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Temporary vegetation disturbance as an explanation for permanent loss of tidal wetlands

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[1] Coastal ecosystems respond to sea level and sediment supply change according to complex, three-way interactions between vegetation, hydrology, and sediment transport. While biogeomorphic feedbacks preserve the morphology of intertidal surfaces covered by marshland, we demonstrate with numerical model and field experimentation that temporary disturbance to vegetation facilitates rapid and widespread degradation. Vertical accretion slows in disturbed areas, allowing localized submergence of the marsh platform, tidal prism enlargement, and permanent channel network expansion. Vegetated portions of an episodically disturbed platform accrete more rapidly than rates of relative sea level rise, giving submerging marshland the appearance of maintaining elevation. This feedback between vegetation disturbance and channel erosion, and its effect on platform accretion, may explain peculiar patterns of wetland loss in Europe and North America. **Citation:** Kirwan, M. L., A. B. Murray, and W. S. Boyd (2008), Temporary vegetation disturbance as an explanation for permanent loss of tidal wetlands, *Geophys. Res. Lett.*, *35*, L05403, doi:10.1029/2007GL032681.

1. Introduction

[2] Recent changes in rates of sea level rise (SLR) and sediment delivery are significantly altering coastal ecosystems and landforms, and understanding their response to future environmental change has been identified as a scientific priority [*Anderson et al.*, 2001]. Wetlands are the most ecologically and economically valuable of all coastal environments, with their total ecosystem services estimated to be worth about $5 trillion per year [*Costanza et al.*, 1997]. However, in apparent response to recent changes in sea-level rise rates (SLRR) and land-use related decreases in sediment delivery rates, wetlands in large portions of North America and Europe are deteriorating to open water or bare mudflats [*Reed*, 1995; *Hartig et al.*, 2002; *Kearney et al.*, 2002; *Van der Wal and Pye*, 2004]. Recent work suggests that tidal marshes respond to SLR and sediment delivery changes in a particularly complex fashion, governed by three-way interactions between vegetation, hydrology, and sediment transport [*D'Alpaos et al.*, 2007; *Kirwan and Murray*, 2007]. Yet for nearly 30 years, the "survival or submergence" of marshes has been examined by comparing rates of vertical accretion with rates of SLR [*DeLaune et al.*, 1978; *Reed*, 1995].

[3] Peculiar patterns of marsh loss highlight the need to better understand how these systems respond holistically to environmental change, and suggest one-dimensional comparisons between accretion and SLR rates are insufficient to explain intertidal stability. For example, interior marsh loss in New York and Southern England is dominated by the dissection of the marsh platform by an expanding channel network rather than vertical drowning [*Hartig et al.*, 2002; *Van der Wal and Pye*, 2004]. Perimeter marsh loss also occurs in these regions, presumably due to wave erosion, a process we do not consider. Although sea-level induced channel network expansion would be consistent with conceptual [*Allen*, 1997] and some numerical [*D'Alpaos et al.*, 2007] models, field measurements and other model experiments suggest that network extent either is not determined solely by, or is out of equilibrium with, tidal prism volume and platform elevation relative to sea level [*Marani et al.*, 2003; *Hood*, 2007; *Kirwan and Murray*, 2007]. Furthermore, identifying SLR as a primary cause of marsh loss is complicated because in several regions (e.g., New York, Southern England, and British Columbia) marshes have submerged and eroded despite measured accretion rates that equal or exceed relative SLRR [*Williams and Hamilton*, 1995; *Hartig et al.*, 2002; *Van der Wal and Pye*, 2004].

[4] Here we present results of numerical model and field experiments suggesting that localized and temporary disturbance to vegetation can trigger widespread and permanent loss of marshland and expansion of the channel network in other parts of the system, particularly at rapid SLRR or low sediment delivery rates. In both the model and field experiments, rapid degradation of a healthy marsh occurs, while maintaining a positive balance between accretion and SLR in the surviving marsh areas.

2. Methods

[5] We simulate the response of tidal marshes to vegetation disturbance and SLR using a previously described numerical model (see *Kirwan and Murray* [2007] for model details and sensitivity to parameter values). In the model, bed surfaces accrete in proportion to their depth below high tide, the amount of vegetation they support, and the suspended sediment concentration. An increase in water depth stimulates biomass productivity up to an optimal depth, beyond which it suppresses growth [*Morris et al.*, 2002]. Model experiments reported here also include an exponential decrease in suspended sediment concentration with distance from the nearest channel, which leads to leveed channels. Channels erode when bed shear stress exceeds the shear strength of cohesive sediment. A gravity-driven transport function, representing processes such as creek-bank slumping, where erosion undercuts plant roots, moves

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sediment downslope and tends to widen channels. The amount of gravity-driven transport leaving each model cell (5×5 m) is inversely proportional to the local biomass of vegetation, reflecting the stabilizing effect of plant roots. Cells within the channel network have elevations too low to permit vegetation, so that the reduction in gravity driven transport only applies at the vegetated banks. Previous experiments show that the platform tends to deepen in response to an increase in SLRR until accretion rates increase enough to match the SLRR, establishing an equilibrium water depth [*Morris et al.*, 2002].

[6] To explore the effect of spatially and temporally limited vegetation disturbance, we subjected marshes in equilibrium with several SLRR to a variety of modeled disturbance regimes. We represent vegetation disturbance by completely removing all vegetation from random cells. While it is clear that disturbance can greatly decrease the productivity of marsh grasses over large spatial scales [e.g., *Silliman et al.*, 2005], most field observations indicate that vegetation typically recovers from biotic and physical disturbances in less than a decade [e.g., *Bertness and Ellison*, 1987], suggesting that bed surfaces have little time to erode before vegetation recolonizes them. Therefore, we limit the absence of vegetation in disturbed cells to either 1, 5, or 10 years (in separate experiments), at which time it recovers to the biomass determined by the cell's new elevation. In this exploratory model, we ignore several processes that may amplify the impact of vegetation disturbance, suggesting our treatment is conservative. For example, local wave generation, peat collapse, and the accumulation of vegetation-suppressing sulfides may expand unvegetated ponds in nature, but do not enlargen patches in the model, nor explicitly inhibit their recolonization [e.g., *Reed*, 1995]. In these experiments, loss of vegetation in a cell due to erosion, submergence, or disturbance, does not increase the intensity (percentage of disturbed cells) of disturbance elsewhere, as might be expected in a marsh disturbed by grazing mammals or snails [e.g., *Silliman et al.*, 2005].

[7] Like previous morphologic models of marsh evolution, we assume biomass productivity is a good proxy for total biomass, and do not discern between above-ground and below-ground accretionary processes. As knowledge of intertidal environments increase, more sophisticated treatments of vegetation may be appropriate. In particular, including more specific disturbance regimes (e.g., disturbances that are spatially clustered) and how productivity varies with sea level for multiple species [e.g., *D'Alpaos et al.*, 2007] are likely to alter certain aspects of the system's behavior. Therefore, we consider this an initial modeling endeavor, designed to explore basic feedbacks between vegetation and sediment transport rather than to make detailed predictions for a specific marsh.

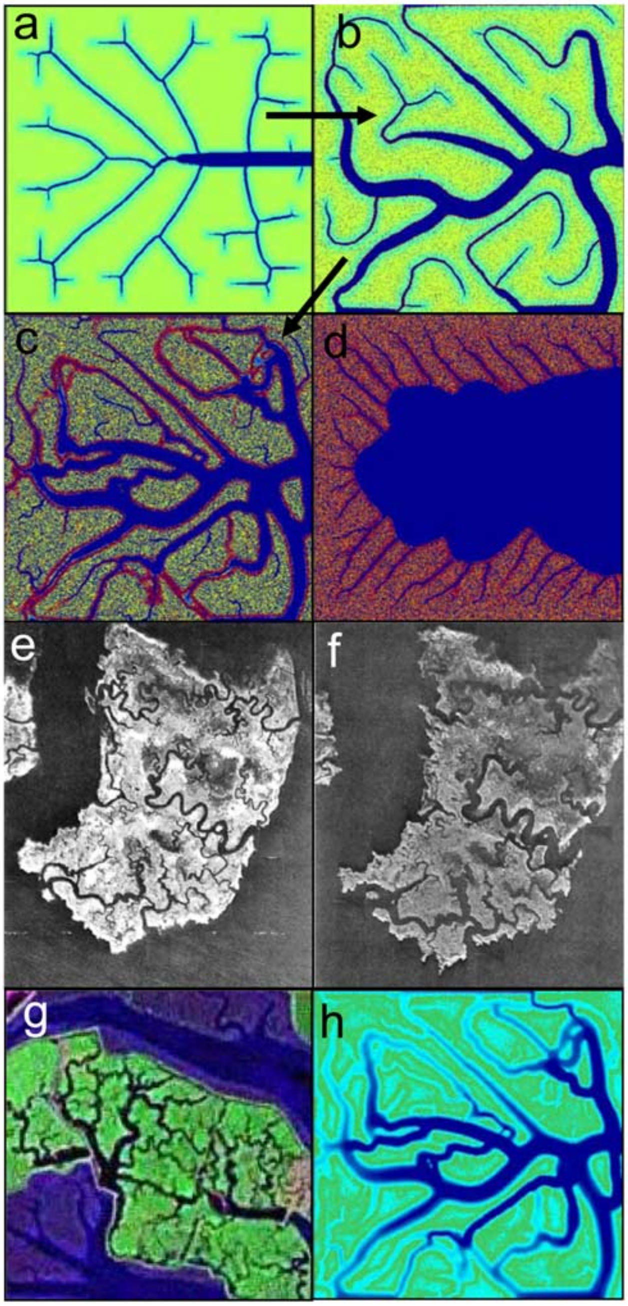

Figure 1. Comparisons of marsh loss and channel widening between modeled and natural channel networks. (a, b) Deep, narrow channel networks widen in response to temporary, minor disturbance, resulting in permanent loss of channel-adjacent vegetation. Dramatic dissection of the platform occurs (c) under higher disturbance regimes and (d) where sediment supply is decreased ten-fold. Photographs from Jamaica Bay, New York [*Hartig et al.*, 2002] show increased network dissection between (e) 1959 and (f) 1998. (g) Landsat image of Blackwater Estuary, U.K shows extremely wide channels. Color of model figures denotes biomass productivity where redder colors indicate higher productivity and bluer colors represent lower productivity. (h) Color denotes platform elevation to highlight ponds and corresponds to experiment shown in Figure 1c. Model experiments run under constant 10mm/yr SLRR, 4m tidal range, and 0.02 g/L suspended sediment concentration, with: no disturbance (Figure 1a), 5% disturbance, 5 yr recovery (Figure 1b), 50% disturbance, 5 yr recovery (Figures 1c and 1h), and 50% disturbance, 10 yr recovery (Figure 1d). In the model and each of the photograph locations, accretion rates on the vegetated platform are greater than or equal to the SLRR.

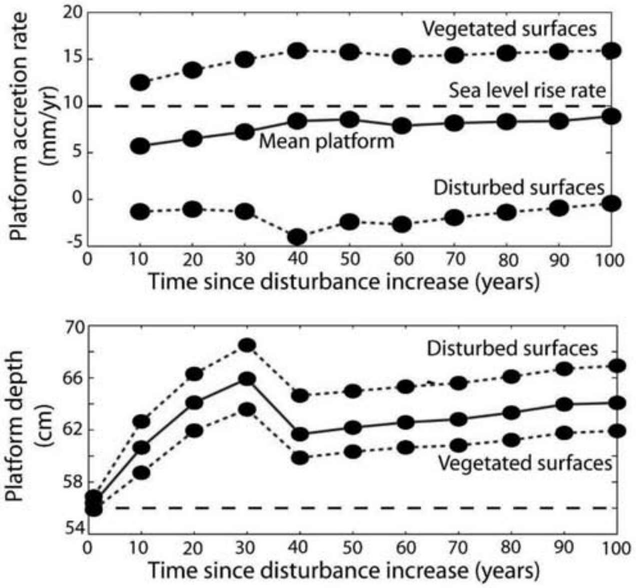

Figure 2. The response of platform accretion and depth to an increase in the intensity of vegetation disturbance under a constant SLRR. Model experiment corresponds to Figures 1b and 1c where disturbance increased from 5% to 50% of platform cells. The dashed line in the bottom graph represents the depth below high tide for which vegetated surfaces accrete at the same rate as SLR. Surfaces deepen beyond this equilibrium depth when disturbed, and will accrete faster than SLR when they are recolonized by vegetation. Therefore, vegetated surfaces accrete faster than SLR even while the platform is submerging. (Platform shallowing between 30 and 40 years after disturbance increase is due to increased sediment availability from channel dissection during this interval.)

[8] In addition to model experiments, we also conducted enclosure experiments at two locations on Westham Island on the Fraser River Delta, British Columbia where Snow Geese feed on *Scirpus americanus*, the dominant marsh grass. In the experiment, relative elevation and stem biomass were measured non-destructively at the beginning and end of the growing season in 121 permanent 1.25 × 2.25 m plots for two years. Wire enclosures excluded geese from 66 of the plots.

3. Results

[9] Vegetation disturbance led to platform deepening, the formation of ponds, and channel network expansion in all model experiments (Figure 1). On the platform, accretion rates temporarily decrease in disturbed cells and water depths increase, creating a number of small depressions. Based on deposition and SLR rates alone (i.e. no erosion) it takes a disturbed cell about 500 years to exceed depths capable of supporting vegetation, even at a high SLRR (10 mm/yr). Since the duration of disturbance is orders of magnitude less than this estimate, elevation change is relatively small in the absence of erosion, and vegetation on the platform typically recovers following the end of disturbance. When the disturbance ceases, newly vegetated depressions accrete rapidly, exceeding the SLRR, until the depressions have filled to their vegetated equilibrium depth.

[10] The onset of disturbance, or an increase in disturbance intensity, causes the mean platform depth to increase until a new steady state evolves. The mean platform accretion rate drops immediately following disturbance onset, but increases in parallel with water depth, until the mean accretion rate approaches the SLRR (Figure 2). However, the spatially and temporally variable pattern of disturbance leads to a heterogeneous mosaic of accretion rates. Cells that have recently been disturbed (relatively high elevation) accrete very slowly, while cells that have been disturbed for a longer period of time (relatively low elevation) accrete more rapidly. Non-vegetated cells accrete more slowly than the SLRR, and vegetated cells accrete at a rate greater than or equal to the SLRR. Therefore, local measurements of accretion in vegetated portions of a disturbed marsh will not represent overall platform behavior and may give a submerging platform the appearance of maintaining elevation.

[11] Mean platform deepening, through the formation of small depressions, enlarges the tidal prism volume flowing through the channel network. Increased water velocities lead to channel incision and deepening. Gravity-driven transport, representing creek bank slump, widens channels as they deepen. Because this down-slope transport is decreased by vegetation biomass, this process is particularly effective where vegetation is disturbed. In this manner, the channel network expands into disturbed cells adjacent to the channel network. Once part of the network, patches tend to quickly erode beyond depths capable of supporting vegetation. Therefore channel network expansion converts episodically vegetated, high elevation platform cells into permanently unvegetated cells. This results in a positive feedback where unvegetated surfaces deepen and further enhance the tidal prism, allowing the channel density to greatly increase and convert uninterrupted platforms into individual marsh islands bounded by channels (Figures 1c and 1h).

[12] The model result that temporary vegetation disturbance can lead to permanent elevation and biomass change is consistent with field observations. For example, vegetation disturbance appears to be causing marsh loss on the actively prograding Fraser River delta in British Columbia. Long term accretion rates exceed SLR in many portions of the delta [*Williams and Hamilton*, 1995], though marshes on Westham Island, a protected bird sanctuary, are actively eroding. Our geese exclusion experiments indicate that geese herbivory reduces biomass productivity in these marshes by at least 60%. Portions excluded from geese accrete faster than SLR, but remaining portions erode at ~1 cm/yr (Figure 3).

4. Discussion

[13] Patterns of vegetation disturbance, accretion, and channel network evolution observed in the model experiments may explain patterns of marsh loss in New York and England where marsh is disturbed by biogeochemical processes [*Hartig et al.*, 2002] and the worm *Nereis diversicolor* [*Paramor and Hughes*, 2004], respectively (Figure 1). In both cases, SLR has been questioned or dismissed as an explanation for the loss of interior marshes since measured

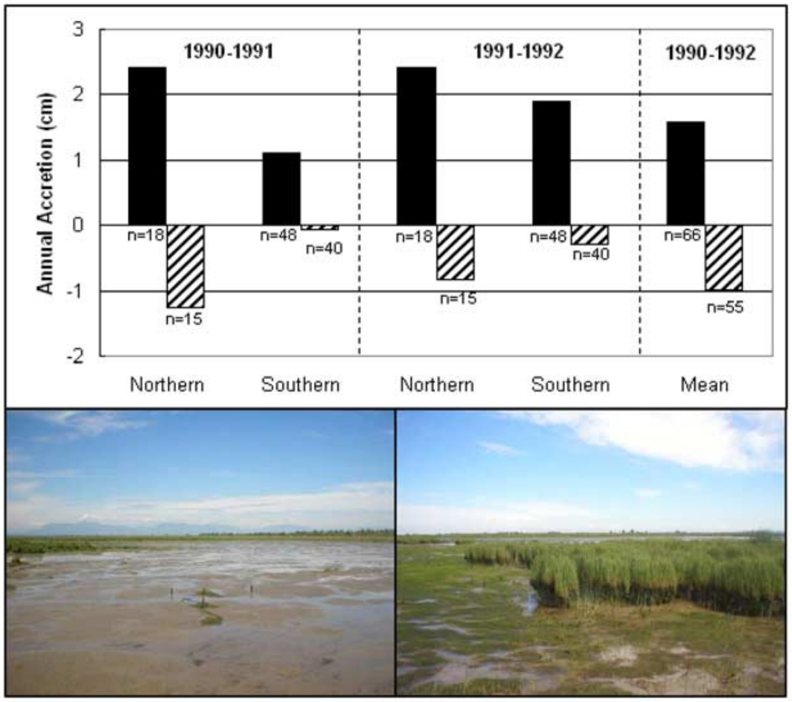

Figure 3. Marshes disturbed by geese herbivory in Westham Island, British Columbia. Marshes accrete faster than SLR when geese are excluded (solid bars), but erode in their presence (slashed bars). Where geese herbivory is intense, the lower bed elevations allow more rapid wave erosion, converting remaining high marsh vegetation pedestals to mudflats.

accretion rates match or exceed SLRR [*Hartig et al.*, 2002; *Paramor and Hughes*, 2004; *Van der Wal and Pye*, 2004]. Our model experiments indicate that vegetated patches lose elevation when disturbed, but accrete rapidly when recolonized by vegetation. A recently re-vegetated patch will accrete faster than the SLRR, while a patch that has long been vegetated will accrete in equilibrium with SLR. Therefore, measurements of accretion on vegetated portions of an intensely or recently disturbed platform will tend to exceed SLRR, giving a submerging platform the appearance of maintaining elevation (Figure 2).

[14] In disturbed marshes in New York and England, widening of the existing channel network, and the incision of new channels into the platform causes considerable marsh loss [*Paramor and Hughes*, 2004; *Van der Wal and Pye*, 2004]. Our model and field experiments suggest that this network expansion could be the result of disturbance-induced lowering of mean-platform elevations. A coupling between platform submergence and channel dissection is surprising. A number of measurements of tidal channel density, drainage area elevation, and tidal prism volumes in marshes in both Italy and the United States suggest that platform elevation is not tightly coupled with drainage density [*Marani et al.*, 2003; *Hood*, 2007]. We hypothesize that vegetation's effect on accretion and bank slumping is responsible for this apparent disparity, as model simulations with undisturbed vegetation show increased biomass productivity and limited channel-network response to platform deepening [*Kirwan and Murray*, 2007].

[15] The magnitude of marsh response to temporary disturbance in our model experiments essentially depends on the amount of deepening that occurs in disturbed cells before vegetation grows back. Therefore, the amount of channel dissection should be a function of SLRR and sediment delivery; under an identical disturbance routine, marshes are more responsive to disturbance at high SLRR and low suspended sediment concentrations (Figures 1d and 4). If rates of SLR and sediment delivery do indeed influence the response of marshes to vegetation disturbance, then marshes that formed and are stable under a low SLRR or high sediment supply may become unstable. In these marshes, moderate vegetation disturbance may have led only to slight channel widening and dissection in the past because favorable SLR and sediment supply conditions allowed rapid vegetation recovery. However, our model experiments suggest that even without a change in disturbance regime, these marshes may become much more dissected and inundated under scenarios of accelerated SLR or reduced sediment supply. In our experiments,

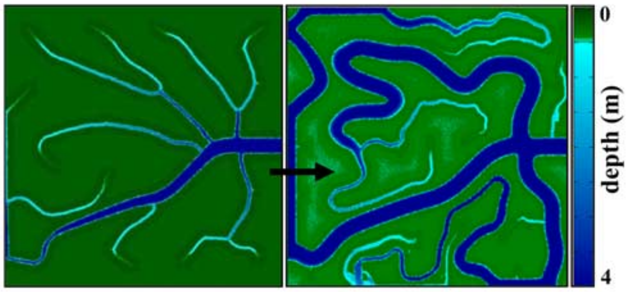

Figure 4. Modeled response of platform with minor vegetation disturbance to an increase in SLRR (1–5 mm/yr). Disturbance regime (5% of platform disturbed, 1 yr recovery) remains constant, suggesting that marshes and their channel networks are more sensitive to disturbance at higher SLRR.

channel dissection leads to increased sediment delivery to portions of the platform that were once far from the channel network, greatly enhancing the stability of the remaining platform. It seems likely that, in the absence of this feedback (Figure 1d), marshes dominated by organic accretion (e.g., where tidal amplitude and sediment availability is low) could have unstable platforms and even greater channel dissection at high SLRR. Perhaps such a response is occurring in marshes of the Chesapeake Bay and Mississippi River Delta Plain, where relative SLRR exceed 10 mm/yr and sediment delivery has been reduced [*Reed*, 1995; *Kearney et al.*, 2002].

[16] Our model experiments and field observations suggest that changes to vegetation productivity and channel morphology in marshes are slight in response to long-term changes in SLRR and sediment supply alone, but temporary disturbance to vegetation facilitates dramatic shifts. Alternative state theory typically focuses on how changing environmental conditions trigger biological shifts [e.g., *Beisner et al.*, 2003]. We suggest that in tidal wetlands, even temporary biological shifts can trigger substrate change, and thus change the environmental conditions themselves (i.e. relative sea level). Because vegetated surfaces tend to accrete more rapidly than SLRR in areas experiencing episodic vegetation disturbance, conventional comparisons between vertical accretion in vegetated areas and SLRR may not adequately forecast wetland survival.

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