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Sea level driven marsh expansion in a coupled model of marsh erosion and migration

Matthew L. Kirwan[1], **David C. Walters**[1], **William G. Reay**[1], and **Joel A. Carr**[2]

[1]Department of Physical Sciences, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, USA, [2]Patuxent Wildlife Research Center, U.S. Geological Survey, Laurel, Maryland, USA

Key Points:

- Accelerated sea level rise leads to marsh expansion along gently sloping, unhardened coasts
- Loss of marsh and natural flood protection is inevitable where barriers limit migration into uplands
- Fluxes of organisms and sediment across adjacent ecosystems lead to increase in system resilience

Supporting Information:

- Supporting Information S1

Correspondence to:
M. L. Kirwan,
kirwan@vims.edu

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Abstract Coastal wetlands are among the most valuable ecosystems on Earth, where ecosystem services such as flood protection depend nonlinearly on wetland size and are threatened by sea level rise and coastal development. Here we propose a simple model of marsh migration into adjacent uplands and couple it with existing models of seaward edge erosion and vertical soil accretion to explore how ecosystem connectivity influences marsh size and response to sea level rise. We find that marsh loss is nearly inevitable where topographic and anthropogenic barriers limit migration. Where unconstrained by barriers, however, rates of marsh migration are much more sensitive to accelerated sea level rise than rates of edge erosion. This behavior suggests a counterintuitive, natural tendency for marsh expansion with sea level rise and emphasizes the disparity between coastal response to climate change with and without human intervention.

1. Introduction

Coastal wetlands protect coasts from storms, improve water quality, sequester carbon, and export organic matter that supports estuarine and marine food webs [*Barbier et al.*, 2011]. These ecosystem services depend nonlinearly on wetland size and particularly the width of wetlands between developed land and the sea [*Barbier et al.*, 2008; *Temmerman et al.*, 2013]. For more than 30 years, the vulnerability of wetlands to relative sea level rise (RSLR) has been primarily evaluated through comparisons between rates of RSLR and vertical soil building [e.g., *Stevenson et al.*, 1986; *Morris et al.*, 2002; *Langley et al.*, 2009; *Kirwan et al.*, 2010], whereas wetland size is most fundamentally determined by changes in the position of their seaward and landward boundaries [*Brinson et al.*, 1995; *Schwimmer and Pizzuto*, 2000].

Fascinating feedbacks between tidal flooding, plant growth, and sediment transport allow marshes to adapt to a wide range of RSLR rates in the vertical dimension [*Kirwan and Megonigal*, 2013]. For example, flooding associated with RSLR stimulates the growth of some types of marsh vegetation, enhancing mineral sediment settling and organic matter production, so that marshes build elevation more quickly under faster rates of RSLR [*Morris et al.*, 2002; *Kirwan et al.*, 2010; *Hill and Anisfeld*, 2015]. However, recent work suggests that marshes may be intrinsically fragile in the lateral dimension, where waves erode marsh edges, which leads to increased fetch and even greater rates of erosion [*Mariotti and Fagherazzi*, 2013; *Mariotti and Carr*, 2014]. Since large-scale marsh progradation typically occurs only in the most extreme sedimentation cases (e.g., delta growth) [*Gunnell et al.*, 2013] or in protected low-energy embayments [*Redfield*, 1972], this conceptual framework suggests that marsh loss may be nearly inevitable even in the case where soil building is enough to offset RSLR in the vertical dimension [*Fagherazzi*, 2013; *Mariotti and Fagherazzi*, 2013].

However, marshes also respond to RSLR by migrating into adjacent uplands where they are not restricted by topographic and anthropogenic barriers such as dykes, seawalls, and revetments [*Brinson et al.*, 1995; *Hussein*, 2009; *Feagin et al.*, 2010; *Smith*, 2013; *Raabe and Stumpf*, 2016]. The processes by which marshes replace upland vegetation are poorly understood, but simple topographic analyses suggest that 1 m of RSLR could inundate an area of land similar in magnitude to the present-day extent of coastal marshes in the continental U.S. [*Morris et al.*, 2012]. Whether this potential source of new marshland can offset predicted losses due to RSLR remains unexplored and depends in part on decisions to defend or abandon coastal property and infrastructure [*Feagin et al.*, 2010; *Kirwan and Megonigal*, 2013]. Here we present a new model of marsh erosion, accretion, and migration and compare its behavior to observations from the York River Estuary in Virginia to explore the competition between processes that build and erode marshes under accelerated sea level rise. When marshes are connected with their adjacent uplands, we find that accelerated sea level rise can lead to a counterintuitive net expansion of coastal marshes.

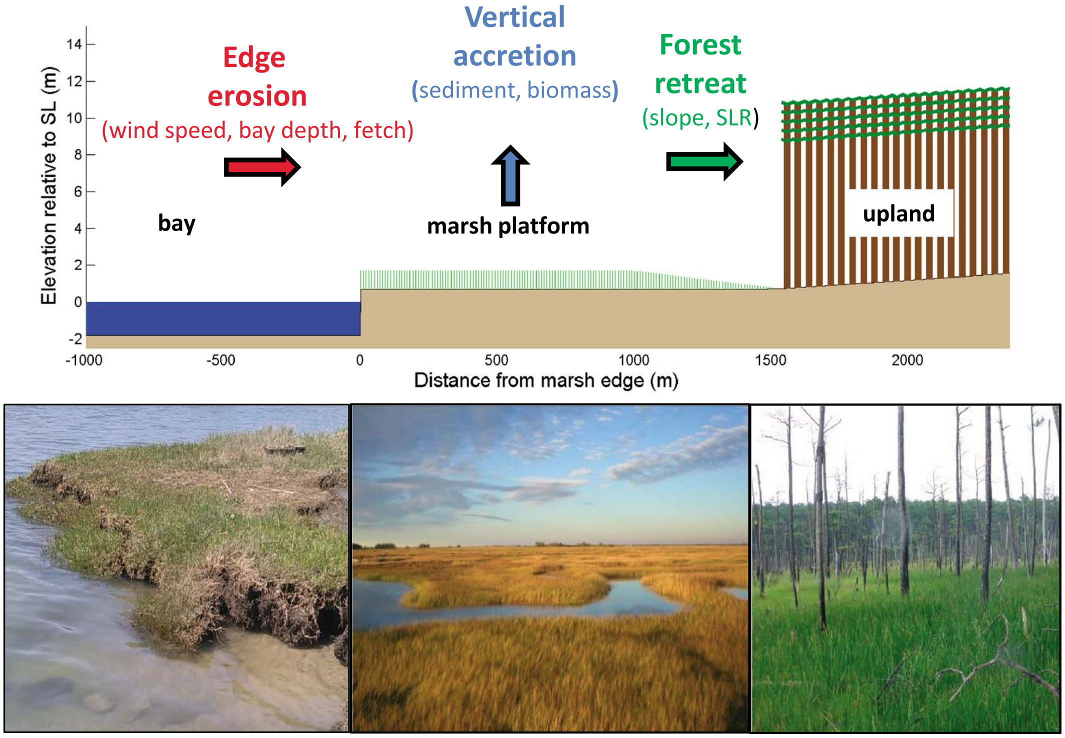

Figure 1. Schematic diagram of model approach illustrating the coupling between subtidal, intertidal, and terrestrial ecosystems and the dominant variables responsible for the evolution of each component. Elevations are relative to mean sea level and represent the initial conditions for model experiments summarized in Figures 2 and 3. Photographs show marsh edge erosion, the vegetated marsh platform, and marsh migration into adjacent forested uplands.

2. Numerical Model of Marsh Erosion and Migration

Our modeling approach approximates salt marsh evolution through time along a transect connecting subtidal ecosystems (e.g., a lagoon, estuary, or bay), the intertidal marsh platform, and adjacent terrestrial ecosystems (Figure 1). We integrate a simple parametrization of marsh migration into uplands with existing models of the marsh-bay boundary [*Mariotti and Carr*, 2014] and marsh platform accretion [*Kirwan and Mudd*, 2012] (see supporting information). The width of the salt marsh platform expands or contracts through time, where waves, bay morphology, and sediment supply influence the position of its seaward boundary and progressive inundation of the upland slope influences the position of its landward boundary.

Following previous work [*Mariotti and Fagherazzi*, 2013; *Mariotti and Carr*, 2014], we model the position of the seaward marsh boundary (B_s) and its impact on bay width as the balance between marsh progradation and erosion.

$$B_s = k_e W - k_a w_{sf} p^{-1} C_r \tag{1}$$

The term on the left reflects erosion rates that are proportional to the wave power density (W) [*Schwimmer*, 2001], which is computed empirically based on wind speed and the width and depth of the bay [*Young and Verhagen*, 1996]. The term on the right reflects deposition of sediment within the bay and is proportional to the settling velocity (w_{sf}), sediment bulk density (p), and suspended sediment concentration (C_r). The wave-induced bed shear stress acting on the mudflat determines C_r. A constant characteristic wind speed is leveraged in all simulations, and fetch evolves according to changes in bay width. Bay depth evolves according to the mass balance between the size of the bay, internal sediment exchange between the bay and marsh, and sediment exchange with an imposed external sediment source [*Mariotti and Carr*, 2014; see supporting information]. Therefore, the position of the seaward boundary evolves not only in response to the interaction between waves and bay morphology but also in response to the elevation and width of the marsh platform.

Following many previous modeling efforts that focus on the building of salt marsh soils in the vertical dimension [e.g., *Allen*, 2000; *Kirwan et al.*, 2010; *Fagherazzi et al.*, 2012], we model marsh vertical accretion (d*z*/d*t*) as the sum of mineral (a_m) and organic (a_o) contributions to soil volume:

$$\mathrm{d}z/\mathrm{d}t = (a_\mathrm{m} + a_\mathrm{o})/\rho_\mathrm{m} \tag{2}$$

where ρ_m is the density of the marsh soil, calculated empirically from the organic content of deposited sediment [*Neubauer*, 2008]. The mass of mineral sediment deposited on the marsh surface, a_m, depends on the local concentration of suspended sediment (C_x) and settling velocity (w_sm) integrated over the duration of flooding, so that mineral deposition rates tend to increase with increasing flooding duration [*Fagherazzi et al.*, 2012]. C_x is the local suspended sediment concentration, which decreases exponentially [*Christiansen et al.*, 2000] with distance from the marsh edge, *x*, such that $C_x = C_\mathrm{r}e^{-\lambda x}$. C_r is the reference sediment concentration as determined by wave-induced shear stresses at the marsh-bay boundary described above, and λ is the coefficient describing the reduction in suspended sediment concentration across the marsh platform. This formulation does not allow topography to influence C_x and thus represents a simplification of how suspended sediment concentration varies across the marsh platform [*D'Alpaos et al.*, 2007; *Da Lio et al.*, 2013]. The mass of organic sediment contributing to soil elevation is proportional to the refractory component of the annual belowground organic matter production [*Morris et al.*, 2012; *Kirwan and Mudd*, 2012; *Da Lio et al.*, 2013; *Ratliff et al.*, 2015]. For simplicity, we assume that production is a quadratic function of the depth of water above the marsh surface at high tide, which most explicitly represents marshes dominated by *Spartina alterniflora* [*Morris et al.*, 2002] or *Schoenoplectus americanus* [*Kirwan and Guntenspergen*, 2015]. Biomass production of multiple species across an elevation gradient, or in other marsh types, may not always follow this pattern [*D'Alpaos et al.*, 2007; *Da Lio et al.*, 2013; *Kirwan and Guntenspergen*, 2015]. Nevertheless, this formulation of vertical accretion accounts for spatiotemporally varying relative roles of mineral and organic contributions across the marsh platform, with mineral deposition dominating marsh accretion near the seaward boundary and at low elevations and organic matter accumulation tending to dominate accretion near the landward boundary.

Salt marsh migration into adjacent uplands represents a fundamental process by which marshes respond to sea level rise [*Brinson et al.*, 1995; *Feagin et al.*, 2010; *Raabe and Stumpf*, 2016] but has yet to be incorporated into dynamic, process-oriented models of coastal evolution. In this initial effort, we assume for simplicity that marsh migration occurs continuously as uplands become progressively inundated by tides [*Brinson et al.*, 1995], so that the position of the landward marsh boundary, B_l, can be approximated as

$$B_\mathrm{l} = R/m \tag{3}$$

where *m* is the slope of the adjacent upland and *R* is the RSLR rate. Although more complicated ecological processes related to facilitation or competition between marsh and upland species may play a role in defining the upland-marsh boundary [*Kirwan et al.*, 2007; *Poulter et al.*, 2009; *Smith*, 2013], analysis of historical imagery indicates that our approach accurately characterizes migration over century timescales [*Raabe and Stumpf*, 2016].

This modeling framework captures several key feedbacks driving marsh evolution and the interactions between marshes and adjacent ecosystems. First, positive feedback between fetch and lateral erosion leads to runaway erosion or progradation of the seaward marsh boundary through time [*Mariotti and Fagherazzi*, 2013]. Erosion of the bay bottom and marsh edge both increase suspended sediment concentrations [*Mariotti and Carr*, 2014]. Therefore, erosion tends to increase mineral deposition rates and the vertical resilience of marshes to sea level rise [*Kirwan et al.*, 2010; *Mariotti and Carr*, 2014]. Due to the imposed decrease in sediment concentration with distance from the bay, this feedback is strongest near the bay-marsh boundary, so that vertical drowning in our model most commonly occurs in the interior of the marsh platform rather than on the seaward marsh edge [e.g., *Kearney et al.*, 1988; *Ratliff et al.*, 2015]. Second, vegetation growth contributes to marsh elevation through organic matter contributions to soil volume and is itself dependent on relative marsh elevation (i.e., flooding frequency). As organic matter production is maximized for an intermediate flooding duration [e.g., *Morris et al.*, 2002], accretion rates in the landward portion of the marsh platform decline toward zero at the upland boundary but tend to increase with accelerated sea level rise. These feedbacks tend to stabilize marsh elevations within the intertidal zone for moderate RSLR rates and prevent marshes from transitioning to upland vegetation. For long flooding durations associated with high RSLR rates and low suspended sediment concentrations, however, feedback between flooding duration and reduced organic matter production

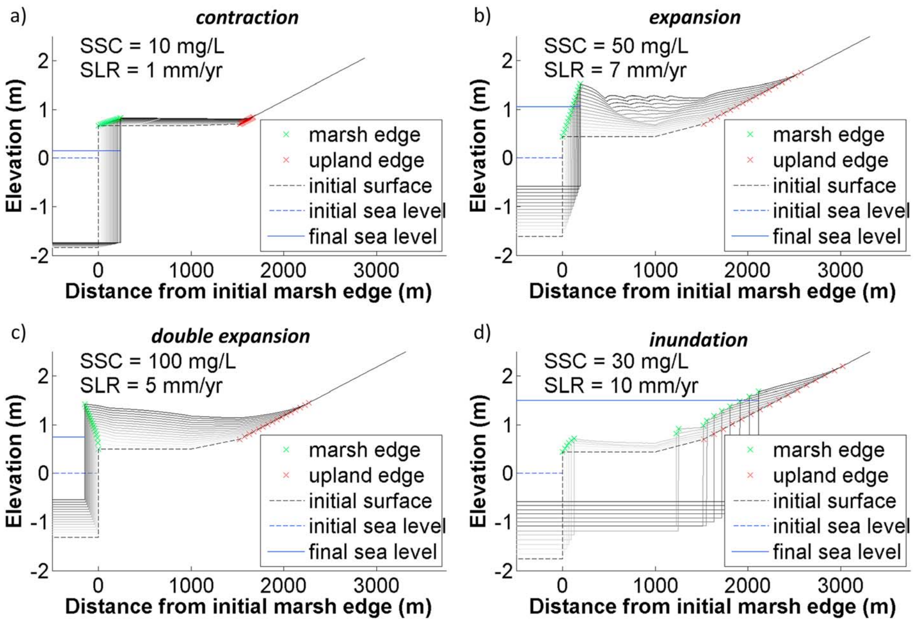

Figure 2. Basic model behavior showing four possible outcomes: (a) marsh contraction, (b) expansion, (c) double expansion, and (d) inundation. The dashed line represents the initial topography, and solid lines represent the topography in 10 year time steps for the duration of each 150 year simulation. Elevations are relative to initial mean sea level. Since bay depth is spatially uniform, only the elevation of the first 500 m of the 5 km bay is shown. Green points represent evolution of the bay-marsh shoreline, and red points represent evolution of the marsh-upland boundary. Dashed and solid blue lines represent initial and final sea level, respectively. The slope of adjacent uplands is 0.001 in each experiment. SSC = external suspended sediment concentration; SLR = rate of relative sea level rise.

leads to progressive inundation of the marsh platform. Lastly, changes in the seaward and landward boundaries of the marsh platform lead to changes in marsh width through time, so that processes at both ends of the transect influence the exchange of sediment between the marsh and bay.

3. Basic Model Behavior: Scenarios of Contraction and Expansion

To illustrate basic model behavior, we first consider the coupled evolution of the bay-marsh-upland system under a variety of RSLR rates and suspended sediment concentrations (SSC) on a gently sloping upland ($m = 0.001$), typical of Atlantic and Gulf coastal plains. Experiments begin with a 5 km wide bay of uniform depth, 1 km wide salt marsh of uniform elevation, 5 km wide upland of constant slope, and a ramp of variable width connecting the marsh platform and upland slope (Figure 1; dashed line in each panel of Figure 2). Experiments start with bay depths and marsh elevations that are in equilibrium with the imposed rate of RSLR and SSC. We model topographic change through time in 1 m wide cells with an annual time step and end each experiment after 150 years. The tidal range in these simulations is 1 m.

For gently sloping uplands, relatively low RSLR rates and SSC lead to a contraction in marsh width through time, driven by erosion of the marsh edge and limited marsh migration into uplands ("contraction," Figure 2a). Positive feedback between fetch and erosion would tend to enhance erosion rates, but this effect was balanced by an increase in the elevation of the marsh edge relative to sea level, so that erosion rates remained temporally constant. Moderate RSLR rates and SSC lead to an expansion in marsh width through time, driven by migration into uplands that is faster than edge erosion ("expansion," Figure 2b). Though the same processes determining edge erosion are active in this scenario, the faster rates of RSLR lead directly to more rapid rates of marsh migration. High SSC and low-moderate RSLR rates lead to expansion of marshes in both the seaward (progradation) and landward (migration) directions ("double expansion," Figure 2c). Finally, high rates of RSLR and low SSC lead to vertical marsh drowning ("inundation," Figure 2d). Drowning begins in the marsh interior where low SSC limits vertical accretion, and the position of the seaward marsh edge jumps landward when erosion through the levee exposes a large unvegetated area. In this scenario, marshes persist only through the development of a rapidly migrating fringe marsh in former uplands.

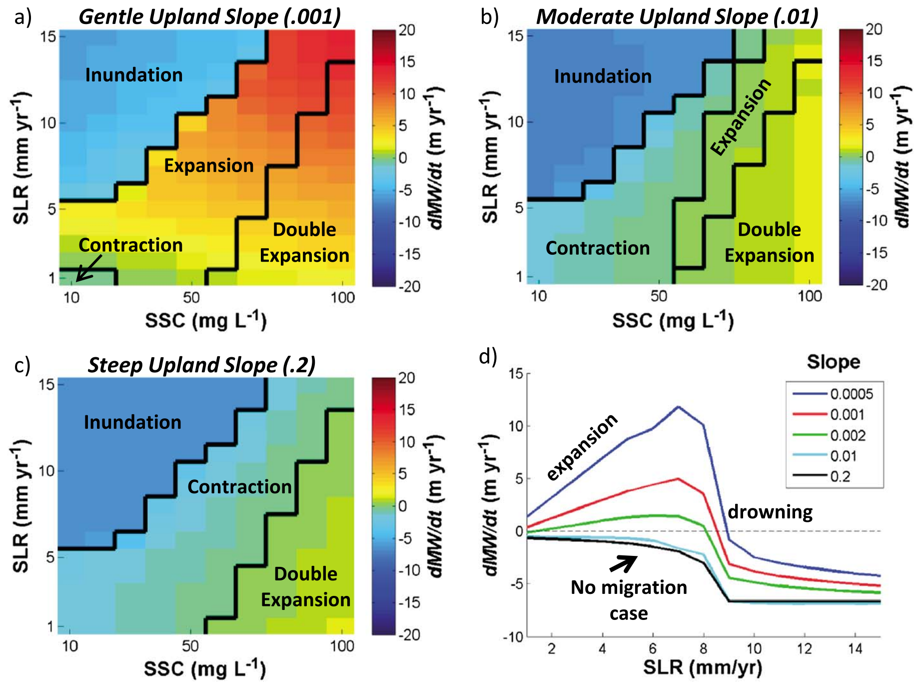

Figure 3. (a–c) Phase diagrams illustrating the dependence of lateral marsh evolution on relative sea level rise (SLR) and sediment supply (SSC) and its sensitivity to the slope of adjacent uplands. Colors represent the rate of change in marsh width (dMW/d*t*) averaged over a 150 year simulation, where blues indicate rapid decrease in marsh width and reds indicate rapid increase in marsh width. Figure 3a shows a gentle upland slope (0.001) representative of coastal plains, Figure 3b shows a moderate upland slope (0.01) representative of glaciated coasts, and Figure 3c shows a steep upland slope (0.2) representative of active margin coasts. The phase boundary between marsh contraction and marsh expansion moves toward higher SLR rates and SSC between Figures 3a–3c, indicating that the potential for net marsh expansion decreases with increasing upland slope. (d) Marsh expansion rate as a function of sea level rise for a variety of upland slopes and a single external sediment supply (40 mg L^{-1}). Increasing SLR rates lead to increasing marsh expansion rates until a threshold SLR rate is exceeded and drowning occurs. The steep upland slope example implicitly represents a "no migration" scenario associated with hardened coasts common in Europe and Asia.

Next we consider the influence of the adjacent upland slope in determining whether a marsh expands or contracts in response to sea level rise. Figures 3a–3c report the parameter combinations leading to each of the four basic model outcomes and the average rate of marsh width change. For gently sloping coastal plain uplands ($m < 0.001$), net marsh expansion occurs for a wide variety of parameter combinations, where marsh expansion rates increase with SSC and RSLR rate up to a maximum of ~20 m yr^{-1} (Figure 3a). For moderately sloping uplands representing glaciated coasts ($m \sim 0.01$), marsh contraction is the far more common model outcome, where relatively low rates of marsh expansion (~1 m yr^{-1}) occur only for the highest SSC and RSLR conditions (Figure 3b). For steeply sloping uplands representative of active margin coasts ($m > 0.02$), slow marsh migration rates lead to net marsh contraction unless SSC is high enough to cause seaward progradation (Figure 3c). Therefore, the slope of adjacent uplands is a fundamental factor influencing the tendency for marshes to expand or contract as well as the rate of change.

While the observation that a low upland slope favors marsh expansion is conceptually intuitive, these model experiments also allow insight into more unpredictable RSLR impacts that arise from connectivity between adjacent ecosystems. Previous work suggests that an increase in RSLR rate should cause both faster rates of marsh erosion [*Mariotti and Fagherazzi*, 2010] and migration [*Feagin et al.*, 2010], so that competition between these two processes is complex. Our results uniquely suggest that an increase in RSLR rate will cause a shift from marsh contraction to marsh expansion until RSLR rates become so high that they lead to rapid marsh inundation (Figure 3). Net marsh expansion rates increase with RSLR rates for a variety of upland slopes (Figure 3d). This phase of accelerating marsh expansion persists until a threshold rate of RSLR is exceeded (8–9 mm yr^{-1} for the conditions simulated in Figure 3d), at which point vertical drowning of the interior marsh platform leads to a decrease in marsh width.

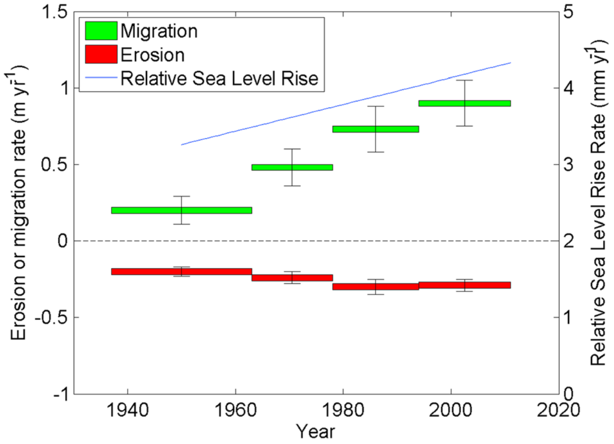

Figure 4. Historical evolution of Goodwin Island, VA (USA) inferred from historical maps and aerial photography. Rates of marsh migration and edge erosion represent spatially averaged rates across the entire island (error bars represent 95% confidence intervals about the interval mean value). Relative SLR rates at Gloucester Point, VA based on *Ezer and Corlett* [2012]. Marsh migration rates accelerate through time, whereas marsh erosion rates remain temporally constant, suggesting a tendency for accelerated sea level rise to favor net marsh expansion.

4. Historical Evolution of Goodwin Island

The general model outcome that marsh expansion rates increase with RSLR rates for gently sloping uplands (Figure 3) implies that marsh migration rates are more sensitive to the rate of RSLR than marsh erosion rates. We test this key model result by considering the temporal evolution of Goodwin Island, located in the York River estuary of the Chesapeake Bay (Virginia, U.S.). This location is part of a hot spot of twentieth century sea level acceleration, driven by gradients in local and regional subsidence and changes in the position of the Atlantic Gulf Stream [*Sallenger et al.*, 2012].

Analysis of historical maps and imagery (see supporting information) indicates that Goodwin Island marshes are eroding laterally at 0.25 m yr^{-1} (1937–2011) and that this rate has not changed appreciatively through time with RSLR (Figure 4). Marshes are migrating into retreating forests at 0.5 m yr^{-1} (1937–2011), so that marshes are increasing in width through time. In contrast to steady marsh erosion rates, spatially averaged marsh migration rates have increased from 0.2 m yr^{-1} (1937–1963) to 0.9 m yr^{-1} (1994–2011) (Figure 4), consistent with the approximate tripling in the rate of regional sea level rise [*Kemp et al.*, 2009]. Though this analysis is simplistic and limited to a single location, agreement with model observations suggests that marsh migration into uplands is more sensitive to RSLR than marsh edge erosion and that net marsh expansion may be a widespread outcome of accelerating RSLR in low-relief coastal plain settings.

5. Discussion and Implications

These simple model experiments and field observations suggest that the most fundamental aspects of marsh evolution (e.g., expansion versus contraction, survival versus submergence) can only be evaluated with an approach that considers important couplings between adjacent ecosystems. Many field and modeling studies have explored the conditions under which marshes can survive RSLR by building soil elevation [e.g., *Stevenson et al.*, 1986; *Langley et al.*, 2009; *Morris et al.*, 2002; *Kirwan et al.*, 2010; *Ratliff et al.*, 2015]. However, our results demonstrate that this classic approach represents an incomplete concept of marsh resilience because marsh size is largely independent of the ability of existing marshes to build vertically until very rapid RSLR rates induce widespread drowning (Figure 3d). For example, marshes may diminish in size even when they are fully capable of surviving in the vertical dimension (Figure 2a), and marshes persist by migrating landward even when threshold RSLR rates are exceeded and the marsh platform drowns (Figure 2d). Recent modeling of the seaward marsh edge also emphasizes the importance of lateral processes in determining marsh resilience to environmental change [*Mariotti and Fagherazzi*, 2013; *Mariotti and Carr*, 2014], but integrating with the extended marsh platform and adjacent upland leads to new insight. For example, models of the seaward edge alone suggest that accelerating RSLR will tend to enhance erosion and lead to near-inevitable marsh loss [*Fagherazzi*, 2013; *Mariotti and Fagherazzi*, 2013]. In contrast, our results suggest that migration allows marshes to potentially expand in response to RSLR even though they are eroding at their seaward boundary (Figure 2b). Thus, the tendency for marshes to expand with moderate acceleration in RSLR suggests that connectivity between marshes and upland ecosystems leads to greater marsh resilience to RSLR than could be predicted with conventional methods.

Humans have long interrupted the flux of sediment and organisms across adjacent ecosystems, though the impact of connectivity on ecosystem resilience is varied and difficult to quantify [*Peters et al.*, 2008;

Bostrom et al., 2011]. A key premise of sea level driven marsh expansion is the potential for marshes to migrate into adjacent uplands. In salt marshes, human actions to defend uplands from the impacts of RSLR actively disconnect upland from wetland ecosystems. Construction of dykes, revetments, and seawalls results in "coastal squeeze" where erosion of the seaward salt marsh edge leads to marsh loss because it cannot be compensated by migration [*Van der Wal and Pye*, 2004]. The "no migration" case of a steep upland slope in Figure 3 offers an implicit view of how hardened shorelines respond to changes in RSLR in our coupled model of bay-marsh-upland evolution. In this scenario, marsh contraction occurs even for rates of RSLR that can be offset by vertical soil building. In contrast to the more general tendency for marshes to expand with accelerating rates of RSLR, these results suggest that shoreline hardening leads to near-inevitable marsh loss and that disconnectivity leads to less resilient ecosystems.

Global losses due to coastal flooding now exceed US$6 billion per year [*Hallegatte et al.*, 2013]. Flood defense strategies involve hard structures, ecosystem engineering, or a combination of both, and there is vigorous debate over their relative merits [*Temmerman et al.*, 2013; *Ma et al.*, 2014; *Feagin et al.*, 2015]. Because ecosystem-based flood protection increases with wetland width [*Barbier et al.*, 2008; *Temmerman et al.*, 2013], our results suggest that the near-inevitable salt marsh loss along hardened coasts leads to a scenario where accelerating RSLR rates lead to simultaneous increases in flood risk and decreases in natural flood protection. However, our results also indicate that marsh erosion is less sensitive to RSLR than marsh migration into unhardened uplands. This behavior suggests a counterintuitive, natural tendency for marsh expansion with RSLR and emphasizes the disparity between coastal response to climate change with and without human intervention. Since expansion occurs despite some loss of existing marsh, management efforts to establish migration corridors rather than preserve existing marsh could uniquely exploit sea level rise to build marshes and maintain natural flood protection simply by not defending the coast.

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