

Tidal dissipation morphodynamic feedback triggers loss of microtidal marshes

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Supplemental Material

1. Previously explored hydro-morphodynamic feedbacks

This section summarizes previously studied feedbacks between hydrodynamics, morphodynamics, and intertidal vegetation development which can alter marsh trajectories. These feedbacks are similar to the long-term tidal dissipation feedback discussed in this paper, but are distinct phenomena which occur over different timescales and may overprint each other at a given location.

1.1 Interactions between tidal range, tidal prism, and vertical accretion

Vertical accretion may reduce the tidal prism through a purely geometric effect, i.e., without changing the tidal characteristics. In landscape models which hold tidal range constant (Kirwan and Guntenspergen, 2010; D’Alpaos and Marani, 2016; Mariotti, 2020), intertidal vertical accretion simply subtracts from the tidal prism while the tidal range (the difference between high and low tidal level) is unchanged. A smaller tidal prism will result in shallower channels and transport less sediment in this case (Mariotti, 2020).

Tidal prism can also be affected by changes in tidal range. Marsh accretion tends to cause shoaling which increases the tidal range in strongly convergent estuaries with larger tidal ranges (Du et al., 2018; Cai et al., 2022). However, less convergent and longer estuaries with smaller tidal ranges experience a decreased tidal range with shallowing intertidal areas (Friedrichs and Madsen, 1992; Du et al., 2018; Payandeh et al., 2022). Modeling studies which explore this phenomenon often apply simplified formulations for sediment accretion to approximate morphodynamic development in intertidal marshes while neglecting subtidal/channel areas (Du et al., 2018; Alizad et al., 2022; Cai et al., 2022; Payandeh et al., 2022).

High fidelity hydro-morphodynamic models have considered feedbacks between tidal range and aggradation in both intertidal and subtidal areas. These feedbacks operate on small spatial (~1 km; Boechat Albernaz et al., 2023) and/or temporal (10-100 yrs; Zhang et al., 2018; Boechat Albernaz et al.,

2020) scales relative to the entire evolution of a marsh embayment or river delta, but generally confirm that shallowing water depths results in tidal dissipation rather than amplification especially in microtidal settings.

Physical experiments conducted in a scaled tidal embayment similarly show a reduction in tidal prism, and presumably tidal range, due to the emergence of vegetated intertidal areas in an open embayment transitioning to a partially filled estuary (Weisscher et al., 2022, 2023; Kleinhans et al., 2022). Generally, landward areas continued to aggrade relative to sea level throughout each experiment but relatively little aggradation ever occurred in landward reaches of the estuary. This suggests that frictional dissipation should limit the filling of an estuary or marsh over long timescales. The effects of long-term tidal dissipation across the transition from an open embayment to an extensive fully-filled marsh remain unconstrained.

1.2 Sediment starvation by vegetation

On a local scale (10^2 m), the establishment of vegetation in shallow intertidal areas can have the effect of slowing flow velocities and promoting rapid sedimentation along the marsh edge. As a result, inorganic sediment concentration rapidly decreases moving from channels to the marsh interior. Inorganic accretion decays exponentially with distance in microtidal marshes and can become negligible less than 10^2 m into the marsh platform (Duran Vinent et al., 2021). The marsh interior then becomes more dependent on organic accretion and prone to ponding (Mariotti, 2020; Duran Vinent et al., 2021). In some cases, sediment starvation by vegetation may cause interior marshes several hundred meters from a large channel to collapse (Boechat Albernaz et al., 2023) or simply never form (Boechat Albernaz et al., 2020) if the channel network is unable to sufficiently respond and deliver sediment through the vegetation.

Vegetation establishment in seaward areas of long estuaries may also trap sediment locally and create a deficit in landward areas several kilometers away (Boechat Albernaz et al., 2020; Brückner et al., 2020). This can lead to the preferential maintenance of seaward marshes at the expense of forming landward marshes if sediment supply is limited.

1.3 Ebb dominance

Intertidal vegetation establishment and vertical accretion across an embayment can cause the tidal wave to propagate more slowly during low tide than during high tide (Friedrichs and Perry, 2001), causing a distortion of the tidal wave and eventually resulting in stronger currents during ebb than during flood. Ebb dominance may increase sediment export from landward areas and contribute to marsh loss (Boechat Albernaz et al., 2023). If marsh loss begins, ebb dominance may continue to increase (Donatelli et al., 2020) but it may also decrease (Finotello et al., 2023) depending on site specific basin geometry and ecology. Similarly, relative sea level rise may further enhance ebb dominance (Zhang et al., 2020; Jiang et al., 2020; Boechat Albernaz et al., 2023) or lead to flood dominance locally (Passeri et al., 2016; Wachler et al., 2020). Hence, despite being important in some cases, ebb dominance is by no means a universal mechanism to explain sediment export and marsh loss.

1.4 Vegetation mortality from hydrodynamic stressors

Vegetation mortality may be caused by increased hydroperiod (i.e. inundation stress) or erosion from increased flow velocity. Many eco-morphodynamic models implicitly account for inundation stress by

restricting vegetation growth to optimal elevations within the tidal frame (Kirwan and Guntenspergen, 2010; Alizad et al., 2016) and removing vegetation in impounded areas (Mariotti, 2020). Recently developed modules using Delft3D capture more detailed vegetation dynamics – including time dependent vegetation growth, colonization, hydraulic resistance, and mortality – across a landscape with coevolving hydrodynamics (Brückner et al., 2019). This coupling has revealed that reduced flow velocity from marsh establishment can increase the hydroperiod locally, causing mortality (Brückner et al., 2019). Mortality from erosion or local hydroperiod enhancement may expedite marsh collapse, and result in multi-decadal lags between initial stressors and rapid marsh loss, by removing vegetation from otherwise suitable elevations (Boechat Albernaz et al., 2023). Rapid devegetation of seaward marshes may also redistribute the tidal prism to overbank areas, resulting in both channel infilling and further inundation stress on the marsh (Temmerman et al., 2012).

2. Details of Modeling Approach

The domain is 22 by 4 km with a 20 m grid resolution. The furthest landward 5 km consists of a permanently inactive upland area bisected by a 200 m subaqueous channel (Fig. S1). This region is included only to allow tidal channels to cross the entire basin without being blocked by an impervious upland boundary, and it is excluded from the analyses presented here.

2.1 Temporally variable water level and wind inputs

Unique water level characteristics (tidal range, period, and sea level anomaly), wind speed, and wind direction are applied at each timestep. Tidal values are obtained by selecting random tidal cycles from a five-year time series (spanning 2007-2011) collected at a NOAA tide gauge located at Bishop's Head, MD. Wind values are taken from a nearby weather station. The data and justification for this procedure can be found in Mariotti & Zapp (2022). The primary aim of this approach is to reasonably capture natural short-term water level fluctuations in an idealized microtidal marsh, with the assumption that they can be applied over a longer timescale (3000 yrs in this case), rather than attempting to replicate a specific real-world field site. Variations in water level characteristics largely reflect the impacts of changing meteorologic conditions. Several studies have documented the outsized impacts of meteorologic conditions on sediment dynamics and vegetation growth in microtidal settings (Voss et al., 2013; Valentine and Mariotti, 2019; Zhu and Wiberg, 2022), so the inclusion of temporally variable forcings is deemed important. Mean tidal range and period are 0.54 m (microtidal) and 0.52 days (semidiurnal), respectively. Mean wind speed is 6.05 m/s. Mean sea level anomaly is imposed as a spatially uniform change in water level across the domain. Distributions of these variable inputs are displayed in Figure S2. It should be noted that the temporal variability of these boundary conditions is trendless due to the random selection of tidal cycles, so there is no change to long-term forcing conditions.

The upper limit of marsh vegetation growth is better described by high water levels than mean water levels (Goodwin and Mudd, 2019) because many species only require occasional inundation. We allow vegetation to grow up to an elevation equivalent to the 90th percentile high tide level (0.67/2 m RSL at seaward boundary) plus the 90th percentile positive MSL anomaly (0.19 m RSL) plus 0.1 m to account for precipitation. This upper bound has been demonstrated to better fit data from field experiments (Mariotti and Zapp, 2022) than the traditional mean high-water boundary (e.g. Morris et al., 2002). Otherwise, marsh accretion follows the same parabolic relationship with flooding depth implemented previously in the model (Mariotti, 2020).

2.2 Tidal dissipation due to friction

In addition to the temporal water level variability described in the previous section, tidal range is spatially variable in the along basin (x) direction due to frictional dissipation, but it is constant in the cross-basin direction (y). At each timestep, tidal level (η) is governed by a nonlinear diffusion equation derived in Friedrichs & Madsen (1992) and expressed as:

$$\frac{\partial \eta}{\partial t} = \frac{1}{b\sqrt{|\partial \eta / \partial x|}} \frac{\partial}{\partial x} \left(\frac{\partial \eta}{\partial x} \int \frac{h^{5/3}}{n} dy \right)$$

where b is spatiotemporally variable inundated width (which controls the water storage), and h is water depth (m) for a given time in the tidal cycle, and n is Manning's roughness coefficient (variable depending on the presence or absence of vegetation). Multiple tidal cycles are passed through this routine with several timesteps per cycle, so here dt corresponds to a timescale of minutes to hours, rather than the 0.2 yr morphodynamic timestep present in the rest of the model. The unique diffusion coefficient is assigned to each value in the x direction and corresponds to cross-sectionally averaged (in the y direction) transmissivity of the embayment with respect to the tidal prism. Both h and n may vary across a given transect, so they are integrated in the y direction. The difference between the largest and smallest values of η over a simulated tidal cycle are assigned as the local tidal range across the morphodynamic timestep. As such, tidal range only varies in the x direction and is held constant in the y direction at a given timestep. This procedure has already been implemented numerically in (Zapp and Mariotti, 2023). The tidal dissipation routine is applied twice at each timestep: once using the unique water level inputs for that step, and once using 90th percentile water level values. The 90th percentile values are used to calculate the upper limit for vegetation growth as described in Section 2.1.

2.3 Model Limitations

Tidal amplification is not possible with the tidal dissipation routine. The model also inherently assumes that bottom friction is dominant over local and advective acceleration, which is the case for the interior of marsh-filled estuaries but not for all estuaries (Friedrichs and Madsen, 1992). For these reasons, we chose an initial embayment geometry which would be classified as a convergent, strongly dissipative estuary according to the classification scheme of (Lanzoni and Seminara, 1998). Tidal amplification would not occur in such a setting, and friction becomes more dominant as the embayment fills, so the tidal dissipation routine is appropriately applied to all basin configurations present in this simulation. If anything, tidal prism conveyance may be underestimated for the first several hundred years.

The hydrodynamics of this model also neglect tidal asymmetry, which has been demonstrated to influence morphodynamic feedbacks over multidecadal timescales in an idealized mesotidal marsh (Boechat Albernaz et al., 2023). The development of ebb-dominance as intertidal area increases during basin filling could lead to sediment export due to increased seaward directed tidal current velocities (Boechat Albernaz et al., 2023). However, this mechanism appears to be relatively less important than tidal dissipation for large embayments with very small tidal ranges. Although peak ebb velocities (1.1 m/s) are slightly larger than peak flood velocities (1.0 m/s) at Blackwater NWR, sediment export is primarily driven by spatial gradients in sediment resuspension (Ganju et al., 2013). Sediment resuspension, both at Blackwater NWR and in the simulation presented here, is strongly controlled by wind waves in landward open water areas, which have developed over decades to centuries under a restricted tidal range. This result also agrees with previous theoretical analysis (Gatto et al., 2017),

indicating that tidal asymmetry (e.g., ebb dominance) is fundamental for the transport of sand but it is less so for the transport of mud, which is instead dominated by spatial advective lags, i.e., those simulated in our model.

3. Impact of vegetation on morphodynamic development

The presence of vegetation in the model is essential for a relatively stable platform of elevations above MSL to become established across the domain. When vegetative processes are turned off and an otherwise identical simulation to that presented in Figure 2 is performed, the platform never fully fills in landward areas and begins to submerge before migrating seaward (Fig. S3). This result is analogous to simulations performed with other models, showing that vegetation helps to retain sediment (D'Alpaos and Marani, 2016). However, this finding is in contrast with a recent study considering a smaller platform with a larger tidal range (Boechat Albernaz et al., 2023). That study demonstrates that the presence of vegetation decreases a system's ability to import and retain sediments due to a decrease in tidal prism (not necessarily tidal range) and the development of ebb-dominance. Here, the microtidal marsh relies more heavily on organic accretion, and the development of wind waves over large interior ponds provides a greater stress in the form of edge erosion. Therefore, the impacts of vegetation on overall marsh trajectory appear to depend on site-specific conditions. For example, the same model used here showed that tidal range attenuation was minimal for a mesotidal case even for a long (20 km) marsh domain (Zapp and Mariotti, 2023).

Although the presence of vegetation is essential to shaping the trajectory of the embayment considered in this study, the frictional effect of marshes has very little direct contribution to the degree of tidal dissipation across the basin. Tidal dissipation is linearly dependent on the Manning coefficient which varies by less than an order of magnitude between vegetated and unvegetated cells, but it is exponentially dependent on water depth which may locally change by two orders of magnitude (see equation in supplemental section 2.2). When tidal range outputs from the simulation presented in Figure 2J-K are recalculated with a spatially uniform Manning coefficient set to the lower unvegetated value, there is very little impact on tidal range at every location and time (Fig. S4). Tidal range is marginally lower but never changes by more than 2% locally when the enhanced frictional effect of vegetation is included in the tidal dissipation routine. Essentially, the presence of very small water depths, which are extremely common in marshes, have a larger frictional impact on tidal conveyance than the direct frictional enhancement due to vegetation.

4. Unvegetated-Vegetated Ratio (UVVR) calculation

UVVR is the ratio of unvegetated area (water, bare land) to vegetated area within a salt marsh. For both the historical imagery at Blackwater NWR and the model simulation, non-intertidal upland areas, as well as offshore subtidal areas (e.g. Fishing Bay) are excluded from the analysis. Vegetation extent in 1938 was manually delineated using georeferenced aerial data (Scott et al., 2009). Modern vegetation extent was obtained from publicly available 2020 NDVI-based classification by the U.S. Fish & Wildlife service. The Blackwater UVVR values in Figure 3 (0.32 and 0.92 for 1938 and 2020 respectively) were calculated over an aerial extent of the same dimensions as the simulation (17 km x 4 km) spanning from Fishing Bay to approximately the location of Golden Hill Rd, Cambridge, MD on the landward side of the largest modern pond.

5. Numerical Simulation Scenarios

In addition to the simulation presented in Figure 2 (with tidal range dissipation, RSLR = 1.5 mm/yr, and $C_0 = 55$ mg/l), we ran an otherwise identical simulation without tidal dissipation which exhibits no marsh loss (Figs. 3, S5). When RSLR is instantaneously accelerated from 1.5 to 4 mm/yr, rapid landward marsh collapse occurs within 300 yrs only if tidal dissipation is present (Figs. 3, S7). System-wide UVVR is impacted by less than 0.01 throughout the simulation if RSLR is gradually increased over a 50 yr period rather than being instantaneously increased.

When sediment supply is decreased by 55% (from 55 mg/l to 25 mg/l at seaward boundary), total marsh area temporarily increases if tidal dissipation is present (Fig. S6). This is because the seaward facing mudflat and tidal channel are both able to deepen and more efficiently convey the tide, lessening the tidal choking effect (Fig. S8). To the extent that land loss does occur under decreased sediment supply, it is primarily focused around the seaward marsh edge rather than the landward ponds.

Figure Captions

Figure S1. The full simulation showing the initialized topography. Inactive upland areas flanking a narrow channel are present in a 5 km long upland region, but not included in the analyses presented here. The marsh can establish within a 60 km² region which initially consists of uplands, intertidal, and subtidal areas. A 2 km long permanent mudflat covers the most seaward portion of the domain.

Figure S2. Distributions of the time-variable water level and wind inputs described in S 1.2. Water level inputs are relatively normally distributed, but span a wide range. The most common wind direction is approximately 45° counterclockwise from the seaward direction, or from Northwest to Southeast.

Figure S3. Embayment morphology through time for a simulation with no vegetation that is otherwise identical to the simulation presented in Figure 2. (A-G) Morphology every 500 yrs. (H) Area that would be classified as marsh if it were present. (I) UVVR. (J) Tidal range at $x = 10$ km. (K) Spatial gradient in tidal range every 1000 yrs.

Figure S4. Percent change in tidal range through space and time compared to simulation presented in Figure 2 if frictional effect of vegetation on tidal dissipation is neglected. Vegetation only marginally decreases the tidal range.

Figure S5. Embayment morphology through time for the spatially constant tidal range simulation plotted in Fig. 3.

Figure S6. Comparison of Unvegetated-Vegetated Ratio (UVVR; A) and total marsh area (B) through time for tidal dissipation simulation (Fig. 2) and an otherwise identical simulation with a spatially uniform tidal range (see Fig. S5). Scenarios with decreased sediment supply (from 55 mg/l to 25 mg/l) starting at $t = 1200, 1400,$ and 1600 yrs and spanning 300 yrs are also displayed for both cases (dashed lines). Change in UVVR from 1938-2020 at Blackwater NWR is displayed as a green arrow starting at an arbitrary time.

Figure S7. Embayment morphology from $t = 1200 - 1500$ yrs for simulation with Relative Sea Level Rise (RSLR) rate held constant at 1.5 mm/yr (i.e. Fig. 2 simulation) and for simulation where RSLR rate is increased to 4 mm/yr over that time period (see Fig. 3).

Figure S8. Embayment morphology from $t = 1200 - 1500$ yrs for simulation with suspended sediment supply (C_o) held constant at 55 mg/l (i.e. Fig. 2 simulation) and for simulation where C_o is dropped to 25 mg/l over that time period (see Fig. S6).

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