The life and death of salt marshes in response to anthropogenic disturbance of sediment supply

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Salt marshes occur extensively along mid-latitude coasts and provide valuable ecosystem services such as filtering pollutants, attenuating waves during storms, enhancing yields of fisheries, and serving as an organic carbon sink (e.g., Costanza et al., 1997). Both the emergence and continued survival of salt marshes are related to the rate of relative sea-level rise (SLR). Following the last glacial maximum, rising sea level from melting glaciers appears to have precluded marsh development. Dating of basal peats, which overlie mineral sediment and mark marsh initiation, suggests that marshes did not become widespread until sea level stabilized at ca. 6–7 kyr B.P. (Shennan and Horton, 2002; Engelhart et al., 2009). The rate of SLR is once again accelerating (Jevrejeva et al., 2008), leading to increased concern over the future survival of salt marshes (e.g., Kirwan et al., 2010). This concern is motivated, in large part, due to losses of vast amounts of wetlands over the past century; for example, 20,000 ha in the San Francisco Bay (Gedan et al., 2009, and references therein) and approximately 4000 km^2 in the Mississippi Delta plain (Day et al., 2000).

Rising sea level is not the only control on the emergence and survival of salt marshes. Day et al. (2000) concluded that lack of sediment, rather than SLR, is the dominant factor in losses of Mississippi Delta marshes. Kirwan et al. (2011, p. 507 in this issue of *Geology*) explore a contrasting scenario wherein a pulse of sediment led to marsh expansion. They dated basal peats in the Plum Island estuary, Massachusetts (United States), and found the marsh rapidly increased in area by 50% during the eighteenth and nineteenth centuries. During this period, sedimentation in the Chesapeake Bay was elevated by an order of magnitude over background rates due to European settlement and subsequent soil erosion (Colman and Bratton, 2003). In addition to this finding, Kirwan et al. (2011) present numerical simulations suggesting that once marshes are established, they can exist at lower sediment supplies than those needed to initiate the marsh.

To understand how salt marshes drown or expand as a result of changing rates of SLR and sediment supply, one must understand the delicate balance between sedimentation, sea level, and vegetation. Many Atlantic and Gulf Coast marshes are dominated by the halophyte *Spartina alterniflora*, which typically occupies elevations that range from mean sea level to mean high tide (McKee and Patrick, 1988). If the marsh platform evolves to an elevation lower than mean high tide, either through reduced sedimentation or an increased rate of SLR, then these marsh plants will die and the marsh will drown. Drowning often results in a rapid loss of marsh elevation; once marsh plants die, the marsh sediments become susceptible to erosion, and marshes rapidly convert to subtidal flats (e.g., Fagherazzi et al., 2006). How, then, might the reverse work? How does an erodable subtidal environment transform into a marsh?

Recent studies of hydrodynamic processes, both on marsh platforms and in the subtidal environment, can give insight into the sudden marsh expansion documented by Kirwan et al. (2011). Using a model incorporating particle settling, boundary shear stress, and wind-wave erosion, Marani et al. (2010) found that the elevation of a subtidal platform is highly sensitive to suspended sediment concentrations (SSC). For a scenario similar to the Venice lagoon (Italy), a doubling of the SSC from 10 to 20 mg L^{-1} would increase the elevation of the subtidal platform by 0.27 m in an estuary with a 1 m tidal range. Further, Marani et al. (2010) found that if SSC increased beyond 55 mg L^{-1}, the subtidal platform would likely shift to a vegetated marsh platform. Even subtle changes to the elevation of the subtidal platform can strongly influence erosion at the edge of fringing salt marshes. This is because the elevation of the subtidal platform controls the potential erosive power of waves.

Mariotti et al. (2010) explored how changes to subtidal elevation can alter the erosive power of waves, which impact marsh edges, by using a wind-wave model and applying it to an estuary in Virginia. They found that a 15 cm increase in the elevation of the subtidal platform could reduce the erosive potential of waves at the marsh boundary by nearly 25%. Such a reduction in erosive potential at the marsh boundary can tip the balance from marsh edge erosion, or stasis, in marsh expansion.

Mariotti and Fagherazzi (2010) demonstrated how a marsh edge could shift from erosion to expansion by increasing sediment supply; the mechanism is a reduction in water depth resulting in wave dissipation. There is now evidence for rapid expansion of marshes, due to anthropogenically derived pulses of sediment, from the Atlantic coast of the United States (Kirwan et al., 2011), the San Francisco Bay (e.g., Gedan et al., 2009), and the outlet of the Yangtze River in China (Yang et al., 2001).

Increasing SSC not only increases the elevation of subtidal platforms, which helps reduce the erosive potential of waves, but it also directly impacts the vegetated marsh. Marsh platforms with greater SSC sit higher in the tidal frame (e.g., Morris et al., 2002). Higher elevations on the marsh platform reduce the tidal prism (e.g., D'Alpaos et al., 2006), which is the volume of water that must flow into and out of the estuary with each tide. This has the effect of reducing bed shear stresses, and enhancing the accretion of the subtidal platform (e.g., Mariotti et al. 2010). This feedback is complicated somewhat by the fact that introduction of a vegetated marsh platform will concentrate flow in marsh channels (Temmerman et al., 2005); more work is needed to determine if flow concentration in channels can overwhelm the effects of a substantially reduced tidal prism.

Kirwan et al. (2011) complement their fieldwork by simulating marsh response to a sediment pulse using a numerical model. Their simulations suggest that marshes can persist even if SSC is reduced to levels below that which was required to form the marsh. The explanation lies again with the coupling between vegetation and sedimentation processes. Marsh vegetation strongly affects the hydrodynamics of flow (e.g., Temmerman et al., 2005; Mudd et al., 2010) and is an effective sediment trap (e.g., Li and Yang, 2009; Mudd et al., 2010). In addition, marsh vegetation contributes directly to marsh accretion through organic sedimentation (e.g., Nyman et al., 2006; Mudd et al., 2009). The combination of these factors means that a marsh is far more efficient at accreting sediment, both organic and inorganic, than an unvegetated mud flat or subtidal platform. The feedbacks involved are summarized in Figure 1. If a marsh is established through a pulse of sediment, the result is an estuary that is a far more efficient at trapping sediment. Thus if sediment supply returns to the pre-pulse level, the marsh may continue to be viable because its enhanced

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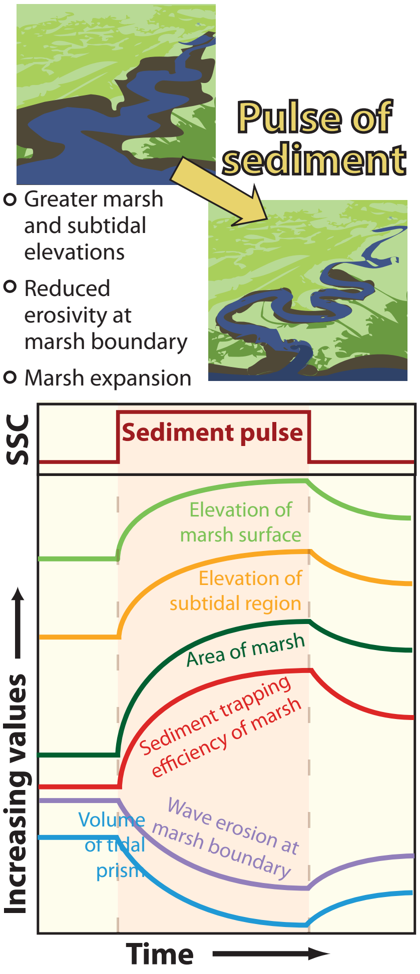

Figure 1. Diagram showing the effects of a pulse in sediment supply on the properties of an estuary and its marshes.

ability to trap sediment can help the accretion rate keep pace with the rate of SLR at an elevation sufficient to maintain vegetation. This is a crucial result. Coastal managers, concerned about wetland loss, have little control over global sea level. They might, however, be able to encourage marsh expansion through a pulse of sediment, perhaps from a managed dam release. Once established, the new marsh, in an estuary with a now smaller tidal prism and a higher trapping efficiency, may be able to persist even when sediment supplies are reduced. This bears the caveat that although a subtidal platform may be converted to a marsh, if the sediment supply is too low to maintain the marsh in face of future SLR, marsh expansion will be unable to halt the drowning of the marsh (e.g., Kirwan et al., 2010).

Due to continued anthropogenic disturbance along coastlines (e.g., Gedan et al. 2009) and accelerating SLR, there is an increasing need for coastal managers to implement policies that will preserve marshes. One would hope that these policies are informed by the best available predictions of marsh evolution, and that quantitative predictions are supplied by robust models. While models such as that presented by Kirwan et al. (2011) can qualitatively reproduce observed marsh expansion, they are limited by a lack of field sites where both driving forces (e.g., sediment supply through time) and the time evolution of the marsh are well constrained. To test existing and future models, we need estuaries that can serve as field laboratories: locations where suspended sediment, bathymetry, marsh elevations, sea level, biomass, marsh stratigraphy, and expansion or retreat of marsh boundaries are measured over an extended period. Using such data sets to constrain the accuracy of marsh models will give coastal managers confidence in predictions of marsh evolution, which is essential if they are to make decisions about potentially costly policies that affect coastal sediment supply.

REFERENCES CITED

Colman, S.M., and Bratton, J.F., 2003, Anthropogenically induced changes in sediment and biogenic silica fluxes in Chesapeake Bay: Geology, v. 31, p. 71–74, doi:10.1130/0091-7613(2003)031<0071:AICISA>2.0.CO;2.

Costanza, R., et al., 1997, The value of the world's ecosystem services and natural capital: Nature, v. 387, p. 253–260, doi:10.1038/387253a0.

D'Alpaos, A., Lanzoni, S., Mudd, S.M., and Fagherazzi, S., 2006, Modeling the influence of hydroperiod and vegetation on the cross-sectional formation of tidal channels: Estuarine, Coastal and Shelf Science, v. 69, p. 311–324, doi:10.1016/j.ecss.2006.05.002.

Day, J.W., Shaffer, G.P., Britsch, L.D., Reed, D.J., Hawes, S.R., and Cahoon, D., 2000, Pattern and process of land loss in the Mississippi Delta: A spatial and temporal analysis of wetland habitat change: Estuaries, v. 23, p. 425–438, doi:10.2307/1353136.

Engelhart, S.E., Horton, B.P., Douglas, B.C., Peltier, W.R., and Tornqvist, T.E., 2009, Spatial variability of late Holocene and 20th century sea-level rise along the Atlantic coast of the United States: Geology, v. 37, p. 1115–1118, doi:10.1130/G30360A.1.

Fagherazzi, S., Carniello, L., D'Alpaos, L., and Defina, A., 2006, Critical bifurcation of shallow microtidal landforms in tidal flats and salt marshes: Proceedings of the National Academy of Sciences of the United States of America, v. 103, p. 8337–8341, doi:10.1073/pnas.0508379103.

Gedan, K.B., Silliman, B.R., and Bertness, M.D., 2009, Centuries of human-driven change in salt marsh ecosystems: Annual Review of Materials Science, v. 1, p. 117–141, doi:10.1146/annurev.marine.010908.163930.

Jevrejeva, S., Moore, J.C., Grinsted, A., and Woodworth, P.L., 2008, Recent global sea level acceleration started over 200 years ago?: Geophysical Research Letters, v. 35 ,L08715, doi:10.1029/2008GL033611.

Kirwan, M.L., Murray, A.B., Donnelly, J.P., and Corbett, D.R., 2011, Rapid wetland expansion during European settlement and its implication for marsh survival under modern sediment delivery rates: Geology, v. 39, p. 507–510, doi:10.1130/G31789.1.

Kirwan, M.L., Guntenspergen, G.R., D'Alpaos, A., Morris, J.T., Mudd, S.M., and Temmerman, S., 2010, Limits on the adaptability of coastal marshes to rising sea level: Geophysical Research Letters, v. 37, p. L23401, doi:10.1029/2010GL045489.

Li, H., and Yang, S.L., 2009, Trapping effect of tidal marsh vegetation on suspended sediment, Yangtze Delta: Journal of Coastal Research, v. 254, p. 915–924, doi:10.2112/08-1010.1.

Marani, M., D'Alpaos, A., Lanzoni, S., Carniello, L., and Rinaldo, A., 2010, The importance of being coupled: Stable states and catastrophic shifts in tidal biomorphodynamics: Journal of Geophysical Research, v. 115, p. F04004, doi:10.1029/2009JF001600.

Mariotti, G., and Fagherazzi, S., 2010, A numerical model for the coupled long-term evolution of salt marshes and tidal flats: Journal of Geophysical Research, v. 115, p. F01004, doi:10.1029/2009JF001326.

Mariotti, G., Fagherazzi, S., Wiberg, P.L., McGlathery, K.J., Carniello, L., and Defina, A., 2010, Influence of storm surges and sea level on shallow tidal basin erosive processes: Journal of Geophysical Research, v. 115, p. C11012, doi:10.1029/2009JC005892.

McKee, K.L., and Patrick, W.H., 1988, The relationship of smooth cordgrass (*Spartina alterniflora*) to tidal datums—A review: Estuaries, v. 11, p. 143–151, doi:10.2307/1351966.

Morris, J.T., Sundareshwar, P.V., Nietch, C.T., Kjerfve, B., and Cahoon, D.R., 2002, Responses of coastal wetlands to rising sea level: Ecology, v. 83, p. 2869–2877, doi:10.1890/0012-9658(2002)083[2869:ROCWTR]2.0.CO;2.

Mudd, S.M., Howell, S.M., and Morris, J.T., 2009, Impact of dynamic feedbacks between sedimentation, sea-level rise, and biomass production on near surface marsh stratigraphy and carbon accumulation: Estuarine, Coastal and Shelf Science, v. 82, p. 377–389, doi:10.1016/j.ecss.2009.01.028.

Mudd, S.M., D'Alpaos, A., and Morris, J.T., 2010, How does vegetation affect sedimentation on tidal marshes? Investigating particle capture and hydrodynamic controls on biologically mediated sedimentation: Journal of Geophysical Research, v. 115, p. F03029, doi:10.1029/2009JF001566.

Nyman, J.A., Walters, R.J., Delaune, R.D., and Patrick, W.H., 2006, Marsh vertical accretion via vegetative growth: Estuarine, Coastal and Shelf Science, v. 69, p. 370–380, doi:10.1016/j.ecss.2006.05.041.

Shennan, I., and Horton, B., 2002, Holocene land-and sea-level changes in Great Britain: Journal of Quaternary Science, v. 17, p. 511–526, doi:10.1002/jqs.710.

Temmerman, S.,Bouma,T.J., Govers, G., Wang, Z.B., De Vries, M.B., and P.Herman, M.J., 2005, Impact of vegetation on flow routing and sedimentation patterns: Three-dimensional modeling for a tidal marsh: Journal of Geophysical Research, v. 110, p. F04019, doi:10.1029/2005JF000301.

Yang, S.L., Ding, P.X., and Chen, S.L., 2001, Changes in progradation rate of the tidal flats at the mouth of the Changjiang (Yangtze) River, China: Geomorphology, v. 38, p. 167–180, doi:10.1016/S0169-555X(00)00079-9.

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