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Overestimation of marsh vulnerability to sea level rise

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Abstract

Coastal marshes are considered to be among the most valuable and vulnerable ecosystems on Earth, where the imminent loss of ecosystem services is a feared consequence of sea level rise. However, we show with a meta-analysis that global measurements of marsh elevation change indicate that marshes are generally building at rates similar to or exceeding historical sea level rise, and that process-based models predict survival under a wide range of future sea level scenarios. We argue that marsh vulnerability tends to be overstated because assessment methods often fail to consider biophysical feedback processes known to accelerate soil building with sea level rise, and the potential for marshes to migrate inland.

For more than 30 years, observations of marsh loss have inspired widespread concern over their ability to survive sea level rise (SLR)1–6. Large-scale marsh loss is globally distributed, with prominent examples found in the Mississippi River Delta4, Chesapeake Bay7, Venice Lagoon8, Yellow Sea9 and the coast of China10. Regional and global assessments predict that SLR alone will lead to a 20–50% loss of marshland by the end of the current century11–14. Marshes buffer coasts from storms, sequester carbon, improve water quality and provide important habitat for commercial fisheries15–18. SLR represents a critical threat to these ecosystem services19,20, which are valued at more than US$10,000 per hectare15,21.

Marshes occur at the interface of land and sea, and their size depends on their ability to build vertically at rates greater than relative SLR, or else to migrate inland at rates faster than erosion at their seaward boundary. In the vertical dimension, mineral sediment deposition rates tend to increase with flooding duration and the rate of SLR22–29, and, similarly in the horizontal dimension, inland migration rates may also increase with the rate of SLR30. Although excessive flooding affects vegetation survival and can trigger marsh collapse, the productivity of several marsh plant species tends to increase with moderate increases in flooding duration31,32. Organic matter production contributes directly to soil building33,34, whereas a denser vegetation canopy attenuates tidal flow and waves, leading to enhanced trapping of mineral sediment35 and reduced erosion rates18,36,37. Together, these eco-geomorphic interactions allow marshes to adapt to SLR31,38, but also produce interesting thresholds and multiple stable states that make prediction of future sustainability difficult39–44.

In contrast to widespread perceptions of marshes as a fragile ecosystem, and landscape models that predict large losses of marshes due to future SLR, current inventories indicate that the total area of US Atlantic and Pacific salt marshes was stable between 2004 and 200945. Moreover, preliminary syntheses suggest that marshes worldwide are generally building in elevation at rates similar to or exceeding the rate of historical SLR46,47 (additional summary data presented below), and dynamic process-based models predict marshes will survive in place under relatively fast rates of SLR (>10 mm yr−1) where sediment delivery to the coast is not restricted by dams41,47,48. Here, we argue that SLR over the next few decades is not an immediate, catastrophic threat to many marshes. Rather, common assessment methods underestimate marsh resilience by not fully accounting for feedbacks that lead to increasing accretion rates with SLR, or the potential for marshes to migrate inland.

Historical marsh stability

Catastrophic predictions of marsh loss in response to future SLR are difficult to defend on the basis of observed marsh responses to historical SLR. Many of today’s marshes formed during a period of moderate SLR 4,000 years ago; sea levels have risen by more than 2 m since then, and rates of SLR have approximately tripled in response to climate warming beginning in the late nineteenth century49–51. Although more flood-tolerant vegetation has invaded high-elevation marshes52, widespread reports of complete marsh loss (that is, conversion to open water) are rare. The most prominent examples of conversion to open water are in locations such as the Mississippi River Delta and Venice Lagoon, where humans have reduced sediment supply and/or amplified subsidence rates6, which makes it difficult to attribute their loss directly to climate-related SLR.

We analysed rates of accretion and elevation change from marshes on the Gulf and Atlantic coasts of North America and Europe by combining, refining and adding to three previous compilations13,46,47. Estimates of elevation change refer to repeated measurements of marsh surface elevation relative to a stable benchmark depth determined with a sediment elevation table (SET), and accretion represents the thickness of sediment above a marker horizon of known age (MH), or determined through radiometric dating46. For each marsh location, we examined the original literature to determine the methodology used and the duration of measurement, and to determine whether a site could be classified as ‘low marsh’ or ‘high marsh’ (that is, low or high in elevation relative to local mean sea level). Low marsh and high marsh were distinguished largely based on plant species composition, where the presence of species such as tall form *Spartina alterniflora*, *Spartina anglica* and *Schoenoplectus americanus* indicated low marsh, and species such as short form *S. alterniflora*, *Spartina patens*, *Distichlis spicata*, *Limonium* sp. and *Salicornia* sp. indicated high marsh. Duplicate measurements, accretion rates determined from radiocarbon analysis and SET-MH rates based on measurements of less than a duration of three years were removed from the dataset. For each site, we compared accretion and elevation change rates to historic SLR rates from the nearest National Oceanic and Atmospheric Administration (NOAA) tide gauge53 or from rates reported in the primary literature (for European sites). If a site was located at an equal distance between two NOAA tide gauges, the average of the historic sea level rates was used. Because of errors associated with elevation and accretion measurements, the dependence of sea level rates on the period of record, and a tendency for short-term marsh accretion rates to fluctuate around historical SLR rates, we considered a marsh to be in the process of submerging if its accretion deficit (elevation or accretion rate minus SLR rate) was greater than 0.5 mm yr−1.

We located 179 unique measurements of accretion or elevation change from the US, Canada, the UK, France and Spain. Simple comparisons with the local rate of historic SLR indicate that 26 of 140 sites are submerging on the basis of measured accretion rates, and that 14 of 39 sites are submerging on the basis of measured elevation change (Fig. 1a). Conventional interpretation of our meta-analysis would therefore suggest that 19–36% of sampled Atlantic coast marshes are submerging. That such a large percentage of marshes are already in the process of submerging in response to historical SLR would certainly be alarming, and fully consistent with catastrophic predictions of ecosystem service loss under future, accelerated SLR.

Simple comparisons between rates of SLR and measured accretion or elevation change have long been the standard for evaluating marsh vulnerability1,2,4,46,54, but this does not adequately characterize the fate of marshes because eco-geomorphic feedbacks tend to increase rates of organic and mineral sediment accumulation as marshes become progressively more flooded27,29,31,32. Our meta-analysis suggests that the mean rate of elevation change for high-elevation marshes is 3.0 mm yr−1, and 6.9 mm yr−1 for low-elevation marshes (Fig. 1b). These average rates are similar to those reported in an earlier synthesis5, and demonstrate two well-established links between marsh elevation change and SLR. First, the high marsh accretion rate is similar to the historical rate of global SLR because marshes build vertically towards an equilibrium elevation high in the tidal frame, where infrequent flooding limits accretion rates to the rate of SLR (Fig. 1c)55. Therefore rates from this portion of the landscape have little relevance to predicting the ability of a marsh to survive accelerating SLR. Second, the meta-analysis indicates that accretion rates could more than double during the transition from high to low marsh, suggesting a strong ability to survive accelerations in SLR. Therefore, a more meaningful assessment of wetland vulnerability should focus on lower elevation portions of marshes that best represent the more frequently flooded conditions expected under future SLR. When we restrict our analysis to accretion measurements made in locations that could be clearly identified as low marsh, we find that less than 5% (2 of 41) of the marshes in the dataset are submerging (Fig. 1a,d).

Analyses based on accretion rather than elevation change may overestimate resilience to SLR because they do not include shallow subsidence and compaction56. However, the two metrics are similar in our database (Fig. 1b), and measurements of elevation change reveal only one additional submerging low marsh site (see Supplementary Information). These comparisons are simplistic, and based on haphazardly distributed studies that do not reflect the actual geographic distribution of marshes. For example, most of the marshes included in our database are from the Atlantic Coast of North America and dominated by *S. patens* or *S. alterniflora*. Although roughly 50% of Atlantic and Gulf Coast marshes in the US are located along the Gulf Coast, only about 10% of accretion estimates in our dataset are from the Gulf Coast. Nevertheless, the meta-analysis demonstrates that the overwhelming majority of sampled Atlantic marshes are building at rates similar to or greater than the rate of SLR, and that assessments based on high marsh accretion rates will overstate the vulnerability of marshes to SLR.

Static landscape models overestimate sea level impacts

Marshes may be vulnerable to faster rates of SLR in the future, even though they have been largely stable in the past. Until very recently57–60, numerical models of marsh evolution generally followed two distinct approaches. Managers and policymakers often rely on large-scale, spatially explicit landscape models to make site-specific predictions (discussed below). These models feature a static topography, or one that evolves at a constant historical rate of elevation change, and do not typically incorporate the eco-geomorphic feedbacks between flooding, vegetation and elevation change that allow marshes to adapt to changes in sea level. Meanwhile, the academic community developed dynamic process-based models that do focus on eco-geomorphic feedbacks, but without making the site-specific predictions that are necessary to inform management decisions (discussed in the next section).

The most basic landscape models assess tidal marsh vulnerability by projecting SLR onto a static topographic representation of the coast, and assume that the landscape does not adjust to SLR. This approach leads to inevitable marsh drowning through time, and predictions that most tidal wetlands will be inundated by the end of the current century61–64. For example, these 'bathtub-style' models predict that 100% of wetlands on a portion of the Yangtze River Delta would be lost with just 0.48 m of SLR62, and that 1 m SLR would lead to a 68% loss of coastal wetlands in 86 developing countries around the world64. More advanced models assume a topographic landscape that evolves at a constant rate of elevation change based on historical measurements. The Sea Level Affecting Marshes Model (SLAMM) is the most prominent example, and has been widely used to inform land managers about coastal wetland vulnerability to SLR14,65–69. In particular, the US Fish and Wildlife Service has used SLAMM to identify SLR threats for 136 coastal National Wildlife Refuge (NWR) sites, where results are used to improve land management and land acquisition decision making70.

A critical shortcoming of SLAMM and other similar landscape models is that they do not simulate the dynamic eco-geomorphic feedbacks that allow marshes to adapt to SLR by accelerating rates of elevation change. Although some recent simulations do incorporate accelerating accretion69, more typical applications assigned temporally constant rates of elevation change based on measured historic trends14. As a result, SLAMM simulations predict catastrophic wetland loss (Fig. 2). For example, in the Chesapeake Bay region (USA), SLAMM modelling predicts an 83% loss of brackish marsh area by 2100 for a 69 cm increase in sea level, and a virtual disappearance of coastal wetland habitat for a 1.5 m increase in sea level66. At the Swanquarter NWR (North Carolina, USA), SLAMM simulations predict conversion of 60% of salt and brackish marshes to tidal flat and open water under 1 m SLR, and near-complete loss under more rapid scenarios71. These results are surprising given that marshland at Swanquarter has actually expanded slightly since 193872. More generally, these catastrophic predictions are difficult to defend on the basis of observations of historical wetland stability (identified in Fig. 1a), migrating marshland in some portions of the mid-Atlantic30 and unchanging total acreage of salt marshes on the Atlantic Coast45.

The disparity between historical stability and catastrophic predictions can probably be explained by the inability of most landscape models to capture non-linear, ecogeomorphic feedbacks that are known to allow marshes to adapt to changes in sea level. The meta-analysis discussed above highlights that the transition from high to low marsh vegetation could more than double rates of vertical accretion (Fig. 1b). For low marsh alone, models based on historical accretion rates will tend to overestimate marsh vulnerability because accretion rates generally increase non-linearly as SLR rates accelerate27. For example, the catastrophic loss of salt marsh predicted by SLAMM simulations of the Georgia Coast is driven by changes in flooding depth that are likely to have been overestimated14,73. There, a dynamic accretion model that incorporates a positive relationship between flooding and accretion predicts that twenty-first-century SLR will lead to a marsh surface that builds at a rate 2–3 times greater than historical rates73. Although landscape models driven by site-specific, constant historical accretion rates result in more realistic evolution of the land surface than static landscape models, neither approach captures the adaptability of wetlands in the vertical dimension through dynamic feedbacks, and both approaches will thus overestimate marsh vulnerability to SLR.

Dynamic models predict marsh survival

A crucial process that should be included in models of marsh response to SLR is the dynamic, eco-geomorphic feedbacks between tidal inundation and increased vertical accretion of mineral and organic sediments. In general, increased tidal inundation promotes more frequent and longer episodes of mineral sediment settling on the marsh platform, enhanced vegetation growth and faster rates of organic matter accumulation29,31,35,32. This feedback results in accretion rates that have accelerated in parallel with historical SLR27, and therefore differs fundamentally from the assumption of a temporally constant rate of marsh accretion used in many landscape models. Dynamic models of marsh vertical accretion account for these nonlinear feedbacks between increased tidal inundation (due to SLR) and increased rates of mineral and organic sediment accretion41,74.

An ensemble of five dynamic accretion models indicates that marshes generally survive relative SLR rates of up to 10–50 mm yr−1, consistent with the observations of stability shown in Fig. 1, but drown at higher rates41. This modelling demonstrates that the range of threshold SLR rates largely depends on the suspended sediment concentration in the water that floods the marsh system, and on the local tidal range (Fig. 3a). Marshes fail to survive SLR rates of just a few mm per year only where the available suspended sediment concentrations are very low (1–10 mg l−1) or where tidal range is just a few decimetres. By inference, interior marshland far from sediment sources is more vulnerable to sea level rise than marsh edges23,24,74,75. Where suspended sediment concentrations are larger than 30 mg l−1 and tidal range exceeds 1 m, the models predict that marshes can adapt to fast relative SLR rates of several centimetres per year41,47.

More recent dynamic modelling confirms the strong ability of marshes to adapt to SLR by feedbacks between inundation and sediment accretion, and their dependency on suspended sediment availability57–60,76. For example, San Francisco bay marshes were predicted to survive moderate to high rates of relative SLR (about 50 to 100 cm) over the next century60, although shifts from high to low marsh habitat may be expected59,60. Large-scale marsh loss was only predicted under assumptions of very high SLR rates (165 and 180 cm over the century) and reduced suspended sediment concentrations (25 mg l−1)57,60. For a marsh in the German Wadden Sea (tidal range ~2 m; suspended sediment concentration ~20–50 mg l−1), modelling revealed that the marsh would survive a threshold SLR rate of 19–22 mm yr−1 until 210076. In summary, dynamic models of marsh vertical accretion indicate that marshes will generally survive relative SLR rates of 10–50 mm yr−1 during the twenty-first century, depending on tidal range and suspended sediment availability (Fig. 3a).

Projections of global eustatic SLR for the twenty-first century predict that SLR rates will gradually accelerate, starting from a present-day rate of 3.7 mm yr−1 to a range of possible rates of up to more than 20 mm yr−1 by 2100 (Fig. 3b). Following the latest IPCC projections77, process-based models predict a probable range from around 0.30 to 0.80 m of eustatic SLR by 2100, corresponding to a range of SLR rates from 2 to 17 mm yr−1 by 2100. Semi-empirical models predict a higher range, between 0.40 and 1.60 m of eustatic SLR by 2100 (8–23 mm yr−1)78. The likelihood of different scenarios is difficult to assess. Actual emissions continue to track high-end ‘business-as-usual’ scenarios79, and process-based IPCC projections have been shown to underestimate contemporary SLR rates80. In addition, the rapid SLR scenarios in the semi-empirical projections are deemed by the IPCC as having low confidence because of physical limitations on the contribution of ice melt to sea level77. SLR projections beyond 2100 have a high uncertainty range and are not further considered in this paper.

The threshold relative SLR rates for marsh survival predicted by dynamic marsh accretion models (generally ranging between 10 to 50 mm yr−1)41 partially overlap with twenty-first century projections of SLR rates (ranging up to 23 mm yr−1 by 2100; Fig. 3b). The dynamic marsh models highlight that marshes in estuaries with very low tidal range (<1 m) and suspended sediment concentrations (<20 mg l−1) will be vulnerable to middle-of-the-road IPCC sea level scenarios, whereas marshes in more favourable conditions may survive even the highest semi-empirical sea level scenarios except in areas with very rapid subsidence. Discerning the likelihood of different sea level scenarios is beyond the scope of this Perspective. Nevertheless, these dynamic vertical accretion models suggest that many marshes will survive in place for the majority of emission and sea level scenarios considered by the IPCC, and that the most rapid scenarios of SLR will not exceed thresholds for marsh survival for several decades.

Although existing vertical marsh accretion models include the important feedback mechanism between accelerating SLR and increased sediment accretion, they do not yet include feedbacks between marsh vertical accretion and other aspects of climate change that may even further enhance the adaptability of coastal marshes to SLR. In particular, the models do not include the influence of elevated atmospheric CO2 concentrations and warmer temperatures on enhanced marsh vegetation productivity, which has been experimentally demonstrated to further increase vertical accretion rates34, and therefore will be likely to increase the threshold SLR rate for marsh survival. Coastal storm events, which may increase in intensity with ongoing climate change81, are known to be important contributors to suspended sediment supply and marsh accretion in otherwise sediment-poor systems (for example, ref. 82). Increasing storm activity would further increase threshold SLR rates for marsh survival76. Therefore, even the most robust vertical accretion models may underestimate the potential for marshes to adapt to SLR.

Point-based assessments ignore migration into uplands

Comparison between rates of elevation change and rates of SLR has been the dominant approach for assessing marsh vulnerability for more than 30 years. This focus on the vertical survival of marshes is expressed in a long-standing tradition of many field-based studies that rely on measured accretion rates2,4,46,54, expert panel assessments that rely on such comparisons13, and point-based numerical models of elevation change (for example, ref. 41). Yet, marsh size is fundamentally determined by the difference between rates of marsh loss due to vertical drowning and lateral erosion, and rates of lateral marsh creation by seaward and landward expansion. Recent modelling indicates that these lateral dynamics are especially important as salt marshes tend to be resistant along the vertical direction but intrinsically fragile along the lateral direction44,83.

With accelerated SLR and reduced sediment inputs to the coastal ocean84,85, it may be expected that salt marshes are becoming less able to expand seawards, except at locations near rivers with large sediment loads42,86. Therefore, a primary mechanism for marsh survival is transgression into adjacent uplands. Marsh migration is already occurring in low-lying areas, where saline intrusion driven by SLR triggers forest dieback and causes agricultural losses87–91 (Fig. 4). Historical maps, aerial photographs and satellite imagery indicate that this transgression has been significant at regional scales over the past century87,90. These studies suggest that the rate of marsh migration is largely controlled by the topographic slope of adjacent uplands, but perhaps punctuated by storms that allow salt tolerant vegetation to replace large swaths of dying trees at the forest–marsh boundary30,72,87.

Topographic data and landscape-scale numerical models suggest that transgression of marshes into adjacent uplands may allow marshes to survive, or even expand, in response to future SLR. In areas where boundary deterioration of salt marshes seems to be the dominant erosive process, typical lateral erosion rates are on the order of 1 m yr−1 or less92. Although rates of marsh transgression have rarely been measured, they may occur at similar rates (0.5–6.8 m yr−1)30,90,91 (Fig. 4a). Preliminary model simulations from a coupled model of marsh erosion, accretion and migration suggest that gently sloping uplands favour net marsh expansion (migration > erosion) (Fig. 4c), whereas steeply sloping uplands favour marsh contraction (erosion > migration) (Fig. 4d)93. Historical sea level rise has led to net marsh expansion in a portion of the Florida Gulf coast90, and topographic projections across the Eastern Gulf of Mexico coast suggest that up to 440 km2 of marshes and mangroves could be created in adjacent uplands for just a 0.2 m rise in sea level89. High-resolution topographic data from a portion of the Texas Gulf Coast shows that a mild increase in sea level promotes net expansion of salt marshes and associated ecosystem services, due to migration of marsh vegetation upland94. Preliminary analysis of topographic data indicates that 11,000 km2 of uplands in the continental US could be inundated by a 1 m rise in sea level95. This represents a large portion of existing intertidal area, which totals about 16,000 km2 (ref. 95). Therefore, marsh transgression into uplands could potentially offset up to 78% of losses, even if all existing marshes were to drown or erode in place. Meta-analysis of historical accretion measurements (Fig. 1) and dynamic accretion models (Fig. 3), however, suggest that many existing marshes will survive in place. In the hypothetical scenario that there is no loss of existing marsh, this topographic data analysis95 suggests that marsh transgression into uplands could potentially lead to a near doubling in marsh area.

Marsh expansion into adjacent uplands can be obstructed by a steep landscape or by anthropogenic barriers near the coast, such as constructions built to defend dwellings and infrastructures from more frequent flooding events. For example, approximately 17% of Chesapeake Bay and its tributaries are hardened by riprap, seawalls, bulkheads and other structures96. Artificial structures border almost all marsh areas in northwest European estuaries97, and are a primary constraint on future marsh survival in many Pacific (USA) marshes57. The erosion of marshes from the ocean side and hardened shorelines at the mainland side result in ‘coastal squeeze’, with salt marshes and coastal ecosystems confined to a shrinking area and prevented from migrating into adjacent uplands20,97. Recent work in Maine (USA) and New Brunswick (Canada) highlighted that although some salt marshes are vulnerable to coastal squeeze due to either the presence of impervious artificial surfaces or steep topography in the upland, other marshes are free to migrate inland, thus mitigating erosion at the ocean side20. In contrast, salt marshes in the UK and the Netherlands contracted in size over the past decades because transgression limited by dykes could not compensate for sustained lateral retreat of up to several metres per year98,99. Interestingly, these marshes were accreting vertically at rates similar to SLR, emphasizing the importance of integrating lateral and horizontal approaches when assessing wetland vulnerability.

These examples suggest that marsh survival is possible even at high rates of SLR, as long as the marsh is allowed to transgress inland and compensate marsh erosion at the ocean boundary. The survival of salt marsh ecosystems is therefore not dependent solely on the preservation of the current marshlands, but will also depend on the ability of marshes to transgress inland without encountering natural or artificial obstacles.

Recommendations for future research

Observations of marsh deterioration and conversion to open water indicate that there are limits to marsh adaptability in places such as coastal Louisiana. Nevertheless, our meta-analysis indicates that most marshes have not yet reached those limits, and our review suggests that the sensitivity of marshes to SLR can be overstated by both field- and modelling-based assessments. Successful ecosystem management depends on accurate assessments of vulnerability. We therefore recommend the following guidance to avoid systematic bias, and to improve forecasts of marsh response to SLR:

- Point-based measurements of marsh elevation change and accretion should focus on frequently flooded, lower-elevation portions of the marsh landscape, where plant productivity and sediment deposition are not limited by historical rates of SLR. There, measurements across environmental gradients (for example, salinity, sediment, elevation and nutrients) will allow prediction of ecogeomorphic processes under conditions that are most representative of future accelerated SLR.

- The traditionally strong but narrow focus on marsh adaptability in the vertical dimension should be complemented by a better understanding of the processes that control the lateral position of marsh boundaries. More study is needed to discern how climatic and anthropogenic forces influence migration of marshes into adjacent uplands, erosion or progradation of the seaward edge, and expansion of interior ponds. This work is critical to guide processes-based models that need to evolve to integrate vertical and lateral responses of marshes to SLR.

- Analysis leading to management decisions should be based on landscape-scale models that include migration of marshes into uplands, and dynamic feedbacks through which vertical accretion rates increase with accelerating SLR. Accurate predictions will depend on site-specific accretion measurements, particularly from low-elevation marsh zones (as stressed in the first point, above) and an inventory of anthropogenic barriers to marsh migration.

Several promising landscape models have recently been developed that include dynamic accretion rates and simple marsh migration57–60,69. The recommendations above may help guide this type of approach, and provide models with more site-specific data needed to inform large-scale coastal management. Preliminary results from these models demonstrate that dynamic accretion rates and inland migration lead to highly resilient marshes. For example, modelled San Francisco Bay marshes expand under most sea level and management scenarios57. Further investigation in this region suggests that the availability of low-lying land for wetland migration is a first-order determinant of marsh fate, and that extensive marsh loss occurs only for extremely rapid rates of SLR (180 cm per century)60.

Although SLR is a ubiquitous factor contributing to the evolution of estuarine and coastal landscapes, our review suggests that its direct impact may not be a critical threat to many tidal wetlands over the next several decades. Specifically, we highlight that the total size of US Atlantic and Pacific marshes is currently stable45, the vast majority of Atlantic marshes in our meta-analysis are building vertically at rates faster than or similar to historical SLR (Fig. 1a,d), accretion rates may double in response to sea level acceleration (Fig. 1b), and that models incorporating dynamic accretion and/or marsh migration predict stable marshes under all but the highest future sea level scenarios (for example, Fig. 3). The most dramatic examples of marsh loss are in regions of the world where humans have modified fluxes of sediment and nutrients, and enhanced relative SLR rates through anthropogenic subsidence6. We therefore suggest that marsh vulnerability research should continue to broaden in scope to include other aspects of global change such as eutrophication and reduced sediment supply (see, for example, refs 85,100), and especially the interaction between SLR and human response.

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Author contributions

M.L.K. designed the study, E.E.S. conducted the meta-analysis, and all authors wrote the paper.

Additional information

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Competing financial interests

The authors declare no competing financial interests.

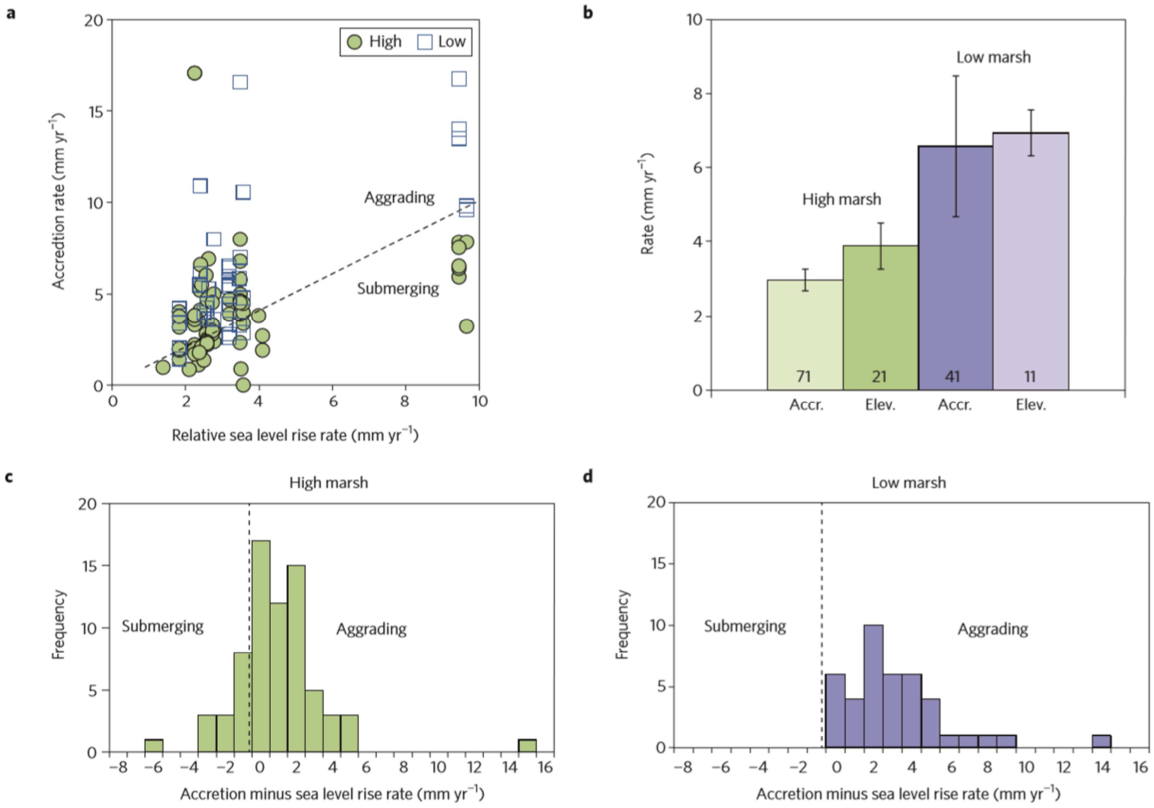

Figure 1 | Meta-analysis of vertical accretion and elevation change rates of Atlantic and Gulf Coast salt marshes in North America and Europe. The graphs are based on the compilation and re-analysis of data from refs 13,46,47. a, Comparison between local relative sea level rise rate and accretion rate for low- and high-elevation marshes. The black dashed line represents an equilibrium condition where marshes are building vertically at the same rate that sea level rises. Points below the line represent marshes that are submerging, and points above represent those that are surviving. b, Mean accretion and elevation change rates for low- and high-elevation marshes. The number in each column represents the number of measurements, and error bars represent standard error. Two-tailed Student t-tests indicate that accretion and elevation change rates are not significantly different from each other ($P >> 0.1$), but that differences between low- and high-elevation marshes are significant ($P = 0.0001$ for accretion rate, $P = 0.05$ for elevation). c,d, Frequency distributions of accretion rates relative to local relative sea level rise rates for high (c) and low marshes (d), where negative rates indicate submerging marshes and positive rates represent aggrading marshes. Because they are frequently flooded, low-elevation marshes build faster than highelevation marshes. This meta-analysis demonstrates the extent to which reliance on historical measurements from high-elevation marshes will overstate marsh vulnerability to accelerating sea level rise.

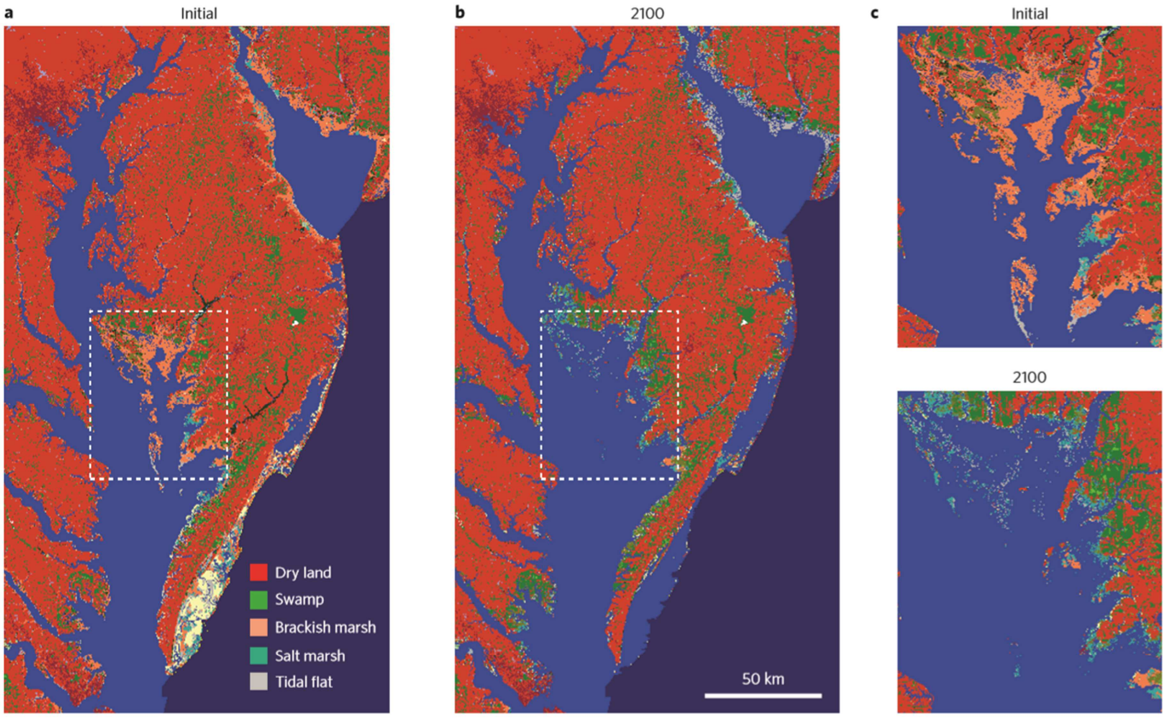

Figure 2 | An example of a SLAMM model simulation illustrating near-complete loss of marshes in Chesapeake and Delaware Bay (USA) in response to 1 m sea level rise65. a,b, Initial (a) and final (b) conditions of the marshes. c, Enlarged views of the region outlined with dashed rectangles in a,b. Vulnerability is overestimated because the model typically incorporates a temporally constant accretion rate, informed by historical measurements, rather than accretion rates that increase with inundation duration73 (see, for example, Fig. 1b).

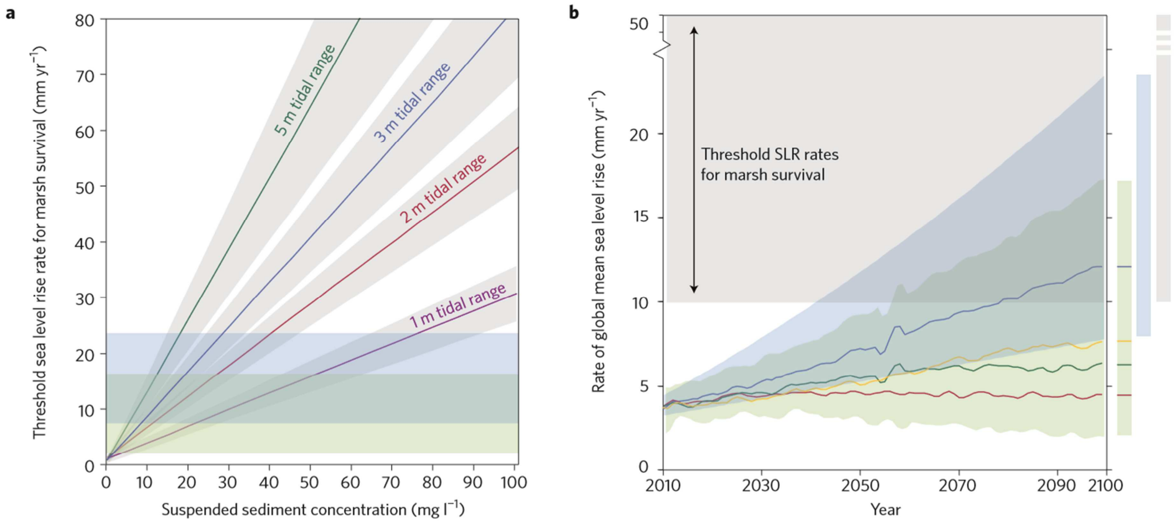

Figure 3 | Maximum rates of sea level rise for marsh survival. a, Threshold rates of sea level rise, above which marshes are not able to survive, predicted by an ensemble of 5 dynamic marsh models (from ref. 41). Threshold rates for marsh survival are relatively high because these marsh models incorporate dynamic ecogeomorphic feedbacks through which accretion rates increase with inundation duration (for example, Fig. 1b). Each coloured line represents the mean threshold rate as a function of suspended sediment concentration and spring tidal range. Grey bands around each coloured line indicate ±1 standard error on the predicted threshold rates of sea level rise. The predicted probable range of global sea level rise rates in 2100 is indicated by the pale green band for process-based model projections by IPCC AR577 and by the pale blue band for semi-empirical projections78. The darker green band represents overlap between them. b, Predicted probable ranges of global mean sea level rise rates during the twenty-first century based on processbased models by IPCC AR577 (green band, combined for RCP2.6, 4.5, 6.0 and 8.5) and based on semi-empirical projections78 (blue band), compared with the most likely range of predicted threshold rates of sea level rise for marsh survival41 (grey band). The red curve denotes the median of IPCC AR5 processbased projections for RCP2.6; green, RCP4.5; yellow, RCP6.0; and blue, RCP8.5. The error bars on the right indicate the ranges in 2100.

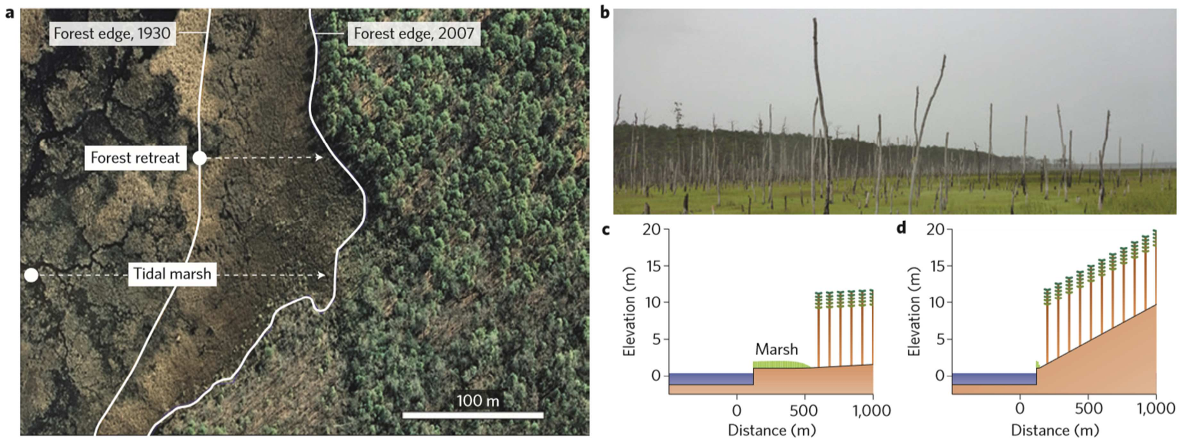

Figure 4 | Marsh migration into adjacent uplands. a, Aerial photograph of a portion of the Delaware Bay estuary (New Jersey, USA) showing ~50 m of landward forest retreat and marsh migration between 1930 and 200730. b, Ground-based photograph of the forest–marsh transition zone in the Chesapeake Bay estuary (Maryland, USA), showing the creation of new marshland under stressed and dead trees88. c,d, Exploratory model simulation showing the expansion (c) or contraction (d) of marsh width in response to constant sea level rise as a function of upland slope93. Model simulations began with identical marsh widths (100 m); distance = 0 m refers to the initial seaward marsh extent. Modelled erosion rates were similar in both simulations, so differences in final marsh width reflect migration rates associated with different upland slopes.