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PERSPECTIVES

Marshes Are the New Beaches: Integrating Sediment Transport into Restoration Planning

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Abstract

Recent coastal storms and associated recovery efforts have led to increased investment in nature-based coastal protection, including restoration of salt marshes and construction of living shorelines. In particular, many of these efforts focus on increasing vertical elevation through sediment nourishment, where sediment is removed from the tidal channel and placed on the marsh plain, or preventing lateral erosion through shoreline protection. In the USA alone, millions of dollars have been allocated or spent on these coastal protection solutions over the last few decades because of their perceived sustainability and ecologically positive co-benefits including habitat provision and carbon sequestration. These projects would benefit from integration of sediment transport pathways, budgets, and metrics during planning and modeling of restoration outcomes, in order to evaluate sustainability before investment. This is analogous to the decades of experience with coastal management and engineering on the open coast. Salt marshes are geomorphic features that rely partially on external sediment supply to maintain their network of tidal channels, intertidal flats, and marsh plain. Removing sediment from one component of the overall system to nourish another component may be counterproductive, given that the net sediment budget is unchanged. For example, dredging a tidal channel beyond its equilibrium condition will cause it to fill with sediment from the tidal flat or elsewhere in the system. This may cause slumping of the marsh edge, or over-deepening of other sections of the channel to compensate. Similarly, shoreline protection that prevents edge erosion hampers the marsh plain's ability to accrete on the levee and naturally transgress landward or it starves other components of the system of regularly supplied sediment. A limited vertical or lateral-only perspective, instead of a three-dimensional perspective, during project planning and evaluation may lead to suboptimal decision-making regarding restoration priorities, approaches, and outcomes. I contend that before significant investments are made in marsh restoration through sediment nourishment or shoreline protection, sediment transport measurements and models that consider sediment dynamics should be integrated into the early phases of restoration planning. This will help identify where and under what conditions marsh restoration will most likely be successful and economically justified. Triaging and prioritizing is then possible, which is a sustainable approach for restoration, given the persistent vulnerability of marshes to sea-level rise, storms, and sediment deficits.

Keywords Salt marsh restoration · Sediment transport · Thin-layer sediment placement · Living shorelines

Storms, Coastal Protection, and Sediment-based Restoration

Coastal storms in the USA, including tropical and extratropical cyclones cause significant damage to coastal infrastructure, communities, and ecosystems; over the last few decades, major storms such as Hurricanes Katrina, Sandy, Maria, Irma, Harvey, and Matthew have resulted in over US$400 billion in damages (Smith and Katz 2013). The dominant impact from these storms at the land interface is storm surge, caused by a combination of increased water level, waves, precipitation, and winds. In response to these recent storms, many efforts have been proposed to increase the resilience of the coast, reduce storm surge, and protect coastal infrastructure and ecosystems. "Hard" engineering proposals range from inland storm barriers (Sustainable Solutions Lab 2018) to offshore dunes (Rebuild by Design 2018), which may disrupt coastal ecosystems. Because of these

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concerns, many coastal managers have considered "nature-based" solutions to coastal protection, such as salt marshes and "living" shorelines (Wamsley et al. 2010; Fagherazzi 2014).

Salt marshes and living shorelines (e.g., oyster reefs, rock, placed vegetation) provide a range of ecosystem services (Barbier et al. 2011; Grabowski et al. 2012). Salt marshes provide critical habitat for a variety of flora and fauna, store carbon through burial, assist with nutrient cycling, and attenuate waves and currents (Chmura et al. 2003; Sousa et al. 2010; Möller et al. 2014). Living shorelines similarly provide a substrate for enhanced ecosystem function as compared to hardened shorelines and dissipate wave energy on the salt marsh coastline (Scyphers et al. 2011). These two features are therefore invoked frequently as sustainable mechanisms to reduce storm surge and coastal erosion, respectively, while providing co-benefits that are ecologically desirable.

In response to the aforementioned recent coastal storms, federal, state, and local agencies have supported salt marsh restoration and living shoreline construction as strategies to protect coastal infrastructure without compromising ecosystem function (Fig. 1). For example, grants administered by the National Fish and Wildlife Federation (NFWF) in response to Hurricane Sandy have funded numerous projects in Northeast USA (NFWF 2014). These projects range from hectare-scale addition of dredged sediments on marsh plains to increase elevation to complete re-establishment of tidal networks over entire marsh complexes (> 3000 ha). Construction of living shorelines near retreating estuarine coasts has also been supported across variable length scales, and application to individual privately held land parcels has also been promoted (NOAA 2017). The rapid initiation of these projects, ostensibly due to the perceived immediate need for coastal protection, has prevented a thorough reckoning of their suitability and sustainability (Reed et al. 2018). Perhaps the most critical gap has been integration of sediment transport processes into assessing the viability and likelihood of project success.

In this perspective, I begin by reviewing the well-documented importance of sediment dynamics and associated three-dimensional processes to marsh sustainability and recent developments linking sediment budgets and integrative metrics with geomorphic trajectory. I then discuss the relative neglect of sediment transport dynamics in models which are commonly used to evaluate future marsh trajectory. Examples of restoration, including thin-layer deposition and living shorelines, are then used to illustrate the shortcomings of a vertical or lateral-only perspective that does not integrate sediment transport dynamics during restoration planning; I briefly note the contrasting example of open coast management where sediment transport is now commonly integrated into planning. I then review two large-scale restoration efforts that have benefitted from a wealth of sediment transport research, and how those findings have informed restoration planning. Concluding recommendations suggest opportunities to integrate measurements and conceptual models of sediment transport into the planning of sustainable marsh restoration at all spatial scales.

Salt Marsh Response to Sediment Supply

Redfield (1972) presented an early framework for the importance of external sediment supply for marsh sustainability. In his seminal paper on salt marsh biology, he notes the role of sediment in controlling not only the morphology of the marsh

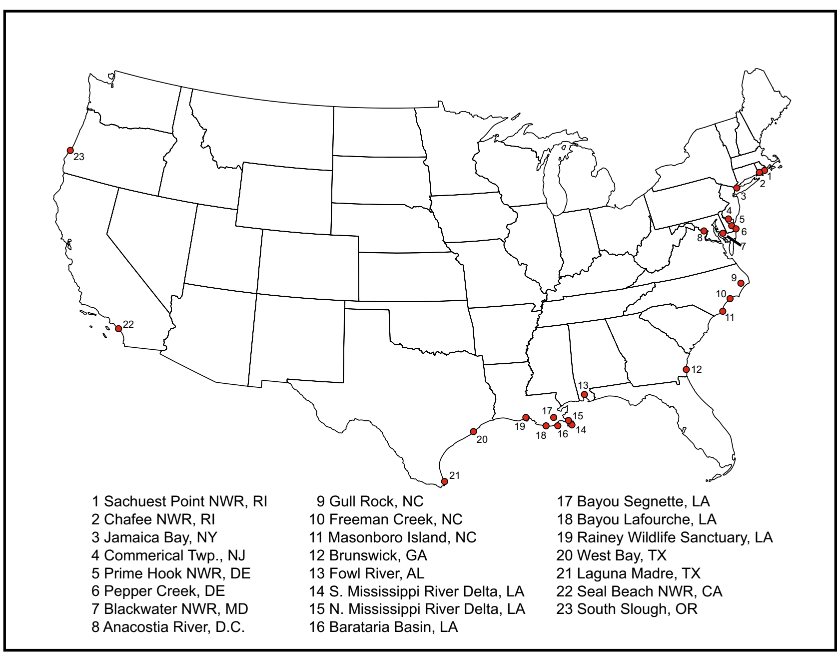

Fig. 1 Thin-layer sediment placement projects addressing marsh restoration (US Army Corps of Engineers 2018). Additional projects planned or underway are not included

plain but also the interaction between the marsh plain, scarp, intertidal flat, and channel. Interestingly, he addressed these interactions with the implication of a neutral sediment budget, i.e., no net import or export of sediment. For example, he states

> As the marsh builds upward with rising sea level the margin of the creek becomes unstable so that the peat tends to break off and slump into the channel … Blocks of peat break off from the face of the slumped margin and fall into the channel where they decompose. The products of their decomposition and other sediments accumulate in the creek bottom. As a result, the bottom of the creek tends to rise as the marsh increases in elevation … (p. 232)

and

> Sediment accumulates in the cracks formed by the slumping of the bank and becomes vegetated by the outgrowth of rhizomes and by seeding. It is deposited also on the slumped surface and the blocks of peat which break off from it, tending to counteract the effect of slumping. Thus turf is formed which reconstitutes the marsh and counteracts the effects of erosion. A healing process takes place which tends to keep the creek in very much the same position and to adjust its size to that required to carry its load of tide water. (p. 233)

These clear mechanistic processes can be observed in all salt marshes and with a neutral sediment budget and no sea-level rise, this suite of processes will result in a stable marsh-channel configuration (Fagherazzi et al. 2012). Since Redfield (1972), numerous studies have expanded on these sediment transport processes through observations, conceptual models, and idealized numerical models. Friedrichs and Perry (2001) presented a synthesis of salt marsh morphodynamics that mechanistically addressed multiple factors that control salt marsh response to sediment supply. They focused on the role of vegetation in trapping external sediment, the importance of external source concentration and proximity, and the role of tidal channels in supplying external sediment. Friedrichs and Perry (2001) also note the importance of edge erosion in supplying sediment to the marsh plain, enabling it to maintain elevation in response to sea-level rise. They also point out the tendency for dredged channels to trap sediment normally destined for the marsh plain. These two salient points have important ramifications for living shorelines and sediment addition projects, which are discussed below.

Mariotti and Fagherazzi (2013) and Fagherazzi et al. (2013) used idealized models of marsh evolution to demonstrate that salt marshes are rarely in equilibrium and are constantly responding to external factors, primarily waves, sea-level rise, and external sediment supply. They also show that sea-level rise does not need to be invoked to account for widespread marsh loss; sediment deficits in combination with ubiquitous wave erosion can account for marsh loss over shorter timescales. Kirwan et al. (2016) observed that a majority of marshes appear to be vertically stable in response to sea-level rise, highlighting the importance of lateral processes such as wave erosion and sediment transport to marsh vulnerability.

Because research to date has focused disproportionately on vertical dynamics (Kirwan et al. 2016), integrating multi-dimensional sediment transport processes, budgets, and metrics in salt marsh restoration planning and modeling is not common. More precisely, the measurement of sediment transport pathways and budgets has been relatively underdeveloped despite the clear role of sediment in marsh trajectory, as described by Redfield (1972) and many others since. Several seminal studies on sediment transport in salt marsh channels established estimates of sediment budgets, though many were hampered by a lack of continuous measurement technology or insufficient temporal coverage. Few studies employed rigorous sediment flux measurement methods; Suk et al. (1999) was one of the first to methodically account for tidal-to-annual timescale sediment fluxes in a salt marsh channel. Subsequent studies (Ganju et al. 2005; 2013; 2015; Rosencranz et al. 2016) further established the concept of using sediment budgets as integrative metrics to diagnose salt marsh vulnerability in an analogous framework to Fagherazzi et al. (2013). Specifically, a marsh complex that is exporting sediment must be unstable, whether due to marsh plain disintegration, edge erosion, or channel export; while a marsh complex that is importing sediment at a rate sufficient to match sea level rise may be stable and maintaining its lateral and vertical position or expanding.

New integrative metrics have expanded the ability to evaluate marsh geomorphic trajectory on multiple spatiotemporal scales. Ganju et al. (2017) synthesized sediment budgets from eight wetland complexes on the US Atlantic and Pacific coasts, and demonstrated a relationship between sediment budget, unvegetated-vegetated marsh ratio (UVVR), and sediment-based lifespan. Their work showed that even the most sediment-rich marsh complex in the study was not importing enough sediment to keep pace with relative sea-level rise. The study also identified a critical UVVR ~ 0.10, indicating that marshes with higher UVVRs may already be rapidly converting to open water due to myriad destabilizing processes (e.g., herbivory, sea-level rise, sediment deficits). While useful, the UVVR-sediment budget relationship is correlative and not necessarily causal; the mechanisms governing this relationship are still under investigation (e.g., Mariotti 2016) and should be explored in the context of marsh restoration. Nonetheless, the implication is that the UVVR is an integrative metric that can be applied at broad spatial scales and can identify stable and unstable marshes. A further implication is that sediment budgets can establish the current and potential lifespans of sediment addition projects. Despite the clear linkages between sediment transport dynamics and three-dimensional processes on marsh stability, the conceptual and numerical models that guide most restoration planning do not integrate these processes at the outset.

Appropriate Use of Numerical Models for Predicting Marsh Trajectory

Numerical models are often used in evaluating future scenarios of marsh coverage, in response to sea-level rise, land-use change, and restoration. Because of the inherent biological processes at work in salt marshes, which tend to act in the vertical dimension (Cahoon et al. 2015), most models have tended to neglect three-dimensional, coupled biophysical processes, especially dynamic sediment transport (e.g., Morris et al. 2002; Mogensen and Rogers 2018; Propato et al. 2018). Though these models have been modified to be spatially explicit (Alizad et al. 2018), they nonetheless consider marshes as one-dimensional, vertically dynamic systems, where elevation change is dependent on local processes such as aboveground and belowground biomass production, sediment biogeochemistry, and to a lesser degree, external sediment input (Cahoon et al. 2006; Morris et al. 2002; Swanson et al. 2014). One of the cornerstones of this approach is tracking marsh evolution through surface elevation tables (SETs, Webb et al. 2013), which can measure total elevation change of a point on the marsh over annual and longer timescales. While valuable for tracking processes that result in vertical change, this approach does not account for major modes of marsh failure, including open-water expansion and edge erosion; in fact, some of the most horizontally unstable marshes have the highest rates of vertical accretion (Ganju et al. 2015).

Neglect of three-dimensional sediment transport processes will compromise our ability to deliver coherent predictions about the future vulnerability of salt marshes. Salt marshes are inherently estuarine geomorphic features and are subject to the same biophysical mechanisms that control estuarine geomorphology; yet, we have developed and applied models without these processes to management questions with insufficient transparency and assessment (Mogensen and Rogers 2018). For example, one primary consideration when modeling estuarine sediment transport is mass conservation of sediment, i.e., is the predicted evolution consistent with known sediment inputs and outputs to the system. However, most marsh models impose a constant sediment concentration (Morris et al. 2002; Alizad et al. 2018), often used as a calibration parameter, with no accounting for the net input of sediment created by the model, and any consideration of whether that input is realistic given known sediment supply to the system; in most cases, the sediment supply is not measured over sufficient spatiotemporal scales. Furthermore, these models cannot account for the dynamic sediment transport processes including wave erosion, transport through channels, spatiotemporal gradients in sediment concentration, or expansion of open-water ponds. These points become important when attempting to deploy such models to estimate trajectory, lifespan, and response of marshes to restoration projects, or to hindcast documented cases of marsh loss.

The way forward involves better integration of sediment transport dynamics into numerical and conceptual models of marsh response when planning restoration and modeling potential outcomes. For example, D'Alpaos and Marani (2016) used a biogeomorphic model with multiple vegetation species to show how sea level rise and sediment supply interacted with elevation and species distribution. Importantly, they showed that vegetative cover and expansion increased with reduced sea level rise and increased sediment supply, echoing the results of Fagherazzi et al. (2013). Another example is Mariotti (2016), who used observations of open-water conversion to develop hypotheses about the connection between sea-level rise, tidal range, sediment supply, vegetative feedbacks, and pond expansion. He explored the conditions under which stable marshes may respond to ephemeral pond creation or experience runaway pond expansion and loss of marsh plain; he showed varying sensitivity to sediment supply depending on the tide range and relative sea-level rise rate. Larger tide range marshes required less external sediment to maintain marsh plain integrity, while lower tide range marshes experienced pond collapse and expansion at relatively higher external supply. Such explorations of process feedbacks and parameter space provide a clear path for both researchers and managers to improve integration of these processes into deterministic models and decision-making tools. Additionally, we should improve our capacity for measuring sediment dynamics and integrative metrics at multiple scales to inform these models. Continuous monitoring of sediment fluxes is rare in estuaries, and even rarer in salt marsh complexes, but these data are critical to establish the present-day sediment budgets needed to guide restoration. Additionally, there is no consistent framework for evaluating open-water area of marshes through time, despite the fact that this is a dominant mode of marsh loss. Remote-sensing methods, including satellite imagery and aerial photography, can be mined for historical and present-day UVVR, which may give clearer guidance regarding marsh vulnerability, prioritization of restoration efforts, monitoring of restoration success, and modeling of outcomes.

Application of these Concepts to Marsh Restoration and Living Shorelines

The gaps in our application of sediment transport principles to restoration are evident in two common practices: thin-layer placement and construction of living shorelines. The former employs a vertical-only perspective, while the latter considers a lateral-only perspective. Here, I outline these two restoration approaches and demonstrate how a three-dimensional view that integrates sediment transport can increase the sustainability of the projects.

Marsh restoration efforts over the past few decades (USACE 2018) have implemented a process referred to as thin-layer placement (also known as thin-layer deposition, sediment augmentation, sediment replenishment). This process involves the placement of external sediment, either from local dredging of tidal channels, inlets, or offshore areas, using sprayers or large pipes. The goal is to increase vertical position relative to the tidal frame (somewhat precisely to mimic optimal position for biomass production), and/or fill open-water ponds that may be expanding.

Thin-layer placement projects are often undertaken, however, with limited knowledge of the underlying sediment transport pathways and/or budget. If one considers three contrasting systems with robust sediment transport measurements, the importance of sediment budgets prior to restoration becomes clear. For example, at Blackwater National Wildlife Refuge, a relatively small-scale thin-layer placement of 57,000 yd^3 (44,000 m^3) was proposed (USFWS 2015), which amounts to 13,200,000 kg (at a density of 300 kg/m^3). Ganju et al. (2013) estimated sediment export from the larger-scale Blackwater system at 1 kg/s (or 86,400 kg/day), which suggests that the addition of sediment would be offset by the underlying export from elsewhere in the system in less than 6 months. While the spatial scale of the restoration project is limited, placing it in the context of the overall sediment regime is important to understand the cumulative impact of multiple small-scale projects that may be undertaken in the future. Conversely, at Seal Beach National Wildlife Refuge, where thin-layer placement has been performed (Thorne et al. in review), pre- and post-placement sediment fluxes are nearly neutral (Rosencranz et al. 2016; Thorne et al. in review), suggesting that any sediment placement would not be offset by losses elsewhere in the system under present conditions. Additionally, the environmental settings of these two regions are very different: Blackwater is in a largely undeveloped area, while Seal Beach is completely constrained by urban and residential development. In the latter case, landward migration is impossible; therefore, attempts to maintain local elevation are justifiable given habitat concerns for endangered species. Lastly, in a sediment-importing system such as portions of Forsythe National Wildlife Refuge, New Jersey (e.g., Dinner Creek, Ganju et al. 2017), thin-layer placement to fill open-water areas may be appropriate given the rates of edge erosion (Leonardi et al. 2016) and prevention of runaway pond expansion (Mariotti 2016).

Apart from the sediment budget aspect of thin-layer placement, when considering the geomorphology and hydrology of the system, it is possible that these interventions may actually accelerate marsh deterioration (Fig. 2). For example, many projects (USACE 2018) source the sediment from tidal channels within the marsh complex. Following Redfield's (1972) mechanistic framework, this would cause the channel to fill in with material from either the intertidal flat or slumped marsh blocks. Given a neutral or negative sediment budget, this eventually causes lateral retreat of the marsh edge along the channel. In some cases, this may be tolerable, especially if the sediment is used to fill in open-water ponds that would otherwise expand and meet the channel, leading to runaway expansion as noted above (Mariotti 2016).

The construction of living shorelines is a recent restoration approach that is laterally focused, and would benefit from a whole system assessment during the planning stages. The construction of any shoreline protection system, living or otherwise, is intended to reduce wave and current-induced erosion of the intertidal flat and lateral retreat of the marsh scarp, ostensibly increasing the resilience of marsh systems. In theory, such systems will maintain the seaward position of the marsh and maintain the intertidal flat elevation or even promote deposition on the flat (Fig. 3). From a sediment budget perspective, however, shoreline protection ultimately modifies existing sediment pathways, both locally and regionally. While maintaining the lateral position of the marsh appears desirable, the reduction of sediment erosion and resuspension from the scarp and intertidal flat will reduce the vertical deposition on the marsh levee (Hopkinson et al. 2018), thereby reducing its elevation relative to sea level. This will require a local increase in elevation only through autochthonous deposition, with less external sediment supply. One can argue that promoting deposition on the intertidal flat will eventually lead to marsh expansion into that area; however, this is dependent on whether there is sufficient external sediment available for trapping in the first place. Secondly, from a regional sediment budget perspective, we must realize that trapping sediment in one location ultimately starves some other location from that sediment, a point which is abundantly clear from open coast, sandy shoreline settings (Dean and Dalrymple 2004). In a natural system with ongoing sea-level rise, the expectation is that lateral erosion supplies the marsh plain with sediment, enabling landward transgression (Reed 1988; Hopkinson et al. 2018). Ultimately, the timescales over which sea-level rise, lateral erosion, vertical accretion, and landward migration occur will govern how important shoreline hardening is for marsh resilience. This will necessarily be site-specific, but estimating those timescales must be done with dynamic sediment transport processes in mind.

The relationship between these engineering approaches and the geomorphic function of the system is analogous with sandy shorelines. For decades, we have invested in beach nourishment, jetties, groynes, and other stabilization techniques with the intended outcome of retaining sediment, maintaining shoreline position, and enhancing beach elevation (Program for the Study of Developed Shorelines 2018). It is

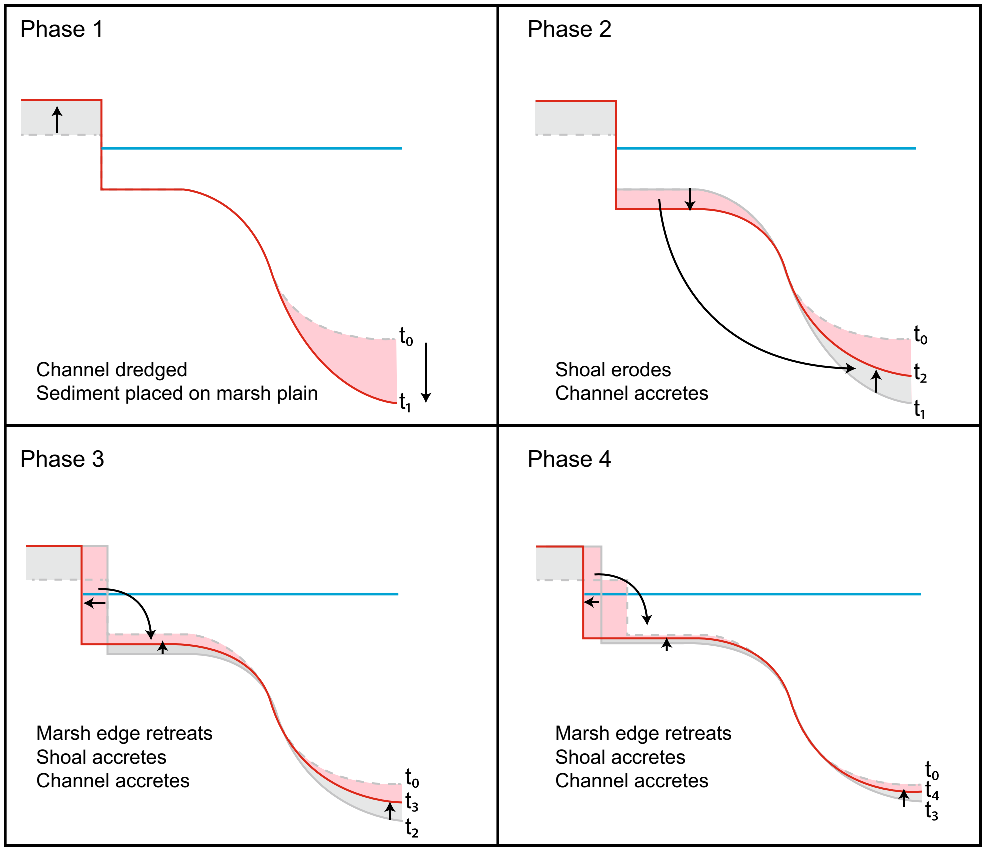

Fig. 2 Conceptual diagram of channel, shoal, and marsh plain response to channel deepening in a neutral sediment budget marsh complex. In phase 1, at time = t_1, the channel is dredged, and sediment is placed on the marsh plain. In phase 2, the channel-shoal profile attempts to return to a quasi-equilibrium profile, and the shoal (or elsewhere in the system) erodes to supply the channel with sediment. In phase 3, the increased shoal depth leads to less wave dissipation and greater wave energy reaching the marsh edge, leading to marsh edge erosion and retreat, which supplies the shoal with new sediment. In phase 4, this process continues until a quasi-equilibrium vertical profile is reached

now clear that placing sediment along shorelines with strong alongshore transport gradients may result in limited lifespan of the improvement, while we also know that structures intended to trap sand eventually cause erosion of down-transport locations (Dean and Dalrymple 2004). These realizations have resulted in increased appreciation of sediment budgets before and after beach nourishment or structure construction (Stive et al. 2013; de Schipper et al. 2016). Wave and alongshore sediment transport modeling, though not a requirement for these projects, is increasingly common for gauging the influence of the intervention from a hydrodynamic and geomorphic standpoint. For example, sourcing sediment from an offshore location creates a sediment sink and a possible modification of the wave climate, both of which affect the efficacy of the ensuing sediment nourishment on the shoreline (Bender and Dean 2003). Modeling these processes, while still subject to error and uncertainty (Thieler et al. 2000), at least incorporates some of the dominant physical processes that control geomorphic evolution of the coast.

As postulated above, there is a tendency to consider marshes as primarily vertical systems, with reduced focus on three-dimensional processes and sediment transport dynamics. It is obvious, however, that if sediment-based techniques are implemented to restore marshes, project planning must consider sediment transport as a primary control on marsh trajectory. The modeling of these processes is still relatively in its infancy (as compared to hydrodynamic modeling), but recent advances have shown that idealized models of coupled biophysical processes and improved spatially integrative monitoring can provide significant insight relevant to restoration.

Examples of Marsh Restoration that Utilize Sediment Transport and Budgets

There are some examples of marsh restoration projects that include full recognition of sediment transport pathways and budgets due to decades of investment in sediment transport research and integrative budgets. Nonetheless, it is not broadly accepted that planning marsh restoration or evaluating outcomes requires integrating sediment transport processes. While forward-thinking restoration is taking place in many regions, the dearth of sediment transport measurements in marsh systems and lack of dynamic sediment transport processes in applied marsh models is evidence of that point.

In the Mississippi River Delta region of Louisiana, ongoing marsh loss (Day et al. 2000) and the ensuing reduction in storm protection, along with post-Deepwater Horizon funding, have led to increased investment in marsh creation. The importance of the Mississippi River sediment load to the geomorphic development of the entire deltaic system precludes the neglect of sediment transport when engaging in sediment-based

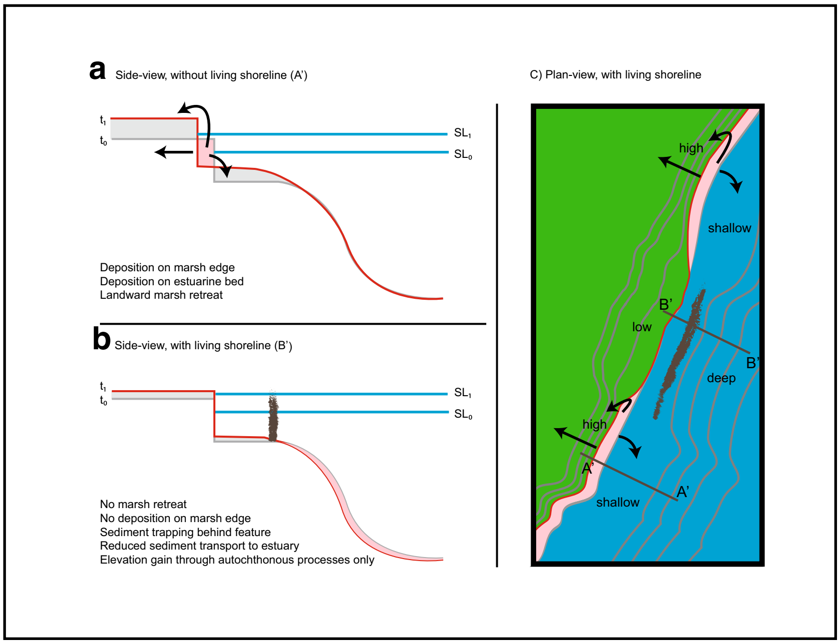

Fig. 3 Conceptual diagram of channel, shoal, and marsh plain response to shoreline protection in a neutral sediment budget marsh complex. Without shoreline protection (**a**), wave energy erodes the marsh edge while sea level rises (SL_0 to SL_1), causing the entire planform to accrete vertically through internal sediment recycling (i.e., cannibalization), while the marsh-estuary boundary moves landward through a natural transgression process. With shoreline protection (**b**), wave energy does not reach the marsh edge; therefore, sediment does not mobilize to supply the marsh plain or shoal. Some deposition behind the structure will occur as estuarine sediment is trapped; however, overall transport to the estuary will be reduced. The marsh plain can still grow vertically through autochthonous processes including organic material burial, but overall, the vertical growth will be reduced given the lack sediment mobilization. From the plan-view perspective (**c**), the overall geomorphic and topo-bathymetric continuum between marsh levee and plain, shoal, and estuary (or channel) is modified by shoreline protection, and natural landward migration is prohibited, decreasing the overall resilience of the system

restoration (Kesel 1989; Day et al. 2007; Allison and Meselhe 2010; Allison et al. 2012). For example, recent marsh creation projects have used river channel sediments (which are ultimately exported to the birdfoot delta, inner shelf, and beyond) to build flats and marsh plain to offset marsh loss elsewhere in the system (Coastal Protection and Restoration Authority 2017). In fact, the CPRA Coastal Master Plan indicates that the Mississippi River channel sediments are renewable “approximately every five years”, acknowledging the importance of understanding sediment budgets before moving sediment between components of the geomorphic system. Given the original watershed source of these sediments, the engineering of the channel-levee system, and the eventual fate of these sediments, dredging the navigation channel to build marshes is a sustainable sediment transfer that does not increase the vulnerability of the system (interactions between channel deepening and levee integrity is beyond the scope of the perspective, as is long term sediment yield of the watershed).

The San Francisco Bay/Sacramento-San Joaquin Delta region is similarly characterized by a large, dynamic sediment signal and a rich history of sediment transport research (Gilbert 1917; Porterfield 1980; McKee et al. 2013). The ongoing decline in watershed sediment loads (Wright and Schoellhamer 2004) at a time of increased interest of wetland restoration led to concerns over sediment availability and its relation to wetland restoration success (Williams and Faber 2001; Orr et al. 2003). In the South San Francisco Bay, the reintroduction of tidal flows to diked, subsided salt ponds was intended to create tidal marsh habitat and practitioners there were aware of sediment budget constraints prior to large-scale restoration (Williams and Orr 2002; Phillip Williams and Associates 2006). Shellenbarger et al. (2013) estimated the potential sediment availability to the restoration area from both estuarine and watershed sources, demonstrating that estuarine sources could fill the accommodation space over centennial timescales, but not within the 50-year project timeframe. They also showed that timing of restoration, i.e., when to reopen ponds to tidal action, could be optimized to capitalize on increased sediment supply from the watershed during the wet season. Although projects are not typically planned with prior knowledge of sediment transport pathways, they often benefit from fortuitous sediment transport regimes. Carl’s Marsh, in Northern San Francisco Bay, was a former diked agricultural plain on the edge of the tidal Petaluma River (Siegel 1998). Restoration consisted of opening the plain to tidal flows and within a decade, the plain had rapidly accreted and revegetated. This large sediment import was due to the presence of an estuarine turbidity maximum (ETM) in the Petaluma River (Ganju et al. 2004), where suspended-sediment concentrations routinely exceeded 1000 mg/L on every tide. The marsh served as a trap for this sediment on flood tides, with insufficient velocity on ebb tides to export the sediment. Conceptual models (Fletcher et al. 1992; Darke and Megonigal 2003; Ganju et al. 2013) have included the importance of ETMs on marsh sediment supply and sustainability, again demonstrating the need to consider the interaction of tidal channel processes with the marsh plain.

The examples from the Louisiana Gulf Coast and San Francisco Bay are on a cumulative spatial scale that is much larger than typical thin-layer placement and living shoreline projects, though each individual project is planned on a "marsh unit" scale. Assessing the cumulative impacts of these projects is not straightforward, but recent work (Diefenderfer et al. 2011) shows that integration of site-specific measurements with deterministic physical models can help scale up the impact of several projects to the broader landscape scale. The spatial scale of the project does not dictate the importance of sediment, as the physical processes operate on the same timescales, and over the same geomorphic units: tidal channel, intertidal flat, marsh scarp, and marsh plain. A unifying sediment-based geomorphic framework simplifies assessing multiple projects, as maintaining a positive sediment budget and stable planform across multiple sites will result in a positive sediment budget and stable planform across the larger scale.

Conclusions and Recommendations

The sediment transport lessons learned from sandy, open coast shorelines have not been integrated into our planning and monitoring of marsh restoration projects, despite the underlying similarity in terms of geomorphic response to sediment transport and budgets. Large investments in marsh restoration and protection can be evaluated in terms of the sediment transport pathways, which will help ascertain critical information about the viability and lifespan of such projects, as well as the most beneficial action. A more holistic approach to marsh restoration planning should include integration of channel and intertidal flat processes and evolution, as well as the role of open-water conversion and edge erosion. The latter is a fundamental resilience mechanism which allows the marsh to build vertically while retreating laterally (Hopkinson et al. 2018), while the former is a significant threat that can lead to runaway marsh loss (Mariotti 2016). Addressing these issues requires spatially comprehensive baseline data for marsh elevation, UVVR, shoreline position, and sediment budgets. The first three of these can be estimated using remote-sensing methods, which could provide a pathway to nationally consistent baseline data products; however, estimating sediment budgets is time-consuming and requires in situ measurements. While Ganju et al. (2015, 2017) provided simplified proxies for sediment budgets, it is equally important to develop conceptual models of sediment transport (Ganju et al. 2013) to guide the adaptive management process. With observational data on geomorphology, tidal hydrodynamics, wind patterns, and river inflow, it is possible to diagnose potential sediment sources and transport mechanisms for salt marshes and integrate those processes into successful restoration planning, monitoring, and modeling.

As an example of the application of these concepts, a back-barrier marsh in a suspended-sediment poor environment will likely rely on storm-induced overwash from the ocean side to periodically move the sand-marsh line landward (Walters and Kirwan 2016); the marsh ultimately can expand landward in concert with the barrier island. Therefore, restoration efforts could focus on the connectivity of the marsh with the ocean-facing barrier (Miselis et al. 2016), while attempting to fill any open-water areas that may expand in the interim. In the case of an estuarine fringing marsh, the natural process of edge erosion, levee building, and landward transgression can be halted by shoreline protection, living or otherwise. If preservation of this marsh is essential to meet species conservation goals, for example, managers should recognize that armoring of the shoreline may reduce vertical deposition on the levee and possibly enhance erosion seaward of the shoreline and elsewhere in the marsh complex.

Lastly, the use of numerical models to inform restoration should be guided by observed modes of marsh failure and succession. Biologically focused, vertical-only models are useful to establish the optimum elevation for marsh restoration, and potential for landward migration into upland areas. However, these models need to account for sediment conservation, with more rigorous assessment, and should be tested against historically observed marsh failure and transgression. More physically based, deterministic models should be used to explore parameter space, and guide management through identifying tipping points related to sediment supply, relative sea-level rise, wave erosion, open-water conversion, and integrative, three-dimensional processes.

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