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Marsh Processes and Their Response to Climate Change and Sea-Level Rise

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Abstract

In addition to their being vital components of mid- to high-latitude coastal ecosystems, salt marshes contain 0.1% of global sequestered terrestrial carbon. Their sustainability is now threatened by accelerating sea-level rise (SLR) that has reached a rate that is many times greater than the rate at which they formed and evolved. Modeling studies have been instrumental in predicting how marsh systems will respond to greater frequencies and durations of tidal inundation and in quantifying thresholds when marshes will succumb and begin to disintegrate due to accelerating SLR. Over the short term, some researchers believe that biogeomorphic feedbacks will improve marsh survival through greater biomass productivity enhanced by warmer temperatures and higher carbon dioxide concentrations. Increased sedimentation rates are less likely due to lower-than-expected suspended sediment concentrations. The majority of marsh loss today is through wave-induced edge erosion that beneficially adds sediment to the system. Edge erosion is partly offset by upland marsh migration during SLR.

- Despite positive biogeomorphic feedbacks, many salt marshes will succumb to accelerating sea-level rise due to insufficient mineral sediment.
- The latest multivariate marsh modeling is producing predictions of marsh evolution under various sea-level rise scenarios.

- The least well-known variables in projecting changes to salt marshes are suspended sediment concentrations and net sediment influx to the marsh.
- We are in the infancy of understanding the importance and processes of marsh edge erosion and the overall dynamicism of marshes.
- This review defines the latest breakthroughs in understanding the response of salt marshes to accelerating sea-level rise and decreasing sediment supply.
- Climate change is accelerating sea-level rise, warming temperatures, and increasing carbon dioxide, all of which are impacting marsh vegetation and vertical accretion.

1. INTRODUCTION

Salt marshes exist in protected coastal saltwater environments at the interface between the uplands and the coastal ocean. They are found in warm to cool latitudes (≥30°C) (**Figure 1**), being outcompeted by mangroves in warmer regions (Duarte et al. 2008). Back-barrier salt marshes began forming 3.5 to 3.0 ka BP when the rate of sea-level rise (SLR) decelerated, allowing sandy barriers to stabilize and creating protected bays and lagoons (e.g., US East and Gulf Coasts; India's east coast; the Algarve, Portugal; Atlantic coast of Europe). Concurrently, there was a slowdown in the drowning of river valleys, causing sediment accumulation along estuary margins (e.g., Chesapeake and Delaware Bays, US East Coast; the Thames, England; the Elbe, Germany; Qiantang Estuary in Hangzhou Bay, China; Kuskokwim River, Alaska), while larger, more sediment-rich rivers formed deltas that prograded onto the inner continental shelf (e.g., the Mississippi, Copper, Rhone, Ebro, and Po) (see the present example in **Supplemental Figure 1**). These low-energy,

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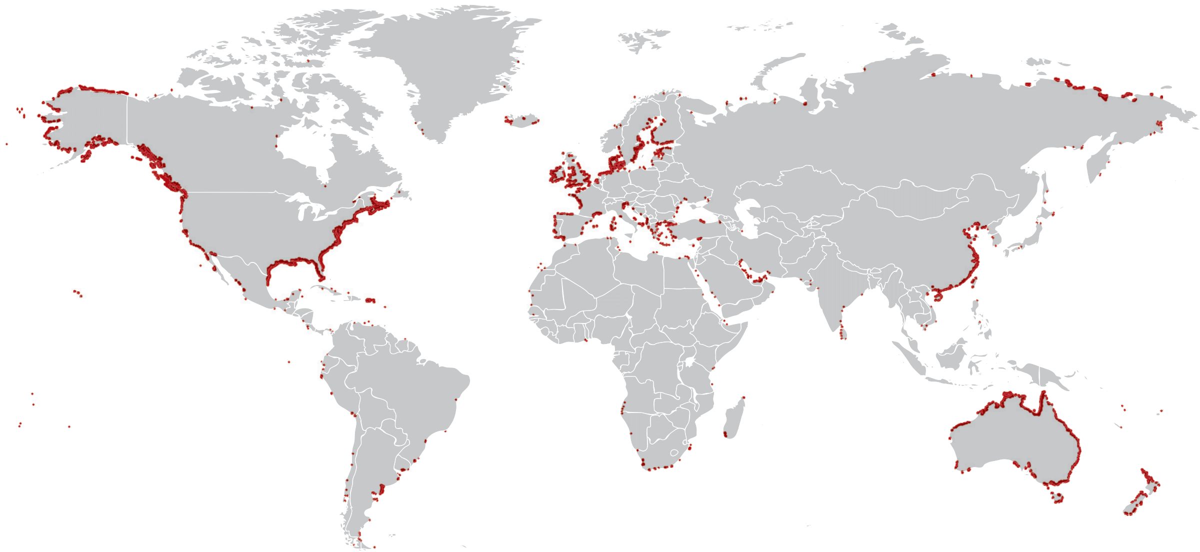

Figure 1

Global distribution of salt marshes. Data from Mcowen et al. (2017).

Table 1 Rate of sea-level rise during salt marsh formation

Location	Curve database	Rates (mm/year)	Reference(s)
Chezzetcook, Nova Scotia	Basal peats and forams	1.7 from 1000 to 1800 AD 1.6 from 1800 to 1900 AD	Gehrels et al. (2005)
Phippsburg, Maine	Basal peats and forams	0.5–1.4 from 5.7 to 3.0 ka BP 0.2–0.8 from 3.0 ka BP to present	Gehrels et al. (1996)
Wells, Maine	Basal peats and forams	0.7–2.2 from 5.7 to 3.5 ka BP 0.0–0.6 from 3.5 ka BP to present	Gehrels et al. (1996)
Northern Massachusetts	Basal peats	0.80 ± 0.25 from 3.3 to 1.0 ka BP 0.52 ± 0.62 from 1.0 to 0.15–0.5 ka BP	Donnelly (2006)
Hudson River, New York	NA	1.2 ± 0.2 during late Holocene	Pardi et al. (1984)
Delaware	Basal peats	1.2 ± 0.2 during late Holocene	Belknap & Kraft (1977), Nikitina et al. (2000)
Eastern shore, Virginia	Basal peats	0.9 ± 0.3 during late Holocene	Engelhart et al. (2009)
Central to southern North Carolina	Basal peats	0.82 ± 0.02 since 3903–3389 cal a BP	Horton et al. (2009)
West Brittany, France	Basal peats	0.90 ± 0.12 since 6.3 ka BP	Stéphan et al. (2014)
Northern Scotland	Basal peats and other	Stable with ±40.0 cm of change during past 2 ka	Gehrels et al. (2006), Barlow et al. (2014)
Ho Bugt, Denmark	Basal peats and other	1.0 during past 4 ka	Gehrels et al. (2006)
Pounawea, New Zealand	Peats and forams	0.3 ± 0.3 from 1500 to 1900 AD	Gehrels et al. (2008)
East coast, South Korea	NA	0.74 from 5.4 ka BP to present	Han (1994)

Abbreviation: NA, not available.

depositional environments were the birthplaces of our modern marshes. In barrier island settings, marshes became well developed and areally more extensive in regions where tidal ranges (TRs) are ≥1.4 m (sensu Hayes 1979). Numerous stratigraphic studies indicate that marshes encroached onto uplands as sea level rose (Mudge 1862). However, the majority of salt marshes developed on top of tidal flats and have gradually built vertically from intertidal environments dominated by low marsh grasses formed between mid- and high tide to platform marshes that exist near high tide to supratidal elevations [e.g., Plum Island Sound, Massachusetts (**Supplemental Figure 2**); Wells, Maine (Gehrels et al. 1996); Whale Beach, New Jersey (Donnelly et al. 2001); Parramore Island, Virginia; Kiawah Island, South Carolina (Duc & Tye 1987)].

Supplemental Material >

During their formation and throughout their evolution the rate of SLR was relatively slow, between 0.2 and 1.6 mm/year (**Table 1**). The sustainability of marshes is now threatened by accelerating SLR that is many times greater than the rate under which they initiated and evolved. For example, the Romney marsh north of Boston contains a 2-m-thick peat that began forming 3.1 ka BP when sea level was rising at about 0.8 mm/year, a rate that slowed to 0.52 mm/year around 1 ka BP (Donnelly 2006). The rate of SLR in Boston Harbor is now 2.88 mm/year, which far exceeds the rate occurring when the Romney marsh built to a supratidal elevation. Eventually, SLR will outpace most marshes' ability to accrete vertically (Crosby et al. 2016) (**Figure 2**) and/or compensate for marsh loss by expanding laterally inland (Kirwan et al. 2016b). Threshold crossings and rates of marsh deterioration, either through bank erosion or by conversion of platform marsh to open water, have been estimated using models (e.g., Schile et al. 2014, Kirwan et al. 2016b), but there is a great deal of uncertainty associated with both the projected rates and the complex response of the marsh.

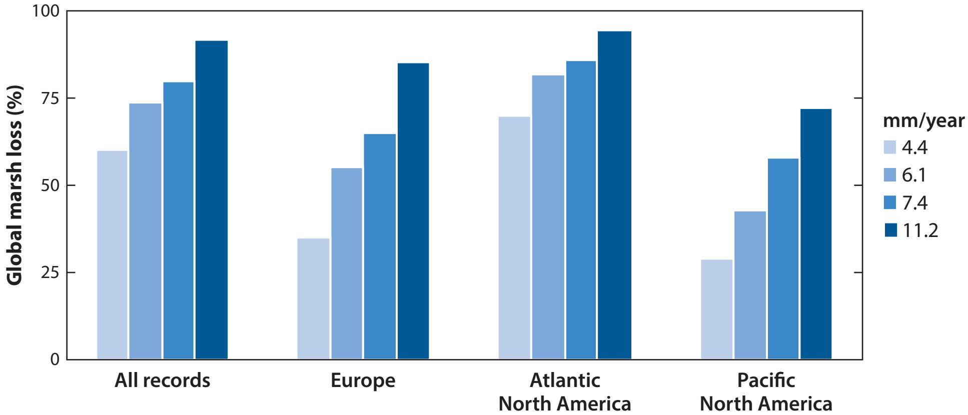

Figure 2

Predicted percentages of global marsh loss due to drowning given the present rate of vertical accretion for different scenarios of sea-level rise. Figure adapted from Crosby et al. (2016).

In addition to being vital components of coastal ecosystems, filtering runoff and providing nursery grounds for commercial fish stocks, salt marshes contain 0.1% of global sequestered terrestrial carbon (Quintana-Alcantara 2014). Widespread erosion of creek banks in many marshes as well as the expansion of salt pannes and pools (Wilson et al. 2014) through bacterial and chemical decomposition converts organic sediment to carbon dioxide (CO_2) and methane (CH_4), both greenhouse gases, warming and providing positive feedbacks to SLR. Marshes are important landforms for lessening the widespread flooding caused by storm surges and providing a platform upon which sandy barriers can retreat (Brenner et al. 2015, Deaton et al. 2017). During the past decade, numerous field investigations and modeling studies have revealed the complex dynamics and potential fragility of these systems in response to accelerating SLR. Most of the major deltas of the world have experienced a substantive reduction in sediment load and are sinking at rates much greater than global rates of SLR (Saito et al. 2009, Syvitski et al. 2009). As this trend continues, vast wetlands will be consumed.

Recent research has demonstrated that marshes are not static, vertically accreting platforms controlled by simple inorganic sedimentation and belowground biomass production and decomposition. Rather, new studies have shown that marshes are dynamic ecological systems that respond to storms and numerous interactive hydrologic, biologic, sedimentologic, and geochemical processes.

As our ability to run increasingly complex numerical simulations has improved with dramatic advances in computing power, modeling studies have become an essential part of our investigative tool kit. This work provides important contributions to our predictions of how marsh systems will respond to greater frequencies and durations of tidal inundation and in quantifying tipping points, when marshes will ultimately begin to disintegrate. To complement this, physical models of marshes, including flume studies, are shedding light on the mechanics of marsh erosion, particularly in combination with crab bioturbation and geochemical processes (Möller et al. 2014, Farron 2018, Reef et al. 2018).

This review examines recent advances that have helped to better quantify marsh processes, their dynamic behavior, and their projected evolution in our changing environment. We start in Section 2 by introducing the progress made in numerical modeling of marshes, a tool that has contributed to all areas of salt marsh research. In Section 3 we then summarize advances in marsh hydrodynamics, which underlie most other marsh processes. Next, we examine the dynamic nature of marshes, first looking at processes that shape the platform surface in Section 4 on vertical accretion and Section 5 on ecogeomorphology and then addressing processes impacting salt marsh boundaries in the sections on marsh edge erosion and upland expansion and response to SLR (Sections 6 and 7, respectively). We move on in Section 8 on storm sedimentation to consider the potential impact of localized, periodic events, and, finally, we discuss the likely response of marsh systems to future environmental change in Section 9 on climatic impacts.

2. NUMERICAL MODELING OF MARSHES

The use of numerical modeling in salt marsh research has grown exponentially over the last two decades (**Supplemental Figure 3*a***). In addition, models provide a unique predictive capability that cannot be matched by physical models or determined purely from lab or field experiments. In the face of climate change, and the intrinsic sensitivity of marshes to factors such as SLR, it is understandable that the use of models has become so central to salt marsh science (**Supplemental Figure 3*b***).

Supplemental Material >

Models in the geosciences fall along a continuum from complex simulation models to focused exploratory models that simplify the full physics, chemistry, or biology (Murray et al. 2014) (**Supplemental Figure 3*b***). Models also range from one-dimensional (1D) models [e.g., the Marsh Equilibrium Model (MEM)] (Morris et al. 2002) to two-dimensional (2D) models operating over a transect (e.g., Marani et al. 2013) or planform domain (e.g., D'Alpaos et al. 2005, Mariotti & Fagherazzi 2013) to complex three-dimensional (3D) models solving a suite of equations across a grid. The latter can record vertical erosion/deposition history as well as lateral interactions or feedbacks (e.g., Temmerman et al. 2007, Alizad et al. 2016). The Sea Level Affecting Marshes Model (SLAMM), a 2D model, has been widely used to assess coastal landscape evolution, despite being developed to map ecosystem change, rather than morphology, and lacking certain physical processes and feedbacks beyond a fixed rate. Many of the more complex 3D models use a hydrodynamic model, such as Delft3D (Lesser et al. 2004) or Finite Volume Community Ocean Model (Chen et al. 2003), linked to sediment and vegetation modules based on existing 1D models. The equations behind MEM, for example, have been incorporated into a number of more complex 1-, 2-, and 3D models (e.g., Mudd et al. 2004, 2009, 2010; Kirwan & Murray 2007; Schile et al. 2014; Alizad et al. 2016).

Ultimately, the ranges of time and spatial scales in marsh evolution limit the ability of scientists to produce a fully comprehensive model. The building blocks of salt marsh geomorphology (hydro-, sediment, and ecosystem dynamics) interact in multiple ways, leading to complex feedbacks (**Supplemental Figure 4*a***). For example, an increase in plant productivity can lead to greater flow baffling and, thus, greater sediment deposition and direct capture of sediment on stems. This increased deposition results in higher nutrient levels and increased elevation, each of which affects plant productivity differently, with elevation also influencing the rate of sediment deposition through an impact on the depth and time of inundation. Beyond the complex feedbacks, salt marsh processes operate on timescales ranging from microseconds (turbulence), minutes to hours (waves, tides, sediment transport, storms), months to years (plant growth, edge erosion, channel incision), and decades (changes in ecotone or channel sinuosity) to tens or hundreds of years (elevation change or inland migration). Similarly, each timescale is associated with a range of spatial scales from grain-on-grain interactions to landscape-scale evolution (Coco et al. 2013) (**Supplemental Figure 4*b***). Building on the shortest spatial or timescales is still not possible computationally without shortcuts to scale up the results when modeling bottom up. For example, upscaling is often performed by simple multiplication, applying a month of change 12 times to provide a year's response. This approach may miss feedbacks or the exact timing of a threshold crossing. Likewise, models that rely on upscaling need to incorporate the short-term impacts of events, such as hurricanes. Either approach, upscaling or simplifying processes, will create error or uncertainty in the results, in some cases to a level that they become meaningless (Coco et al. 2013).

Many mechanisms, particularly ecophysical relationships, are yet to be fully described numerically. As significant as the problem of integrating processes at different scales is, there is insufficient observational evidence to either validate model results or provide an empirical solution where no numerical solution exists for a process. These problems vary by discipline. Marsh hydrodynamics can be well described by solution of the Navier–Stokes equations, and there are existing terms designed to incorporate the impact of morphology, vegetation, or sediment type, such as a Manning number, which alters the bed friction imparted on the flow. However, factors such as the importance of vegetation on soil strength (Howes et al. 2010, Deegan et al. 2012), the importance of edge erosion to sediment supply (Hopkinson et al. 2018), or the impact of fauna on erosion rates (Smith 2009, Wilson et al. 2014, Farron 2018) are only just being identified or quantified. Likewise, human factors (development, impact of boat traffic, and so on) are rarely included in salt marsh models, as they tend to be site specific and difficult to generalize. By necessity, therefore, many models exclude certain mechanisms or parameters.

For example, in the application of a 1D model to a 2D space, it is common that each point in the 2D domain responds to the forcing based on its individual conditions but has minimal interactions with neighboring points (e.g., SLAMM) (Schile et al. 2014). This excludes potentially important factors, such as lateral (clonal) propagation of vegetation rather than seeding or even continuity or conservation of mass. Many models (e.g., SLAMM) apply either a fixed or varying accretion rate across the entire domain, regardless of the sediment availability at the modeled location. Yet Kirwan et al. (2010) demonstrated that suspended sediment supply can be a limiting factor in marsh resilience to SLR.

Models provide a significant opportunity to explore and predict salt marsh evolution but are limited by the parameters they include and the quality of the empirical relationships or boundary conditions that underlie them. It is important to understand the assumptions and limitations of any model when interpreting the results. That said, numerical models have been the backbone of many important advances over the past few decades. The MEM (Morris et al. 2002) led to a general acceptance that salt marsh vegetation production varied with relative sea level, and individual grass species have an optimum level. Fagherazzi et al. (2006) demonstrated the importance of locally generated waves on the development of the bimodal elevation observed between marsh platform and tidal flats. The tidal instantaneous geomorphologic elementary response (TIGER) model (Fagherazzi et al. 2008) showed the importance of vegetation on ebb dominance observed in small marsh channels. Much of our understanding of channel network evolution has stemmed from models (Marani et al. 2002; D'Alpaos et al. 2005, 2006) and likewise the dynamics of marsh ponds (Mariotti & Fagherazzi 2010, Mariotti & Carr 2014). The contribution by modeling studies is described and discussed in context within the topical sections of this review.

3. MARSH HYDRODYNAMICS

Tidal flow that flushes salt marshes once or twice daily is the primary hydrodynamic forcing controlling their biology, chemistry, and geomorphology. The past few decades have seen advances in our understanding of both channelized flow and the dynamic equilibrium between flow and morphology as well as new insights into patterns of circulation when the marsh platform is flooded and drained. Moreover, there has been a growing body of evidence highlighting the importance of meteorological forcings including extreme storm surges and local wind-generated waves.

The relationship between channel dimensions and tidal velocity is well established for the tidal inlets leading to salt marsh systems (cf. D'Alpaos et al. 2010); however, a growing body of work has clearly shown that a similar mechanism operates by coupling the volume of the tidal flow (i.e., tidal prism) to the drainage density of the tidal creek network and for channel cross sections throughout the marsh system (Marani et al. 2004, D'Alpaos et al. 2010, Stefanon et al. 2012, Lanzoni & D'Alpaos 2015). Beyond this generalization, however, tidal channel networks exhibit considerable variability and a poor adherence to scaling relationships compared to fluvial systems (D'Alpaos et al. 2005, Jiménez et al. 2014). Differences in sediment type, vegetation, or local hydrodynamics can produce neighboring drainage basins that have entirely different planforms and hypsometries as well as exhibit different relationships between drainage area and channel dimensions (Fagherazzi et al. 1999; Marani et al. 2002, 2004; Rinaldo et al. 2004).

Salt marsh tidal hydrodynamics produce in-channel or overplatform flow depending on the level of the tide. The marsh platform sits close to the mean high-water level, and thus, during most of the tidal cycle, tidal and wave processes operate within channels. Tidal currents in salt marsh channels are bidirectional and usually driven by water slope rather than channel slope (Rinaldo et al. 1999, Coco et al. 2013). Knowledge of how these in-channel flows operate is important for determining estuarine circulation, sediment transport pathways, and marsh and channel evolution. It is well established that tides in sandy bays and estuaries are often organized into mutually exclusive flood and ebb channels (e.g., van Veen et al. 2005). In the deeper, narrower, more sinuous channels of salt marshes (Marani et al. 2002, 2004), recent studies have shown the tendency for flood and ebb flows to operate within the same channel but along mutually exclusive streamlines (Fagherazzi et al. 2004, Li et al. 2008). This pattern can impact channel morphology, causing increased bank slumping along areas where strong ebb tidal flow impinges along the channel bank (Fagherazzi et al. 2004).

Salt marsh creeks can be roughly classified as either higher-order, open-ended channels or lower-order, dead-end creeks with different tidal signatures. The larger, high-order creeks experience greater peak velocities (~1 m/s) occurring at mid-tide when water levels are below bank-full stage in the channel. Low-order (small) salt marsh creeks may exhibit a bed gradient, which enhances late ebb flow and retards early flood currents. However, flow is often strongly impacted by the surrounding vegetated and adjacent intertidal areas. Low-order channels experience relatively low flow velocities (~0.1–0.6 m/s) with velocity transients (surges) at close to bank-full conditions. Fagherazzi et al. (2008) demonstrated the importance of the frictional resistance imparted by the vegetation on channel flow. Using their TIGER model, they showed that the ratio of velocity over the marsh to that in the channel is directly responsible for the hysteresis effect that often contributes to ebb dominance in marshes (**Supplemental Figure 5**). Alizad et al. (2016) confirmed the importance of these observations with respect to SLR, showing that increasing water levels over the marsh platform will reduce frictional resistance, both due to the bed and from marsh vegetation. This increases flow rates and creates a more even circulation. This will impact erosional-depositional processes and ultimately channel networks and marsh geomorphology and evolution.

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When water levels overtop the bank, at high tidal levels or during meteorological tides, overbank flow occurs. This creates convoluted transport pathways and impacts the residence times within tidal watersheds (Sullivan et al. 2015). During overbank flow, conservation of mass or momentum within an individual channel may not always exist due to exchanges with adjacent channels. Using a combination of Deltf3D model simulations and dye visualizations across the marsh, Sullivan et al. (2015) studied the complexity of tidal flow over an inundated marsh surface.

Platform topography was incorporated into the model via a real-time kinematic digital elevation model collected at a resolution of 0.25–5.0 m. They observed and modeled the development and decay of complex overmarsh flow patterns during each tide including simultaneous divergence and convergence, large-scale rotations, and contrasting flood and ebb pathways. This complexity is primarily controlled by submergence and emergence of fine-scale topography on the marsh platform. Numerical models of flow variation across a marsh surface also demonstrate that erosion potential reaches maximums at the tip of channels where flow is focused into the creek (D'Alpaos et al. 2005).

The presence of microtopography or small capillary creeks (<1 m wide) on the marsh platform has a significant impact on salt marsh circulation as a whole, including channel flows (Fagherazzi et al. 2008, Cea & French 2012). Velocities in these channels respond strongly to variations in the intertidal bathymetry and bed friction (Cea & French 2012). Modeling efforts by Zhao et al. (2010) reinforced the importance of fine-scale topography, including the presence of small channels, in controlling flow across the marsh.

Salt marshes are shallow environments with much of the open-water area in the form of ponds or channels. Wave energy decreases markedly with distance from the ocean, and local fetches are often small; thus, it would seem that wave activity would have little effect on marsh processes. Yet, a growing body of work suggests that waves have a significant impact on marsh geomorphology. For example, marsh platform edge erosion has been shown to be closely related to incident wave power density (Marani et al. 2011). Moreover, recent research emphasized the importance of wave processes within marsh systems in resuspending tidal flat sediment as well as producing sediment through edge erosion. Both of these processes are instrumental in supplying sediment to the marsh platform and sustaining the marsh in a regime of accelerating SLR (Fagherazzi et al. 2006, Mariotti & Fagherazzi 2010, Mariotti & Carr 2014) (see Section 6).

The morphology of the marsh edge significantly impacts shoaling and breaking waves as well as overland flow. The edge is often an abrupt boundary that drastically increases friction due to the shallower water depth and the prevalence of vegetation. Both wave and tide-induced flows experience a sharp reduction in energy, dropping off logarithmically with distance into the marsh (Leonard & Croft 2006, Möller 2006, Möller et al. 2014) (**Figure 3**). When tidal water entirely overtops vegetation, flow is divided into a lower region within the vegetation that exhibits weak velocities and low turbulence. Scaling upward above the canopy, flow increases, inducing strong shear stresses on the underlying vegetation (Neumeier 2007, Howes et al. 2010). The lower limit

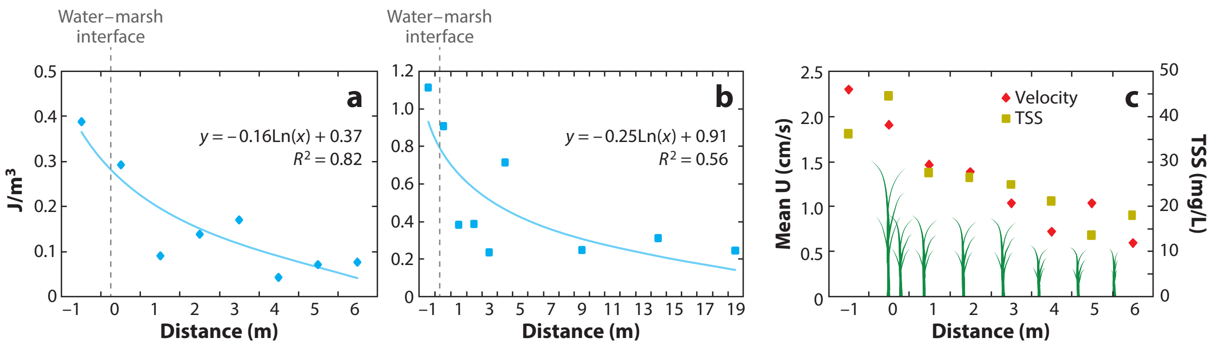

Figure 3

Comparison of change in turbulent kinetic energy with distance from the marsh edge (*a*) for tidal flow only and (*b*) when small wavelets (wave heights <15 cm) were superimposed on tidal currents. (*c*) Total suspended solid (TSS) measured from the marsh edge when only tidal currents prevailed. Figure adapted from Leonard & Croft (2006).

of the turbulent upper flow occurs at a height above where approximately 85% of the biomass exists. There is a strong correspondence between biomass (stem diameter and density) and turbulence intensity, which in turn is closely related to sediment deposition (Neumeier & Amos 2006). Feedbacks between vegetation and geomorphology are discussed below; many involve the effects of vegetation on hydrodynamics (Möller & Spencer 2002, Morris et al. 2002, Fagherazzi et al. 2008, Alizad et al. 2016).

4. VERTICAL ACCRETION

Since their formation, salt marshes have survived slowly rising sea level by building vertically and extending laterally onto uplands (Mudge 1862, Shaler 1888, Redfield 1965). Whether these same processes will allow salt marshes to withstand the present regime of accelerating SLR (Nerem et al. 2018) has been a topic of debate for more than two decades. The high rate of relative SLR along coastal Louisiana (9 mm/year) (Nienhuis et al. 2016) provides an ideal laboratory to assess sedimentation processes on salt marshes and, ultimately, their future stability. Early on, Reed (1995), working on the Mississippi River Delta plain, recognized that tidal imports, vegetation, and depositional processes on marshes would be altered directly or indirectly by the frequency of tidal flooding and the period of inundation (hydroperiod). Reed (1995) noted that due to the complexity of the temporal and spatial scales controlling the processes involved in above- and belowground mass additions and losses, predicting the future resiliency of marshes was likely to be largely inaccurate. While the processes and rates of peat decomposition have been well studied (e.g., Valiela et al. 1985, Benner et al. 1991, Negrin et al. 2012), the decay of marsh peat in response to greater flooding is not well constrained (but see Kirwan & Megonigal 2013).

A major advance for holistically evaluating future salt marsh sustainability came from the pioneering work of Morris et al. (2002) through their field studies at North Inlet, South Carolina. They demonstrated that *Spartina alterniflora* reaches optimum productivity at a certain depth below mean high water, which is close to the bottom of its vertical range, as identified by Pomeroy et al. (1981). Below this depth, plants produce less biomass, and toward the upper limits of its growing range, *S. alterniflora* transitions to a stunted form, which is also biologically less productive. This relationship between productivity and tide level is a homeostatic process that allows the marsh to exist as sea level rises through various feedback mechanisms (Morris et al. 2002). For example, if sea level rises at a faster rate than the marsh surface populated by stunted *S. alterniflora* can maintain, then eventually the tall form *S. alterniflora* will replace the stunted form. Not only do these robust plants make a greater contribution to belowground biomass than the stunted form, but also they trap suspended sediment more efficiently due to their greater stem density and at a higher rate because of the increased frequency and duration of tidal flooding and storm inundation associated with their lower position in the tidal frame (Morris et al. 2002, Mudd et al. 2010). These positive feedbacks allow the marsh surface to increase its rate of vertical accretion, thereby increasing the resiliency of the marsh to rising sea level. At some rate of SLR, however, even tall form *S. alterniflora* may be unable to generate biomass and trap sediment at a sufficient rate to match the increasing water depth and will perish.

Given an understanding of the above relationships and acknowledging that the rate of SLR is accelerating (Jevrejeva et al. 2012), numerous researchers have formulated models of marsh systems in an attempt to predict their future evolution under various relative SLR scenarios. A uniform consensus has not emerged, and even individual investigators have changed their position as more data have been acquired. Kirwan et al. (2010) studied the adaptability of marshes to rising sea level by numerically modeling vertical accretion rates based on the marsh elevation relative to sea level, TR, and estimates of suspended sediment for each system. They explored differences

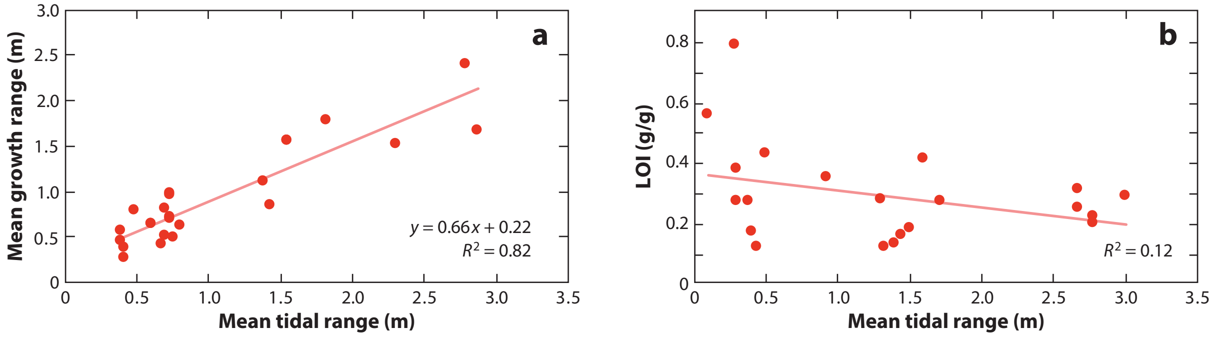

Figure 4

(*a*) Plot of growth range of *Spartina alterniflora* versus tidal range. Data taken from McKee & Patrick (1988). (*b*) Plot of loss on ignition (LOI) versus tidal range using data from Morris et al. (2016) for brackish to saltwater marshes in the United States. Note that there is little correlation between LOI and tidal range.

in vegetation growth, sediment transport regimes, and modes of vertical accretion (mineral and organic) for slow, moderate, and rapid rates of SLR (after Rahmstorf 2007). They determined that moderate rates of SLR enhanced the growth of vegetation and rate of sedimentation, especially in a regime of high suspended sediment concentration (SSC). They also noted that marshes were less vulnerable to SLR in areas of higher TR (Kirwan et al. 2010).

The influence of TR was explored in more detail in a second paper (Kirwan & Guntenspergen 2010) where the authors attributed the vulnerability of microtidal (TR < 2.0 m) marshes to the limited vertical growth range of the vegetation (Day et al. 1995, Friedrichs & Perry 2001) and the increase of water flooding and draining the marsh. The resiliency of mesotidal (TR = 2.0–4.0 m) and macrotidal (TR > 4.0 m) marshes is explained, in part, by the larger swath of upper intertidal zone (above mean sea level) (Mitsch & Gosselink 2000) that marsh grasses occupy with increasing TR (**Figure 4*a***). In these settings, when the low range of marsh vegetation can no longer keep pace with SLR, it will succumb to hypoxia and eventually transition to a tidal flat. However, the large area of marsh above this level will still be viable; microtidal marshes do not have this luxury. Friedrichs & Perry (2001) have also suggested that the stability of marshes in higher TR environments might be related to the greater supply of suspended sediment due to greater tidal inundation. Although this may be true for some systems, there is no clear relationship between TR and supply of suspended sediment to coastal ocean or to back-barrier systems. For example, the suspended loads of the river systems draining into the Gulf of Maine, where spring TRs vary from 2.6 to 6.0 m, are very low (3.6 to 11.7 mg/L) (Weston 2014). These low values are explained by the dominance of physical weathering processes in the drainage basins and the fact that several episodes of Pleistocene glaciation have stripped away the saprolite, leaving behind barren bedrock and thin mantles of till in the mountainous regions. This low suspended sediment leads to low inorganic sedimentation, despite the large TR. Conversely, the microtidal (0.3 m) coast of Louisiana is dominated by discharge from the Mississippi River and its tributaries, where the average SSC is 258 mg/L (Weston 2014).

In a recent study of eight microtidal marshes along the East and West Coasts of the United States, Ganju et al. (2017) used channel sediment fluxes to model the long-term vulnerability of these systems to SLR. As expected, they found a close correlation between the overall marsh sediment budget and the net influx of SSC (flood minus ebb SSC). Moreover, all eight marshes had a net sediment deficit with respect to rising sea level, resulting in life spans ranging from 83 to

5,230 years. Half of the marshes are predicted to convert to open water or tidal flat in 350 or fewer years. The study also found that the vegetated versus unvegetated extent of the marsh correlates well with the sediment budget and the future of the marsh. Hence, as the extent of open water area within marshes increases, their ability to trap sediment is reduced, accelerating their deterioration (Ganju et al. 2017).

A positive sediment budget was reported as responsible for constructing new marshlands in Plum Island Sound, Massachusetts (Kirwan et al. 2011a). Based on stratigraphic and chronologic data, Kirwan et al. (2011b) speculated that marsh expansion was due to an increase in sediment influx resulting from deforestation during European settlement. Although sediment discharge from coastal basins would seemingly have increased during this period, the deranged drainage of the glaciated landscapes of this region produced numerous swamps and small catchments that trap stream-transported sediment. Moreover, stone walls built at the edges of farmers' fields were efficient dams that retained overland sediment transport. Thus, the exact influence of deforestation to marsh systems requires more research.

French (2006) suggested that the processes responsible for marsh growth correlate with TR as microtidal marshes tend to build vertically primarily through the production of belowground biomass, whereas marshes occurring in higher TR environments rely on imported sediment. If this was a pervasive trend, then the organic content of marsh peats should decrease with increasing TR. However, published data for marshes along the East, Gulf, and West Coasts of the United States (Morris et al. 2016) indicate little correspondence between TR and loss on ignition values (**Figure 4*b***). The lack of correspondence with TR suggests that other factors dictate how marshes build vertically and why they exhibit differences in organic versus inorganic content. These factors include marsh elevation, SSC of the tidal waters, frequency and duration of tidal flooding, processes and rates of peat decomposition, and potential sediment delivery via storm surge or ice rafting.

For example, an accretion study of four Long Island, New York, marshes looked at variable salinities, TRs (0.25–3.0 m), and geomorphic settings (Kolker et al. 2010). Multiple chronologies of marsh accretion and inorganic sedimentation were averaged for each site, and then these composite values were averaged for the four sites and plotted over the twentieth century. The authors found a high correlation between accretion and inorganic deposition rates, concluding that accretion rates are a function of variations in mineral fluxes rather than changes in belowground biomass production. This same study showed good evidence that a long-term acceleration in the rates of marsh accretion and mineral deposition tracked well with estimates of global SLR and temperature changes.

Scientists studying salt marshes in eastern Long Island and southern New England have used field observations and photogrammetric analysis to demonstrate substantive erosion over the last several decades due to marsh edge retreat, expanding bays, widening and headward erosion of tidal creeks, island loss, and enlargement of interior depressions. For example, in Jamaica Bay, New York, marsh islands have decreased in size by 12% (Hartig et al. 2002); Rhode Island marshes have declined by 17.3% (Watson et al. 2017); and marshes in Cape Cod have diminished by 10% to >30% (Smith 2009). These authors attribute marsh loss to a variety of causes, including marsh grass herbivory, storm-related increases in TR, decrease in sediment supply, anthropogenic impacts, and—most importantly—SLR. Similarly, a study of estuarine marshes in southeastern England showed that between 1973 and 1988, individual marshes decreased in areal extent by 9.9% to 55% due to a combination of land reclamation and, more importantly, erosion (Doody 2004). The authors concluded that various enclosures separating the marsh from the surrounding uplands contributed to degrading the marshes. These barriers preclude marshes from retreating inland and compound areal losses due to erosion by preventing upland expansion.

Stralberg et al. (2011) looked at marsh sustainability within 15 subregions of San Francisco Bay using a hybrid of the Marsh98 model (Krone 1987, Orr et al. 2003) that included feedbacks between elevation and sediment inputs with constant rates of organic accumulation for specific regions. Their results indicated a general future shift from high- to low-elevation marsh habitats for all modeled scenarios with a loss of high marsh and gains in low marsh and mudflats. They found that to sustain marshes mid-TR will require SSC of greater than 300 mg/L for high rates of SLR (1.65 m/century) and between 100 and 150 mg/L for low rates of SLR (0.5 m/century). In a second modeling study of four sites within San Francisco Bay, Swanson et al. (2013) used a more sophisticated marsh accretion model [Wetland Accretion Rate Model of Ecosystem Resilience (WARMER)] encompassing feedbacks between organic matter accumulation and elevation, a nonlinear relationship between inorganic sediment accumulation and elevation, and temporally varying SLR. Again, the results showed a universal lowering of marsh elevation at all sites by the end of the century with a strong correlation between marsh survival and sediment supply. Finally, a third study (Schile et al. 2014) looking at the sustainability of four highly mature marsh sites (3 to 5 ka in age) in upper San Francisco Bay employed the MEM (Morris et al. 2002), which emphasizes interrelationships among marsh elevation, plant productivity, and rates of accretion. Their findings were consistent with earlier investigations of marsh resiliency in San Francisco Bay, indicating that when the SLR rate is 100 cm/century or greater, most of the marsh will transition to a low marsh, tidal flat, or open water (**Supplemental Figure 6**). Most recently, the future of Pacific coast marshes from mid-California to Washington has been explored using the WARMER model (Thorne et al. 2018). The 14 sites studied encompassed marshes with variable TRs (1.75 to 3.38 m), suspended sediment delivery, SLR rates (Southern California: 1.74 ± 0.63 mm/year; Washington: 0.62 ± 0.59 mm/year), and elevation capital (height above mean high water). For high SLR scenarios, Thorne et al. (2018) found that, excepting two sites with high accretion rates related to relatively high SSC, all the study sites will lose their entire middle and high marsh habitats and 86% of the marshes will be converted to tidal flats or subtidal environments.

Supplemental Material >

Despite many predictions of wide-ranging destruction of salt marshes over the next few centuries due to accelerating SLR and insufficient supply of sediment, there are studies with a more positive outlook, particularly for the immediate future. Examining many predictive studies, Kirwan et al. (2016a) suggested that over the next few decades SLR is not an immediate catastrophic threat to marshes. This viewpoint is consistent with the data-based assessment of Dahl & Stedman (2013), who showed that between 2004 and 2009 the areal extent of saltwater marshes on the Atlantic, Gulf of Mexico, and Pacific coasts of the United States decreased by only 2.4%, and 99% of losses occurred along the Gulf coast and were likely a consequence of hurricane impacts. Kirwan et al. (2016a) supported the sustainable marsh paradigm through a detailed compilation and review of accretion data for US, Canadian, and European marshes (following Cahoon et al. 2006, French 2006, Reed 2008). They collated data for 179 sites and showed that low marshes and a majority of high marshes are keeping pace or aggrading faster than present rates of SLR (**Figure 5**). Moreover, the authors stressed that as the rate of SLR increases and marsh areas are inundated more frequently, biogeomorphic feedbacks will enhance their survival by increasing sedimentation; possibly a warmer climate may also lead to greater marsh productivity due to higher temperatures and CO_2 concentrations (Langley et al. 2009). A field study of marshes in the Elbe Estuary in Germany reinforced the position that low marshes may keep pace with SLR, but high marsh will likely transition to low marsh (Butzeck et al. 2015).

Positive feedbacks may enhance the longevity of marshes; however, a sometimes-overlooked reality of any future marsh scenario is the broader impact of the ultimate conversion of high marsh to low marsh. Not only do supratidal habitats disappear, vastly changing the ecology of marshes (Veloz et al. 2013), but also the tidal prism of the back barrier increases. The change in hypsometry

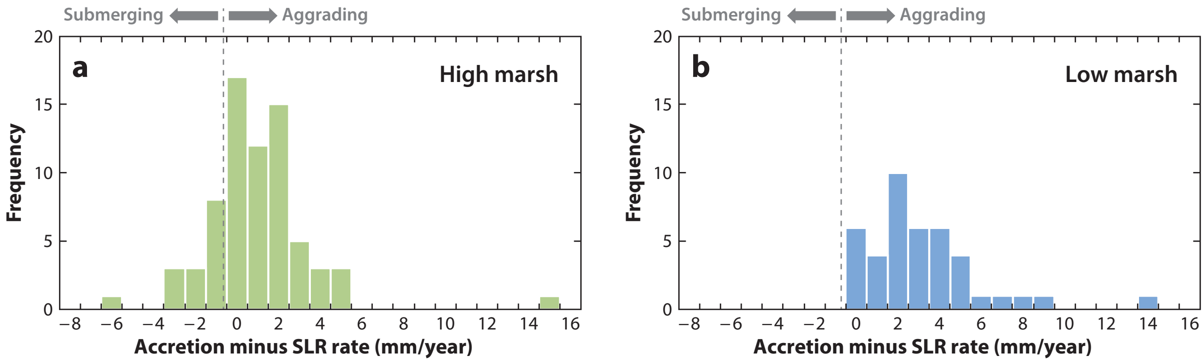

Figure 5

Compilation of sites showing the difference between accretion rates and relative rates of SLR for high and low marshes for the Gulf coast and Atlantic coast of North America and Europe. Figure adapted from Kirwan et al. (2016a). These data show that most marshes are presently keeping pace with SLR.

and increase in tidal exchange have long-term consequences for volumes and pathways of sediment transport throughout the back-barrier system as well as the redistribution of coastal sand resources (FitzGerald et al. 2018). It should also be recognized that the volume of suspended sediment supplied to the marsh system is not unlimited, and historically the volume of suspended sediment contributed to estuaries and the coastal ocean via rivers has been decreasing (Syvitski et al. 2005, Weston 2014). Some researchers (Hopkinson et al. 2018) have invoked marsh edge erosion as a possible source of sediment that augments the supply of suspended sediment derived from rivers and the coastal ocean. Regardless, as high marsh is converted to low marsh, the available suspended sediment to build the marsh vertically is finite and the ability of flooding tides to contribute sediment to the marsh surface will be at an increasing deficit relative to accelerating SLR. For example, within the Plum Island Estuary (PIE) in northern Massachusetts the high platform *Spartina patens* marsh is more than three times the areal extent of the low *S. alterniflora* marsh (Farron 2018). Measured vertical accretion rates for a limited section of this marsh average 2.5 mm/year for the high marsh compared to 7.6 mm/year for the low marsh. Likewise, the inorganic contents of the peat from these two types of marshes are 60% and 80%, respectively (Wilson et al. 2014). Additional data indicate that these rates are reasonable values for the entire PIE marsh system (Connell 2017, Hughes et al. 2017). These measurements clearly indicate that to maintain the same low marsh accretion rate, an order of magnitude more suspended sediment is required once the high marsh is fully converted to low marsh. The flat nature of high platform PIE marshes (80% of high marsh <30 cm in relief) suggests that large areas of the high marsh will be responding to accelerating SLR contemporaneously (**Figure 6**). A boundless suspended sediment supply does not exist in most coastal marshes, and this limitation must be considered when citing positive ecogeomorphic feedbacks in modeling marsh sustainability.

5. ECOGEOMORPHOLOGY

Acceptance of important feedbacks among vegetation, geomorphology, and vertical marsh accretion has led to a drastic increase in cross-disciplinary studies. The consequence of these interactions is the emergence of ecogeomorphology as a subdiscipline within salt marsh science. The term ecogeomorphology was first introduced in the literature by Viles (1988) and defined as the

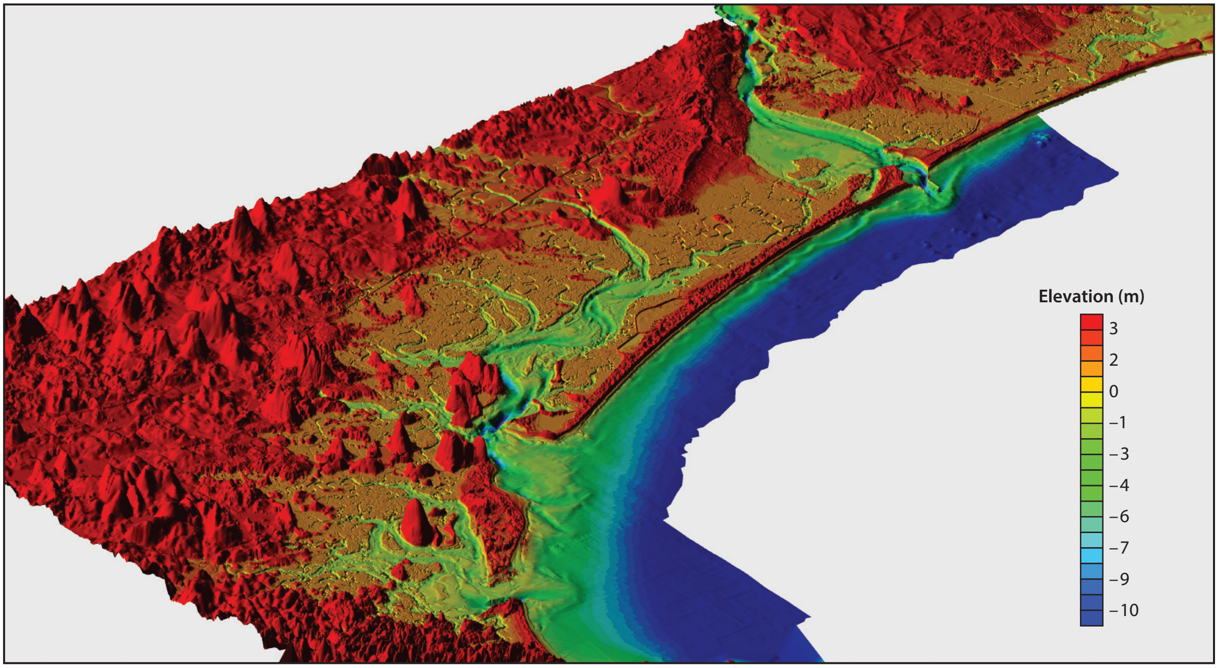

Figure 6

Digital elevation model of Plum Island Sound and the Merrimack River estuary illustrating the flat nature of the high platform marsh. Figure courtesy of Ioannis Georgiou.

study of how plants, animals, and microorganisms impact the development of landforms, including the consequent influence of resulting geomorphology on the ecosystem.

Supplemental Material >

Beyond its role in accretion, the presence of vegetation changes the geotechnical properties of the soil; the increase in organic content has a significant impact on the bulk density (Morris et al. 2016) (**Supplemental Figure 7**). Constant feedbacks between vegetation, soil, hydrodynamics, and fauna exist. For example, the bulk density may affect how easily a soil is eroded and removed by flowing water or the ease with which it is burrowed (Le Hir et al. 2007). The ease of burrowing may attract or deter herbivorous crabs, whereas rooting or a desirable hydroperiod may attract them (Vu et al. 2017). Vegetation also plays a key role in anchoring sediment and reducing erosion by buffering flows and through rooting. Increasingly, studies have included measurements of the shear strength of marsh soils in different settings, comparing this value to the biomass, vegetation type, or nutrient levels to understand patterns of erosion (Howes et al. 2010, Turner 2011, Wilson et al. 2012, Graham & Mendelssohn 2014). Some studies have also suggested that, under specific circumstances, vegetation may enhance erosion, through either motion and momentum exchange with the vegetation (Feagin et al. 2009) or attachment to the roots of vegetation that are removed by high-energy storms (Howes et al. 2010). Temmerman et al. (2007) demonstrated that, while vegetation can improve stability within the stand, proximal sediments may be more exposed to erosion and scour, thus encouraging creek growth around the vegetation.

Marsh faunas can also be landscape modifiers, and an increasing number of studies have attempted to identify and quantify the impact of these ecosystem engineers (e.g., Vu et al. 2017). Widdows & Brinsley (2002) reviewed the impact of several ecosystem engineers, identifying both biostabilizers and biodestabilizers. Biostabilizers include mussels, microphytobenthos, macroalgae, and salt marsh macrophytes. These organisms increase resistance to flow, physically shield or anchor the bed sediments, and enhance sediment cohesiveness. Microbes and algae, although small, can impact sediment transport processes (Fagherazzi et al. 2014). For example, extrapolymeric secretions by microphytobenthos enhance grain adhesion in fine sediments, and microbial assemblages may increase sediment capture and retention by plants. Biodestabilizers include clams, snails, crabs, and other bioturbators that increase surface roughness and reduce the strength of soils and resistance to erosion. The impact of fauna may be direct or indirect. For example, preferential grazing may cause a change in vegetation or loss of vegetation. This impact on the plants may in turn determine marsh erodibility (e.g., Perillo & Iribarne 2003). Alternatively, polychaete burrowing may directly resuspend sediment.

Many studies have focused on crab species, perhaps because of their ubiquity and high population densities in marshes (e.g., Perrillo & Iribarne 2003, Holdredge et al. 2008, Hughes et al. 2009, Vu et al. 2017). Burrowing and grazing by crabs can reduce the integrity of or kill vegetation, reducing the sediment-trapping or soil-stabilizing potential of plants (Holdredge et al. 2008, Bertness et al. 2009). Wilson et al. (2012) found that burrowing crabs fundamentally changed the geotechnical properties of the soils, altering not just the strength but also the organic content, bulk density, and conditions impacting decomposition (**Figure 7**). Large-scale excavation or the

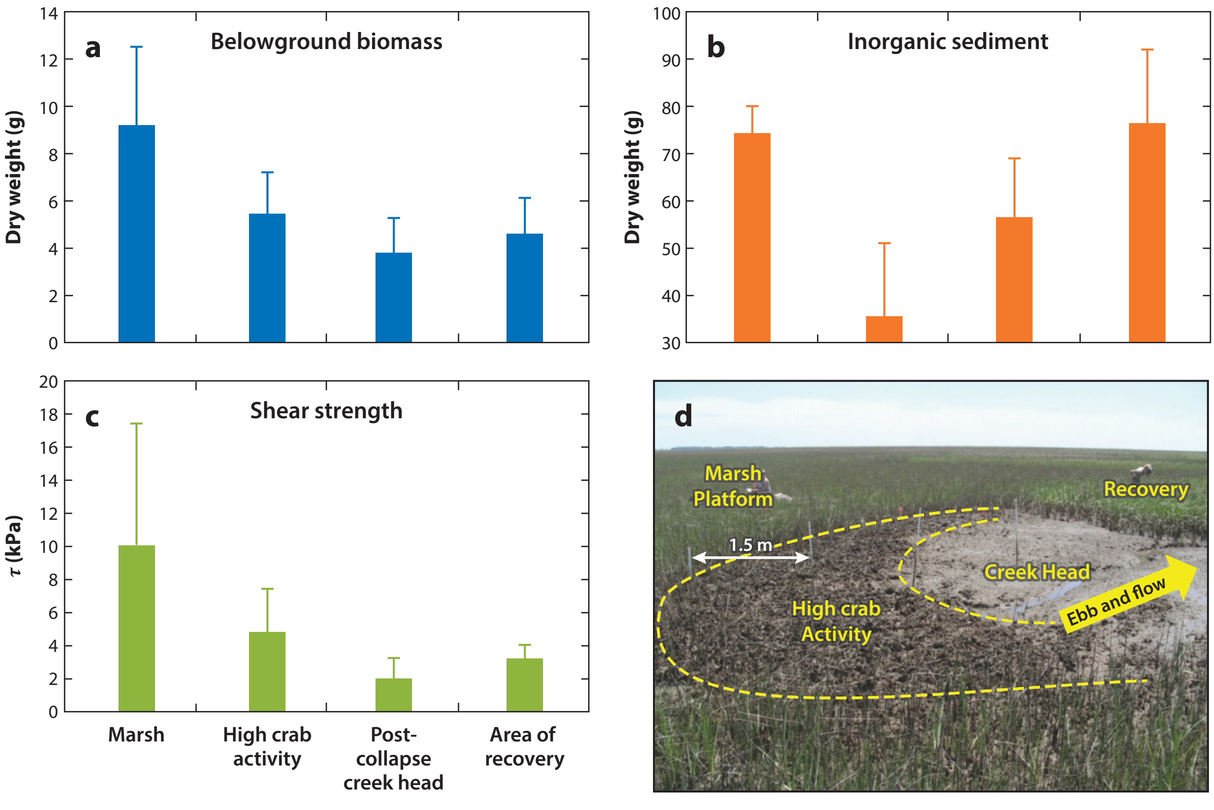

Figure 7

Impact of crabs on the geotechnical properties of soil comparing the undisturbed marsh platform, the boundary of the creek head where there are high crab population densities, the creek head where the burrows have collapsed due to flooding, and an area of recovery behind the incising creek head. Crab activity reduced (*a*) belowground biomass and rooting but also (*b*) inorganic content as the sediment was removed by burrowing or erosion. (*c*) Areas with low biomass also exhibit low soil strengths. Crab activity increases oxygenation and thus decomposition in the creek head. (*d*) Illustration of the zones. Figure adapted from Wilson et al. (2012).

building of structures, such as the chimneys built by *Uca pugnax*, changes the surface roughness and consequently impacts the turbulence and shear in supernatant flows (Meng et al. 2012, Farron 2018). The presence of burrows in regularly flooded marsh soils increases the soil water content and decreases sediment density, both of which act to reduce shear strength and resistance to erosion (Le Hir et al. 2007). The loosening of soils and active digging also impact SSCs, providing a source of sediment for other areas on the marsh (Wang et al. 2017). The formation of fecal or feeding pellets and burrow structures repackages formerly compacted sediment, altering the effective grain size of the sediment by creating larger aggregate particles (Grabowski et al. 2011). This increases the potential for erosion, with softer, less dense mud and aggregates that behave like larger sand particles having a lower threshold shear stress (Le Hir et al. 2007). These activities can all have a significant impact on salt marsh morphology (Paramor & Hughes 2004, Hughes et al. 2009, Escapa et al. 2015, Smith & Green 2015).

Perillo & Iribarne (2003) specifically addressed the impact of fauna on tidal networks, challenging the paradigm that marshes inherit creeks from tidal flats and undergo little or very slow modification after formation. They provided three examples from marshes in South America where new creeks are initiated through ecogeomorphic dynamics. The first two examples involved the hydraulic connection of pannes created by hypersalination, vegetation change, and grazing. Similar dynamics are observed in New England marshes where pannes exhibit a cyclicity. They form under hypersaline conditions, which remove vegetation, deepening them sufficiently to create a hydraulic head that drives the incision of a new creek. This drains the pool and allows revegetation and recovery of marsh platform elevation (Wilson et al. 2014). Wilson et al. (2010) also indicated that pools and pannes are dynamic features of northern salt marshes rapidly infilling with sediment when drained. Mariotti (2016) modeled this pond cyclicity and compared areas with different TRs and sediment strength (New Jersey and Louisiana). He concluded that while ponding can be cyclic, under conditions of SLR, if the pond deepens to below the limit for vegetation growth, the cycle will devolve to a runaway transition to a tidal flat.

Perillo & Iribarne's (2003) third example of creek evolution involves crab (*Chasmagnathus granulata*) activity removing vegetation and increasing erodibility, which lead to topographic lows. Ultimately the low areas connect to form a creek. Similar facilitation of creek development has been observed along the Atlantic coast of the United States by the herbivorous crab *Sesarma reticulatum*, which forms localized dense populations near creek heads (Hughes et al. 2009, Wilson et al. 2012). *Sesarma* have also been found in large numbers along creek banks in New England, where their activities have led to widespread plant die-off (Holdredge et al. 2008, Bertness et al. 2009, Coverdale et al. 2012). These sites are consequently more vulnerable to wave erosion, leading to large-scale retreat of marsh edges (Bertness et al. 2009, Smith & Green 2015).

6. MARSH EDGE EROSION

Numerous scientific studies have published time lines for when marshlands will submerge and be converted to open water as they respond to the ongoing regime of accelerating SLR (see Section 4). However, it should be recognized that the primary cause of areal marsh loss today and in the near future is marsh edge erosion (Marani et al. 2011) and not submergence or increased drainage density. Exceptions occur where marshes have experienced significant human impacts, such as the lower Mississippi Delta plain, where large areas of marsh have been converted to open water because of canal construction, impoundments, subsidence related to oil and gas extraction, increased levee heights cutting off fluvial sedimentation, and other actions (Turner & Boyer 1997, Penland et al. 2000). Similar types of anthropogenic alterations have also led to marsh losses along the eastern coast of Texas (White & Morton 1997), in the Wadden Sea (Dijkema 1997), and in

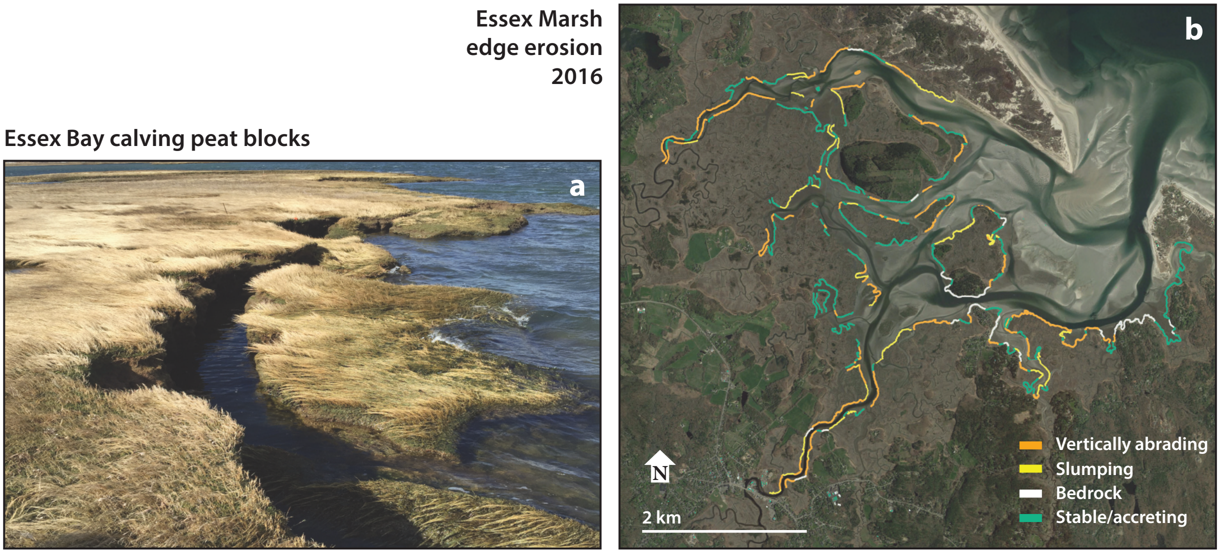

Figure 8

(*a*) Calving peat blocks in Essex Bay, Massachusetts. (*b*) Marsh edge map for Essex Bay, Massachusetts. Types of marsh edges are described in the text. Note the variability of edge type and the different settings in which these types occur.

deltaic regions (e.g., the Nile) (Stanley & Warne 1998). Marsh edge erosion, however, is a ubiquitous process.

Erosion of the platform edge frequently produces a vertical face, but other resultant morphologies also exist, including sloped and terraced edges, overhangs, and slump blocks of various forms (**Figure 8*a***; **Supplemental Figure 8**). Modeling studies have shown that the interactions of wave energy and tidal stage are primary factors in determining whether the profile is vertical, sloping, or terraced (Tonelli et al. 2010). Edge morphology is ultimately a product of erosional-depositional processes (Bendoni et al. 2014) but is also affected by the stratigraphy and shear strength of the peat and underlying sediment (Francalanci et al. 2013), age and height of the marsh face, and TR. A single marsh edge may exhibit different erosive responses depending on its stage of evolution. For example, along the exposed boundary of a retreating marsh where peat deposits sit atop tidal flat sediment, edges may experience undercutting due to preferential wave and/or tidal current erosion of the unconsolidated sand or mud compared to the higher shear strength of the overlying peat. This condition leads to tensional cracks and ultimately to slump block formation (Francalanci et al. 2013; Bendoni et al. 2014, 2016). The interaction of slump block geometry and subsequent wave energy and tidal currents (sensu Hackney & Avery 2015) can protect the marsh edge behind blocks while at the same time focusing wave erosion in adjacent regions.

Supplemental Material >

As shown by numerous investigators, the marsh platform can achieve a state of vertical equilibrium in a regime of slowly rising sea level (Morris et al. 2002, French 2006, Kirwan et al. 2010). This is contrasted by the intrinsic instability of the marsh in the horizontal direction, particularly in regions of low sediment contribution and high rates of SLR (Mariotti & Fagherazzi 2013, Bendoni et al. 2016). The fact that edge erosion has been recorded in early marsh literature (Yapp et al. 1917, Johnson 1925) and is a ubiquitous feature characterizing portions of most marshes worldwide suggests a response to a common stress or part of a natural evolution. Globally, marshes have wide ranges in age (**Table 2**), but most began forming one to several thousand years ago and

Table 2 Examples of marsh edge erosion rates

Location	Rate (m/year)	Reference(s)
Venice Lagoon, Italy	0.3–3.0	Cavazzoni & Gottardo (1983), Day et al. (1998), Marani et al. (2011)
Upper Delaware Bay, Delaware	0.2–7.3	Schwimmer (2001)
Barataria and Breton Sound, Louisiana	0.7–1.6	Wilson & Allison (2008)
Hog Island back barrier, Virginia	0.4–2.2	McLoughlin et al. (2015)
New River Estuary, North Carolina	0.3–1.0	Currin et al. (2015)
Point aux Pins, Alabama	0.4 (average)	Sharma et al. (2016)
Great Marsh, Massachusetts	0.2–2.0	Leonardi & Fagherazzi (2015), A.B. Novak, P.D. Phippen & G.E. Moore, unpublished data

evolved during a period of relatively slow SLR. It is evident that marsh edge erosion predates the most recent acceleration in SLR.

It is well established that back-barrier marshes begin forming once sedimentation along the upland boundary or on a tidal flat reaches a threshold elevation within the tidal frame producing a hydroperiod with short enough duration to support halophytic vegetation (Redfield 1972, Reed & Cahoon 1992, Dijkema 1997). Whereas this process would seem to suggest that marshes and tidal flats form a continuous gradual slope, Fagherazzi et al. (2006) have made a convincing case that marshes and tidal flats have distinctly different stability elevations. Their modeling work is based on local wind-generated waves combined with tidal currents producing critical shear stresses necessary to resuspend tidal flat sediment. Tidal flats are stable at lower tidal elevations because wave energy is sufficient during higher tidal elevations to resuspend sediment and maintain equilibrium between erosion and sediment influx.

In the model, marshes exist where sedimentation decreases depth, reducing wave energy and eventually allowing vegetation to colonize. The bimodal hyposometry of Venice Lagoon marsh and tidal flats appears to corroborate their findings (Fagherazzi et al. 2006). Building on the initial work of Silliman et al. (2005), who suggested that marsh edge erosion was a foreseeable consequence of differential sedimentation rates between marsh and tidal flats, Mariotti & Fagherazzi (2010) produced a coupled marsh–tidal flat ecogeomorphic model incorporating the influence of waves, tides, sediment transport, and vegetation feedbacks for different sediment supply and SLR scenarios. Their results show that marsh edge scarps are produced when adjacent tidal flats deepen due to lower sediment supplies and/or higher rates of SLR, which allow greater wave energy to transition across the flats and reach the marsh boundary. As the contribution of sediment from rivers is declining along many coasts (e.g., Weston 2014) and the rate of SLR is accelerating (Nerem et al. 2018), it would appear that condition will increasingly promote scarped marsh edges.

The rate at which marsh edges retreat has been studied by many investigators through the examination of wave energy, geotechnical character of the marsh peat, peat thickness, tidal flat geometry, and other factors. As seen in **Table 2**, retreat rates vary from tens of centimeters to several meters per year. Many of these studies have shown that for exposed marshes adjacent to open bays or wide tidal channels, the erosion rate is primarily a function of wave power. For example, Schwimmer (2001) demonstrated that marsh retreat over a three-year period in Delaware Bay was correlated to wave power (determined from wind data and bay dimensions and bathymetry) through a power law relation (exponent = 1.1; adjusted R^2 = 0.8). Marani et al. (2011) conducted a similar study for Venice Lagoon using aerial photography, wind, and bathymetric data and considering the height of marsh scarp. Their results indicate that the volume of sediment eroded from the marsh edge has a linear relationship with wave power density ($R^2 = 0.89$). A second study in northern Venice Lagoon (Bendoni et al. 2016) using field measurement of marsh edge retreat rates showed a linear correlation between wave energy flux and erosion rate on monthly timescales. When areas exhibiting slumps were included in the retreat history, the correlation was less well defined. The poorer relationship was explained by the observation that mass failures result from long-term accumulated forces and are not necessarily related to a single high-energy event.

The importance of moderate-term temporal response of the marsh edge to wave forcing was underscored in an investigation of eight marsh sites in the United States, Australia, and Italy (Leonardi et al. 2016a) (**Figure 9**). Based on two decades of data, Leonardi et al. (2016a) found that hurricanes and major storms produced less than 1% of retreat rate and that most of the erosion is attributed to moderate storms with return periods of 2.5 months. This trend was also demonstrated in a study of eroding marsh shoreline in New Jersey (Leonardi et al. 2016b) (**Supplemental Figure 9**). Although a strong correlation exists between marsh erosion and wave power ($R^2 = 0.62$; $p < 0.05$) (**Figure 9**), there is considerable spread in erosion rate values for a given dimensionless wave power. This trend emphasizes that other factors, such as the edge height and the biologic, sedimentologic, and geotechnical character of the peat and underlying sediment, impart susceptibility to edge erosion.

Supplemental Material >

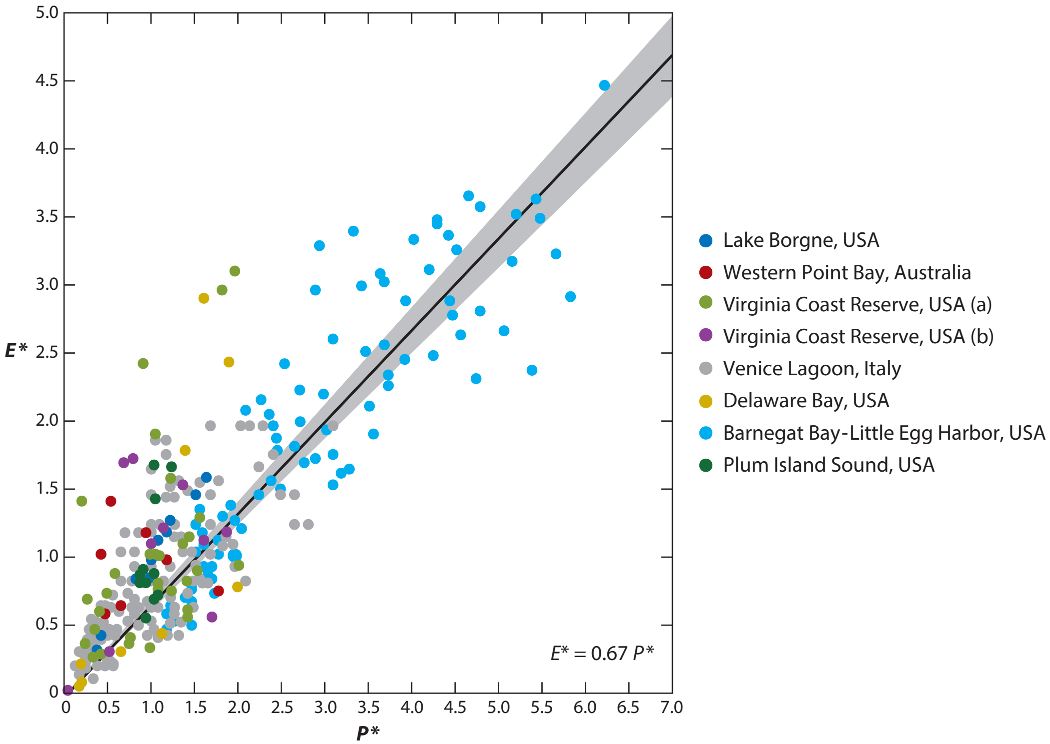

Figure 9

A plot of dimensionless wave power ($P^* = P/P_{\mathrm{ave}}$) versus dimensionless edge retreat rate ($E^* = E/E_{\mathrm{ave}}$). Figure adapted from Leonardi et al. (2016a). Although a strong correlation exists between the two parameters, the scatter in the data demonstrates that other factors in addition to wave power affect erosion rates.

Eroding marsh edges are not only found along open bays and wide channels; they also occur in low-energy environments. In a study of the Essex estuary within the Great Marsh of northern Massachusetts, the marsh edge type was mapped in the field into four shoreline categories: (*a*) stable to accretionary; (*b*) bedrock or large-sized gravel beaches, often containing high-tide pocket marshes (<30 m long); (*c*) calving with slump blocks composing >50% of the shoreline; and (*d*) vertical to steeply inclined abrading marsh face with fewer than 20% slump blocks (**Figure 8**). In the Great Marsh, peat blocks generally decompose and disintegrate over five to ten years, so the presence of slump blocks in the intertidal or subtidal zone does not necessarily indicate a recent calving event. In this one estuarine/back-barrier marsh system 70% of the shoreline is characterized by erosion. As viewed in **Figure 8*b***, wave exposure does not have a deterministic influence on the formation of calving or vertical eroding shorelines. Rather, the map demonstrates that different marsh erosional shorelines extend deeply into protected landward portions of the estuary.

Mariotti et al. (2016) discussed the presence of slump blocks occurring along fairly narrow channels (15 to 20 m wide at bank-full stage) where historical data indicate little or no long-term channel widening. Their model envisioned preferential deposition of suspended sediment along creek margins building channel banks vertically. They suggested that at steady state, marsh edge calving and subsequent slump block decomposition are balanced by vertical channel bank accretion resulting in soil creep of the marsh platform toward the unbuttressed creek margin. While this process may be operative along some marsh creek systems, peat blocks are not a feature common to many secondary marsh channels; where they do occur, they are usually nonuniform and discontinuously distributed. This trend would suggest that some small creeks are relatively stable or that other erosive processes are involved in marsh soil creep dynamics. Deegan et al. (2012) suggested that slump blocks along creek margins can be due to coastal eutrophication whereby increased nutrients cause greater microbial decomposition of belowground organic matter leading to decreased bank stability. Their field experiment was conducted in a limited creek area; thus, its widespread applicability is unknown.

Leonardi & Fagherazzi (2015) suggested that the morphology, as well as retreat rate, of eroding marsh edges is related to the frequency and magnitude of wave energy. Their modeling work suggests that irregular margins are produced along low-energy shorelines, where isolated sporadic calving occurs during infrequent extreme events and is related to local marsh internal variability and cumulative long-term stresses. Conversely, uniform, continuously eroding margins occur along high-energy shorelines that experience frequent large-magnitude wave events. General observations of marshes show a wide variability in edge morphology, and while the Leonardi & Fagherazzi model explains simple marsh sites, it appears that the physical character of some marshes may override the influence of wave energy. This is particularly true in regions where marshes have evolved in glaciated terrains where substrates (bedrock and glacial deposits) crop out at marsh edges or control peat thickness. In other regional settings, the sedimentary framework (Oertel et al. 1989) may impart similar influences on marsh edge morphology. Human alterations may also impact erosion rates and edge patterns. For example, the southern margin of Essex Bay in Massachusetts is directly exposed to wave impact during frequent northeast storms; however, this crenulate shoreline is mostly a product of drainage ditch geometry promoting preferential erosion (**Supplemental Figure 10**).

Supplemental Material >

As a final insight, it would seem unlikely that marsh edges have been eroding at the same rate throughout their history. Depending upon the evolution of the back barrier, the open water area of the bay may have been expanding or filling with sediment, which would have increased or diminished wave energy causing increasing or decreasing marsh edge erosion, respectively.

However, if we use the present-day erosion rate from **Table 2** and extend that rate over the life of the marsh (conservatively estimated at 1,000 to 3,000 years) (**Table 1**), then marshes would have retreated from 200 m to 21.9 km. These are distances comparable to retreat of the Louisiana delta plain back-barrier marshes. However, this is a region of multicausal subsidence with high rates of relative SLR (Penland & Ramsey 1990) and is not the norm for nondeltaic barrier coasts. When we use the average retreat distance of 1.56 m/year from **Table 2**, marshes would have lost from 1.56 to 4.68 km for a 1–3 ka age marsh, respectively. In many regions this degree of erosion would have removed most of the areal marsh. The point of this exercise is to demonstrate that the initiation and rates of marsh retreat are still poorly understood. The fact that marsh peats are inherently less stable with increasing thickness (age) may indicate that marsh edge erosion is initiated only when bay widths and depths and peat thickness reach certain thresholds. Finally, in northern latitudes the effects of freeze and thaw, ice wedging, and ice loading are not well studied or quantified but may have an important effect on edge erosion (Argow & FitzGerald 2006).

7. UPLAND EXPANSION AND RESPONSE TO SEA-LEVEL RISE

In a regime of SLR, marsh migration onto uplands or the transformation of existing fresh and brackish marshes to salt marsh may partially offset losses caused by the processes of deterioration discussed above (White & Kaplan 2017) (**Figure 10**). A study using field data and a simple 1D elevation model performed along the backside of Galveston Island for different SLR scenarios showed that marshes may actually increase in total area during low to moderate rates of SLR (Feagin et al. 2010). However, the expansion of the marsh onto uplands along the rear border of a barrier island is likely to be coincident with an overall narrowing and drowning of the barrier and consequent storm overtopping and barrier breaching (FitzGerald et al. 2018), which may ultimately limit marsh growth.

Field observations have been made of both the natural and anthropogenic impediments that retard or prevent marsh migration onto uplands in a regime of SLR (Doody 2004, Feagin et al. 2010, Torio & Chmura 2013). Brinson et al. (1995) showed that vegetative succession in Virginia coastal borderlands in unfettered slope conditions is sporadic and triggered by intrusion of brackish water, encroachment of tidal creeks, wave erosion, or increasing water depth. In a modeling study of rising sea level along northern Chesapeake Bay, Hussein (2009) isolated upland slope as the primary factor governing the conversion of uplands to high marsh; however, the scatter in his data indicated a strong imprint by other factors. A historical study by Smith (2013) for the period between 1930 and 2006 documented the effects of SLR along Delaware Bay, showing that the interface between the upland retreating forest and the landward migrating salt marsh becomes blurred and separated due to the establishment and expansion of the invasive species *Phragmites*. *Phragmites* tends to colonize the stressed zone between marsh and forest because it expands quickly and is more tolerant of higher salinity and moisture conditions than forest species (**Supplemental Figure 11**). Once it is established, the salinity must reach high levels before marsh plants will replace *Phragmites*; thus, during the 76 years covered in the analyses, upland forest loss was not compensated by marsh gain (Smith 2013).

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A holistic approach to understanding the response of the salt marsh to SLR must consider the entire set of interacting factors that govern marsh expansion onto uplands as well as erosional and depositional processes, including biogeomorphic feedbacks and the redistribution of inorganic and organic sediment. A recent modeling study by Kirwan et al. (2016b) integrated numerous previous modeling efforts with new ideas to address specific marsh processes, such as position of the marsh edge (Mariotti & Fagherazzi 2013, Mariotti & Carr 2014), vertical accretion (Morris et al. 2002, Temmerman et al. 2003, D'Alpaos et al. 2007, Kirwan & Murray 2007, Mudd et al. 2009, Kirwan et al. 2010, Fagherazzi et al. 2012), upland marsh migration (Feagin et al. 2010, Raabe & Stumpf 2016), and various types of biogeomorphic feedbacks (e.g., Morris et al. 2002,

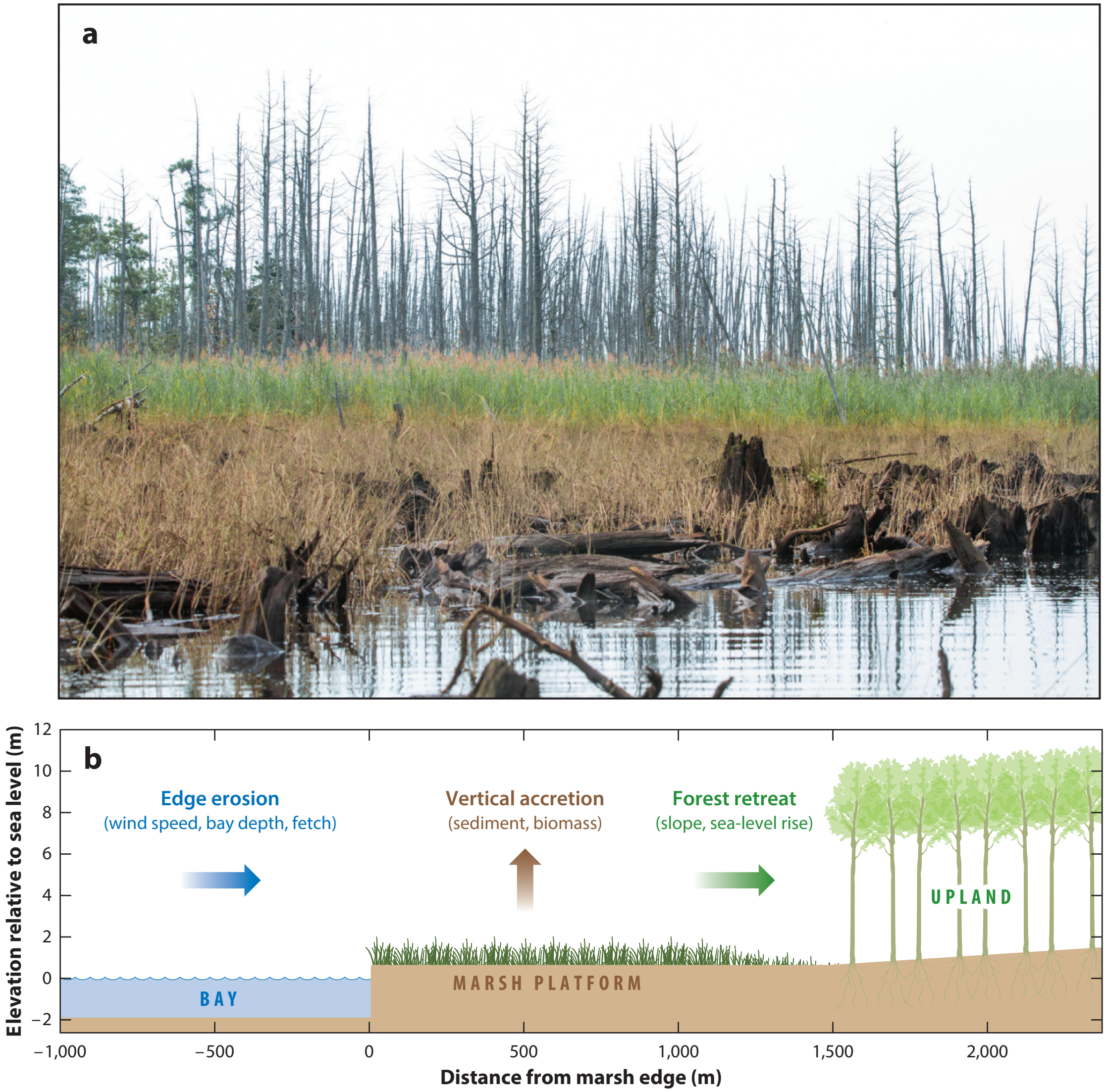

Figure 10

(*a*) Ghost forest behind Amelia Island, Florida. (*b*) Conceptual diagram illustrating the processes affecting the areal extent of marshes. Figure adapted from Kirwan et al. (2016b).

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Da Lio et al. 2013, Mariotti & Fagherazzi 2013). Their model results (**Supplemental Figure 12**) show that for moderate SLR and moderate to high suspended sediment scenarios, the marsh actually expands in extent along low upland slopes (0.001). For this case, while the marsh platform accretes vertically at a pace compensating for rising sea level, expansion of the marsh onto the uplands occurs at a rate exceeding marsh loss through edge erosion (Kirwan et al. 2016b) (**Supplemental Figure 12**). Their findings also show that marshes contract under low SLR conditions because marsh edge erosion proceeds at a faster rate than new marsh is forming on uplands. Finally, they found that marshes succumb to inundation when SSCs are relatively low ($\leq$30 mg/L) and rates of SLR are relatively high (10 mm/year).

Although the Kirwan et al. (2016b) comprehensive model represents a considerable advancement in the ability to forecast the future of marshes, there are still difficulties in accurately predicting site-specific response, even for given SLR scenarios. For example, while present models provide for different rates of sedimentation on the marsh surface based on distance from the water edge and elevation, they are run with an unrestricted suspended sediment supply and without accounting for variability in seasonal estuarine sediment influxes, preferential erosion versus depositional sites within the marsh tidal network, and the effects of storm and winter processes. It must be appreciated that the volume of suspended sediment entering a marsh system via the coastal ocean, streams, rivers, or overland or being sourced through cannibalism from the marsh itself is limited. Thus, as the marsh evolves and conditions demand greater inorganic deposition, suspended sediment supply will eventually reach a deficit. In addition, the upland boundaries of marshes exhibit vastly different geologic characteristics. For example, in coastal plain settings generally the upland slope is very low (<0.001) and mostly uniform so that marsh gains during SLR over the long term are strictly a function of distance of inundation times the length of the coast. In contrast, the New England glaciated coast has much steeper slopes (>0.01) (Farron 2018) and highly irregular boundaries, with numerous reentrants and promontories. Over the long term, the marsh gains are small due to steep slopes; however, this condition is compensated for by the longer length of marsh-upland boundary per unit length of coast compared to that in coastal plain settings. Likewise, the varying level of human development and existing infrastructure will also create different limitations to landward migration at different sites.

8. STORM SEDIMENTATION

Scientists continue to debate the net impact of major storms on wetlands. High-energy events may be beneficial to salt marshes because of net deposition that occurs during surge inundation or detrimental due to surface excavation or edge erosion by storm waves (see Section 6). A post–Hurricane Katrina study of the Caernarvon wetlands in upper Breton Sound, Louisiana, showed that brackish marshes experienced extensive erosion and conversion to open water when compared to adjacent salt marshes. This was attributed to the relatively shallow rooting of vegetation and low soil shear strength. More saline marshes exhibited little erosion, a consequence of higher soil shear strengths and deep plant rooting (Howes et al. 2010). Moreover, the lack of evidence of erosion, such as large excavated peat blocks on the surface of the salt marsh, along the direct pathway of Katrina suggests that hurricanes do not cause the wide-scale excavation of saline marshes as has been interpreted from marsh stratigraphy at other locations (Nikitina et al. 2014). Rather, it is possible that many of the erosional contacts seen in the stratigraphy are better explained by the noncatastrophic dynamicism of marshes (e.g., Wilson et al. 2010, 2014). Regional studies of hurricane impacts in Louisiana suggest that most erosional features are related to fresh to brackish conditions, where marsh soils are weaker (Cahoon 2006, Morton & Barras 2011).

The occurrence of event sedimentation on wetlands has been well established and includes studies documenting extratropical deposits on salt marshes in northwest Florida (Goodbred & Hine 1995) and seasonal sedimentation on marshes in Terrebonne Bay, Louisiana, accompanying the passage of frontal systems (Reed 1989) as well as numerous hurricanes (**Supplemental Table 1**). It has been recognized by several investigators studying coastal Louisiana that hurricane deposits help marshes keep pace with SLR, especially in regions with high subsidence rates (Cahoon et al. 1995). The most detailed investigations of tropical storm deposits followed the passage of Hurricanes Katrina and Rita in 2005. Turner et al. (2006) reported that more than 131×10^6 metric tons of sediment were deposited in chenier and delta plains in Louisiana, with deposit thickness ranging from ∼0 to 30 cm (average of 5.18 cm). McKee & Cherry (2009) measured

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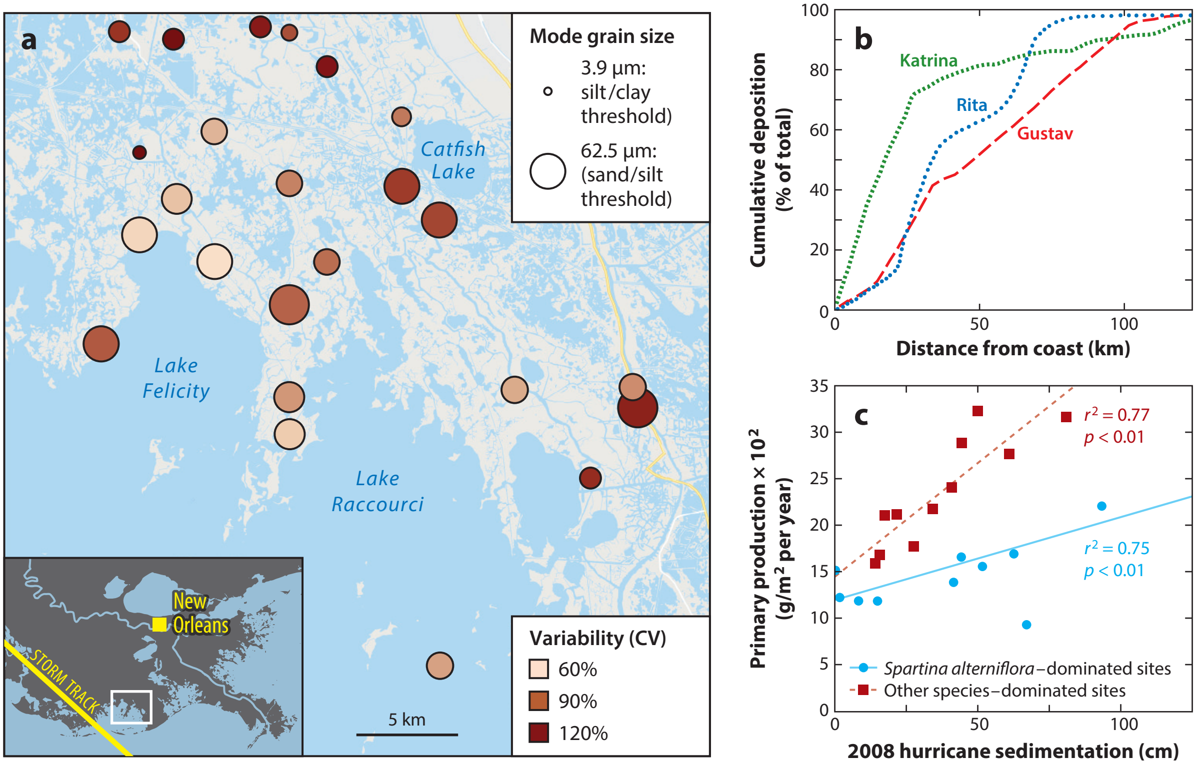

Figure 11

(*a*) Grain size trends for Hurricane Gustav deposits in upper eastern Barataria Bay. Gustav storm track shown as a black line on the inset. Figure adapted from Tweel & Turner (2012). (*b*) Graph illustrating sediment deposition as a function of distance from the coast along Louisiana for Hurricanes Katrina, Rita, and Gustav. Data taken from Tweel & Turner (2012). (*c*) Data collected following the impact of Hurricanes Gustav and Ike in 2008. Note that primary production in the wetlands increases with increasing hurricane sedimentation. Abbreviation: CV, coefficient of variance. Figure adapted from Baustian & Mendelssohn (2015).

similar average thicknesses, but with a smaller range, in the Hurricane Katrina storm layer at Big Branch Marsh, Louisiana, and Pearl River, Mississippi. Tweel & Turner (2012) studied hurricane sedimentation in this same approximate geographic region, documenting deposits from Katrina and Rita in 2005 and Ike and Gustav in 2008. They established some important patterns of hurricane sedimentation, including that most of the sediment was deposited within 20 km of the coast (**Figure 11*a***). Likewise, they showed a general trend of decreasing grain size, bulk density, and mineral content away from the coast (**Figure 11*b***; **Supplemental Figure 13**), which is consistent with a decrease in storm surge and landward flow velocities. As the competency of the currents diminishes, denser mineral grains would be deposited preferentially, and the less dense organic particles would remain in the water column and move further onshore. Eventually, they would be deposited, producing lower marsh bulk densities. A recent study of coastal wetlands in Louisiana attributed 65% of the inorganic surface sediment (upper 24 cm of soil) in the abandoned delta region as a product of storm surge deposition (Tweel & Turner 2014). This value increased to 80% in the chenier region of western Louisiana. Subsequent dating of sediment cores from the delta plain revealed a close correlation between the timing of inorganic layers and periods when a single hurricane or cluster of hurricanes impacted the coast. This led the investigators to conclude that the sea, rather than rivers, contributes most sediment to the marshes of the Mississippi River

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Delta (Turner et al. 2007). The Louisiana Birdfoot, Wax Lake, and Atchafalaya deltas are obvious exceptions to this trend.

Although the above investigations demonstrate the importance of event sedimentation in the vertical growth of marshes, a chronostratigraphic study by Nyman et al. (2006) using cores obtained throughout coastal Louisiana suggests that variability in marsh accretion is controlled by organic accumulation rather than mineral sedimentation. This is a curious finding given that the inorganic component of the peat is four times greater than the organic (by weight) (Nyman et al. 2006) and that a single high-magnitude storm can deposit more sediment than an entire year of high-frequency, low-magnitude cold fronts (Cahoon et al. 1995). Other studies have shown that introducing hurricane deposits to the marsh has ancillary benefits of increasing primary production, which is attributed to a new supply of nutrients, root occupation within the new sediment, and less stressful soil conditions (McKee & Cherry 2009, Baustian & Mendelssohn 2015) (**Figure 11*c***). A regional study of US marshes by Cahoon (2006) demonstrated that the net elevation change resulting from storm sedimentation is also affected by subsurface processes, which can be attributed to compaction, decomposition, root growth, soil swelling, and other positive and negative elevation factors. In certain deltaic settings, such as Breton Sound in southeast Louisiana, the greatest contribution of inorganic sediment to the marsh system is not from low-frequency hurricanes but rather Mississippi River discharge through breaks in the levee and river sediment movement upbasin and onto the marsh surface during the passage of frontal systems, elevated tides, and river flooding (Smith et al. 2015). However, this latter case is unusual because Breton Sound is adjacent to several spillways along the eastside of the Mississippi River.

A few studies have attempted to correlate sedimentation trends to wave suspension and flow conditions during hurricanes. One such example, using Delft3D, produced realistic sedimentation simulations along the Louisiana coast (Liu et al. 2018). Modeling the conditions during Hurricane Gustav, the researchers estimated net sediment deposition in the coastal wetlands, identified major sources of the sediment, and produced sediment budgets for Terrebonne and Barataria Basins that agreed favorably with field measurements made by Tweel & Turner (2012). If hurricane sedimentation patterns and thicknesses can be modeled successfully, these results could be combined with storm recurrence statistics and lead to more robust predictions of marsh accretion. The inclusion of event sedimentation and increased storminess resulting from climate change (Emanuel 2005, Webster et al. 2005) has been modeled for the backside of the German island of Sylt using different SLR scenarios to forecast the future resiliency of marshes (Schuerch et al. 2013). The model results indicate that an increase in storm magnitude and frequency coupled with abundant nearby fine-grained tidal flat sediment can increase the salt marsh accretion by up to 3 mm/year.

9. CLIMATIC IMPACTS ON MARSH FUNCTIONS

Increased levels of atmospheric CO_2 and the attendant rising temperatures impact marshes directly by affecting plant productivity and accelerating the rate of SLR. Rising temperatures also increase the rate at which marsh peat and leaf litter decompose, thereby affecting the long-term elevation of the marsh.

9.1. Future Elevated Carbon Dioxide

Concentrations of atmospheric CO_2 have increased from 280 ppm in preindustrial times to 400 ppm today and are estimated to range from 478 to 1,099 ppm by 2100 (Bernstein et al. 2008). Global warming is stressing marshes due to SLR; however, increased inundation may be partly offset by greater production of belowground and aboveground biomass caused by increased CO_2

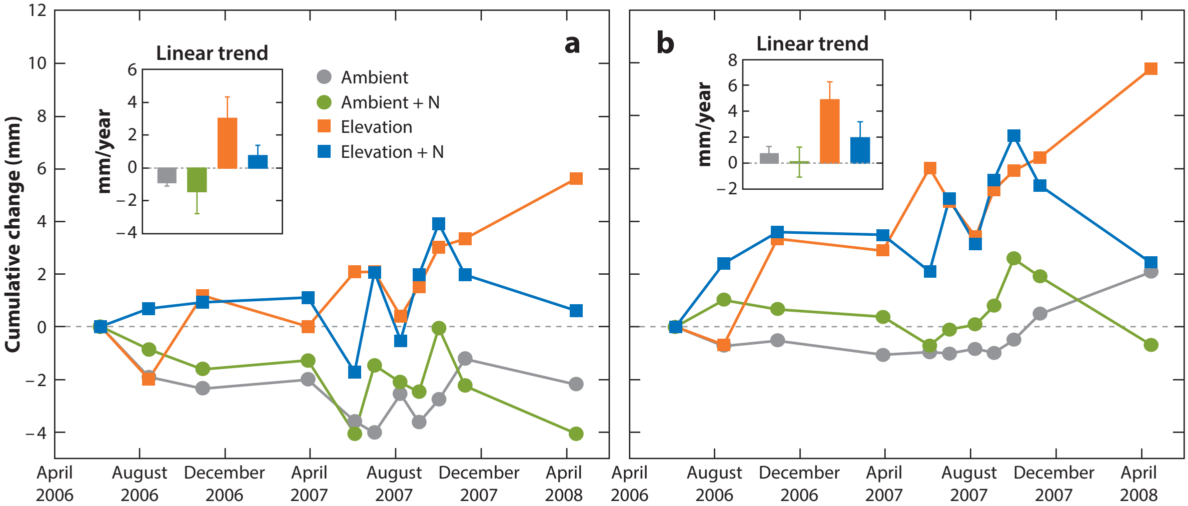

Figure 12

Results of a field study of a brackish marsh in Chesapeake Bay, Virginia, where plants were exposed to elevated concentrations of CO_2 and soil N. Figure adapted from Langley et al. (2009). Increased levels of CO_2 stimulated greater plant growth, resulting in increased (*a*) surface elevation and (*b*) root thickness compared to nontreated areas. Elevated N had little positive influence. Abbreviations: CO_2, carbon dioxide; N, nitrogen.

levels. This balance may depend on other factors including rainfall, hydroperiod, salinity, and marsh grass species (e.g., differences are observed between C_3 and C_4 plants) (for a full review, see Erickson et al. 2007).

In a glasshouse mesocosm experiment, living sods of brackish water marsh vegetation containing C_3 (*Schoenoplectus americanus*) and C_4 species (*S. patens*) were subjected to varying levels of CO_2, salinity, and hydroperiod to assess changes in surface elevation through time (Cherry et al. 2009). These experiments suggest a positive correlation between future elevated CO_2 conditions and production of C_3 plants at belowground biomass, resulting in positive elevation change. The study also showed that the response of C_4 species to variable forcings was complex and direct correlations between elevation change and CO_2 or salinity were not found.

In a follow-up field study, Langley et al. (2009) exposed plots of marsh to relatively high levels of CO_2 (340 ppm, simulating 2100 projections) and nitrogen (25 g/m^2 per year) and compared the response of the marsh to ambient conditions. Field results showed a slight elevation loss in ambient CO_2 conditions (−0.9 mm/year) in contrast to an elevation gain in the elevated CO_2 treatment (3.0 mm/year) (**Figure 12**). Moreover, they found that nitrogen had little impact to the system. Using the same mesocosm design as Cherry et al. (2009), Langley et al. (2009) showed that soil expansion and marsh elevation gain due to belowground production were enhanced by elevated CO_2 levels during intermittent flooding and lower salinities with no effect at higher salinities. An important finding of this study indicated that future SLR conditions (elevated CO_2 levels, constant flooding, increased salinities) will lead to high belowground productivity.

More recently, an ecomorphodynamic modeling study using available input data examined future elevation changes to the marsh platform as a consequence of variable rates of relative SLR, SSC, and nutrient levels when atmospheric CO_2 is raised by 400 ppm (Ratliff et al. 2015). As in the previous investigations (Cherry et al. 2009, Langley et al. 2009) results of the Ratliff et al. (2015) modeling study suggest that doubling of the CO_2 concentration will increase the aboveground and belowground biomass, producing greater vertical accretion rates and increased deposition of inorganic suspended sediment, respectively. Their findings also corroborate the earlier results of Cherry et al. (2009) showing that C_3 plants will preferentially benefit from increased CO_2 levels and may outcompete C_4 species.

9.2. Elevated Temperatures

While field and mesocosm experiments have been used to study the impact of higher levels of CO_2, projecting the effects of increasing temperature on the world's marsh systems is not as simple due to difficulties in replicating tidal environmental conditions (e.g., Gray & Mogg 2001). One means of overcoming this limitation is by comparing marsh systems along latitudinal gradients, which translate to differences in both temperature and length of growing season. In one such study, Kirwan et al. (2009) assembled *S. alterniflora* data from 48 locations, including those of Turner (1976), spanning the Gulf of Mexico through the eastern seaboard of the United States to southern Canada. Kirwan et al. (2009) showed a close relationship between end-of-season live aboveground biomass and latitude (**Figure 13**) and reasonable correlations between plant productivity and mean annual temperature and mean annual growing degree days (>10°C). Their results suggest that *S. alterniflora* aboveground productivity will increase by about 27 g/m^2 per year for each degree Celsius of warming. By projecting the productivity-temperature trend for a 2–4°C rise by 2100 (Bernstein et al. 2008), Kirwan et al. (2009) predicted that annual productivity will increase by 10–40%. Importantly, Kirwan et al. (2009) noted that while this projection appears to be appropriate for northern marshes, southern marshes may have already reached an optimal growing temperature and productivity may actually decline with future rising temperatures.

Kirwan & Mudd (2012) used an ecogeomorphic numeric model to examine how changes in plant productivity and decomposition, driven by rising CO_2 levels and temperatures, affect the deposition of inorganic suspended sediment and accumulation of organic carbon on the marsh platform. They determined that temperature increases during low rates of SLR favor inorganic accumulation whereas high rates of SLR produce greater sequestration of organic carbon (**Supplemental Figure 14**). This scenario predicts an increase in carbon burial during the first half of the twenty-first century and a deceleration after 2050. Not only will future increases in global warming affect plant productivity, but also increasing temperatures will impact SLR and

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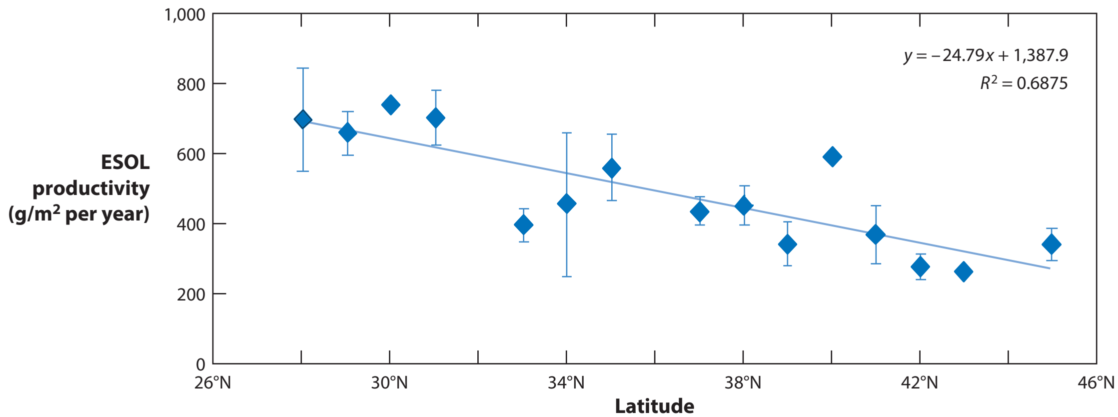

Figure 13

Trend in *Spartina alterniflora* productivity versus latitude. Figure adapted from Kirwan et al. (2009). Results indicate greater productivity in warmer, lower latitudes. Abbreviation: ESOL, end-of-season live.

rates of organic decomposition. A short-term field litterbag experiment measured organic decay rates during a seven-week period of the growing season within an *S. alterniflora* zone at Phillips Creek, Virginia (Kirwan & Blum 2011). Although their study was temporally and spatially limited, Kirwan & Blum showed that decomposition rates increased by about 20% for each degree of warming during the early growing season. They attributed this trend to greater fungal and bacteria activity resulting from warmer temperatures.

Kirwan et al. (2014) conducted a longer-term study (three years) to determine organic decay rates in *S. patens* and *Schoenoplectus americanus* marshes spanning from South Carolina to Nova Scotia. Average soil temperatures in their study area ranged from 13°C at Kouchibouguac (Nova Scotia) to 29°C at Blackwater (Maryland). The regression they produced indicates 3% and 6% increases in decay rate per degree Celsius in the seasonal and latitudinal experiments, respectively, which is substantially lower than the earlier Kirwan & Blum (2011) study. Moreover, these lower estimates of decomposition with warming suggest that greater plant productivity in response to increasing CO_2 and temperature may help to sustain marshes in a regime of accelerating SLR. This conclusion is reinforced by the study of Kirwan et al. (2013), which demonstrated that future accelerating rates of SLR will lead to minor increases in peat decay rates.

SUMMARY POINTS

1. Most of the world's salt marshes are <3,500 years old; they formed in protected depositional settings during a period when the rate of SLR was 0.2 to 1.6 mm/year. Their sustainability is now threatened by accelerating SLR that is many times greater than when they were evolving, a rate that may outpace the marshes' ability to add sediment and build belowground biomass. In addition to providing many ecosystem services and protecting the coast, marshes sequester terrestrial carbon. The potential deterioration of marshes and conversion of their organic sediment to CO_2 and CH_4 will increase greenhouse gases, thereby providing positive feedbacks to global warming and SLR.
2. Increasingly complex numerical models have dramatically improved our understanding of the interrelationships among marsh processes and our ability to predict their fate in response to accelerating SLR. Models are used to quantify thresholds and determine rates of marsh growth and deterioration. Modeling has also allowed us to explore factors governing the susceptibility and rate of marsh edge erosion as well as the migration of marsh onto uplands. Additionally, physical models of marshes, including flume studies, are shedding light on the mechanics of marsh erosion, particularly in combination with crab bioturbation and geochemical processes.
3. Although SLR is accelerating, researchers have stressed the resiliency of marshes due to inherent ecogeomorphic feedbacks. They have shown that greater periods and frequencies of tidal inundation will result in increased deposition of suspended sediment and production of belowground biomass; these processes increase the vertical accretion rate of the marsh tending toward equilibrium. The future fate of marshes will ultimately be dependent on the rate of SLR and SSC, as belowground organic production will reach a maximum. Lower rates of SLR, higher SSC, and larger tidal ranges are more conducive to marsh longevity.
4. Many of the predictive numerical models invoke a constant SSC inundating the marsh, although more sophisticated models account for decreased sedimentation across the

marsh surface due to flow deceleration and trapping by plants. However, these models fail to recognize that suspended sediment in most estuarine and back-barrier settings is limited and as portions of the marsh are flooded more frequently, the increase in tidal prism will be sourced primarily from the coastal ocean where the SSC is typically much lower than in the marsh system.

5. Recent research highlights the complex feedbacks that operate in marsh systems, including feedbacks between geomorphology and tidal prism, and ecogeomorphic processes whereby vegetation, fauna, sedimentation, and flow dynamics interact on multiple levels to influence each other.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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