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Rates of Mainland Marsh Migration into Uplands and Seaward Edge Erosion are Explained by Geomorphic Type of Salt Marsh in Virginia Coastal Lagoons

Jessica A. Flester[1,2] and Linda K. Blum[1]

[1]Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22904-4123

[2]**Corresponding author: Jessica A. Flester,** jaf3bc@virginia.edu, phone 434-924-0560, fax 434-982-2137

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Abstract

Complexities of terrestrial boundaries with salt marshes in coastal lagoons affect salt marsh exposure to waves and sediments creating different potentials for marsh migration inland and seaward-edge erosion, and consequently, for marsh persistence. Between 2002-2017, migration and edge erosion were measured in three mainland geomorphic marsh types (headland, valley, hammock) and were used to assess the rate and spatial extent of marsh change for a Virginia coastal lagoon system. Treelines, shorelines, and marsh perimeters were delineated in ArcGIS at 1:600 resolution. All marsh types increased in spatial extent; increases were greatest for the valley type (0.58 ha ± 0.31 ha or + 0.32% per annum). Measured rates of migration (headland > valley > hammock) and erosion (headland > hammock > valley) for each geomorphic type were averaged and applied to obtain changes in these same marsh types at the regional scale. At this scale, valley marsh area increased (82.5 ha or 5.5 ha a^{-1}) more than the other two marsh types combined. This analysis demonstrates the critical influence that geomorphic type has on lateral marsh responses to sea-level rise and that efforts to conserve or restore salt marshes are most likely to be successful when focused on valley marshes.

Introduction

Throughout the mid-Atlantic region of the USA, sea-level is rising at an increasing rate and coastal wetlands are disappearing simultaneously. While the global rate of sea-level rise throughout most of the 20th century was approximately 1.8 mm yr^{-1}, since the start of the satellite sea-level record in 1993, the average rate of global sea-level rise has been about 3.1mm yr^{-1} (Lindsey 2020). Although sea-level rise is occurring globally, there are spatial variations in the rates of sea-level rise (Sallenger et al. 2012). Within the mid-Atlantic region, along the Atlantic seaside of Virginia's Eastern Shore, relative rates of sea-level rise are more rapid than the global rate; recorded rates at Wachapreague, Virginia are 3.2 ± 0.3 to 5.37 ± 0.69 mm yr^{-1}, recorded from 1930 to 1993 and 1978 to 2019 respectively (Nerem et al. 1998; NOAA 2019). While these rates of relative sea-level rise seem insignificant, they can have highly significant horizontal effects that threaten the persistence of salt marsh ecosystems (Reed et al. 2008).

Salt marsh persistence as sea-level rises is dependent on the ability of these wetlands to either keep pace with sea-level rise through vertical growth (organic matter accumulation and mineral sediment deposition) or, when adjacent to uplands, to migrate inland at a faster rate than they are eroding or submerging to maintain area, as described in Cahoon et al. 1998, Reed et al. 2008, Schieder et al. 2018, among others. Here we focus on the rates of horizontal migration into adjacent uplands and marsh edge erosion. Marsh migration, also frequently referred to as marsh transgression, is a process driven by sea-level rise and disturbance events such as intense storms and hurricanes (Cahoon et al. 1998). Rates of mainland marsh migration throughout the eastern and southern coasts of the United States vary widely; from 0.1 m a^{-1} to 6.78 m a^{-1} (Table 1, and references cited therein). Although evidence of marsh migration is obvious in mainland marshes of the mid-Atlantic, Virginia lagoon systems (Figure 1a), these rates of migration have not been documented previously.

Erosion of marsh seaward edges is another key process impacting marsh persistence. To understand persistence in terms of marsh spatial extent, namely, changes in net area of a marsh, both marsh gain (marsh migration) and marsh loss (edge erosion) must be considered. Others have reported the edge erosion rate to vary from 0.1 m a^{-1} to over 3 m a^{-1} (Table 1, and references cited therein). Edge erosion also is obvious in many mid-Atlantic marshes where exposed roots at the seaward marsh edge show evidence of dislodged sediment and the slumping of pieces of marsh into the lagoon (McLoughlin et al. 2015) (Figure 1b). Edge erosion is driven by land subsidence, sea-level rise, and wave energy (Day Jr. et al. 1998; McLoughlin et al. 2015).

Henceforth in the text we will use the term 'change in marsh spatial extent' to refer to change in marsh area from both upland marsh migration and marsh edge erosion. Because the processes that drive change in marsh spatial extent and the rates of these processes are different, rates at one site cannot be used to predict rates at another site. Geomorphic process modeling techniques can be used to make predictions about changes in marsh area and require measurements of processes like marsh migration and edge erosion to validate the models. While drivers responsible for differences in the extent of changes in marsh spatial context are widely accepted, one factor that has not been considered on Virginia’s Eastern Shore is marsh geomorphic classification. Other studies have found that marsh geomorphology can impact rates of marsh response and resilience to sea-level rise (e.g., Reed et al. 2008; Mitchell et al. 2017). In our study, we used a classification system based on the geological evolution of coastal lagoon systems as described by Oertel and Woo (1994). The geomorphic classification of a marsh could be a simple, critical indicator of both upland migration and marsh edge erosion rates. In the work we present here, we sought to determine if, at the scale of individual marshes, with the potential to migrate into upland areas, the type of geomorphic setting is an indicator of marsh persistence under a regime of increasing sea levels experienced over the past fifteen years.

A wide variety of salt marsh geomorphic types are characteristic of coastal lagoon systems, including those on the seaside of Virginia's Eastern Shore. The Eastern Shore of Virginia includes some of the most pristine coastal wetlands on the Atlantic coastline. Classification of Virginia's coastal-lagoon marshes include three main landscape settings: mainland-fringe marshes, mid-lagoon marshes, and backbarrier-fringe marshes (Oertel and Woo 1994). Backbarrier-fringe marshes are associated with the lagoonal side of barrier islands, mid-lagoon marshes are marsh islands surrounded by open water or mud flats, and mainland-fringe marshes are found along the mainland side of lagoons. Oertel and Woo (1994) defined five mainland-fringe marsh geomorphic types: valley, headland, hammock, interfluve, and tidal channel marshes. Here we focus on the three mainland-fringe types that are directly adjacent to the upland and have the potential to migrate inland; valley, headland, and hammock marshes.

The chief characteristic of valley marshes is that they are almost entirely surrounded by the mainland and are well protected from high-energy lagoonal events, e.g., hurricanes and Nor'easters. Additionally, valley marshes experience landward sediment transport resulting in fine-grained fill at the valley margins that generates platforms for marsh colonization (Figure 2). Headland marshes run parallel to the coast, tend to have relatively low slopes, and are mostly or entirely exposed to adjacent lagoons; this marsh type is not well protected from lagoonal events. Hammock marshes are sandwiched between the mainland and hammock islands which are generally parallel but not connected to the mainland shore. The hammock islands protect these marshes from lagoonal wave action. Hammock marshes have low slopes (though not as low as headland marshes) and suspended sediment load plays an important role in the preservation potential of this marsh type. In Oertel and Woo's (1994) classification system, tidal channel marshes are disconnected from uplands so that there is no opportunity for upland marsh migration with this geomorphic type, while interfluve marshes are rare in this system and were not considered in our study.

In this study, we sought to determine the proportion of valley, headland, and hammock marshes on the mainland of the Virginia barrier island-coastal lagoon system; to document rates of change in marsh spatial extent in the Virginia barrier island-coastal lagoon system's mainland salt marshes; and to investigate whether marshes of different geomorphic types show different rates of marsh migration, rates of edge erosion, and/or net area created over the study period. We hypothesized that marsh geomorphic types with greatest exposure to open water would show equivalent rates of edge erosion and marsh migration, while marsh geomorphic types that have greater protection from wave energy and storm surge would show lower rates of edge erosion than marsh migration into uplands. Therefore, we predicted that valley and hammock marshes would have greater rates of net area gain than headland marshes.

Methods

Site Description

The Atlantic seaside of the lower, Virginia portion of the Delmarva Peninsula is a barrier island-coastal lagoon system. This system extends, generally north to south, 110 km from Chincoteague to Fisherman's Island at the mouth of the Chesapeake Bay, and east to west from the barrier island beaches to the mainland's topographic elevation high that divides the lower Delmarva upland into seaside and Chesapeake Bay-side watersheds (Figure 3a). We refer to this system (including the mainland watersheds) as the Virginia Coast Reserve Long-Term Ecological Research site (hereafter, VCR LTER). The human population density of the mainland VCR LTER watersheds is low, approximately 44,147 people live in the two counties that are the lower Delmarva Peninsula that comprise 1750 km^2 (United States Census Bureau). The barrier islands that are the eastern most boundary of the VCR LTER are the largest stretch of coastal wilderness left on the eastern coast of the United States. Of the 14 barrier islands, 12 are wholly under conservation management by the Federal Government, the Commonwealth of Virginia, or The Nature Conservancy and are uninhabited. The remaining two are sparsely populated. Much of the mainland is under conservation easement (Barnes et al. 1997). In addition to undeveloped barrier islands and mainland watersheds, the VCR LTER is characterized by extensive salt marshes associated with the mainland watersheds and barrier islands, and by marsh islands surrounded by open water lagoons and mudflats.

Relative to marshes in other barrier island-coastal lagoon systems, the naturally low sediment supply from the small upland watersheds (Brinson et al. 1995) and frequent storm disturbance (Hayden and Hayden 2003) in combination with the rapid rate of local sea-level rise may decrease the ability of marshes in Virginia's barrier island-coastal lagoons to persist in the future as the climate changes (Mariotti et al. 2010; Sallenger Jr. et al. 2012; NOAA 2019). This relatively pristine system offers a unique opportunity to examine how rates of salt-marsh migration and seaward-edge erosion respond to sea-level rise in a location where anthropogenic impacts are minimal and rates of relative sea-level rise are high.

Twelve marshes along the seaside coast of the lower Delmarva Peninsula, the VCR LTER, were selected for this study (Fig 3a, Table 2). These twelve sites were selected because they are geomorphically distinct, and nine of the twelve sites have been the focus of other studies carried out by the VCR LTER for over 30 years. All marshes on the seaside of the VCR LTER were identified and classified using methods outlined by Oertel and Woo (1994). To select the final three study sites and achieve equal sample size by geomorphic type, three sites were chosen randomly using a random number generator until the sample size equaled four marshes per each of the three geomorphic types. Four valley marshes (Green's Creek, Upper Phillip's Creek, Folly Creek, and Mill Creek), four headland marshes (Indiantown, Steelman's Landing, Cushman's Landing, and GATR Tract), and four hammock marshes (Woodland Farm, Box Tree, Wise Point, and Oyster Harbor) were identified for this study using Virginia Base Mapping Program (VBMP) aerial imagery from 2002.

Study sites were classified based on geomorphology using marsh geomorphic characteristics outline by Oertel and Woo (1994). We considered three of the five types of mainland marshes described by Oertel and Woo (1994); headland, valley, and hammock. The system-wide delineations of marsh area were done at a scale of 1:10,000, a more detailed resolution than has been previously used to determine marsh area (Schieder et al. 2018; United States Fish and Wildlife Service National Wetlands Inventory).

Marsh Migration, Edge Erosion, and Change in Marsh Area

Rates and areas of marsh migration (e.g. marsh gain) and edge erosion (e.g. marsh loss) and change in area were determined using ArcGIS and VBMP aerial imagery from 2002 and 2017. The 2002 orthoimagery was flown from February 14th to February 24th, 2002 with a two-foot resolution, and the 2017 orthoimagery was flown from 2:43 pm to 6:22 pm on February 26th, 2017 with a one-foot resolution. It is unclear at what time of day the 2002 imagery was flown;

therefore, it is unknown whether the 2002 and 2017 images were taken at similar points in the tidal cycle which could add to error in marsh shoreline delineations. Hand-delineations were done using imagery with a resolution of 1:600 for the twelve marsh sites used to determine rates of marsh migration and shoreline erosion. Limitations of this approach included potentially inconsistent flight times between the two years in question with regard to tidal cycle, and error associated with hand delineations with respect to the determination of where the boundaries between marsh and tree- or shoreline exist in the imagery. In cases where shadows were present at the uplands, the shadowed areas were grouped with the coastal maritime forest. The boundary between high salt marsh and forest was delineated by hand-digitizing 2002 and 2017 imagery, and the area between the 2002 and 2017 treelines was determined for each site (Fig 3b). Rates of marsh migration (ha m^{-1} a^{-1}) were calculated by dividing the total area of marsh migration (ha) by the duration of the study period (15 years). The rate of migration was normalized to the length of 2002 treeline (m) due to preliminary findings that showed a strong relationship between marsh area (ha) and treeline length (m) (Pearson's product-moment correlation, $R = 0.73$, $p = 0.007$). Similarly, marsh area (ha) showed a strong relationship with shoreline length (m) (Pearson's product-moment correlation, $R = 0.96$, $p < 0.000$); thus, the rate of edge erosion was normalized by 2002 shoreline length.

Edge erosion between 2002 and 2017 was determined by hand-digitizing 2002 and 2017 imagery (Fig 3b). Differences between the 2002 and 2017 marsh edges were used to determine the area (ha) of erosion for each marsh. Similar to rates of marsh migration, rates of edge erosion (ha m^{-1} a^{-1}) were calculated by dividing the total area of erosion (ha) by the duration of the study period (15 years) and by 2002 edge length (m).

Because the treeline and shoreline for each marsh were not the same length (e.g. Upper Phillip's Creek treeline length was 3,457 m and shoreline length was 1,298 m), the change in the spatial extent of individual marshes could not be calculated by simple difference between shoreline erosion rates and marsh migration rates. To calculate the net change in individual marsh area over the 15-year study period, the difference of the area gained and lost for each marsh was obtained. To allow for comparison among marshes of vastly different spatial extent, the net area gained (or lost) was expressed as a proportion (in percent) of the size (ha) of the marsh in 2002. We did not consider change in marsh area with respect to the formation or disappearance of ponds within the marsh. Although ponding can lead to changes in marsh area (Ganju et al. 2015; Mitchell et al. 2017), during the time period of this study no change in the number or extent of ponds was observed at our study sites.

The 2017 delineated treelines and marsh edges were confirmed through personal observations by walking the along both types of boundaries and comparing them to printouts of the delineated boundaries. There were few discrepancies, such as areas that appeared in the imagery to be coastal forest that were in fact salt marsh and vice versa, but where differences were observed, the delineated boundaries were adjusted to account for field observations.

Data Analysis

The marsh migration rate, edge erosion rate, net change in marsh area, and net change in marsh area expressed as percentage change did not meet assumptions of homogeneity of variance or normality of distribution of residuals to allow analysis by ANOVA. Therefore, a Kruskal-Wallis test, a non-parametric analysis of variance, was used to determine statistical differences among geomorphic types. The percent area change data were transformed using an arcsine transformation to make them appropriate for use in the Kruskal-Wallis analysis. A Dunn's post-hoc test was used to determine significance of pairwise comparisons. RStudio (R version 3.6.1) and the R package *dunn.test* were used for all statistical analyses.

Results

Mainland marshes on the seaside of the Eastern Shore of Virginia were classified according to Oertel and Woo (1994), and the abundance and spatial extent of the five geomorphic types determined. Next, we examined rates of marsh migration, edge erosion, and change in marsh area between 2002 and 2017 for the three dominant marsh types in this region.

Classification of Mainland Marsh Geomorphic Type

Mainland-fringe marshes are a significant portion of the total marshland on the seaside of the Eastern Shore of Virginia. The mainland-fringe marshes compose 36%, mid-lagoon marshes 20%, and backbarrier marshes the remaining 44% of the total seaside marshland (3.77×10^4 ha) (personal observation, J. Porter, data from NOAA Coastal Change Analysis Program). Recall that mid-lagoon marshes are marsh islands surrounded by open water or mud flats and backbarrier marshes are associated with the lagoonal side of barrier islands. Of the mainland marshes, the number of valley marshes was larger than any of the other four geomorphic types (47.5%). The next most abundant was headland marshes (33.2%), followed by hammock marshes (14.7%). The remaining number (4.6%) were tidal channel and interfluve marshes (Fig 4a). Based on spatial extent, tidal channel and interfluve marshes were dominant (6,210 ha), followed by headland (2,277 ha), valley (2,193 ha), and hammock (1,137 ha) (Fig 4b). For the 5,607 ha of marshes that directly adjoin the mainland, headland and valley marshes, each made up approximately 40% (for a total of 80%) of the mainland marsh area, while hammock marshes constituted the remaining 20% of mainland marsh area adjoining the mainland (Fig 4c).

Marsh Migration

Marsh migration into uplands occurred for all marshes examined regardless of geomorphic type (Fig 5a, Table 3); however, the rates of migration were significantly different (Kruskal-Wallis test, $\chi^2 = 9.84$, $\alpha = 0.05$, $p = 0.01$) among the three types (Fig 5b). Marsh migration rates were highest for headland marshes and ranged from 2.46×10^{-5} to 4.5×10^{-6} ha m^{-1} a^{-1} (mean ± SE, $3.7 \times 10^{-5} \pm 4.52 \times 10^{-6}$ ha m^{-1} a^{-1}); followed by valley marshes which ranged from 8.13×10^{-6} to 1.65×10^{-5} ha m^{-1} a^{-1} ($1.25 \times 10^{-5} \pm 6.27 \times 10^{-6}$ ha m^{-1} a^{-1}); and hammock marshes which ranged from 4.30×10^{-6} to 7.48×10^{-6} ha m^{-1} a^{-1} ($5.85 \times 10^{-6} \pm 2.92 \times 10^{-6}$ ha m^{-1} a^{-1}) (Fig 5b, Table 3). Headland marshes showed significantly higher rates of marsh migration than hammock marshes (Dunn's post-hoc test, $\alpha = 0.025$, $p = 0.0009$), while valley marsh rates of migration were not significantly different from the other two marsh geomorphic types.

Marsh Edge Erosion

Marsh edge erosion was detected only in headland and hammock marshes. The one exception was Oyster Harbor Marsh (hammock marsh) for which edge erosion was undetectable because the marsh edge did not change over the study period (Fig 6a, Table 3). Although there was no statistically significant difference in the rates of erosion between headland and hammock marshes (Dunn's post-hoc test, $\alpha = 0.025$, $p = 0.12$), the mean rate of headland erosion (2.58×10^{-5} ha m^{-1} a^{-1}) was larger than that of hammock marshes (1.51×10^{-6} ha m^{-1} a^{-1}). The wide range of erosion rates for headland marshes (1.05×10^{-5} to 5.04×10^{-5} ha m^{-1} a^{-1}) likely is responsible for obscuring any significant difference between headland and hammock marshes. Though the rates of erosion for the four headland marshes were highly variable, as a group, headland marshes eroded significantly faster than valley marshes (Dunn's post-hoc test, $\alpha = 0.025$, $p = 0.0016$) (Fig 6b). This is likely due to the lack of detectable edge erosion for the four valley marshes, where, in fact, the marsh edge moved seaward. Erosion rates for headland marshes were from 1.05×10^{-5} to 5.04×10^{-5} ha m^{-1} a^{-1} (mean ± SE, $2.58 \times 10^{-5} \pm 8.73 \times 10^{-6}$ ha m^{-1} a^{-1}) and hammock marshes from 0 to 4.77×10^{-6} ha m^{-1} a^{-1} ($1.51 \times 10^{-6} \pm 7.56 \times 10^{-7}$ ha m^{-1} a^{-1}). Valley marshes were characterized by negative rates of marsh edge erosion, in other words, the marshes expanded seaward. This is likely due to accretionary processes driven by the delivery of subtidal sediments converted to intertidal deposits. Edge erosion rates for the valley marshes ranged from -7.8×10^{-6} to -1.1×10^{-5} ha m^{-1} a^{-1} ($-5.85 \times 10^{-6} \pm 2.92 \times 10^{-6}$ ha m^{-1} a^{-1}) (Fig 6b).

Change in Marsh Spatial Extent

All sites showed a net increase in absolute marsh area over the study period, but statistically significant difference among geomorphic types was not detected (Kruskal-Wallis test, $\chi^2 = 1.88$, $\alpha = 0.05$, $p = 0.39$) (Fig 7, Table 3). In some cases, the increase during this time was small (e.g., 0.01 ha at Steelman's Landing) while the largest increase (0.89 ha) was at Upper Phillip's Creek (Fig 7a, Table 3). By geomorphic type, area change was lowest for the hammock marshes (mean ± SE, 0.11 ha ± 0.05 ha), intermediate for valley marshes (0.36 ha ± 0.18 ha) , and highest for headland marshes (0.48 ha ± 0.24 ha) (Fig 7b).

When the mean change in area by marsh type was expressed as the percentage change relative to marsh size (area) in each marsh type, (Fig 8a) the change was lowest for the headland (mean ± se, 0.96% ± 0.48%); intermediate for the hammock (5.13% ± 2.57%); and greatest for the valley

(6.52% ± 3.26%) types although no statistically significant differences were detected among the geomorphic types (Kruskal-Wallis test, $\chi^2 = 5.11$, $\alpha = 0.05$, $p = 0.77$) (Fig 8b).

Discussion

Marsh migration and edge erosion are occurring throughout VCR LTER seaside mainland marshes at rates that result in net marshland increase (Fig 7). The combined net increase in the spatial extent of these twelve marshes was 3.79 ha over the fifteen-year study period. When the geomorphic classification of marshes was considered, the increase in salt marsh area at the upland boundary and the erosion of salt marsh at the edge did not occur at the same rate across the types; instead, the increases and losses were related to marsh geomorphic type (Fig 5, Fig 6, Table 3). The processes that resulted in net marsh increase did not occur equally across the three marsh types (Fig 7, Table 3). While it was not possible to detect a significant difference in net marsh increase by geomorphic type, the large variance associated with the small number of replicates likely limited our ability to detect such a difference (Fig 7b).

We found that headland marshes showed the highest rates of marsh migration, followed by valley marshes, and hammock marshes (Fig 5). Headland marshes have hydric upland soils, low slopes, and are afforded little to no protection from the adjacent lagoon (Oertel and Woo 1994; Ricker 1999); these characteristics make them susceptible to marsh migration and edge erosion. Both valley and hammock marshes are well protected from the lagoons, but valley marshes show greater potential for marsh migration as sediment inputs from the surrounding watershed at valley marsh margins create platforms for marsh colonization at upland boundaries (Oertel and Woo 1994). Additionally, under conditions of sea-level rise, valley marsh tidal creeks erode landward, creating dense drainage networks into the uplands that facilitate marsh migration.

Hammock marshes, which do not show as dense drainage networks (May 2002), are protected from lagoons and lagoonal events by a shoreline-parallel hammock of land that separates the marsh from the lagoon, making them less susceptible to both marsh migration and edge erosion (Fig 5, Fig 6).

In addition to the highest rates of marsh migration, headland marshes also showed the highest rates of marsh edge erosion as a consequence of their direct exposure to adjacent lagoons (Fig 6). Hammock and valley marshes are distinguished from headland marshes in that they have a tidal creek marsh edge as opposed to a shoreline edge parallel to open water. Thus, valley and hammock marsh edges do not allow for undercutting to the same extent as the edges of headland marshes do, making valley and hammock marsh types less susceptible to edge erosion (Fig 6). The behavior and characteristics of a shoreline edge (headland) are far different from those of a creek edge (hammock and valley), particularly in the valley marshes, where gains in marsh area (negative rates of edge erosion) may be indicative of tidal creek expansion into the marsh platform and deposition of the eroded materials along creek banks resulting in marsh progradation. Because the tidal creek network is less dense in hammock marshes, we did not see a similar gain in area at the marsh edge as in valley marshes. The results of this study suggest that exposure to lagoonal events and lagoonal energy were important components of geomorphic type controlling rates of migration and erosion. Further interrogation of the role of exposure in marsh response to sea-level rise are warranted.

For each geomorphic type, we extrapolated the rates of marsh migration and edge erosion to the regional scale of the entire mainland marsh complex on the VCR LTER. Assuming that the average rates of marsh migration and erosion of each geomorphic type apply to the greater VCR LTER, the result of this extrapolation showed that over the fifteen-year study period, a total of

86.2 ha of new marsh were created at the upland boundaries (41.5 ha headland, 3.13 ha hammock, and 41.6 ha valley) while 13.1 ha of marsh loss occurred at the marsh edges (33.4 ha headland, 2.02 ha hammock, -22.3 ha valley), for a net increase in marsh area of 73.2 ha (8.18 ha headland, 1.09 ha hammock, 63.9 ha valley), including the 3.79 ha of net marsh gain in the twelve study sites.

Not accounting for geomorphic type may lead to over- or underestimates of marshland area change. For example, when geomorphic marsh type was not considered and the average rate of marsh net increase for the twelve marshes examined (4.21% increase in fifteen years) was used to determine marsh gains for all mainland marshes with upland boundaries (i.e., 5,607 ha of combined headland, valley, and hammock marshes), the predicted regional gain was 236 ha of marsh; nearly four times more than the gains obtained when geomorphic type was considered (73.2 ha). These results suggest that, at least in the case of the VCR LTER with a relatively small sample size and the scale of variability within a marsh geomorphic type, not accounting for geomorphic type can lead to gross overestimations of marsh area gain.

Valley marshes had high rates of migration, and often, an increase in marsh extent at the water's edge; thus, this regionally abundant and spatially extensive geomorphic type (Fig 4 a,c), accounted for most of the regional marsh area increase. Regional headland marsh net area increase was low (Fig 7) due to the high rate of erosion along the marsh edge (Fig 6), even while the rate of headland marsh migration into uplands was high (Fig 5). Due to the protected nature of the hammock marshes as well as the relatively low number of hammock marshes across the Eastern Shore of Virginia, little change was observed at the hammock marsh boundaries and resulted in a low amount of net change in area across the region. Thus, in terms of resilience to sea-level rise, these results suggest that Virginia Eastern Shore valley marshes are the most likely to persist at current rates of sea-level rise.

Similar results were obtained in a coastal plain estuary by Mitchell et al. (2017) who examined marsh gains and losses along the York River on Virginia's Western Shore of Chesapeake Bay. These authors found that valley marshes (termed "embayed" marshes in their study) were particularly resilient to marsh loss associated with rising sea-levels when compared to marshes near the high energy regions of the estuary where the York River enters Chesapeake Bay. The geomorphic setting of marshes at the confluence of the York River and Chesapeake Bay is analogous to the headland marshes we examined. The similar findings of Mitchell et al.'s study in a coastal plain estuary (2017) and ours in a barrier-lagoon estuary strongly suggests that geomorphic settings offering protection from high energy regions of estuaries may create conditions conducive to salt marsh persistence in a variety of estuarine systems as well.

The gain in marsh area found in this study indicates persistence for mainland marshes, but these gains may be insufficient to offset marsh losses elsewhere in the barrier island system (e.g., mid-lagoon marsh islands and barrier-island marshes). For example, backbarrier and mid-lagoon marshes constituted 65% of the total marsh area lost in the VCR LTER from 1871 to 1962 when sea-level rise rates were lower than current rates (Knowlton 1971). More recent estimates of mid-lagoon marsh-island change range from gains of 0.09% per annum to losses of 0.67% per annum (Erwin et al. 2004); for backbarrier island marshes, losses averaged 0.23% per annum (970 ha over 32 years) for nine of the fifteen the VCR LTER barrier islands (Zinnert et al. 2019). Thus, increases in marsh extent along the mainland are insufficient to replace marshes lost throughout the entire barrier-lagoon system.

As rates of sea-level rise experienced at the VCR LTER accelerate (Kemp et al. 2009; Mariotti et al. 2010; Sallenger Jr. et al. 2012), additional geomorphic factors such as land subsidence and slope may influence marsh persistence. Subsidence, the downward movement of Earth's crust relative to Earth's center, is a large contributor to rates of relative sea-level rise in the Mid-Atlantic (Boon et al. 2010; Eggleston and Pope 2013). Although rates of subsidence have been relatively well monitored in the Chesapeake Bay region, little is known about rates of subsidence on the Eastern Shore of Virginia (Boon et al. 2010). There are two main causes of land subsidence in the Chesapeake Bay region: aquifer compaction from groundwater withdrawal and glacial isostatic adjustment (Eggleston and Pope 2013). The Eastern Shore of Virginia likely shares the same subsidence processes as the Chesapeake Bay region (aquifer compaction from groundwater withdrawal and glacial isostatic adjustment), and therefore is thought to be experiencing similarly high rates of subsidence (Boon et al. 2010; Eggleston and Pope 2013). Subsidence can substantially impact coastal wetlands, as these ecosystems are sensitive to small changes in elevation and flooding (Eggleston and Pope 2013). Therefore, as marshes decrease in elevation relative to mean sea-level, they become susceptible to drowning and eventual loss. Additionally, both sea-level rise and increases in storminess, two observed characteristics of the VCR LTER (Hayden and Hayden 2003; Mariotti et al. 2010), are expected to accelerate marsh edge erosion (Schwimmer 2001) leading to a decrease in marsh area at the marsh edge.

Marsh migration is occurring at the marsh upland in nearby Chesapeake Bay (Kirwan et al. 2016; Schieder et al. 2018) and throughout the seaside of the Virginia Eastern Shore (this study; Kastler and Wiberg 1996); but this process may be limited by land surface slope from the marsh edge to the upland boundary. As slopes steepen, overland marsh migration can stall as the conditions appropriate to support marsh vegetation decreases (Brinson et al. 1995). Additionally, local landowners whose land is adjacent to salt marshes may choose to prevent the migration of salt marsh species onto their land using physical barriers (Kirwan et al. 2016; Schieder et al. 2018). This is significant because if marsh gain is halted at the upland while marsh loss is accelerating at the marsh edge, there will be a net loss in marsh area as conditions become too wet for emergent marsh vegetation to persist (Brinson et al. 1995).

The persistence of salt marshes that migrate into upland ecosystems may be accompanied by both desirable (e.g., increased carbon sequestration) and undesirable (e.g., loss of biodiversity) effects. Marsh migration results from increases in flooding that promote the formation of wetland soils and growth of wetland vegetation (Brinson et al. 1995). Salt stress exacerbates the loss of woody upland vegetation (Kozlowski 1997), leading to further changes to plant species composition and functioning of the coastal landscape through loss of coastal forests (Kirwan and Gedan 2019). The loss of coastal forests is often highly undesirable to landowners, in part due to decreases in property value with proximity to wetlands (Bin and Polasky 2005; Field et al. 2017). The loss of maritime forests also can include decreased plant and animal diversity (Garner et al. 2015, Menon et al. 2010, respectively), increased prevalence of invasive plants (Smith 2013), or increased carbon sequestration (Morris et al. 2012), among others. Recognition that marsh migration may be accompanied by both desired and unwanted effects is critical to conservation and land management efforts in the coastal landscape.

To inform local management decisions and development of policy, a better understanding of local marsh resilience and persistence is needed and requires knowledge not only of sea-level rise, sediment loads, local soil characteristics, but also geomorphic setting. This study provides estimates of the relationship between marsh migration and edge erosion based on geomorphic classifications to better estimate marsh gains and losses, and to support predictive modeling efforts on which to based local land management decisions. Given that approximately 78% of the North American Atlantic coastline (Zinnert et al. 2019) and 10% of the worldwide coastlines (Stutz and Pilkey 2011) are barrier island-coastal lagoon systems like those examined herein, consideration of marsh geomorphic type may prove to be a valuable coastal land management tool beyond the Virginia Eastern Shore seaside.

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Table 1. Previously observed rates of marsh migration into uplands or shoreline-edge erosion.

Site	Area (km ^{2}) or Treeline length (km)	Marsh migration rate (m yr^{-1})	Edge erosion rate (m yr^{-1})	Net area change (ha)	Reference
Cedar Creek Marsh, Maryland	N/A	3.51±2.0 - 6.78±7.4	N/A	N/A	(Hussein 2009)
Elkhorn Slough, California	N/A	0.1	N/A	N/A	(Wasson et al. 2013)
Delaware Bay, New Jersey	101 km	0.5513	N/A	N/A	(Smith 2013)
Big Bend Gulf Coast, Florida	0.30 km	2.3	1.2	3,900	(Raabe and Stumpf 2015)
Chesapeake Bay region	311 – 318 km^2	0.49 ± 0.36	0.53	700	(Schieder et al. 2018)
Various locations	N/A	N/A	0.1 - >3.0	N/A	(Fagherazzi et al. 2015)
Venice Lagoon, Italy	2.564x10^{-3} km^2	N/A	1.2 - 2.2	N/A	(Day Jr. et al. 1998)
VCR LTER, Virginia	12 km shoreline	N/A	1.0 – 1.6	N/A	(McLoughlin et al. 2015)

Table 2. GPS coordinates, area, slope, and geomorphic type of marshes studied at VCR LTER.

Marsh	Latitude	Longitude	Area (ha)	Slope*	Geomorphic Type**
WP	37.130493	-75.951775	3.83	ND	Hammock
GATR	37.167154	-75.941306	102.01	0.00135	Headland
CLM	37.174845	-75.942933	34.08	0.00568	Headland
SLM	37.181199	-75.941789	16.65	0.00357	Headland
OHM	37.287773	-75.929451	0.86	0.01851	Hammock
MC	37.228300	-75.937484	1.35	ND	Valley
ITM	37.345984	-75.901236	65.05	0.02569	Headland
BT	37.395788	-75.877052	13.81	0.00251	Hammock
UPC	37.458622	-75.833203	29.18	0.00037***	Valley
WF	37.482108	-75.818884	9.67	0.00289	Hammock
GC	37.485049	-75.814596	4.16	0.00196	Valley
FC	37.693734	-75.631452	2.21	ND	Valley

*slope measured from shoreline to treeline in 2002; slopes not determined for three marshes
**based on Oertel and Woo (1994)
***slope measured from low marsh to high marsh

Table 3. Rates of marsh migration into uplands, seaward marsh edge erosion, and net change in marsh area during the fifteen-year study period. Rates and net area change are shown for each study site and the mean (± SE) rate for each geomorphic type is shown.

Geomorphic Type	Marsh Location	Rate of Area Change (10^{-5} ha m^{-1} a^{-1})		Net Change 2000-2017 (ha)
		Upland Migration	Seaward Erosion	
Valley	Upper Phillips Creek (UPC)	1.16	-1.10	0.89
	Greens Creek (GC)	1.65	-0.78	0.27
	Folly Creek (FC)	0.81	-0.35	0.13
	Mill Creek (MC)	1.40	0.11	0.14
	Mean (± SE)	**1.25 ± 0.63**	**-0.59 ± 0.29**	**0.36 ± 0.18**
Hammock	Wise Point (WP)	0.43	-0.02	0.019
	Oyster Harbor (OHM)	0.75	0.00	0.15
	Woodland Farm (WF)	0.46	0.15	0.09
	Box Tree Marsh (BT)	0.71	0.48	0.16
	Mean (± SE)	**0.59 ± 0.29**	**0.15 ± 0.08**	**0.11 ± 0.03**
Headland	Indian Town Marsh (ITM)	2.46	1.05	0.53
	Cushman's Landing Marsh (CLM)	4.21	1.70	0.82
	GATR	3.63	2.56	0.56
	Steelman's Landing Marsh (STM)	4.50	5.04	0.01
	Mean (± SE)	**3.70 ± 0.45**	**2.58 ± 0.87**	**0.48 ± 0.17**

[a] Positive values indicate erosion (loss of marsh); negative values indicate progradation (i.e., increases in marsh area)

Figure Captions

Fig 1. Evidence of (A.) marsh migration and (B.) edge erosion at the VCR LTER, a US mid-Atlantic coastal-lagoon system. (A.) Standing dead trees at the marsh upland boundary are evidence of salt stress and marsh migration into the upland. (B.) Exposed roots at the marsh edge are evidence of erosion from daily, continuous undercutting of the marsh edge by wave action from adjacent open waters.

Fig 2. Schematic illustrating the morphology of valley, headland, and hammock marshes. Interfluve- and tidal channel-type marshes are not shown. Marshes indicated by gray shading, open water by diagonal stippling, mainland upland by white fill, and upland hammocks by closely-spaced random stippling. Note mainland parallel orientation of hammock and headland marshes and perpendicular orientation of valley drainage. From, Oertel and Woo (1994)

Fig 3. Geographic setting of (A.) the study sites at the Virginia Coast Reserve Long-Term Ecological Research site (VCR LTER). Grey inset is of the United States eastern coast. Expanded map is the Virginia Eastern Shore with the VCR LTER shaded green. Marsh study sites and geomorphic type are indicated with blue circles (headland), green triangles (hammock), and red stars (valley). Study site abbreviations are Folley Creek (FC), Greens Creek (GC), Woodland Farm (WF), UPC (Upper Phillips Creek), Boxtree (BT), Indiantown marsh (ITM), Oyster Harbor marsh (OHM), Mill Creek (MC), Steelman's Landing marsh (SLM), Cushman's Landing marsh (CLM), GATR Tract (GATR), and Wise Point (WP). (B.) An example of ArcGIS delineated marsh migration and edge erosion between 2002 (red line) and 2017 (blue line) at Cushman's Landing Marsh (CLM). Imagery from the Virginia Base Map Program 2002 and 2017.

Fig 4. Distribution of marsh geomorphic types at the VCR LTER including islands. “Other” includes interfluve and tidal channel marshes. (A.) Abundance of mainland marsh geomorphic type; valley, hammock, and headland marshes comprise 95% of the total number of mainland marshes at the VCR LTER. (B.) Proportion of geomorphic types based on total marsh area within the VCR LTER. The “Other” category is 52.5% of the total mainland marsh area because, on average, tidal channel marshes are large, relative to the average size of individual valley, hammock, and headland marshes; interfluve marshes are rare and small.

Fig 5. Comparison of marsh migration rates by study site (A.) and by marsh type (B.) with geomorphic type indicated. (A.) X-axis labels indicate individual marsh acronyms. Marshes are arranged from south to north. (B.) Box plots of migration rates by marsh type. Quartiles are shown by box, and median by bolded horizontal line. Upper whiskers extend to the highest value that is no further than 1.5 * the inter-quartile range (IQR), and lower whiskers extend to the lowest value no further than 1.5 * IQR. Data beyond the extent of the whiskers were deemed "outliers" and are represented by a solid black dot. Number of replicates were four for each geomorphic type: headland, valley, and hammock. Letters above box plots indicate statistical differences; differences are based on Kruskal-Wallis ($\alpha = 0.05$) and post-hoc Dunn’s test ($\alpha = 0.025$).

Fig 6. Comparison of edge erosion rates by study site (A.) and by marsh type (B.) with geomorphic type indicated. (A.) X-axis labels indicate individual marsh acronyms. Marshes are arranged from south to north. Negative edge erosion is an increase in marsh area at the marsh edge. (B.) Box plots of edge erosion rates by marsh type. Quartiles are shown by box, and median by bolded horizontal line. Upper whiskers extend to the highest value that is no further than 1.5 * the inter-quartile range (IQR), and lower whiskers extend to the lowest value no further than 1.5 * IQR. Data beyond the extent of the whiskers were deemed "outliers" and are represented by a solid black dot. Number of replicates were four for each geomorphic type: headland, valley, and hammock. Letters above box plots indicate statistical differences; differences are based on Kruskal-Wallis (α = 0.05) and post-hoc Dunn's test (α = 0.025).

Fig 7. Comparison of change in marsh area by study site (A.) and by marsh type (B.) with geomorphic type indicated. (A.) X-axis labels indicate individual marsh acronyms. Marshes are arranged from south to north. (B.) Box plots of change in marsh area by marsh type. Quartiles are shown by box, and median by bolded horizontal line. Upper whiskers extend to the highest value that is no further than 1.5 * the inter-quartile range (IQR), and lower whiskers extend to the lowest value no further than 1.5 * IQR. Data beyond the extent of the whiskers were deemed "outliers" and are represented by a solid black dot. Number of replicates were four for each geomorphic type: headland, valley, and hammock. No significant differences were detected among marsh types based on Kruskal-Wallis test with α = 0.05.

Fig 8. Comparison of area gained normalized by the size (area) of marsh in 2002 represented as a percent shown by (A.) study site and (B.) marsh type. (A.) X-axis labels indicate individual marsh acronyms. Marshes are arranged from south to north. (B.) Box plots of percent area change by marsh type. Quartiles are shown by box, and median by bolded horizontal line. Upper whiskers extend to the highest value that is no further than 1.5 * the inter-quartile range (IQR), and lower whiskers extend to the lowest value no further than 1.5 * IQR. Data beyond the extent of the whiskers were deemed "outliers" and are represented by a solid black dot. Number of replicates were four for each geomorphic type: headland, valley, and hammock. No significant differences were detected among marsh types based on Kruskal-Wallis test with $\alpha = 0.05$.

Figure 1

656 Figure 2

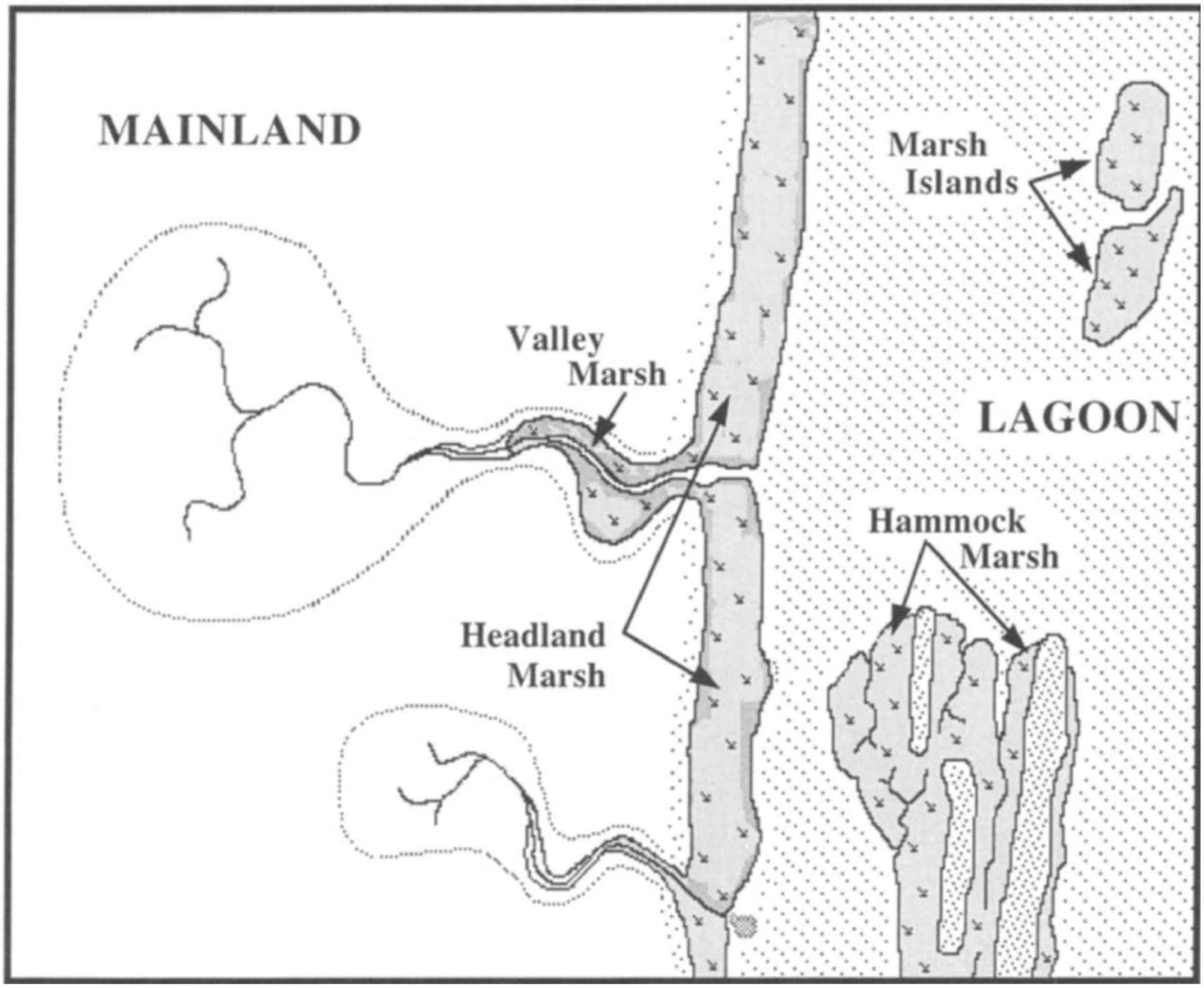

MAINLAND
Marsh
Islands
Valley
Marsh
LAGOON
Hammock
Marsh
Headland
Marsh

Figure 3

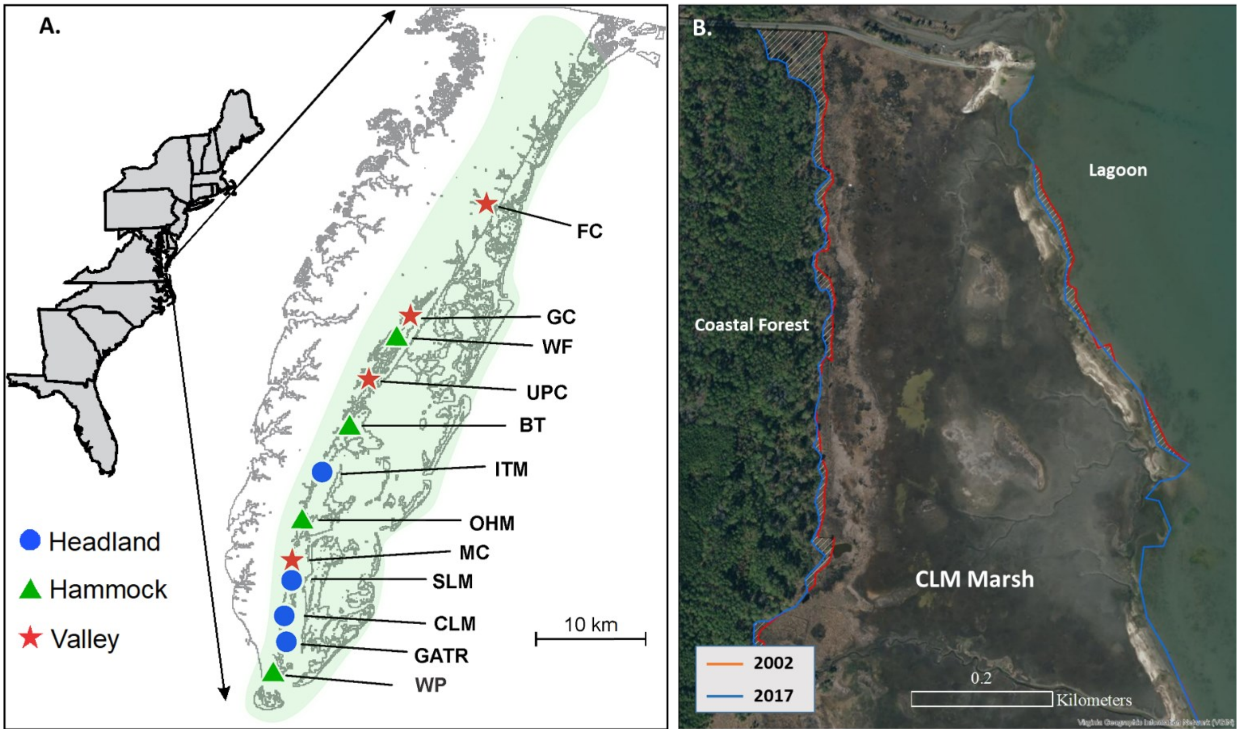

A.
FC
GC
WF
UPC
BT
ITM
OHM
MC
SLM
CLM
GATR
WP
Headland
Hammock
Valley
10 km
B.
Lagoon
Coastal Forest
CLM Marsh
2002
2017
0.2
Kilometers

Figure 4

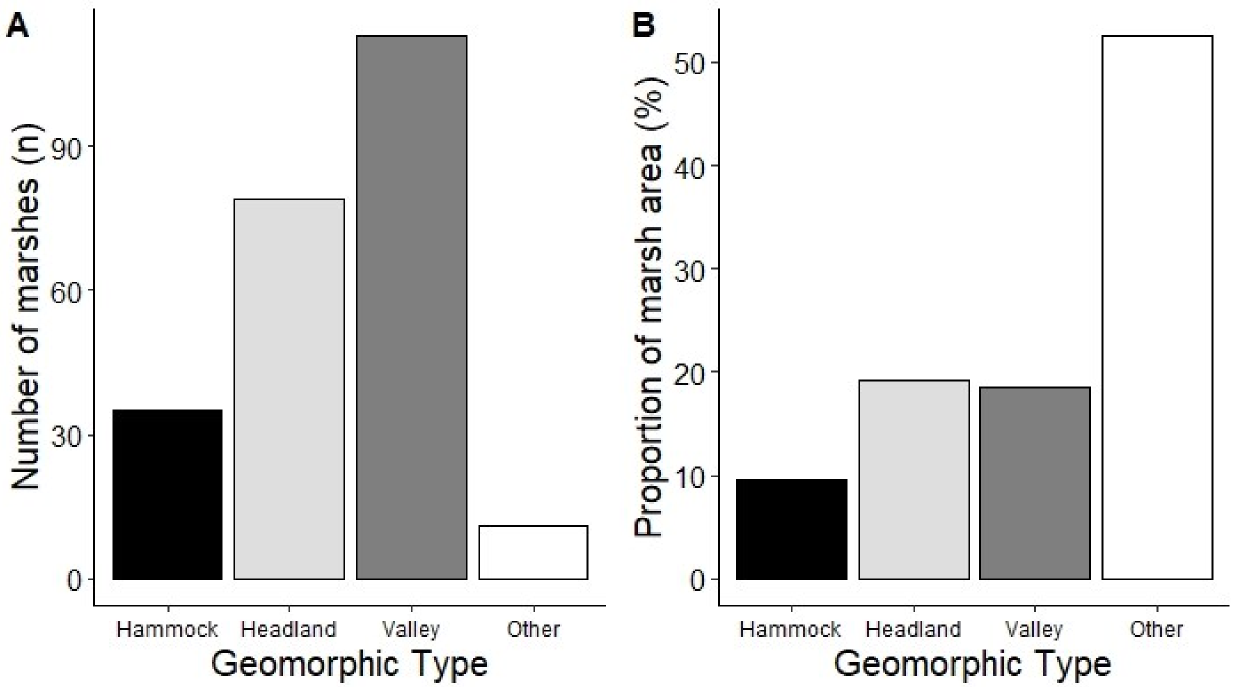

A
Number of marshes (n)
0
30
60
90
Hammock
Headland
Valley
Other
Geomorphic Type
B
Proportion of marsh area (%)
0
10
20
30
40
50
Hammock
Headland
Valley
Other
Geomorphic Type

Figure 5

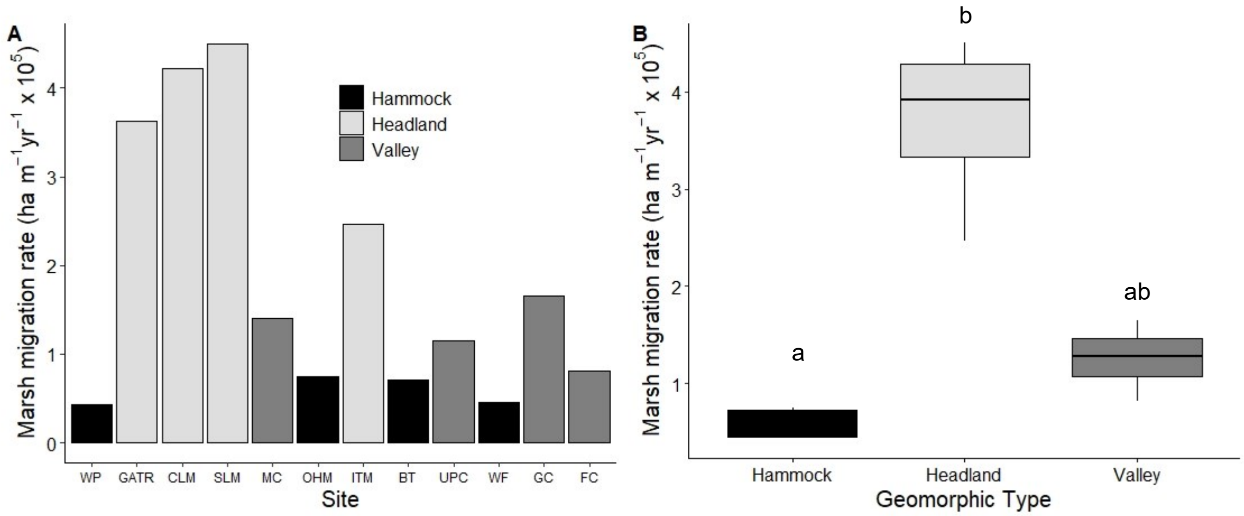
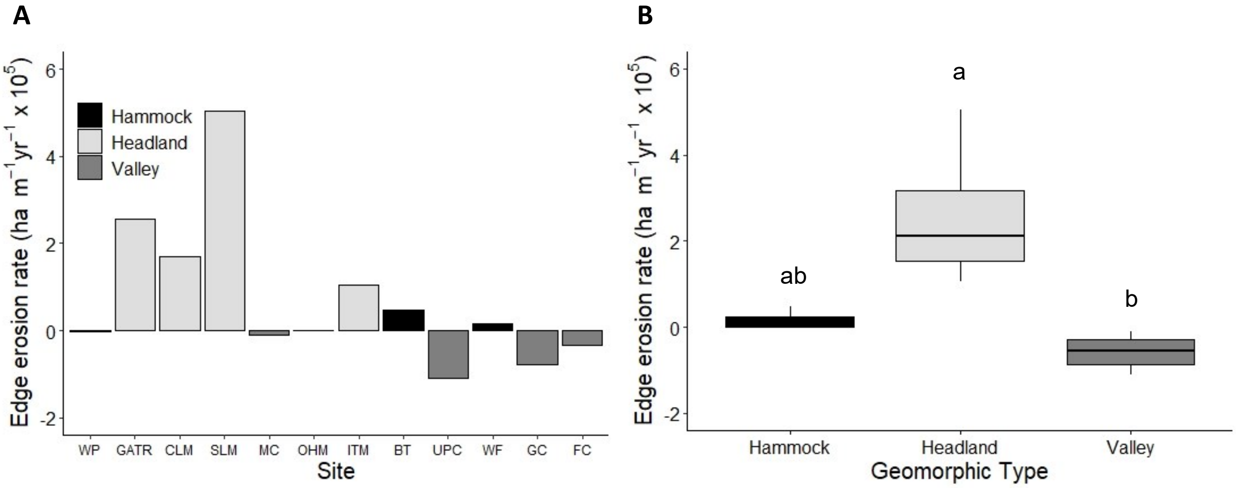

A
Marsh migration rate (ha m^{-1} yr^{-1} x 10^5)
Hammock
Headland
Valley
WP
GATR
CLM
SLM
MC
OHM
ITM
BT
UPC
WF
GC
FC
Site
B
b
ab
a
Hammock
Headland
Valley
Geomorphic Type

Figure 6



A
B
Edge erosion rate (ha m^{-1} yr^{-1} x 10^{5})
Hammock
Headland
Valley
WP
GATR
CLM
SLM
MC
OHM
ITM
BT
UPC
WF
GC
FC
Site
a
ab
b
Hammock
Headland
Valley
Geomorphic Type

Figure 7

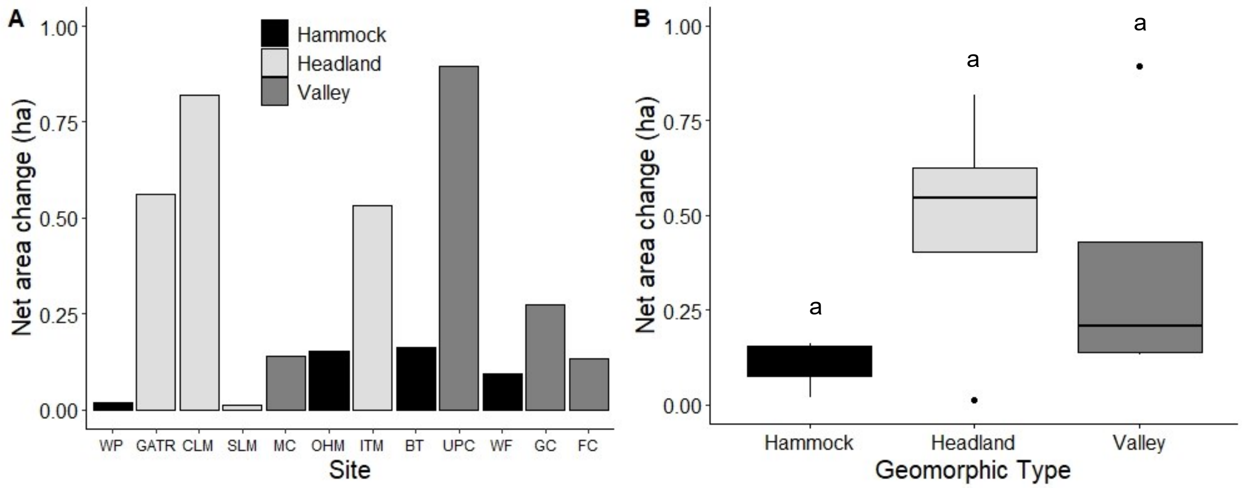
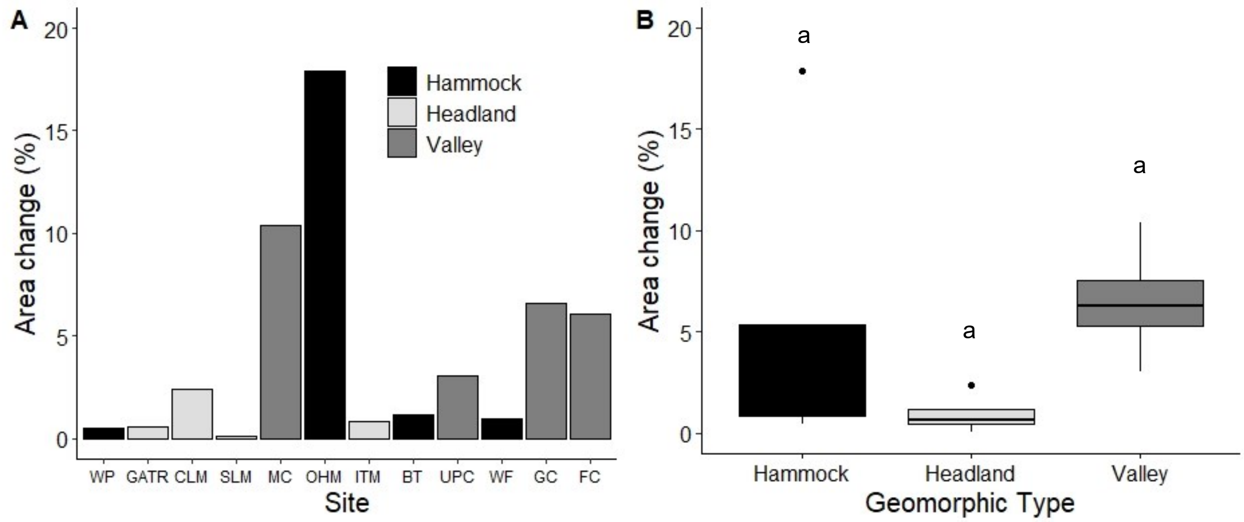

A
B
Hammock
Headland
Valley
Net area change (ha)
1.00
0.75
0.50
0.25
0.00
WP GATR CLM SLM MC OHM ITM BT UPC WF GC FC
Site
a
a
a
Hammock
Headland
Valley
Geomorphic Type

Figure 8


A
Hammock
Headland
Valley
Area change (%)
0
5
10
15
20
WP
GATR
CLM
SLM
MC
OHM
ITM
BT
UPC
WF
GC
FC
Site
B
a
a
a
Area change (%)
Hammock
Headland
Valley
Geomorphic Type