A coupled geomorphic and ecological model of tidal marsh evolution

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The evolution of tidal marsh platforms and interwoven channel networks cannot be addressed without treating the two-way interactions that link biological and physical processes. We have developed a 3D model of tidal marsh accretion and channel network development that couples physical sediment transport processes with vegetation biomass productivity. Tidal flow tends to cause erosion, whereas vegetation biomass, a function of bed surface depth below high tide, influences the rate of sediment deposition and slope-driven transport processes such as creek bank slumping. With a steady, moderate rise in sea level, the model builds a marsh platform and channel network with accretion rates everywhere equal to the rate of sea-level rise, meaning water depths and biological productivity remain temporally constant. An increase in the rate of sea-level rise, or a reduction in sediment supply, causes marsh-surface depths, biomass productivity, and deposition rates to increase while simultaneously causing the channel network to expand. Vegetation on the marsh platform can promote a metastable equilibrium where the platform maintains elevation relative to a rapidly rising sea level, although disturbance to vegetation could cause irreversible loss of marsh habitat.

accretion | erosion | sea level | vegetation | wetland

Subsidence, erosion, sea-level rise, and anthropogenic changes to sediment delivery rates are affecting coastal marshes worldwide. In some regions these influences are converting significant portions of marshland to open water (1, 2). The fate of intertidal salt marshes is of societal importance and scientific interest; marshes provide highly productive habitat and serve as nursery grounds for a large number of commercially important fin and shellfish (3, 4). Additionally, marshes offer great value as buffers of coastal storms in cities such as New Orleans, which is separated from the Gulf of Mexico by marshland (5, 6).

A variety of vertical accretion models have been used to address the response of tidal marshes to environmental change, including accelerated sea-level rise and reduced sediment supply (7, 8). In these models, bed elevation of the marsh platform is adjusted according to a deposition rate that is proportional to water depth at high tide, a proxy for duration and frequency of inundation. In such models, an increase in the rate of sea-level rise is accompanied by an increase in water depth until the increasing deposition rate becomes equal to the sea-level rise rate. With the exception of recent work by Morris *et al.* (9), these models neglect the role of vegetation, despite Redfield's (10) hypothesis that vegetation and physical processes influence morphodynamics equally strongly in the intertidal zone. Vegetation traps inorganic sediment and provides a source of organic sediment. Based on field measurements, Morris *et al.* (9) argue that biomass density, and therefore deposition rates, increase with water depth up to some optimal depth. The role of biomass density in enhancing deposition rates in their model reinforces the tendency for the marsh platform to approach an equilibrium water depth at which the deposition rate equals the rate of sea-level rise. This depth depends on the type of vegetation, the rate of sea-level rise, and the concentration of suspended inorganic sediment. An increase in the rate of sea-level rise, or a reduction in sediment supply, is compensated by deepening of the marsh platform, which increases deposition rates.

Measured accretion rates generally indicate that long-term vertical accretion rates on a vegetated marsh platform are nearly equal to rates of sea-level rise (11), suggesting that models considering only vertical accretion of the platform capture some of the morphodynamic interactions that are important in marshes. However, morphodynamics in the intertidal zone are not governed solely by depositional processes on the platform, but also by interactions between the platform and channel network. For example, channels deliver sediment to and from the marsh platform (11), and platform characteristics control the size and path of the tidal prism, strongly influencing channel network evolution (10). While an accelerating sea level should promote an increase in water depth and deposition rate on the marsh platform, the expanding tidal prism will also tend to promote increased erosion and expansion of the channel network, reducing the marsh area (12). A holistic approach, including simultaneous modeling of platform and channel processes, is therefore needed to more fully explore the morphologic response of tidal marshes to environmental change.

Challenges arise when attempting to model the coupled evolution of the marsh platform and channel network; the endeavor requires some form of hydrodynamic calculations to model erosion in the channel network and the incorporation of vegetation effects on both deposition and erosion. Recent modeling efforts have met some of these challenges. Mudd *et al.* (13) have developed a model that varies deposition rates as a function of horizontal distance from a channel and vegetation density, but do not include channel erosion. Fagherazzi and Sun (14) and D'Alpaos *et al.* (15) have modeled channel network erosion, but do not address the marsh platform. Marciano *et al.* (16) model combined deposition and erosion processes as the channel network develops, but do not consider vegetated surfaces. These models all involve a constant sea level and sediment supply. We have developed a more holistic numerical model of tidal marsh morphodynamics, including hydrodynamic-driven and vegetation-influenced evolution of the channel network and spatially variable vegetation-influenced accretion on the marsh platform. The model includes a coupling between vegetation effects and tidal-channel widening that leads to surprising results regarding marsh stability under changing environmental forcing. This model is applicable over the large spatial and temporal scales necessary for assessing the response of coastal wetlands to sea-level rise and sediment supply changes. A simplified treatment of tidal hydrodynamics, and the inclusion of only a minimum number of processes, allows us to model key interactions

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over broad temporal and geographic scales while maintaining monthly temporal resolution.

Model Processes

Each model iteration begins with a topographic surface, partitioned into 5 × 5-m cells, inundated to high-tide water level. Variations in flow velocity within a tidal cycle are not explicitly treated; instead, we begin by finding the total volume of water draining through each cell during a single ebb flow. Water drains off of the marsh platform, through the channel network, and out of the basin according to flow directions defined by a parametrically represented water surface. Over the marsh platform this surface consists of a constant curvature Poisson form, which connects to the channel edges, representing an approximate solution to the more complex hydrodynamic equations for slow, friction-dominated flow over nearly flat marsh surfaces (17). The channel network is defined as the cells with elevations at least 20 mm below mean platform height, which are also connected to the outlet by other channel cells. Flow within a channel is limited to directions with progressively decreasing along-channel distances to the outlet. Together, the platform water surface and channel water-routing rules define the watershed draining through each cell. Following Rinaldo *et al.* (18), the volume (V) of water that flows through a given cell is related to high-tide level (s) and the bed elevations (z) of its watershed (w):

$$V = \int_w [s - z(x, y)]dxdy. \quad [1]$$

Cells with elevations below low tide do not drain completely, thereby limiting the maximum value of $(s - z)$ to the tidal range. The volume of water passing through each cell is divided by a characteristic time scale, 3 h, to obtain a water discharge characteristic of near-peak flow (19).

The discharge in each cell is divided by high-tide water depth and cell width to estimate water velocity. Dividing discharge by some water depth is necessary to ensure that for a given discharge velocity is higher in shallower areas than in deeper areas. Because we are not modeling variations of flow within the tidal cycle, we must choose a single water surface elevation from which to measure these depths. We choose the high-tide water surface elevation so that calculated depths are positive across the entire platform. Although peak velocities in natural marshes occur at lower water levels, the characteristic time scale mentioned above serves as a calibration parameter, adjusted to give reasonable velocities in channels. The erosion rate depends on bed shear stress, τ_b:

$$\text{Erosion rate} = m^*(\tau_b - \tau_c)/\tau_c\ , \quad [2]$$

where m is a constant (0.0014 kg/m^2 per s) and τ_c represents a threshold shear stress (0.4 N/m^2) below which no erosion occurs (19). τ_c may be spatially variable in nature, particularly as a function of biomass. However, such a dependence would be ineffective in the model, because τ_b rarely exceeds τ_c on the vegetated marsh platform, which is likely also the case in nature (20). We use $\tau_b = (\rho f_c v^2)/8$, where v represents velocity, f_c is a dimensionless friction factor (0.02), and ρ is the density of water (21). Fagherazzi and Furbish (19) estimate that most erosion occurs during intermittent, near-peak flows, totaling ≈600 min (10 h) per month. Therefore, we multiply the erosion rate by 10 min (assuming two tidal cycles per day) to calculate the amount of erosion in a single tidal cycle. For simplicity, we explicitly model ebb flow only, although 10 min represents the combined duration of erosion during ebb and flood flow. Our treatment does not include asymmetries between ebb and flood flow, consistent with Fagherazzi and Furbish (19), who model the shape of an individual channel cross-section. In nature, marshes dominated by ebb flow tend to have lower platform elevations and greater channel cross-sectional areas, relative to marshes dominated by flood flow (11).

Following Morris *et al.* (9), the deposition rate in each cell depends on the concentration of sediment suspended above the marsh platform, C_{ss}, and the biomass productivity, B, of each cell:

$$\text{Deposition rate} = (k_1^* C_{ss} + k_2^* B)^* D, \quad [3]$$

where k_1 (0.00009 m^3·g^{-1}·yr^{-1}) and k_2 (0.000015 m^2·g^{-1}) are constants of proportionality (9). k_2 represents both the effect of sediment trapping by vegetation and the below-ground accumulation of organic matter. As in previous aggradation models (7–9) the deposition rate is proportional to high tide water depth, D.

The amount of vegetation in each cell is calculated as:

$$\text{Biomass productivity} = aD + bD^2 + c, \quad [4]$$

where $a = 28$, $b = -0.093$, and $c = -270$, adapted from Morris *et al.* (9) to fit a 4-m tidal range (22). This function, based partly on field measurements, assumes a water depth at which biomass is most productive, below which salinization limits growth, and above which anoxia limits growth (9). Relationships between water depth, biomass productivity, and sediment deposition were determined through long-term field experiments on *Spartina alterniflora*, the dominant marsh grass in North America (9). Like Morris *et al.* (9), we assume that vegetation's influence on sediment transport can be modeled by using annual biomass productivity as a proxy for total biomass.

In the model, slope-driven sediment transport smoothes the topographic surface, representing processes including creek bank slump. The gravitationally driven sediment flux, $q_{s,g}$, out of a cell and into a neighbor cell is proportional to the slope, S, to that neighbor:

$$q_{s,g} = (\alpha - \beta B)^* S, \quad [5]$$

where $(\alpha - \beta B)$ is a topographic diffusivity that depends on the biomass, B, in the higher elevation neighbor, representing the stabilizing character of plant roots. We use $\alpha = 3.65$ m^2·yr^{-1} and $\beta = 0.0019$ m^4·g^{-1} so that, following Murray and Paola (23), the slope-driven transport is reduced by approximately two orders of magnitude for the maximum biomass densities, conservatively consistent with field experiments on terrestrial river banks (24).

All changes in biomass density and bed elevation are calculated at the end of each iteration (one tidal cycle) and multiplied by 120 to give a time step of 2 months, assuming two tidal cycles per day.

We conduct model experiments over a 3 × 3-km square basin. Independent variables include sea-level rise rate, suspended sediment concentration, and the presence or absence of vegetation. Each experiment models the evolution of the marsh channel-platform morphology until it reaches a dynamic equilibrium, in which elevation change everywhere equals the rate of sea-level rise and water depth remains constant.

Marsh Development and the Effect of Vegetation

One set of model experiments involved a constant 1 mm·yr^{-1} rise in sea level (Fig. 1). The initial topography consisted of a completely subtidal, slightly sloping basin with a subtle radial channel network ($\ll$1 m relief) and small random elevation perturbations (amplitude of 0–0.0002 m) superimposed. High deposition rates in deep water caused basin infilling and a reduction in the size of the tidal prism. Progradation of the developing platform caused constriction of existing channels into a few deeper channels with greater discharge [see supporting information (SI) *Appendix*]. The resulting channel

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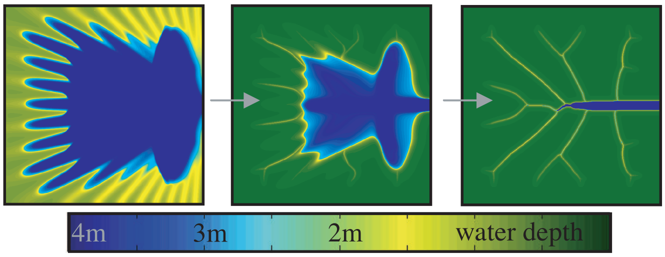

Fig. 1. Development of marsh platform and channel network under constant 1 mm/yr sea-level rise, 0.02 g/liter suspended sediment concentration, and 4-m tidal range. Color scale represents water depth (blue denotes subtidal bed elevation; dark green denotes nearly supratidal bed elevation).

network differs from the initial conditions in size, orientation, and number of channels, indicating that the initial channel network does not determine model behavior. Observations from older versions of the model, in which the subtle initial channel network was not imposed, confirm this interpretation.

In the channel network, deepening caused depth-dependent deposition rates to increase, whereas the diminishing tidal prism caused erosion rates to decrease. On the platform, basin infilling caused deposition rates to decrease asymptotically to the rate of sea-level rise. When net accretion rates were everywhere equal to the rate of sea-level rise, dynamic equilibrium was reached and the model run was completed. In other models of tidal-channel network development (14, 15), channels erode into an existing surface. In contrast, the channels in our model result chiefly from depositional processes. Despite our simplified hydrodynamic treatment, this mode of channel formation is consistent with modeling of sandy tidal basins involving a more detailed hydrodynamic component (16).

To determine the effect of vegetation on marsh morphology, we conducted a pair of model runs prohibiting and allowing the growth of plants. The sediment trapping effects of plants resulted in higher deposition rates on the marsh platform, and ultimately in shallower and more spatially uniform equilibrium water depths, compared with the mud-flat platform in the no-vegetation run (Fig. 2). Progradation of the vegetated platform further constricted the channel network. Channel density and widths were smaller than in the unvegetated scenario, through the combined effect of more rapid deposition rates and plants stabilizing channel banks against slump. Adjustments to values of vegetation-related parameters result in predictable morphological differences, but do not change the general behavior of the system (see *SI Appendix*).

Response to Environmental Change

To observe responses of the marsh platform and channel network to environmental change, we subjected the equilibrium morphologies produced under a constant 1 mm·yr^{-1} sea-level rise and 0.02 g/liter suspended sediment concentration to an abrupt 10-fold increase in the rate of sea-level rise (Fig. 2) or a 10-fold decrease in suspended sediment concentration (data not shown). In all four scenarios, platform depths increased. Additionally, water velocities and erosion rates increased in response to the expanding tidal prism, causing channel depth and network density to increase. The adjustment in channel geometry continued until erosion rates were everywhere compensated by more rapid depth-dependent deposition rates, producing a new equilibrium configuration.

In the model experiment without vegetation, the platform converted entirely to open water (Fig. 2). In the absence of vegetation, slope-driven transport widened channels as they deepened because of an increasing tidal prism. In the experiment with vegetation, increased equilibrium water depths on the platform were accompanied by increased biomass productivity, which promoted greater deposition rates and more stabilization against creek bank slump. Thus, whereas channel expansion converted the unvegetated platform entirely to open water, the vegetated platform resisted much of this change.

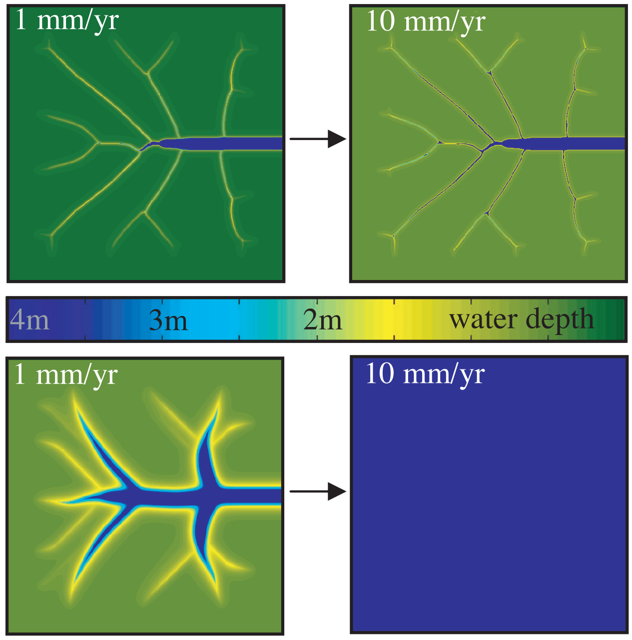

Fig. 2. Equilibrium morphologies produced by increasing rate of sea-level rise to 10 mm/yr. (*Upper*) Morphologies are vegetated. (*Lower*) Morphologies are not vegetated. Response to reduced sediment supply is qualitatively the same but is not shown.

Discussion and Implications

In this initial modeling exercise we have included a limited number of processes and treat them in highly simplified ways, both to allow investigation of long time-scale behaviors of the spatially extended system and maximize the clarity of the potential insights (25). These simplified treatments are not likely to produce an accurate simulation of the details of a particular locality. For example, we apply a formulation of vegetation growth quantified at one location and for a single species (albeit the dominant one in much of North America). In reality, multiple species often compete for resources and differentially allocate biomass between above-ground and below-ground regions. In the model, the deposition rate (implicitly representing both above-ground and below-ground processes) is simply proportional to above-ground biomass. Relationships between organic matter accretion and water depth may not mimic inorganic sediment deposition patterns, potentially limiting the model's applicability in marshes dominated by organic accretion. We also assume suspended sediment concentrations are spatially uniform. However, sediment concentrations are observed to decrease with distance from tidal channels (11), an effect that will be incorporated in more elaborate versions of the model in the future. In addition, the technique we use to route water is based on an assumption of friction-dominated hydrodynamics. This assumption is appropriate for shallow flow over vegetated surfaces (17), but is likely to be less accurate for flow over unvegetated mudflats.

The simplifications necessary to model long-term, large-scale marsh behaviors would be problematic for a "simulation model," (25) designed to reproduce nature in a quantitatively precise manner and make detailed quantitative predictions. However, this effort should be interpreted as an "exploratory" model (25), allowing an initial investigation of how key interactions between ecological and physical processes govern the basic response of tidal marshes to changing sea level and sediment supply.

Despite the simplifications, our model captures several basic characteristics of marsh systems. For example, the model creates a channel network that widens rapidly downstream and a generally flat platform morphology with water depths and rates of biomass productivity that are similar to those observed in nature (9, 11). Furthermore, field observations of channel network development are at least consistent with our model. Redfield (10), for example, first hypothesized that constriction of flow by an expanding vegetated platform aided the development of the channel network, and many have observed the general long-term stability of channels (11). The model results are consistent with these observations and suggest vegetation as the primary control of stability. Although our simplifications prohibit a quantitatively precise reproduction of morphology (meandering channels, for example), the basic similarities between modeled and natural morphology suggest that the novel potential insights produced by model experiments, discussed below, are relevant to natural marshes under changing forcing conditions.

Tidal marshes are commonly assumed to be nearly in equilibrium with environmental change because measured rates of accretion are similar to rates of sea-level rise (11). Models and field studies demonstrate that a moderate increase in platform water depth promotes sediment deposition and suggest that marshes have some ability to preserve their morphology in response to environmental change (refs. 7, 9, 11, and 26; although also see refs. 1, 2, and 27). However, our model shows that such change is accompanied by expansion of the channel network, converting vegetated surfaces into unvegetated surfaces. Our model experiments show that in the absence of vegetation the coupled response of deepening and erosion by channel expansion can cause the intertidal surfaces to degrade rapidly to completely subtidal surfaces. In contrast, previous models of vertical accretion (7, 9, 12) would suggest that as an intertidal platform becomes lower in elevation relative to sea level, surfaces will simply accrete faster, maintaining their morphology in response to environmental change. Analyses of vertical accretion rates alone therefore miss important 3D effects from tidal flow and erosion. Because channels in model runs including vegetation do not widen significantly even under rapid and extreme increases in the sea-level rise rate, our model experiments offer a potential explanation for why channel networks tend to be stable in the field (e.g., ref. 10), despite conceptual models that suggest they should be responsive to sea-level change (12).

The dramatic difference in response to environmental change between vegetated and unvegetated surfaces indicates that the presence of vegetation is critical for maintaining an intertidal surface under conditions of increasing sea-level rise rate or reduced sediment supply and leads to an interesting implication for vegetation disturbance (Fig. 3). Because vegetation–accretion interactions promote shallower equilibrium water depths on a vegetated surface than on an unvegetated surface, disturbance to vegetation will tend to cause an increase in water depth. Our model experiments show this change in depth to be small under low rates of sea-level rise, but larger under high rates of sea-level rise (e.g., Fig. 2). If the new water depth, in the absence of vegetation, is greater than a maximum depth in which vegetation can grow, then vegetation cannot grow back. Disturbance of identical intensity may therefore be temporary under low rates of sea-level rise, but permanent when accompanied by high rates of sea-level rise. Model experiments lead to a similar prediction concerning suspended-sediment concentration; for a given rate of sea-level rise, vegetated platforms might be absolutely stable under high sediment delivery rates, but prone to irreversible vegetation loss under lower delivery rates (Fig. 4). Thus, our model suggests that a highly productive marsh accreting rapidly in response to sea-level rise could be in a "metastable" equilibrium, sensitive to perturbation and prone to conversion to a largely open-water basin. The model results in Fig. 2 implicitly indicate the response under a high sea-level rise rate when all vegetation is removed from the basin, over a sufficient duration that bed elevations decrease significantly. Further work is necessary to explore the consequences of more spatially and temporally limited vegetation disturbance.

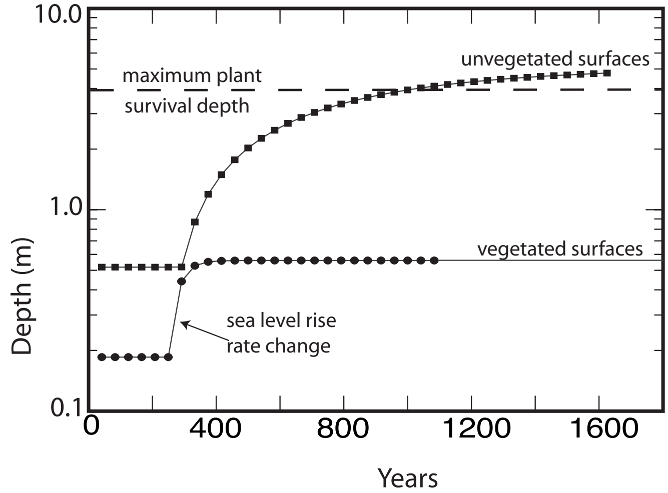

Fig. 3. Model results showing a vegetation-induced metastable response to increased rates of sea-level rise. The increase in water depth after a 10 mm/yr rate of sea-level rise is small when the platform is vegetated (bottom line), but large when the platform is unvegetated (top line). Disturbance to vegetation under low rates of sea-level rise (left side) will not cause depths to exceed those capable of plant regrowth. Disturbance to vegetation under high rates of sea-level rise (right side) will cause permanent vegetation loss and erosion of the platform (e.g., Fig. 2). Biomass productivity (data not shown) in the vegetated experiment mimics water depth.

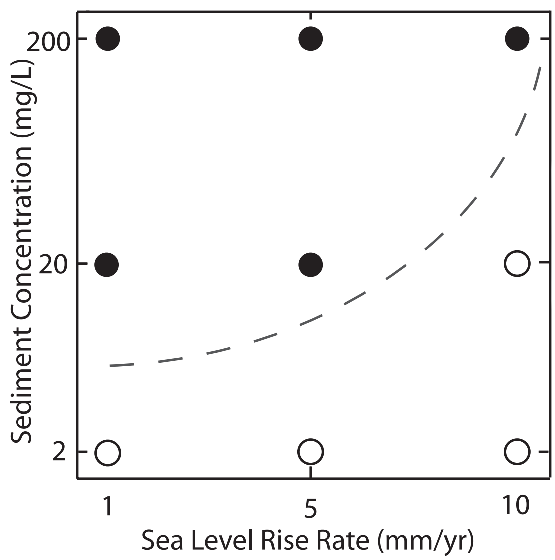

Fig. 4. Stability diagram of intertidal surfaces. Solid circles denote conditions leading to stable platform. Open circles denote metastable conditions, where disturbance to vegetation could lead to irreversible conversion of intertidal environments to open water.

The North American Atlantic coast features extensive marshland despite significantly reduced rates of sediment delivery resulting from land-use changes in the last century and a half, including reforestation and dam construction (28). Perhaps, then, the expansive marshland observed today is a metastable, relict feature that developed under higher sediment supply rates in the past. For example, sedimentation rates in the Chesapeake Bay and Coastal Massachusetts increased 4 to 10 times after European settlement and deforestation (29, 30), and marshes of the Plum Island Estuary in Massachusetts were likely restricted to the fringes of an open-water basin until some time after 680 years B.P. (31). If coastal marshes are in metastable equilibrium, or become metastable in future decades, our model predicts that vegetation will tend to limit the adjustment of marsh morphology to reduced rates of sediment supply and possible sea-level acceleration, but that disturbance to vegetation may trigger rapid degradation.

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