Mainland Seaside Salt Marsh Response and Resilience to Sea-Level Rise on The Eastern Shore of Virginia, USA

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ABSTRACT

Sea-level rise is a major threat to salt marsh persistence on the Eastern Shore of Virginia, an area experiencing relatively rapid rates of rising sea-levels. Salt marshes respond both vertically and laterally to persist and function as sea-levels rise. Salt marshes of differing geomorphologies may be responding to rising sea levels in different ways and at different rates due to variations in factors like protection from high-energy lagoonal events and wave energy. There is an increased interest in understanding how quickly mainland seaside salt marshes on the Eastern Shore of Virginia are changing in both elevation and area, and there is an interest in models that assess the resilience of salt marshes to rising sea-levels. The overarching goals of this study were to understand better how mainland seaside salt marshes on the Eastern Shore of Virginia respond to rising sea levels and to evaluate how resilient these marshes are to sea-level rise.

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 the Eastern Shore of Virginia. Using ArcGIS, it was found that all marsh types increased in spatial extent; increases were greatest for the valley type (0.58 ha ± 0.31 ha or + 0.32% per year). 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 response to sea-level rise, and the reliance of Eastern Shore of Virginia salt marshes on marsh migration to persist and function.

Elevations were measured between 1999 and 2019 through Real Time Kinematic surveys in nine mainland seaside salt marshes on the Eastern Shore of Virginia. Sites were classified as headland, valley, or hammock marsh types. The rates of elevation change were almost uniformly negative across all sites (-14.7 ± 1.2 mm yr^{-1} , mean ± SE). Elevation change rates differed among sites and among marshes based on geomorphic classification (hammock > valley > headland). The nearly uniformly negative rates of elevation change found here indicate that, perhaps, salt marshes on the Eastern Shore of Virginia rely primarily on lateral responses to sea-level rise to maintain area rather than vertical responses.

Using multiple indicators of marsh resilience, The Marsh Resilience to Sea-Level Rise (MARS) model was created to assess the resilience of these coastal wetlands to sea-level rise. The model was applied to nine salt marsh sites on the Eastern Shore of Virginia. Resilience scores were on a scale of 1 to 5, 1 indicating low resilience and 5 indicating high resilience. The model resilience scores suggested that nine study sites uniformly had low relative resilience to sea-level rise, ranging from -5.51 to 3.26, with an average index score of 0.06 ± 0.41. Mean resilience index scores at sixteen National Estuarine Research Reserve sites ranged from 1.06 to 4.1 with an average index score of 2.47 ± 0.24 (Raposa et al. 2016). The results of this study suggest that Eastern Shore of Virginia mainland salt marshes may be some of the least resilient marshes to SLR in the coastal United States. Further improvements to the MARS model should be made as

critical processes for marsh persistence, such as marsh migration into uplands, that tend to vary either by marsh or by marsh geomorphic type are not included in this model as it stands.

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Chapter 1.

Introduction

1.1 Background and Motivation

A majority of the coastal wetlands in the Mid-Atlantic region of the United States are salt marshes (Haaf et al. 2015). On Virginia's Eastern Shore, there are approximately 6,475 ha of salt marshes, equating to 20% of the area of the Eastern Shore (Glick et al. 2008). These wetlands provide a multitude of economically valuable ecosystem services including disturbance control, waste treatment, flood protection, positive contributions to rates of local fisheries productivity, and carbon sequestration (Craft et al. 2009, Haaf et al. 2015, Feagin et al. 2010). Because salt marsh ecosystems are uniquely situated at the interface between land and sea (Craft et al. 2009), their persistence is threatened by the rapid, current rate of sea-level rise. Therefore, if salt marshes do not persist in an environment of rising sea-level, the valuable ecosystem services they provide will be lost.

Throughout the coastal Mid-Atlantic, wetlands are disappearing due to rising sea-levels; however, sea-level is not rising at the same rate everywhere (Sallenger et al. 2012). The relative sea-level rise of an area is dictated by local factors such as land subsidence and accretion, isostasy, tectonic land movement, and water temperature (Eggleston and Pope 2013). The global average rate of sea-level rise is estimated around 3.1 mm yr^{-1}, but on the Eastern Shore of Virginia recorded rates of relative sea-level rise range from 4.28 to 5.37 mm yr^{-1} (Mariotti et al. 2010, NOAA Tides & Currents). Although this rate of relative sea-level rise may seem insignificant, in low topography coastal regions, like those of the Eastern Shore, even low rates of sea-level rise can have highly significant lateral effects that threaten the persistence of salt marsh ecosystems (Reed et al. 2008).

Text Box 1. Definitions

Persistence: The ability of the marsh to continue existing, either through maintaining or increasing in area over time.

Resilience: The ability of the marsh to remain in the same ecosystem state when exposed to chronic and acute disturbances.

For marshes to persist as sea-level rises, the rate of vertical growth of a marsh must equal or exceed the rate of relative sea-level rise (Cahoon et al. 1998) and/or lateral marsh migration (the conversion of uplands to salt marsh) must offset marsh area eroded or submerged (Cahoon et al. 1998). The rise of marsh surface elevation is caused largely by mineral sediment deposition and organic matter accumulation (Cahoon et al. 1998). Previous studies show that organic matter accumulation within marsh soil is a significant contributor to surface elevation change (Hatton et al. 1983, Bricker-Urso et al. 1989, Blum 1993, Callaway et al. 1997, Blum and Christian 2004, Chmura and Hung 2004). While surface sediment deposits are also significant contributors to the vertical increase of marsh elevation globally, below ground processes of organic matter accumulation can be of equal or greater importance, especially on the Eastern Shore of Virginia (Cahoon et al. 1998). Estimates are that up to 60% of elevation increases can be attributed to plant root growth in Virginia Coast Reserve (VCR) salt marshes (Blum 1993, Blum and Christian 2004). Both organic matter accumulation and surface sediment deposition that result in vertical change occur gradually and cumulatively.

In contrast to vertical change, migration events result from disturbances in upland vegetation such as intense storms (Cahoon et al. 1998). Thus, the rate of marsh migration is typically punctuated rather than constant because disturbance events that stress or kill upland vegetation allow marsh vegetation to capitalize and move inland (Cahoon et al. 1998). Typically, this process is comprised of a disturbance that allows marsh vegetation to jump forward to create a new equilibrium position with little change until the next disturbance event (Cahoon et al. 1998). It should be noted that relative sea-level rise is the driving force behind both marsh migration and elevation increase (Cahoon et al. 1998).

Although much of the literature indicates that marshes are extremely susceptible to submergence due to changes in relative sea-level, Kirwan et al. (2016) suggest that marsh vulnerability is overstated. These authors argue that often assessments of marsh vulnerability do not consider feedback processes that amplify soil deposition and marsh elevation increases, and thus, the potential for marshes to migrate. Additionally, these authors state that reports of complete marsh loss are rare except in locations where sediment supply to the coastal wetlands has been significantly reduced (Kirwan et al. 2016). This finding is significant to the VCR Long Term Ecological Research Program (LTER) because mainland marshes there have a naturally low sediment supply (Brinson et al. 1995), are subjected to frequent disturbance (Hayden and Hayden. 2003), and local sea-level rise is relatively rapid (Mariotti et al. 2010) such that marsh submergence due to sea-level rise is occurring simultaneously with migration (Brinson et al. 1995). Furthermore, individual marsh geomorphic types may respond differently to rising sea-levels, largely due to differences in protection and sediment inputs (Oertel and Woo 1994). The geomorphic setting of a marsh could be a simple, critical indicator of both upland migration and marsh edge erosion rates. Consequently, it is important to investigate the response of different marsh geomorphologies as to better be able to predict marsh response to sea-level rise.

The VCR has been recognized by a multitude of organizations (e.g. United Nations and U.S. Department of the Interior) as one of the last remaining examples of costal wilderness on the Atlantic coastline of the United States. Conserving the unique natural and economic value of these lands requires management tools to support sound land management decisions. One potential tool for land managers on the Eastern Shore to use to evaluate marsh persistence in the face of sea-level rise is the Marsh Resilience to Sea-Level Rise (MARS) model (Raposa et al. 2016), a model that uses quantitative multimetric indices to assess marsh resilience. This model is the first multimetric index model to be used for the purpose of evaluating and comparing relative wetland resilience. Historically, multimetric indices have been developed for benthic aquatic ecosystems to compare habitat quality across sites to inform management decisions (Diaz et al. 2004, Pinto et al. 2009). These indices are useful because they provide information on the system’s condition or status by incorporating several quantitative metrics, such as rates of marsh elevation change and local rates of sea-level rise, that each provide critical information on a characteristic or process of the system (Pinto et al. 2009). The MARS model has been applied to sixteen National Estuarine Research Reserve System (NERRS) marshes (Raposa et al. 2016), and in this thesis it was applied to nine mainland seaside marshes to understand the relative resilience of Eastern Shore of Virginia salt marshes.

1.2 Summary of specific research objectives

The research objectives of this thesis may be divided into two general questions: 1) do Eastern Shore of Virginia mainland seaside salt marshes in different geomorphic settings respond to sea-level rise in the same way and 2) how resilient are these marshes to sea-level rise. From these general questions the following specific questions emerged:

1) Do salt marshes in different geomorphic settings respond to sea-level rise in the same way?
    a. What are the rates of marsh surface elevation change in VCR mainland salt marshes?
    b. Are these rates different based on marsh zone, site, or salt marsh geomorphic classification (as defined by Oertel and Woo 1994)?
    c. What is the proportion of different marsh geomorphic types in the Virginia barrier island-coastal lagoon system?
    d. What are the rates of marsh migration and edge erosion in VCR mainland salt marshes?
    e. Are these rates different based on salt marsh geomorphic classification (as defined by Oertel and Woo 1994)?

2) How resilient are these marshes to sea-level rise?
    a. What is the relative resilience of the marshes in this study to sea-level rise according to the MARS model, and how do they compare to salt marshes across the coastal United States?

b. How useful is the MARS model as a marsh resilience assessment tool to be used locally by land managers on the Eastern Shore of Virginia? Are there ways to improve the model?

1.3 Approach

To assess whether marshes in different geomorphic settings respond similarly to sea-level rise, first, marshes of different mainland seaside salt marsh geomorphologies were identified using aerial imagery in GIS and the classification scheme outlined by Oertel and Woo (1994). Next, the rates of marsh elevation change (mm yr^{-1}), migration inland (ha m^{-1} yr^{-1}), and edge erosion (ha m^{-1} yr^{-1}) were measured and compared across the geomorphic types. Marsh elevation change was measured in nine sites through GPS RTK surveys using Trimble R10.2 survey equipment. Rates of marsh migration inland and edge erosion were measured in twelve sites, nine of which were the same marshes in which the RTK surveys were conducted, using aerial imagery from 2002 and 2017 in GIS. To assess the relative resilience of nine marshes on the Eastern Shore of Virginia to sea-level rise, the MARS model was utilized. This model incorporated local data for each site, including data that I collected during field work (elevation change rate (mm yr^{-1}), tidal range (m), mean high water (m), organic matter content of marsh soil (%)), as well as other, readily-available data such as local rates of sea-level rise (mm yr^{-1}). Resilience scores were compared among marshes on the Eastern Shore of Virginia, and to sixteen NERRS marshes throughout the coastal United States to better understand the context of the resilience scores and whether the model requires more information to improve resilience estimates.

1.4 Thesis organization

The chapters of my thesis take the form of several manuscripts. One of these manuscripts, Chapter 2, is currently in review. Each chapter of my thesis generally follows the format of a standard scientific article and each includes an independent abstract as well as an independent reference list. My thesis is comprised of five chapters. This chapter, Chapter 1, is an introduction to the thesis and lays out the research questions. Chapter 2 focuses on the lateral marsh response to sea-level rise and addresses questions 1c, 1d, and 1e. Chapter 3 focuses on the vertical marsh response to sea-level rise, addressing questions 1a and 1b. Chapter 4, includes the evaluation of a model designed to predict marsh resilience to sea-level rise and addresses questions 2a and 2b; data presented in Chapter 3 are used in the model. The discussion section of Chapter 4 integrates the findings presented in Chapters 2, 3, and 4. Given that each chapter was originally written to stand alone, some of the introductory material in each chapter is repetitive. The final chapter of this thesis, Chapter 5, is a short summary of the findings and conclusions of the previous chapters.

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Chapter 2.

Rates of mainland marsh migration into uplands and seaward edge erosion are explained by geomorphic type of salt marsh in Virginia coastal lagoons

J.A. Flester and L.K. Blum. *In review*. Rates of mainland marsh migration into uplands and seaward edge erosion are explained by geomorphic type of salt marsh in Virginia coastal lagoons.

2.1 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 Virginia coastal lagoon system. Treelines, shorelines, and marsh perimeters were delineated in ArcGIS. 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 yr^{-1}) more than the other two marsh types combined. This analysis demonstrates the critical influence that geomorphic type has on horizontal 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.

2.2 Motivation

Throughout the mid-Atlantic region of the USA, sea-level is rising at an increasing rate and coastal wetlands are disappearing simultaneously. Although 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} (NOAA https://www.climate.gov/new-features/understanding-climate/climate-change-global-sea-level). Along the Atlantic seaside of Virginia's Eastern Shore, relative rates of sea-level rise are more rapid than the global rate; recorded rates are 4.28-5.37 mm yr^{-1} (Mariotti et al. 2010, NOAA 2019). Although these rates of relative sea-level rise seem insignificant, they can have highly significant lateral 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 (Cahoon et al. 1998, Reed et al. 2008, Schieder et al. 2018). 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. Rates of mainland marsh migration throughout the eastern and southern coasts of the United States vary widely; from 0.1 m yr^{-1} to 6.78 m yr^{-1} (Table 2.1, and references cited therein).

Table 2.1. 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)
Virginia Coast Reserve, Virginia	12 km shoreline	N/A	1.0 – 1.6	N/A	(McLoughlin et al. 2015)

Although evidence of marsh migration is obvious in mainland marshes of the mid-Atlantic, Virginia lagoon systems (Figure 2.1a), these rates of migration have not been documented previously.

Figure 2.1. Evidence of (a) marsh migration and (b) edge erosion at the VCR, 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.

Erosion of marsh seaward edges is another key process impacting marsh persistence. To understand persistence in terms of marsh spatial extent, *viz.*, changes in net area of a marsh, both marsh gain (marsh migration) and marsh loss (edge erosion) must be considered (Fagherazzi et al. 2015). Others have reported the edge erosion rate to vary from 0.1 m yr^{-1} to over 3 m yr^{-1} (Table 2.1, 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 2.1b). Edge erosion is driven by land subsidence, sea-level rise, and wave energy. (Day Jr. et al. 1998, McLoughlin et al. 2015).

The processes that drive upland migration and edge erosion and the rates of each are different, therefore rates at one site cannot be used to predict rates at another site. Although drivers responsible for differences in the extent of marsh migration and edge erosion are widely accepted, one factor that has not been considered is the geomorphic setting. The geomorphic setting 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 the regime of increasing sea-level rise 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. Classification of

Virginia’s coastal-lagoon marshes include three main types: 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. A characteristic of marshes associated with the mainland is that they migrate landward as sea-level rises, particularly in settings where sediment supply is limited (Brinson et al. 1995). Oertel and Woo (1994) defined five mainland-fringe marsh geomorphic types: valley, headland, hammock, interfluve, and tidal channel 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 2.2).

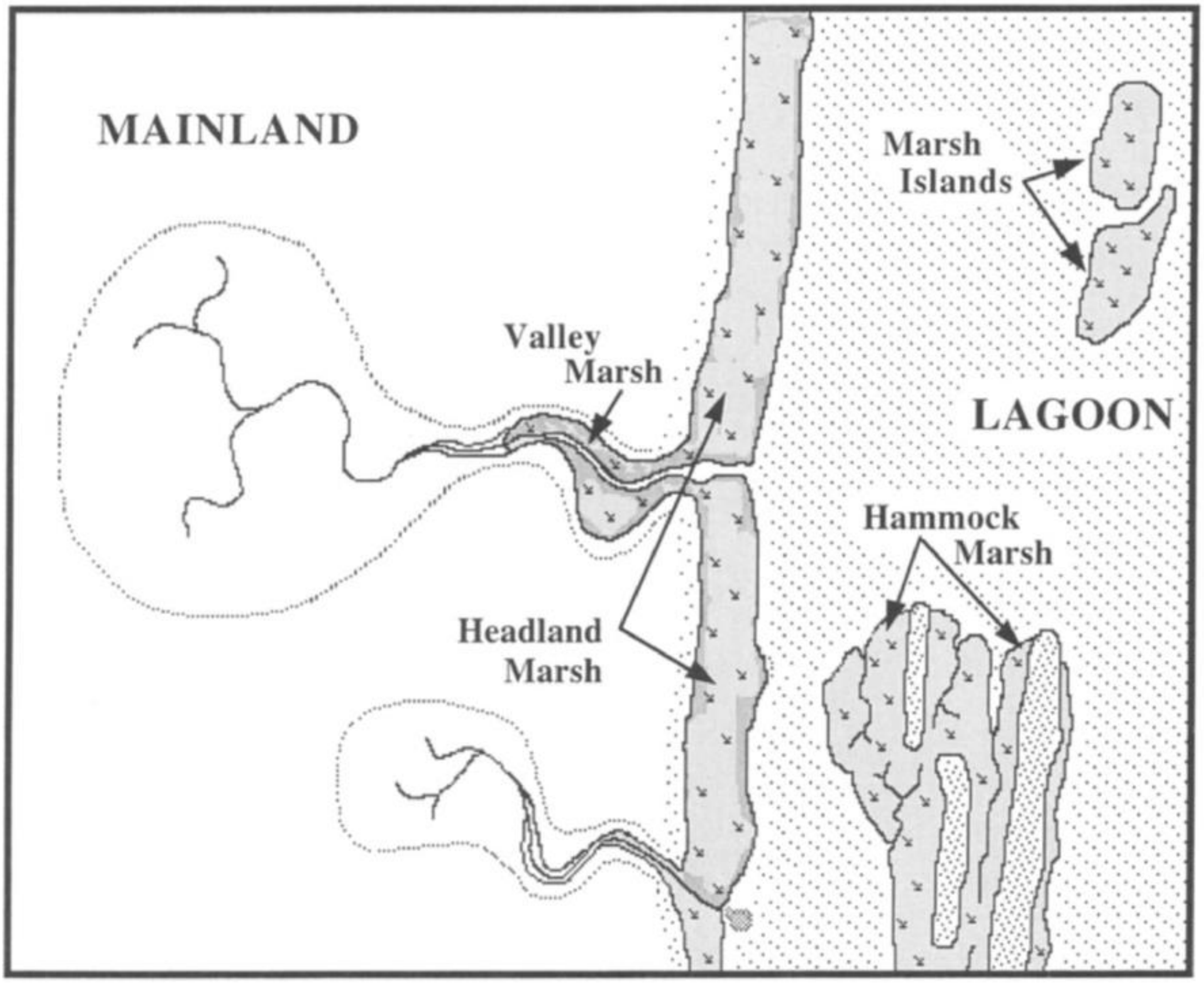

Figure 2.2. Schematic illustrating the morphology of valley, headland, and hammock marshes. Interfluve- and tidal channel-type marshes are not shown. Marshes indicated by gray shading, open water by diagonal stippling, mainland upland by white fill, and upland hammocks by closely-spaced random stippling. Note mainland parallel orientation of hammock and headland marshes and perpendicular orientation of valley drainage. From, Oertel and Woo (1994).

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 hammocks 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.

This study sought to determine the proportion of mainland valley, headland, and hammock marshes of the Virginia barrier island-coastal lagoon system; to document marsh migration and edge erosion rates of 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 geomorphic types Oertel and Woo (1994) with greatest exposure to open water would show equivalent rates of edge erosion and marsh migration, while marshes 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.

2.3 Approach

Site description

The Atlantic seaside of the lower, Virginia portion of the Delmarva Peninsula is a barrier island-coastal lagoon system that extends, generally north to south, 110 km from Chincoteague (the Maryland-Virginia border) south 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 2.3a).

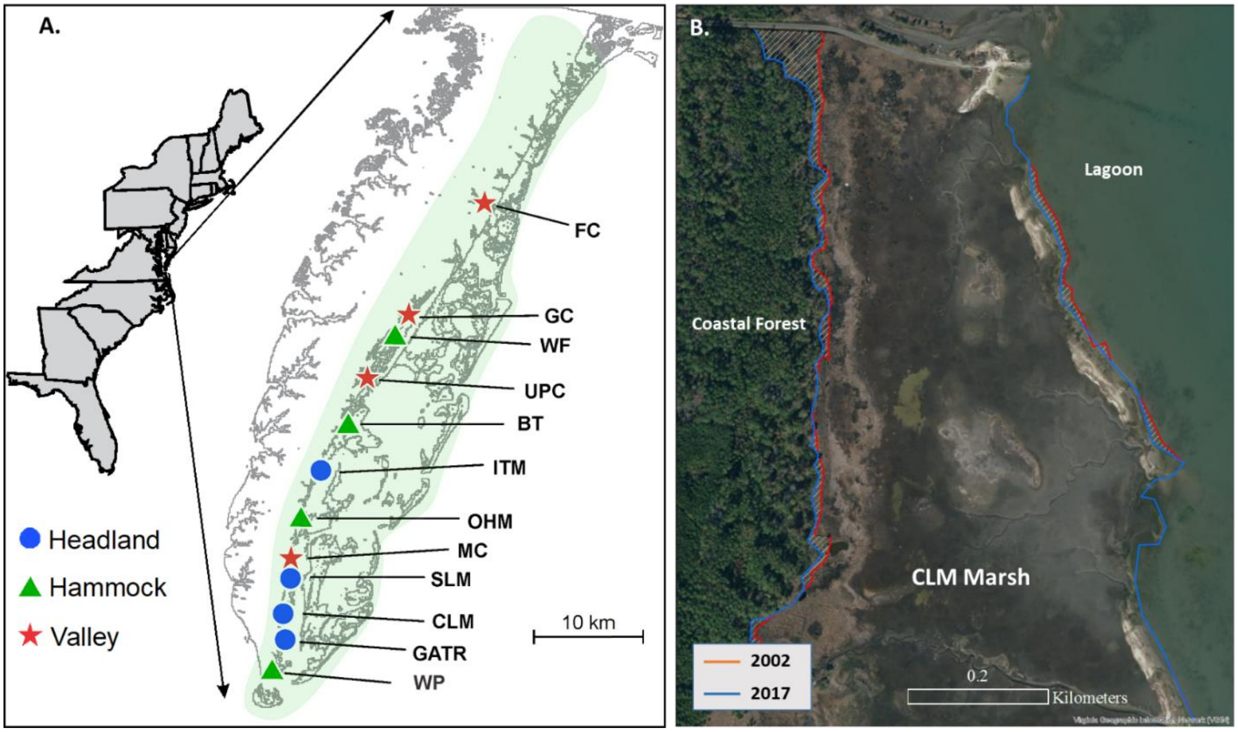

Figure 2.3. Geographic setting of (A.) the study sites at the Virginia Coast Reserve Long-Term Ecological Research site (VCR LTER), and (B.) ArcGIS delineated marsh migration and edge erosion between 2002 (red line) and 2017 (blue line) at Cushman's Landing Marsh (CLM). A. Grey inset is of the United 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. Imagery from the Virginia Base Map Program 2002 and 2017.

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 (https://www.census.gov/quickfacts/fact/table/northamptoncountyvirginia,accomackcountyvirginia, accessed 12-5-2019). 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 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 (Figure 2.3a, Table 2.2).

Table 2.2. Location, area, slope, and geomorphic type of marshes studied at VCR LTER.

Marsh	Latitude	Longitude	Area (ha)	Slope*	Geomorphic Type**
WP	37.13	-75.95	3.83	ND	Hammock
GATR	37.16	-75.94	102.01	0.00135	Headland
CLM	37.17	-75.94	34.08	0.00568	Headland
SLM	37.18	-75.94	16.65	0.00357	Headland
OHM	37.28	-75.92	0.86	0.01851	Hammock
MC	37.22	-75.93	1.35	ND	Valley
ITM	37.34	-75.90	65.05	0.02569	Headland
BT	37.39	-75.87	13.81	0.00251	Hammock
UPC	37.45	-75.83	29.18	0.00037***	Valley
WF	37.48	-75.81	9.67	0.00289	Hammock
GC	37.48	-75.81	4.16	0.00196	Valley
FC	37.69	-75.63	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

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. The remaining three sites were chosen randomly 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. The VBMP is part of the Virginia Information Technologies Agency

(VITA) Integrated Services Program (ISP). Statewide aerial imagery is collected on a four-year cycle through the VBMP and is available for download through the Virginia Geographic Information Network (VGIN) website (https://vgin.maps.arcgis.com).

Study sites were classified based on geomorphology using marsh geomorphic characteristics outline by Oertel and Woo (1994). From the Virginia-Maryland border in the north to Fisherman's Island at the southern tip of the Eastern Shore, only mainland marshes were classified. We considered the five types of mainland marshes described by Oertel and Woo (1994); headland, valley, hammock, interfluve, and tidal channel. Marshes located between valleys that drain into the lagoon, have direct exposure to the coastal bays, and that had an orientation parallel to the mainland were considered headland marshes. Valley marshes are marshes formed along stream channels, perpendicular to the shore, completely surrounded by the mainland, and well protected from open water. Hammock marshes occur between upland areas oriented parallel to the mainland. Interfluve marshes occur between streams at high elevations. Tidal channel marshes occur on the margins of tidal channels that scour and fill other areas of the lagoon system and do not adjoin upland areas. To distinguish tidal channels from tidal creeks, we considered tidal channels to be wider than 30 meters. Unlike tidal creeks, tidal channels are described as having a natural levee (Oertel and Woo 1994). Although tidal channel marshes are the largest category of mainland marsh, our focus on marsh migration into the terrestrial areas of the mainland allowed us to exclude tidal channel marshes from this analysis. The system-wide delineations of marsh area were done at a scale of 1:10,000, a higher resolution than has been previously used to determine marsh area (Schieder et al. 2018).

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 with a pixel resolution of 2 feet. Delineations were done for the twelve marsh sites used to determine rates of marsh migration and shoreline erosion.

The boundary between high salt marsh and forest was delineated by hand-digitizing 2002 and 2017 imagery and the area was determined between the 2002 and 2017 treelines (Figure 2.3b). Rates of marsh migration (ha m^{-1} yr^{-1}) were calculated by dividing the total area of marsh migration (ha) by the duration of the study period (15 years). The area of change was normalized to the length of 2002 treeline (m) because of the large difference among headland, valley, and hammock marshes. By normalizing to length of treeline, removed biases due to the large differences in the size of the marshes.

Edge erosion between 2002 and 2017 was determined by hand-digitizing 2002 and 2017 imagery (Figure 2.3b). 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} yr^{-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).

The change in the spatial extent of individual marshes could not be calculated by simple difference between shoreline erosion rates and marsh migration rates 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). To calculate the net change in individual marsh area over the 15-year study period, the area created by marsh migration of the treeline and the area lost due to shoreline erosion were determined in ArcMap by summing the areas between 2002 and 2017 treelines and their respective shorelines, and by difference the area gained (or lost) for each marsh was obtained. To allow for comparison among marshes of vastly different spatial extent, the 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 of 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, comparing them to printouts of the delineated boundaries. There were few discrepancies, but where differences were observed, the delineated boundaries were adjusted to account for field observations.

Data analysis

The marsh migration rate, edge erosion rate, and net change in marsh area 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. 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.

2.4 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 back-barrier 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). 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 (Figure 2.4a).

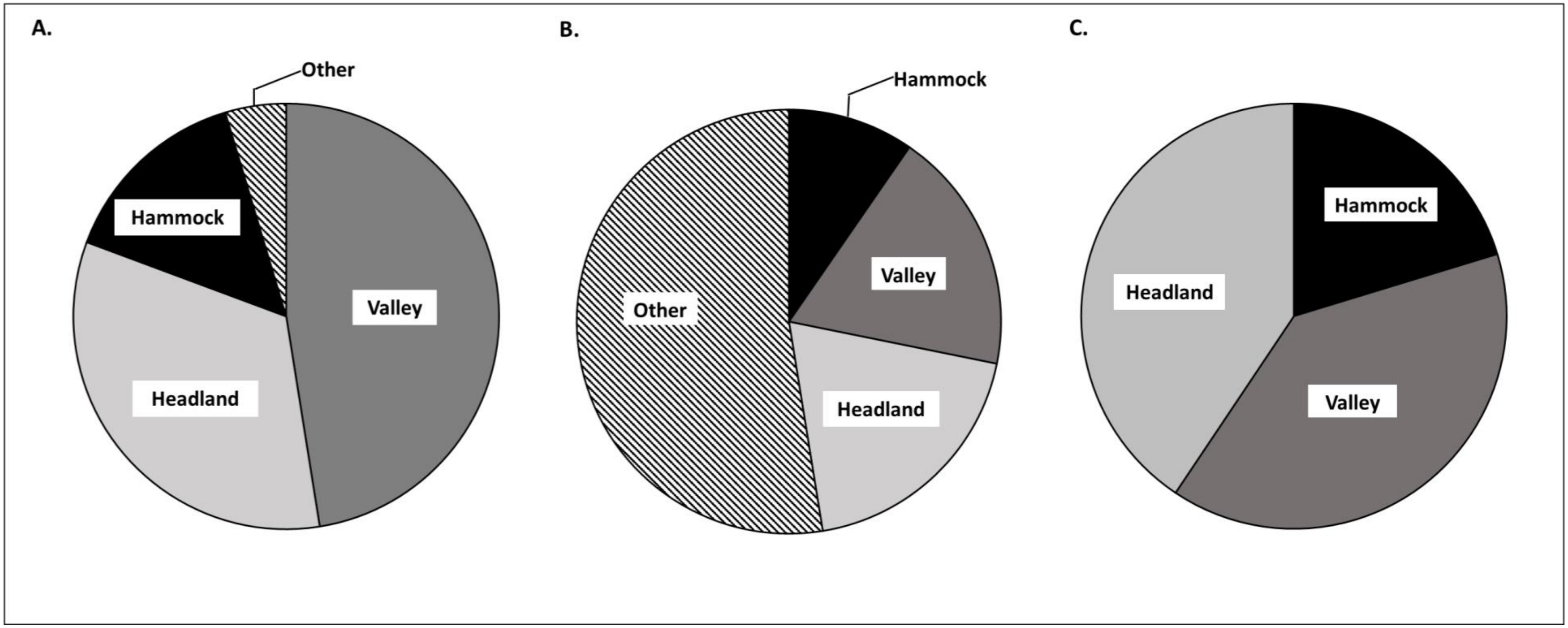

Figure 2.4. Distribution of marsh geomorphic types at the VCR LTER. “Other” includes interfluve and tidal channel marshes. (a) Abundance of mainland marsh geomorphic types. Valley, hammock, and headland marshes comprise 95% of the total number of mainland marshes at the VCR LTER. (b) Proportion of geomorphic types based on total marsh area within the VCR LTER. The “Other” category is 52.5% of the total area because tidal channel marshes are associated with each mainland geomorphic marsh types. (c) Proportion of geomorphic types based on total marsh area within the VCR LTER after removing the “Other” classification.

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) (Figure 2.4b). 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 (Figure 2.4c).

Marsh migration

Marsh migration into uplands occurred for all marshes examined regardless of geomorphic type (Figure 5a); 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 (Figure 2.5b).

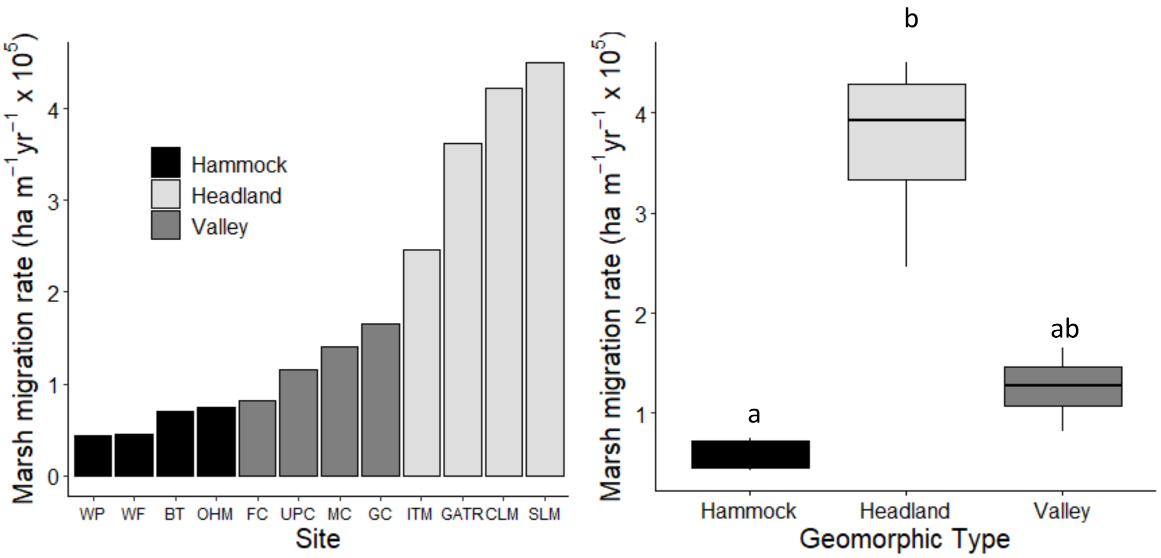

Figure 2.5. Comparison of marsh migration rates by study site (a) and by marsh type (b) with geomorphic type indicated. (a) X-axis labels indicate individual marsh acronyms. Marshes are arranged by migration rate. (b) Box plots of migration rates by marsh type. Quartiles are shown by box, and median 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 (α = 0.05) and post-hoc Dunn’s test (α = 0.025).

The rate of marsh migration was greater for headland marshes than for hammock marshes (Dunn’s post-hoc test, α = 0.025, p = 0.0009), while valley marshes were intermediate between the two. Marsh migration rates for headland marshes ranged from 2.46 x 10^{-5} to 4.5 x 10^{-6} ha m^{-1} yr^{-1} (mean ± SE, 3.7 x 10^{-5} ± 4.52 x 10^{-6} ha m^{-1} yr^{-1}); valley marshes from 8.13 x 10^{-6} to 1.65 x 10^{-5} ha m^{-1} yr^{-1} (1.25 x 10^{-5} ± 6.27 x 10^{-6} ha m^{-1} yr^{-1}); and hammock marshes from 4.30 x 10^{-6} to 7.48 x 10^{-6} ha m^{-1} yr^{-1} (5.85 x 10^{-6} ± 2.92 x 10^{-6} ha m^{-1} yr^{-1}) (Figure 2.5b).

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 (Figure 2.6a).

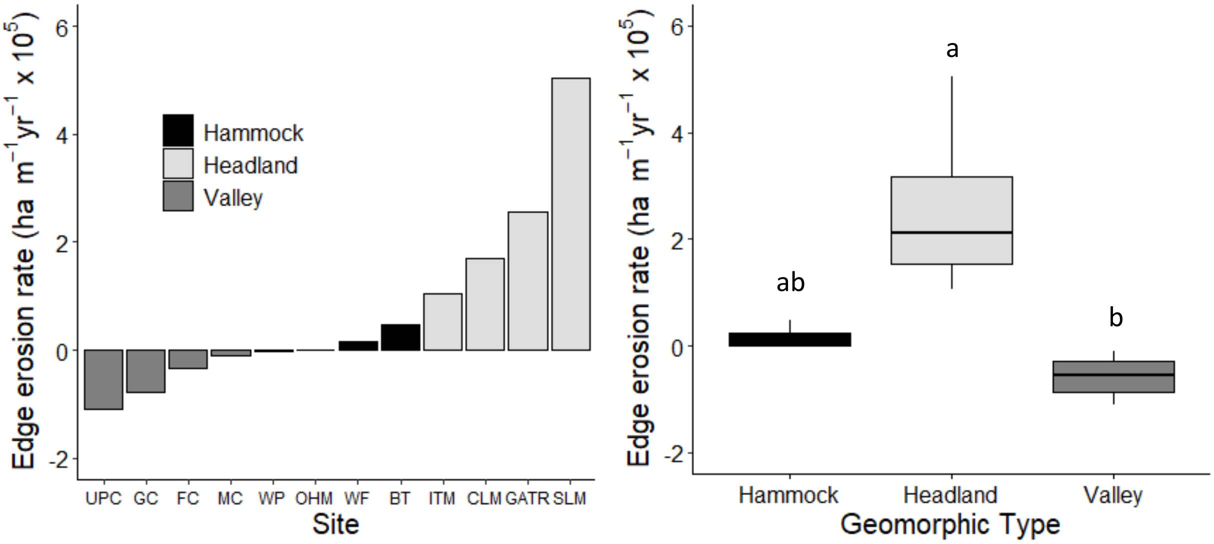

Figure 2.6. Comparison of edge erosion rates by study site (a) and by marsh type (b) with geomorphic type indicated. (a) X-axis labels indicate individual marsh acronyms. Marshes are arranged by edge erosion rate. Negative edge erosion is an increase in marsh area at the marsh edge. (b) Box plots of 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 ($\alpha = 0.05$) and post-hoc Dunn's test ($\alpha = 0.025$).

Although there was no detectable difference in the rates of erosion between headland and hammock marshes, the mean rate of headland erosion (2.58 x 10^{-5} ha m^{-1} yr^{-1}) was larger than that of hammock marshes (1.51 x 10^{-6} ha m^{-1} yr^{-1}). The wide range of erosion rates for headland marshes (1.05 x 10^{-5} to 5.04 x 10^{-5} ha m^{-1} yr^{-1}) likely is responsible for obscuring any 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, $\alpha = 0.025$, $p = 0.0016$) (Figure 2.6b). This is likely due to the lack of detectable edge erosion for the two 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} yr^{-1} (mean ± SE, $2.58 \times 10^{-5} \pm 8.73 \times 10^{-6}$ ha m^{-1} yr^{-1}) and hammock marshes from 0 to 4.77×10^{-6} ha m^{-1} yr^{-1} ($1.51 \times 10^{-6} \pm 7.56 \times 10^{-7}$ ha m^{-1} yr^{-1}). Valley marshes were characterized by negative rates of marsh edge erosion or, in other words, at the marsh edge subtidal sediments were converted to intertidal through accretionary processes during the study period. Edge erosion rates for the valley marshes ranged from -7.8×10^{-6} to -1.1×10^{-5} ha m^{-1} yr^{-1} ($-5.85 \times 10^{-6} \pm 2.92 \times 10^{-6}$ ha m^{-1} yr^{-1}) (Figure 2.6b).

Change in marsh spatial extent

All sites showed a net increase in marsh area over the study period (Figure 2.7a). In some cases, the increase during this time was small (e.g., 0.01 ha at Steelman's Landing) while the increase (0.89 ha) was largest at Upper Phillip's Creek (Figure 2.7a). 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) (Figure 2.7b).

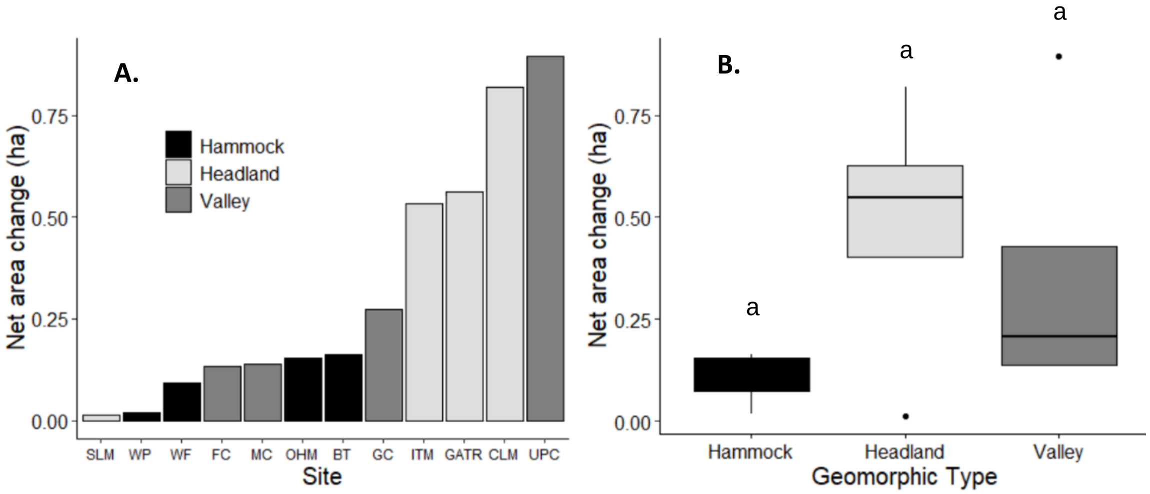

Figure 2.7. Comparison of change in marsh area by study site (a) and by marsh type (b) with geomorphic type indicated. (a) X-axis labels indicate individual marsh acronyms. Marshes are arranged by change in marsh area. (b) Box plots of change in marsh area by marsh type. Quartiles are shown by box, and 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.

When the mean change in area by marsh type was expressed as the percentage increase relative to the total marsh area in each marsh type, (Figure 2.8a) 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 (Figure 2.8b).

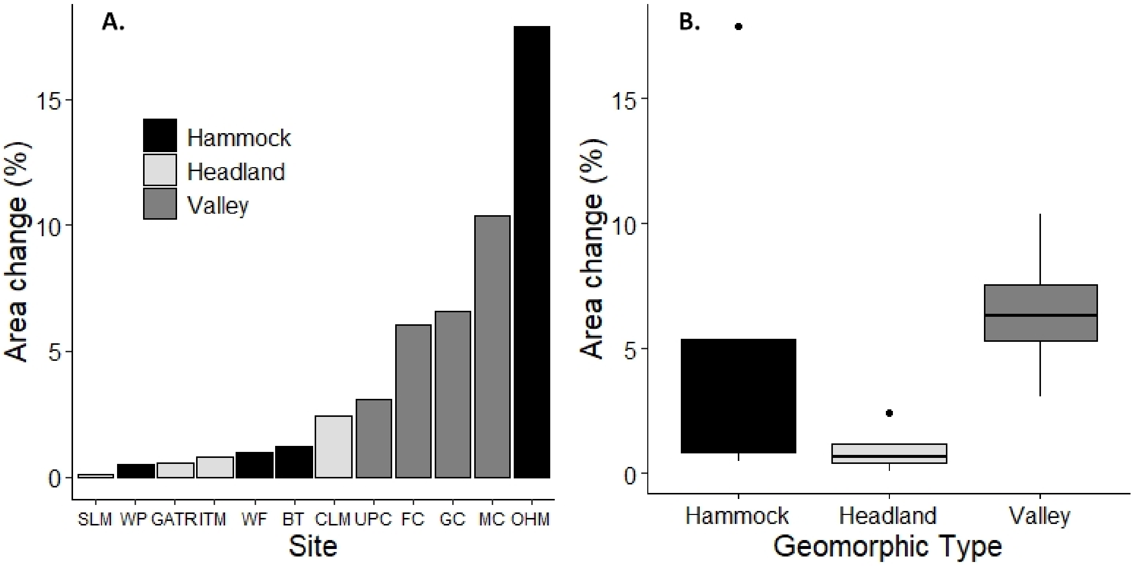

Figure 2.8. Comparison of area gained normalized by the size (area) of marsh in 2002 represented as a percent shown by (a) study site and (b) marsh type. (a) X-axis labels indicate individual marsh acronyms. Marshes are arranged by percent area change based on initial marsh size (2002). (b) Box plots 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 α = 0.05.

2.5 Discussion

Marsh migration and edge erosion are occurring throughout VCR LTER seaside mainland marshes at rates that result in net marshland increase (Figure 2.7). The 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 (Figure 2.5, Figure 2.6). The processes that resulted in net marsh increase did not occur equally across the three marsh types (Figure 2.7). Although 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 (Figure 2.7b).

The relationship between open water and the upland can influence the rates of both marsh migration and edge erosion. Differences in these rates are likely due to differences in the relative protection from adjacent lagoons from wind waves when tides are below the marsh plant rooting zone and high energy hurricanes and Nor'easters (McLoughlin et al. 2015). We found that headland marshes showed the highest rates of marsh migration, followed by valley marshes, and hammock marshes (Figure 2.5). 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 headward, creating dense drainage networks and allowing for more marsh migration than hammock marshes which do not show as dense drainage networks (May 2002). Hammock marshes are protected from lagoons and lagoonal events by a shoreline-parallel hammock of land which separates the marsh from the lagoon, making them less susceptible to marsh migration and edge erosion (Figure 2.5, Figure 2.6).

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 (Figure 2.6). This exposure allows for waves to undercut and erode the marsh edge, causing a lateral retreat and loss of marsh area at the marsh edge as described by McLoughlin et al. (2015). Hammock and valley marshes are distinguished from headland marshes in that they do not have a shoreline parallel to open water. In contrast, 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 less susceptible to edge erosion (Figure 2.6). 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. We do not see a similar gain in area at the marsh edge as in valley marshes because the tidal creek network is less dense in hammock marshes

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).

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).

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 (Figure 2.4 a,c), accounted for most of the regional marsh area increase. Regional headland marsh net area increase was low (Figure 2.7) due to the high rate of erosion along the marsh edge (Figure 2.6), even while the rate of headland marsh migration into uplands was high (Figure 2.5). 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 valley marshes are the most likely to persist at current rates of sea-level rise.

Although a gain in marsh area indicates persistence for mainland marshes, 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). Within the context of the greater VCR LTER marsh system, barrier islands and mid-lagoon marshes constituted 65% of the total marsh area loss from 1871 to 1962 (Knowlton 1971). More recent estimates of mid-lagoon marsh island loss range from 0.20% per annum (9% from 1949 to 1994) for Gull Marsh to 0.67% per annum for Curlew Bay Marsh, while gains of 0.09% per annum (4% from 1949 to 1994) were observed at Mockhorn Island (Erwin et al. 2004). Regional VCR LTER barrier island net marsh loss rates are 7.3%, or 970 ha over 32 years (0.23% per annum) (Zinnert et al. 2019). Indeed, Knowlton's analysis of marsh loss throughout VCR LTER lagoons suggests 18% marsh loss from 1871 to 1962 when sea-level rise rates were lower than current rates of sea-level rise.

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 (Boon et al. 2010), 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 have an expiration date that is controlled 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).

Most models predicting marsh persistence do not consider marsh geomorphic type, marsh migration, or edge erosion (Morris et al. 2002, Craft et al. 2009, Alizad et al. 2016, Raposa et al. 2016). Marsh persistence models tend to include input factors that are related to changes in the vertical dimension, such as: soil accretion rates, total suspended sediment load, soil organic matter content, tidal range, marsh elevation, hydrodynamics, and sea-level rise (e.g., Morris et al. 2002, Craft et al. 2009, Alizad et al. 2016, Raposa et al. 2016). Often, these models fail to include the importance of changes in the lateral dimension of marshes (marsh migration and edge erosion), leading to an incomplete understanding of marsh response and persistence (but, see Kirwan et al. 2016).

Additionally, many prediction efforts currently focus on regional scales, while land managers are frequently focused on local scale (individual marsh) persistence or restoration. 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 to support local 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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Chapter 3.

Vertical marsh response to sea-level rise in mainland seaside salt marshes on the Eastern Shore of Virginia, USA

3.1 Abstract

Salt marshes change both vertically and laterally to persist as sea-levels rise. Here, I investigated how salt marshes on the Eastern Shore of Virginia, a hot-spot for relative sea-level rise, have responded vertically to rising sea-levels. Between 1999-2019 elevations were measured through Real Time Kinematic (RTK) resurvey of known points measured in 1999 in nine mainland seaside salt marshes on the Eastern Shore of Virginia. The results of these surveys were used to examine marsh surface elevation change rates in four ways: (a) among marsh zones within individual marshes, (b) among marshes for individual zones, (c) among all nine sites (whole-marsh average rate of elevation change), and (d) among marshes based on geomorphic classification. The rates of elevation change were almost uniformly negative across all sites. Elevation change rates were different among marsh zones within three of the nine study sites, among all nine sites, and among marshes based on geomorphic classification. The nearly uniformly negative rates of elevation change found here indicate that, perhaps, salt marshes on the Eastern Shore of Virginia rely primarily on lateral responses to sea-level rise (i.e. salt marsh migration into uplands) to maintain area extent rather than vertical responses.

3.2 Motivation

A majority of the coastal wetlands in the Mid-Atlantic region of the United States are salt marshes (Haaf et al. 2015). On Virginia's Eastern Shore, there are approximately 6,475 ha of salt marshes, equating to 20% of the area of the Eastern Shore (Glick et al. 2008). These wetlands provide a multitude of economically valuable ecosystem services including disturbance control, waste treatment, flood protection, positive contributions to rates of local fisheries productivity, and carbon sequestration (Craft et al. 2009, Haaf et al. 2015, Feagin et al. 2010). Because salt marsh ecosystems are uniquely situated at the interface between land and sea (Craft et al. 2009), their persistence, i.e. their ability to exist in their current location and condition, is threatened by the rapid, current rate of sea-level rise. Therefore, if salt marshes do not persist in an environment of rising sea-level, the valuable ecosystem services they provide will be lost.

Throughout the Mid-Atlantic coast, wetlands are disappearing due to rising sea-levels; however, sea-level is not rising at the same rate everywhere (Sallenger et al. 2012). The relative rate of sea-level rise of an area is dictated by local factors such as land subsidence and accretion, isostasy, tectonic land movement, and water temperature (Eggleston and Pope 2013). The global average rate of sea-level rise is estimated around 3.1 mm yr^{-1}, but on the Eastern Shore of Virginia recorded rates of relative sea-level rise range from 4.28 to 5.37 mm yr^{-1} (Mariotti et al. 2010, NOAA Tides & Currents). While this rate of relative sea-level rise may seem insignificant, in low elevation, flat topography, coastal regions, like those of the Eastern Shore, even low rates of sea-level rise can have highly significant horizontal effects that threaten the persistence of salt marsh ecosystems (Reed et al. 2008).

For marshes to persist as sea-level rises, the rate of vertical growth and/or the lateral marsh migration inland must equal or exceed the rate of relative sea-level rise (Cahoon et al. 1998). The rise of marsh surface elevation is caused largely by mineral sediment deposition and organic matter accumulation (Cahoon et al. 1998). Previous studies show that organic matter accumulation within marsh soil is a significant contributor to surface elevation change (Hatton et al. 1983, Bricker-Urso et al. 1989, Blum 1993, Callaway et al. 1997, Blum and Christian 2004, Chmura and Hung 2004). Although surface sediment deposits are also significant contributors to the vertical increase of marsh elevation globally, belowground processes of organic matter accumulation can be of equal or greater importance, especially on the Eastern Shore of Virginia (Cahoon et al. 1998). Estimates are that up to 60% of elevation increases can be attributed to plant root growth in some Virginia Coast Reserve (VCR) salt marshes (Blum 1993, Blum and Christian 2004). Both organic matter accumulation and surface sediment deposition that result in vertical change occur gradually and cumulatively.

Although much of the literature indicates that marshes are extremely susceptible to submergence due to changes in relative sea-level, Kirwan et al. (2016) suggest that salt marsh vulnerability is overstated. These authors argue that often assessments of salt marsh vulnerability do not consider feedback processes that amplify soil deposition and marsh elevation increases, and thus, the potential for marshes to migrate inland. Additionally, these authors state that reports of complete marsh loss are rare except in locations where sediment supply to the coastal wetlands has been significantly reduced (Kirwan et al. 2016). This finding is significant to the VCR LTER because mainland marshes there have a naturally low sediment supply (Brinson et al. 1995), are subjected to frequent disturbance (Hayden and Hayden. 2003), and local sea-level rise is relatively rapid (Mariotti et al. 2010) such that marsh submergence due to sea-level rise is occurring simultaneously with migration inland (Brinson et al. 1995).

Furthermore, individual marsh geomorphic types may respond differently to rising sea-levels, largely due to differences in protection from waves and sediment inputs (Oertel and Woo 1994). Oertel and Woo (1994) defined five mainland-fringe marsh geomorphic types: valley, headland, hammock, interfluve, and tidal channel marshes (Figure 3.1).

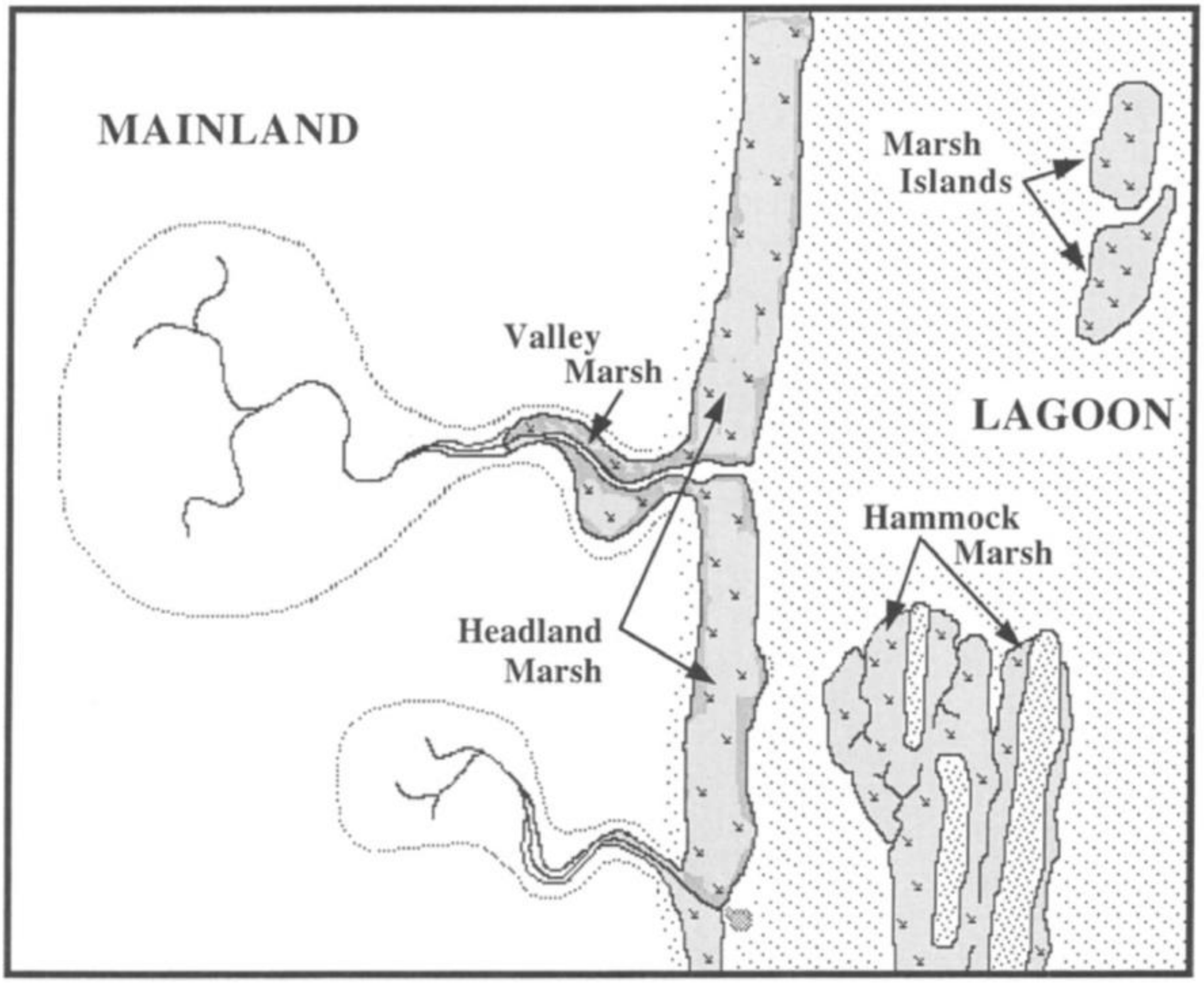


Figure 3.1. Schematic illustrating the morphology of valley, headland, and hammock marshes. Interfluve- and tidal channel-type marshes are not shown. Marshes indicated by gray shading, open water by diagonal stippling, mainland upland by white fill, and upland hammocks by closely-spaced random stippling. Note mainland parallel orientation of hammock and headland marshes and perpendicular orientation of valley drainage. From, Oertel and Woo (1994).

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. 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 hammocks 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. Tidal channel and interfluve marshes were not considered in this study, as site selection was limited to sites with elevation data records.

This study sought to address the following questions:

1. What are the rates of marsh surface elevation change in VCR mainland salt marshes?
2. Are these rates different based on marsh zone, site, or salt marsh geomorphic classification (as defined by Oertel and Woo 1994)?

3.3 Approach

Site descriptions and geomorphic classification

Nine marshes along the seaside coast of the lower Delmarva Peninsula, the VCR, were selected for this study: Greens Creek (GC), Woodland Farm (WF), UPC (Upper Phillip’s Creek), Boxtree (BT), Indiantown marsh (ITM), Oyster Harbor marsh (OHM), Steelman’s Landing marsh (SLM), Cushman’s Landing marsh (CLM), and GATR Tract (GATR) (Figure 3.2, Table 3.1, Appendix A).

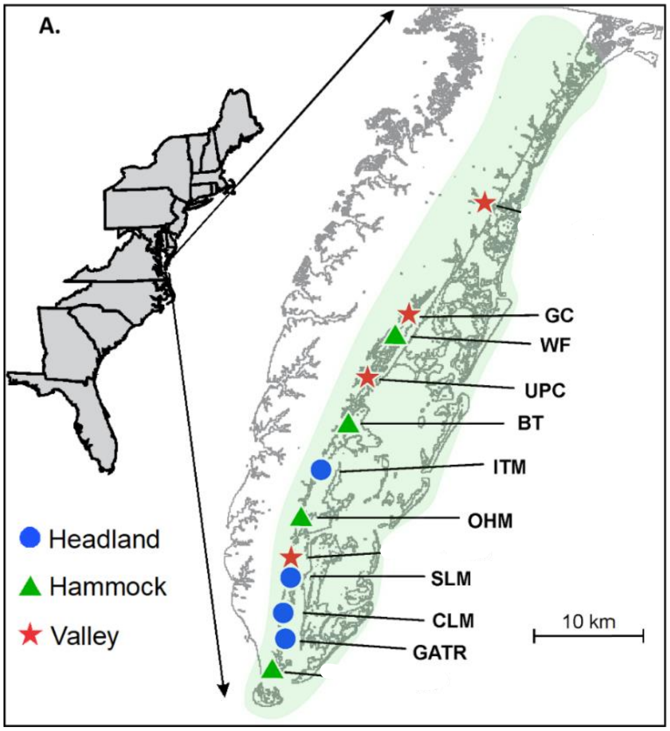


Figure 3.2. Geographic setting of the study sites at the Virginia Coast Reserve Long-Term Ecological Research site (VCR LTER). Gray inset is of the United States eastern coast. Expanded map is the Virginia Eastern Shore with the VCR LTER shaded green. Marsh study sites and geomorphic type are indicated with blue circles (headland), green triangles (hammock), and red stars (valley). Study site abbreviations are Greens Creek (GC), Woodland Farm (WF), UPC (Upper Phillip's Creek), Boxtree (BT), Indiantown marsh (ITM), Oyster Harbor marsh (OHM), Steelman's Landing marsh (SLM), Cushman's Landing marsh (CLM), and GATR Tract (GATR).

Table 3.1. Base station location, mean marsh surface elevation, and geomorphic type of marshes studied at VCR LTER from South to North.

Marsh	Location		Marsh surface elevation (m, NAVD88)*	Geomorphic Type*
	Latitude	Longitude		
GATR	37.16	-75.94	0.51	Headland
CLM	37.17	-75.94	0.79	Headland
SLM	37.18	-75.94	0.47	Headland
OHM	37.28	-75.92	0.56	Hammock
ITM	37.34	-75.90	0.58	Headland
BT	37.39	-75.87	0.79	Hammock
UPC	37.45	-75.83	1.43	Valley
WF	37.48	-75.81	0.73	Hammock
GC	37.48	-75.81	0.47	Valley

*based on GPS surveys done in 2016-2019
**based on Oertel and Woo (1994)

These sites were selected because they are geomorphically distinct, have been the focus of other studies carried out by the VCR LTER for over 30 years, and were the focus of an elevation RTK survey in 1999. Two valley marshes (Green's Creek and Upper Phillip's Creek), four headland marshes (Indiantown, Steelman's Landing, Cushman's Landing, and GATR Tract), and three marshes (Woodland Farm, Box Tree, and Oyster Harbor) were identified for this study using Virginia Base Mapping Program (VBMP) aerial imagery from 2002, in accordance with Oertel and Woo (1994) (Figure 2.1). For more information on how sites were classified based on geomorphology, see Chapter 2.

Real Time Kinetmatic (RTK) surveys

Rates of marsh surface elevation change were determined using Trimble R7 and Trimble R10.2 RTK survey equipment. Eight of the nine study sites (GATR Tract, Cushman’s Landing, Steelman’s Landing, Oyster Harbor, Box Tree, Indiantown, Woodland Farm and Green’s Creek) were surveyed (post-processed kinematic survey) in 1999 by C. Thomas (Thomas and Carlson 1999). Elevations and elevation change in Upper Phillip’s Creek marsh have been recorded since 1997 using surface elevation tables (SETs) (Cahoon et al. 2002, Lynch et al. 2015); additionally, marsh surface elevations were measured through laser-level survey in 1998 (Blum et al. *in press*). Re-survey of these nine sites in 2019 made it possible to determine the rate of surface elevation change for each marsh in this study.

RTK measurements were used to determine marsh surface elevation from high resolution benchmarks established previously in 1997 at Upper Phillip’s Creek (Carlson 2008) and 1999 at the other eight marshes in this study (Thomas and Carlson 1999). The GPS base station (Figure 3.3a.) includes an antenna that collects data from surrounding satellites once a survey is started.

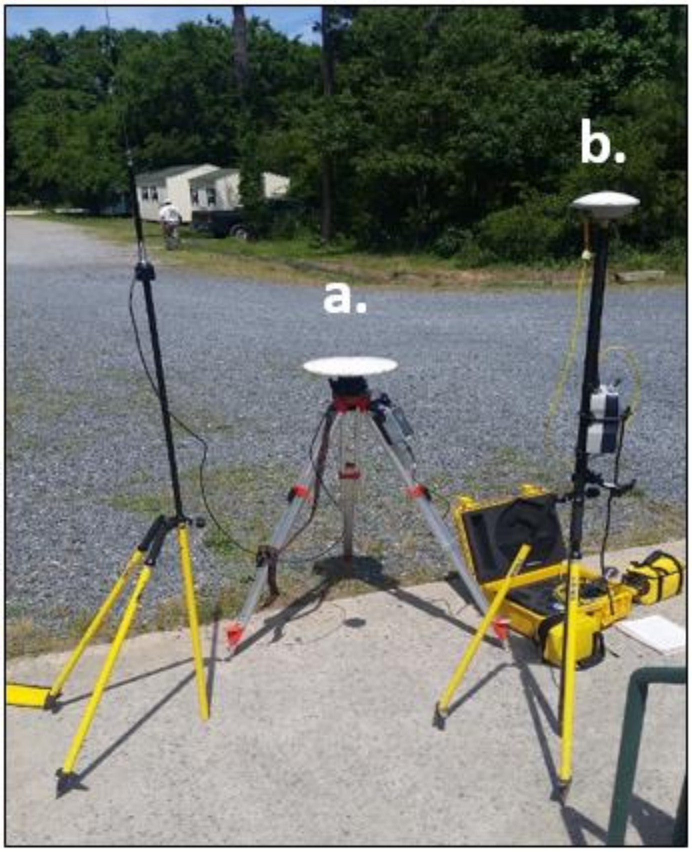
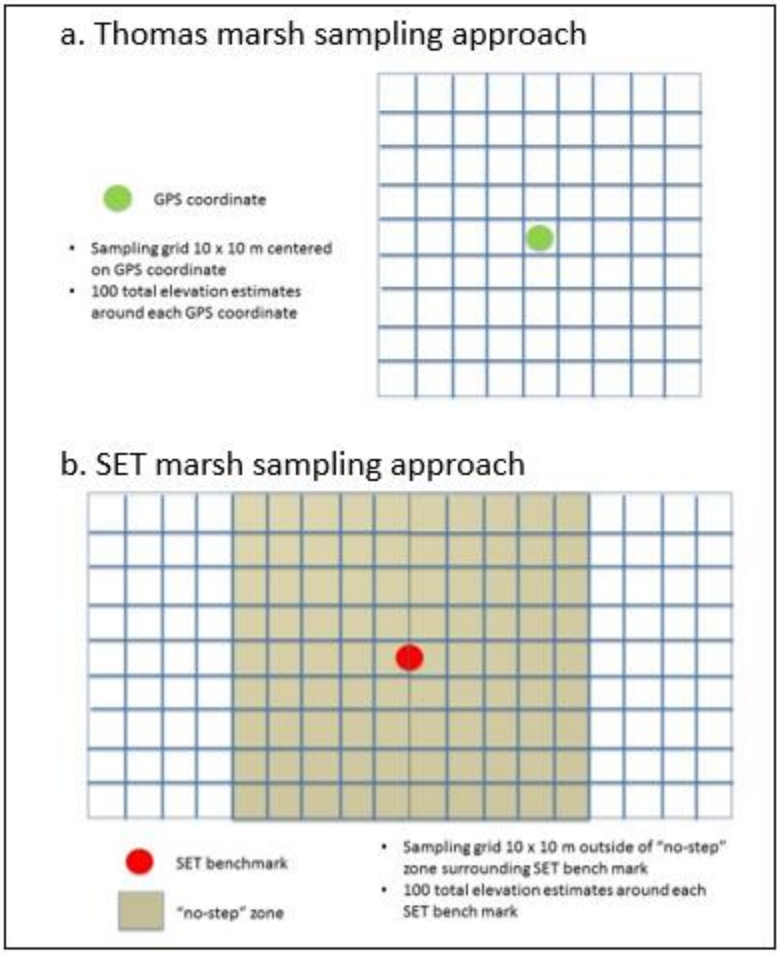


Figure 3.3. Trimble R7 GPS-RTK equipment; 3a shows the base station antenna, and 3b shows the rover unit.

The 2019 surveys were carried out for approximately 2 to 4 hours, in accordance with National Geodetic Survey (NGS) best practices (Gillins et al. 2019, OPUS) to obtain the x, y, and z coordinates of the base monument in each marsh. An RTK rover unit (Figure 2.3b.) was used to determine the elevations of previously surveyed areas in all marshes. The rover unit communicates with satellites and the base station to determine x, y, and z coordinates of the rover sampling points. The base station then records the data which are stored for subsequent processing. The data files collected were converted to an appropriate format using the Convert to RINEX tool and uploaded to the Online

Positioning User Service (OPUS) through the NGS. OPUS provides a solution of the submitted data via email (Appendix B). Note, that the elevation data collected in 1999 for these marshes used a different approach (post-processed kinematic survey) than was used in 2019 (RTK survey).

At all marshes except for UPC, 10 x 10-m plots were centered on sample points previously established in these marshes in 1999 by Thomas (Figure 3.4a; Thomas and Carlson 1999). To find these points, a handheld GPS unit was used (Garmin GPSMAP 78s). Next, the corners of the 10 x 10-m plots were marked with PVC pipes driven into the soil. Because the horizontal accuracy of each GPS point recorded by Thomas was ± 10 m, the expectation was that the 10 x 10-m plots should include the point surveyed in 1999 within the plot. The elevation of 100 points, spaced approximately 1 meter apart, were collected within each plot using the RTK equipment.


a. Thomas marsh sampling approach

b. SET marsh sampling approach

Figure 3.4. Marsh surface elevation sampling approach for a) the marshes included in the 1999 elevation survey by Cassondra Thomas and b) SET sites in Upper Phillip's Creek Marsh (UPC).

In Thomas's 1999 survey, 12 to 16 elevation points were established throughout the creek, low, high, and transition zones of each marsh (Figure 3.5). Therefore, using the grid sampling design (Figure 3.4a) between 1200 and 600 elevation points were surveyed per marsh.

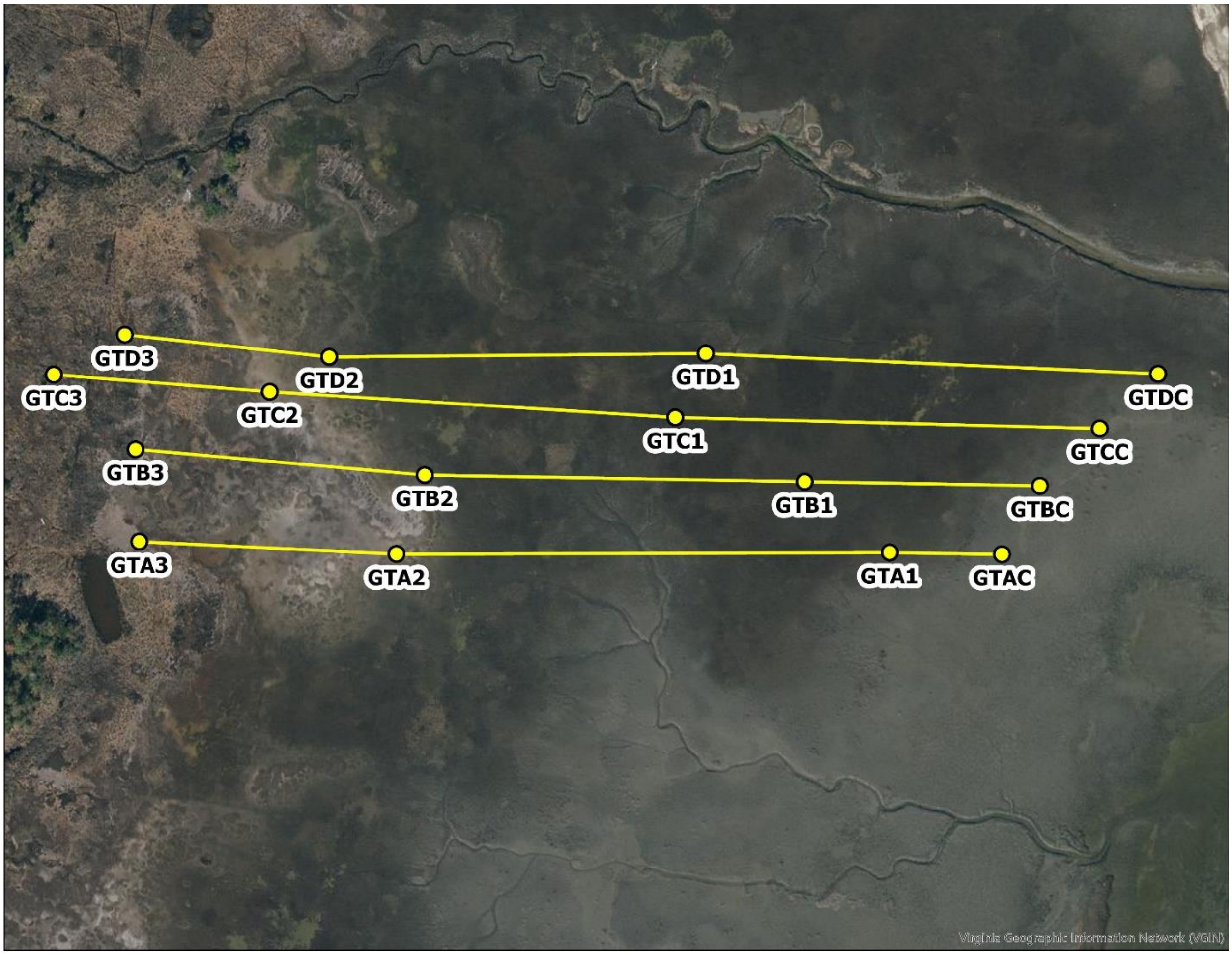


Figure 3.5. Four elevation sampling transects in GATR Tract (GT) marsh (A, B, C, and D). Each transect included one sampling point in the creek zone (C), low marsh zone (1), high marsh zone (2), and forest transition zone (3). This transect approach was used in all study sites.

All of the elevations measured within each grid were averaged to create a single elevation point to allow for a direct comparison to corresponding elevation point from 1999. To determine elevation change, the elevation measured in 1999 was subtracted from the mean elevation of the 100 grid points measured during this study. To obtain the rate of elevation change, the elevation change during the 20-year interval was divided by the time between elevation measurements. Additionally, the rate of elevation change was also determined for each point from 1999 by comparing the elevation of that point to the elevation of the nearest grid point surveyed 2019. Thus, rates of elevation change for each survey point were determined by grid-averaged rates of change and nearest-point rates of change.

The results of paired t-tests comparing grid-averaged rates of elevation change and nearest-point average rates of change within each marsh showed that the two methods for determining rates of elevation change were comparable (Appendix C) (no statistical difference was detected), aside from in Box Tree marsh where in the creek zone, grid-averaged rates of elevation change were positive (mean of 6.94 mm yr^{-1}) and nearest-point average rates of elevation change were negative (-8.02 mm yr^{-1}). Based on field observations, this was likely because the creekbank at this site is steep and the elevation grids in the creek zone at this site included both the areas of the steep creekbank that were eroding into the creek and higher elevation areas directly adjacent to the creekbank.

For the remainder of this chapter, results of the grid-averaged rates of elevation change are reported and discussed because the grid-averaged and nearest-point rates of elevation change were comparable.

At Upper Phillip’s Creek, the elevation survey locations were based around the nine pre-existing marsh Surface Elevation Tables (SET) where marsh-surface elevation is measured at least annually in the low, mid, and high marsh zones. There are three SETs in each marsh zone. To avoid disturbing the marsh surface and compromising future SET data by stepping within the SET boundaries, a 10 x10-m plot was created near each SET

(Figure 3.4b). Within each plot, 100 elevation points were collected at roughly 1m intervals (900 elevation data points total) (Figure 3.4b).

Data Analysis

The elevation rate-of-change data met assumptions of homogeneity of variance (Brown and Forsythe tests, $\alpha = 0.05$, $p > 0.05$) and normality of distribution of residuals (Shapiro-Wilk tests, $\alpha = 0.05$, $p > 0.05$) to allow analysis by ANOVA tests. One-way ANOVA analyses were used to determine statistical differences in: rates of elevation change by marsh zone within each study site, rates of elevation change by marsh zone, rates of elevation change by marsh geomorphic classification, and rates of elevation change by study site. A two-way ANOVA test was used to determine statistical differences in rates of elevation change by marsh zone and marsh geomorphic type. The ANOVA analyses showing statistical differences at the $\alpha = 0.05/n$ level (Bonferroni adjustment where n = the number of comparisons) were followed by a Tukey HSD post-hoc analysis to determine which combination of comparisons were different. Statistical Analysis System (SAS version 9.4) was used for all statistical analyses.

3.4 Results

Rates of elevation change were examined in four ways: (a) among marsh zones within individual marshes, (b) among marshes for individual zones, (c) among all nine sites (whole-marsh average rate of elevation change, obtained by taking the mean of all measured rates of elevation change for a single marsh, e.g. between 900 and 1600 individual measurements), and (d) among marshes based on geomorphic classification. The rates of elevation change were almost uniformly negative across all sites. Elevation change rates were different based on site and geomorphic classification. In some cases, rates of elevation change were different based on marsh zone.

Elevation change rates

Rates of elevation change were mostly negative in all marsh zones at all sites (Table 3.2); the only sites that showed positive rates of elevation change were in Upper Phillip's Creek (all zones), Box Tree (creek zone), and Indiantown (creek and low zones) (Table 3.2).

Table 3.2. Mean rates and standard errors of marsh surface elevation change (mm yr^{-1}) within each marsh zone at all marsh study sites.

Marsh	Marsh Zone				
	Creek	Low	Mid	High	Transition
Green's Creek	-16.0±5.2	-13.2±3.5	N/A	-18.9	-23.4
Woodland Farm	-13.9±1.6	-12.3±1.7	N/A	-15.9±1.6	-16.1±0.7
Upper Phillip's Creek	N/A	13.4±0.2	20.1±4.6	27.6±2.1	N/A
Box Tree	6.9±5.2	N/A	N/A	-6.3±0.3	N/A
Indiantown	14.1±1.1	1.2±3.5	N/A	N/A	-14.1±10.0
Oyster Harbor	-4.4±7.5	-4.8±3.2	N/A	-5.2±3.8	-12.1±11.7
Steelman's Landing	-33.0±6.4	-25.4±1.4	N/A	-31.6±2.0	N/A
Cushman's Landing	-16.4±4.0	-21.9±2.5	N/A	-18.7±0.6	-22.3±1.4
GATR Tract	-20.0±2.0	-21.9±0.5	N/A	-25.6±0.6	-26.7±0.9

Elevation change rates across all marshes ranged from -33.0 mm yr^{-1}, at Steelman's Landing, to +27.6 mm yr^{-1}, at Upper Phillip's Creek (Table 3.2). The mean elevation change rate in each marsh zone across all sites was: -10.3 ± 5.3 mm yr^{-1} in the creek zone, -13.9 ± 4.7 mm yr^{-1-} in the low marsh, 20.1 mm yr^{-1} in the mid marsh, -15.1 ± 6.6 mm yr^{-1} in the high marsh, and -20.9 ± 2.6 mm yr^{-1} in the transition zone. Upper Phillip's Creek was the only marsh where elevation change rates were positive in all three zones where elevations were measured in 1997 and 2019.

Rates of elevation change among zones within individual marshes

Three of the nine study sites showed differences in rates of elevation change by marsh zone: GATR Tract (headland), Box Tree (hammock), and Upper Phillip's Creek (valley). In GATR Tract, creekbank rates of elevation change (-20.0 ± 2.0 mm yr^{-1}) were significantly lower in magnitude than rates of elevation change in the high (-25.6 ± 0.6 mm yr^{-1}) and transition (-26.7 ± 0.9 mm yr^{-1}) zones (Figure 3.6). Rates of elevation change became more negative moving from the creek to the forest transition.

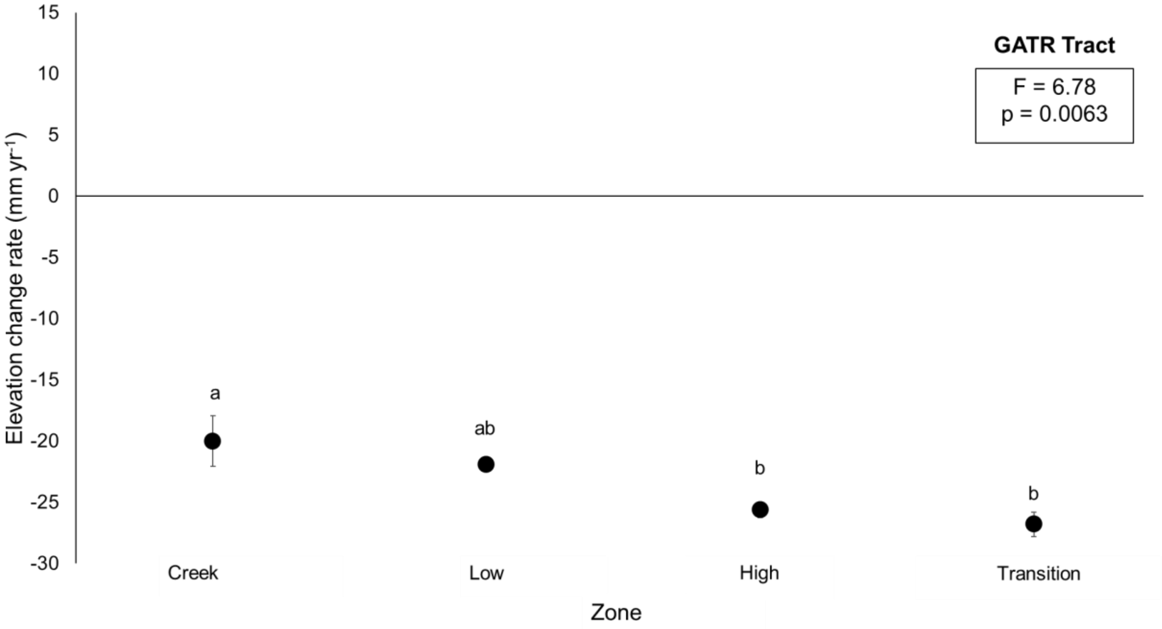


Figure 3.6. Mean rates of elevation change by marsh zone in GATR Tract marsh. Error bars indicate standard error. In the low and high marsh zones, error bars are obscured by the data points. The X-axis labels show the different marsh zones, ordered from creekbank to transition into upland forest. The ANOVA and Tukey HSD post-hoc testing indicated that rates of elevation change in the creek zone were significantly different from rates of elevation change in the high and transition zones. ANOVA results are shown on the figure (df = 15, F = 6.78, α = 0.0083, p = 0.0063) and Tukey results are indicated by letters above the data points. Data points with different letters indicate significant differences.

In Box Tree marsh, creekbank rates of elevation change (6.9 ± 5.2 mm yr^{-1}) were significantly different than rates of elevation change in the high (-6.3 ± 0.3 mm yr^{-1}) marsh zone (Figure 3.7). Similar to GATR Tract, Box Tree rates of elevation change became more negative moving from the creek to the forest transition.

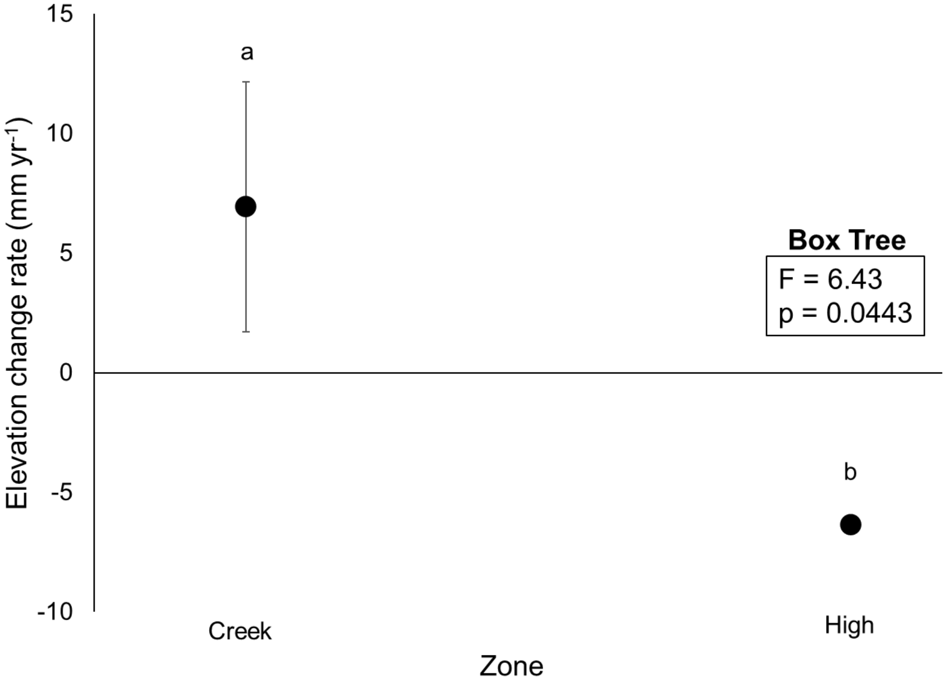


Figure 3.7. Mean rates of elevation change by marsh zone in Box Tree marsh. Error bars indicate standard error. In the high marsh, error bars are obscured by the data points. The X-axis labels show the different marsh zones, ordered from creekbank to high marsh. The ANOVA and Tukey HSD post-hoc testing indicated that rates of elevation change in the creek zone were significantly different from rates of elevation change in the high zone. ANOVA results are shown on the figure (df = 7, F = 6.43, α = 0.05, p = 0.0443) and Tukey results are indicated by letters above the data points. Data points with different letters indicate significant differences at the alpha = 0.05 level.

None of the other study sites showed differences in rates of elevation change by marsh zone ($\alpha = 0.05/n$, $p > 0.05/n$). Although the remaining six study sites did not show statistically significant differences in elevation change by marsh zone, they did show trends similar to Box Tree and GATR Tract, with elevation change rates becoming increasingly negative moving from the creekbank to the forest transition zone (Table 3.2).

Rates of elevation change among marshes for individual marsh zones

Upon initial investigation, rates of elevation change were different based on marsh zone. The middle-marsh zone, a zone specific to Upper Phillip's Creek marsh, showed significantly higher rates of elevation change (df = 10, F = 4.45, α = 0.005, p = 0.0024) compared to all other marsh zones (Figure 3.8a). Upper Phillip's Creek showed high rates of elevation change, therefore zone rates of elevation change were compared across marshes omitting Upper Phillip's Creek. After omitting Upper Phillip's Creek from the analysis, no differences in elevation change rates by marsh zone were detected (Figure 3.8b).

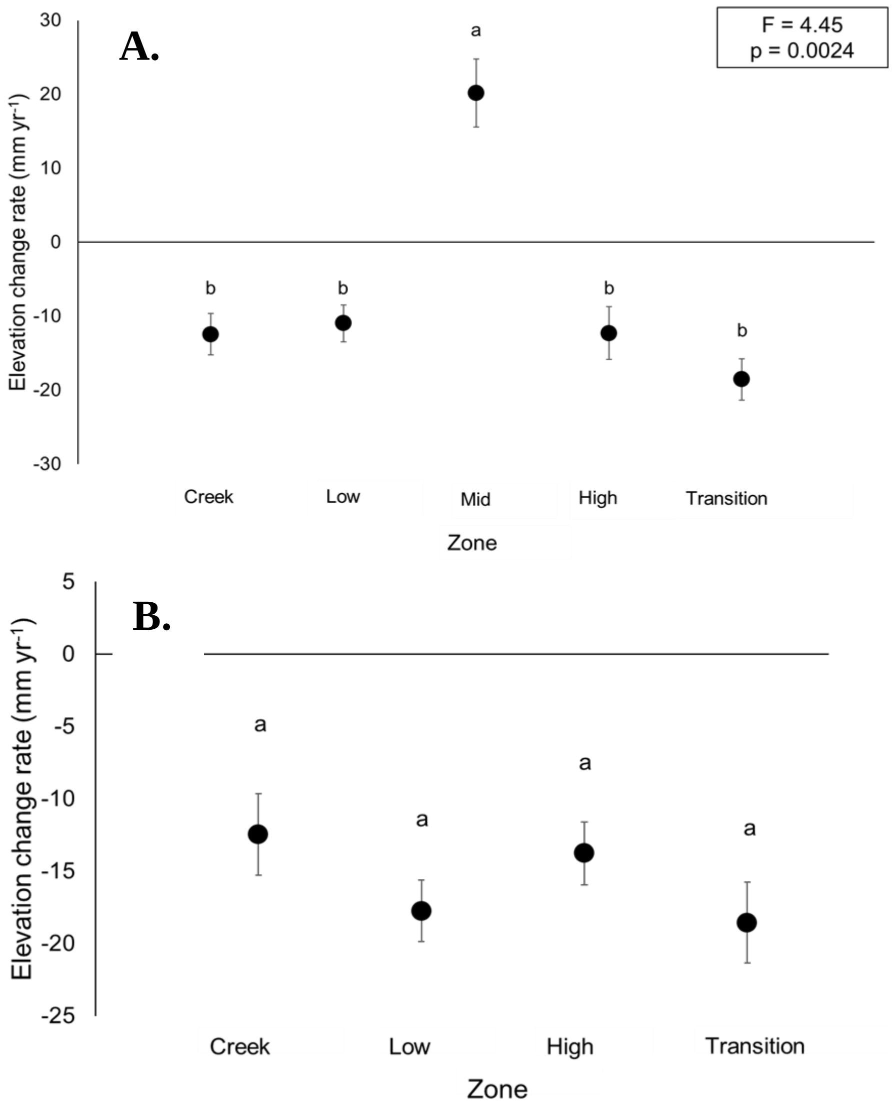


Figure 3.8. (A) Mean rates of elevation change by marsh zone in all sites. Error bars indicate standard error. X-axis labels show the different marsh zones, ordered from creekbank to transition into upland forest. The ANOVA and Tukey HSD post-hoc testing indicated that rates of elevation change in the mid zone (an Upper Phillip's Creek specific zone) were significantly different from rates of elevation change in all other zones. The ANOVA results are shown on the figure (df = 102, F = 4.45, p = 0.0024) and Tukey results are indicated by letters above the data points. Data points with different letters indicate significant differences. (B) Mean rates of elevation change by marsh zone in all sites except Upper Phillip's Creek. Upper Phillip's Creek was removed for this analysis because it showed significantly higher rates of elevation change (see Figure 3.10, Table 3.2). Error bars indicate standard error. X-axis labels show the different marsh zones, ordered from creekbank to transition into upland forest. No significant differences in rates of elevation change by zone were detected.

Rates of whole-marsh elevation change among all marshes

Mean rates of whole-marsh elevation change were nearly all negative across the nine study sites; only two sites, Box Tree and Upper Phillip's Creek, showed positive mean rates of elevation change (0.2 ± 3.4 mm yr^{-1} and 20.4 ± 2.5 mm yr^{-1} respectively). (Figure 3.9).

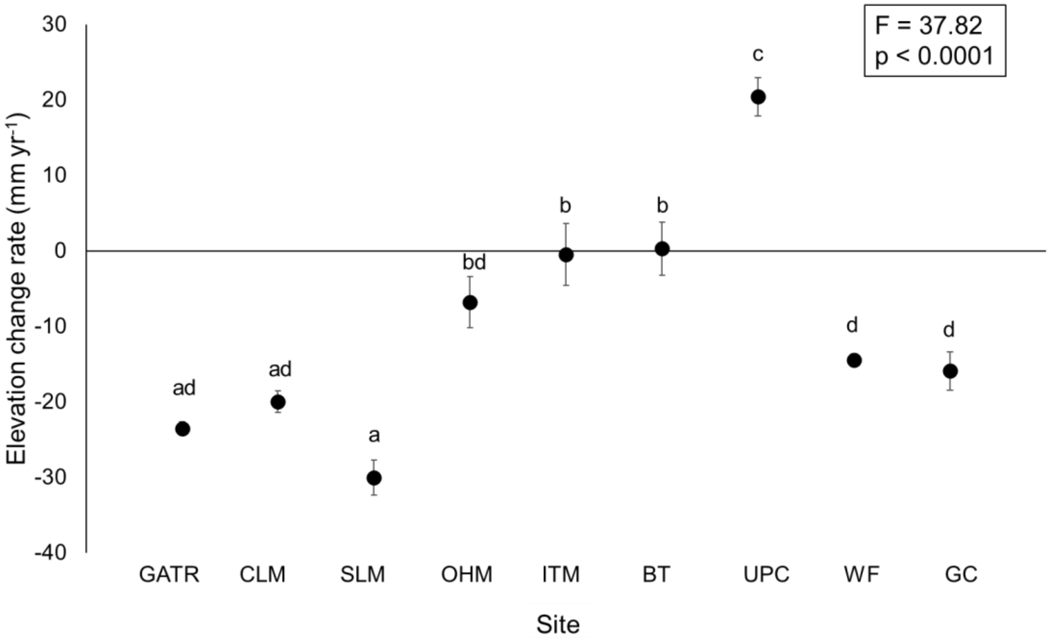


Figure 3.9. Mean rates of elevation change by study site. Error bars indicate standard error. In the cases of GATR and WF, error bars are obscured by the data points. The X-axis labels show the different marsh study sites, ordered from South to North. The ANOVA results are shown on the figure (df = 102, F = 37.82, α = 0.00138, p < 0.0001). Tukey HSD post-hoc results are indicated by letters above the data points. Data points with different letters indicate significant differences.

Elevation change rates in Upper Phillip's Creek (20.4 ± 2.5 mm yr^{-1}) were significantly different than the elevation change rates in all other study sites. Box Tree (0.2 ± 3.4 mm yr^{-1}), Indiantown (-0.4 ± 4.0 mm yr^{-1}), and Oyster Harbor (-6.8 ± 3.3 mm yr^{-1}) had the next most positive rates of elevation change, with both Indiantown and Box Tree showing rates of elevation change close to zero. Steelman's Landing (-30.0 ± 2.3 mm yr^{-1}), GATR Tract (-23.5 ± 0.8 mm yr^{-1}), and Cushman's Landing (-19.9 ± 1.4 mm yr^{-1}) had the most rapid rates of elevation loss over the study period. Woodland Farm (-14.5 ± 0.8 mm yr^{-1}) and Green's Creek (-15.9 ± 2.5 mm yr^{-1}) had intermediate rates of elevation loss that were not significantly different from GATR Tract, Cushman's Landing, or Oyster Harbor.

Rates of whole-marsh elevation change among geomorphic marsh types

Rates of marsh elevation change were significantly different among the three geomorphic types (df = 102, F = 18.93, $\alpha = 0.016$, $p < 0.0001$) (Figure 3.11a). The rates of elevation change were low, but positive, for valley marshes (1.2 ± 4.6 mm yr^{-1}), while hammock marshes lost elevation (-8.4 ± 1.7 mm yr^{-1}) but at a slower rate than headland marshes (-20.0 ± 1.7 mm yr^{-1}). This analysis was also done with Upper Phillip's Creek data removed because rates of elevation change were much higher than all other sites surveyed (Figure 3.9). It is important to note that only one valley marsh, Green's Creek, was then used in this analysis to represent the valley marsh classification. Rates of elevation change were still significantly different among the three geomorphic types (df = 93, F = 10.92, $\alpha = 0.016$, $p < 0.0001$), but the only difference detected was between headland and hammock marshes (Figure 3.10b). Green's Creek was intermediate and not significantly different in rates of elevation change from the hammock or headland marshes (Figure 3.10b). There was no significant interaction detected between marsh zone and geomorphic type (df = 102, F = 3.63, $\alpha = 0.00064$, $p = 0.0029$).

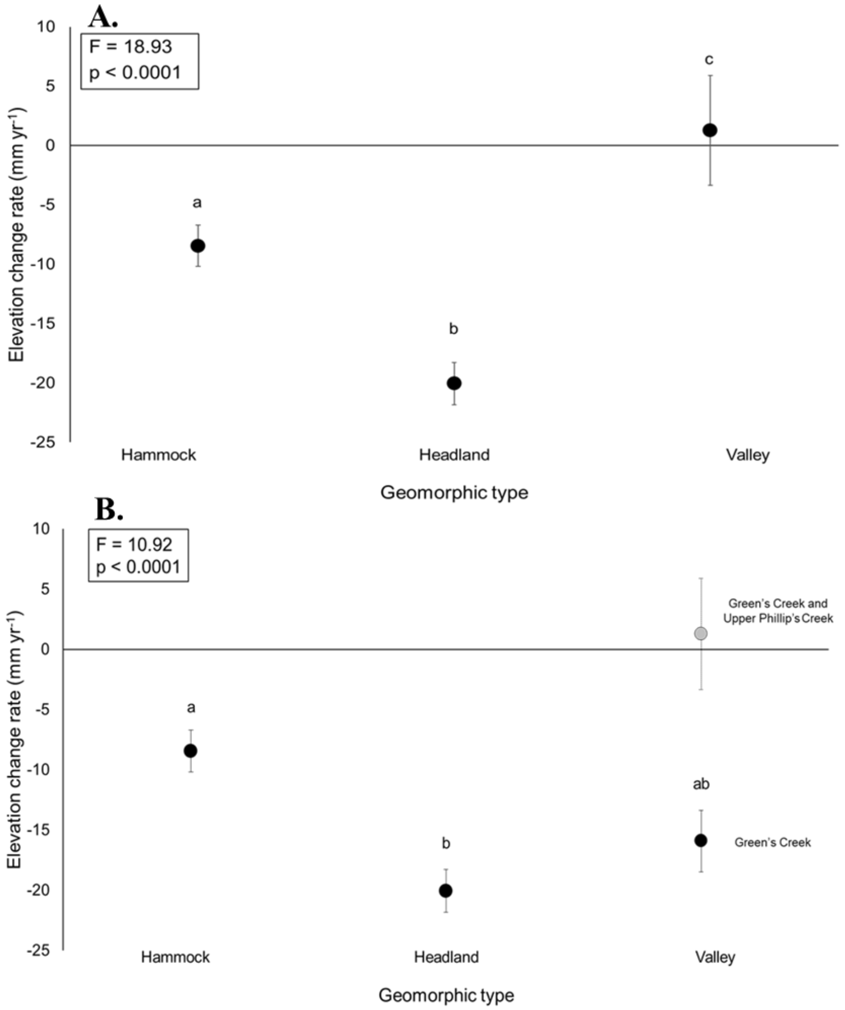


Figure 3.10. Mean rates of elevation change by marsh geomorphic classification. Error bars indicate standard error. The X-axis labels show the different marsh geomorphic types, ordered alphabetically. (A) The ANOVA and Tukey HSD post-hoc testing indicated that rates of elevation change of each geomorphic type were significantly different from one another. The ANOVA results are shown on the figure (df = 102, F = 18.93, $\alpha = 0.016$, $p < 0.0001$) and Tukey post-hoc results are indicated by letters above the data points. Data points with different letters indicate significant differences. (B) ANOVA and Tukey HSD post-hoc tests were performed again after the omission of Upper Phillip's Creek. Here, Green's Creek was the only valley marsh considered in the analyses. Testing indicated that rates of elevation change in hammock marshes were significantly different from rates of elevation change in headland marshes, while valley marshes were intermediate. ANOVA results are shown on the figure (df = 93, F = 10.92, $\alpha = 0.016$, $p < 0.0001$) and Tukey results are indicated by letters above the data points. Data points with different letters indicate significant differences at the alpha = 0.05 level.

3.5 Discussion

The overwhelmingly negative rates of elevation change measured in this study are alarming because the Eastern Shore of Virginia is a hot spot for sea-level rise. In the absence of marsh migration, marshes on the Eastern Shore of Virginia will submerge due to sea-level rise and rapid elevation loss. Three major conclusions emerged from this study: 1) all but one marsh lost elevation over the study period (Figure 3.9); 2) the marshes in this study fell into four groups of elevation change which appear to be correlated with how close the marshes are to one another, -- ones that are closest have the most similar rates of change (Figure 3.12); and 3) the marsh geomorphic type appears to be correlated with rates of elevation change – elevation loss was slower for hammock marshes compared to headland marshes.

Negative rates of elevation change

A wide range of elevation change rates have been measured throughout the Chesapeake Bay region. The results of one study on the Eastern Shore's Mockhorn Island, Virginia, in a low-lying marsh, showed measured rates of elevation change using SETs as being 1.4 ± 1.8 mm yr^{-1} (Erwin et al. 2006). Large negative (and large positive) rates of elevation change in coastal salt marshes are not unique to the sites included in this study. For example, within the Nanticoke estuary, a tributary estuary of the Chesapeake Bay, one study, which included five marsh sites with three SET replicates each, found a range of elevation change rates from -26.2 mm yr^{-1} to 12.85 mm yr^{-1} (Beckett et al. 2016). The decreases in marsh elevation at these study sites occurred even while all sites showed high, positive rates of accretion (estuary wide mean of 12.95 ± 1.32 mm yr^{-1}) (Beckett et al. 2016).

One potential explanation for the high, negative changes in elevation that have been measured both in this study and other studies based in the Chesapeake Bay region is land subsidence. Subsidence is a large contributor to rates of relative sea-level rise in the Mid-Atlantic (Eggleston and Pope 2013, Boon et al. 2010). Land subsidence is defined as the downward movement of earth's crust relative to earth's center (Boon et al. 2010). There are three main geological processes that are considered to be causes of land subsidence in the Chesapeake Bay region: glacial isostatic adjustment (Karegar et al. 2016), dynamic uplift/subsidence from mantle flow (Rovere et al. 2015), and sediment compaction (Miller et al. 2013, Stamps 2020). Aquifer compaction from groundwater withdrawal is also an important contributor to subsidence in this region (Eggleston and Pope 2013, Boon et al. 2010).

The Atlantic Coast of the United States (and Eastern North America more broadly) is located on a passive continental margin. Much of the margin is experiencing some form of vertical land motion due to glacial isostatic adjustment (Karegar et al. 2016). Glacial isostatic adjustment in North America is a "viscoelastic response" of the crust and mantle of the Earth caused by the retreat of the Laurentide Ice Sheet, the last glacial maximum being approximately 20,000 years ago (Karegar et al. 2016, Peltier 2004). The process of glacial isostatic adjustment causes uplift in some areas and land subsidence in others. For example, there has been land uplift in areas formerly under the Laurentide Ice Sheet and land subsidence in areas beyond the former ice sheet margins due to forebulge collapse (Karegar et al. 2016). Glacial isostatic adjustment is thought to be the most dominant of all geologic processes contributing to subsidence in the Chesapeake Bay region (Karegar et al. 2016).

Land subsidence on the Atlantic Coast of the United States is significant and represents the “largest-amplitude proglacial forebulge collapse on Earth” (Karegar et al. 2016). 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 (Boon et al. 2010). The Eastern Shore 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 (Eggleston and Pope 2013, Boon et al. 2010). Subsidence can substantially impact coastal wetlands, as these ecosystems are sensitive to small changes in elevation and flooding (Eggleston and Pope 2013). Land subsidence on the Eastern Shore of Virginia is likely playing a large role in the elevation change rates of the mainland seaside salt marshes included in this study; the scientific community has yet to determine the extent to which subsidence is contributing to both relative sea-level rise and elevation change in the region of the Eastern Shore. However, steps are currently being taken to measure rates of vertical land motion in the region.

In October 2019 NGS and the U.S. Geologic Survey (USGS) along with other collaborators, including me, began a large-scale subsidence survey that included at least 39 sites throughout the Chesapeake Bay region, including the Eastern Shore of Virginia (personal communication, Russ Lotspeich, Vertical Land Motion Workshop). The last time that a large-scale effort to understand vertical land motion in this region took place was in 1974 by Holdhal and Morrison, where rates of subsidence in Wachapreague on the Eastern Shore of Virginia were measured as -3.4 mm yr^{-1} (Holdhal and Morrison 1974). The goals of this survey campaign were to provide a modern measurement of subsidence in the region and to establish methodology for using static GPS to measure vertical land motion (Bloemendaal 2017). Preliminary data suggest that the rate of subsidence on the Eastern Shore of Virginia has accelerated since the first record of subsidence in 1974; the rate of subsidence is now approximately -6.0 mm yr^{-1} (Bloemendaal 2017). This campaign will provide some of the necessary context for studying rates of elevation change in our coastal salt marshes. The mean rate of elevation change in all zones in all marshes was -14.7 ± 1.2 mm yr^{-1}. If we use the preliminary subsidence data from Bloemendaal (2017), approximately 40% of the change in elevation in these marshes may be occurring due to regional subsidence.

Although regional subsidence may explain some of the negative rates of elevation change measured in this study, further investigations into the causes of these negative rates should be undertaken to gain a better understanding not only of why we are seeing such large decreases in marsh elevations, but also of how we might predict marsh elevation decreases moving forward. The rest of this discussion will consider characteristics of the studied marshes as potential indicators of rates of elevation change, in particular geomorphic characteristics including elevation as reflected by plant zonation, elevation capital, spatial proximity, and geomorphic type. The discussion will also address how methodology may be an important explanatory variable for the high negative rates of elevation change measured here.

Rates of elevation change among marshes for individual marsh zones and *among zones within individual marshes*

Of the nine study sites, only two showed significant differences in elevation change rates by marsh zone: GATR Tract and Box Tree. GATR Tract and Box Tree showed increasingly negative rates of elevation change moving from the creekbank zone to the transition zone (Figures 3.6 and 3.7). Although the differences in the rates of elevation change across marsh zones in the other six sites were not statistically significant, it is apparent that, in general, rates of elevation change became more negative moving from the creekbank zone to the transition zone (Table 3.2).

Marsh surface elevation increase is driven largely by two main processes: organic matter accumulation and mineral sediment deposition (Cahoon et al. 1998). Sediment deposition occurs when tides bring suspended sediments onto the marsh which settle on the marsh surface. Organic matter accumulation occurs through below-ground root production, decomposition, and litter accumulation (Cahoon et al. 2006). The amount of sediment deposition on the marsh surface varies spatially. This spatial variation in sediment deposition on the marsh surface is controlled by physical, biological, and geomorphological factors such as marsh elevation, vegetation cover, tidal stage, tidal creek geometry, creek hydrology, TSS loads, and more (Leonard 1997). The relative importance of each of these factors on sediment deposition rates vary depending on local site characteristics. Morris et al. (2002) found that sediment deposition rates were governed largely by the end-of-year biomass of *Spartina alterniflora*: sediment deposition was higher in marsh zones with higher aboveground biomass of *S. alterniflora*. Other studies suggest that sediment deposition on the marsh surface varies spatially with more sediment deposition occurring in closer proximity to the tidal water source (French et al. 1995, Leonard 1997, Christiansen et al. 2000). Therefore, higher elevation marsh zones that are further from the sediment source (e.g. high marsh and transition zones) would have less sediment deposited on the marsh surface because they are less frequently flooded by tides, and when they are flooded by tides it is for a shorter amount of time as compared to creek and low marsh zones. Thus, in terms of the processes that control vertical increases in the marsh surface, i.e. mineral sediment deposition and organic matter accumulation, mineral sediment deposition likely contributes more to surface elevation increases in marsh zones nearer the tidal water source than the zones further from the water source. Essentially, I propose that soil organic matter accumulation is occurring in all marsh zones, but that because the rates of sediment deposition are greater closer to the tidal water source, sediment deposition influences the rate of elevation more than organic matter accumulation nearer to the source of tidal water. This line of reasoning is supported by the results of this study: rates of elevation change decreased with distance from the creekbank zone to the transition zone (Figure 3.6a and b).

The finding that elevation change is greater at lower elevations near the source of tidal water is perhaps at odds with the elevation capital concept outlined by Cahoon et al. (2019). Elevation capital is, “the material accumulated during tidal wetland development that establishes the height of a wetland within the tidal frame” (Cahoon et al. 2019). Cahoon (2015) predicted that marsh areas with higher elevation capital would show higher, positive rates of elevation change and that marsh areas with lower elevation capital would show lower rates of elevation change. His prediction was based on the assumption that marshes experiencing sea-level rise that have elevation deficits become gradually lower in elevation relative to sea-level because the depth, frequency, and duration of flooding increase to the point that the flooding becomes too great to support vegetation thus transforming the area to either mudflat or open water (Orson et al. 1985, Reed 1995, Morris et al. 2002, Cahoon 2015, Raposa et al. 2016, Cahoon et al. 2019). Cahoon’s prediction (Cahoon 2015) was supported by his 2019 study (Cahoon et al. 2019) in Jamaica Bay, NY, USA in which marsh elevation (capital) showed a positive relationship with rates of marsh elevation change (Figure 3.11a). However, in my study, I found the opposite relationship: generally, marsh areas with higher elevation capital showed lower, negative rates of elevation change, and marsh areas with lower elevation capital showed higher, although still mostly negative, rates of elevation change (Figure 3.11b).

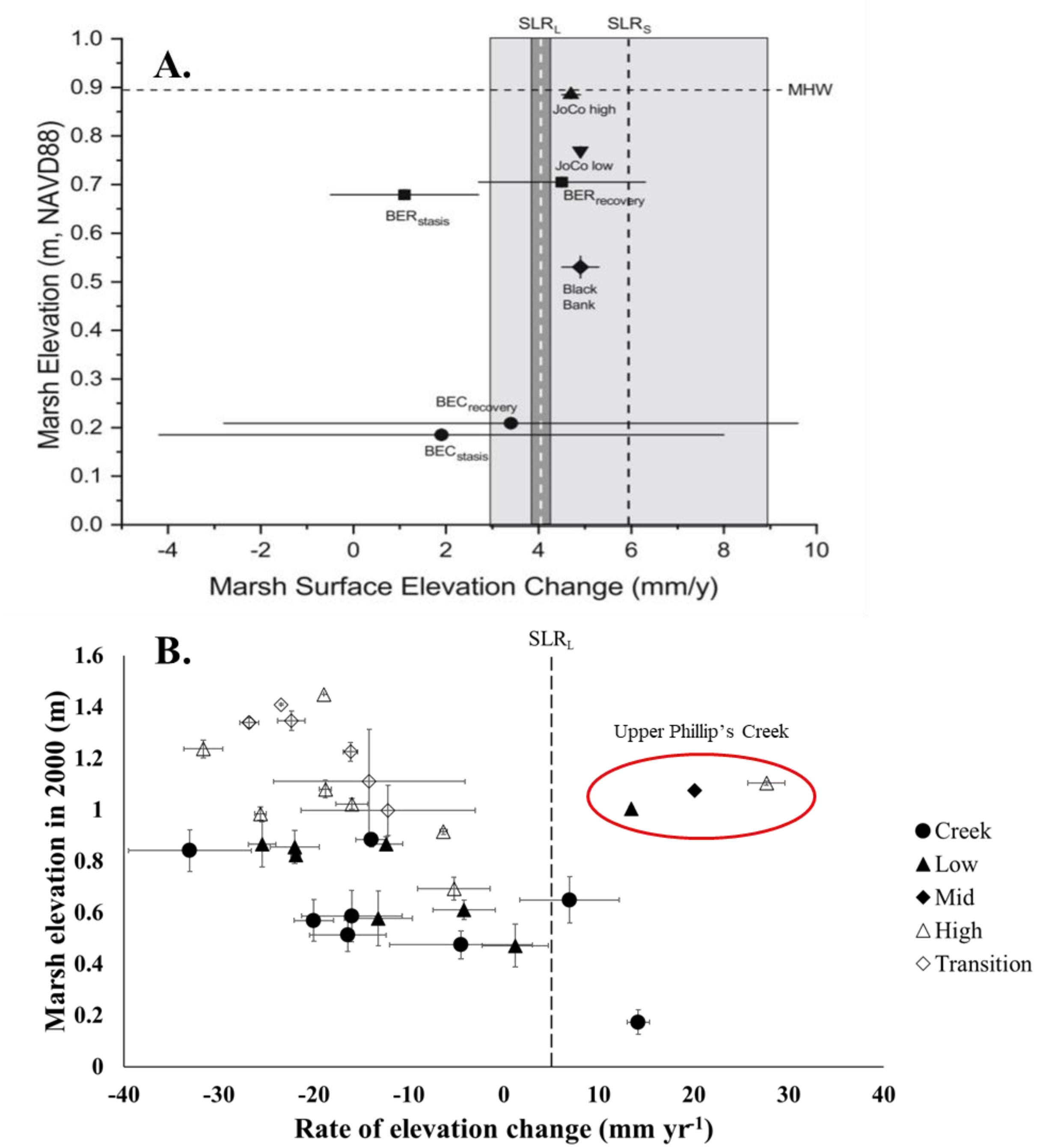


Figure 3.11. The relationship among marsh surface elevation change and marsh elevation (capital) in (a) zones for three different sites in Jamaica Bay, NY, USA from Cahoon et al. 2019 and (b) zones for the nine different sites studied on Virginia's Eastern Shore, USA. X-axis labels show rates of elevation change (mm yr^{-1}) and Y-axis labels show marsh elevations (m). Error bars indicate standard error. Long-term rates of sea-level rise (SLR$_L$) and short-term rates of sea-level rise (SLR$_S$) are labeled for (a) Jamaica Bay, NY, USA, and SLR$_L$ is labeled for (b) Eastern Shore of Virginia, USA. Jamaica Bay marsh elevations were measured in 2002 or 2006, depending on site.

Marsh elevations at the beginning of the study period (1999) were higher than those measured at the beginning of Cahoon et al.'s study (Figure 3.11). Additionally, the range of rates of elevation change measured in this study was much larger than the range of rates measured by Cahoon et al. (2019) in Jamaica Bay. Although Upper Phillip's Creek, circled in red on Figure 3.11b, showed a positive trend between marsh elevation capital and rates of elevation change supporting Cahoon et al.'s (2015) predictions, the remaining eight marshes in this study showed a distinct negative trend between marsh elevation capital and rates of elevation change.

The overall difference in findings between Cahoon et al. (2019) and this study may be due to a variety of differences among local factors that influence changes in marsh elevation such as: shallow subsidence (DeLaune and Pezeshki 1994, Cahoon et al. 1995, Chambers et al. 2019), deep subsidence (Boon et al. 2010, Eggleston and Pope 2013, Karegar et al. 2016), sediment supply (Stevenson et al. 1985, Morris et al. 2002, Kirwan et al. 2010, Hill and Anisfeld 2015), organic matter accumulation (Hatton et al. 1983, Bricker-Urso et al. 1989, Blum 1993, Callaway et al. 1997, Blum and Christian 2004, Chmura and Hung 2004), local hydrology and geomorphology (Oertel and Woo 1994), or rates of sea-level rise (Morris et al. 2002, Kirwan et al. 2010, Hill and Anisfeld 2015, Karegar et al. 2016). Additionally, this difference in findings could be due in part to differences in methodology; Cahoon et al. measured marsh elevation change using surface elevation tables (SETs) and here I used GPS-RTK elevation surveys. These two methods for measuring rates of elevation change can give different results; they will be evaluated later in this discussion. The differences in findings between this study and

Cahoon et al. (2019) serves as a reminder that phenomena observed in marshes at one location that hold explanatory power may not be applicable to marshes in other locations, due to differences in important local drivers and characteristics. Rates of elevation change measured in Jamaica Bay marshes were explained by differences in surface accretion, subsurface shallow expansion driven by root and rhizome biomass, and soil organic matter content (Cahoon et al. 2019). Sites that showed higher surface accretion, subsurface shallow expansion, and soil organic matter content showed higher elevation capital as well as higher rates of marsh surface elevation change (Cahoon et al. 2019). Neither shallow nor deep subsidence were considered explanatory variables (Cahoon et al. 2019). Rates of elevation change in Eastern Shore of Virginia mainland seaside salt marshes are influenced by soil organic matter content (Hatton et al. 1983, Bricker-Urso et al. 1989, Blum 1993, Callaway et al. 1997, Blum and Christian 2004, Chmura and Hung 2004). The rates of elevation change in these salt marshes are also likely influenced by sediment supply (Fagherazzi et al. 2013) which on the Eastern Shore is low (Brinson et al. 1995), land subsidence (Boon et al. 2010, Eggleston and Pope 2013, Karegar et al. 2016) and marsh geomorphology. This study found that marsh geomorphology may be an important, yet understudied, explanatory variable for differences in rates of marsh elevation change.

Ultimately, regardless of the mechanisms that are responsible for the loss, the marshes in this study are losing elevation capital, and as rates of sea-level rise accelerate the length of time to submergence will become shorter.

Rates of whole-marsh elevation change among geomorphic marsh types and among all individual marsh sites

Marsh geomorphology is an important explanatory variable for the differences in rates of elevation change in Virginia mainland seaside salt marshes (Figure 3.10). This may be because geomorphology incorporates a variety of marsh characteristics such as landscape position, suspended sediment load, erosion, migration, protection from storm energy, and more. Headland marshes showed significantly lower rates of marsh elevation change relative to hammock marshes. This is not surprising considering that the magnitude of vertical accretion in headland marshes is limited and that headland marshes tend to migrate inland in response to sea-level rise at a faster rate than they accrete vertically (Oertel and Woo 1994, also see Chapter 2 of this thesis). Although rates of elevation change in the hammock marshes were significantly higher than those of headland marshes, the rates were still negative or close to zero. This may be due to Eastern Shore of Virginia hammock marshes simultaneously relying heavily on suspended sediment loads in the water column to persist (Oertel and Woo 1994) in a region with naturally low sediment supply (Brinson et al. 1995, Lawson et al. 2007, Mcglathery and Christian 2020). Oertel and Woo (1994) concluded that valley marshes would have the highest preservation potential of the three types due to: steep valley walls providing a source of sediment to the valley floor, landward sediment transport as a result of time-lag asymmetry in ebb/flow and grain settling, larger organic matter accumulations, and higher rates of sediment input from the surrounding watershed. This prediction was not supported by the results of this study, where valley marshes (as represented by Green’s Creek) showed intermediate rates of elevation change that were not significantly different from hammock or headland marshes. However, when Upper Phillip’s Creek is included in the comparison of elevation change rates by geomorphic type we find that valley marshes show significantly higher rates of elevation change than headland or hammock marshes (Figure 3.10a), supporting the predictions made by Oertel and Woo (1994). Based on the limited sample size of valley marshes included in this study it would be premature to suggest that valley marshes have the greatest potential for elevation increases.

Not taking geomorphic classification into account may lead to over- or underestimates of elevation change. For example, Upper Phillip’s Creek is a well-studied marsh as well as the site of many VCR LTER studies. If the rates of elevation change measured at Upper Phillip’s Creek were used to represent the rates of elevation change experienced in other Eastern Shore of Virginia mainland salt marshes, the rates of elevation change at these other sites would be significantly overestimated. The very different results for Upper Phillips Creek marsh and for headland vs hammock marshes also points out that studying a range of marshes in different geomorphic settings is necessary to understand salt marsh response to sea-level rise at the landscape scale.

Although rates of elevation change vary by marsh, marshes that are in closer proximity might be expected to have similar rates of elevation change. Most of the rates of whole-marsh elevation change were negative; only two sites showed positive mean rates of elevation change (Figure 3.9). However, four distinct site groupings based on rates of elevation change emerged from the ANOVA and Tukey post-hoc analyses among all the marshes examined during my study. These groupings were distinct based on location along the Eastern Shore of Virginia peninsula: southern-peninsula marshes (GATR Tract, Steelman's Landing, and Cushman's Landing), middle-peninsula marshes (Oyster, Indiantown, and Box Tree), Upper Phillip's Creek, and northern-peninsula marshes (Woodland Farm and Green's Creek). The southern marshes showed the most negative rates of elevation change followed by the northern marshes, the middle marshes, and finally Upper Phillip's Creek. The rates of elevation change of the northern marshes were not significantly different from the rates of elevation change of two of the southern marshes (GATR Tract and Cushman's Landing) and one of the middle marshes (Oyster Harbor), making them intermediate in terms of rates of elevation change.

That sites in closer proximity to one another showed similar rates of elevation change (Figure 3.12) could, in part, be due to in some cases these sites sharing geomorphic classifications

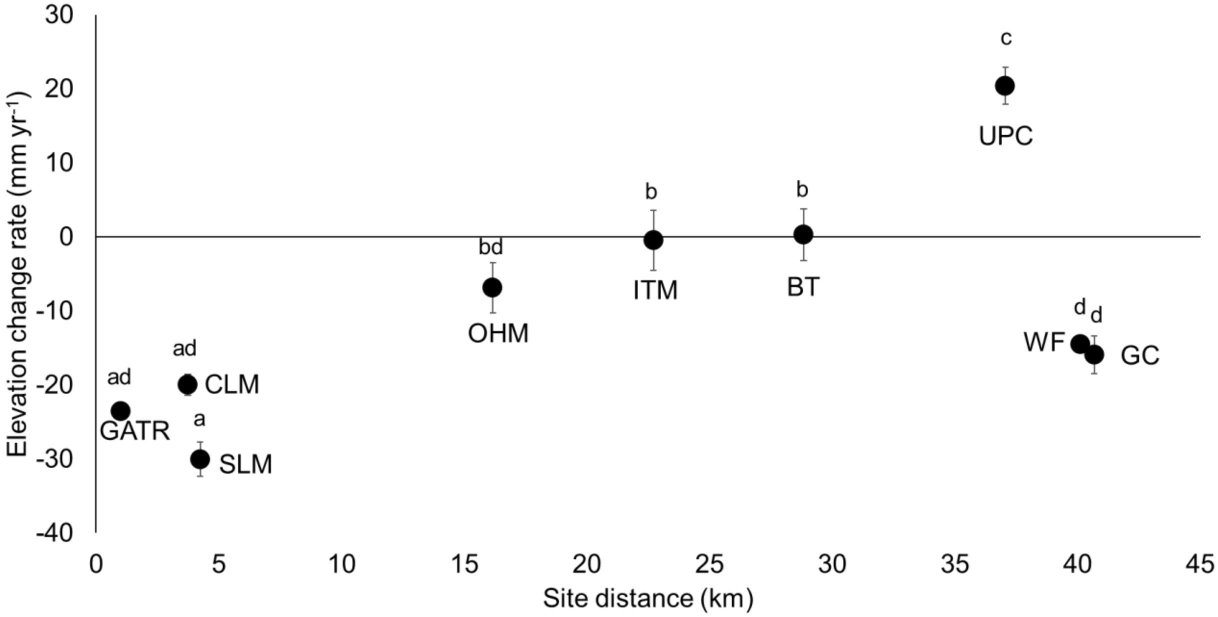


Figure 3.12. Mean rates of elevation change by study site. Error bars indicate standard error. In the cases of GATR and WF, error bars are obscured by the data points. The X-axis labels show the different marsh study sites, ordered from South to North and spaced according to distance from one another in kilometers, starting with GATR Tract at the 1-kilometer mark. Each data point is labeled with an acronym of the marsh it represents. The ANOVA results are shown on the figure (df = 102, F = 37.82, $\alpha = 0.00138$, $p < 0.0001$). Tukey post-hoc results are indicated by letters above the data points. Data points with different letters indicate significant differences.

For example, GATR Tract, Cushman’s Landing, and Steelman’s Landing are the sites that make up the “southern peninsula marshes” and they all share the headland geomorphic classification. Sites in closer proximity showing similar rates of elevation change could also be due to shared geologic processes or geologic characteristics occurring on a multi-site scale. For example, marshes nearer one another that share similar geologic and geomorphic characteristics could be experiencing similar rates of broader-scale processes such as land subsidence, tide range, tidal inundation frequency, duration, and depth, and suspended solids concentrations from the source of tidal water.

Lisa Ricker (1999) divided the Eastern Shore of Virginia into three geographic regions corresponding to the presence of a series of relict ridges located at the edges of the central region: South, Central, and North. Three major terrace plains were identified along the Eastern Shore within the three regions: Metompkin plain, Bell Neck Sand-Ridge complex, and the Kiptopeke plain (Ricker 1999, Mixon 1985). Most of the South region is comprised of the Kiptopeke plain, the Central region is comprised of the Bell Neck Sand-Ridge complex, and the North region is comprised of the Metompkin plain (Ricker 1999). Five of the marshes in this study are located in the South region as defined by Ricker (1999): GATR Tract, Cushman's Landing, Steelman's Landing, Oyster Harbor, and Indiantown. The four remaining marshes (Box Tree, Upper Phillip's Creek, Woodland Farm, and Green's Creek) are located in the Central region as defined by Ricker (1999). Three of the marshes in this study occur along the Kiptopeke plain (GATR Tract, Cushman's Landing, and Steelman's Landing) while the remaining six marshes occur along the Bell Neck Sand-Ridge complex (Oyster Harbor, Indiantown, Box Tree, Upper Phillip's Creek, Woodland Farm, and Green's Creek). All of this is to say that many of the sites in this study share underlying geomorphic and geologic characteristics, i.e. variables that influence rates of elevation change. It is unclear which geologic variables explain the distinct groupings of sites based on location (southern, middle, northern peninsula, and Upper Phillip's Creek); furthermore, the grouping of sites in terms of elevation change by their location along the Eastern Shore of Virginia should be investigated to better understand the underlying processes contributing to differences in rates of elevation change in Virginia seaside coastal salt marshes.

High negative rates and original elevation survey methodology

The rates of elevation change measured here are high and may be explained by the uncertainty of the methodologies used to measure the initial elevations of the marshes in this study. Thomas and Carlson (1999) measured marsh elevations through post-processed kinematic surveys. The accuracy of post-processed kinematic survey is estimated at an accuracy of 4 cm relative to the reference benchmark used. The accuracy of the reference benchmarks relative to the VCR1 benchmark (a High-Accuracy and Resolution Network benchmark) is 2 to 4 cm. Further, the accuracy of the VCR1 benchmark is estimated to the nearest 10 cm, and the 95% confidence limit for the NAVD88 ellipsoidal height is 1.27 cm. Considering all of these uncertainties, a conservative estimate of total uncertainty in the methodology used to establish initial marsh elevations in all sites aside from Upper Phillip’s Creek is approximately 19.27 cm.

Upper Phillip’s Creek showed significantly positive rates of elevation change compared to all other sites that may be due to a difference in methodologies for determining initial marsh elevations and their associated uncertainties. Elevation benchmarks were established in 1992 in Upper Phillip’s Creek using GPS survey and were relative to the VCR1 benchmark (Blum et al. *in press*). In 1998 marsh elevations were determined using laser-level methodology and were relative to the benchmarks established in 1992. The relative accuracy of laser-levels in measuring elevations depends largely on the accuracy of the established benchmarks being used. It is possible that much of the large difference in rates of elevation change between Upper Phillip’s Creek and all other sites (and to those reported I Blum et al. *in press*) may be due to the differences in methodology used to estimate the initial marsh elevations and the uncertainties associated with these approaches. Therefore, the elevation change rates reported here should be viewed while keeping in mind that there are large uncertainties associated with the different elevation measurement approaches used in this study.

Use of GPS-RTK to measure marsh surface elevation

GPS-RTK approaches have been proposed as a useful tool for measuring rates of whole-marsh elevation change. Surface elevation table (SET) approaches to measuring elevation change are used globally (Cahoon et al 2002a, Cahoon et al 2002b): twenty-two states and the District of Columbia, as well as in twenty-two countries worldwide (USGS, https://www.usgs.gov/science/regions/northeast/maryland/science/surface-elevation-table?qt-science_center_objects=0#qt-science_center_objects). Historically, SETs have been the most widely used method for measuring rates of marsh surface elevation change. With 1 to 2 mm accuracy and precision, SET measurements are likely the most accurate methodology available for measuring changes in elevation occurring at a single point on the marsh surface (Cahoon et al. 2002a, Cahoon et al. 1995, Lynch et al. 2015). While SETs may provide more accurate and precise measurements of elevation change than GPS-RTK, they cover a much smaller area of the marsh. For example, in Upper Phillip’s Creek nine SETs are measured annually. Each SET has nine pins that each have a diameter of ~ 3 mm. The nine pins are used in four directions, equaling thirty-six elevation measurements at each SET, and the end of each pin covers an area of 0.7 cm^2 or a total of 0.023 m^2, which is used to describe elevation change of the entire Upper Phillips Creek marsh with an area of 3×10^5 m^2. A similar calculation for the area of marsh that can be measured in the same amount of time as the nine SETs monitored at Upper Phillips Creek shows that a single GPS-RTK elevation measurement covers an area of 31.67 cm^2, depending on the topo shoe that is attached to the bottom of the rover pole which in this case had a diameter of 6.35 cm; therefore, when collecting 900 elevation measurements in Upper Phillip's Creek as I did in this study, 2.85 m^2 were measured using GPS-RTK in approximately the same amount of time as it takes to measure the nine Upper Phillip's Creek SETs. While this is a significant increase in the area measured by GPS-RTK compared to SETs, this still represents a small proportion of the total marsh area. However, because the RTK unit is moved from point to point across the entire marsh (this distance between individual measurements is much greater for RTK that for SETs – meters vs centimeters), a greater proportion of the elevation variance across the whole marsh is captured by these measurements. Thus, the potential to monitor elevation change for whole marshes by GPS-RTK is receiving some interest (personal communication, Laura Mitchell (USFWS Northeast Region) and Philippe Hensel, (NOAA National Geodetic Survey)). An additional advantage of GPS-RTK measurements is that large scale processes like regional subsidence are incorporated into the measurement without the need to resurvey elevation benchmark datums regularly. Currently, the GPS-RTK approach to measuring whole marsh elevations has not yet been widely adopted because the equipment is relatively expensive, learning to operate the equipment is time consuming for users, and accuracy of these measurements varies depending on the number of satellites available during the survey, the accuracy of the known base station elevation, extent of cloud and tree cover, position of the base station relative to large structures, user error, and more (OPUS, https://www.ngs.noaa.gov/OPUS/about.jsp#accuracy).

Future research on marsh surface elevation changes should include both small scale (SET) and large scale (RTK GPS) methods for measuring changes in marsh elevation to create a more holistic understanding of marsh response to sea-level rise. For example, the rates of elevation change measured by GPS-RTK in this study and those reported by Blum et al. (in press) by surface elevation tables (SETs) are similar in that both approaches yield positive rates of marsh surface elevation change between 1997 and 2017 (Table 3.3).

Table 3.3. Comparison of rates of surface elevation change by GPS-RTK to surface elevation tables (SETs) technology in three marsh zones in Upper Phillips Creek marsh. Superscript letters indicate significant statistical differences within the column (a = 0.05; n =3). Rates of elevation change are mm yr^{-1} ± standard error of the mean for 20 years (1997-2017). In 1997, SET site elevations were referenced to the BROWNSV benchmark in Upper Phillips Creek marsh ((+37° 27’ 38.4985028, -75° 50’ 4.961264). The BROWNSV benchmark is referenced to VCR1 (+37° 17' 42.156630", -75° 55' 59.492560", elevation = 8.7000 m), which is a benchmark that is part of the High Accuracy and Resolution Network (HARN). Subsequent to installation of VCR1, the GEOID93 model and a correction for the GEOID12A model were applied to the original data (Thomas and Carlson 1999). VCR1 is referenced to NAVD88. SET data from Blum et al. (in press)

Marsh Zone	mm $year^{-1}$		
	GPS-RTK	SET	Difference
Low	$13.4^{a} \pm 0.3$	$4.8^{a} \pm 0.2$	8.6
Middle	$20.1^{ab} \pm 4.6$	$4.3^{b} \pm 0.2$	15.8
High	$27.7^{b} \pm 2.2$	$3.6^{c} \pm 0.4$	24.1

However, the GPS-RTK the rates of elevation increase measured in my study are more rapid than those obtained by SET; for example rates of GPS-RTK increase are 3 times greater than SET rates adjacent to the low marsh SET sites, and are 12 times more rapid adjacent to the high marsh SET sites. GPS-RTK measurements suggest that elevation change is rapid enough to increase elevation capital in Upper Phillips Creek marsh, while SET measurements indicate either no change (low and middle marsh) or loss of elevation in the high marsh. These differences may simply reflect differences in the spatial scale at which the elevation measurements were made or that the processes resulting in elevation change are non-linear and interact in different ways at different spatial scales. It is not clear which of these measurement approaches, small-scale SET or larger-scale GPS-RTK, provides reliable information about marsh resilience to sea-level rise. Clearly, simply scaling up (or down) measurements made at one spatial scale to another does not appear to be a reliable way to understand marsh elevation dynamics. Alternatively, as discussed above, differences in the surveying approaches used in 1997 and for this study also could account for the discrepancies in rates of change measured with by SET and GPS-RTK. At a minimum, researchers using SETs to monitor changes in marsh elevation should measure the elevation of their primary benchmark using GPS-RTK equipment on at least an annual basis. This is especially critical for regions like the Eastern Shore of Virginia that are experiencing rapid land subsidence relative to sea-level rise.

The negative rates of elevation change measured in Eastern Shore of Virginia salt marshes are concerning because as the land subsides and sea-levels increase, coastal wetlands will disappear if they are unable to migrate inland to maintain spatial extent. Coastal wetland disappearance leads to a loss of the economically valuable ecosystem services these wetlands provide. Although salt marsh migration inland is viewed positively by ecologists and conservationists, it is met with concern by local landowners and farmers. Salt marsh migration into agricultural fields is concerning to local landowners and farmers because it is a zero-sum scenario: if the land becomes suitable salt marsh habitat it is no longer viable to grow traditional, commercial crops. On the Eastern Shore of Virginia, the main bordering land use of conserved wetlands is agriculture (Northampton County Comprehensive Plan 2009). Agriculture has historically been an important industry in both counties that make up the Virginia Eastern Shore, Accomack County and Northampton County. Sixteen percent of the population in Northampton County alone is employed by agriculture, forestry, fishing, and hunting (NCCP 2009). Additionally, agriculture brings in approximately 2 billion dollars annually to Northampton County (NCCP 2009). On the Eastern Shore of Virginia, approximately 474 acres of wetlands are created from low-lying farmland annually (Titus et al. 2010). The average farm size on the Virginia Eastern Shore is 362 acres, making the conversion of farmland to wetland equal to over 1 farm per year (Northampton County Census of Agriculture 2012, Accomack County Census of Agriculture 2012). With sea-level rise rapidly increasing over time and approximately 373 farms on the Virginia Eastern Shore, this conversion rate is concerning for conservationists and farmers alike (Northampton County Census of Agriculture 2012, Accomack County Census of Agriculture 2012).

To inform local management and conservation decisions and development of policy, a better understanding of local marsh persistence is needed and requires knowledge not only of sea-level rise, sediment loads, local soil characteristics, but also large and small scale changes in marsh elevation, including rates of land subsidence. This study provides measurements of salt marsh elevation changes based on salt marsh zones and geomorphic classifications to provide context for future research and local land management decisions.

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3.7 Appendices

APPENDIX A

Figure A-1. Aerial imagery (2013) from VGIN VBMP of Indiantown, GATR Tract, Cushman’s Landing, and Steelman’s Landing.

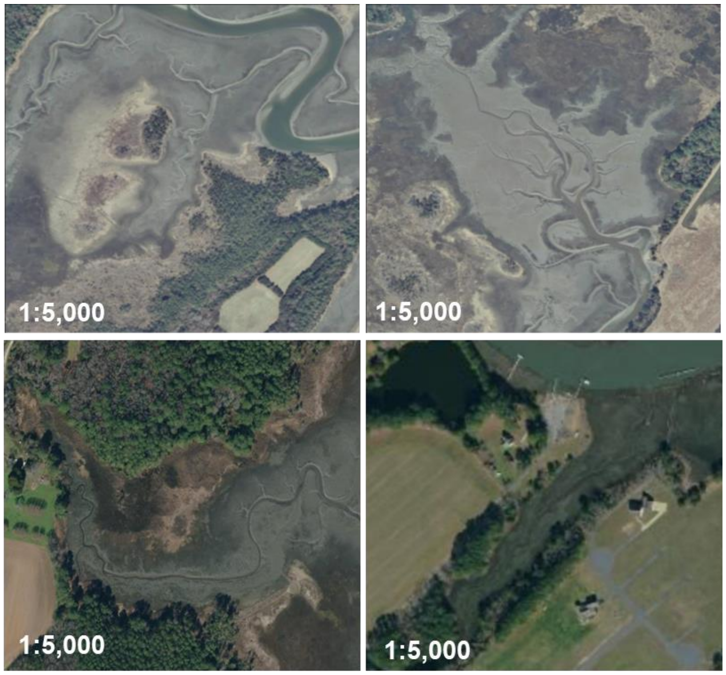

Figure A-2. Aerial imagery (2013) from VGIN VBMP of Green's Creek, Upper Phillip's Creek, (2017) Mill Creek, and (2017) Folly Creek.

Figure A-3. Aerial imagery (2013) from VGIN VBMP of Oyster Harbor, Woodland Farm, Box Tree, and (2017) Wise Point.

APPENDIX B

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 NGS OPUS SOLUTION REPORT
                    ========================

All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: https://www.ngs.noaa.gov/OPUS/about.jsp#accuracy

     USER: jaf3bc@virginia.edu                 DATE: January 20, 2017
RINEX FILE: 1939316r.16o                       TIME: 19:10:37 UTC


  SOFTWARE: page5  1209.04 master96.pl 160321      START: 2016/11/11  17:25:00
 EPHEMERIS: igs19225.eph [precise]                STOP: 2016/11/11  20:12:00
  NAV FILE: brdc3160.16n                    OBS USED:  6935 /  7135   :  97%
  ANT NAME: TRM55971.00     NONE          # FIXED AMB:    35 /    36   :  97%
ARP HEIGHT: 1.5206                        OVERALL RMS: 0.014(m)


 REF FRAME: NAD_83(2011)(EPOCH:2010.0000)            IGS08 (EPOCH:2016.8628)

        X:      1236697.513(m)   0.004(m)          1236696.664(m)   0.004(m)
        Y:     -4923794.234(m)   0.023(m)         -4923792.761(m)   0.023(m)
        Z:      3848012.957(m)   0.005(m)          3848012.886(m)   0.005(m)

      LAT:   37 20 47.42396      0.016(m)       37 20 47.45431      0.016(m)
    E LON:  284  5 57.07951      0.003(m)      284  5 57.06063      0.003(m)
    W LON:   75 54  2.92049      0.003(m)       75 54  2.93937      0.003(m)
   EL HGT:          -36.359(m)   0.017(m)              -37.702(m)   0.017(m)
 ORTHO HGT:            0.536(m)   0.036(m) [NAVD88 (Computed using GEOID12B)]

                      UTM COORDINATES    STATE PLANE COORDINATES
                       UTM (Zone 18)         SPC (4502 VA S)
Northing (Y) [meters]     4133693.108          1115606.685
Easting (X)  [meters]      420213.653          3730262.400
Convergence  [degrees]    -0.54649145           1.57751223
Point Scale                0.99967841           0.99994547
Combined Factor            0.99968411           0.99995118

US NATIONAL GRID DESIGNATOR: 18SVG2021333693(NAD 83)


                           BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
DL3186 LOYX LOYOLA X CORS ARP              N371635.030 W0764143.819   70875.1
AJ8053 COVX CHESAPEAKE LIGHT CORS ARP      N365416.650 W0754245.708   51810.6
DL3889 LOYW LOYOLA LOYW CORS ARP           N373140.995 W0755052.662   20684.8

                NEAREST NGS PUBLISHED CONTROL POINT
FW1023      SCOTT 2                      N372042.136 W0755350.261     351.6
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APPENDIX C

Results of a preliminary paired t-test to compare means of two methods for determining rates of elevation change in each marsh: grid average and nearest point). In most sites both methods were comparable (absolute value of t-stat < t-critical, p-value > 0.05). One site (Box Tree, highlighted below) showed that the means of the two methods were significantly different, however this is explained by field observations noted in the methods sections of this document.

Site	T-test results: comparison of grid average and nearest point rates of marsh elevation change			
	df	t-statistic	t-critical	p-value
Green’s Creek	9	-1.96	2.26	0.08
Woodland Farm	14	1.59	2.14	0.13
Upper Phillip’s Creek	-	-	-	-
Box Tree	7	2.52	1.89	0.04
Indiantown	5	-0.97	2.57	0.38
Oyster Harbor	20	0.62	2.08	0.54
Steelman’s Landing	11	-0.16	2.20	-0.87
Cushman’s Landing	10	-0.27	2.23	0.79
GATR Tract	15	0.25	2.13	0.81

Chapter 4.

Application and assessment of a multimetric index model to evaluate resilience of mainland seaside salt marshes on the Eastern Shore of Virginia, USA

4.1 Abstract

Sea-level rise is threatening the persistence of coastal salt marshes, leading to an increased interest in and need for models that assess the resilience of salt marshes to rising sea-levels. The Marsh Resilience to Sea-Level Rise (MARS) model created by Raposa et al. (2016) has been of interest to researchers and land managers because it combines multiple indicators of salt marsh resilience, it is easy to use, and it allows the user to compare relative resilience scores among marshes at any geographic scale. Here, I applied the MARS model to nine salt marsh sites on the Eastern Shore of Virginia, a hot spot for sea-level rise. Resilience scores were on a scale of 1 to 5, 1 indicating low resilience and 5 indicating high resilience. The model resilience scores suggested that nine study sites uniformly had low relative resilience to sea-level rise; their scores ranged from -5.51 to 3.26, with an average index score of 0.06 ± 0.41. For context, average resilience index scores at sixteen National Estuarine Research Reserve sites ranged from 1.06 to 4.1 with an average index score of 2.47 ± 0.24 (Raposa et al. 2016). The results of this study suggest that Eastern Shore of Virginia mainland salt marshes may be some of the least resilient marshes to sea-level rise in the coastal United States. However, further improvements to the MARS model should be made as critical processes for marsh persistence, such as marsh migration into uplands, are not included in this model as it stands.

4.2 Motivation

Throughout the mid-Atlantic region of the United States of America, sea-levels are rising rapidly and coastal wetlands are disappearing simultaneously (Sallenger et al. 2012). The Eastern Shore of Virginia (ESVA) is considered to be a hotspot for sea-level rise with recorded rates as high as 5.37 mm yr^{-1} (NOAA 2019, Mariotti et al. 2010); much higher than the global average rate of 3.1 mm yr^{-1} (NOAA 2019). There is concern about the resilience and persistence of ESVA seaside mainland marshes because the Eastern Shore is experiencing rapid sea-levels rise. These wetlands provide a multitude of economically valuable ecosystem services, such as storm energy attenuation, water purification, erosion control, carbon sequestration, and habitat for valuable fishery species (Craft et al. 2009, Feagin et al. 2010, Barbier et al. 2011, Haaf et al. 2015). If these wetlands disappear, these important and costly services would no longer be provided. Therefore, evaluating marsh resilience is a priority of researchers and land managers on the ESVA.

To assess marsh resilience, historically, researchers have investigated individual indicators of marsh response to sea-level rise such as marsh surface elevation change, an indicator that is widely considered a key determinant of marsh vulnerability (McFadden et al. 2007, Webb et al. 2013). From the evaluation of these individual indicators, models have been created to simulate changes in a marsh over time and under various conditions (e.g. accelerated rates of sea-level rise). These models have been used to simulate vertical changes in the marsh (Temmerman et al. 2003), model changes in channel networks (Kirwan and Murray 2007), predict long-term morphological fates of tidal embayments

(D’Alpaos et al. 2007), predict sediment characteristics as a function of depth on a salt marsh (Mudd et al. 2009), explain how vegetation regulates marsh elevation toward an equilibrium with sea-level rise (Morris et al. 2002), and predict wetland coverage over time (Clough et al. 2016). Although these models are extremely useful for simulating and predicting specific changes within a marsh over time as well as assessing individual indicators of marsh resilience, they do not explicitly assess marsh resilience.

One approach to assess and compare relative marsh resilience to sea-level rise is the use of multimetric indices (Raposa et al. 2016). Quantitative multimetric assessments have been developed for benthic aquatic ecosystems to compare habitat quality across sites, with the specific goal that the information will be used to inform management decisions (Diaz et al. 2004, Pinto et al. 2009, Raposa et al. 2016). These indices are useful because by including several metrics that each provide critical information on an attribute or process of the system, scores can be assigned that reflect current conditions that, when combined, provide information on the system’s condition or status (Pinto et al. 2009). Multimetric indices differ from numerical marsh models (Morris et al. 2002, Temmerman et al. 2003, D’Alpaos et al. 2007, Kirwan and Murray 2007, Mudd et al. 2009) in that they reflect current conditions rather than make spatially-explicit predictions (Raposa et al. 2016).

Only relatively recently have multimetric indices been used in wetland ecosystems (Miller et al. 2016). The first model to compile multiple metrics to assess marsh resilience to sea-level rise was The Marsh Resilience to Sea-Level Rise (MARS) model (Raposa et al. 2016). The MARS model has been of particular interest in recent years among both researchers and land managers because the model is a quantitative, multimetric approach that classifies relative marsh resilience to sea-level rise. An important distinction of this model from other marsh models is that it is non-numerical, meaning that it is not used to make predictions of how sites will change over time due to rising sea-levels. Rather, this model is a relatively simple assessment of site characteristics that influence marsh resilience (Raposa et al. 2016). Additionally, the MARS model was created, in part, because most existing models for evaluating marsh resilience were created and used for the purpose of examining a single marsh or estuary, focusing on one relatively small region of interest. This model was also created with the explicit objectives of developing a model that is transparent, could be applied by scientists and land managers alike, and could be used to compare marshes at any geographic scale (Raposa et al. 2016).

The conceptual framework behind this model is that in areas where the marsh is dominated by low elevations (Morris et al. 2002, Deegan et al. 2012), the rate of elevation change is low or negative (Webb et al. 2013), the either the sediment input and accretion rates are low (Morris et al. 2002, Cahoon and Guntenspergen 2010), the tidal range is low (Fagherazzi et al. 2012), or the rate of sea-level rise is high (Sallenger et al. 2012, Kirwan and Megonigal 2013), marsh resilience to sea-level rise will be low (Raposa et al. 2016). There are five categories considered in this model: the distribution of elevation levels across a marsh (elevation distribution), the rate of marsh elevation change (marsh elevation change), surface and subsurface deposition and accumulation of material (accretion and sediments), the local sea-level rise rate (sea-level rise), and the local tidal range (tidal range). Each of these categories encompasses one or more of the conditions that are the basis of the conceptual model. These categories are based on a total of ten metrics which are described in the methods section of this chapter (see below). The metrics used in the MARS model were chosen because they have been identified in the literature as reflecting either marsh sensitivity or exposure to sea-level rise (Raposa et al. 2016). Marsh sensitivity to sea-level rise can vary based on natural site differences in characteristics such as proximity to sediment sources and tidal range (Kirwan et al. 2010, Fagherazzi et al. 2012, Raposa et al. 2016), as well as anthropogenic alterations to the marsh through disruption or redirection of sediment supply or eutrophication induced subsidence (Deegan et al. 2012). Variations in marsh exposure to sea-level rise are due to regional oceanographic and local hydrodynamic factors that create site-specific differences in exposure to sea-level rise (Sallenger et al. 2012, Raposa et al. 2016). Using the model's metrics, marsh indices of resilience to sea-level rise are scored and can be compared among marshes at multiple spatial scales and from disparate geographic regions.

The ESVA and its barrier islands are one of the last remaining examples of coastal wilderness on the USA Atlantic coastline. The Virginia Coast Reserve (VCR) has been designated as a United Nations International Man and the Biosphere Reserve, a U.S. Department of the Interior National Natural Landmark, a western hemisphere International Shorebird Reserve Network Site, and an Atlantic Coast Joint Venture Focus Area. Through the combined efforts of The Nature Conservancy, the Commonwealth of Virginia, and federal agencies, over 315 km^2 along 110 km of the Atlantic Ocean shore and the adjacent barrier islands have been protected for conservation and preservation of this system. Ecotourism to these conserved lands contributed $224 million to the local economy in 2011 (Virginia State Tourism Plan, Volume 2 Eastern Shore Regional Section, https://vatc.org/wp-content/uploads/2017/06/VirginiaStateTourismPlanVTC3292013.pdf.). Conserving the unique natural and economic value of these lands requires management tools to support sound land management decisions as climate changes and sea levels rise. The goals of this study were 1) to evaluate the resilience of ESVA selected mainland-seaside salt marshes using the MARS model to compare their relative resilience to one another as well as to other salt marshes across the coastal United States (Raposa et al. 2016) and 2) to evaluate the utility of the MARS model as a marsh resilience assessment tool to be used locally by land managers on the ESVA.

4.3 Approach

Site description

Nine marshes along the seaside coast of the lower Delmarva Peninsula, the VCR, were selected for this study (Figure 4.1, Table 4.1).

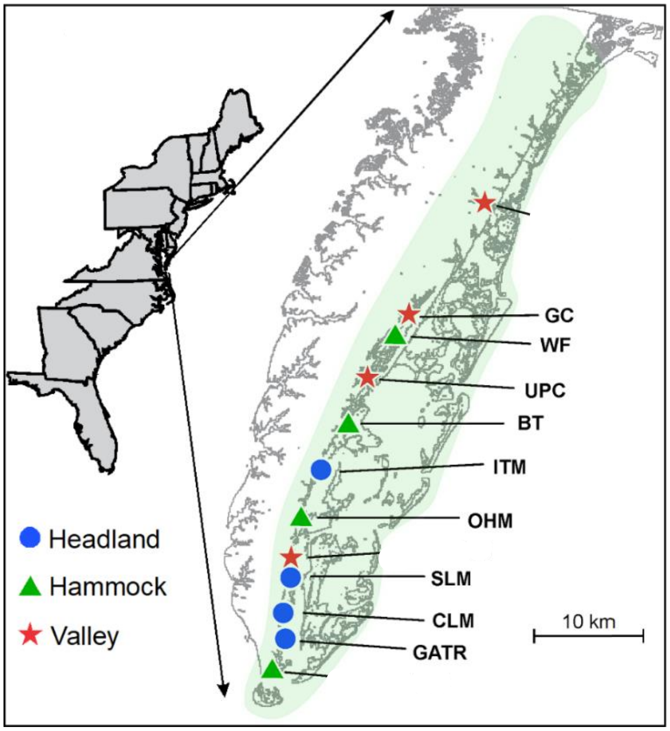

Figure 4.1. Geographic setting of the study sites at the Virginia Coast Reserve Long-Term Ecological Research site (VCR LTER). Gray inset is of the United States eastern coast. Expanded map is the Virginia Eastern Shore with the VCR LTER shaded green. Marsh study sites and geomorphic type are indicated with blue circles (headland), green triangles (hammock), and red stars (valley). Study site abbreviations are Greens Creek (GC), Woodland Farm (WF), UPC (Upper Phillips Creek), Boxtree (BT), Indiantown marsh (ITM), Oyster Harbor marsh (OHM), Steelman's Landing marsh (SLM), Cushman's Landing marsh (CLM), and GATR Tract (GATR).

Table 4.1. Location and geomorphic type of marshes studied at VCR.

Marsh	Latitude	Longitude	Geomorphic Type*
GATR	37.16	-75.94	Headland
CLM	37.17	-75.94	Headland
SLM	37.18	-75.94	Headland
OHM	37.28	-75.92	Hammock
ITM	37.34	-75.90	Headland
BT	37.39	-75.87	Hammock
UPC	37.45	-75.83	Valley
WF	37.48	-75.81	Hammock
GC	37.48	-75.81	Valley

*based on Oertel and Woo (1994)

These sites were selected because they are geomorphically different (see Chapter 2), are the most common geomorphic types of marshes adjacent to the ESVA mainland (see Chapter 2), have been the focus of other studies carried out by the VCR LTER for over 30 years, and have a record of elevation data. Two valley marshes (Green's Creek and Upper Phillip's Creek), four headland marshes (Indiantown, Steelman's Landing, Cushman's Landing, and GATR Tract), and three hammock marshes (Woodland Farm, Box Tree, and Oyster Harbor) were identified for this study using Virginia Base Mapping Program (VBMP) aerial imagery from 2002, in accordance with Oertel and Woo (1994).

MARS model

The MARS model was created to quantify relative marsh resilience to sea-level rise. To evaluate marsh resilience five broad categories were considered in this model: marsh elevation distribution, marsh elevation change, accretion and sediments, sea-level rise, and tidal range (Raposa et al. 2016). Within these five categories, ten metrics were considered: percent of marsh elevation points below mean high water (MHW), percent of marsh elevation points in the lowest third of vegetation distribution, skewness of elevation data, rate of marsh surface elevation change, short term accretion rate (mm yr^{-1}), long term accretion rate (mm yr^{-1}), turbidity (NTU), tidal range, long-term rate of sea-level rise, and short-term inter-annual variability in water levels (Table 4.2). Short-term accretion rates, long-term accretion rates, and turbidity data were not available for all study sites, therefore, organic matter content of the marsh soil was used as an alternative. The rationale for this substitution was that below ground processes of organic matter accumulation can be of equal or greater importance, especially on the ESVA (Cahoon et al. 1998). Although surface sediment deposits are significant contributors to the vertical increase of marsh elevation globally, estimates are that up to 60% of elevation increases can be attributed to plant root growth in VCR salt marshes (Blum 1993, Blum and Christian 2004). Therefore, for this study the sediment/accretion category metrics were replaced with one metric available at all sites: organic matter content (Table 4.2).

Table 4.2. Categories, metrics, and scores of the MARS model, reflecting the addition of organic matter content to the Sediment/accretion category.

Category	Metric	Score
Marsh elevation distributions	Percent of marsh below MHW Percent of marsh in lowest third of plant distribution Skewness	1-5 1-5 1-5
Marsh elevation change	Elevation change rate (mm yr^{-1})	1-5
Sediment/accretion	*Organic matter content of soil (%)*	1-5
Tidal range	Tidal range (m)	1-5
Sea-level rise	Long-term rate of SLR (mm yr^{-1}) Short-term inter-annual variability in water levels (mm)	1-5 1-5

Each metric was scored from 1-5, where 1 represents low resilience to sea-level rise and 5 represents high resilience to sea-level rise (Table 4.2). The metric scoring protocol and thresholds were outlined by Raposa et al (2016):

> “We defined the range of data values associated with each score for each metric. To assign these score definitions, we examined the range of variation of data across all 16 NERR marshes. We omitted extreme outlier values, and then broke the data ranges into evenly spaced categories. For metrics such as marsh elevation change, we also ensured that scores were consistent with an understanding of marsh processes, for instance with marshes that are not currently tracking local long-term sea-level rise receiving low scores. For other metrics such as turbidity, we had no a priori basis for score assignments and simply used categories that encompassed the spread of the data (minus outliers). Once all individual metrics were scored, mean scores were calculated for each broader category that contained more than one metric (metric and category scores were identical for categories with only one metric; e.g., tidal range).”

This same protocol was applied to the organic matter content metric that was used in my study. First, the range of variation of organic matter content data across the nine sites in this study was determined. Then data were divided into evenly-spaced data ranges: 0 to 15%, 15 to 30%, 30 to 45%, 45 to 60%, and 60 to 100%, corresponding to scores of 1, 2, 3, 4, and 5, respectively. The ranges and scores for all other metrics used in the model are included in Table 4.3.

Table 4.3. Numeric thresholds and color codes for individual metrics and all categories and indices (Raposa et al. 2016). For metric scoring from left to right, red = 1, orange = 2, yellow = 3, light green = 4, and dark green = 5. Note that even though Raposa et al. (2016) did not use TSS in their study, scoring thresholds for the metric are also presented because it can be used in lieu of turbidity for future assessments.

Metric thresholds	Percent marsh below MHW	**> 80%**	**> 60%**	**> 40%**	**> 20%**	**≤ 20%**
	Percent of marsh in lowest third of plant distribution	**> 80%**	**> 60%**	**> 40%**	**> 20%**	**≤ 20%**
	Skewness	**> 1.5**	**> 0.5**	**0.5 to -0.5**	**< -0.5**	**< -1.5**
	Elevation change rate (mm yr^{-1})	**≤ 2**	**> 2**	**> 3**	**> 4**	**> 5**
	Short-term accretion rate (mm yr^{-1})	**≤ 2**	**> 2**	**> 3**	**> 4**	**> 5**
	Long-term accretion rate (mm yr^{-1})	**≤ 2**	**> 2**	**> 3**	**> 4**	**> 5**
	Turbidity (NTU) or Total suspended solids (mg L^{-1})	**≤ 10**	**> 10**	**> 20**	**> 30**	**> 40**
	Tidal range (m)	**≤ 0.6**	**> 0.6**	**> 1.2**	**> 1.8**	**> 2.4**
	Long-term rate of SLR (mm yr^{-1})	**> 3.4**	**> 2.6**	**> 1.8**	**> 1**	**≤ 1**
	Short-term inter-annual variability in water levels (mm)	**> 25**	**> 15**	**> 5**	**5 to -5**	**< -5**
Scoring	All metrics	**1**	**2**	**3**	**4**	**5**
	All categories	**< 2**	**< 3**	**< 4**	**< 5**	**5**
	MARS risk	**0 to 1**	**2**	**3**	**4**	**5**
	MARS average	**1**	**> 1**	**> 2**	**> 3**	**> 4**
	MARS ratio	**< -0.5**	**> -0.5**	**> 1.5**	**> 2.5**	**> 3.5**

Category scores were determined by taking the average of the metric scores that were within each category. Three scoring indices were used to determine resilience based on category scores: the MARS risk index, MARS average index, and MARS ratio. The MARS risk index is the total number of categories which scored ≥ 3. The MARS risk index is evaluated on a scale of 0-5, with 0 indicating lowest resilience and 5 indicating highest resilience. The MARS average index is calculated by taking the average of the five category scores. This index is evaluated on a scale of 1-5, where a score of 1 indicates lowest resilience and 5 indicates highest resilience. The MARS ratio index is calculated by dividing the rate of marsh elevation change by the long-term rate of sea-level rise. A ratio <1 indicates decreasing elevation compared to sea-level rise. A ratio >1 indicates higher, positive elevation change compared to the sea-level rise rate.

Metric descriptions and data collection

a. Marsh elevation distribution

The marsh elevation distribution category was made up of three metrics: percent of marsh elevation survey points below MHW, percent of marsh elevation survey points in lowest third of vegetation distribution, and skewness of the frequency distribution of the elevation data (Table 4.4).

Table 4.4. The categories and metrics of the MARS model, as well as the data used to define the metrics.

Category	Metric	Data
Marsh elevation distributions	Percent of marsh below MHW	RTK survey, HOBO water level loggers
	Percent of marsh in lowest third of plant distribution	RTK survey
	Skewness	RTK survey, Excel (Microsoft 365) function “=SKEW()”
Marsh elevation change	Elevation change rate (mm yr^{-1})	RTK survey
Sediment/accretion	Organic matter content of soil (%)	Soil core loss on ignition
Tidal range	Tidal range (m)	HOBO water level loggers
Sea-level rise	Long-term rate of SLR (mm yr^{-1})	Long-term sea-level data from Wachapreague, Virginia NWLON station
	Short-term inter-annual variability in water levels (mm)	Inter-annual variability in sea-level data from Wachapreague, Virginia NWLON station.

The elevation data for these three metrics were collected through Trimble GPS-RTK surveys using Trimble R7 and Trimble R10.2 RTK survey equipment. At each marsh approximately 900 to 1600 elevation points were measured; these points were taken in 10 m x 10 m grids, with an elevation measurement taken at every one-meter node in the grid (see Chapter 3 for details about the grid layout). The location of the center of each grid was selected based on elevation surveys conducted in 1999 by C. Thomas (Thomas and Carlson 1999). The grids were distributed along four transects perpendicular to the source of tidal flooding. Grids were placed in the creek, low marsh, high marsh, and transition zones of each site, where the original survey points from 1999 were still accessible. Four survey points in Steelman's Landing and six survey points in Green's Creek were not accessible due to dense phragmites and forest cover which also caused low Position Dilution Of Precision (PDOP) values during RTK surveys indicating weak satellite geometry, adversely affecting data quality. Therefore, these points were not included in the surveys.

The percent of marsh elevation points below MHW was included in the model because it reflects the strong relationship between the distribution and zonation of marsh plants and flooding tolerance (Morris et al. 2002, Raposa et al. 2016). To determine the percent of the marsh below MHW, water depth was measured using Onset HOBO Water Level Data Loggers (Part #U20L-04) for a period of approximately 30 days within each marsh at the boundary of tall-form *Spartina alterniflora* and short-form *S. alterniflora*. Three HOBO loggers were available for use in this study; thus, water levels in all nine marshes could not be made at the same time. Water levels were measured in sets of three marshes, simultaneously, by placing one logger in each of three marshes. After about one month, the loggers were removed from a marsh, the data downloaded, and the loggers moved to another set of three marshes. Thus, for the nine sites in this study, three HOBO water-level-logger deployments were made: GATR Tract, Cushman's Landing, and Steelman's Landing from July 6th to August 6th, 2018; Oyster Harbor, Indiantown, and Box Tree from October 8th to November 4th, 2018; and Upper Phillip's Creek, Woodland Farm, and Green's Creek from November 4th to December 4th, 2018. To install the loggers, a two-meter section of 7.5-centimeter diameter, 0.0-inch (0.25 mm) slit, PVC well screen with a well point was pushed by hand into the marsh leaving approximately 30 cm above the marsh surface; the loggers were suspended to a depth that placed them below the marsh surface using nylon cord attached to an eyebolt on the inside of the well-screen cap. The well stick-up height, distance from the top of the well screen to the sensor, and elevation of the marsh surface where the well was installed were all measured and recorded for each well.

To account for differences in flooding tolerance among marsh vegetation species, the percent of marsh elevation points in the lowest third of the plant distribution metric was included. This metric reflects the distribution of marsh elevations relative to the observed tolerance at a given marsh (Raposa et al. 2016):

> "For example, a marsh that has vegetation at elevations ranging from 0.5 m to 2.0 m above mean lower low water (MLLW) and 75% of measured elevation points in the lower third of that range (i.e., below 1.0 m) should be less resilient than a marsh with the same elevation range but with only 10% of its elevation points below 1.0 m. Our selection of the lower third of plant distribution rangewas arbitrary; the specific cutoff does not matter as long as it is consistent among all sites. A benefit of this metric is that it only requires determining the entire range of elevations that support marsh plants at each site; a local tidal datum does not need to be calculated because this is an ecologically relevant metric based on observed plant tolerance."

To determine skewness of the elevation data for each marsh the Excel “SKEW” function was used to generate a skewness value. The inclusion of elevation frequency distribution skewness in the model was based on previous work that suggests a right-skewed distribution (positive skewness value) indicates that the marsh vegetation distribution is grouped at lower elevations and is potentially more susceptible to submergence, whereas a left-skewed distribution (negative skewness value) indicates that the marsh vegetation distribution is grouped at higher elevations and is potentially more resilient to sea-level rise (Morris et al. 2005).

b. Marsh elevation change

The marsh elevation change category contained one metric: the rate of marsh elevation change (Table 4.4). The rate of marsh elevation change was determined by comparing the elevations measured in a GPS-RTK survey in 1999 to a resurvey of the same points during a 2016-2019 time period (year of resurvey varies depending on site, for methodology of grid survey please see the description of the marsh elevation distribution category). The change in elevation was then divided by the number of years between elevation measurements to give the rate of elevation change (mm yr^{-1}), in this case between 16 and 19 years. The rate of elevation change for an entire marsh was determined by taking the mean rate of elevation change at each grid (up to 16 grids per marsh). My data fit the criteria outlined by the model creators (Raposa et al. 2016), which specifies that the rate of elevation change must be measured over a period of at least five years.

c. Accretion and sediments

The accretion and sediments category in the model included three metrics: short-term accretion rate (mm yr^{-1}), long-term accretion rate (mm yr^{-1}), and either turbidity (Nephelometric Turbidity Units, NTU) or total suspended sediment concentrations (mg L^{-1}) in the source of tidal water to the marsh. Turbidity can be determined in a variety of ways, one of which being through the use of a nephelometer, an instrument that measures the light scattering of suspended particles, or by determination of suspended sediment mass in a known volume of water (concentration) .

The short-term accretion rates used by Raposa et al. (2016) were defined as the depth of material accumulated during a ten-year time period over marker horizons like those used with surface-elevation tables (SETs see Cahoon and Turner 1989 and Lynch et al. 2015). The long-term accretion rate (mm yr^{-1}) was defined as the amount of material accumulating within fifty- to one-hundred years (or more) as determined using radioactive isotope dating techniques (Raposa et al. 2016). Turbidity was defined as the mean turbidity from water quality sondes over a period of five recent years (Raposa et al. 2016). Short-term accretion data were only available for Upper Phillip’s Creek marsh where marker horizons are examined on a yearly basis. No long-term accretion data were available for any of the marshes. Turbidity data also were not available and total-suspended-solids data were only available for only two marshes, UPC and OHM. I developed an alternative metric based on soil organic matter content to use in this MARS assessment. Organic matter and mineral sediment content are typically reported as percentages based on loss-on-ignition determination of mineral content and, when expressed as a percentage, mineral and organic matter content are inversely related to one other. Because organic matter accumulation in ESVA has been identified as critical to marsh elevation change (Cahoon et al. 1998), I used the organic matter content (% dry soil mass) of marsh soil measured at 16 locations across the marsh was used for all sites in place of Raposa et al.'s (2016) accretion and sediment metric (Table 4.4).

Organic matter content was determined collecting soil cores followed by loss-on-ignition techniques. Two soil cores were collected at randomly selected spots within each of the 2016-2019 elevation sampling grids. The tubing used to collect the cores was 5-cm in diameter and 40-cm long to capture the 20-cm depth of the active root zone in these marshes. The core tubing was driven into the soil to a depth of 20 cm using a sledgehammer, and then checked to be sure compaction of the core was < 2 cm (compared depth to the soil surface inside and outside of the core). The tubing containing the cores was removed from the soil by inserting a shovel under the core tubing to lift the core from the soil. To extrude the soil from the tubing, a wooden dowel with a diameter near to that of the core tubing was used to push the soil sample from the tubing. Extruded soil cores were cut into four, 5-cm long sections, weighed, dried to a constant weight (60° C), and placed in a muffle furnace at a temperature of 450° C to remove the organic matter by combustion. Organic matter content (dried mass – combusted mass) were expressed as percentages normalized to dry mass of the un-combusted sample.

d. Sea-level rise

The sea-level rise category included two metrics: the long-term rate of local sea-level rise and the short-term rate of local sea-level rise (Table 4.4). The long-term rate of sea-level rise was determined using the published rate of change in mean sea-level from the nearest National Water Level Observation Network (NWLON) station: Wachapreague (station ID = 8631044; 37° 36.5’ N, 75 41.1’ W; https://tidesandcurrents.noaa.gov NOAA 2019). The short-term interannual variation in water levels was calculated using data from the same NWLON station as: the mean monthly water level anomaly over the last 10 years (Raposa et al. 2016).

e. Tidal range

To determine the tidal range at each marsh (Table 4.4), water depth was measured using Onset HOBO Water Level Data Loggers (see above) for a period of approximately 30 days. The tidal range was calculated for each marsh by determining the daily tidal range from water-level data collected by the HOBO water-level loggers and the mean tidal range for 30 days of measurement calculated.

Comparisons and statistics

The category scores and the three resilience indices (MARS risk, MARS average, and MARS ratio) generated by the model were compared among marshes. The mean category and index scores obtained in this study were compared to the category and index scores of a nearby Chesapeake Bay NERRS marsh as well as the category, and to index scores from fifteen other NERRS marsh sites from throughout the coastal United States (Raposa et al. 2016). To assess whether the three resilience scores determined for the ESVA marshes examined in my study yield similar estimates of marsh resilience, Pearson Product-Moment Correlations between the three resilience indices were run (SAS version 9.4).

4.4 Results

Marsh elevation distribution

Marsh elevation distribution scores were variable across the nine sites (Table 4.5). The percent of marsh elevations below MHW ranged from 0 to 89%, and the percent of marsh elevations in the lowest third of plant distributions ranged from 17 to 96%. Skewness of the elevation data ranged from -4.78 to 1.91. The range of scores in this category was from 2.7 (low/moderate resilience) to 5 (high resilience to sea-level rise).

Table 4.5. MARS category and index scores for all nine sites. Scores range from 1-5, 1 indicating low resilience and 5 indicating high resilience to sea-level rise. The category scores are color-coded based on resilience scores: negative scores to 1.99 (red), 2.0 to 2.99 (orange), 3.0 to 3.99 (yellow), 4.0 to 4.99 (light green), 5 (dark green). The index scores are color coded based on the thresholds outlined in Table 4.3.

		Sites								
		Cushman's Landing	Indiantown Marsh	Oyster Harbor Marsh	Steelman's Landing Marsh	Upper Phillip's Creek	Box Tree	Green's Creek	GATR Tract	Woodland Farm
MARS Categories	Elevation distributions	4	4.3	2.7	4	4.3	5	1.7	3.3	3
	Marsh elevation change	1	1	1	1	5	1	1	1	1
	Accretion and sediments	1	1	2	1	2	2	1	1	2
	Tide range	1	1	1	1	1	1	1	1	1
	Sea-level rise	2	2	2	2	2	2	2	2	2
MARS Indices	MARS risk	1	1	0	1	2	1	0	1	1
	MARS average	2	2.07	1.93	2	3.07	2.4	1.53	1.87	2
	MARS ratio	-4.67	-0.1	-1.79	-7	3.26	-1.96	-4.07	-5.51	-3.39

Marsh elevation change

Only two of the nine marshes in this study showed overall positive rates of elevation change: Box Tree and Upper Phillip's Creek. Most marshes showed decreases in marsh elevations over the 1999-2019 study period. Rates of marsh-elevation change for the nearly two-decade study ranged from -30 to 20 mm yr^{-1} (Table 4.6). All sites received a score of 1 in this category indicating low resilience, aside from UPC which scored a 5, indicating high resilience.

Table 4.6. Rates of elevation change (mm yr^{-1}), mean high water levels (m), tidal range (m), and organic matter content (%) for all nine sites (mean ± standard error).

	Sites								
	Cushman's Landing	Indiantown	Oyster Harbor	Steelman's Landing	Upper Phillip's Creek	Box Tree	Green's Creek	GATR Tract	Woodland Farm
Elevation change (mm yr^{-1})	-20 ± 1.4	-0.48 ± 4.1	-7 ± 3.4	-30 ± 2.3	20 ± 2.5	0.29 ± 3.5	-16 ± 2.6	-23 ± 0.9	-15 ± 0.8
Mean high water (m)	0.4 ± 0.01	0.25 ± 0.03	0.19 ± 0.02	0.39 ± 0.02	0.30 ± 0.01	0.24 ± 0.02	0.49 ± 0.01	0.64 ± 0.01	0.16 ± 0.01
Tidal range (m)	0.46 ± 0.03	0.19 ± 0.03	0.20 ± 0.03	0.53 ± 0.03	0.37 ± 0.04	0.39 ± 0.05	0.52 ± 0.04	0.54 ± 0.04	0.18 ± 0.03
Organic matter content (%)	17 ± 8.4	14 ± 5.1	30 ± 8.9	8 ± 12.4	34 ± 32.7	46 ± 26.9	5 ± 0.6	7 ± 3.4	17 ± 8.7

Accretion and sediments (now organic matter content)

Organic matter content varied across the nine sites. Average organic matter content of marsh soils across sites ranged from 4.6 ± 0.6% (Green's Creek) to 34.1 ± 32.7% (Upper Phillip's Creek) (Table 4.6). Five sites (Cushman's Landing, Indiantown, Steelman's, Green's Creek, and GATR Tract) received a category score of 1 (OM < 20%, low resilience), and the remaining four sites (Oyster Harbor, Upper Phillip's Creek, Box Tree, and Woodland Farm) received a category score of 2 (20% < OM < 40%, low resilience).

Tide range

Tidal range values across sites ranged from 0.18 ± 0.03m (Woodland Farm) to 0.54 ± 0.04m (GATR Tract) (Table 4.6). All sites received a category score of 1, indicating low resilience (Table 4.5).

Sea-level rise

Rates of local sea-level rise for all sites were sourced from the Wachapreague, Virginia, NWLON tide station. The relative rate of local sea-level rise recorded at Wachapreague and applied to all sites was 5.37 mm yr^{-1}. This is a relatively high rate of sea-level rise; thus, this metric received a score of 1. Short-term inter-annual variability in water levels (mm) was also sourced from the Wachapreague station and applied to all sites. The short-term inter-annual in water levels was recorded as 6 mm, receiving a metric score of 3. Averaging the two metrics in this category, gave the sea-level rise category score for all sites of 3.

MARS indices

Scores among marshes varied little among the three indices (Table 4.5). Based on the MARS risk index, all marshes were classified as having relatively low resilience to sea-level rise (scores of 0 to 2). The MARS average scores were more variable than MARS risk or MARS ratio scores. MARS average scores ranged from 1.53 (low resilience) to 3.07 (moderate resilience). Finally, MARS ratio scores were mostly uniform in that they were all negative, indicating low resilience, aside from UPC which had a MARS ratio score of 3.26 indicating moderate resilience to sea-level rise.

The scores of the three MARS indices were highly, or moderately, correlated with one another (r = 0.83 for the MARS average and MARS risk indices, r = 0.74 for the MARS average and MARS ratio indices, and r = 0.43 for the MARS risk and MARS ratio indices). According to Raposa et al. (2016) correlation of resilience scores across indices suggests that although resilience scores may be different across the three indices, they all reflect similar levels of marsh resilience.

4.5 Discussion

The ESVA mainland-seaside salt marshes have low resilience to sea-level rise, based on the MARS model assessment. Overall, the nine sites included in this study had relatively low mean resilience scores ranging from -1.33 to 2.78, with an overall average index score of 0.06 ± 0.41. These resilience scores are much lower than the scores received by other sites across the coastal United States, suggesting that ESVA salt marshes may be some of the least resilient mainland seaside salt marshes in the United

States, based on the MARS approach. Although the results of this model indicate that ESVA mainland seaside marshes have low resilience to sea-level rise, these marshes are responding to sea-level rise and maintaining, and even gaining, area through marsh migration inland (see Chapter 2). Thus, these marshes may be more resilient to sea-level rise than this model suggests.

Comparison with National Estuarine Research Reserve Sites

Raposa et al (2016) applied their model to sixteen National Estuarine Research Reserve (NERRs) sites across the coastal United States, including one site in the Chesapeake Bay, nearby the ESVA. The average category and index scores from the Eastern Shore study were lower than average category and index scores of the Chesapeake Bay (Raposa et al. 2016) (Table 4.7). The differences in scores were due to the negative rates of elevation change in ESVA marshes, higher relative rates of sea-level rise for the ESVA seaside, and potentially higher rates of regional subsidence, a critical factor contributing to low marsh resilience but not included in the MARS model.

Table 4.7. MARS category and index scores. These scores are a comparison between an average of the nine site scores from this study, and the scores from a nearby site in the Chesapeake Bay, VA from Raposa et al. 2016.

		Eastern Shore Marsh Average Scores*	Chesapeake Bay, VA (Raposa et al. 2016) Scores
MARS Categories	Elevation distributions	3.59	4
	Marsh elevation change	1.44	5
	Accretion and sediments	1.44	3
	Tide range	1	2
	Sea-level rise	2	1.5
MARS Indices	MARS risk	0.89	3
	MARS average	2.09	3.1
	MARS ratio	-2.80	1.1

*Average scores of nine different marshes.

Elevation distribution scores were similar between the sites in this study and the Chesapeake Bay site (Table 4.7) and represented relatively moderate (ESVA) and high (Chesapeake Bay) resilience to sea-level rise. These scores suggest that both the ESVA and Chesapeake Bay sites are predominantly distributed high in their respective local tidal frames (Morris et al. 2002). Marsh elevation change scores were different between the two studies, 1.44 for this study and 5 for Raposa et al. (2016). One possible explanation for the difference in elevation change scores between this study and the NERRS study is that in the NERRS study Raposa et al. (2016) measured rates of elevation change using surface elevation tables (SETs) which only record relatively shallow changes in the marsh surface. In this study we recorded rates of elevation change using GPS-RTK surveys, a method which has lower accuracy than SETs (mm vs cm for

GPS-RTK and SETs respectively), but that is perhaps a more accurate method for measuring changes in marsh elevation because it captures larger scale process that influence changes in elevation such as regional land subsidence. Another explanation for the lower rates of elevation change measured in Eastern Shore marshes compared to the Chesapeake Bay NERRS site is that there are differences in the amount of sediment available for deposition. The Chesapeake Bay site has a large watershed feeding the Bay, while the ESVA seaside lagoons are fed by small creeks and intermittent streams. Therefore, the potential sediment supply on the ESVA likely is lower than that of the Chesapeake Bay. The accretion and sediments category scores were different between the two studies, 1.44 for this study and 3 for Raposa et al. (2016). This is likely because in this study I used organic matter content measurements in place of short- and long-term accretion rates and TSS measurements. Therefore, direct comparisons in this category between the two studies may not be appropriate because I would be comparing scores based on the organic content of marsh soil to scores based on inorganic accumulation. To better compare the accretion and sediments category scores of the two studies, I obtained the inorganic content (%) of the soil cores from each site by subtracting the organic matter content (%) from 100%, under the assumption that through loss-on-ignition the organic matter content (%) + inorganic content (%) = 100%. Here, we now assume that higher inorganic content represents higher mineral sediment deposition on the marsh surface and therefore greater potential to grow vertically (Morris et al. 2002) which leads to higher resilience to sea-level rise. Inorganic content was scored using the inverse of the organic content scoring: 0 to 15%, 15 to 30%, 30 to 45%, 45 to 60%, and 60 to 100%, corresponding to scores of 5, 4, 3, 2, and 1 respectively. The study-wide average score of the accretion and sediments category then became 3.88, somewhat higher than but still similar to the Chesapeake Bay score of 3 (Table 4.7, Table 4.8).

Table 4.8. MARS category and index scores for all nine sites. Here, the accretion and sediments category reflects inorganic soil content scores rather than organic matter content as in Table 4.8. Scores range from 1-5, 1 indicating low resilience and 5 indicating high resilience to sea-level rise. The category scores are color-coded based on resilience scores: negative scores to 1.99 (red), 2.0 to 2.99 (orange), 3.0 to 3.99 (yellow), 4.0 to 4.99 (light green), 5 (dark green). The index scores are color coded based on the thresholds outlined in Table 4.3.

		Sites								
		Cushman's Landing	Indiantown Marsh	Oyster Harbor Marsh	Steelman's Landing Marsh	Upper Phillip's Creek	Box Tree	Green's Creek	GATR Tract	Woodland Farm
MARS Categories	Elevation distributions	4	4.3	2.7	4	4.3	5	1.7	3.3	3
	Marsh elevation change	1	1	1	1	5	1	1	1	1
	Accretion and sediments	4	4	4	3	3	3	5	5	4
	Tide range	1	1	1	1	1	1	1	1	1
	Sea-level rise	2	2	2	2	2	2	2	2	2
MARS Indices	MARS risk	2	2	1	2	3	2	1	2	2
	MARS average	2.4	2.47	2.03	2.2	3.07	2.4	2.13	2.47	2.2
	MARS ratio	-4.67	-0.1	-1.79	-7.0	3.26	-1.96	-4.07	-5.51	-3.39

By altering the accretion and sediments category for the ESVA sites to represent inorganic matter content, the nine-site average MARS risk index score (1.89) and MARS average index score (2.37) increased, but did not increase enough to reflect overall higher resilience.

The sea-level rise category scores between the two studies were comparable, with scores of 2 for the ESVA and 1.5 for the Chesapeake Bay. Although these low resilience scores in the sea-level rise category indicate that both sites are threatened by high rates of sea-level rise, this is perhaps even more concerning on the ESVA, where mainland salt marshes are decreasing in elevation (marsh elevation change category score of 1.44 , low resilience) while the Chesapeake Bay NERRS marsh is increasing in elevation (marsh elevation change category score of 5, high resilience).

The MARS resilience-index scores from this study were in all cases lower than index scores from the Chesapeake Bay in Raposa et al. (2016). The average resilience index score in this study was 0.06 while the average index score in the Chesapeake Bay was 2.4 (Raposa et al. 2016). Both average index scores (0.06 and 2.4) are relatively low scores of resilience. For context, average resilience index scores at the sixteen NERRs sites in the Raposa et al. study (2016) ranged from 1.06 to 4.1 with an average index score of 2.47 ± 0.24. Thus, the average resilience-index scores for both Virginia mainland-seaside marshes and the Chesapeake Bay marsh are lower than the average resilience score from marshes from around the coastal United States. In the case of the marshes included in this study, the average resilience index score fell below the minimum of what was recorded in the MARs model publication (Raposa et al. 2016), suggesting that ESVA mainland seaside salt marshes are some of the least resilient marshes to sea-level rise in the United States.

Limitations of the MARS model: marsh migration

The ESVA seaside-mainland salt marshes have low resilience to sea-level rise according to the MARS model. This model evaluates vertical changes in the marsh surface and processes that contribute to vertical changes in the marsh surface. However, the mainland-seaside salt marshes on the ESVA rely heavily on marsh migration to persist as sea levels rise, and therefore, these marshes may be more resilient to rising sea levels than the MARS model suggests. This aligns with previous assessments of marsh vulnerability in the literature. Although much of the literature indicates that marshes are extremely susceptible to submergence due to changes in relative sea-level, Kirwan et al. (2016) suggest that marsh vulnerability is overstated. These authors argue that often assessments of marsh vulnerability do not consider feedback processes that amplify soil deposition and marsh elevation increases, and thus, the potential for marshes to migrate inland. Additionally, these authors state that reports of complete marsh loss are rare except in locations where sediment supply to the coastal wetlands has been significantly reduced (Kirwan et al. 2016).

Over a 15-year time period (2002-2017) in twelve Virginia Eastern Shore salt marshes (nine of which were the sites included in this model), all sites showed a net increase in area due to rates and areas of marsh migration outweighing rates and areas of marsh edge erosion. In some cases, the increase during this time was small (0.01 ha at Steelman’s Landing) while in other cases the increase in area was relatively large (0.89

ha at Upper Phillip's Creek) (Chapter 2, and Flester and Blum, in review). Although the results of this study indicate that in all but one marsh (see Chapter 3 and Blum et al. in press) marsh elevations on the mainland seaside of the ESVA are decreasing over time, and that marsh resilience to sea-level rise of these sites is low, these sites are persisting largely through increases in marsh area due to marsh migration inland (see Chapter 2).

Marsh migration is possible, in part, to slopes low enough to allow for marsh colonization into the forested uplands. In addition to slope, the soil characteristics of the upland boundary, specifically whether the soil is hydric, can be important for predicting marsh migration into the forest. Lisa Ricker (1999) created a model to predict relative forest resistance to state change on the ESVA that incorporated slope, elevation, and soil drainage class. The Ricker model suggests that a marsh-adjacent forest that has a low slope, low elevation, and hydric soils will have low resistance to state change, i.e. low resistance to marsh migration. For this study, Ricker divided the ESVA into three geographic regions corresponding to the presence of a series of relict ridges located at the edges of the central region: South, Central, and North. Five of the marshes in this study are located in the South region as defined by Ricker (1999): GATR Tract, Cushman's Landing, Steelman's Landing, Oyster Harbor, and Indiantown. The four remaining marshes (Box Tree, Upper Phillip's Creek, Woodland Farm, and Green's Creek) are located in the Central region. The results of this study suggested that marsh-adjacent forests within the South region would have relatively low resistance to state change while the forests within the Central region would have relatively low or intermediate resistance to state change (Ricker 1999). Indeed, all sites from my study showed marsh migration into adjacent upland forests, and, overall, the marshes within the South region showed higher rates of marsh migration (mean ± SE, 3.1 ± 0.67 ha m^{-1} yr^{-1}) than marshes in the Central region (0.99 ± 0.26 ha m^{-1} yr^{-1}). Marsh migration is a critical process of marsh persistence in transgressive settings like the ESVA, thus, perhaps slope and soil characteristics of adjacent uplands should be considered when trying to determine a marsh's relative resilience to sea-level rise. This is especially true if, rather than to determine whether a marsh will continue to persist in situ, the goal of a resilience model is to determine whether marshes will persist as sea levels rise, inclusive of whether the marsh has shifted in location.

To improve the MARS model for use on the ESVA, metrics involving horizontal changes in the marsh should be incorporated. I suggest incorporating marsh migration rates, marsh edge erosion rates, net lateral movement rates, and slope into the model. Marsh migration rates indicate how quickly the marsh is expanding into the upland, marsh edge erosion rates indicate how quickly the marsh is being eroded, the net rate of lateral change in the marsh indicates whether marsh is being lost or gained, and slope is an indicator of whether marsh migration into the adjacent upland is possible or probable.

Although marsh migration is occurring at the marsh upland boundary in nearby Chesapeake Bay (Kirwan et al. 2016, Schieder et al. 2017) and throughout the seaside of the Virginia Eastern Shore (see Chapter 2, and Kastler and Wiberg 1996, Flester and Blum *in review*), this process may have an expiration date that is controlled 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. 2017). This is significant because if marsh gain is halted at the upland while marsh loss is occurring at the marsh edge and rates of sea-level rise are accelerating, there will be a net loss in marsh area as conditions become too wet for emergent marsh vegetation to persist (Brinson et al. 1995). In which case, these marshes may ultimately be as vulnerable as the MARS model suggests.

4.6 References

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Chapter 5.

Synthesis and Significance

5.1 Synthesis and Significance

The results of this thesis provide a better understanding of salt marsh response to sea-level rise and allow for better predictions of future marsh spatial extent, persistence, and resilience. The information provided allows for comparisons among marshes within the VCR and will allow researchers to better understand Eastern Shore of Virginia mainland salt marshes in a global context through comparisons to other marsh sites from across the world. Prior to this study, it was unknown how and at what rate Eastern Shore of Virginia mainland salt marshes were responding to sea-level rise. Here, I documented rates of processes that are critical to the persistence and resilience of salt marshes to rising sea levels at the VCR, specifically: marsh migration, edge erosion, and elevation change.

In all marshes studied, migration exceeded erosion leading to a net gain in area at each study site, indicating that these marshes are persisting over time. The rates of elevation change measured here were high and overwhelmingly negative, suggesting that these marshes rely on lateral processes to persist in the face of rising sea levels. The MARS model suggests that Eastern Shore of Virginia mainland salt marshes have low resilience to sea-level rise; however, this model only considers vertical components of marsh response to sea-level rise. In marshes within transgressive settings like the VCR, lateral components of marsh response to sea-level rise can be paramount to marsh persistence and resilience. Therefore, the MARS model should be improved to include lateral components of marsh response to sea-level rise, such as net area gain, migration rates, and edge erosion rates.

Marsh geomorphic type was a key variable in determining rates of area (marsh migration and edge erosion) and elevation change. This finding is particularly significant because it provides a relatively simple method for understanding and estimating the relative rates of marsh response to sea-level rise; it offers some understanding of the relative response of a marsh to sea-level rise merely by knowing the geomorphic type of the marsh in question. By geomorphic type, area change was lowest for the hammock marshes (0.11 ha ± 0.05 ha, mean ± SE), intermediate for valley marshes (0.36 ha ± 0.18 ha), and highest for headland marshes (0.48 ha ± 0.24 ha). When these results were extrapolated to the entire Virginia Eastern Shore for marshes of the same geomorphic type, over the fifteen-year study period, valley marshes exhibited the greatest amount of marsh area gain compared to headland and hammock marshes (63.9 ha, 8.18 ha, and 1.09 ha, respectively), for a net increase in marsh area of 73.2 ha (see Chapter 2). Based on geomorphic type, elevation change rates and the direction of change also were different (see Chapter 3); the rate of change was low, but positive, for valley marshes (1.2 ± 4.6 mm yr^{-1}, mean ± SE), while hammock marshes lost elevation (-8.4 ± 1.7 mm yr^{-1}) but at a slower rate than headland marshes (-20.0 ± 1.7 mm yr^{-1}). Clearly, accounting for geomorphic type rather than using estimates from a single, well-studied marsh or a group of similar-type marshes is critical to understanding marsh dynamics at regional scales. For example, not accounting for marsh geomorphic type lead to a four-fold overestimation of marsh area increase (Chapter 2) and suggests that all marshes along the sea-side mainland of the Virginia Eastern Shore are losing elevation capital (Chapter 3).

The results of the analysis of the MARS model (Chapter 4) may be particularly useful to land managers, policymakers, local landowners, and researchers alike who have an interest in comparing the response of multiple marshes to sea-level rise. While it might be tempting to use tools like the MARS model developed to assess the relative vertical resilience of many marshes, my results show that this approach may overestimate susceptibility of marshes to sea-level rise in a transgressive setting like that considered in this thesis. All nine sites included in my study had relatively low resilience scores that ranged from -1.33 to 2.78, with an average index score of 0.06 ± 0.41. These scores are much lower than those received by 16 other sites across the coastal United States (Raposa et al. 2016), suggesting that the salt marshes I examined may be some of the least resilient salt marshes in the United States. However, the Virginia Eastern Shore salt marshes are responding to sea-level rise by maintaining, and even gaining, area through marsh migration inland (see Chapter 2). Thus, these marshes may be more resilient to sea-level rise than this model suggests.

When sea-level rises and the slope of the land is low enough to allow marsh migration, marsh replaces upland landcover types (Brinson et al. 1995). Currently, salt marshes along the mainland of the Virginia Eastern Shore are persisting as sea levels rise largely through lateral increases in area: marsh migration outweighed edge erosion leading to net gains in area at all study sites (this thesis). In the long-term, marsh migration into the uplands on the Virginia Eastern Shore will eventually halt due to steepening slopes. However, in the shorter-term, conversion from one land cover type to another can have economic consequences and marsh migration may be halted by building manmade barriers to protect agricultural fields, forests, or developed land creating conflicts between land owners, land managers and policymakers even when the value of ecosystem services provided by marshes is higher than the value of the uplands (Fagherazzi et al. 2019). Thus, engagement with stakeholders, such as local landowners whose land is adjacent to these migrating marshes, will become increasingly important to safeguard the persistence of wetlands with high conservation or restoration potential. Research, like that which is reported in this thesis, offers insight into how coastal ecosystems respond to sea-level rise and supports informed management and policy decision-making in coastal communities. It also provides a portion of the knowledge necessary to identify which marshes have the greatest conservation or restoration potential to as sea levels continue to rise.

5.2 References

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