SEDIMENT LOADING

Watershed sediment cannot offset sea level rise in most US tidal wetlands

Scott H. Ensign[1]*, Joanne N. Halls[2], Erin K. Peck[3]

Watershed sediment can increase elevation of tidal wetlands struggling against rising seas, but where and how much watershed sediment helps is unknown. By combining contiguous US datasets on sediment loads and tidal wetland areas for 4972 rivers and their estuaries, we calculated that river sediment accretion will be insufficient to match sea level rise in 72% of cases because most watersheds are too small (median 21 square kilometers) to generate adequate sediment. Nearly half the tidal wetlands would require 10 times more river sediment to match sea level, a magnitude not generally achievable by dam removal in some regions. The realization that watershed sediment has little effect on most tidal wetland elevations shifts research priorities toward biological processes and coastal sediment dynamics that most influence elevation change.

Tidal wetlands are changing in location, extent, and type as sea level rises (*1*). Multidisciplinary efforts to predict these changes are working to inform management actions to help tidal wetlands offset sea level rise. One major focus is addressing how river-borne sediment contributes to tidal wetland elevation change under current (*2*) and future (*3*) climate and land use change, and how reservoir management (*4*) and dam removal (*5*) may augment coastal sediment loads. However, few near-coastal river gaging stations measure watershed sediment delivery directly to the coastal zone (*6*), and influential studies on the balance between river sediment flux and the tidal wetland area receiving that sediment have focused on very large rivers and their dams (*2*, *3*, *7*, *8*). This paucity of river sediment data and the bias of disciplinary discourse focusing on large rivers has, not unexpectedly, swayed studies on estuaries and tidal wetlands to frame hypotheses based on the patterns observed for large rivers and their tidal wetland deltas. Given that smaller rivers exponentially outnumber large rivers at the coast (*9*) and provide a large cumulative sediment load on active margins (*10*, *11*), a coast-wide accounting of all rivers' sediment fluxes and associated tidal wetland elevation change is needed to recenter expectations for the role rivers play in delivering sediment to tidal wetlands.

We addressed this need by assessing the extent to which contemporary river sediment load can offset the relative elevation loss of tidal wetlands occurring due to sea level rise across all rivers that drain to the contiguous US shoreline. We define this relationship as the accretion balance (i.e., the rate of vertical accretion on tidal wetlands due to river sediment minus a 2020 modeled rate of relative sea level rise: (*12*) for each cluster of tidal wetlands adjoining each estuary. Other wetland processes (organic matter production, compaction, subsidence, etc.) and non-riverine sediment sources were not included so that we could explore geographic patterns in the relationships between watershed size, river sediment delivery, and tidal wetland extent. Our intent was not to predict either an actual rate of tidal wetland sediment accretion or the future fate of a tidal wetland, but rather to describe the potential contribution of each river's sediment load to its adjoining tidal wetlands. Comparing our predictions for 93 tidal wetlands around the United States with previously reported accretion rates led us to infer four categories of tidal wetland condition with implications for research and management.

Regional differences in river sediment contribution to tidal wetland accretion

We developed a geospatial model (*13*, *14*) to predict the height that river-transported sediment could equate to if spread across tidal wetlands adjoining that river's estuary. The predicted annual sediment load for every river in the contiguous United States entering tidal waters with a watershed greater than 1 km^2 was derived from the US Geological Survey's SPAtially Referenced Regression On Watershed (SPARROW) attributes model; this load was converted to volume and distributed across tidal wetlands (as defined by the US Fish and Wildlife Service's National Wetland Inventory) adjoining that estuary. Estimated sediment load, tidal wetland area receiving this load, and bulk density of deposited river sediment affect uncertainty; we systematically increased the sediment load and underestimated tidal wetland area to intentionally overestimate the height of river sediment accretion (*13*). We did not adjust height downward to account for autocompaction or organic matter decay that would occur over time because our focus was merely a snapshot of annual change. Rivers and their estuaries were investigated at three spatial scales: (i) each tributary of an estuarine channel network, (ii) the aggregated estuarine network (as defined by the National Hydrography Dataset's

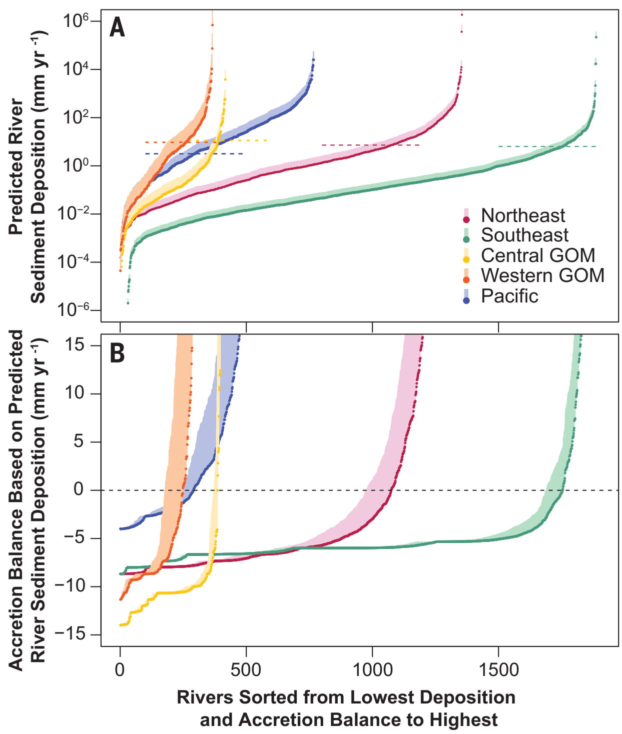

Fig. 1. Accretion and accretion balance of tidal wetlands adjoining 4972 rivers. (**A**) Accretion of river sediment on adjoining tidal wetlands (points) and SPARROW-derived sediment load regression uncertainty applied to each river's sediment load (lighter shaded bars extending upward from points). Dashed horizontal lines show the modeled 2020 rate of sea level rise for each region (*12*). (**B**) Values in (A) converted to accretion balance by subtracting the local rate of sea level rise. Both panels show the combination of terminal paths draining less than 21 km^2 and level paths draining more than 21 km^2 (*13*).

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level path and terminal path attributes, respectively), and (iii) a coast-wide scale spanning many terminal path estuaries.

The height of river sediment accretion ranged over 10 orders of magnitude, with rates in the Pacific and Western Gulf of Mexico generally higher than that of the Northeast, Southeast, and Central Gulf of Mexico (Fig. 1A); in these areas, accretion of river sediment lagged local sea level rise in at least 72, 90, and 89% of estuaries, respectively. By contrast, 48 and 69% of estuaries in the Western Gulf of Mexico and Pacific, respectively, could receive enough river sediment to offset sea level rise (Fig. 1B; all percentages reported throughout are based on the upper estimate of river sediment load represented by lighter shading in Fig. 1). These are likely overestimates of the potential accretion rate and subsequent accretion balance because we assumed all river-transported sediment was deposited on tidal wetlands (not subtidal areas) immediately adjoining the channel, and we modeled river sediment deposition along sub-estuaries without removing that sediment load from the supply available to the next sub-estuary downstream. Above and below ground organic matter production in tidal wetlands can generally add 3 mm yr^{-1} of elevation gain (*15*); adding this elevation to each of the results (Fig. 1B) only raised the percent of tidal wetlands capable of exhibiting positive accretion balance to 34, 14, 13, 52, and 91% in the Northeast, Southeast, Central Gulf of Mexico, Western Gulf of Mexico, and Pacific, respectively.

Small watersheds dominate the coast

Regional differences in river-transported sediment accretion and resulting accretion balance are a function of the distribution of watershed sizes, the effect of watershed size and sediment yield on sediment load, and wetland extent. Not unexpectedly (*9*), the distribution of watershed size is highly skewed toward very small watersheds (Fig. 2A identifies the 90th percentile; the median watershed sizes are 27, 7.5, 33, 12, and 25 km^2 in the Northeast, Southeast, Central Gulf of Mexico, Western Gulf of Mexico, and Pacific, respectively). These very small watersheds fringe the US coastline and their inclusion here sets the current study apart from previous continental-scale analyses of wetland condition that are limited to watersheds >50 km^2 (*16*), 100 km^2 (*17*), 10,000 km^2 (*18*), or 14,000 km^2 (*19*). The cause of regional differences in accretion balance (Fig. 1) becomes apparent when contrasting sediment loads with tidal wetland areas across regions (Fig. 2B). In all regions, the median sediment load of the smallest 90% of watersheds is several orders of magnitude less than the median of the largest 10% of watersheds. Thus, most US rivers are generally very small and their sediment loads too low to contribute a sediment

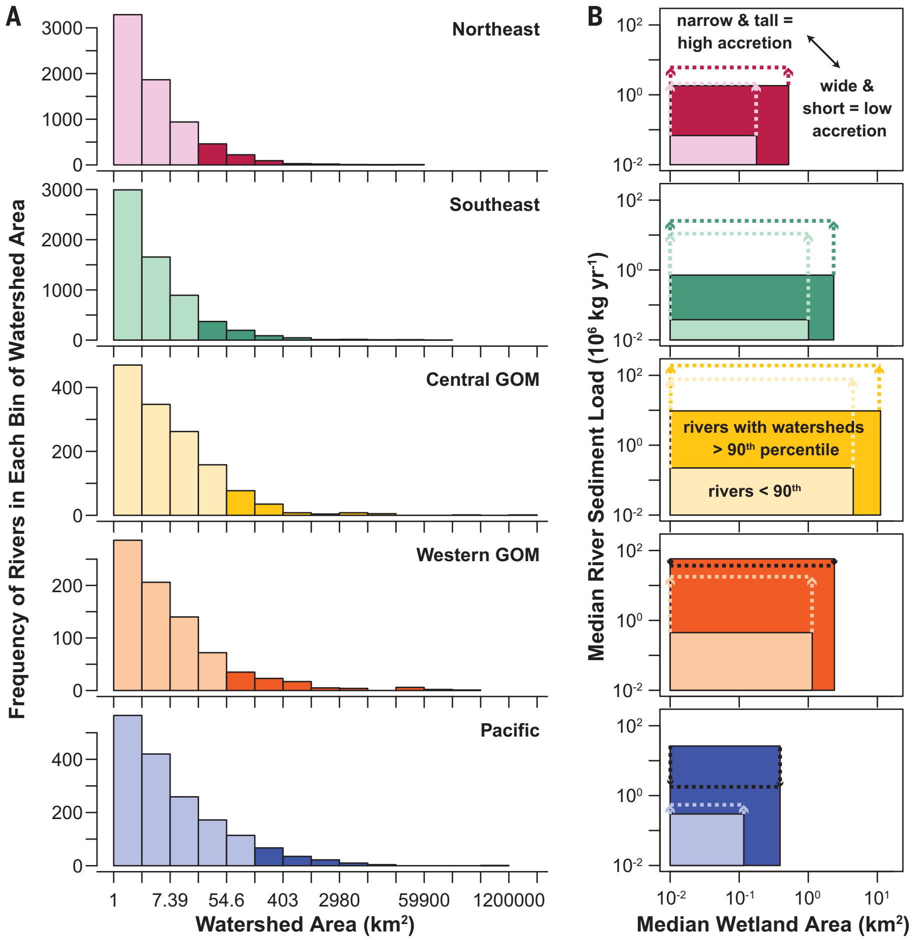

Fig. 2. The distribution of watershed size, sediment loads, and wetland area. (**A**) Histogram of watershed size at the coastline (according to the national hydrography dataset's level path attribute) with the largest 90th percentile noted by darker colors. (**B**) The median sediment load and tidal wetland area for rivers below and above the 90th percentile of watershed area; dashed lines indicate the river sediment load required to equal the regional rate of sea level rise on the median tidal wetland area shown. Narrow and tall bars indicate high accretion rates, with high sediment loads spread over a relatively small wetland area.

volume to their tidal wetlands area that meaningfully affects elevation. If instead the tidal wetland area scaled in proportion with watershed size and corresponding sediment load, we would not have observed large deficits between wetland area and the sediment load required to offset sea level rise (dashed lines in Fig. 2B).

In addition to the fine-scale results presented in Figs. 1 and 2, we explored how coast-wide aggregate sediment loads could affect tidal wetlands (*13*). We assumed annual coast-wide mixing and homogenous distribution of river sediments, which may be realistic only for watersheds dominated by one or more large rivers. At this coarser scale of analysis we found that most areas on the East Coast had aggregate river sediment loads equating to accretion rates less than 3 mm yr^{-1} below local rates of sea level rise, whereas most coastal areas in the western Gulf of Mexico and Pacific coasts had aggregate river sediment loads capable of generating more than 3 mm yr^{-1} above sea level rise (Fig. 3).

The role of large river floods

Our analysis is based on average sediment loads from 1999 to 2014; therefore the influence of river floods of longer recurrence intervals are underrepresented in the results. Larger river floods may increase sediment delivery to estuaries, but watershed hydrology, geography, and estuarine morphology dictate the proportion that is trapped by coastal plain rivers before it reaches the estuary (*20*, *21*) versus how much is passed through to estuarine and offshore depocenters (*22*). This mixture of recently delivered river sediment and geologically older sediment derived from erosion of coastal landforms may be resuspended by tidal currents (especially where flood-dominant tidal asymmetry exists) (*23*, *24*), maintained within the turbidity maximum zone (*25*), and ultimately delivered to adjoining tidal wetlands.

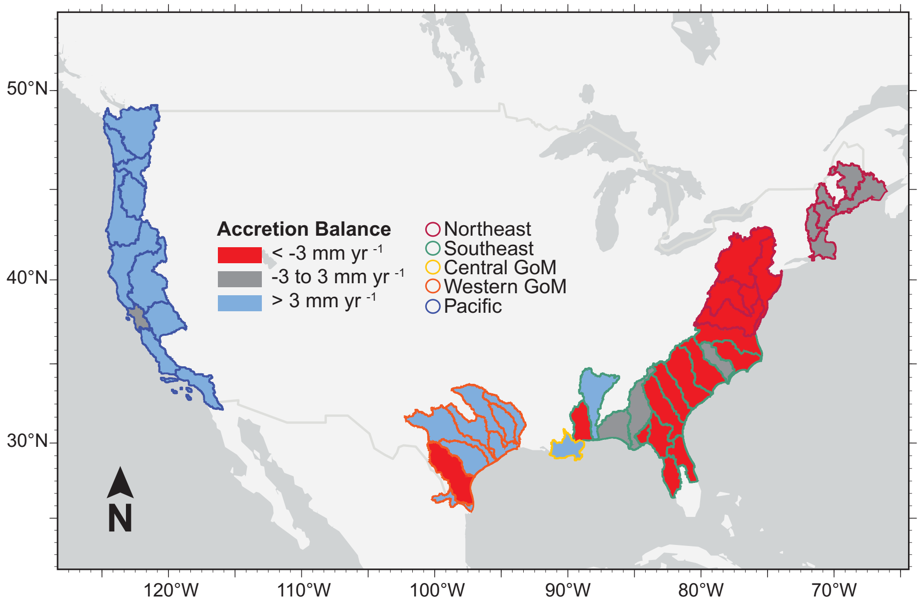

Fig. 3. Coast-wide accretion balance (accretion due to river sediment minus regional sea level rise) if all rivers' sediment subsidized regional tidal wetlands. If all river sediment within each Hydrologic Unit Code 4 boundary was dispersed evenly across all tidal wetland area, most areas in the Eastern United States and parts of the Gulf of Mexico would lag regional sea level rise by more than 3 mm yr^{-1} (3 mm yr^{-1} approximates how much wetland organic matter production could boost annual accretion). Some regions are omitted because appropriately scaled sediment load summary data were not available.

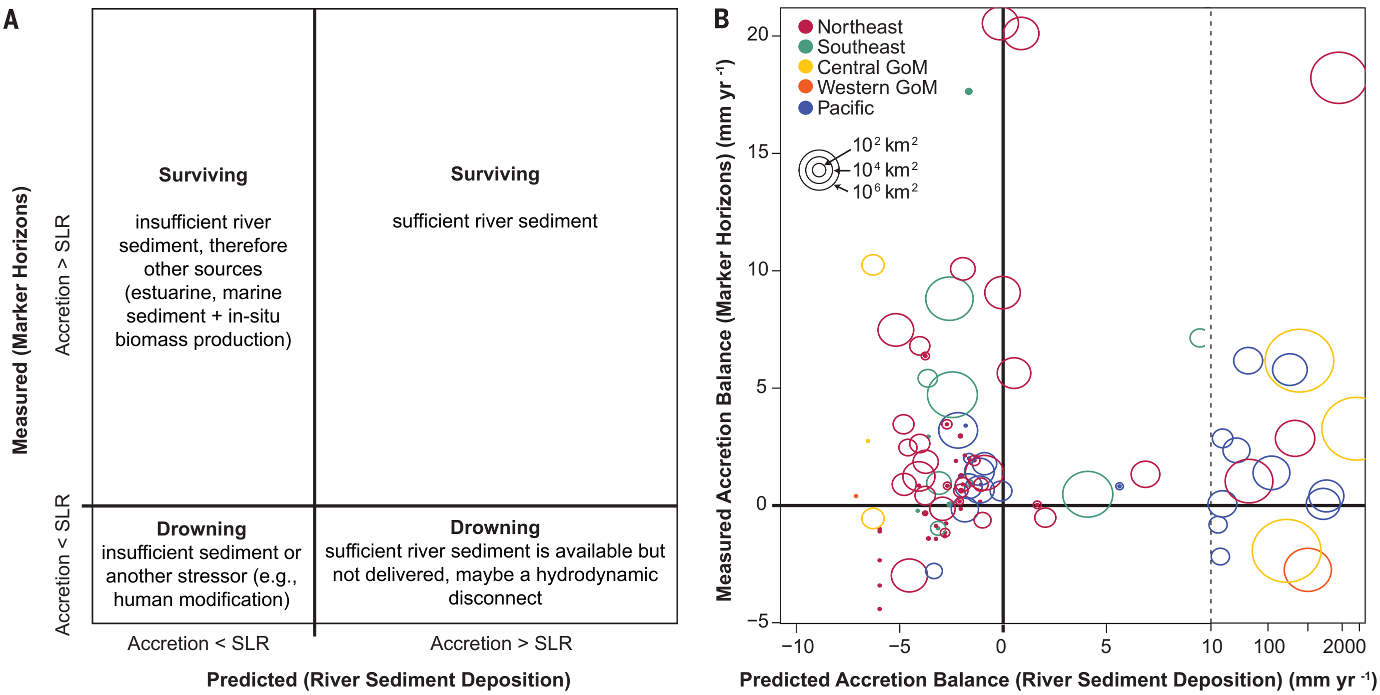

Fig. 4. Measured accretion balance of tidal wetlands versus predicted river-derived sediment accretion and sediment loads. (**A**) A conceptual parsing of potential relationships between river-derived sediment accretion and measured tidal wetland accretion with possible inferences. (**B**) Measured (from marker horizon measurements report in the literature) and predicted tidal wetland accretion balance. Circle size is proportional to watershed area; note break from linear to log-scale axis at 10 mm yr^{-1} on the horizontal axis.

Yet sediment delivery to estuaries from large watersheds (>10^3 km^2) and their coastal plain rivers during large floods may be lower than upstream measurements would suggest (*26*, *27*), in part because effects due to backwater slow and spread floodwater across broad coastal plains and enhance sediment deposition near the head of tide (*28*, *29*). Ultimately, the response of tidal wetlands to sea level rise over just the next decade will have considerable consequences on coastal habitats (*30*). Therefore, the exclusion of river floods with long recurrence intervals in our analysis may not necessarily affect our interpretation of the role of river sediment on tidal wetlands in the short term, particularly given the uncertainty in the magnitude of sediment actually delivered to estuaries during these events.

Inferring sediment dynamics from predicted versus observed accretion rates

We compared our predicted river sediment accretion balances with 93 marker horizon accretion measurements and their corresponding accretion balances reported in the literature for tidal wetlands around the United States (in many cases averaged from multiple measurements at one site) (*13*). Given that our predictions account for river-supplied sediment—but not other factors affecting accretion balance—it was not expected that our predictions would correlate with observations. Instead, the intention with our comparison was to identify conditions indicative of sediment source and dynamics (Fig. 4A).

This analysis revealed that 22% of the measured-predicted pairs were both positive, indicating that river sediment delivered to these particular wetlands was capable of accounting for all of the measured accretion (upper right quadrant of Fig. 4B). In 23% of the pairs, both measured and modeled accretion balance were negative (lower left quadrant of Fig. 4B), suggesting that all sources of sediment were insufficient, and/or that compaction, diagenesis, or other processes are predominant. In 5% of the pairs, measured accretion balance was negative but modeled was positive, suggesting that river sediment supplies are sufficient but hydrodynamic processes prevent their delivery and accumulation on tidal wetlands and/or internal wetland processes such as compaction reduce wetland elevation. In 51% of the pairs, measured accretion balance was positive but modeled was negative (upper left quadrant of Fig. 4B), suggesting that another source of sediment besides modern river delivery of watershed sediment was required, such as near coastal sources (*31*) and marine sources (*32*), and/or that above and below ground autochthonous organic matter supply (*33–35*) is sufficient to offset sea level rise. River sediment load was not statistically related to tidal wetland sediment accretion (fig. S2; linear regression F statistic of 0.0079, 76 d.f., r^2 = −0.013, P = 0.929), as might be suspected from the high proportion of sites in the upper left quadrant of Fig. 4B. Unreasonably high predicted accretion balances are a result of our conservative modeling in which all river sediment is trapped on tidal wetlands, and in which tidal wetland area is often underrepresented in our model. We cannot be confident that these percentages represent the overall population of estuaries and tidal wetlands across the contiguous United States because the literature compiled (and those sites that are commonly studied) are not a random geographic selection of estuaries across all regions (*13*).

From the perspective of wetland research and habitat risk management, the inference that estuarine and marine sediment sources must help offset modern river sediment loads at these sites would warrant further focus on hydrodynamic factors affecting that sediment delivery and ecological factors affecting biomass production and decomposition (*33–35*). By contrast, habitat risk management for tidal wetlands that are drowning (Fig. 4B, lower right quadrant) could infer a physical or hydrodynamic impediment that prevents abundant river sediment from reaching tidal wetlands. This approach of parsing the influence of river sediment supply relative to measured accretion can help refine the research hypotheses addressed with other spatial (*36*) and conceptual (*37*) models of marsh dynamics.

The measurements of tidal wetland accretion and our predictions differ in their spatial scale: Measurements are specific to approximately one square meter whereas the modeled counterpart represents an entire grouping of tidal wetlands ranging in area from 0.1 to 100 km^2. This difference is most relevant to interpreting sites where spatial heterogeneity in sediment deposition may produce measurable positive accretion balance in some areas despite the overall negative condition for the mosaic of tidal wetlands (Fig. 4B, upper left quadrant). Given that most sites compared here share this condition and that wetland organic matter cannot drive all sites into positive accretion balance, we can infer that additional sediment sources and high spatial heterogeneity in tidal wetland accretion are common.

Discussion

River-borne sediment alone is insufficient to provide the needed elevation gain for tidal wetlands in most estuaries in the Northeast, Southeast, and parts of the Gulf of Mexico. Appreciation for this fact should reduce expectations for sediment connectivity between rivers and estuaries in the Eastern United States and instead focus attention on the hydrodynamic and ecological factors governing tidal wetland accretion. Although river sediment accretion is only one process of many contributing to tidal wetland elevation gain, our study reveals how minor a contribution this generally is. We attribute this pattern to the small size of most watersheds where they enter tidal waters, and the relatively small sediment loads produced as a result. Relative to the East Coast and eastern Gulf of Mexico, higher sediment yields, larger watershed sizes, and smaller areas of tidal wetlands in the western Gulf of Mexico and Pacific coasts generate greater potential for river-derived sediment accretion. These geographic patterns in the relationship between watershed size, river loads, and tidal wetland area have been previously recognized at local scales, but this is the first continent-wide examination of broader patterns in these relationships and their influence on estuaries and their tidal wetlands.

A frequent premise of coastal research (*22*, *38*) and a message in the popular science press (*39*) is that dams have reduced river sediment loads to the US coast and jeopardized tidal wetlands dependent on that river sediment. In reality, dam removal can enhance coastal sediment (*40*) and restore sediment conveyance across high gradient coastlines (*11*, *41*). Yet the effect of dams on a broader size range of rivers (most dams occur on small, not large rivers: (*42*) and resulting trends in coastal sediment delivery over time and space are not consistently negative (*43–46*). Our results show that at least 47% of rivers in the United States have river-derived accretion rates less than 0.5 mm yr^{-1}, and thus river sediment load would have to increase by at least one order of magnitude, not just single multiples, to appreciably affect tidal wetlands. For example, in the lower Hudson River valley sediment behind dams is roughly equal to 2 years of that region's sediment load (*5*). In the South Atlantic Bight, sediment interception by dams has decreased river loads by 55% (*47*), but care should be taken in translating these changes to the coast (*26*, *48*). At the broadest scale, North American rivers transport 19% less sediment to the coast than prior to human development (*49*). Therefore, dam removal—particularly on rivers crossing low gradient coastal plains on the Atlantic and Gulf of Mexico coastlines—may not ameliorate tidal wetlands threatened by sea level rise.

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SUPPLEMENTARY MATERIALS

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Methods
Figs. S1 to S3
Tables S1 to S6
References (*56*–*79*)

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Editor's summary
Sea-level rise threatens to overtake coastal wetlands, but elevation-building processes, including deposition of sediments from upstream, can help keep wetlands above water. Ensign *et al*. investigated whether watershed sediment loads are enough to keep up with sea-level rise at US coasts (see the Perspective by Larsen and Milligan). Their model conservatively estimated that incoming sediment loads may be sufficient in the western Gulf of Mexico and Pacific coasts but insufficient in other regions where most watersheds are smaller. Local accretion is often higher than predicted from the model, suggesting an important role for biological processes to raise marsh elevation in the face of sea-level rise. —Bianca Lopez

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