh resilience (Fig. 2). In general, Southern Hemisphere stations (Australia and South Africa) are in estuaries subject to millennia of stable or falling sea levels, with micro- to mesotidal marshes on high, stable intertidal platforms typically low in percentage of soil organic carbon (table S1 and data S1). North Atlantic coastlines (Bay of Fundy, Canada; UK; Belgium) are predominantly macrotidal, have been subject until recently to relatively stable (< ±0.5 mm year^{-1}) or falling sea levels over the past few thousand years, have low soil organic carbon content, and are situated adjacent to waters with high total suspended matter. Coastlines in the network that are subject to low rates of sea level rise over the past few millennia include two large river deltas with a microtidal regime (the Mississippi, USA; the Ebro, Spain) and microtidal to mesotidal barrier estuaries and embayments (Venice Lagoon, Southern California; the US Gulf of Mexico chenier plains and estuaries).

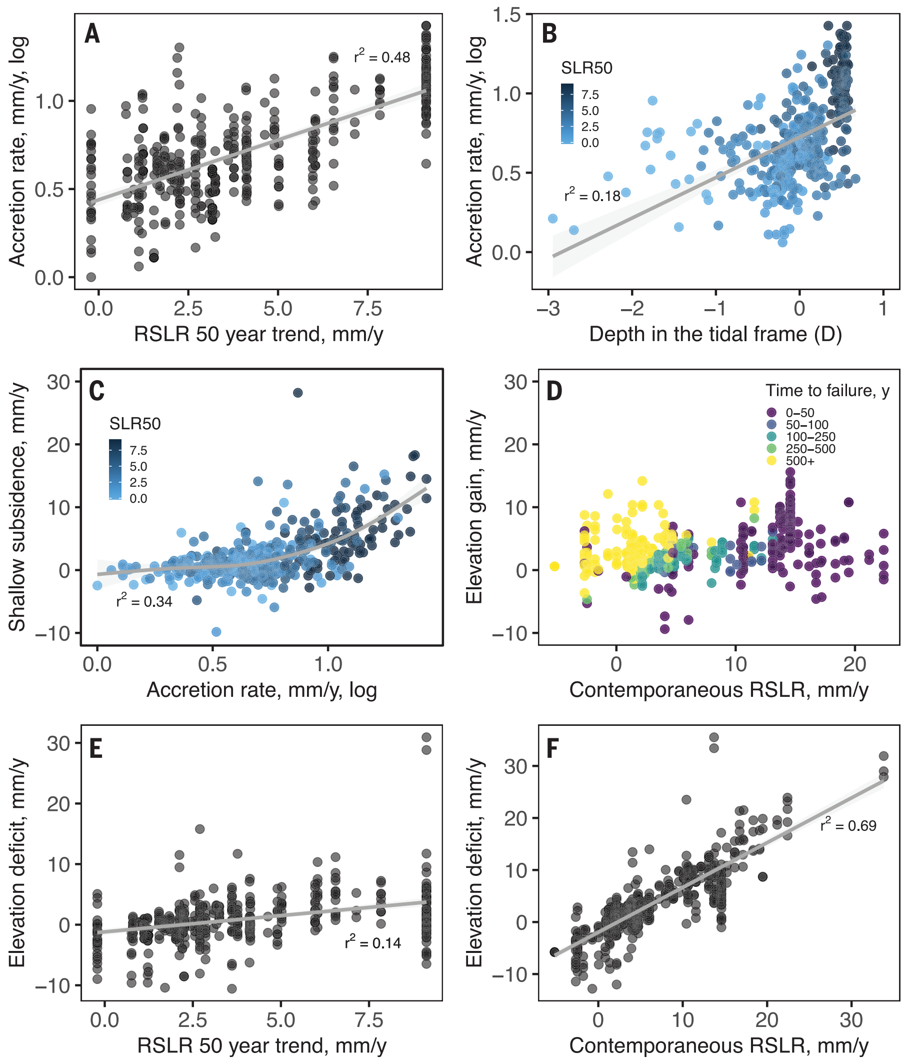

Fig. 3. The increasing vulnerability of tidal marshes to RSLR. (**A** and **B**) Accretion increases in parity with the 50-year RSLR trend (A) and with marshes lower in the tidal frame (B). (**C** and **D**) However, the rate of shallow marsh subsidence increases with the rate of vertical accretion, with an upward inflexion as RSLR increases between 5 and 10 mm year^{-1} (C), suppressing elevation adjustment to RSLR (D). (**E** and **F**) As a result, the deficit between elevation gain and RSLR increases with the 50-year RSLR trend (E) and the contemporaneous RSLR trend, the period over which individual SET-MH stations were measured (F). In (B) and (C), points are colored for the 50-year RSLR trend in mm year^{-1}, and in (D) for estimated time to failure (years) under the elevation deficit against the 50-year RSLR trend (*20*).

The US Atlantic and North Pacific coastlines have been subject to relatively high rates of RSLR for several millennia, forming organic-rich marshes situated within barrier and embayment geomorphic settings. Contemporary RSLR varies between coastlines as a result of vertical land movement and climate variability (*25*), with relatively high rates of RSLR occurring in the Gulf of Mexico, the US North Atlantic, and parts of the North Pacific coasts and lower RSLR in most European and Southern Hemisphere sites (data S1).

This variability in RSLR allowed us to identify RSLR influences on marsh surface elevation change, and on mechanisms driving the latter, including vertical accretion and shallow subsidence. SET-MH stations were monitored for an average of 10.1 years (range: 3.5 to 20.0 years) over periods for which RSLR at nearest tide gauges (hereafter "contemporaneous" RSLR: $\bar{x} = 6.81 \pm 6.41$ mm year^{-1}) was significantly higher than both the 50-year average ($\bar{x} = 3.75 \pm 2.73$ mm year^{-1}; $P < 0.001$) and the 3000-year average derived from glacio-isostatic modeling (*20*) ($\bar{x} = 0.65 \pm 0.72$ mm year^{-1}; $P < 0.001$). This range of RSLR values encompassed rates associated with marsh retreat in the Holocene stratigraphic record (*10*, *13*, *14*). We therefore tested three hypotheses concerning the feedback among RSLR, vertical accretion, and elevation gain: (i) The rate of vertical accretion would increase with RSLR; (ii) the rate of vertical accretion would correspond to sediment availability; and (iii) vertical accretion would correspond to marsh elevation gain. We determined the extent to which these relationships are influenced by climatic, environmental, and edaphic conditions (table S2), including soil bulk density and organic carbon.

The most important predictor of the rate of vertical accretion at a global scale was the 50-year RSLR trend ($r^2 = 0.48$, $P < 0.0001$). The observation of vertical accretion parity with increased RSLR aligns with the predictions of feedback models suggesting marsh resilience to RSLR (*7*, *8*, *12*), although the relationship was stronger in organic than in minerogenic marshes (fig. S1). Marsh accretion across the network was higher at sites that are lower in the tidal frame [Fig. 3B; as measured by dimensionless *D* (*20*), an indicator of submergence (*26*), $P < 0.0001$]. Annual average suspended matter in adjacent waters explained less than 10% of global-scale variability in vertical accretion (fig. S2), and the incorporation of tidal range as an additional variable [as has recently been suggested (*12*)] did not improve the prediction of the rate of vertical accretion (linear regression $r^2 = 0.03$; $n = 410$) or the r^2 [typically <0.01 for low marshes (i.e., $D > 0$; $n = 168$)], contrary to model projections (*5*, *7*, *12*). Vertical accretion on marsh surfaces in settings of low total suspended matter suggests an important role for accretion of autochthonous sediment (i.e., organic and/or locally resuspended mineral matter). One caveat is that satellite-derived measures of suspended matter may not represent sediment concentrations at the point of deposition, particularly in channelized estuarine settings. However, hydrogeomorphic setting was also not strongly predictive of the rate of vertical accretion (fig. S2).

Although vertical accretion was the most important control on surface elevation gain at the global scale ($r^2 = 0.3$; fig. S2), shallow subsidence mediates the relationship between vertical accretion and surface elevation gain (*27*, *28*) (Fig. 1 and Fig. 3C). Shallow subsidence was greater under higher accretion rates ($r^2 = 0.34$, $P < 0.0001$; Fig. 3C and fig. S3) and higher contemporaneous and 50-year RSLR ($r^2 = 0.16$, $P < 0.0001$; fig. S3). As a result, on average less than half of the sediment accreted above marker horizons translated into surface elevation gain, and this proportion decreased between 5 mm year^{-1} and 10 mm year^{-1} of contemporaneous RSLR ($P < 0.0001$). The deficit between surface elevation gain and RSLR trend increased linearly with RSLR in all settings (Fig. 3, E and F), as did the proportion of SET-MH monitoring stations subject to an elevation deficit (Fig. 4).

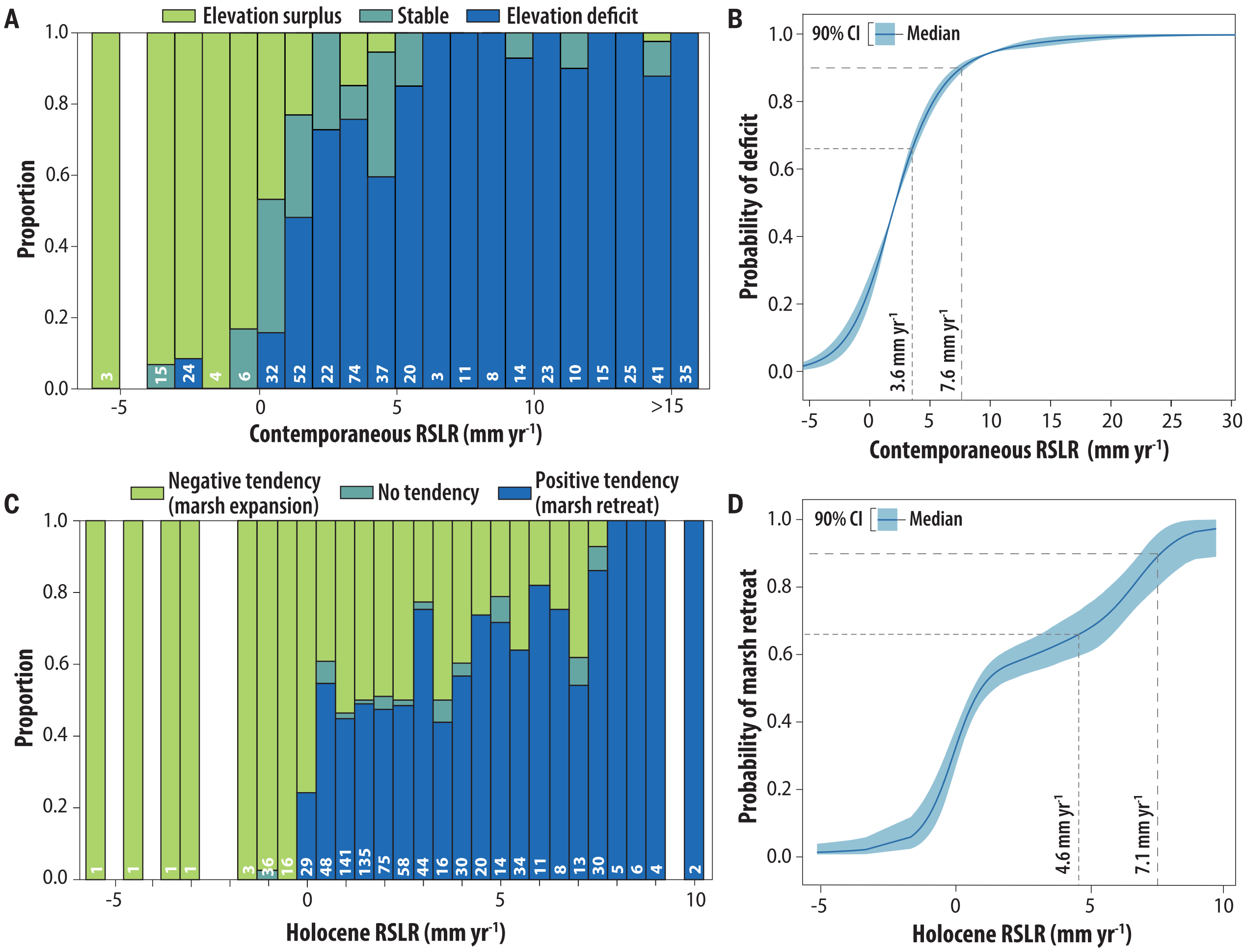

Fig. 4. Rates of relative sea level rise and marsh responses in the observational and paleo record. (**A**) Histogram of SET-MH monitoring stations showing elevation deficit, elevation surplus, and stability (parity) with contemporaneous RSLR. (**B**) Modeled probability of an elevation deficit with different rates of RSLR. (**C**) Histogram of paleo-marsh index points showing positive, negative, and no tendency in relation to RSLR in UK Holocene marshes (*13*). (**D**) Modeled probability of positive sea level tendency (i.e., sinking within the tidal frame) associated with different rates of Holocene RSLR. Numbers of observations for each RSLR increment are shown at the base of each column.

Marshes in the SET-MH network transition from a predominance of elevation surplus to elevation deficit over a similar range of RSLR, as has been historically observed in UK Holocene marshes (Fig. 4), which provide a record that is unique for the number of index points associated with a range of RSLR histories (*13*). Contemporary observations from the tidal marsh SET-MH network, which accounts for shallow subsidence, were therefore consistent with observations of tidal marsh and mangrove behavior during periods of relatively rapid sea level rise in the Holocene record (*10*, *13*, *14*, *22*). Cumulative probabilities based on Bayesian modeling using the SET-MH record suggest that a drowning trajectory is likely (66% probability) at 3.6 mm year^{-1} and 4.6 mm year^{-1} in UK Holocene marshes and very likely (90% probability) at 7.6 mm year^{-1} in the SET-MH record and 7.1 mm year^{-1} in UK Holocene marshes (*13*) (Fig. 4). Although several sites in the US Gulf and Atlantic coastlines had a contemporary rate of elevation gain exceeding 8 mm year^{-1}, these same sites had the lowest median projected time to open-water conversion, as estimated by the time to reach minimum survival elevation (*20*) (table S5). The elevation subsidy provided by their proximity to eroding shorelines (fig. S4) may represent laterally migrating levees (*29*), a precursor to marsh failure (table S4 and fig. S5).

In locations where sea level has been stable (<±0.5 mm year^{-1}) or falling over recent millennia (i.e., the macrotidal marshes of the North Atlantic and the Southern Hemisphere Australian and South African marshes), soil organic carbon concentrations were significantly lower (on average less than half) relative to marshes subject to millennial-scale RSLR ($P < 0.0001$; table S1 and fig. S6). Gradually rising sea levels can both promote and preserve highly organic marshes (*18*, *30*) by increasing plant productivity, increasing organic carbon burial, reducing oxidation, and slowing decomposition. At a global scale, the proportion of organic carbon in accreting sediments across our network was better explained by the 3000-year RSLR trend (r^2 = 0.23; $P < 0.0001$) than by contemporaneous RSLR (r^2 = 0.07; $P < 0.0001$; fig. S6). Sites with higher bulk density and lower percent organic carbon had lower rates of subsidence (table S1 and fig. S1) and a higher proportion of vertical accretion contributing to elevation gain, consistent with predictions (*9*). In these locations, shorelines were relatively stable and the proportion of vegetated to unvegetated marsh cover (*20*) was high (table S1).

The mechanisms promoting tidal marsh adjustment under low rates of sea level rise appear less effective under high rates of sea level rise. The substrates undergoing marsh elevation gain are increasingly subject to autocompaction and subsidence under increased accretion and inundation depth. The elevation response is nonlinear, and above a primary breakpoint between 5 and 10 mm year^{-1} of vertical accretion, a higher proportional loss to subsidence constrains elevation adjustment in response to accelerating RSLR. This observation reconciles the instrumental record with probabilities of tidal marsh adjustment emerging from paleostratigraphic records during phases of high RSLR during the Holocene. Both datasets suggest a low likelihood ($P < 0.1$) that tidal marshes will be retained in situ under global average rates of RSLR attained by mid-century under high-emissions scenarios, and by the end of the century under midrange-emissions scenarios (*25*). These rates of RSLR are already reached in subsiding deltas occupied by tidal marshes. Under these circumstances, tidal marsh survival will increasingly depend on their upland migration.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Figs. S1 to S6
Tables S1 to S5
References (*31*–*65*)
Data S1

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Science

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Will marshes rise up or sink?

Marsh ecosystems are vulnerable to rising sea level, in addition to land-use change and other human activities. Studies have shown that some marshes are gaining elevation, making them remarkably resilient to rising seas; however, results vary across locations and between contemporary and Holocene records. Comparing data from 97 sites on four continents, Saintilan *et al*. found that the relationship between sediment accretion and marsh subsidence explains the variable responses to sea-level rise. Marshes accrete more sediment, keeping up with sea-level rise up to a point, but sediment subsidence increases nonlinearly with accretion such that at higher rates of sea-level rise, marshes begin to sink. Marshes are unlikely to keep up with rising seas under current climate change projections. —BEL

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