Marsh Collapse Does Not Require Sea Level Rise

BY SERGIO FAGHERAZZI, GIULIO MARIOTTI, PATRICIA L. WIBERG, AND KAREN J. McGLATHERY

Sea level rise is only one of the causes of deterioration of coastal wetlands. What really matters is the sediment budget of a salt marsh and its surroundings.

ABSTRACT. Salt marshes are among the most productive ecosystems on Earth, providing nurseries for fish species and shelter and food for endangered birds. Salt marshes also mitigate the impacts of hurricanes and tsunamis, and sequester large volumes of carbon in their peat soil. Understanding the mechanisms responsible for marsh stability or deterioration is therefore a key issue for society. Sea level rise is often viewed as the main driver of salt marsh deterioration. However, while salt marshes can reach equilibrium in the vertical direction, they are inherently unstable in the horizontal direction. Marsh expansion driven by sediment supply rarely matches lateral erosion by waves, creating a dynamic landscape. Recent results show that marsh collapse can occur in the absence of sea level rise if the rate at which sediment is eroded at marsh boundaries is higher than the input of sediment from nearby rivers or from the continental shelf. We propose that the horizontal dynamics and related sediment fluxes are key factors determining the survival of salt marshes. Only a complete sediment budget between salt marshes and nearby tidal flats can determine the fate of marshes at any given location, with sea level rise being only one among many external drivers. Ancient Venetians understood this dynamic very well. They manipulated the supply of sediment to the Venice lagoon, Italy, in order to control the long-term evolution of the intertidal landscape.

Figure 1. Allegory of the struggle between land and sea in the Venice lagoon, Italy. The banner reads: "An element opposes another element." *From Trevisan (1715)*

THE ENDLESS STRUGGLE BETWEEN LAND AND SEA AT SALT MARSH BOUNDARIES

In 1715, Bernardo Trevisan published his treatise on the Venice lagoon, Italy. In a now famous engraving by Andrea Zucchi, he presented an allegory of two women violently fighting at the shore (Figure 1). One of them is semi-undressed, as if she were emerging from a swim in the ocean, with algae covering her head. She is the sea. Her foe has a thick canopy of marsh vegetation replacing the hair. She represents the land. The two women are pushing each other, trying to dislodge the enemy and conquer ground. The wrestlers seem well matched, and it is hard to determine who will win. The sea already has a foot on land, indicating a possible temporary victory, but the struggle is clearly ongoing. The city of Venice lies at the horizon, an engaged bystander waiting for the final outcome of the battle. This allegory represents the endless struggle between land and ocean for the control of Venice. The banner reads: "An element opposes another element."

Mainland people fleeing barbaric invasions built the city-state of Venice on marshlands around the fifth century CE. It quickly developed into one of the most powerful mercantile states in human history. At its apogee, the city was the third largest in Europe and the terminus for lucrative goods that traveled from the Far and Middle East on the Silk Road. For population density and diversity and cultural and economic relevance, Venice was qualitatively the equivalent of New York City in the twentieth century.

Venice's location—surrounded by water—was critical for its defense. Venetians understood that the intertidal landscape is extremely dynamic, with rivers, waves, and currents constantly reshaping the coast and creating a complex succession of salt marshes, tidal flats, and channels. The ongoing silting of the lagoon was of particular concern in the fifteenth century. Large rivers, carrying sediment from the mountains to the ocean, were debouching into the lagoon, infilling large areas. Similar shallow lagoons were converted to land both north and south of the Venice lagoon, cutting off coastal cities from the ocean.

To counteract the silting of the lagoon, Venetians executed one of the most complex engineering projects of human history. Between the fifteenth and eighteenth centuries, they diverted all rivers discharging into the lagoon, eliminating direct sediment input and thus saving the sea from the land. (Sediment brought by overwash events or through tidal exchange at the inlets was negligible compared to the sediment discharged by rivers.) It is important to note that Venetians were not aware of possible oscillations in sea level, and the rate of sea level rise was probably much lower than it is now for

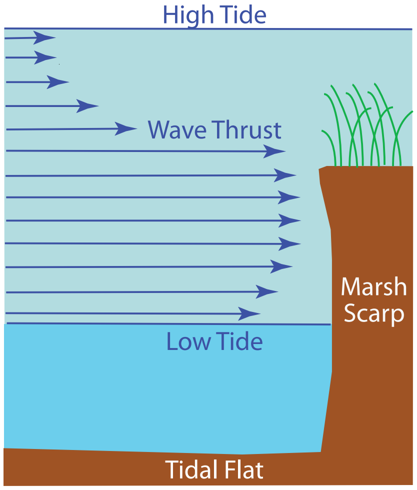

Figure 2. Thrust exerted by waves on a marsh scarp. The thrust is maximum when the water level is just below the marsh platform and decreases during high tides or storm surges. *Modified after Tonelli et al. (2010)*

most of Venice's history.

Other societies have also dealt with the delicate equilibrium between land and sea. Ancient Chinese relocated coastal cities at the mouth of the Yellow River due to complex erosion/accretion patterns (Chen and Zong, 1998), and Frisians were among the first to erect dykes to hold back the advances of the sea (Charlier et al., 2005). Today, we recognize salt marshes as among the most productive ecosystems on Earth, providing nurseries for fish species and shelter and food for endangered birds. They are important to humans because they mitigate the impacts of hurricanes and tsunamis and sequester large volumes of carbon in their peat soil. Understanding the mechanisms responsible for marsh stability or deterioration is therefore a key issue for society.

The long experience of Venetians with the intertidal landscape provides a series of exceptional insights into the evolution of these environments and on how to protect them from change. Two observations are still valid today:

1. There is an eternal struggle between the land and the ocean at salt marsh boundaries; thus, equilibrium seems precarious.
2. Rivers are major players in intertidal morphodynamics, providing sediment for salt marsh expansion.

Here, we define horizontal equilibrium as when the lateral area of a salt marsh is constantly maintained at the centennial time scale, that is, the marsh boundaries do not migrate in time.

WAVE EROSION OPPOSES MARSH EXPANSION

If sediment discharged by rivers is the major player in salt marsh formation, erosion caused by waves is the opposing element. Waves control erosion along marsh boundaries (van der Wal and Pye, 2004; Mariotti et al., 2010; Tonelli et al., 2010), and loss of marsh area through marsh edge erosion has been observed in many coastal environments, with rates ranging from ~ 0.1 m to > 3 m yr^{-1} (e.g., Day et al., 1998; Schwimmer, 2001; Wilson and Allison, 2008; Marani et al., 2011; Sean McLoughlin, Virginia Coast Reserve Long Term Ecological Research, *pers. comm.*, 2013). Indeed, new evidence shows that salt marshes are particularly weak when exposed to wave action.

Marsh scarps expose bare sediment below the vegetation surface, and this material can be easily removed by incoming waves (Feagin et al., 2009). Recent results at the Virginia Coast Reserve Long Term Ecological Research (LTER) site show that when the water elevation equals marsh elevation, waves exert the maximum thrust on the scarp and are therefore the most dangerous for erosion. These water-level conditions are very common during a tidal cycle, and suggest that storm surges are not necessarily responsible for scarp deterioration (Tonelli et al., 2010; Figure 2). Downcutting at the scarp toe is also common along marsh boundaries, resulting in cantilever failure and detachment of large blocks. Removal of the vegetated surface often takes place during moderate storms, and once the protective vegetation mantle is gone, waves easily erode the bare sediment (Figure 3). While marshes seem very resilient in the vertical direction as a result of sediment input, they are weak in the horizontal because of erosion caused by waves.

BIOLOGY AFFECTS SEDIMENT STRENGTH AND MARSH BOUNDARY EROSION

Sediment and ecological characteristics also contribute to erosional processes at marsh boundaries. Much of the alongshore variability in marsh erosion is attributable to small-scale, local variations, such as the morphology of the edge, sediment grain size, vegetation characteristics, and the abundance of bivalves and burrowing crabs (Phillips, 1986; Feagin et al., 2009; Sean McLoughlin, *pers. comm.*, 2013).

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These physical and biotic characteristics determine erosion resistance and exposure to wave activity.

Aboveground vegetation slows flow velocities, traps sediment, and attenuates waves and turbulence (Christiansen et al., 2000; Leonard and Croft, 2006; Mudd et al., 2010; Riffe et al., 2011). At the same time, belowground roots and rhizomes help to stabilize marsh sediment (Coops et al., 1996; Micheli and Kirchner, 2002; Sean McLoughlin, *pers. comm.*, 2013) and play an important role in reducing erosion. Edge stability is a function of the binding capacity of the root system to sediment, which is determined by the biomass, length, diameter, and tensile strength of the roots (van Eerdt, 1985). Root strength typically decreases with depth, making marsh edges susceptible to undercutting. Excessive nutrients can also weaken creek banks and marsh boundaries, triggering slumping and lateral erosion. In fact, high nutrient levels increase aboveground leaf biomass, decrease the dense, belowground biomass of bank-stabilizing roots, and increase microbial decomposition of organic matter, leading to weaker, more porous soil (Deegan et al., 2012).

Sediment shear strength increases as the ratio of root biomass to sediment mass increases, and marshes with dense root mats are generally more resistant to erosion from wave attacks and tidal currents (van Eerdt, 1985; Allen, 1989; Micheli and Kirchner, 2002; Watts et al., 2003). However, Feagin et al. (2009) failed to find a relationship between belowground biomass and edge erosion, and attributed erosion resistance to sediment characteristics, including bulk density, percent sand, water content, and organic matter. Their results suggest that above a threshold bulk density of 0.9 g cm^{-3}, increases in the fractions of very coarse sand and bulk density lead to higher erodibility. In contrast, McLoughlin (2010) found a strong inverse correlation between bulk density, fraction of sand, and erosion rate. Less-consolidated sediment is more easily eroded than firmer, muddier sediment, and edges with sandy sediment are typically more susceptible to undercutting from wave action than those with finer-grained sediment (Allen, 1989).

The abundance and composition of invertebrates in marshes, including burrowing crabs and bivalves, also influence marsh edge resistance to erosion (McLoughlin, 2010). Dense, interconnected crab burrows, which can reach densities as high as 700 m^{-2} along some marsh edges, decrease sediment shear strength and increase permeability and water content, ultimately reducing soil strength and erosion resistance (Allen and Curran, 1974; Montague, 1980; Escapa et al., 2008). On the other hand, the presence of bivalves such as the ribbed mussel *Guekensia demissa* may stabilize marsh edges and reduce erosion rates by both slowing wave and current velocities and binding sediment to the root mat (Bertness, 1984).

Intertidal oyster reefs adjacent to marsh edges may similarly reduce wave energy and erosion rates (Meyer et al., 1997; Piazza et al., 2005; Scyphers et al., 2011). Within the Virginia Coast Reserve, median erosion rates for four marshes located in proximity to oyster reefs (but not directly fronted by reefs) are 0.1–0.2 m yr^{-1} over the last 50 years (Taube, 2013). These rates are within the wide range of erosion rates observed at mainland marsh sites without nearby reefs (McLoughlin, 2010; Taube 2013), but smaller than rates observed on island or back-barrier marshes fronting large expanses of open water (Sean McLoughlin, *pers. comm.*, 2013).

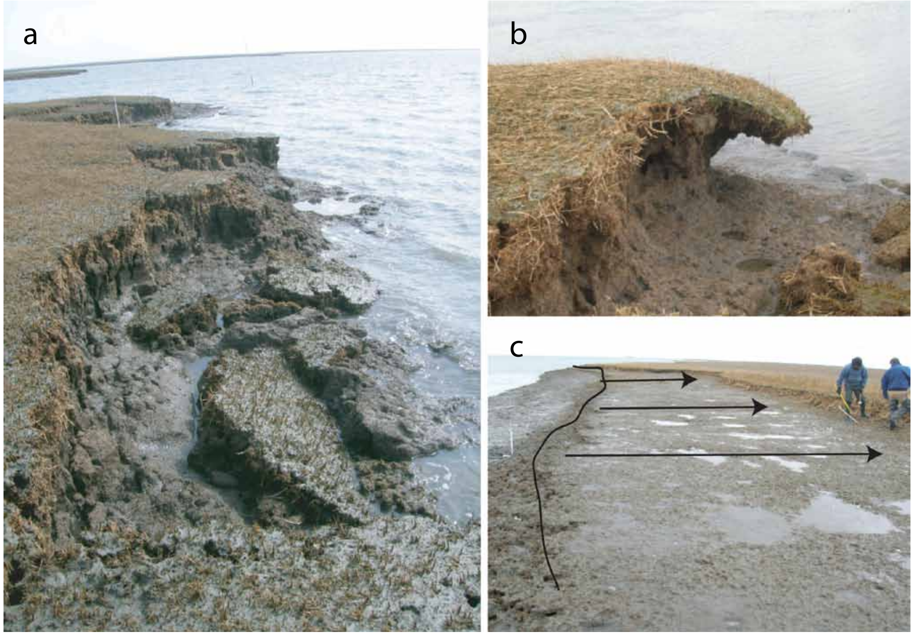

Figure 3. Different mechanisms of marsh boundary degradation by wave erosion at the Virginia Coast Reserve Long Term Ecological Research site: (a) slumping, (b) undercutting, and (c) root scalping (removal of the active root layer forming a denuded terrace). *Adapted from Fagherazzi et al. (2013)*

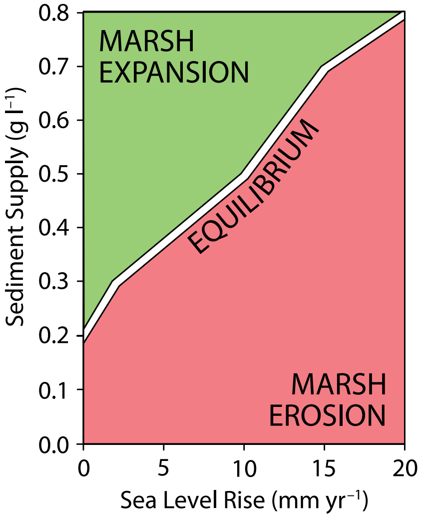

Figure 4. Occurrence of marsh lateral erosion/expansion as a function of sea level rise and sediment supply for a given wave climate (results from the model of Mariotti and Fagherazzi, 2010). Lateral equilibrium exists only for specific values of sediment supply and sea level rise. Marsh erosion can also occur for a constant sea level, if sediment availability is low.

Measurements of wave transformations across oyster reefs in the Virginia Coast Reserve LTER indicate that they can significantly dissipate wave energy when water depths are below mean high water, but are less effective when water depths are greater (Taube, 2013), similar to the findings of Fagherazzi and Wiberg (2009) regarding wave-generated bed shear stresses in shallow coastal bays.

A PARADIGM SHIFT: MARSHES AS NONEQUILIBRIUM LANDSCAPES

There is strong evidence that salt marshes are very resilient to increases in sea level (Kirwan et al., 2010). An increase in sea level results in more flooding of the marsh surface, and, therefore, there is more time for sediment to settle on the platform (Reed, 1995; Temmerman et al., 2005). This feedback keeps the marsh tied to sea level so that it tracks fast sea level variations (D'Alpaos et al., 2011). Ecogeomorphic feedbacks also favor the vertical stability of marshes. Some of the most common marsh plants increase their biomass if the marsh platform level decreases; more biomass promotes belowground organic production and aboveground sediment trapping, increasing marsh elevation in the long run (Fagherazzi et al., 2012). For example, Morris et al. (2013, in this issue) show that plant productivity at the Plum Island Sound LTER, Massachusetts, and North Inlet, South Carolina, respond positively to variations in mean high water at annual time scales. As a result, most marshes display accretion rates that are higher than local rates of sea level rise as long as sediment is available in the water column. Numerical models indicate that vertical drowning and marsh collapse result only from extremely high rates of sea level rise of > 10 mm yr^{-1} (Kirwan et al., 2010). Marsh resilience to drowning is thus strongly related to sediment supply.

As discussed above, marsh boundaries are very sensitive to wave erosion. Whereas marshes can find an equilibrium elevation with respect to sea level and maintain such equilibrium when sea level increases, they seem unable to maintain their horizontal extent. The intrinsic weakness of the marsh scarp prevents the marsh from attainting static equilibrium in which neither erosion nor progradation occur. Even modest storms are able to wash away sediment that cannot be replaced at roughly the same time. Dynamic equilibrium, when erosion equals progradation, also seems unlikely in the long term. Figure 4 shows results of a numerical model of the dynamics of a marsh boundary (Mariotti and Fagherazzi, 2010). For a given sea level rise and wave climate, equilibrium is only present for a very specific value of sediment supply. However, sediment supply is an external variable—a function of nearby rivers and other sediment sources—and mechanisms that would tune its value to match local wave erosion are not present.

The main reason for this lack of equilibrium is that processes responsible for marsh expansion are weakly linked, if at all, to processes responsible for marsh erosion. Sediment availability is mostly dictated by riverine inputs to the coast, and therefore has a terrestrial origin, while coastal processes dictate wave erosion, which is largely disconnected from the presence of rivers.

MARSH COLLAPSE DOES NOT REQUIRE SEA LEVEL RISE

Because waves in coastal bays are locally generated by wind, the extent of the tidal flat plays a principal role in the wave regime. The larger and deeper the tidal flat, the larger the waves (Fagherazzi and Wiberg, 2009). As a result, large tidal flats promote erosion of the marsh boundary.

Based on this simple observation, Mariotti and Fagherazzi (2013) determined a critical tidal flat size in the lagoons of the Virginia Coast Reserve LTER. This critical size, of the order of a few square kilometers, strongly depends on sediment availability to the system. Tidal flats larger than this critical size continue to enlarge as the larger waves erode the salt marsh boundary and increase the size of the tidal flat that then increases wave height, thus establishing positive feedback that leads to catastrophic marsh deterioration. Tidal flats smaller than the critical size will instead shrink, due to marsh expansion and a decrease in wave-induced erosion of the marsh boundary, leading to the complete conversion of tidal flats to salt marshes. This model suggests that the coexistence of salt marshes and tidal flats is always transitory; bays either tend to become filled with salt marshes or are transformed into wave-dominated open water (Figure 5).

Sediment availability determines whether marshes prograde seaward and counteract wave erosion. Large amounts of sediment, either coming from rivers or imported from the continental shelf by tidal exchange through the inlets (Figure 5), allow marsh progradation even in the presence of waves (Yang et al., 2001, 2002). The model of Mariotti and Fagherazzi (2013) shows that sediment availability increases the critical tidal flat size, preventing irreversible marsh erosion. Tidal flats that would enlarge when little sediment is available might shrink when more sediment is present. Conversely, a disappearing tidal flat might switch to erosive conditions if sediment availability suddenly decreases. For very large sediment availability, all tidal flats will be transformed into salt marshes, independent of the size of nearby tidal flats.

Sea level rise deepens the water over tidal flats and increases the sediment flux from tidal flats to salt marshes. Such processes change the tidal flat equilibrium, increasing wave energy and hence indirectly promoting marsh boundary erosion. However, this effect is relatively small compared to the role played by tidal flat size and sediment availability. Mariotti and Fagherazzi (2013) show that differences in sea level rise (0–10 mm yr^{-1}) do not explain the different erosional behavior of tidal flats at various sites along the US Atlantic coast. Sediment availability and the size of nearby tidal flats seem to be the major factors determining the dynamics of marsh boundary erosion. An unexpected finding of Mariotti and Fagherazzi (2013) is that erosion of the marsh boundary occurs even in the absence of sea level rise. Indeed, marsh boundaries can be degraded by waves even if sea level remains constant.

In fact, high inputs of sediment can counteract very fast rates of sea level rise (Yang et al., 2001). If the rate at which waves and currents are removing sediment from the marsh boundary is higher than the rate at which sediment is provided by rivers and by the adjacent sea or continental shelf, the marsh will enter into an erosive state, and this state can be irreversible even in absence of sea level rise (Mariotti and Fagherazzi, 2013).

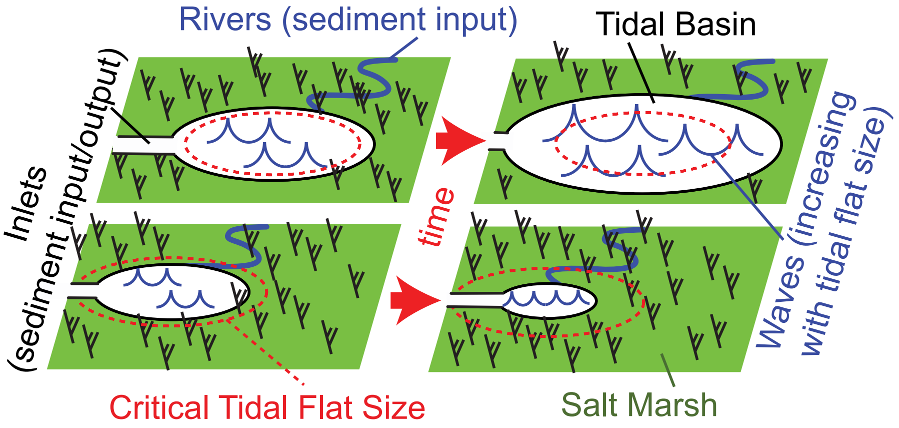

Figure 5. Evolution of tidal bays subject to wave erosion at the boundaries, sediment inputs from rivers, and sediment exchange with the ocean. If the tidal flats are larger than a critical size, irreversible marsh erosion occurs. On the contrary, a small tidal flat area (smaller than the critical size) promotes infilling and marsh formation.

ASSESSING MARSH RESILIENCE: A SEDIMENT BUDGET APPROACH

Focusing on whether marshes can keep pace with sea level rise might not be the correct direction to take in order to understand the fate of salt marshes. It may be wise for our society to consider measures to prevent coastal erosion that might include removal of dams, as is being done in the western United States to enhance salmon fisheries, and river diversion. (Note that more than $2.5 billion were spent on beach nourishment on the East Coast and Gulf of Mexico in the last century; see Trembanis et al., 1999.) Waters of the Mississippi River have been concentrated into one distributary to improve navigation; now there is consideration of diverting some of those waters to provide more sediment to Louisiana marshes (Nittrouer et al., 2012).

Here, we advocate a holistic approach based on a detailed analysis of a marsh's sediment budget and surroundings, including the key role of vegetation in sediment transport processes. All sediment fluxes from marshes to nearby tidal flats, as well as the role of tidal channels in providing or removing sediment, must be quantified at each marsh location.

The absence of horizontal stable equilibrium means that salt marshes lack internal feedbacks that can counteract variations in wave regime and sediment supply. A conservation strategy aimed at preserving salt marsh extension might therefore be undermined by the dynamic nature of these landforms. Rather than preserving marshes in their present conditions, coastal managers should instead promote marsh expansion by providing enough sediment to the intertidal area. They can also target a specific ratio of salt marsh to tidal flat area for a given system, without addressing local erosion or progradation.

> “RECENT RESULTS SHOW THAT MARSH COLLAPSE CAN OCCUR IN THE ABSENCE OF SEA LEVEL RISE IF THE RATE AT WHICH SEDIMENT IS ERODED AT MARSH BOUNDARIES IS HIGHER THAN THE INPUT OF SEDIMENT FROM NEARBY RIVERS OR FROM THE CONTINENTAL SHELF.”

The major threat for marsh survival is lack of sediment supply rather than sea level rise because horizontal change in salt marshes occurs faster than vertical change. Sea level rise endangers marsh survival only if sediment is scarce, and it is not much of a problem if there is an abundance of sediment.

Furthermore, sediment inputs to the coastal ocean have changed more over the past century than rates of sea level rise. Anthropogenic reduction of sediment supply due to dam construction (Syvitski et al., 2005) is potentially catastrophic for salt marshes. Sea level rise can only exacerbate existing erosive processes by trapping large amounts of sediment on the marsh platform. This sediment is no longer available to promote marsh formation and counteract lateral erosion (Mariotti and Fagherazzi, 2013).

While our findings are readily applicable to coastal areas with substantial river inputs, they also apply to fringing marshes, in which the ocean is the sediment source. Again, a marsh can expand even in presence of sea level rise if sediment supply and organogenic accumulation are large enough to offset drowning and lateral erosion (e.g., Redfield, 1965).

As a final observation, it is not difficult to envision how ancient Venetians would counteract today's threat from the ocean that is resulting in the rapid disappearance of salt marshes in the Venice lagoon. They would most surely enhance the sediment supply to the coast by removing dams or diverting rivers, the opposite of what they did to prevent infilling several centuries ago.

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