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Effects of Marsh Edge Erosion in Coupled Barrier Island-Marsh Systems and Geometric Constraints on Marsh Evolution

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Key Points:
- Overwash-sustained narrow marsh state is wider and more persistent but still transient in the presence of wave edge erosion
- Edge erosion increases marsh resilience because it is a more efficient sediment source than surface erosion via drowning
- If a marsh platform and bay bottom are keeping up with sea level, marsh edge behavior can be predicted by geometry and net sediment input

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Effects of Marsh Edge Erosion in Coupled Barrier Island-Marsh Systems and Geometric Constraints on Marsh Evolution

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Abstract Previous results show that overwash provides an important sediment source to back-barrier marshes, sustaining a narrow marsh state under conditions in which marsh drowning would otherwise occur. We expand the coupled barrier island-marsh evolution model GEOMBEST+ to explore the effects of wind waves on back-barrier marshes. We find that the addition of marsh edge erosion leads to wider, more resilient marshes and that horizontal erosion of the marsh edge is a more efficient sediment source than vertical erosion of the marsh surface as it drowns. Where marshes and bays are vertically keeping up with sea level, and the net rate of sediment imported to (or exported from) the basin is known, the rate of marsh edge erosion or progradation can be predicted knowing only the present basin geometry, sea level rise rate, and the net rate of sediment input (without considering the erosion or progradation mechanisms). If the rate of sediment input/export is known, this relationship applies whether sediment exchange with the open ocean is negligible (as in basins dominated by riverine sediment input) or is significant (including the loss of sediment remobilized by waves in the bay). Analysis of these results reveals that geometry and stratigraphy can exert a first-order control on back-barrier marsh evolution and on the marsh-barrier island system as a whole and provides new insights into the resilience of back-barrier marshes and on the interconnectedness of the barrier-marsh system.

Plain Language Summary Sand washed across barrier islands during storms (called overwash) provides sediment for salt marshes behind those islands, and can allow a marsh which otherwise would drown to grow vertically fast enough to keep up with sea level. We use a barrier island-marsh evolution model (GEOMBEST+) to see what effect marsh edge erosion by waves has on overwash-supported marshes. Consistent with previous research, we find that wave erosion can make marshes more resilient by freeing sediment that can be used elsewhere on the marsh surface. We add that horizontal erosion of the marsh edge provides more sediment per volume eroded than vertical erosion of the marsh surface. This is because the bottom layers of the marsh contain more sediment (that can stay on marsh surfaces), while the surface layers include plant material (that drifts away or decomposes). We also find that when the marsh and bay are keeping up with sea level, expanding or eroding the marsh is the only way to change the volume of the bay, so how fast the marsh is expanding or eroding can be predicted using geometry, knowing only the size of the basin, sea-level-rise rate, and the net rate of sediment import or export.

1. Introduction

Salt marshes and barrier islands are ecosystems of great economic and ecological importance; barrier islands are often heavily populated and serve as vacation destinations, and salt marshes provide a number of ecosystem services including water filtration, flood protection, and habitat for commercially and ecologically important species (Barbier et al., 2011). Both barrier islands and salt marshes are dynamic environments that, because of their low relief, are especially vulnerable to future changes in sea level and storm intensity (FitzGerald et al., 2008; Kirwan & Megonigal, 2013).

Salt marshes tend to maintain their elevation relative to rising sea level through the deposition of mineral sediment and the production of organic matter (e.g., D'Alpaos, 2011; FitzGerald et al., 2008; Friedrichs & Perry, 2001; Kirwan & Megonigal, 2013; Reed, 1995). As sea level rises, in the absence of flood protection measures, marshes tend to be flooded for longer periods of time and can therefore trap more inorganic sediment, resulting in vertical accretion of the marsh platform (Marani et al., 2010). However, this feedback is limited by inorganic sediment supply and relative sea level rise (RSLR) rates. If RSLR rates are too high relative to sediment supply, a marsh will drown, decreasing in elevation to the level of an adjacent tidal flat (Day et al., 2011; Kirwan et al., 2010; Marani et al., 2007; Morris et al., 2002; Reed, 1995). Even in the absence of RSLR, if the basin is deep enough for waves capable of eroding the marsh edge to form, significant loss of marsh can occur due to lateral erosion of the marsh platform by wind waves (e.g., Fagherazzi et al., 2013; Marani et al., 2011; Mariotti & Fagherazzi, 2013; Nyman et al., 2006; Schwimmer, 2001). As the marsh boundary erodes laterally, the basin's fetch increases, allowing larger waves to form and leading to enhanced erosion. Conversely, if sediment concentrations are high enough for the marsh edge to prograde, fetch decreases, making waves smaller and accelerating progradation. Previous research has shown that because of these paired feedbacks, the existence of a partially filled marsh basin is an unstable state (Mariotti & Fagherazzi, 2010) and that there is a critical basin width (determined chiefly by suspended sediment concentrations) below which marshes tend to prograde until they completely fill a basin and above which wave action is sufficiently strong to erode marshes completely, leaving an open bay (Mariotti & Fagherazzi, 2013).

In response to RSLR, barrier islands and barrier spits tend to migrate landward and maintain elevation relative to sea level (Bruun, 1988). Barrier migration is facilitated by storms that erode sediment from the beach and nearshore seabed (the "shoreface") and deposit it via overwash processes on the top and back side of an island, raising island elevation and moving the shoreface, shoreline, and barrier landward. The rate of RSLR, the composition and erodibility of underlying stratigraphy (Moore et al., 2010), and substrate slope (Brenner et al., 2015; Moore et al., 2010; Wolinsky & Murray, 2009) affect island migration, which will tend to occur at the rate necessary to liberate sufficient sediment from the shoreface to maintain island elevation relative to sea level (Moore et al., 2010; Wolinsky & Murray, 2009). If sufficient sand cannot be eroded from the shoreface, or if sand cannot be supplied to the island interior to maintain island elevation (e.g., where shoreline fortifications prevent overwash from occurring), a barrier may disintegrate (e.g., Masetti et al., 2008; Moore et al., 2014; Lorenzo-Trueba & Ashton, 2014).

Although the impacts of climate change and sea level rise on marshes and barrier islands have been the topic of many previous studies, we are only recently beginning to understand that interactions between these two adjacent environments are important in determining how barrier-marsh systems evolve (Brenner et al., 2015; FitzGerald et al., 2008; Walters et al., 2014; Walters & Kirwan, 2016). For example, when a barrier migrates over a back-barrier marsh platform, less sand is required to raise the elevation of the back of the island than would be required if the barrier progrades into a back-barrier bay (Wolinsky & Murray, 2009). The tendency of the back-barrier marsh to keep up with RSLR reduces the accommodation space that the barrier needs to fill, thereby allowing for a slower island migration rate (Brenner et al., 2015; Walters et al., 2014) and reducing the likelihood of barrier disintegration. In this scenario, fine-grained marsh sediment can eventually become exposed on the shoreface, reducing the amount of sand available to the barrier and resulting in an increase in island migration rate (Brenner et al., 2015). This scenario can also result in a loss of marsh extent if the back-barrier marsh cannot prograde into the bay as fast as the island is migrating (Deaton et al., 2017). On the other hand, overwash from barriers can be an important source of sediment for back-barrier marshes (e.g., Walters et al., 2014; Walters & Kirwan, 2016), allowing a marsh that would otherwise drown to maintain its elevation, resulting in a long-lasting "narrow marsh" state (e.g., Figure 1), identified in model results and in satellite observations of marsh widths for the Virginia Barrier Islands (Walters et al., 2014). For some time, a narrow marsh in this state will maintain its elevation, while mainland-attached marshes farther away from the sediment source (here a barrier) will drown.

In Walters et al. (2014), in the long-term this narrow marsh state almost always eventually progrades to fill the basin or drowns. However, Walters et al. (2014) did not consider the effects of wave edge erosion, which is a primary cause of marsh loss (e.g., Leonardi & Fagherazzi, 2014; Marani et al., 2011; Priestas et al., 2015). Such model simplification and the intentional omission of the some of the processes and interactions occurring in complex natural morphodynamic systems can facilitate insights about what processes and interactions are most important in those systems (Murray, 2003). To increase the level of realism of the model framework of Walters et al. (2014), and to test the importance of wave edge erosion in the evolution of marsh-barrier systems, we expand on the morphological behavior model GEOMBEST+ (Geomorphic Model of Barrier, Estuarine, and Shoreface Translation + Marsh, developed by Walters et al., 2014) to include the addition of

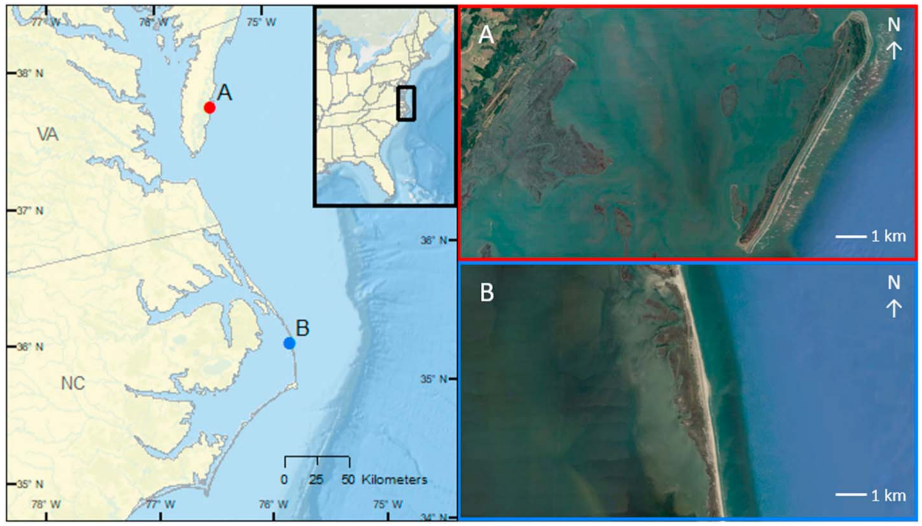

Figure 1. Illustrative examples of two narrow back-barrier marshes on the East Coast of the United States. (a) Hog Island, Virginia, and (b) a section of Cape Hatteras National Seashore, North Carolina.

wave effects on back-barrier marshes and create GEOMBEST++ (GEOMBEST+ + Waves). GEOMBEST+ is a 2-D morphological behavior model representing the evolution of a cross-shore transect from the base of the shoreface to the mainland and including a barrier, marsh, and bay. GEOMBEST+ combines the conservation of mass with geometric constraints on sediment availability and placement, given some commonly employed assumptions (chiefly involving equilibrium elevations and shapes of some parts of the cross-shore profile, representing negative morphodynamic feedbacks). GEOMBEST+ facilitates exploration of barrier island evolution on long timescales, as influenced by spatially varying stratigraphy and topography/bathymetry, possibly representing real world settings (e.g., Moore et al., 2010). With the addition of back-barrier processes represented in the model (Walters et al., 2014), and the improvements to those processes in this work, GEOMBEST++ offers an opportunity to further examine the interactions between barriers and back-barrier environments. A more detailed model description, including model assumptions, follows in section 2.

Our goals are to further investigate the persistence of the overwash-sustained narrow marsh state identified by Walters et al. (2014). We do not seek to represent any particular barrier island-marsh system but more broadly to improve our understanding of how interactions between barrier islands and marshes can influence the evolution of the system as a whole. In the process, we explore the consequences of some assumptions and simplifications commonly employed in models of marsh/bay morphodynamics. Our results highlight the constraints that geometry and conservation of mass impose on back-barrier basins as they evolve in response to RSLR and build on our understanding of how wave edge erosion can increase marsh resilience (e.g., Mariotti & Carr, 2014).

2. Model Description: GEOMBEST and GEOMBEST+

GEOMBEST (Geomorphic Model of Barrier, Estuarine, and Shoreface Translation) tracks the evolution of a two-dimensional, cross-shore coastal transect extending from the mainland to the base of the shoreface, as this profile responds to RSLR and sediment supply over timescales of decades to millennia (Brenner et al., 2015; Moore et al., 2010; Stolper et al., 2005). The model tends to maintain an equilibrium profile extending across the barrier island and shoreface (e.g., Murray & Moore, 2018; Rosati et al., 2013) and operates on the principle of sediment conservation, representing the effects of the transport of sand among three domains: shoreface, barrier island, and back barrier (Figure 2a). As sea level rises, the profile moves upward to maintain its elevation relative to sea level (representing negative morphodynamics feedbacks; Murray & Moore, 2018) and landward to the cross-shore position required to conserve sand, which is redistributed among the three domains. While stratigraphy in natural back-barrier systems is complex (e.g., Hein et al., 2012; Odezulu et al., 2018; Rodriguez

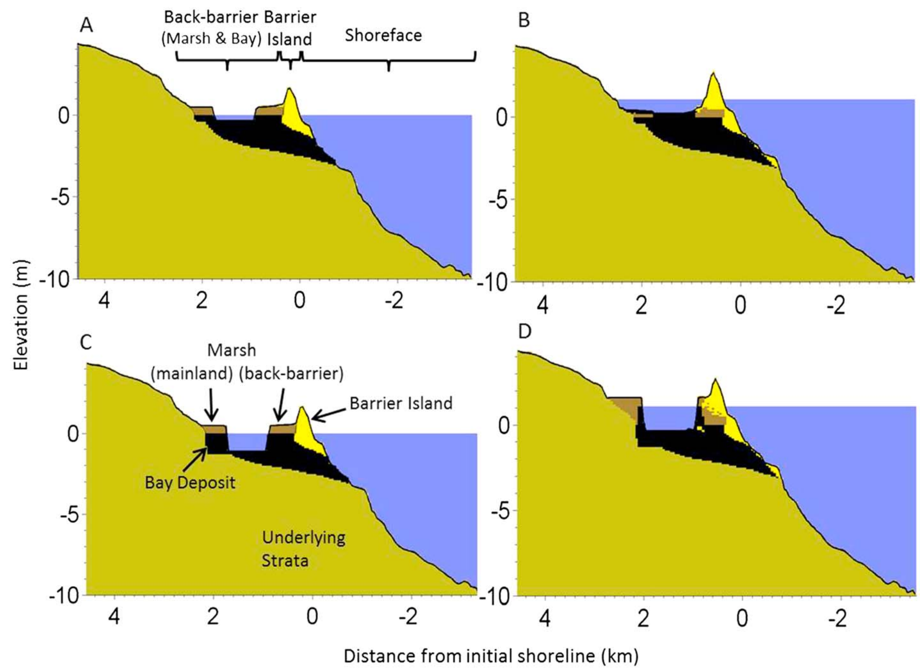

Figure 2. (a) Initial condition and (b) model output after 1 m of total RSLR for a GEOMBEST+ simulation of an initially narrow marsh without wave edge erosion (e.g., from Walters et al., 2014). (c) Initial condition and (d) model output after 1 m of total RSLR from GEOMBEST++ (including wave edge erosion). For both simulations, overwash volume flux = 1.4 m^2/yr and BAR/RSLRR ≈ 0.3; simulations are identified with a black box in Figures 4a and 4c. (a) also shows the three model domains, and (c) shows the stratigraphic units and the deeper equilibrium depth of the bay compared to Walters et al. (2014).

et al., 2018), stratigraphy in the model is by necessity simplified: the user can define stratigraphic units and establish the erodibility and proportions of sand and mud for each (thus approximating the important influence stratigraphy can have on barrier migration through variations in yield strength). Stratigraphic units have distinct boundaries, but this assumption is relaxed in the back barrier in recent versions of the model (GEOMBEST+ and GEOMBEST++); the sand content of the marsh can vary temporally and spatially.

Designed to represent the cumulative effects of storms over decadal to millennial timescales, the barrier component of the model operates on a 10-year time step. As a result, the model does not resolve events of individual storms such as erosion of dunes or individual overwash events but instead represents a long-term average of the island profile. The height and/or volume of the sandy part of the barrier can, however, change over time as the profile tends toward equilibrium. The model allows the user to set a sediment import/export rate, representing influx or loss of sediment from gradients in alongshore transport, which can be an important cause of shoreline retreat (e.g., Cowell et al., 1995). However, as we are specifically interested in the interactions between overwash and marsh width, we focus on the cross-shore impacts of SLR and increasing storm frequency (via overwash volume flux) in this study and do not consider alongshore transport. As we focus in this study on the behavior of the back barrier, we describe the evolution of this model domain in detail below. For more information on the shoreface and barrier components of the model, we refer the reader to Moore et al. (2010).

GEOMBEST+ (Geomorphic Model of Barrier, Estuarine, and Shoreface Translation + Marsh), developed by Walters et al. (2014), adapts components of the marsh-tidal flat model from Mariotti and Fagherazzi (2010) into GEOMBEST so that the back-barrier domain, including marsh and/or shallow bay, evolves dynamically according to rates of SLR and fine-grained sediment supply. In this version of the model, GEOMBEST+, which we use and further expand upon in this study, evolution of the back-barrier geometry depends on the rate of RSLR and the rate of sediment supply (including both overwash sand and fine-grained sediment). Overwash is represented as a characteristic volume flux of sand from the barrier to the back barrier; the model does not resolve individual overwash events, but sand deposited in the back barrier is conserved, and layers of sand are preserved in the marsh stratigraphy. GEOMBEST+ does not explicitly include flood tidal deltas, which

Table 1
Definitions of Variables and Abbreviations

Variable/abbreviation	Definition
RSLR	Relative sea level rise
d_R	User-defined maximum bay depth
E_{max}	User-defined maximum erosion rate
E_B	Gross bay bottom erosion rate; previously referred to by Walters et al. (2014) as "bay bottom erosion rate"
d	Bay depth
u_b	Orbital velocity
τ	Shear stress
ρ	Water density
f_w	Friction factor
τ_c	Critical shear stress
a	A constant used in gross bay bottom erosion calculation
A_B	Gross bay deposition rate
Q_B	Net import of fine-grained sediment to the bay
E_m	Wave edge erosion
W	Wave power
H	Wave height
c_g	Group velocity
h	Height from bay bottom to surface of marsh platform
k_e	Erodibility coefficient for marsh edge
BAR	Basin accretion rate, Q_B divided by basin width
BAR/RSLRR	Ratio of basin accretion rate to RSLR rate
Q_{OW}	Overwash flux volume
d_b	Depth of the bay relative to MHWL
d_m	Depth of the marsh platform relative to MHWL
R	RSLR rate
L	Cross-shore width of the basin
$Q_{s,in}$	Net volumetric sediment input rate
Q_{OM}	Contribution of organic matter to accretion of marsh platform
Q_d	Organic matter lost to decomposition or dispersal

can be important sources of sand to the back barrier over long timescales (e.g., Hein et al., 2012). The flux of sand into the back barrier termed "overwash" could, for the purposes of sediment budgets, be considered to consist of both overwash and sand transported through breaches or ephemeral inlets. However, because sand washed over the island is the main source of sand for the back-barrier (barrier-attached) marshes of interest in our study, we focus here on that mechanism. The model does not include eolian transport of sediment, as it is negligible at distances away from the dune, which are smaller than typical cell sizes (which are on the order of 50–100 m; Rodriguez et al., 2013). Although sand is conserved in all three domains, fine-grained sediment is only conserved in the back barrier, because once fine-grained sediment is exposed on natural barrier shorefaces by prolonged shoreface erosion, it can be eroded but not redeposited in this high-energy environment.

While the barrier component of GEOMBEST+ still operates on a 10-year time step, back-barrier (marsh and bay) processes occur over a shorter sub–time step, determined by the time it takes for the bay to reach a user-defined maximum depth (d_R) approximating the equilibrium depth (the depth at which vertical accretion and erosion are equal or for the net deposition rate equals the rate of RSLR). Bay bottom erosion in GEOMBEST+ (E_B)decreases with depth (d) until reaching zero at the approximated equilibrium depth (d_R) such that

$$E_B = E_{\text{max}}\left(\frac{1-d}{d_R}\right). \tag{1}$$

where E_{max} is a user-defined maximum erosion rate (see Table 1 for list of variables). The gross sediment deposition rate (A_B) within the bay (representing riverine and/or net coastal sediment input) is obtained by distributing the net import of sediment to the bay (Q_B) over the width of the bay.

During each model time step, the back-barrier environment evolves through five main stages (Figure 3): (1) sea level rises; (2) barrier island sand is moved into the back barrier through overwash; (3) Q_B is distributed evenly across the bay; (4) bay bottom erosion occurs according to equation (1); and (5) fine-grained sediment eroded from the bay bottom is used first to build the marsh platform up to mean high water level and then preferentially deposited on the edges of the bay allowing the marsh to prograde (Mariotti & Fagherazzi, 2010). Stages (3) through (5) comprise the back-barrier component of the model, which operates on a faster sub–time step and so iterate multiple times in one model time step. The landward and back-barrier sides of the bay each receive half of the total available fine-grained sediment distributed in stage (5). Once the marsh platform has reached mean sea level, 50% of the sediment used to build it up to mean high water comes from the creation of organic material (the remaining 50% comes from fine-grained sediment). This ratio of organic to fine-grained sediment comes from field data collected by Walters and Moore (2016a). Where a marsh is present, accretion rate in the model does not depend on elevation or flooding frequency. Instead, when sufficient inorganic sediment is available, marsh accretion rate matches the rate of SLR, representing the long-term effects of a dependence on elevation/flooding frequency (e.g., Morris et al., 2002). The model does not resolve the profile shape of marsh boundary because its location is representative of the net effects of erosion and progradation including small and large events (such as mass wasting).

3. Methods

We develop a new version of this model—which we will call GEOMBEST++ (Geomorphic Model of Barrier, Estuarine, and Shoreface Translation + Marsh + Waves)—in which we (1) replace the formulation for bay bottom erosion with a more physically based approach and (2) incorporate erosion of the marsh edge by wind waves.

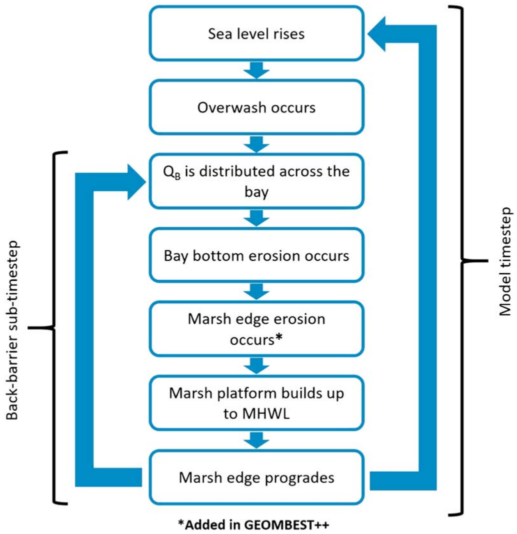

Figure 3. Flowchart depicting the evolution of the back-barrier environment in the model. The back-barrier sub–time step iterates multiple times during one model time step, with number of iterations depending on the rate of erosion of the bay bottom. Marsh edge erosion was added in the development of GEOMBEST++ (i.e., it is not represented in GEOMBEST+).

Bay bottom erosion in GEOMBEST+ is depth dependent, decreasing with depth until reaching zero at the equilibrium depth (equation (1)). Because the equilibrium depth of a bay is dynamic in natural systems, varying with the size of the waves and the amount of fine-grained sediment input (Fagherazzi et al., 2007), we replace the previous formulation with a more physically based one driven by shear stress. In GEOMBEST++, we calculate wave height and wave period using the relationships between wave height and energy developed by Young and Verhagen (1996) and then use the orbital velocity (u_b; based on linear wave theory)—a function of bay depth, fetch, and wind speed—to calculate the shear stress (τ) according to

$$\tau = \frac{1}{2} f_w \rho u_b^2 \tag{2}$$

(Dean & Dalrymple, 1991), where ρ is water density and f_w is a friction factor equal to 0.03. (We experimented with different values of f_w, but changing this value did not affect the results significantly, so for simplicity we chose a reasonable constant value for a smooth bed; Wikramanayake & Madsen, 1991.) Gross bay bottom erosion (E_B; replacing equation (1)) is then related to the difference between shear stress and the critical shear stress τ_c through

$$E_B = a(\tau - \tau_c) \tag{3}$$

where a is a constant equal to 4.12×10^{-4} kg/(m$^2 \cdot$ s $\cdot$ Pa; Mariotti & Fagherazzi, 2010) and τ_c is 0.2 Pa (consistent with values used in Mariotti and Fagherazzi, 2013, and Fagherazzi and Wiberg, 2009). For simplicity and to enhance the clarity of insight, we assume an equant basin and do not consider anisotropic wind. Instead, we use the cross-shore bay width as the fetch. If there was a predominant wind direction, the two sides of the marsh/bay could experience different amounts of erosion, which would introduce a translation of the bay (which we do not investigate in this work) and a change in size. As in GEOMBEST+, the gross sediment deposition rate (A_B) within the bay (representing riverine and/or net coastal sediment input) is obtained by distributing the net import of sediment to the bay (Q_B) over the width of the bay. The gross bay bottom erosion rate (E_B, equation (3)) depends on sediment characteristics (through τ_c) and on wave characteristics and depth (through τ). Net erosion or deposition is determined by the difference between A_B and E_B. Because E_B decreases with depth, bay depth tends to converge to a steady state value in which deposition balances erosion plus RSLR (Fagherazzi et al., 2007). For greater depths, deposition outpaces erosion ($A_B > E_B$ and net deposition occurs), and the depth shallows toward the equilibrium (and vice versa). We use this dynamic formulation to calculate equilibrium depth (at which E_B + RSLR rate = A_B) in the model. The time to reach this equilibrium sets the time step for the back-barrier component of the model, meaning that the bay adjusts to equilibrium instantaneously in the model (i.e., we do not resolve smaller timescales). This treatment represents the results of previous modeling showing that the timescale for approaching equilibrium depth is very small compared to the timescale for changes in bay width (Mariotti & Fagherazzi, 2013).

We calculate wave edge erosion (E_m) using the wave power (W) following the methods of Mariotti and Fagherazzi (2013) and Marani et al. (2011)

$$W = \frac{\rho g}{16} H^2 c_g \tag{4}$$

$$E_m = \frac{W k_e}{h} \tag{5}$$

where wave height (H) is again calculated from Young and Verhagen (1996), c_g is the group velocity (assumed equal to $\sqrt{gd}$ for shallow water waves), h is the height from the bay bottom to the surface of the marsh platform, and k_e is an erodibility coefficient for the marsh edge equal to 0.14 m$^3 \cdot$ yr $\cdot$ W. Altering the value of k_e would alter the rate at which sediment is mobilized from marsh erosion for the same wave power, which would tend to alter the rate at which the back barrier evolves in the model. This value is within the range of values for k_e calculated by Mariotti and Fagherazzi (2013).

We represent four stratigraphic units in the model: an underlying stratigraphy (75% sand), bay facies (100% fine-grained sediment), marsh facies (50% organic material and 50% fine-grained sediment), and barrier island facies (100% sand; Figure 2c). We distinguish sand and fine-grained sediment on the basis of grain size and settling velocity and represent cohesion not through sediment properties but by treating erosion as dependent on bed shear stress (see equation (3) above). Across the entire model domain we use a cell size of 50 m (cross-shore width) by 0.1 m (height).

The algorithm for distributing sediment in the back barrier in GEOMBEST++ is much the same as in GEOMBEST+, but with the addition of wave edge erosion it is modified to (Figure 3): (1) sea level rises; (2) barrier island sand is moved into the back barrier through overwash; (3) Q_B is distributed evenly across the bay; (4) bay bottom erosion occurs according to equations (2) and (3); (5) wave power is calculated from equation (4), and wave edge erosion occurs according to equation (5); and (6) fine-grained sediment eroded from the bay bottom and the marsh edge is combined and used first to build the marsh platform up to mean high water level and then preferentially deposited on the edges of the bay (resulting in net progradation of the marsh edge if deposition outpaces erosion; Mariotti & Fagherazzi, 2010). As in GEOMBEST+, the landward and back-barrier sides of the bay each receive half of the total available fine-grained sediment distributed in stage (6); between mean sea level and mean high water half the sediment used to build the marsh comes from the creation of organic material, and the profile shape of the marsh boundary is not resolved. Stages (3) through (6) operate on the faster back-barrier sub–time step (determined by the length of time required to reach the equilibrium depth) and so iterate multiple times in one model time step. Because coarser grain sizes are unlikely to travel far in natural bays (in the absence of high tidal current velocities, not considered here), if sand is eroded from the edge of the marsh in step (5), it is redeposited on the bay bottom in the same location it was eroded from before sediment is redistributed in step (6). Organic material eroded as part of the marsh unit is lost from the system, representing decomposition and/or dispersal.

We consider only one tidal range, though we acknowledge that previous research has shown that marshes with higher tidal ranges experience less bottom erosion from wind waves (D'Alpaos et al., 2012) and are generally more stable and more resilient to RSLR (e.g., D'Alpaos et al., 2011, 2012; Kirwan & Guntenspergen, 2010). The tidal range could affect the rates of marsh erosion (by affecting the proportion of the marsh platform sediment column that contains organic matter), but this is beyond the scope of this study. All fine-grained sediment, from both marsh and bay stratigraphic units, is conserved in the back barrier—i.e., we do not consider sediment export to the ocean. We discuss this important simplification in section 5.1.

Our model runs span a range of fine-grained sediment input rates, RSLR rates, and overwash volume fluxes across the parameter space defined by Walters et al. (2014; Figure 4). Walters et al. (2014) demonstrated that marsh width increases with Q_B and decreases with RSLR rate and that both dependencies can be expressed through the ratio of basin accretion rate (BAR; i.e., the accretion rate that results when Q_B is spread across the initial width of the basin) to RSLR rate (BAR/RSLRR). Thus, we examine the effects of varying BAR rather than varying the Q_B and RSLR rate individually. When the BAR/RSLRR ratio is 1, the fine-grained sediment input is sufficient for the basin to accrete at a rate equal to the rate at which space is created by RSLR. Thus, a high BAR/RSLRR value (>1) means that sediment input is high compared to the rate of space creation, and a low value (<1) means that space is being created faster than fine-grained sediment input can fill it. We considered five BAR/RSLRR values evenly spaced on a log scale between 0.1 and 10. Overwash flux volume (Q_{OW}) ranges from 0.2 to 2 m^2/yr in increments of 0.6. For each BAR/RSLRR and overwash volume flux combination we ran model simulations with an initially full basin (a 1,800-m wide basin filled with marsh) and an initially narrow marsh (about 500 m wide on both sides of the 1,800-m wide basin), resulting in a total of 40 simulations. These initial marsh widths are the same as in Walters et al. (2014); however, in our experiments bay depths are greater because the new dynamic bay bottom erosion calculation results in a deeper equilibrium depth for the bay than the previous formulation (Figure 2; see section 5 for potential impacts of this change on our findings relative to those of Walters et al., 2014). Following Mariotti and Fagherazzi (2013), we use a wind speed of 8 m/s for all simulations, because the average wind events make the greatest contribution to marsh edge erosion (Leonardi et al., 2016). We run the model for 100 years with no RSLR and the necessary Q_B and Q_{OW} inputs to establish the initial condition of a full basin or narrow marsh. This also ensures that the bay has reached the appropriate equilibrium depth for the marsh width. To ensure that the barrier moves over the same section of underlying substrate in each simulation (and thereby to control for the effect of substrate slope on simulation outcome), model simulations then run for 1 m of total RSLR, regardless of the RSLR

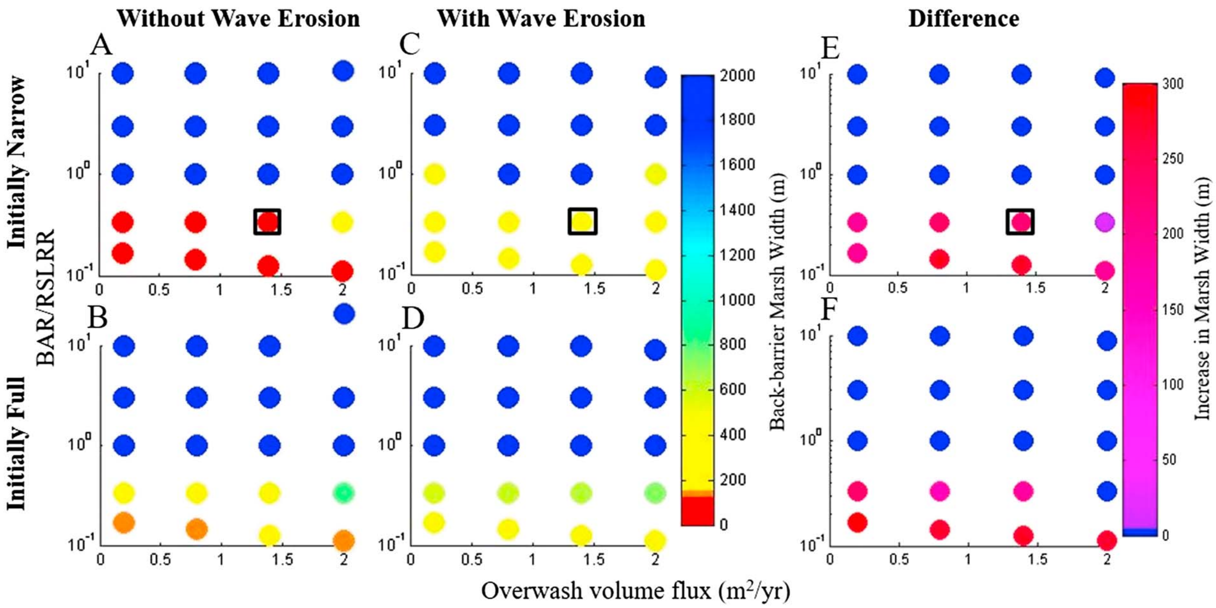

Figure 4. Phase diagram showing the distribution of back-barrier marsh widths after 1 m of total RSLR for a selection of initially (a) narrow marshes and (b) full basins from experiments using GEOMBEST+ (without wave edge erosion; Walters & Moore, 2016b) and the same initially (c) narrow marshes and (d) full basins using GEOMBEST++ (including wave edge erosion). (e and f) The increase in marsh widths between (a) and (c) (initially narrow marshes) and (b) and (d) (initially full basins), respectively. Black boxes in (a) and (c) correspond to the images in Figures 2b and 2d, respectively.

rate. Thus, simulations run for 120–1,000 model years (not including spin-up), with longer runs corresponding to slower RSLR rates.

Although marshes form on both the back-barrier and landward sides of the basin, we measure only the width of the back-barrier attached marsh (from the dune limit to the landward marsh edge; see Figure 2c), because the width of this marsh is directly influenced by Q_{OW} and the migration rate of the barrier. Therefore, when discussing a marsh width in reference to the model, unless otherwise noted, we are always referring to the back-barrier (barrier-attached) marsh. We use the same categories of marsh widths defined by Walters et al. (2014) to classify our results: full basins ($>$ ~800 m), narrow marshes (150–400 m), and empty basins ($<$150 m).

4. Results

Overall, the addition of wave edge erosion to GEOMBEST+ results in back-barrier marshes that are on average wider after 1 m of total RSLR than when wave edge erosion is not included (Figures 4e and 4f). Without wave edge erosion, for both initial conditions (initially narrow marshes and initially full basins), final marsh widths fall into all three categories (full basins [$>$ ~800 m], narrow marshes [150–400 m], and empty basins [$<$150 m]; Walters et al., 2014, Figures 4a and 4b) after 1 m of RSLR (Walters et al., 2014). With the inclusion of wave edge erosion, for the initial condition of a full basin, narrow marshes remain as wide as 700 m after 1 m of RSLR (Figure 4d). Initially, narrow marshes fall into the range of 150–450 m wide after 1 m of RLSR (Figure 4c). For both initial cases, final marsh widths are approximately 200 m wider on average than they are when wave edge erosion is not accounted for (Figures 4d and 4e), and narrow marshes survive under a wider range of conditions in the presence of wave edge erosion. In addition, none of the runs reach the empty basin state, and narrow marshes exist at lower Q_{OW} values and lower BAR/RLSR rates when the effects of wave edge erosion are included. After an additional meter of RSLR, the results are qualitatively the same as those of Walters et al. (2014): whereas 18 of our 40 model runs yield narrow marshes after 1 m of RSLR, all but five simulations have converged from the narrow marsh state to the full or empty basin state after 2 m of total RSLR (Figure 5a).

The new formulation for equilibrium depth of the bay is sensitive to wind speed. However, the choice of wind speed (and therefore the equilibrium depth of the bay) does not affect the final outcome of our model

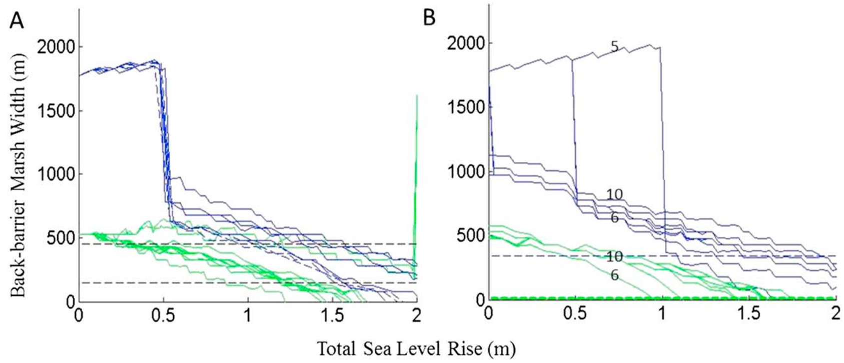

Figure 5. (a) Evolution of marsh widths over 2 m of total RSLR (we run the model for a total amount of sea level rise rather than a set length of time). Initially, full basins are in blue and initially narrow marshes are in green. The dashed lines represent the range of marsh widths defined in Walters et al. (2014) as narrow (150–450 m). The apparent sudden increase in marsh width for the initially narrow marshes that fill the basin occurs when the narrower back-barrier marsh merges with the wider mainland-attached marsh, and the width of contiguous marsh behind the barrier suddenly increases to the combined width. (b) Sensitivity to wind speed. Evolution of marsh width for an initially full basin (blue; overwash volume flux = 0.2 m^2/yr, BAR/RSLRR ≈ 0.3) and an initially narrow marsh (green; overwash volume flux = 1.4 m^2/yr, BAR/RSLRR = 0.125) for wind speeds ranging from 5 to 10 m/s. The lines for 6 and 10 m/s are labeled. The dashed lines of corresponding color represent the marsh width for the same input conditions after 1 m of total RSLR from the results from Walters et al. (2014; i.e., without wave edge erosion and therefore without any dependence on wind speed). After 1 m of RSLR, slight changes in the landscape slope change the basin area, resulting in the shift from a full to narrow basin for the 5 m/s wind speed at 1 m of total sea level rise.

experiments; rather, it changes the timescale (Figure 5b). For higher wind speeds (and deeper bays) marshes erode more slowly, but the choice of wind speed does not determine whether the marsh is filling the basin or eroding away. We discuss this counterintuitive model behavior below.

5. Discussion

5.1. Geometry and Conservation of Mass Constraints

Understanding these results requires consideration of the roles that geometry and conservation of mass play in determining the rate at which a marsh erodes laterally. RSLR rate and basin width determine the rate at which accommodation space is created in a basin, whereas sediment inputs (e.g., fine-grained contributions [here Q_B], production of organic material, and overwash delivery [Q_{OW}]) determine the rate at which space is filled. The balance between these factors then determines whether a basin is emptying or filling with sediment. In the model, as in nature, this can occur through (1) changes in bay depth, (2) changes in the elevation of the surface of the marsh relative to sea level, and/or (3) changes in the location of the marsh edge (i.e., through progradation or lateral erosion).

In our experiments, bay depth can change over time as it adjusts to the equilibrium depth determined by the width of the bay (which changes more slowly than depth) and the size of the resulting waves, sediment supply rate, and RSLR rate. This process is most apparent in the initially full basin case (see Figure 6 for an example). If Q_B is too low to allow the entire marsh to keep up with RSLR, the middle of the marsh drowns. Recall that sediment eroded from the marsh and bay is deposited preferentially on the edges of the basin (after Mariotti & Fagherazzi, 2010); this, combined with the spatial dependence on Q_{OW}, makes the middle of the marsh the farthest from sediment sources. The drowning of the middle of the marsh creates a small, shallow bay and allows waves to form in the back barrier. (The tendency of the Young and Verhagen, 1996, wave model to overestimate bed shear stress values for shallow depths may affect the timescale for the bay to become deep enough for bay bottom erosion to commence and then for the depth to approach equilibrium. However, erosion would inevitably begin as the marsh continued to drown, and because we assume that the timescale for depth adjustments is very fast compared to the timescale for adjustments in marsh width, we do not expect the results to depend on which wave model we use.) These waves result in further marsh loss through marsh edge erosion, which increases the bay fetch, resulting in increased wave heights and a deeper bay (Figures 6b and 6c). Thus, in this initially full basin case, the basin is emptying of sediment through all

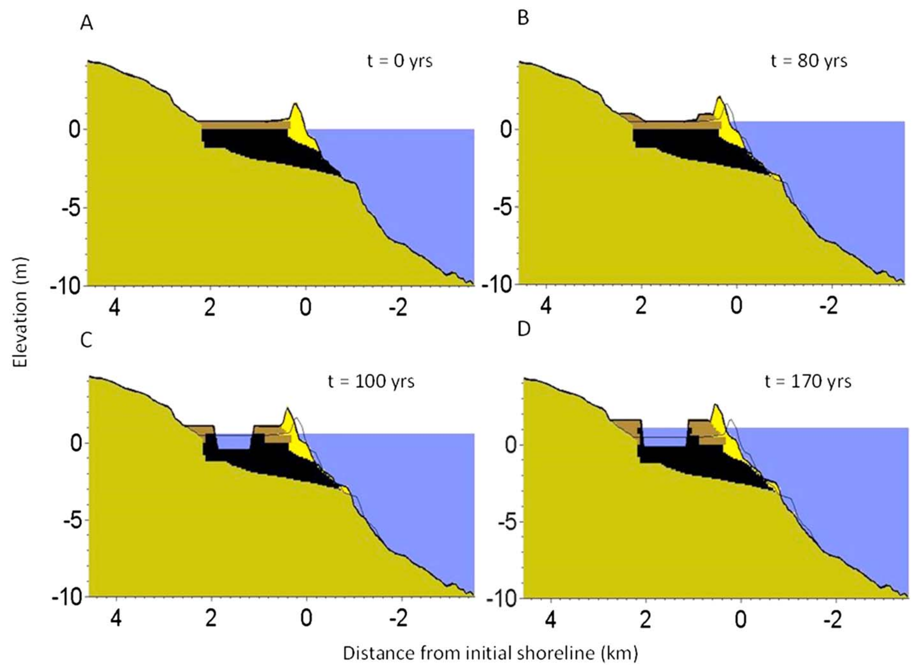

Figure 6. Evolution of an initially full marsh over 1 m of total RSLR. (a) Initial condition of a full marsh. (b) The center of the marsh, farthest from the sediment sources, cannot maintain its elevation. (c) The center of the marsh drowns, and as waves begin to form in the resulting bay, it quickly deepens and widens, eroding the marsh edge. (d) Final condition of a narrow marsh (~475 m wide) after 1 m of RSLR. The black outline in (b)–(d) shows the initial landscape.

three types of adjustment: changes in bay depth, erosion of the marsh edge, and erosion of the marsh surface (i.e., drowning).

These considerations of geometry and conservation of mass provide an insight into why marshes in the initially full-basin cases are wider after 1 m of RSLR than those of Walters et al. (2014; Figure 2). As the marsh drowns in the center of the basin and a bay forms, sediment is eroded from the bay bottom and deposited on the edges of the marsh. The equilibrium depth in our formulation depends dynamically on the strength of the waves (which depends on the width of the basin and the wind speed) and is deeper than the equilibrium depth chosen by Walters et al. (2014). Because the bay erodes to a deeper depth and sediment is conserved, more sediment is moved to the marsh edge resulting in a wider marsh.

While this behavior may seem counterintuitive, we can understand it by considering the relationship between marsh width and wind speed in the model (Figure 5b). Recall that although changing the wind speed (and therefore the equilibrium depth) does not change the final outcome of a model experiment, it does change the timescale. Higher wind speeds lead to deeper equilibrium depths and taller marsh edges, which produce more sediment per increment of lateral erosion. Therefore, if the balance between sediment supply and rate of RSLR remains the same, to create space at the same rate, the marsh edge must erode more slowly for a higher wind speed (i.e., a taller marsh). This is consistent with suggestions that the volumetric marsh erosion rate, rather than the lateral erosion rate, is proportional to wave power (e.g., Marani et al., 2011; McLoughlin et al., 2015). (We discuss the relevance of this result to natural marshes in section 5.3.) The model runs of Walters et al. (2014), with their shallower equilibrium depth, could be equated to having a lower wind speed. In fact, the lowest wind speeds we tested produce results most similar to those of Walters et al. (2014) at 1 m of RSLR (see the dotted lines in Figure 5b).

Turning to the case of the initially narrow marsh, the change in bay depth over the course of a model run is small (Figures 2c and 2d), and the amount of fine-grained sediment made available from erosion of the bay bottom is negligible compared to the amount made available by edge erosion. This is because the increase in bay fetch, and therefore in wave height, is not as large as that of the initially full basin, and so the equilibrium depth does not change significantly from the initial equilibrium condition. Erosion of the marsh edge leads to an increase in sediment available for deposition on the marsh surface, preventing drowning as sediment is

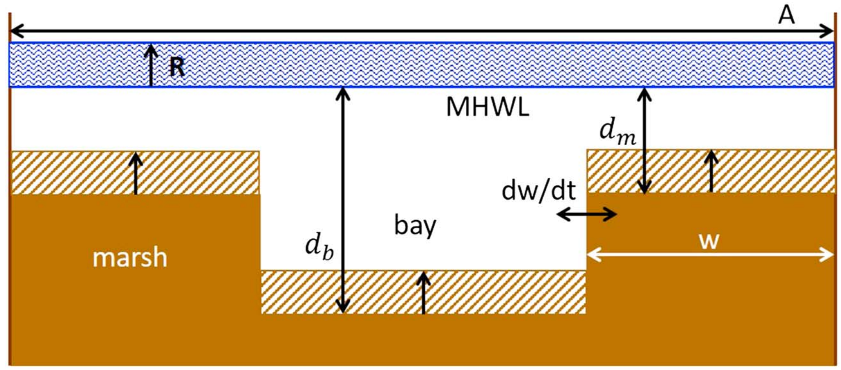

Figure 7. Schematic of a case where the marsh and bay are keeping up with sea level, and so the only way the basin can empty and fill with sediment is by moving the location of the marsh boundary. *A* is the area of the basin, *R* is the amount of RSLR, d_b is the depth of the bay, d_m is the depth of the marsh, *w* is the marsh width, and *dw/dt* is the rate of change of the marsh width. The blue stippled area represents the space created by RSLR during a unit of time, and the brown hatched area represents the space filled by vertical accretion of the marsh and bay bottom surfaces. If the volumetric rate of net sediment input equals the rate space is being created by RSLR, *w* cannot change. However, if the rate of sediment input is greater than (less than) the rate space is being created, the marsh boundary must prograde (erode).

redistributed from the bay bottom and marsh edges to the marsh surface (e.g., Mariotti & Carr, 2014). Because edge erosion prevents marsh drowning, we can infer that both the marsh platform and the bay bottom are keeping up with RSLR (e.g., Marani et al., 2007, 2010).

Given the considerations of geometry and mass conservation discussed above, if both the marsh platform and bay bottom keep up with RSLR, then the third type of adjustment, marsh edge progradation or erosion, is the only way the basin can fill with or empty of sediment. In this case, because the balance between the rate of space creation and the rate of sediment input (potentially including riverine input, exchange through inlets, and overwash) controls whether the marsh edge erodes or progrades, we can actually make predictions about what is happening to the marsh edge without representing the mechanisms of marsh progradation and erosion. For example, if the rate of sediment input is not sufficient to balance the rate of space creation, then the amount of open water in the basin must be increasing (i.e., the basin must be emptying of sediment), and thus, if both the marsh surface and bay bottom are keeping up with RSLR, the marsh edge must be eroding laterally. In addition, the rate of lateral erosion can be predicted by the difference between the rate of sediment input and the rate of space creation. In other words, if *w* is the width of one side of the marsh (Figure 7), then

$$2\frac{dw}{dt}(d_b - d_m) = Q_{s,in} - RL \tag{6}$$

where d_b and d_m are the depths of the bay and marsh relative to mean high water level, *R* is the RSLR rate, and *L* is the cross-shore width of the basin. *RL* is the rate of space creation, and $Q_{s,in}$ is the net volumetric sediment input rate. In our model formulation, $Q_{s,in}$ consists of

$$Q_{s,in} = Q_B + Q_{OW} + Q_{OM} - Q_d \tag{7}$$

where Q_{OM} is the contribution of organic matter to the accretion of the marsh platform and Q_d is the organic matter lost to decomposition or dispersal as the waves remobilize sediment on the marsh edge. When $Q_{s,in}$ is greater than *RL* (the rate of sediment input is greater than the rate of space creation), the marsh will prograde, and vice versa.

5.2. Stratigraphy and Composition Constraints

Although the difference in equilibrium depth between our formulation and that of Walters et al. (2014) provides extra sediment to the marsh in the initially full basin case, in the case of the initially narrow marsh, the bay is already at its equilibrium depth and the initial marsh is the same width as in Walters et al. (2014; see Figures 2a and 2c for a comparison of the initial conditions in our formulation and that of Walters et al., 2014). Given that the sediment provided from net bay bottom erosion is negligible in this case, the change

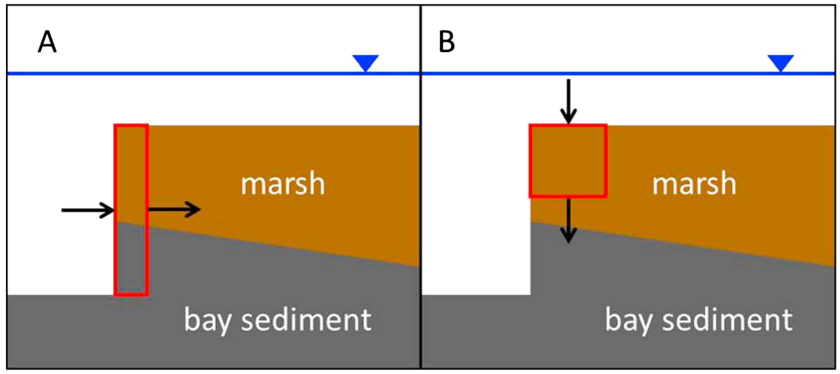

Figure 8. Difference in efficiency as a sediment source between lateral erosion and vertical erosion of the marsh platform. (a) Lateral erosion of a certain volume of the marsh platform erodes both marsh (50% organic material and 50% fine-grained sediment) and bay sediment (100% fine-grained sediment). (b) Vertical erosion of the same volume of sediment erodes only marsh sediment, resulting in only half the amount of fine-grained sediment being remobilized as through lateral erosion.

in the formulation of the equilibrium depth cannot fully explain the increase in marsh width. So why are initially narrow marshes still wider after 1 m of total RSLR than they were without wave edge erosion? One part of the answer is that taller marsh edges need to erode more slowly (they yield more sediment per unit of lateral erosion) to satisfy the constraints of geometry and conservation of mass, as discussed above. A second part of the answer involves stratigraphy and sediment compositions; the marsh edge is a more efficient sediment source than the marsh surface.

Without wave edge erosion, the sediment redistributed to the marsh platform comes only from vertical erosion of the bay bottom or other drowned parts of the marsh surface. However, with wave edge erosion, it also comes from lateral erosion of the marsh edge. A portion of the sediment volume eroded from the marsh (50% in our experiments) is not conserved, representing organic matter, which would be lost to decomposition or dispersal. Therefore, vertical erosion of the drowned marsh surface yields proportionally less fine-grained sediment than lateral erosion of the marsh edge, which includes both marsh and underlying bay sediment (e.g., Figure 8). Because edge erosion liberates more inorganic, fine-grained sediment per total volume of sediment eroded relative to vertical erosion of the marsh surface, less of the marsh platform needs to be eroded to provide an adequate fine-grained sediment supply to maintain elevation in the remaining marsh. This mechanism for moving sediment to the top of a marsh platform temporarily prevents narrow marshes from drowning, allowing marshes to keep up with RSLR under lower BAR/RSLRR conditions (higher rates of RSLR and/or lower sediment inputs) than they otherwise would. This behavior, and the fact that the narrow marshes remaining after 1 m of RSLR have largely disappeared after 2 m of RSLR (Figure 5a), agrees with previous findings (i.e., Mariotti & Carr, 2014) that edge erosion temporarily increases marsh resilience but that under sufficiently high RSLR rates or sufficiently low sediment supply rates marshes will eventually drown.

5.3. Limitations

Some of our results seem counterintuitive, especially those arising from the constraints of geometry and conservation of mass. The results depend on assumptions represented in the model parameterizations. How relevant to natural marshes the results are depends on the realism of those model assumptions. One key assumption is that an equilibrium depth is established rapidly compared to the timescales for horizontal marsh change. This assumption, consistent with and widely employed in previous modeling investigations (e.g., Mariotti & Fagherazzi, 2013; Walters et al., 2014), is supported by observations of bimodal elevation distributions in well-studied marsh systems (e.g., the Mississippi delta (Wilson & Allison, 2008), Venice lagoon (Carniello et al., 2009; Fagherazzi et al., 2006), and Virginia Coast Reserve), where bed erosion primarily depends on wave characteristics.

In the model, when bay bottom and marsh are both keeping up with RSLR, elevations are typically restricted to the levels of those two features. In natural marshes, elevations are less cleanly divided into the two modes. For example, in some basins where a marsh edge is eroding, a portion of the previous marsh platform remains at an intermediate elevation between that of the marsh and the tidal flat, without being eroded immediately to the level of a tidal flat (e.g., Wilson & Allison, 2008). However, this intermediate elevation zone can be a transient feature, so that the shape of the boundary of the marsh translates marshward in an approximately steady state without affecting the sediment budget. (In the model, we do not resolve the shape of the marsh boundary, implicitly assuming that the zones of intermediate depth are smaller than our cell size, 50 m consistent with Wilson and Allison, 2008. In this case, the height of the retreating profile—the elevation difference between tidal flat and marsh—is the only quantity relevant to the mass balance.) In the case of a transient zone of intermediate depth along a moving marsh boundary, model results can be related to natural environments despite the strong model tendency toward bimodality of elevations. In some basins, however, the assumption of bimodal depths is not a good approximation. For example, bays with a large influence from tidal currents (e.g., the Scheldt estuary; Wang & Temmerman, 2013) exhibit a range of bay depths rather than one equilibrium tidal flat depth. For a given basin, the less applicable our model assumption of wave-driven equilibrium bay depths is, the less relevant our model results will be.

In some natural circumstances, bay depth could vary not only spatially but temporally—again limiting the relevance of the assumption of a well-defined equilibrium depth. For example, consider a basin subjected to a highly variable wind regime and in which fine sediment is conserved in the back-barrier environment. During high-wind events, the bed may be eroded to a relatively deep depth. However, if the marshes are already at an equilibrium elevation influenced by the sediment concentrations during the high-wind events, the sediment will ultimately be redeposited on the bay bottom. The result of intermittently strong winds and sediment conservation could be a bay in which the depth is typically small, but with a significant thickness of poorly consolidated mud. In such a circumstance, present, for example, in some areas of the NC Outer Banks, the relationship between wind speed and marsh edge erosion would likely be very different than in the model results (Figure 5b).

In this model, as in other models (e.g., Mariotti & Carr, 2014; Mariotti & Fagherazzi, 2013), we neglect temporal variations in wind speed for simplicity. A constant wind speed implies a single, constant equilibrium depth. In this case, stronger wind corresponds to a deeper equilibrium depth (and therefore taller marshes). For a given difference between space creation rate (RSLR times the basin area) and net sediment input rate, taller marsh edges tend to create more space per increment of erosion and therefore to erode more slowly (given the constraints of geometry and conservation of mass). Therefore, in the model results, higher wind speeds lead to more slowly eroding marsh edges. However, these results are not likely to be relevant for natural basins in which bay depth fluctuates with wind speed. In such a natural circumstance, the intermittent high-wind events would be eroding marsh edges that are short (relative to a basin where wind speeds are consistently high), at least early in the event, and marsh progradation during the calm periods would be accentuated by the more typical shallow bay depths. For this reason we do not take the counterintuitive relationship between higher wind speed and wider marshes (Figure 5b) as a literal prediction about what to expect in natural basins.

A last key model assumption involves sediment import and export. In GEOMBEST++ and previous iterations, sediment import is specified as a forcing variable. This treatment differs from some other studies such as Mariotti and Fagherazzi (2013), in which net sediment import/export was related to the difference between the concentration of sediment in the bay and in the ocean. This latter approach best represents a system with limited riverine input and significant inlet exchange (such as the Virginia Barrier Islands; Figure 1a), whereas the approach in GEOMBEST++ is more representative of a system with riverine input and little sediment exchange with the ocean (such as the North Carolina Outer Banks, where inlets are spaced far apart; e.g., Jalowska et al., 2015; Figure 1b); recall, however, that we do not seek to represent any specific location with our model experiments). We explored a variable sediment export rate in GEOMBEST++ by conducting model experiments in which a fixed percentage of sediment remobilized by waves is lost from the system, representing sediment loss via exchange with the coastal ocean. Such a loss can be expected to result in an exponential loss of marsh width, as bay widening leads to increases in wave power and thus increases in the amount of sediment eroded and the amount of sediment lost. In our experiments the treatment of the underlying stratigraphy of the basin dominates and prevents this from occurring, and we do not present these model experiments.

5.4. Implications

Neither of the approaches discussed above for representing net sediment import/export rates is appropriate for all situations, and the limitations of both approaches demonstrate the need for a new kind of marsh model, which allows suspended sediment concentrations and sediment exchange to evolve dynamically, accounting for sediment input from rivers and variable sediment exchange with the ocean, which depends on the concentration of sediment in the basin. At the limit in which tidal prism (tidal range) is small and river water discharge is relatively large, the sediment concentrations in the basin at the end of the flood tide would be dominated by the concentration in the river, and (assuming that the concentration during ebb tide is in equilibrium with the waves and is lower than the river sediment concentration) river sediment would be deposited mostly in the basin with little lost offshore. This scenario is closer to that represented in GEOMBEST++. On the other hand, if river water discharge is small relative to tidal prism, the effective concentration imported to the basin would be dominated by the concentration in coastal waters (as net sediment import/export would depend on the difference between the concentration produced by waves and that in the coastal ocean) as in Mariotti and Fagherazzi (2013) and Mariotti and Carr (2014).

However, we believe that the insights arising from considering geometry and conservation of mass remain important when sediment exchange with the coastal ocean is considered. In that case, knowing that the net rate of sediment input depends on the sediment concentration both in the bay and in the ocean, and sediment concentration in the bay depends on the rate of marsh edge erosion. Still, in both cases, if the net rate of sediment input, the rate of space creation at a snapshot in time, and the height of the marsh edge are known, the rate of erosion or progradation of the marsh edge can be predicted (assuming that the bay bottom and marsh surface are keeping up with sea level). With collection of the appropriate data, this model prediction is testable. The rate of space creation could be determined by the basin area and SLR rate. The rate of net sediment import or export could be determined with river discharge, tidal prism, and sediment concentration (in the river, surrounding ocean, and in the bay during ebb tide). Then, given the data verifying that the bay bottom and marsh surfaces were keeping up with sea level, you could predict the rate of marsh edge erosion or progradation (using the elevation difference between the marsh and the bay bottom) and compare it with historical data.

One of the main implications of the GEOMBEST++ model experiments, consistent with Mariotti and Carr (2014), is that marsh edge erosion tends to slow marsh loss. This result should be relevant to all natural basins prone to drowning. However, in basins for which sediment exchange with the open ocean is important, an opposing tendency comes into play: marsh edge erosion tends to increase sediment concentrations during ebb tide, decreasing the net sediment input rate, making bays expand laterally faster than they would if sediment exchange with the ocean were negligible. In such basins, if marshes are not threatened with drowning, marsh edge erosion could increase marsh loss (as intuitively expected). In basins for which sediment exchange with the open ocean is negligible, this opposing tendency does not come into play, and edge erosion will consistently tend to increase marsh resilience.

These competing tendencies could also have implications for the management of natural marshes. For example, stabilizing marsh shorelines by installing rip-rap or "living shorelines," which prevent marsh edge erosion (without affecting marsh inundation), may have unintended consequences, depending on the conditions of the basin. For basins in which marshes are not threatened in the near future with drowning, and sediment exchange with the open ocean dominates the sediment budget, marsh edge stabilization will likely have the desired effect of increasing marsh resilience. However, if marshes are imminently threatened with drowning, marsh edge stabilization may lead to marsh loss (relative to what would happen in the absence of stabilization). These implications suggest that factors affecting marsh drowning (local RSLR rate, sediment concentration, and vegetation type) should be accounted for when marsh protection is considered. This exploratory research points to the need to better understand back-barrier processes to provide reliable bases for management decisions and suggests that a strategy that is customized for basin type and characteristics may be more effective than a one-size-fits-all management approach.

The newly recognized distinction between erosion of marsh edges and marsh surfaces, in terms of their efficiency in producing sediment useful for maintaining remaining marshes (and which is the case regardless of the boundary conditions for sediment input/output), demonstrates the importance of considering the effects of stratigraphy and compositional differences in the evolution of back-barrier marsh systems. The differences in inorganic sediment liberation rate resulting from the erosion of marsh edges versus marsh surfaces can shift the balance between the rate of space creation and space filling, potentially influencing marsh resilience by affecting how much marsh can be maintained or how rapidly it is lost.

Deaton et al. (2017) show that under some circumstances the sediment input and basin geometry do not allow a back-barrier marsh to prograde as quickly as the associated barrier island is migrating, ultimately resulting in loss of the back-barrier marsh due to burial of the marsh by the island. However, given the interdependencies between barrier islands and back-barrier marshes, increased resilience for back-barrier marshes, even if only temporary, has important implications for barrier islands. As long as a back-barrier marsh continues to exist, it will reduce the accommodation space that the associated barrier needs to fill—decreasing the likelihood that the barrier-marsh system will disintegrate. In turn, survival of barrier islands affects how long back-barrier marshes, supported by localized overwash deposition from the sandy part of barriers, will ultimately persist (Walters et al., 2014). Our modeling result that these overwash-sustained narrow marshes persist in the presence of wave edge erosion, combined with existing observational evidence (a statistically significant peak in distribution of satellite observations of marsh widths in the Virginia Barrier Islands for narrow marshes of ~400 m; Walters et al., 2014; Walters & Moore, 2016c), strengthens the conclusion of Walters et al. (2014) that overwash can temporarily support marshes under conditions with lower sediment availability and higher RSLR rates than would otherwise be possible. Thus, lateral erosion of marsh edges, through its effect on the sediment input/output balance and sediment redistribution, can influence the overall evolution of the coupled marsh-barrier island system.

6. Conclusions

Overwash from barrier islands provides an important sediment source for back-barrier marshes, sustaining them under SLR rate or sediment supply conditions under which they would otherwise drown. This important relationship between marshes and barrier islands and the existence of a resulting long-lasting narrow back-barrier marsh state, proposed by Walters et al. (2014), persists even in the presence of marsh edge erosion by wind waves. However, it is a temporary state; even in a closed system such as our model, without sediment loss to the ocean, the narrow marsh is transient and the basin tends toward the stable states of completely full or completely empty of marsh, similar to the results of Mariotti and Fagherazzi (2013). Our results also suggest that wave edge erosion may enhance marsh resilience not only by providing a mechanism to move sediment from the marsh edge to the marsh surface and prevent drowning (e.g., Mariotti & Carr, 2014) but also, dependent on the stratigraphic composition of the marsh, by providing a more efficient sediment source than vertical erosion of drowned marsh platform. Older marsh sediments eroded from the lower part of the marsh scarp may have a higher concentration of inorganic sediment, which can be redeposited on the marsh, while newer surface layers may have a higher proportion of organic material, which may be lost to decomposition or dispersal when eroded. Combined, these results emphasize the first-order control that geometry and stratigraphy can have on the evolution of marsh-barrier systems. Where a marsh and bay both maintain equilibrium elevations relative to sea level, and the net sediment budget is known, the behavior of the marsh edge (the rate of erosion or accretion) can be predicted based on basin geometry and the rates of sea level rise (space creation) and sediment supply. If the rate of sediment import or export is known, for instance, at a snapshot in time, this control on marsh evolution applies regardless of basin conditions or model assumptions about sediment exchange with the ocean (i.e., to both open and closed systems).

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