Impacts of Seagrass Dynamics on the Coupled Long-Term Evolution of Barrier-Marsh-Bay Systems

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Key Points:

- Seagrass is generally beneficial for adjacent marsh, but may enhance marsh erosion when sediment export from the back-barrier is negligible
- Expanding (contracting) seagrass meadows operate as dynamic sinks (sources) of sediment that impact adjacent marsh and barrier evolution
- Seagrass reduces barrier island migration rates in the absence of back-barrier marsh by filling accommodation space in the bay

Abstract

Seagrass provides a wide range of economically and ecologically valuable ecosystem services, with shoreline erosion control often listed as a key service, but can also alter the sediment dynamics and waves within back-barrier bays. Here we incorporate seagrass dynamics into an existing barrier-marsh exploratory model, GEOMBEST++, to examine the coupled interactions of the back-barrier bay with both adjacent (marsh) and non-adjacent (barrier island) subsystems. While seagrass reduces marsh edge erosion rates and increases progradation rates in many of our 288 model simulations, seagrass surprisingly increases marsh edge erosion rates when sediment export from the back-barrier basin is negligible because the ability of seagrass to reduce the volume of marsh sediment eroded matters little for back-barrier basins in which all sediment is conserved. Our model simulations also suggest that adding seagrass to the bay subsystem leads to increased deposition in the bay, reduced sediment available to the marsh, and enhanced marsh edge erosion until the bay reaches a new, shallower equilibrium depth. In contrast, removing seagrass liberates previously-sequestered sediment that is then delivered to the marsh, leading to enhanced marsh progradation. Lastly, we find that seagrass reduces barrier island migration rates in the absence of back-barrier marsh by filling accommodation space in the bay. These model observations suggest that seagrass meadows operate as dynamic sources and sinks of sediment that can influence the evolution of coupled marsh and barrier island landforms in unanticipated ways.

Plain Language Summary

Seagrass often grows in coastal bays sheltered behind barrier islands and salt marshes. While seagrass provides essential habitat for marine organisms, it also makes waves in the bay smaller and helps hold sediment in place. We use a barrier-marsh-bay computer model (GEOMBEST++) to investigate how seagrass impacts the evolution of neighboring marsh and barrier island landforms. In our model simulations, we find that the presence of seagrass in the bay generally reduces the loss of marsh, but under certain conditions may actually increase marsh loss. Additionally, we find that when seagrass is added to the bay, the marsh responds temporarily by

eroding more rapidly because sediment that would otherwise be added to the marsh is instead held within the bay by seagrass. When seagrass is removed, in contrast, sediment that was once held within the bay by seagrass is free to deposit on the marsh, causing the marsh to expand. Lastly, we find that, when no marsh exists, the presence of seagrass slows the landward migration of the barrier island. Our results suggest that it is important to consider the effects of seagrass on adjacent landforms in order to better understand or predict the evolution of the entire barrier-marsh-bay landscape.

1 Introduction

Barrier islands, which account for over 10% of the world's continental coastline (Stutz & Pilkey, 2011), are narrow, low-lying landforms separated from the mainland by fringing salt marshes and shallow bays. These barrier-marsh-bay systems are valuable economically and ecologically: barrier islands are often heavily populated, serve as tourism hotspots, and protect the mainland shore from waves and storm surge; marshes also buffer the impact of storms on coastal regions, sequester carbon, and are especially productive and diverse ecosystems (Kirwan & Megonigal, 2013); shallow bays and their seagrass meadows provide critical habitat and food resources for economically important faunal communities (Barbier et al., 2001). However, the low relief of such landforms yields a dynamic system that is vulnerable to sea level rise, changes in sediment supply, and storms.

Barrier islands and salt marshes are naturally resilient environments. In response to relative sea-level rise (RSLR), barrier islands tend to migrate upward and landward, thereby maintaining subaerial exposure (Bruun, 1988). The process of overwash, whereby sediment from the shoreface and beach is transported landward of the dune crest during storms, facilitates landward migration, allowing an island to gain elevation both through overwash deposition and by moving up-slope (Donnelly et al., 2006). Using the morphological behavior model GEOMBEST (Geomorphic Model of Barrier, Estuarine, and Shoreline Translation) initially developed by Stolper et al. (2005), Moore et al. (2010) find that the erodibility and composition of the substrate, followed by the substrate slope, RSLR rate, and sediment supply rate, are the most important factors in determining the rate of island migration. Marshes on the other hand tend to maintain their elevation relative to sea-level through physical and biological feedbacks that couple the rate of RSLR with the rate of soil accretion (Friedrichs & Perry, 2001; Kirwan & Murray, 2007; Kolker et al., 2010; Marani et al., 2007; Morris et al., 2002; Reed, 1995). As sea-level rises, marshes flood for longer periods of time, allowing for enhanced mineral sediment deposition (Cahoon & Reed, 1995). Productivity of certain marsh grass species also tends to increase with flooding duration, up to a point, so that sea-level rise results in a larger accumulation of soil organic matter (Kirwan & Guntenspergen, 2012; Kirwan & Megonigal, 2013; Morris et al., 2002). As a result of these feedbacks, the rate of vertical marsh accretion tends to equilibrate towards the rate of RSLR, allowing many marshes to survive moderate accelerated RSLR rates (Kirwan & Megonigal, 2013; Morris et al., 2002).

If overwash fluxes are insufficient to maintain island elevation relative to sea level, or if shoreface response rates are insufficient to maintain barrier geometry during landward migration, barrier islands can respond by disintegrating or drowning in place (FitzGerald et al., 2008; Lorenzo-Trueba & Ashton, 2014; Moore et al., 2010). Similarly, marshes will drown and transition to tidal flats if RSLR is too fast for sediment accumulation on the marsh platform to keep pace (Crosby et al., 2016; Jankowski et al., 2017; Kirwan et al., 2010; Marani et al., 2007; Morris et al., 2002; Reed, 1995). RSLR, however, is not requisite for marsh collapse, which can also occur from wind wave erosion at marsh margins (Fagherazzi et al., 2013; Mariotti & Fagherazzi, 2013; van der Wal & Pye, 2004). Because larger and deeper bays produce bigger waves, the progradation or erosion of a marsh boundary induces a positive feedback that tends to either completely fill or empty a basin of marsh (Mariotti & Fagherazzi, 2013).

Recent studies have highlighted the importance of interactions between adjacent coastal subsystems in determining overall system behavior and evolution (McGlathery et al., 2013; Walters et al., 2014). For example, in modeling experiments the presence of a back-barrier marsh reduces the rate of island migration by reducing accommodation space in the back-barrier bay (Brenner et al., 2015; Lorenzo-Trueba & Mariotti, 2017; Walters et al., 2014). Using GEOMBEST+, an extension of the GEOMBEST model coupled with components from the marsh-tidal flat model of Mariotti and Fagherazzi (2010), Walters et al. (2014) find that overwash from barrier islands can also be an important source of sediment for marshes, allowing for the maintenance of narrow fringing marshes in a long-lasting, metastable state under conditions in which they otherwise would not occur. Additionally, sediment derived from the lateral erosion of a marsh bank, when transferred to the marsh platform, reduces the likelihood of marsh drowning and allows for the persistence of a high-elevation marsh platform for a considerable amount of time (Carniello et al., 2009; Lauzon et al., 2018; Mariotti & Carr, 2014).

The presence or absence of seagrass significantly alters the sediment dynamics of shallow back-barrier bays. Seagrass meadows reduce wave energy reaching marsh edges and shorelines by reducing wave height (e.g. Bradley & Houser, 2009; Fonseca & Cahalan, 1992) and attenuate wave and current shear stresses acting on the sediment bed, thereby enhancing deposition and reducing resuspension of fine sediment (e.g. Carr et al., 2010; Carr et al., 2012a; de Boer, 2007). The reduction of sediment in the water column produces a more favorable light environment for the growth of seagrass. This positive feedback for seagrass growth can induce bistable system dynamics where dense meadows with clear water and bare sediment beds with turbid water are both stable states of the system (Carr et al., 2010; McGlathery et al., 2013; van der Heide et al., 2007). Bistable systems respond nonlinearly to environmental drivers, are prone to abrupt shifts from one state to the other as the result of only small changes in environmental conditions, and possess limited ability to recover to a pre-disturbance state (Scheffer et al., 2001; van der Heide et al., 2007).

The potential bistability of seagrass systems coupled with their significant hydrodynamic impacts on sediment dynamics and waves suggest that seagrass can play an important role in the evolution of the entire barrier-marsh-bay system. While previous work has investigated the evolution of shallow coastal bay, back-barrier marsh, and barrier-island subsystems in isolation (e.g. Carr et al., 2010; Carr et al., 2012b; Carr et al., 2016; Mariotti & Fagherazzi, 2013; Moore et al., 2010) or considered the effects of connections to a single adjacent subsystem (e.g., Brenner et al., 2015; Carr et al., 2018; Lauzon et al., 2018; Mariotti & Carr, 2014; Mariotti & Fagherazzi, 2010; Walters et al., 2014), no study has previously examined the coupled dynamics of these subsystems all together. Here we develop an integrated barrier-marsh-bay system model – herein named GEOMBEST++Seagrass – by incorporating seagrass dynamics into GEOMBEST++ from Lauzon et al. (2018). Using this new integrated model, which we parameterize with various datasets from the Virginia Coast Reserve (USA), we run three sets of model experiments to examine the long-term (decadal to centurial) impacts of seagrass dynamics on the coupled evolution of barrier-marsh-bay systems. Our first set of simulations explores the effect of seagrass on marsh width; our second investigates the impacts of adding (removing) seagrass to (from) the bay on adjacent marsh; our third and final set of simulations examines the effect of seagrass on barrier island migration. The goal of this work is not to numerically predict the impacts of seagrass in specific locations or settings, but rather to explore and explain the complex, large-scale behavior of barrier-marsh-bay systems and the key feedbacks and mechanisms that give rise to it.

2 Methods

2.1 Parameterization Site

Our modeling approach uses generalized inputs and initial conditions from Hog Island and Hog Island Bay at the Virginia Coast Reserve (VCR) to inform the model and provide a coherent starting point for our simulations. However, by examining across broad ranges of input values beyond what is observed in the VCR, our simulations are designed to investigate coupled dynamics of barrier-marsh-bay systems in general. The VCR is a Long Term Ecological Research (LTER) site located on the Atlantic side of the Delmarva Peninsula, in the mid-Atlantic Bight, USA (Figure 1). Direct human impact on the barrier islands, marshes, and bays of the VCR has been minimal since the mid-20th century (Orth & McGlathery, 2012), making it an ideal location to study natural couplings between components of a barrier island system. The barrier islands of the VCR are mixed-energy, tide-dominated, and generally migrating landward (Oertel & Kraft, 1994), and are accompanied by a number of shallow back-barrier bays fringed on both sides by *Spartina alterniflora* salt marshes. *Zostera marina* (eelgrass) dominated the bays of the VCR system until the 1930s, when a hurricane caused seagrasses already under stress from disease to go locally extinct (Orth et al., 2006). Restoration efforts beginning in the 1990s have since resulted in significant recovery of seagrass in the VCR (Orth et al., 2006; Orth & McGlathery, 2012). The VCR is located in an area experiencing 3-4 times the global average of RSLR acceleration, resulting in an average of 3-4 mm yr^{-1} of sea level rise for the past six decades (Sallenger, 2012).

Hog Island is a 12 km long, mixed-energy barrier island within the central section of the VCR. It is characterized by high relief relative to other VCR islands, with dune ridges typically 3-4 m above the NAVD 88 datum (Oster & Moore, 2009), and for this reason is also less frequently disturbed (Wolner et al., 2013). Hog Island is backed by Hog Island Bay, which is approximately 12 km wide in the cross-shore direction and has a tidal range of 1.2 m. About 50% of the bay is less than 1 m deep at mean low water (Richardson et al., 2014). Bay bottom sediment ranges from fine silt to fine sand, and wind-driven waves dominantly control suspended sediment concentrations and light availability (Lawson et al., 2007). Meadows of *Zostera marina* exist in the bay between depths of 0.6 and 1.6 m at mean sea level (McGlathery et al., 2012), with the only major meadow located approximately 1500 m from the island-side marsh edge and averaging about 850 m in width (in the cross-shore direction) and 2.5 km in length. The seagrass components of GEOMBEST++Seagrass are therefore parameterized specifically for *Zostera marina*, and we discuss the potential impacts of using different species in section 4.1 below.

2.2 Model Development

GEOMBEST++Seagrass (Geomorphic Model of Barrier, Estuarine, and Shoreface Translation + Marsh + Waves + Seagrass), developed as an extension of GEOMBEST+ and GEOMBEST++, is a two-dimensional cross-shore morphological behavior model that simulates the morphologic and stratigraphic evolution of a barrier-island coastal transect from the shoreface to mainland over times scales of decades to millennia in response to RSLR and changes in sediment supply (Brenner et al., 2015; Lauzon et al., 2018; Moore et al., 2010; Stolper et al., 2005; Walters et al., 2014). Model formulation in GEOMBEST++Seagrass is based on the principles of sediment conservation and assumes that over sufficiently long time scales (e.g., decadal or greater) the shoreface and barrier profile tends to remain invariant, i.e. an equilibrium profile tends to be maintained. With each time step, the equilibrium profile shifts vertically to maintain its position relative to sea level, and horizontally to the cross-shore position that conserves sand. GEOMBEST++Seagrass can depart from its equilibrium morphology, however, if user-specified, depth-dependent erosion and accretion rates are insufficient for shoreface erosion to maintain the equilibrium profile (Moore et al., 2010). The model domain consists of three functional realms (shoreface, barrier-island, and back-barrier marsh/bay) and allows the user to define distinct stratigraphic units that comprise the coastal tract (Figure 2). Each stratigraphic unit has unique erodibility and sand content parameters that constrain the volume of sand able to be eroded on the shoreface in a given time step. Fine-grained sediment is conserved only in the back-barrier realm, as it cannot be redeposited in a high-energy shoreface environment. The back-barrier realm is dynamic, with bay depth and marsh progradation/erosion evolving as a function of sediment supply, wave size, and RSLR. Moore et al. (2010), Walters et al. (2014), and Lauzon et al. (2018) provide detailed descriptions of the model formulation.

In GEOMBEST++Seagrass, seagrass attenuates waves reaching the marsh edge (which is dependent not only on the width of the meadow but also the varying shoot density) and alters the equilibrium depth of the back-barrier bay both for areas with seagrass and without. As described in more detail in the sub-sections that follow, the back-barrier realm in GEOMBEST++Seagrass evolves in the following manner during each 10-year time step: 1) sea level rises; 2) overwash sand is distributed onto the back-barrier marsh and potentially into the bay; 3) fine sediment flux into the back-barrier basin is distributed evenly across the bay bottom; 4) seagrass grows in all suitable locations, or dies in locations where conditions have become unsuitable, according to a shoot density-depth look-up table; 5) the bay bottom, if currently shallower than the equilibrium depth according to a depth-fetch look-up table, erodes to its new equilibrium depth; 6) waves in the back-barrier bay erode marsh edges, with seagrass reducing wave heights and therefore the volume of sediment eroded; 7) organic material eroded from the marsh unit is lost from the system; 8) a fixed percentage of the suspended sediment eroded from the bay bottom and marsh edge is exported from the system via tidal inlet exchange; 9) remaining sediment eroded from the bay bottom and marsh edges is first used to build the remaining marsh platform up to sea level, then redeposited at both marsh edges to prograde the marsh. As such, horizontal translation of marsh boundaries is controlled by competition between edge erosion and progradation.

2.2.1 Wave Dynamics

In the model, seagrass reduces the height of waves reaching the marsh edge. To compute the wave height (*H*), we use the semi-empirical equation from Young and Verhagen (1996):

$$H = \frac{U^2\left(0.2413\left[\tanh A \tanh\left(\frac{B}{\tanh A}\right)\right]^{0.87}\right)}{g} \quad [1]$$

$$A = 0.493\left(\frac{gD}{U^2}\right)^{0.75}$$

$$B = 0.00313\left(\frac{gF}{U^2}\right)^{0.57}$$

where g is gravitational acceleration, U is the wind speed, D is the depth, and F is the fetch (see Table 1 for a list of variables and abbreviations). Following Lauzon et al. (2018) and Mariotti and Fagherazzi (2013), we use the average wind speed from the VCR, 8 m/s, as average wind speed events contribute the most towards marsh edge erosion (Leonardi et al., 2016).

The shoot density and width of a seagrass meadow modify the attenuation of waves reaching the marsh edge. Following Kobayashi et al. (1993) and Bradley and Houser (2009), we approximate wave height attenuation as the exponential function

$$H_x = He^{-cx} \qquad [2]$$

where H_x is the attenuated wave height leaving the seagrass meadow, H is the initial wave height entering the seagrass meadow calculated from equation (1), x is the meadow width along the transect, and c is the effective wave decay coefficient. To represent the effect of shoot density on the wave decay coefficient, which roughly exhibits a positive 1:1 relationship in laboratory experiments (Manca et al., 2012), we vary the effective wave decay coefficient as a function of meadow density:

$$c = c_{max}\left(\frac{d}{d_{max}}\right) \qquad [3]$$

where c_{max} is the maximum wave decay coefficient, d is the shoot density of the seagrass meadow, and d_{max} is the maximum shoot density a meadow can achieve in the model.
We use a value of 0.01 for the maximum decay coefficient, which is the average value of dense meadows from the field measurements of Bradley and Houser (2009) and consistent with measured and calculated values from other studies (cf. Manca et al., 2012; Sanchez-Gonzalez et al., 2011). While in reality seagrass wave attenuation involves complexities such as canopy bending, leaf and shoot structure and geometry, the ratio of canopy height to water depth, and gaps in meadow cover, such complexity is beyond the simplified approach of this model.

In the model, the height of a wave entering a seagrass meadow decays exponentially as it passes through the meadow. Once the wave leaves the seagrass meadow, however, wave height increases again across the fetch separating the meadow and the marsh edge. To account for both attenuation and regrowth of waves, the model calculates an effective fetch as the sum of 1) the fetch associated with the attenuated wave height, H_x (i.e. the fetch that would produce the height H_x in the absence of seagrass), and 2) the fetch of the regrowth area (Figure S1). This effective fetch is used in equation (1) to calculate the final wave height reaching the far marsh edge when seagrass is present. If no seagrass is present in the bay, the full fetch of the bay is used to calculate the final wave height reaching the far marsh edge.

2.2.2 Marsh Edge Erosion and Progradation

Following Marani et al. (2011) and Mariotti and Fagherazzi (2013), we use linear wave theory to calculate the wave power (W) at the marsh edge:

$$W = \frac{\rho g}{16} H^2 c_g \qquad [4]$$

where ρ is the water density, H is the wave height, and c_g is the group velocity calculated as $\sqrt{gD}$ assuming shallow water waves. The wave power from equation (4) is used to calculate the volume of marsh edge erosion (E_m), also following Marani et al. (2011) and Mariotti and Fagherazzi (2013):

$$E_m = \frac{W k_e}{h} \qquad [5]$$

where k_e is an erodibility coefficient set equal to 0.14 $m^3 yr^{-1} W^{-1}$ (Lauzon et al., 2018), and h is the height of the marsh platform. Based on volumetric organic content estimates from VCR marshes by Walters et al. (2014), the marsh unit above sea level in the model is composed of 50% organic matter and 50% mineral sediment. To represent decomposition and dispersal, all organic matter eroded from the marsh unit is lost from the system. In contrast, all suspended sediment that is deposited at the bay margins as marsh (i.e. within the tidal range) is augmented by adding 50% to represent organogenic sediment production.

Following the original formulation of Walters et al. (2014), the fraction of fine sediment (sand excluded) eroded from the bay bottom and marsh edges and retained within the back-barrier basin is sent to the marsh, where it is used first to build the remaining marsh platform up to sea level then redeposited at the margins of the bay to prograde the marsh. This formulation is supported by Mariotti and Fagherazzi (2010), who show that fine sediment preferentially accumulates at the mainland and barrier boundaries of a tidal flat, along with the fact that the bay bottom is at or near its equilibrium depth and thus is unable to receive additional sediment.

2.2.3 Bay Depth

GEOMBEST++Seagrass assumes a rapid approach to the equilibrium depth by instantaneously adjusting the bay bottom at each time step to a new equilibrium depth based on an empirical fetch-depth lookup table (see section 2.3.1 below for details). The equilibrium depth of a system is determined by the balance between wave erosion and sediment deposition at the bay bottom, and tends to be achieved over a much faster timescale than horizontal changes in bay/marsh dimensions (Mariotti and Fagherazzi, 2010). Because this study focuses on the evolution of the barrier-marsh-bay system over timescales involved in marsh erosion and progradation, we do not resolve the approach of the bay bottom to its equilibrium depth. Assuming a rapid approach to an equilibrium depth equates to the model assumption that any excess fine sediment eroded from the bay bottom, including the seagrass meadow, cannot be redeposited on the bay bottom and must be transported to the marsh or lost from the system. Cells with seagrass will have shallower equilibrium depths than bare bay cells according to the fetch-depth lookup table, a parameterization that captures the effects of seagrass in natural systems tending to reduce erosional shear stresses and augment vertical sediment accretion with the addition of organic matter (without explicitly modeling these processes). The bay sediment flux (BSF) represents the volume of sediment spread across the bay from a combination of fluvial inputs, temporary storm surge channels, and inlet exchange; the amount of bay accretion for each time step is determined by dividing the BSF by the width of the bay. If the BSF accretes the bay bottom to a depth shallower than the equilibrium depth, the bay adjusts to its equilibrium depth by removing sediment, which is then transported either out of the system via tidal inlet export (section 2.2.4 below) or to the marsh. If there is insufficient sediment available to accrete the bay bottom up to a new shallower equilibrium depth, the bay will not be able to reach that equilibrium depth in one time step alone and thus the ability of the bay to accrete to its equilibrium depth becomes time-dependent. In such a case, bay cells containing seagrass trap 125% of the available BSF allotted to bare cells to account for the enhanced sediment trapping capabilities of seagrass meadows (Potouroglou et al., 2017). (While this value was chosen semi-arbitrarily due to the difficulty of constraining such a parameter, observational analyses compiled in Potouroglou et al. (2017) suggest that this amount is a reasonable and conservative estimate.) When seagrass is present in the bay, the effective fetch rather than the full fetch is used to set the equilibrium depths for all cells in the bay. This effective fetch is calculated using equations (1-3) as described in section 2.2.1 and illustrated in Figure S1. Therefore, the bare portions of a bay partially covered with seagrass will have a shallower equilibrium depth than bare portions of a seagrass-free bay of the same fetch.

2.2.4 Back-barrier Export

In the preceding versions of the model (i.e. GEOMBEST, GEOMBEST+, and GEOMBEST++), all mineral sediment is conserved within the back-barrier realm. To account for inlet sediment exchange with the open ocean, we add a simple user-defined export percentage (f_{ex}) to GEOMBEST++Seagrass that modifies the volume of suspended sediment eroded from the bay bottom and marsh edge (E_{total}) retained within the back-barrier:

$$E_{retained} = E_{total}\,(1 - f_{ex}). \qquad [6]$$

2.2.5 Meadow Width

The width of the meadow within the bay (w_m) is limited by the user-defined percent bay cover (PBC), which defines the spatial limits of available seagrass habitat as a function of bay width (F): $w_m = PBC \cdot F$. This approach creates a seagrass meadow with a buffer between the meadow and the marsh edge on either side, which represents the more turbid conditions near the marsh boundaries that can prohibit seagrass growth. As the bay widens, more seagrass habitat becomes available if within a suitable depth range, which in turn allows the meadow to widen. We center the seagrass meadow habitat within the bay for all experiments in this study; the impacts of unequal wave energy distribution at the two margins of the bay is a detail we do not explore here. As such, a PBC of 0.5 will produce a seagrass meadow that covers the middle 50%

of the bay bottom and changes dynamically with a changing bay width (if the bay is at a depth suitable for seagrass growth).

2.3 Model Parameterization

2.3.1 Depth-fetch lookup table

To establish a relationship between equilibrium depth and fetch in the model, we first extracted multiple bathymetric transects in all VCR bays from a digital elevation model constructed from the best-available bathymetric data (Richardson et al., 2014). Transects are parallel to the dominant wind direction (15°N; Fagherazzi & Wiberg, 2009), vary in length from approximately 1 to 12 km, and run from basin margin to the opposite basin margin. We then plotted the average depth of both the bare portions of each transect and the portions where seagrass is present over the length of each transect, fit two logarithmic curves to the data (one for seagrass and one for bare sediment bed), and then extracted values along these curves to construct a fetch-depth look-up table (Figure S2). (We use the average depth across each transect because the entire bay in GEOMBEST++Seagrass has a uniform equilibrium depth, i.e. the bay in equilibrium is flat-bottomed.) As such, there are two possible equilibrium depths associated with a single fetch that depend on whether seagrass is present or absent.

2.3.2 Shoot density-depth lookup table

To determine the shoot density of seagrass in each cell, we constructed a shoot density-depth look-up table using a 7-year chronosequence of structural seagrass data resulting from the successive seeding of large replicate *Zostera marina* plots in Hog Island Bay (McGlathery, 2013). Plots were seeded in 2006-2008 and shoot density was measured mid-summer annually 1-7 years after seeding. We first binned the data points by depth for years 3-6 using bins of 0.05 m and found the maximum shoot density for each bin. We then plotted the maximum densities as a function of plot depth, fit a smooth curve, and extracted values along the curve to construct the shoot density look-up table (Figure S3). We omitted years 1 and 2 from analysis to ensure the shoot density measurements represent established meadows, and omitted year 7 which exhibits low shoot densities characteristic of meadows under temperature stress. Shoot density in the look-up table reaches zero at approximately 1.75 m in depth, consistent with the depth limit of

1.8 m identified in modeling of seagrass in Hog Island Bay by Carr et al. (2012a). Accordingly, we set the bistable zone in the look-up table to 1.55-1.75 m in depth to resemble the bistable range modeled by Carr et al. (2012a). As such, seagrass is able to grow within this depth range only in locations where seagrass was present in the prior time step.

2.3.3 Initial Conditions

We developed the initial morphology of the study site by extracting five cross-shore profiles spaced at 1 km intervals across the southern half of Hog Island from an integrated topographic and bathymetric digital elevation model (Richardson et al., 2014). The profiles extend from the middle of the Delmarva Peninsula to approximately 5 km offshore. We then averaged the five profiles to create a representative profile of the modern morphology of Hog Island. We developed the stratigraphy of the site using core interpretations from Finkelstein and Ferland (1987), where we place the top of each identified stratigraphic unit relative to the modern surface profile. The sand percentage relative to mud of each unit is based on estimates from the core data and is given in Figure 2. In addition, we combined the mixed flat (high energy lagoon) and muddy tidal flat units identified in Finkelstein and Ferland (1987) into one bay unit in order to simplify the stratigraphy under the bay, and the sand proportion for this new estuarine unit is calculated as a weighted average based on the approximate cross-sectional areas of the mixed flat and muddy tidal flat units. The idealizations and simplifications made in constructing the initial profile and stratigraphy are appropriate given our goal of assessing the dynamics of fundamental barrier-marsh-bay couplings rather than effects of specific locations and stratigraphies.

3 Model Simulations and Results

We use the newly-designed GEOMBEST++Seagrass model to assess the impact of seagrass dynamics on the evolution of adjacent (marsh) and non-adjacent (barrier) subsystems. We designed our experiments to provide insights into 1) the effect of seagrass on marsh width; 2) the impacts of adding (removing) seagrass to (from) the bay; and 3) the effect of seagrass on barrier island migration. In all simulations, following the values of Walters et al. (2014), we use an overwash volume of 0.2 m^3/m/yr and an overwash accretion rate of 0.001 m/yr that produces an overwash length extending 200 m into the back-barrier, values that all fall within the lower end of ranges reported in VCR overwash fan surveys (Fisher et al., 1974; Leatherman et al., 1977; Leatherman & Zaremba, 1987). We use values from the lower end of observed range because Hog Island is characterized by high relief and is less frequently subjected to overwash processes relative to other VCR islands (Wolner et al., 2013; Young et al., 2007). Additionally, we use a PBC of 0.5 for all model simulations presented in this work.

3.1 Marsh Width

To assess the impact of seagrass dynamics on the evolution of the back-barrier marsh, we run simulations with and without seagrass at 48 combinations of BSF and RSLR parameter values, with BSF ranging from 10-80 m^3/m/yr in increments of 10 and RSLR ranging from 2-7 mm/yr in increments of 1. This results in 96 unique simulations for each parameter space. We designed the dimensions of this parameter space to accommodate the transition between eroding and prograding systems, not to necessarily represent measured or estimated ranges. To control for the effect of the antecedent substrate slope in these experiments (see Moore et al., 2010), we ensure each simulation transverses the same stretch of underlying substrate by running each simulation to a total of 1 m of RSLR (therefore simulations with higher RSLR rates run for shorter durations than simulations with lower RSLR rates). We calculate the difference in the final width between the corresponding seagrass and no seagrass pairs at each location across the parameter space at the end of each simulation. All simulations begin with or without seagrass at their equilibrium depths to control for the effects of adding and removing seagrass, and with an initial marsh width of 2 km. We varied this parameter space by three values of f_{ex} to see how the interaction of the back-barrier bay with the ocean affects simulation outcomes (Figure 3), bringing the total number of simulations to 288.

In all modeled cases the presence of seagrass increases the progradation rates of prograding marshes. Additionally, when some of the sediment eroded from the bay bottom and marsh edge is exported from the bay, seagrass tends to reduce marsh edge erosion rates for eroding marshes (Figure 3b-c). Surprisingly, when sediment export is negligible, seagrass tends to increase marsh erosion rates in the model (Figure 3a).

We identify three primary mechanisms that drive the patterns observed in the parameter space (Table 2). First, seagrass reduces the volume of sediment eroded from the marsh edge and thus lost from the system by attenuating wave height reaching the marsh edge, which favors reduced erosion and increased progradation rates. Second, the erosion of the seagrass meadow during marsh expansion and the sequestration of sediment within the meadow during marsh contraction both regulate the delivery of sediment to the marsh. As the marsh expands farther into the bay, the seagrass meadow shrinks because the encroaching marsh reduces available habitat. The sediment eroded from the edges of the shrinking seagrass meadow is not re-deposited within the bay but rather transported to the marsh (a fundamental assumption of the model), resulting in further marsh progradation and further seagrass loss. Marshes in the presence of seagrass tend to prograde exponentially as a result of this positive feedback, whereas marshes without seagrass tend to prograde linearly (Figure S4). In the reverse case, an expanding seagrass meadow coupled to a receding marsh can sequester sediment that would otherwise be delivered to the marsh and thereby increase marsh erosion rates. (However, this effect is often negligible in an eroding system as there is little available excess sediment to sequester to begin with.) Thus, in the model, the redistribution or sequestration of sediment from or within a seagrass meadow increases both progradation rates and erosion rates, respectively.

A third primary mechanism controls model results: seagrass reduces the equilibrium depth of the bay, which in turn introduces geometric effects. When seagrass is present, the waves propagating across the bay are smaller, resulting in shallower equilibrium depths both within the seagrass meadow and for the bare portions of the bay as well. Smaller waves in a shallower back-barrier bay will reduce the volume of sediment eroded at the marsh edge and therefore tend to favor decreased marsh erosion rates (e.g. Christianen et al., 2013). However, this is offset in the model because, all other things being equal, a shallower bay (i.e. a shorter marsh scarp) requires more lateral marsh erosion (progradation) than a deeper bay for every unit volume of sediment eroded (deposited). Thus, relative to the volume of sediment removed from or added to the marsh edge, the marsh will erode or prograde in a shallower system more rapidly than in a deeper system, which is dependent on the model assumption that the volumetric marsh erosion rate, as opposed to the lateral erosion rate, is proportional to wave power (equation (5); e.g. Marani et al., 2011). Lauzon et al. (2018) first identified this phenomenon to explain how faster winds, by deepening the bay, can result in slower marsh erosion rates (though, in our version of the model, depth is controlled by fetch and the presence or absence of seagrass). This is exacerbated by the incorporation of organic matter – which is assumed lost when eroded to represent decomposition and dispersal – within the upper 0.5 m of the marsh unit in the model. In this manner, a shorter scarp results in a greater proportion of eroded marsh sediment lost from the system, i.e. a marsh with a shorter scarp is a less efficient source of sediment than a marsh with a taller scarp (Lauzon et al., 2018). On the other hand, when the marsh is prograding in the model, a shallower bay will also result in a greater proportion of the available suspended sediment redeposited at the bay margin as marsh (i.e. within the tidal range) rather than the underlying bay stratigraphic unit. This will enhance marsh expansion because the sediment deposited as marsh has the unique benefit of being augmented by organic sediment production in the model. In sum, these geometric effects related to a shallower equilibrium depth tend to increase both progradation and erosion rates. The impact of seagrass on marsh width depends on the competition among these three mechanisms (less marsh volume eroded, meadow redistribution or sequestration of sediment, and shallower equilibrium depth; Table 2).

Seagrass has no effect on the width of the marsh when RSLR rates are high and BSF volumes low. This occurs because the marsh erodes completely away by the end of both the seagrass and no seagrass simulations, resulting in a marsh width difference of zero. While the above mechanisms for altering the rate of marsh edge erosion are still present, their signal is completely overwhelmed by the extreme erosion rates under these forcing conditions. This indicates that seagrass is incapable of impacting marshes that have a strongly negative sediment budget. Increasing or decreasing the PBC for these experiments does not change the general findings; rather, the effects of seagrass simply become more pronounced with increasing size of the seagrass meadow (Figure S5).

3.2 Addition and Removal

To demonstrate the impacts on marsh width of adding or removing seagrass to or from a system, we run a suite of four 1000-year simulations in which seagrass is added or removed after the first 100 years (Figure 4). In addition, we run control cases for each simulation in which the state change does not occur in order to see how the marsh would have evolved had seagrass not been added or removed. The input parameters for each scenario are given in Table S1. We select the parameter values shown for presentation because they best demonstrate the governing sediment supply principles that occur when adding and removing seagrass to and from a system without being masked by other competing factors affecting marsh width (e.g. exceptionally fast erosion rates). However, although the magnitude of the effect changes, these principles apply for every simulation no matter the experimental conditions.

When seagrass is added to the back-barrier system (Figure 4a-b), the seagrass meadow and surrounding bare portions of the bay sequester all of the sediment delivered to the bay until the bay bottom accretes to its new, shallower equilibrium depth. During this period, the marsh receives less sediment than it otherwise would, causing it to erode. In the prograding system (Figure 4b), the marsh erodes following the addition of seagrass for approximately 90 years until the bay reaches its equilibrium depth, then begins to prograde. Despite the short-term erosional period, the progradation rate is greatly increased due to the presence of seagrass, allowing the marsh to surpass the control simulation after 600 years. In the eroding system (Figure 4a), the marsh erodes more rapidly following the addition of seagrass; however, once the bay reaches its new equilibrium depth, the marsh begins to erode less rapidly than the control case in the presence of seagrass.

In contrast, the removal of seagrass causes a significant marsh progradation event (Figure 4c-d). When the seagrass disappears after year 100, the bay bottom erodes to its new, deeper equilibrium depth, sending a pulse of sediment to the marsh and causing the marsh in both simulations to prograde. In the prograding system (Figure 4d), while the removal of seagrass increases marsh width in the short term, the lack of seagrass has adverse effects in the long term; marsh width in the prograding system is eventually surpassed by the control simulation after approximately 800 years because of its slower progradation rate without seagrass, despite receiving the initial pulse of sediment. In the eroding system (Figure 4c), the removal of seagrass initially causes the marsh to rapidly prograde, but a lack of seagrass in the bay increases erosion rates over the rest of the simulation; despite the initial sediment pulse, the marsh erodes to a narrow width roughly equal to the control simulation after approximately 500 years. Given sufficient time, all simulations will tend to reach one of two stable states: a back-barrier either full of marsh or a back-barrier with very narrow or nonexistent marsh (cf. Mariotti & Fagherazzi, 2010; Walters et al, 2014). However, the addition or removal of seagrass to or from the system significantly alters the approach of the marsh to these steady states (i.e. the rates of marsh change).

3.3 Island Migration

Lastly, we conduct a set of simulations to investigate the impacts of seagrass dynamics on long-term barrier island migration rates. These simulations run for 1000 model years both with and without seagrass at a constant RSLR rate of 4 mm/yr and varying BSF to maintain a relatively constant width. The input parameters for each simulation are given in Table S1. We begin the simulations at 3 different initial marsh widths (0, 2 km, and full basin) and run each scenario both with seagrass and without (except for the full basin). Island migration rate is calculated as the slope of the linear regression of shoreline position over time.

When no back-barrier marsh exists, the presence of seagrass decreases island migration rates by 8% (Figure 5), amounting to 168 m less of translation over the 1000-year simulation. When the back-barrier marsh width is greater than 0 m, the island migrates more slowly and seagrass has no impact on the rate of migration. Migration rates are identical for islands backed by 2 km of marsh (regardless of the presence or absence of seagrass) and a bay completely full of marsh.

4 Discussion

4.1 Model Limitations

Limitations with the previous iterations of the model, some of which carry over into this version of the model, have been discussed by Walters et al. (2014) and Lauzon et al. (2018). These include the inability to address alongshore heterogeneities and couplings between adjacent barrier segments; a constant wind speed; a uniform elevation of the marsh platform; and the assumptions related to the treatment of importing/exporting back-barrier sediment as a forcing variable (which is representative of systems with riverine sediment input and little exchange with the ocean). Here we focus on the limitations pertinent specifically to this work.

Because the model is not designed to resolve morphology at shorter timescales, and to significantly reduce simulation run-times and computational effort, we run model simulations with 10-year time steps. As a consequence of the model treating marsh-edge erosion and deposition separately, a longer time step results in a greater volume of marsh-edge erosion and accretion within a single time step. Depending on the bay fetch, a significant portion of the marsh can erode in one 10-year time step alone, resulting in sediment redeposition below sea-level as part of the bay unit. As a result, much of the marsh unit is often not preserved below low tide. The lack of marsh stratigraphic preservation below low tide will slightly decrease erosion rates and increase progradation rates in our model simulations by reducing the amount of organic matter lost from the system in later time steps. Although this temporal coarseness tends to reduce the accuracy of the marsh stratigraphy, it is sufficient for our analysis which focuses on general large-scale behavior. Even if the model is run with a shorter time step, there is little change quantitatively in the results and no change in general conclusions we draw from them (Figure S6).

Another limitation arising from the use of a 10-year time step is that the model does not resolve the seasonal seagrass cycle. High temperatures limiting seagrass growth from late summer to senescence during cold winter months can reduce biomass by as much as 50-80% (e.g. Carr et al., 2012b; Koch et al., 2009). Carr et al. (2018) find that a reduction of seagrass biomass in the fall/winter increases the amount of sediment delivered to the marsh, whereas dense seagrass limits the amount of sediment sent to the marsh in spring/summer months (however, enough sediment is still supplied to the marsh to avoid vertical loss via drowning). Because a reduction of seagrass biomass in fall and winter months generally coincides with storm events (Koch et al., 2009), the lack of seasonality may cause the model to overestimate the ability of seagrass to reduce the volume of marsh eroded. Thus, the ability of seagrass to reduce marsh erosion rates in back-barrier systems where some of the suspended sediment is lost to the ocean would likely be lessened slightly if seasonality is resolved in the model. The model similarly does not resolve individual storms or longer periods of anomalous climate conditions (e.g. a year of unusually strong winds) that can alter marsh width, bay depth, and seagrass density around quasi-equilibrium values. Rather, we model the longer-term changes that average across such fluctuations, an appropriate approach for addressing the longer-term dynamics of the system.

The exponential decay model used for seagrass wave attenuation, while appropriate for short distances, can cause complete decay of waves over sufficiently longer distances. Given the relatively large width of the Hog Island basin (~12 km), the seagrass meadow is usually large enough to fully attenuate the wave height as the wave leaves the far edge of the meadow. This is unrealistic for constant wind forcing which should maintain some (reduced) wave height over the meadow. As such, the attenuation of waves is likely overestimated in the model, which may also lessen the ability of seagrass to reduce marsh erosion rates in back-barrier systems where some of the suspended sediment is exported to the ocean, though this is likely insignificant given other simplifications related to this approach.

In GEOMBEST++Seagrass, the size of the seagrass meadow is determined by the PBC (a fixed percentage of the fetch centered within the bay) and an empirically-derived depth range, and the shoot density of a meadow is also determined by its depth (cf. Collier et al., 2008; Olsen et al., 2002). In reality, the spatial coverage and density of seagrass is complex, and depends on a number of other factors such as physical disturbance and hydrodynamic regime (Cunha et al., 2005), light attenuation within the water column (Enríquez & Pantoja-Reyes, 2005; Ralph et al., 2007), bed sediment grain size (Lawson et al., 2007), seasonal temperature fluctuations (Carr et al., 2012b), local variation in environmental variables (e.g. nutrients and dissolved inorganic carbon; Alcoverro et al., 1995), rates of colonization/expansion (Kendrick et al., 1999), and bioturbation (Townsend & Fonseca, 1998). Modeling density shifts from these various processes is beyond the appropriate complexity of the model, as the incorporation of such small-scale processes would reduce interpretability, generality, and computational efficiency of the model without increasing our understanding of the processes and mechanisms responsible for the large-scale dynamics we observe. However, the impact of marsh expansion/contraction on potential seagrass habitat is underdeveloped. A model formulation, for example, that defines a threshold distance between seagrass and the marsh edge, as opposed to a fixed percentage of the bay, would result in nearly invariable wave power reaching the marsh regardless of bay width. This effect would theoretically limit the positive feedbacks that tend to empty or fill the bay with marsh (Mariotti & Fagherazzi, 2013). Further development of the impacts of the island and marsh on the seagrass meadow to create a stronger two-way coupling is an area for future research.

While the seagrass components of the model in the simulations presented for this study are parameterized specifically for *Zostera marina*, other seagrass species may impact the waves and sediment accretion of estuarine environments differently. Species of greater size and/or density can be expected to result in greater sediment accretion and wave attenuation relative to species of lesser size and/or density (e.g. Mendez et al., 1999). Therefore increasing (reducing) the size and/or density of the species in our model parameterizations would tend to result in an increase (decrease) in the severity of the impacts the model predicts for *Zostera marina*. For sufficiently small and/or sparse species, the impacts of seagrass discussed in this work may be negligible and irrelevant. *Zostera marina*, however, is especially relevant for our study because it is a globally prevalent species (Short et al., 2007) that is found along much of the world's barrier coastline (cf. Stutz & Pilkey, 2011).

Because the model assumes an instantaneous adjustment to the equilibrium depth of the bay (which is achieved only if enough sediment is available), the marsh response to seagrass addition or removal in some of our simulations may be faster or perhaps greater in magnitude than expected in a system where such a change in depth would take longer than a year to achieve. The model formulation for the equilibrium depth also assumes that depth is closely linked to fetch and the presence or absence of seagrass. This assumption may render the results of this study less relevant to natural systems where depth is not closely tied with fetch or seagrass, such as environments with large temporal variation in wind, convoluted open-water geometries, or strong tidal currents. Given the limitations discussed herein, GEOMBEST++Seagrass is not capable of, nor designed for, reproducing or predicting the impacts of seagrass at particular settings or under specific conditions, but instead is meant to demonstrate the coupled dynamics of barrier-marsh-bay systems in general. The simple nature of our model parameterizations may limit the numerical accuracy of the simulation results (thus rendering the consideration of uncertainty in our results irrelevant), but many of the assumptions and simplifications we made are constrained by or derived from observational data so that the compound effects of many processes at smaller time and space scales are represented. This approach of basing models on emergent variables and interactions rather than the finer scale processes that collectively produce them is most appropriate for studies like ours with the goal of exploring and explaining the key feedbacks that lead to complex behavior of large-scale systems (Murray, 2007).

Although most aspects of our modeling results are consistent with documented real-world behavior (e.g. Christiansen et al., 1981; Heine et al., 1987) and predictions from other models (e.g. Carr et al., 2018; Lorenzo-Trueba & Mariotti, 2017) as discussed in the following sub-sections, some aspects – chiefly, seagrass increasing marsh erosion rates when sediment in the back-barrier is conserved – have yet to be supported by observations from natural environments. Comparing some of our model results to observations is challenging for a variety of reasons: 1) a general dearth of long-term seagrass maps; 2) the 1930's mass-wasting disease that caused seagrass to go locally extinct in areas on both sides of the North Atlantic, including the VCR (Orth et al., 2006), thus reducing the potential study window; 3) difficulty in separating the effects of seagrass from other mechanisms of change in natural environments; and 4) difficulty in constraining the controlling parameters, e.g. BSF and f_{ex}, of natural environments to compare with model results. Observational research beyond the scope of this project is needed to continue testing of these results. Despite many model simplifications that may limit our results quantitatively, our findings emphasized herein depend only on the fundamental interactions we have represented and are likely to apply to actual systems.

4.2 Marsh Erosion and Progradation

For prograding marshes, seagrass increases progradation rates in the model under all modeled scenarios because all mechanisms that impact the marsh increase marsh progradation rates (Table 2): 1) seagrass reduces the volume of sediment eroded from the marsh edge; 2) the shrinking of the seagrass meadow during marsh expansion feeds the marsh additional sediment; 3) seagrass leads to a shallower bay that requires more progradation in order to deposit the same unit volume of sediment, and results in a greater proportion of the available suspended sediment redeposited within the tidal range as marsh, which has the unique benefit of being augmented by organic sedimentation.

The story for eroding marshes, however, is more complicated. Why does seagrass tend to reduce marsh edge erosion rates when some sediment is exported from the bay, but increase marsh edge erosion rates when all sediment is conserved? Of the three mechanisms identified in Table 2, only the reduction in the volume of marsh eroded *decreases* erosion rates (the other mechanisms tend to *increase* erosion rates). Thus, the competition between the reduction in marsh volume eroded and the other mechanisms determines whether seagrass will increase or decrease marsh erosion rates. When all sediment is conserved within the back-barrier, and given the basic model assumption that sediment eroded from the bay and marsh edge is preferentially redeposited at the bay margins, most sediment will eventually return to the marsh regardless of how much was initially eroded. Therefore, under these conditions the reduction of marsh volume eroded has relatively little impact and the other mechanisms related to morphology, geometry, and stratigraphy tend to dominate, resulting in increased erosion rates for eroding marshes (Figure 3a-c). However, when some sediment is exported, the reduction in marsh volume eroded (that occurs in the presence of seagrass) has greater influence, resulting in a decrease of erosion rates in the case of eroding marshes (Figure 3d-i). This model result suggests that the ability of seagrass to reduce wave energy reaching the marsh edge matters only in leaky back-barrier systems where sediment is not conserved. These model dynamics are simplifications of mechanisms that operate in natural marshes: increases in wave erosion (as when seagrass is absent) lead to increases in suspended sediment concentrations, which causes more sediment to be lost as ebb tidal currents leave the back-barrier system. This effect of higher gross marsh erosion rates is negated when sediment export is negligible because suspended sediment is ultimately redeposited in the back-barrier environment.

In closed back-barrier systems, our results suggest that the impacts of seagrass on marsh evolution are more related to morphology and stratigraphy rather than wave power. An assumption of 100% retention of sediments within the back-barrier is not directly applicable to any natural system, but the export threshold at which seagrass shifts from enhancing to decreasing erosion rates is difficult to constrain for natural systems using this exploratory model. Nevertheless, our results suggest seagrass may in fact increase – or at least fail to reduce – marsh loss in back-barrier systems with severely limited exchange with the ocean, and that the greater the extent of sediment conservation within the back-barrier, the less relevant the volume of marsh erosion is to the evolution of the marsh. For systems with significant exchange with the ocean, our model predicts, in general agreement with the coupled seagrass-marsh model of Carr et al. (2018), that seagrass tends to increase marsh progradation rates and reduce marsh erosion rates.

4.3 Seagrass Beds as Source and Sink

Our model results indicate the importance of considering seagrass meadows as dynamic sources and sinks of back-barrier sediment. We suggest that seagrass dynamics can play a significant role in regulating the amount of sediment delivered to the adjacent marsh system and may impact coupled evolution on timescales of decades to centuries. Sediment is sequestered within seagrass meadows when vegetation colonizes new areas and is liberated from meadows when vegetation dies. This can happen both over time through the lateral retreat/expansion of the seagrass meadow edge, or rapidly through the wholesale loss/gain of seagrass meadows. Common causes for wholesale seagrass loss from natural systems include disease, storms, or anthropogenic stressors (Orth et al., 2006), while seagrass gain is often achieved via natural colonization or anthropogenic seeding practices, e.g. in the VCR (Orth et al., 2006). Encroachment (retreat) of the marsh-bay boundary can produce incremental loss (gain) of the seagrass meadow as available habitat decreases (increases).

Our results predict that adding seagrass to the back-barrier bay reduces the amount of sediment delivered to the marsh until the bay reaches its new, shallower equilibrium depth, leading to increased erosion or reduced progradation rates for that time period. On the other hand, removing seagrass liberates previously-sequestered sediment that is then delivered to the marsh, leading to a significant marsh progradation event. Carr et al. (2018) find a similar relationship between meadow re-establishment and transitory periods of increased marsh erosion rates, as well as meadow loss and reduced erosion (or increased progradation) rates. Previous studies have observed the release of sediment following the death of seagrass meadows in barrier and estuarine environments and the subsequent impacts on adjacent landforms. Heine et al. (1987) studied the response of a barrier island coastline to the loss of an extensive nearshore seagrass meadow in Florida and found that sediment remobilized from the former meadow widened the beach and lengthened the island by 30% within 15 years. Similarly, Christiansen et al. (1981) correlate two periods of rapid shoreline progradation in a natural embayment in Denmark with two seagrass mortality events. Following the decline of seagrass from 1930s mass-wasting disease in the North Atlantic, Rasmussen (1973) describes the formation of long supratidal sand bars and intertidal flats in Horsens Fjord, Denmark, and Wilson (1949) details the expansion of embayed shorelines in the Kingsbridge Estuary of southwestern England. In addition, results from sediment transport modeling experiments by Donatelli et al. (2018) show that the presence of seagrass in the back-barrier reduces sediment bed shear stresses for the entire bay, including areas without seagrass, which decreases suspended sediment concentrations and consequently reduces sediment flux to adjacent salt marsh. Our results show that this reduction in sediment delivery can significantly impact marsh erosion over decades to centuries.

Interactions with the adjacent marsh also contribute to incremental seagrass loss and gain. When marshes are prograding into the bay in the model, the seagrass meadow loses suitable habitat and shrinks. At the edges of the meadow, where seagrass dies and shoot density converts to zero, the bay erodes to a deeper equilibrium depth. The sediment liberated from this conversion of seagrass to bare sediment is then delivered to the marsh platform, thereby enhancing marsh progradation and further reducing the size of the seagrass meadow. A similar positive feedback exists for eroding marshes. When marshes are eroding in the model, more seagrass habitat becomes available for colonization at the edges of the meadow. As seagrass colonizes new habitat, the edges accrete to a new shallower equilibrium depth, thereby sequestering sediment that would otherwise go to the marsh. As a result, the marsh erodes faster and the seagrass meadow continues to expand. In this way, seagrass tends to reinforce the natural tendency of a back-barrier basin to either empty out or fill up with marsh (Mariotti & Fagherazzi, 2010; Mariotti & Fagherazzi, 2013). Taken together, our results emphasize the role of sediment as an essential but limited commodity: the growth or preservation of one landform is necessarily at the expense of other coupled landforms, especially in systems where sediment is conserved.

4.4 Island Migration

We find that seagrass reduces barrier island migration rates in the model when there is no back-barrier marsh in place. Walters et al. (2014) and Lorenzo-Trueba and Mariotti (2017) have previously shown how the presence of a back-barrier marsh decreases island migration rates by reducing accommodation space in the back-barrier bay. An island migrates more slowly in such a case because less sediment has to be eroded from the front of the island in order to fill the accommodation space behind the island. Seagrass also reduces back-barrier accommodation simply by decreasing the equilibrium depth of the bay. In the model simulations presented in this work, seagrass reduces the rate of island migration by 8%; the exact percent reduction, though, can vary nonlinearly depending on the difference in equilibrium depths between seagrass and no-seagrass runs, which is controlled by fetch, BSF, and RSLR. However, this reduction in accommodation only impacts island migration if it is within the zone over which the barrier island migrates, i.e. only if the marsh is essentially non-existent. This means that seagrass in the model is able to impact island migration rates only when the bay and island subsystems become adjacent, and is unable when the subsystems are non-adjacent. Because seagrass fills less accommodation space than marsh directly behind the barrier, island migration rates in a bay with seagrass but without marsh are still greater than if any marsh were present. Nevertheless, in the absence of marsh, these results suggest that seagrass can help stabilize barrier islands and reduce their vulnerability to RSLR.

5 Conclusions

Our numerical simulations using the exploratory model GEOMBEST++Seagrass reveal important coupled interactions among seagrass meadows of the back-barrier bay and the adjacent salt marsh and barrier island. Model results from a suite of 288 simulations suggest that seagrass increases progradation rates and under many circumstances reduces erosion rates. However, these simulations also demonstrate that the ability of seagrass to reduce the volume of marsh sediment eroded matters little for back-barrier basins in which all sediment is conserved; in fact, in our simulations, other mechanisms that tend to increase erosion rates control the evolution of the marsh under these conditions. In addition, our model results suggest the importance of considering seagrass meadows as dynamic sources or sinks of back-barrier sediment. An expanding or accreting meadow will increase marsh erosion rates, and a contracting or eroding meadow will increase marsh progradation rates – at least until a new equilibrium depth is achieved. Lastly, similar to fringing back-barrier marsh, seagrass slows island migration rates by reducing accommodation space in the bay when no marsh exists. Together, these results demonstrate the complexity of coupled barrier-marsh-bay dynamics, which vary depending on time, external forcing, and internal conditions. Accounting for the complex behavior of these couplings may be necessary for understanding and predicting long-term barrier-marsh-bay evolution.

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Table 1. Definitions of Variables and Abbreviations

Variable/Abbreviation	Definition
RSLR	Relative sea-level rise
H	Wave height
U	Wind speed
D	Bay depth
F	Fetch
c	Effective wave decay coefficient
c_{max}	Maximum wave decay coefficient
d	Effective shoot density
d_{max}	Maximum shoot density
W	Wave power
ρ	Water density
c_g	Group velocity
E_m	Volume of sediment eroded from marsh edge
E_{total}	Volume of sediment eroded from bay bottom and marsh edge
k_e	Erodibility coefficient for marsh edge
h	Height of marsh platform (i.e. marsh scarp)
f_{ex}	Export percentage of back-barrier realm
w_m	Width of the seagrass meadow
PBC	Percent bay cover of the seagrass meadow
BSF	Bay sediment flux

Mechanism	Progradation rates	Erosion rates
Less Marsh Volume Eroded	Increase	Decrease
Meadow Redistribution or Sequestration of Sediment	Increase	Increase
Shallower Equilibrium Depth	Increase	Increase

Table 2. Seagrass-Generated Mechanisms Affecting Marsh Width

Figure 1. Map of Hog Island and Hog Island Bay (HIB) within the Virginia Coast Reserve (VCR) on the Delmarva Peninsula, VA, USA.

Figure 2. Example model output from GEOMBEST++Seagrass showing model realms and stratigraphic units. The percentage of inorganic sediment consisting of sand is given in brackets, with the remaining fraction consisting of mud. The marsh unit is composed of 50% organic matter.

Figure 3. Difference in marsh width after 1 m of relative sea level rise (RSLR) between simulations with seagrass and without across a range of BSF volumes and RSLR rates. Phase spaces are varied by f_{ex} (percent of suspended inorganic sediment lost from the back-barrier bay). Marshes prograde in the simulations within the phase space above the diagonal line and erode in the simulations below the line.

Figure 4. Marsh width over time for a suite of simulations in which seagrass is added or removed after 100 years (colored lines). The marshes erode in the red simulations and prograde in the blue simulations. Black lines are the control cases for each simulation in which the state change does not occur. When marsh completely fills the back-barrier basin, marsh width remains constant (flatlines) at around 6 km.

Figure 5. Island migration rate as a function of marsh width for runs with seagrass (green) and without (black). Simulations run for 1000 years at a constant RSLR rate of 4 mm/yr. BSF volumes vary among the simulations to hold the initial marsh widths constant.

Figure 1.

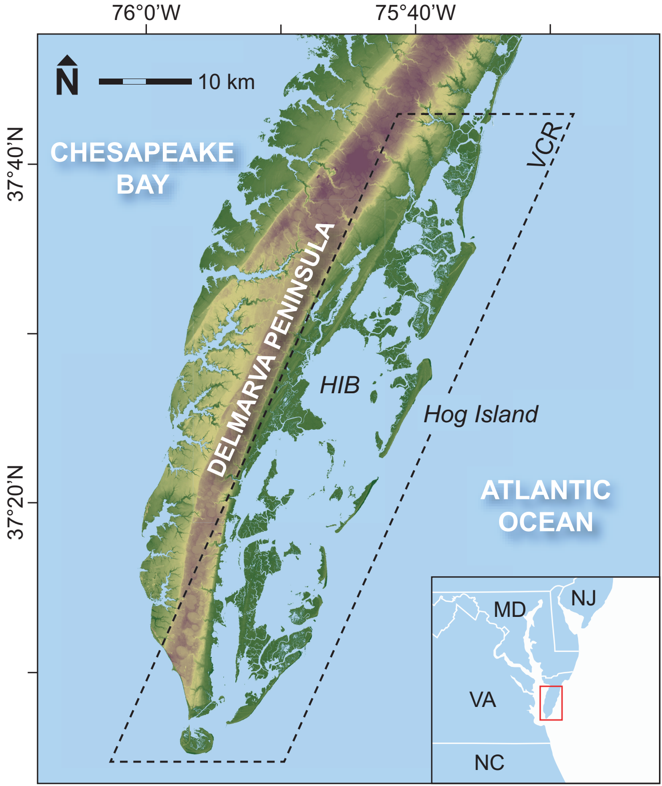
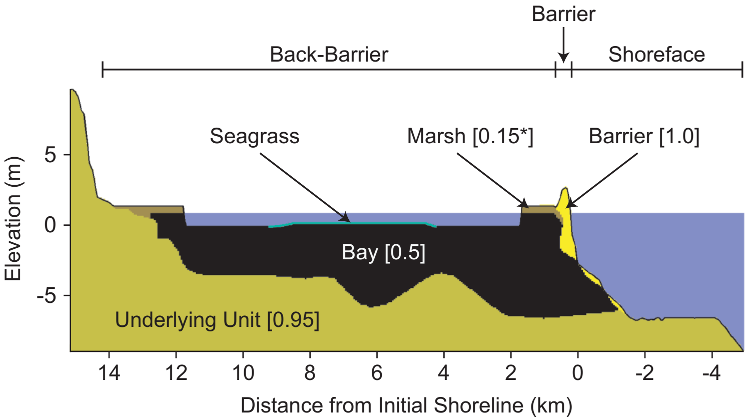

76°0'W
75°40'W
37°40'N
37°20'N
N
10 km
CHESAPEAKE
BAY
VCR
DELMARVA PENINSULA
HIB
Hog Island
ATLANTIC
OCEAN
MD
NJ
VA
NC

Figure 2.



Barrier
Back-Barrier
Shoreface
Seagrass
Marsh [0.15*]
Barrier [1.0]
Bay [0.5]
Underlying Unit [0.95]
Elevation (m)
5
0
-5
14
12
10
8
6
4
2
0
-2
-4
Distance from Initial Shoreline (km)

Figure 3.

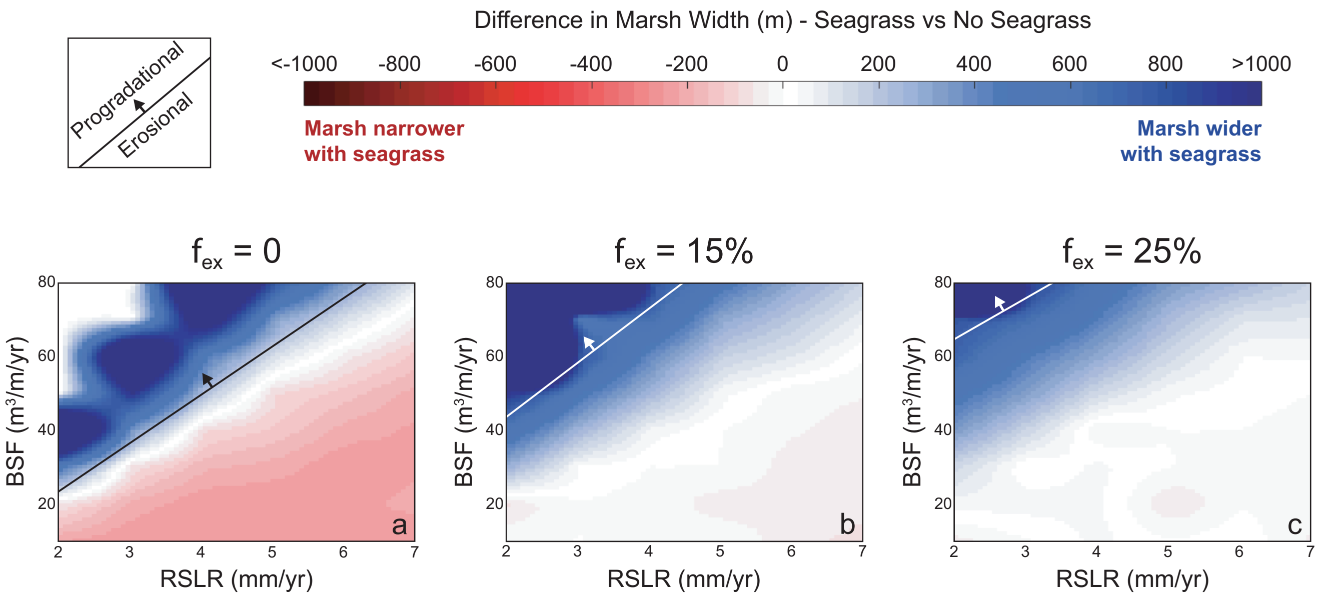
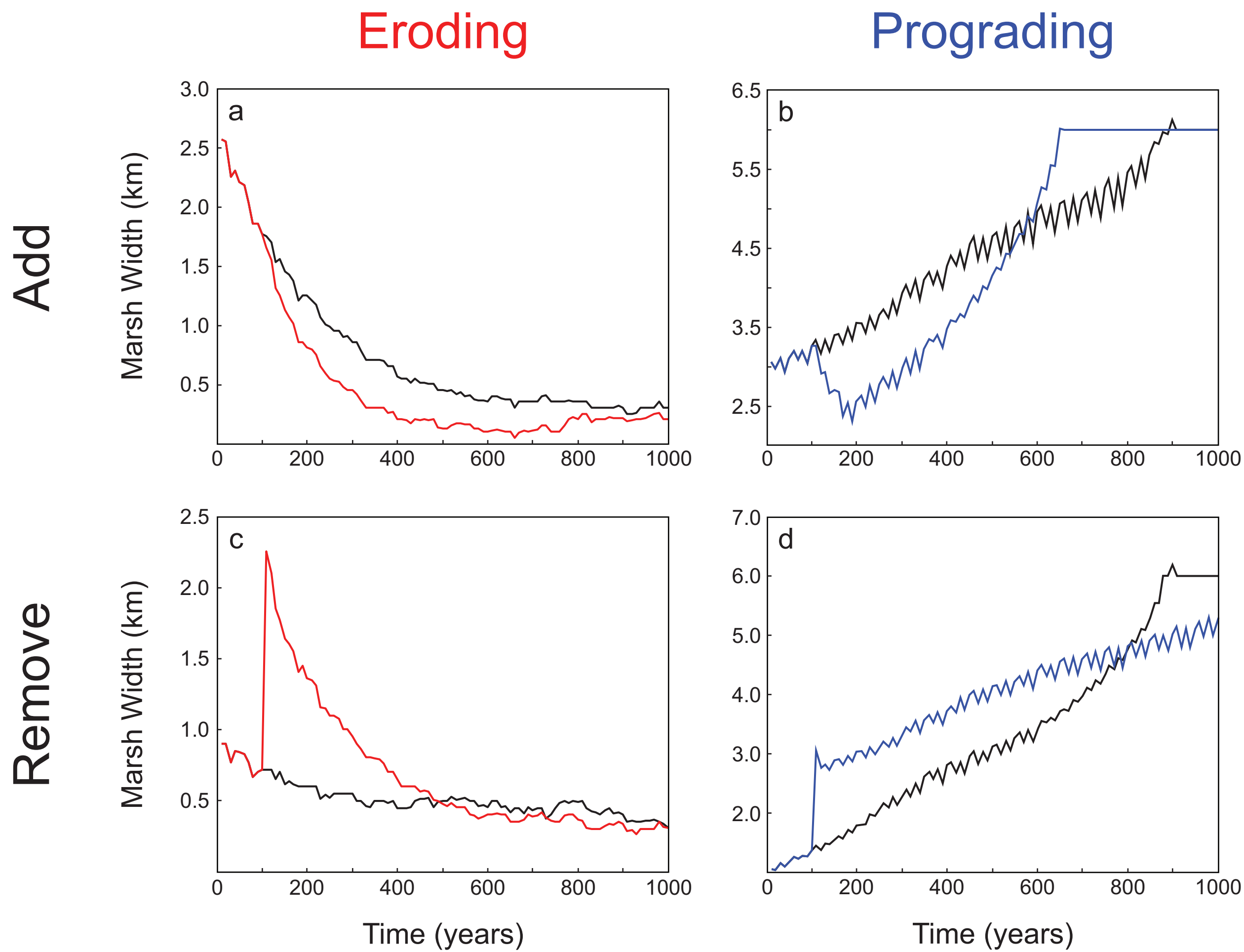
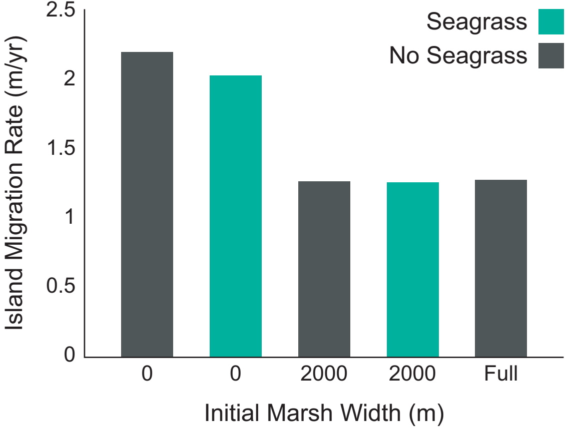

Progradational
Erosional
Difference in Marsh Width (m) - Seagrass vs No Seagrass
<-1000 -800 -600 -400 -200 0 200 400 600 800 >1000
Marsh narrower with seagrass
Marsh wider with seagrass
f_ex = 0
f_ex = 15%
f_ex = 25%
BSF (m³/m/yr)
RSLR (mm/yr)
80 60 40 20
2 3 4 5 6 7
a
b
c

Figure 4.



Eroding
Prograding
Add
Remove
Marsh Width (km)
Marsh Width (km)
a
b
c
d
3.0
2.5
2.0
1.5
1.0
0.5
6.5
5.5
4.5
3.5
2.5
2.5
2.0
1.5
1.0
0.5
7.0
6.0
5.0
4.0
3.0
2.0
0
200
400
600
800
1000
Time (years)
Time (years)

Figure 5.



Seagrass
No Seagrass
Island Migration Rate (m/yr)
2.5
2
1.5
1
0.5
0
0
0
2000
2000
Full
Initial Marsh Width (m)