Salt-Marsh Loss in a Barrier-Island System: Parramore and Cedar Islands, VA, from 1957 to 2012

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at George Mason University

by

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DEDICATION

I dedicate this thesis to my husband, Steve. His support throughout both my coursework and the writing of this document has been unending. He is my biggest cheerleader, and I would not have finished this process without him. I also would be remiss not to include my parents for always believing in me, and setting me up to be where I am today. And lastly, to my older siblings, for setting the bar very high.

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ABSTRACT

SALT-MARSH LOSS IN A BARRIER-ISLAND SYSTEM: PARRAMORE AND CEDAR ISLANDS, VA, FROM 1957 TO 2012

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Salt marshes can accrete and maintain their elevation with rises in sea level up to a certain rate before becoming inundated and converting to open water. This study examined the backbarrier salt marshes of the Parramore and Cedar barrier-island system along Virginia's Eastern Shore to determine whether they are maintaining their areal extent in the face of increasing relative sea-level rise. Based on NOAA tide gauge stations, relative sea-level rise rates along the Delmarva Peninsula range from 3.60 mm/yr for 1951 to 2014 at Kiptopeke, VA to 5.73 mm/yr for 1975 to 2014 at Ocean City Inlet, MD to 6.02 mm/yr for 1975 to 2014 at Chesapeake Bay Bridge Tunnel, VA. The Kiptopeke, VA tide gauge rates may be subdued by geological complexities of the underlying Chesapeake Bay Impact Crater, making the relative sea-level rise rate lower than neighboring stations. The rate of salt-marsh change was determined using historic aerial photographs from 1957, 1994, and 2012. The rate of total salt-marsh loss was 9.3 ±1.2 ha yr^{-1} (0.20 ±0.02% yr^{-1}) from 1957 to 1994 and increased to 14.0 ±0.63 ha yr^{-1}

($0.33 \pm 0.01\%\ yr^{-1}$) from 1994 to 2012. The increase in the marsh loss rate is attributed to the barrier fringe marsh, primarily along the landward edge of Cedar Island, VA because of overwash processes and landward island rollover. The barrier fringe marsh loss rate increased from $0.35 \pm 0.02\%\ yr^{-1}$ (1957-1994) to $0.95 \pm 0.01\%\ yr^{-1}$ (1994-2012). The other two types of marsh, island marsh and mainland marsh, had near constant marsh loss rates over the two incremental time periods, $0.17 \pm 0.02\%\ yr^{-1}$ and $0.16 \pm 0.02\%\ yr^{-1}$, respectively. The short-term barrier fringe marsh loss rate, $0.95 \pm 0.01\%\ yr^{-1}$, is similar to the findings for one sample area from a previous study in the region, $0.93\%\ yr^{-1}$ (Kastler and Wiberg, 1996). However, the same study estimated an island marsh loss rate of $0.27\%\ yr^{-1}$, higher than the island marsh loss rate found in this study ($0.17 \pm 0.02\%\ yr^{-1}$). For the period 1852-1962, Knowlton (1971) found an island marsh loss rate of 0.16% yr^{-1}, similar to this study's island marsh loss rate ($0.17 \pm 0.02\%\ yr^{-1}$) from 1957 to 2012. Therefore, the island marsh loss rate is not increasing over time. The stability in marsh loss rates in two out of the three marsh types during a period of increasing sea-level rise does not support the three-stage runaway transgression model for mixed-energy barrier islands as proposed by FitzGerald et al. (2006) at this time.

INTRODUCTION

Coastal salt marsh sustainability in the face of increasing rates of relative sea-level rise is the focus of much scientific research (Kirwan and Megonigal, 2013; Woodroffe and Murray-Wallace, 2012; Day et al., 2011; Kirwan et al., 2010). Defined as well vegetated saline intertidal flats, salt marshes occur at the boundary of saline and fresh-water environments, or brackish estuaries (Frey and Basan, 1985). Salt marsh formation occurs either where waves are highly subdued, or behind a barrier than blocks the open ocean energy; the establishment of salt marsh grasses occurs in low energy environments (Friedrichs and Perry, 2001). Tidal range and tidal duration are the most important factors in salt marsh distribution (Frey and Basan, 1985). Tides inundate salt marshes and supply sediment, the marsh grass traps the sediment, and the marsh vertically accretes, building soil elevation. The sedimentation rate must be greater than or equal to the sea-level rise rate in order for the salt marsh to survive (Kerwin and Megonigal, 2013). Other factors affecting salt marsh development include energy flow, nutrient flow, wave energy, storms, sediment composition, and species composition (Reed, 1990; Frey and Basan, 1985; Friedrichs and Perry, 2001). The inundation periods also flush out the soil and keep the vegetation from experiencing a potentially lethal, hypersaline growing environment (Morris et al., 2002). Marsh expansion can happen rapidly; once plants take root, they slow down the water flow and encourage sedimentation. Conversely, the water logging of plants and subsequent sediment loss can decrease marsh elevation just as rapidly (Friedrichs and Perry, 2001).

For 1901 to 2010, the global mean sea-level rise has been estimated at 1.7 mm/yr, whereas for 1993 to 2010, it has been estimated at a higher 3.2 mm/yr (IPCC, 2014). Local relative sea-level rise can vary markedly from global averages because of isostatic factors such as earth crust subsidence or rebounding. The Virginia Coast Reserve barrier islands along the outer coast of the southern Delmarva Peninsula are part of a region whose rates of relative sea-level rise are higher than the global average because of isostatic factors. In Kiptopeke Beach, VA (approximately 30 miles southwest of the Virginia Coast Reserve), the relative sea-level rise increased from 3.03 mm/yr for 1960 to 1984 to 3.98 mm/yr for 1985 to 2009 (Sallenger et al., 2012). It is important to note that the Kiptopeke tide gauge is located directly above the Chesapeake Bay Impact Crater formed when a meteorite struck 35 million years ago. The close proximity to the impact crater may be minimizing subsidence effects that the rest of the region is experiencing (Boon et al., 2010). The Kiptopeke station has lower relative sea-level rise rates than neighboring areas, such as Ocean City, MD (5.73 mm/yr) and Chesapeake Bay Bridge Tunnel, VA (6.02 mm/yr) as documented by NOAA (2015b). Erwin et al. (2006) calculated the rate of relative sea-level rise in the Virginia Coast Reserve at 3.9 mm/yr for at least a 50-year period.

Barrier-island systems are defined as a required set of the following six interacting sedimentary environments: mainland, backbarrier lagoon (estuary), inlet and inlet deltas, barrier island, barrier platform, and shoreface (Figure 1) (Oertel, 1985).

Within barrier-island systems, salt marshes develop along the estuary side of the barrier island (fringe marsh), along the mainland (mainland marsh), and as marsh islands in the backbarrier estuary (island marsh) (Figure 3). During periods of rising sea level, barrier islands often migrate landward and the marsh on their landward side decreases in areal extent or moves landward with the barrier island and associated estuary, if not blocked by natural or human-created barriers (Walters et al., 2014; Morris et al., 2002). The island-migration rate may be related to the amount of back-barrier sedimentation, back-barriers with rich sand deposits result in a slower migration rate (Brenner et al., 2015).

Tidal inlets of the barrier island system (Figure 2) acts as a connection between the open ocean and the estuary, moving tidal water and sediments into and out of the barrier island system (Oertel, 1981). Tidal inlets remain open because of the tidal currents operating through them (Hayes and Fitzgerald, 2013). Tidal inlet size will change in response to infilling of the backbarrier bay, and to changes in sea level (Oertel, 1981). As shown in Figure 2, inlet shoals can develop on either end of the inlet based on forces affecting sedimentation. Shoals developing on the landward side of the inlet are referred to as flood-tidal deltas because sedimentation during the flood tide (from low tide to high tide) causes them to develop. On the seaward side, shoals that develop there are referred as to ebb-tidal deltas because sedimentation on the ebb tide (from high tide and low tide) causes them to develop. Along mixed-energy coasts, tidal currents influence inlet morphology, and ebb-tidal deltas tend to be large and well developed, whereas flood-tidal deltas are small and poorly developed (Hayes and Fitzgerald, 2013).

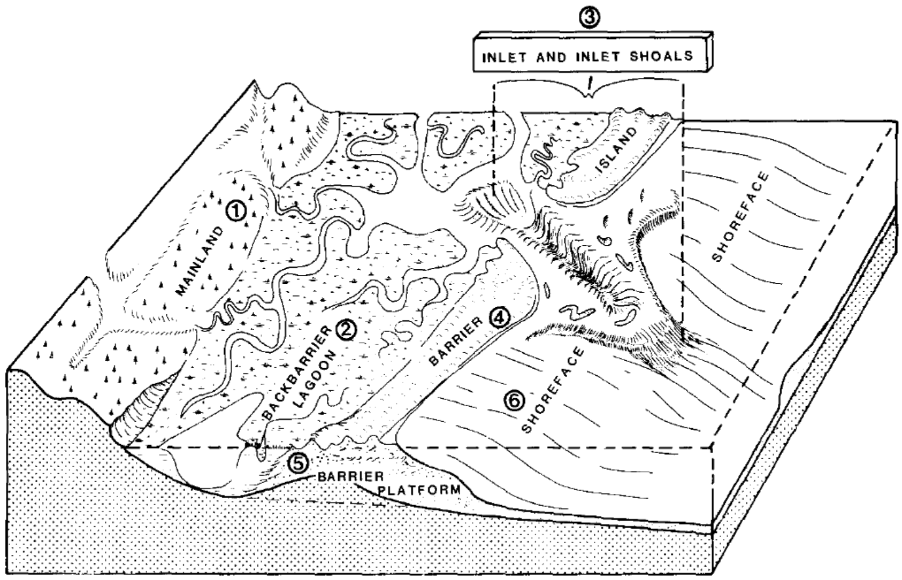

Figure 1. Barrier-island system with the six required interacting sedimentary environments (Oertel, 1985)

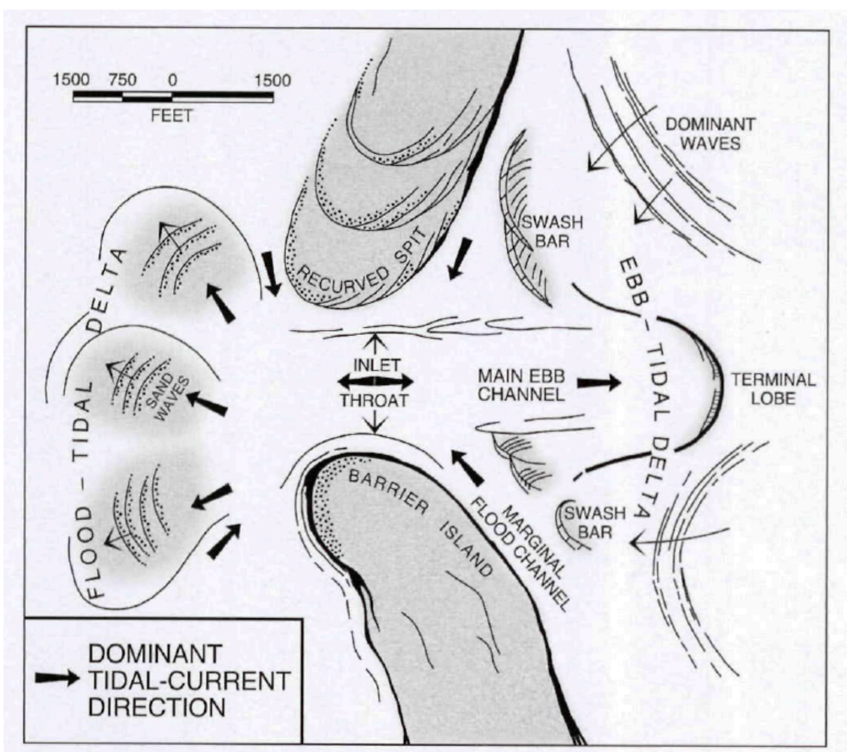

Figure 2. Tidal inlet morphology showing the three primary components: ebb-tidal delta, inlet throat, and flood-tidal delta (Hayes and FitzGerald, 2013)

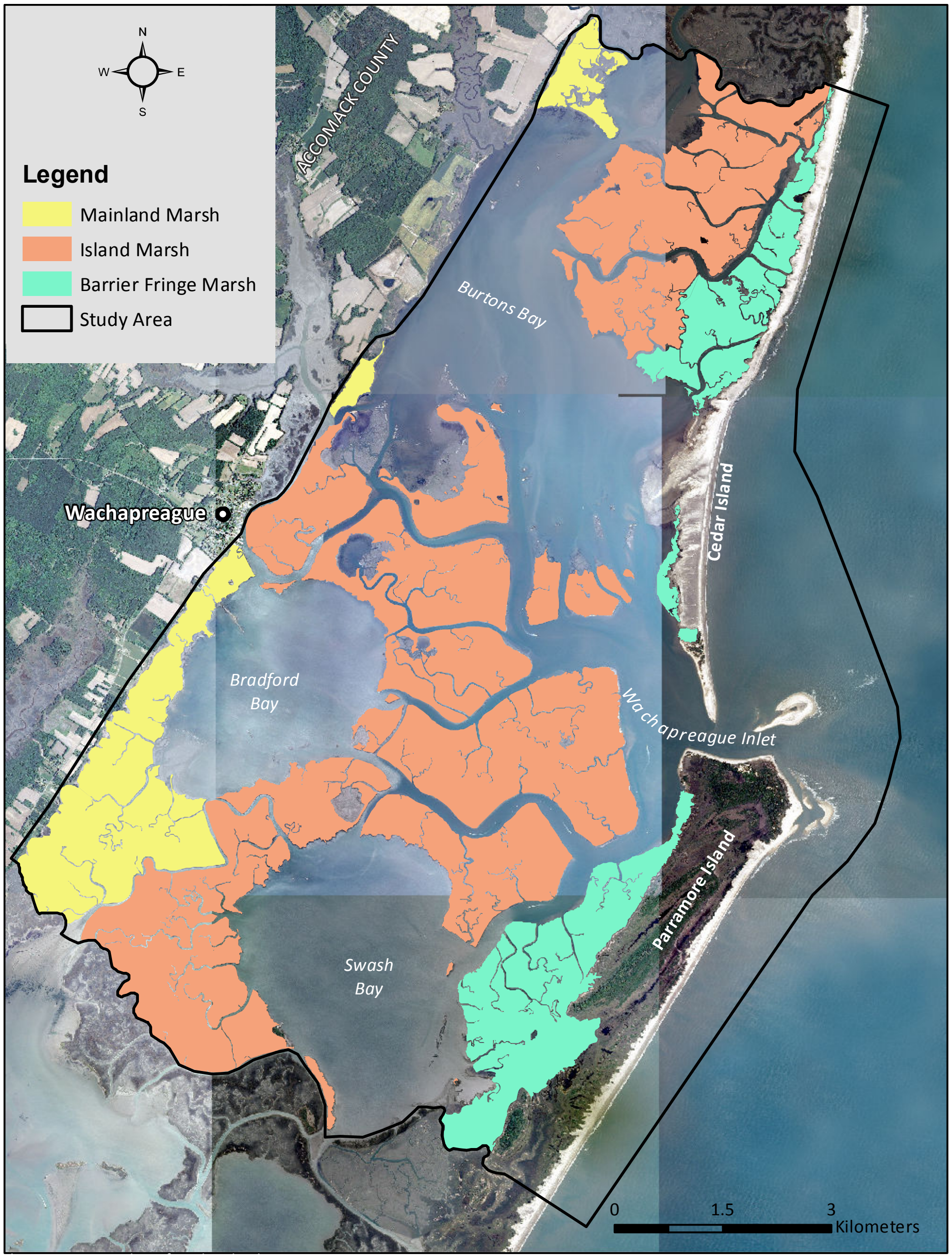

Figure 3. Marsh types in the study area barrier-island system

Salt marshes generally develop in times of lower relative sea-level rise rates (e.g., 0.5 to 2 mm/yr), but they can withstand higher rates once established (Engelhart and Horton, 2012; Kirwan and Megonigal, 2013). Approximately one thousand years ago, the rate of relative sea level rise was 1.3 mm/yr in the Virginia Coast Reserve area and marsh islands flourished (Hayden et al., 1991). A complex feedback system allows salt marshes to vertically accrete during higher rates of sea-level rise, which prevents their drowning and conversion to mudflats and open water; however, if the rate of relative sea-level rise is too fast, it can inundate and overwhelm salt marshes (Reed and Cahoon, 1992; Kirwan and Megonigal, 2013). The exact rate of sea-level rise that would cause salt marsh drowning to occur depends on a variety of factors, including sediment availability, tidal range, tidal duration, vegetative growth responses, storms, and available migration space (Kirwan and Megonigal, 2013; Erwin et al., 2006; Reed, 1990).

In Louisiana, at a relative sea-level rise rate of ~10 mm/yr, a marsh with high sediment supply is surviving, while a neighboring marsh with low sediment availability is being submerged (Kirwan et al., 2010). The Virginia barrier islands along the southern Delmarva Peninsula provide an example in which the vertical accretion rate may not be keeping pace with the rate of relative sea-level rise.

Study Area

The study area is on Virginia's Eastern Shore along the outer coast of the southern Delmarva Peninsula within the Virginia Coast Reserve. The Virginia Coast Reserve is part of a long-term ecological research network owned by The Nature Conservancy. This mixed-energy barrier-island system provides a unique study area because it is mostly a natural system and is undeveloped. This study focused on Cedar Island and Parramore Island within the Virginia Coast Reserve, which includes the tidal service area of Wachapreague Inlet, incorporating approximately the southern half of Cedar Island and northern half of Parramore Island and west to the mainland shoreline (Figure 5). The tidal prism is estimated to be 1.2 x 10^8 m^3 using a function of the backbarrier area (87,505,814 m^2) and the diurnal tidal range (Davis and FitzGerald, 2004). Tidal prism is the water volume that passes in or out through a tidal inlet during one half tidal cycle (e.g., from high tide to low tide), excluding any freshwater input from rivers. The average mean and diurnal tidal ranges in this area are 1.2 m and 1.4 m, respectively (CO-OPS, 2015b). The Virginia Coast Reserve is affected by both winter extratropical storms and storm surge from hurricanes as methods of landscape changes. Table 1 shows the specific coastal processes operating in the study area.

Table 1. Coastal processes operating in the estuaries of the Virgnia Coast Reserve

Coastal process	Value	Source
Mean tidal range	1.2 m	CO-OPS, 2015b
Diurnal tidal range	1.4 m	CO-OPS, 2015b
Eustatic sea-level rise (1993–2010)	3.2 mm/yr	IPCC (2014)
Relative sea-level rise (1975–2014, Ocean City, Maryland)	5.73 mm/yr	NOAA (2015b)
Subsidence rate (Maryland)	1.2 mm/yr	Engelhart et al. (2009)
Wachapreague Inlet tidal prism (April 2011)	6.09 x 10^7 m^3	Richardson (2012)

Both islands have been dynamic for the last 150 years; Cedar Island has migrated landward while Parramore Island has experienced clockwise rotational instability (Gaunt, 1991; Leatherman et al., 1982). Over the short term, both islands have experienced increased retreat rates (Richardson and McBride, 2007, 2011). Parramore Island retreated 12.2 m/yr from 1998 to 2010 and Cedar Island retreated 15.4 m/yr from 2007 to 2010 (Richardson, 2012).

Dividing Cedar and Parramore Islands is Wachapreague Inlet, a deep and relatively stable tide dominated inlet that is characterized by a large, well-developed ebb delta, a deep inlet throat with a maximum depth of 21.9 m, and a small flood-tidal delta, as documented by Byrne et al. (1974) and Richardson (2012). Wachapreague Inlet is ebb tide dominated, having a greater ebb velocity, and net ebb transport (out of the estuary) of bottom sedimentary materials (Boon and Byrne, 1981). The greater ebb velocity is caused by an ebb tide duration that is less than the flood tide duration. The asymmetry of the ebb tide and flood tide duration is a function of the basin hypsometry (the distribution of surface area with height) and the inlet channel configuration (Boon and Byrne, 1981).

Relative sea level in this region is influenced by both eustatic and isostatic factors. Isostatic sea-level rise occurs because of subsidence from glacial forebulge collapse (Engelhart et al., 2011). The study area is located south of the extent of the Laurentide Ice Sheet at the last glacial maximum, 21 thousand years before present. In response to the weight of the ice sheet, a forebulge in the earth crust occurred out in front of the ice sheet that affected the Mid-Atlantic region. As the Laurentide Ice Sheet retreated, since the last glacial maximum to present, the crust under it has rebounded, whereas the forebulge is collapsing in turn, causing subsidence (Engelhart et al., 2011; Peltier, 1996). Figure 4 shows the relationship of post-glacial rebound and glacial forebulge collapse. Engelhart et al. (2009) determined that the subsidence rate in Virginia was approximately 0.9 mm over the last century because of the forebulge collapse. Table 2 outlines the rates of relative sea-level rise along the coast from north to south with our study area located in between the Ocean City and Chesapeake Bay Bridge Tunnel tidal stations. The higher sea-level rise rates in this area caused by subsidence may provide insight for future sea-level rise response in areas that are currently experiencing lower sea-level rise rates.

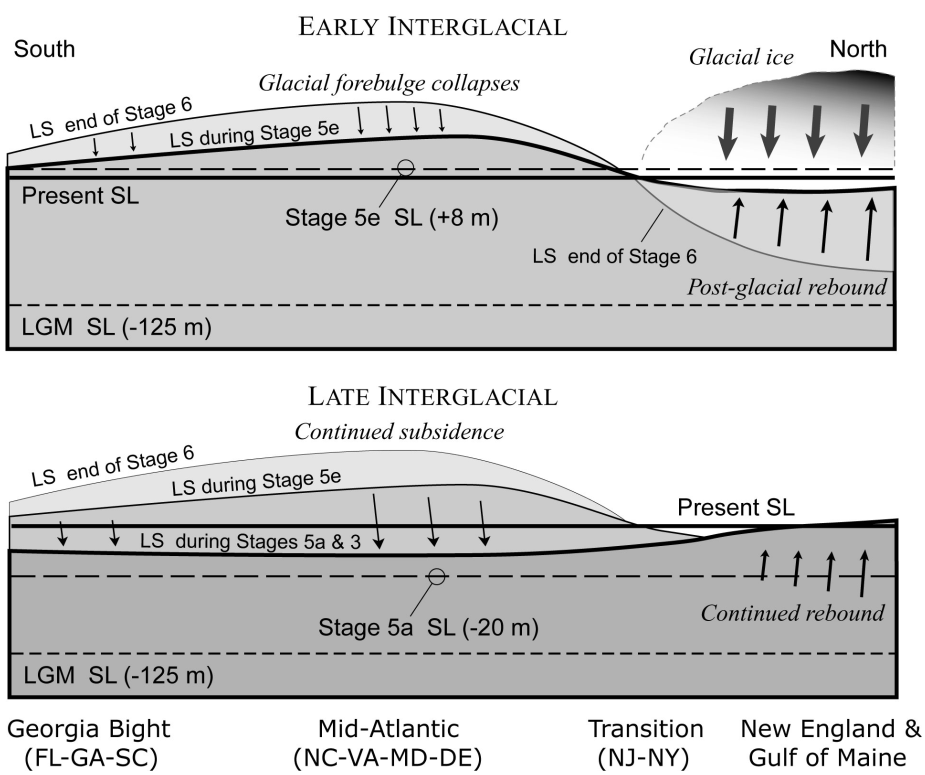

Figure 4. Post-glacial rebound and forebulge collapse, LS-land surface, SL-sea level, LGM-last glacial maximum, Stage-marine isotope stages, Stage 6-191 ka, Stage 5e-123 ka, Stage 5a-82 ka (Hobbs et al., 2008)

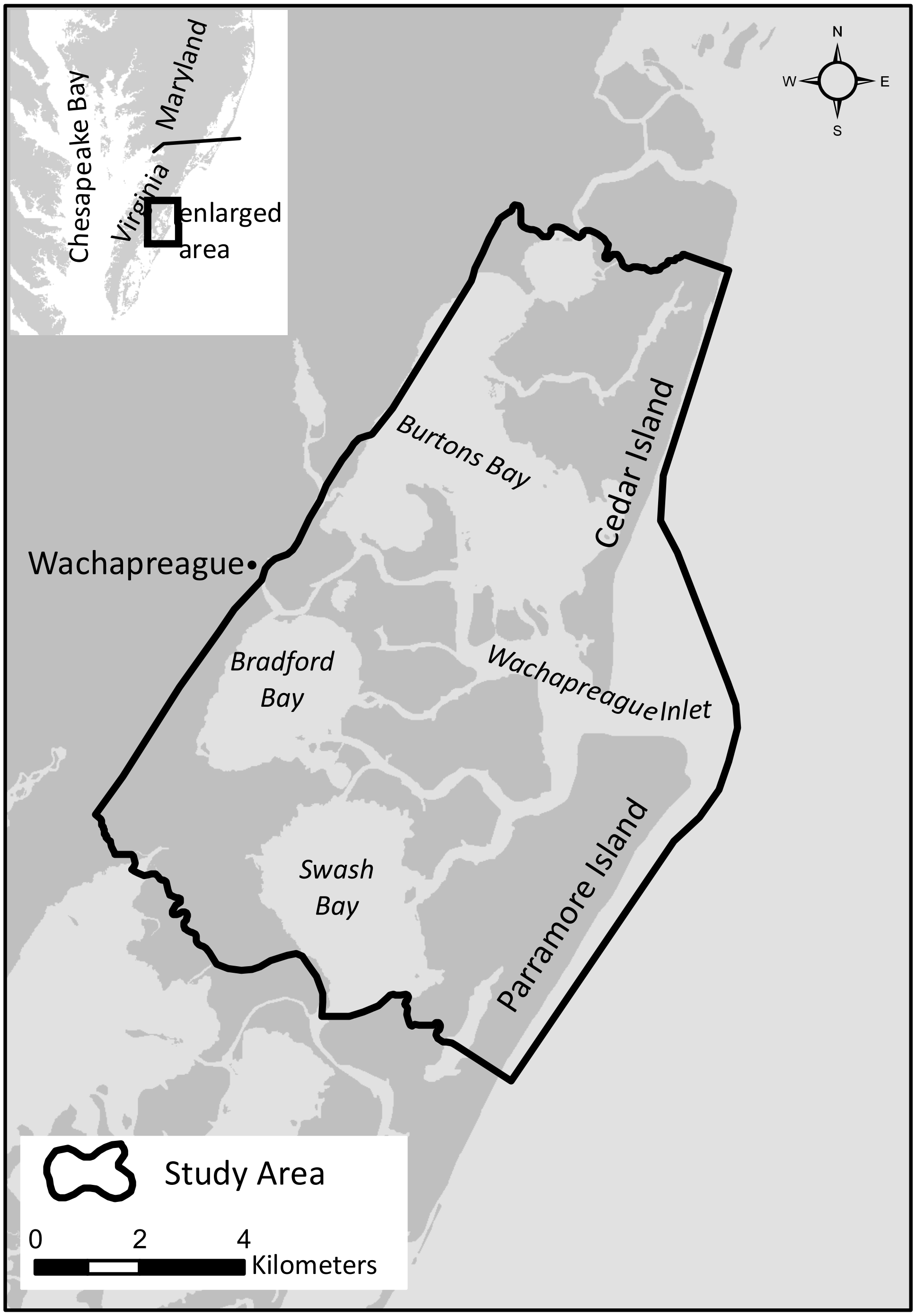

Figure 5. Study Area

Table 2. Alongshore trend in relative sea level rise rates based on tide gauge data along the U.S. mid-Atlantic coast (NOAA, 2015b)

Tide Gauge Location	Start Year	End Year	MSL Trend in mm/yr (+/- 95% CI)
The Battery, NY	1856	2014	2.84 (0.09)
Sandy Hook, NJ	1932	2014	4.08 (0.22)
Atlantic City, NJ	1911	2014	4.08 (0.16)
Cape May, NJ	1965	2014	4.62 (0.57)
Philadelphia, PA	1900	2014	2.94 (0.19)
Reedy Point, DE	1956	2014	3.60 (0.51)
Lewes, DE	1919	2014	3.41 (0.25)
Ocean City Inlet, MD	1975	2014	5.73 (1.01)
Kiptopeke, VA	1951	2014	3.60 (0.34)
Chesapeake Bay Br. Tunnel, VA	1975	2014	6.02 (0.79)
Oregon Inlet Marina, NC	1977	2014	3.85 (1.29)
Beaufort, NC	1953	2014	2.83 (0.37)

Previous Research

Erwin et al. (2006) used sediment elevation tables to determine marsh accretion rates and found that marshes in the Virginia Coast Reserve were not keeping pace with sea-level rise over a four-year period (1999–2003). The rates at which salt marshes accrete vertically have been estimated at 1.5 mm/yr for island marshes, and 4.2 mm/yr for barrier fringe marshes (NRC, 1987). A more recent review of published accretion rates found that *S. alterniflora* marshes have an average accretion rate of 6.1 mm/yr (FitzGerald et al., 2006). Boon and Byrne (1981) modeled Swash Bay, a marsh basin behind Parramore Island, and found the hypsometry caused a flood tide duration 0.8 h longer than the ebb tide during. The shorter ebb tide indicated a greater peak velocity sediment transport out of the main Swash Bay channel.

Table 3 summarizes previous research in the Virginia Coast Reserve to determine salt-marsh area change. Knowlton (1971) estimated that between 1852 and 1962, a 16% marsh loss occurred in the Virginia Coast Reserve island marshes (four sample areas distributed from Mockhorn Island in the south to Wallops Island in the north), which was attributed primarily to barrier island migration, and secondly to other factors including wind erosion, channel migration, and human activities. Erwin et al. (2004) documented a 10.2% marsh loss between 1949 and 1994 in a small area of island marsh near Curlew Bay, just west of Wachapreague Inlet. Kastler and Wiberg (1996) analyzed aerial photography at three marsh sites (barrier fringe, island marsh, and mainland marsh) within the Virginia Coast Reserve, just south of the study area, to determine the salt-marsh change. A 7.2% loss of the barrier fringing marsh (Parramore Island) between 1982 and 1990, and a 10.6% loss of the island marsh (Chimney Pole) between 1949 and 1990 were documented (Kastler and Wiberg, 1996). Kastler and Wiberg (1996) attributed the barrier fringe marsh loss to beach retreat and burial by sediment transported landward by overwash processes, counteracted by some marsh accretion into the estuary. The island marsh loss occurred mainly as erosion along the marsh edges caused by estuarine tidal processes.

Table 3. Previous marsh change study results in the estuaries of the Virginia Coast Reserve

Previous study	Marsh type	Years studied	Change (%)	
			Total	Per Year*
Knowlton (1971)	Island	1852–1962	−16.0	−0.16
Kastler and Wiberg (1996)	Barrier fringe	1982–1990	−7.2	−0.93
Kastler and Wiberg (1996)	Island	1949–1990	−10.6	−0.27

*averaged annual rate

As described by Kastler and Wiberg (1996), marsh change in this area is greatly influenced by tidal currents and barrier island migration (in the form of overwash). As such, examining how barrier-island systems evolve over time should explain marsh loss or gain in the system. The Parramore-Cedar barrier-island system is experiencing increasing relative sea-level rise, and FitzGerald et al. (2006) developed a conceptual model of mixed-energy barrier islands behavior during such a period.

The FitzGerald et al. (2006) three-stage model (Figure 6) predicts that in times of accelerating sea-level rise, sand trapping at tidal inlets causes the conversion of estuarine marsh into open water because less sediment is nourishing the marsh surface and vertical marsh accretion is inhibited. This marsh loss increases the tidal prism, traps more sand in ebb- and flood-tidal deltas, and causes fragmentation and transgression of the barrier island chain. The change from a stable barrier island to Stage 1, referred to as Marsh Decline, occurs when the rate of relative sea-level rise has increased enough to inundate and convert parts of the marsh to open water. The conversion of marsh to open water increases the tidal discharge and strengthens the tidal flow. The increase in the tidal flow increases the size of the tidal inlet. The subsequent increased tidal prism facilitates additional sediment trapping on the ebb-tidal and new flood-tidal deltas. Increased sediment trapping decreases the ability of marsh to accrete, and the marsh inundation and degradation continues in Stage 2, Fringing Marsh and Marsh Island. At this point only small marsh areas remain, and the tidal prism continues to increase such that the barrier-island system becomes flood-tide dominated. This causes landward sand movement, and the barrier island migrates landward. Moving into Stage 3, Runaway Transgression, the island continues to migrate landward and many new inlets form (FitzGerald et al., 2006).

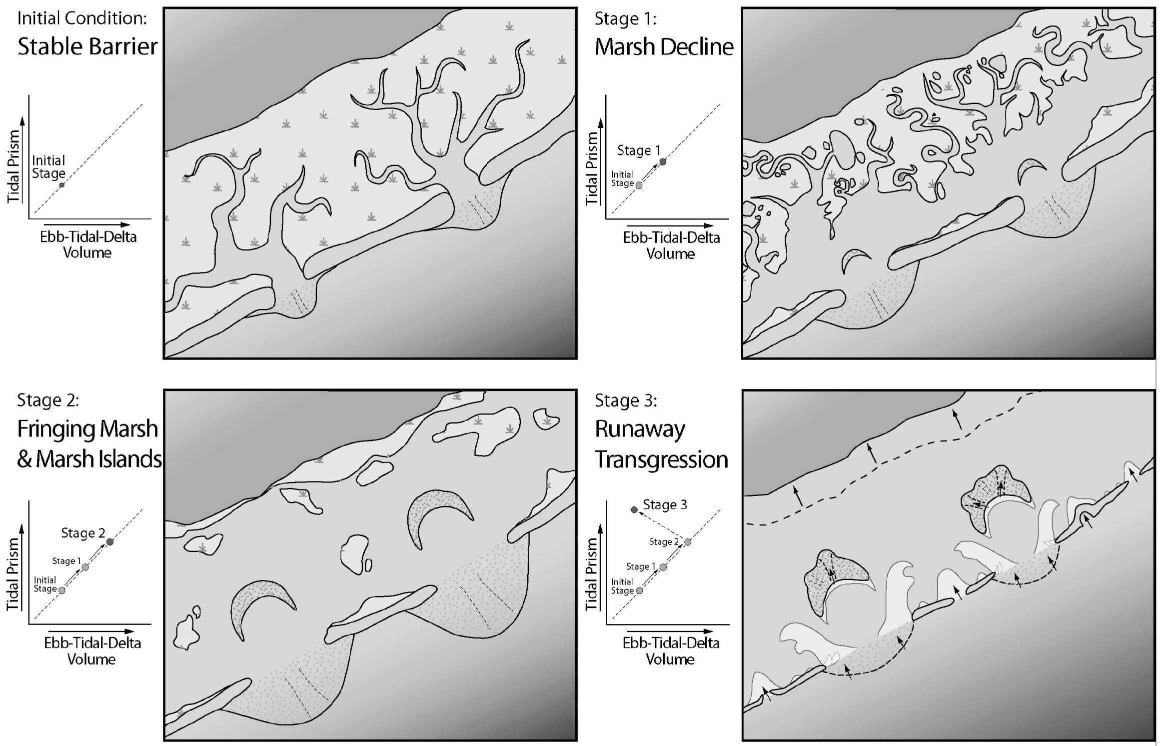

Figure 6. Three-stage Runaway Transgression Model (FitzGerald et al., 2006)

HYPOTHESES

Research Questions

1. Historically, is the salt marsh area landward of Parramore and Cedar Islands decreasing, stable, or expanding?
2. If change has occurred, where are the losses and gains in marsh area occurring (tidal creek expansion, ponding, edge erosion, washover, etc.)?
3. Are the sample marsh change areas of Kastler and Wiberg (1996) representative of overall marsh changes in the barrier-island system, under-representative, or over-representative?
4. If change has occurred, do the salt-marsh changes refute or support FitzGerald's et al. (2006) three-stage model?

Multiple Working Hypotheses

1. No change occurred in salt marsh area over time.
2. The decrease in salt marsh over time in the study area is similar to the results of the Kastler and Wiberg (1996) study of the backbarrier marshes in the southern Parramore Island system.
3. The change in salt marsh over time in the study area is different than the results of the Kastler and Wiberg (1996) study of the backbarrier marshes in the southern Parramore Island system.

4. The decrease in salt marsh area is such that it matches Stage 1 of FitzGerald's et al. (2006) three-stage model, and therefore supports the model.
5. The change in salt marsh area is such that is does not match any stages in FitzGerald's et al. (2006) three-stage model, and therefore refutes the model.

Purpose

Kastler and Wiberg (1996) examined small marsh areas in the barrier-island system to calculate change rates. The barrier fringing marsh studied was directly north of Quinby Inlet, which is known to be a dynamic area subject to short-term and long-term changes. Examining only that portion of the Parramore Island barrier fringing marsh might be overlooking the larger dynamic system because sediment may be redistributed around the island. Sediment eroding from some parts of the marsh can promote vertical accretion in other parts of the marsh (Kirwan and Megonigal, 2013). My study investigated a larger area of backbarrier marsh served by Wachapreague Inlet in order to capture the possibility of marsh erosion in one area and marsh accretion elsewhere caused by sediment redistribution. The changes in salt marsh area in the Parramore and Cedar barrier-island system were determined over three time periods: 1957 to 1994, 1994 to 2012, and 1957 to 2012 and were compared to Kastler and Wiberg's (1996) sample areas to determine whether they are representative of the larger system over a longer period. Furthermore, my change findings were compared to Knowlton (1971) to determine whether the marsh change rate is slowing, accelerating, or remaining stable. The results were used to test the FitzGerald et al. (2006) three-stage model.

My aim is not to determine the mechanism(s) by which marsh change occurs, but to determine how much change occurs over three distinct time periods (1957, 1994, and 2012), and in which part of the marsh system it occurs. This knowledge will inform subsequent studies that chose to investigate the mechanisms that operate in this and similar marsh systems. Investigating the entire system will provide useful information for other studies such as the appropriate scale at to examine marsh change to approximate the consequences of accelerating sea level rise.

Objectives

1. To determine the change of salt marsh area in the Parramore and Cedar barrier-island system over three time periods (i.e., 1957, 1994, and 2012) and compare them to Kastler and Wiberg's (1996) findings for the sample of Parramore Island fringe marsh and Chimney Pole island marsh, as well as compare them to Knowlton (1971) results.

2. To use the findings in Objective 1 to determine if the Parramore and Cedar barrier-island system supports or refutes FitzGerald's et al. (2006) three-stage model of barrier island evolution.

METHODS

Timeframe

High-resolution aerial photography was used to manually delineate the extent of salt marsh at three time points: October 14, 1957; March 20, 1994; and May 12, 2012. This allowed for the change in salt marsh extent to be calculated for three time periods, 1957 to 1994, 1994 to 2012, and 1957 to 2012. The years were chosen based on availability, complete coverage of study area, and quality of aerial photographs.

Data Sources

The details of the aerial photographs used for each year are shown in Table 4. The 1957 aerial photographs were obtained from the USDA Farm Service Agency Aerial Photography Field Office (APFO). Thirteen photographs covered the study area, and were scanned at 12.5 microns and provided in digital format by the APFO. The 1994 aerial photographs were downloaded from USGS's Earth Explorer data portal in Digital Orthophoto Quadrangle (DOQ) format. The 2012 aerial photographs from the USDA National Agricultural Imagery Program were also downloaded from USGS's Earth Explorer data portal. Figure 7 shows a sample area of each year's aerial photography.

Table 4. Aerial photography for analysis

Image Type	Date	Source	Scale/Resolution	Georeferenced
Black and White	October 14, 1957	Farm Service Agency, US Department of Agriculture	1:20000 (scanned at 12.5 microns)	No
Color Infrared	March 20, 1994	National Digital Ortho Program (NDOP)	1m	UTM Zone 18N
Multi Resolution 4 band	May 12, 2012	National Agricultural Imagery Program (NAIP)	1 m	UTM Zone 18N

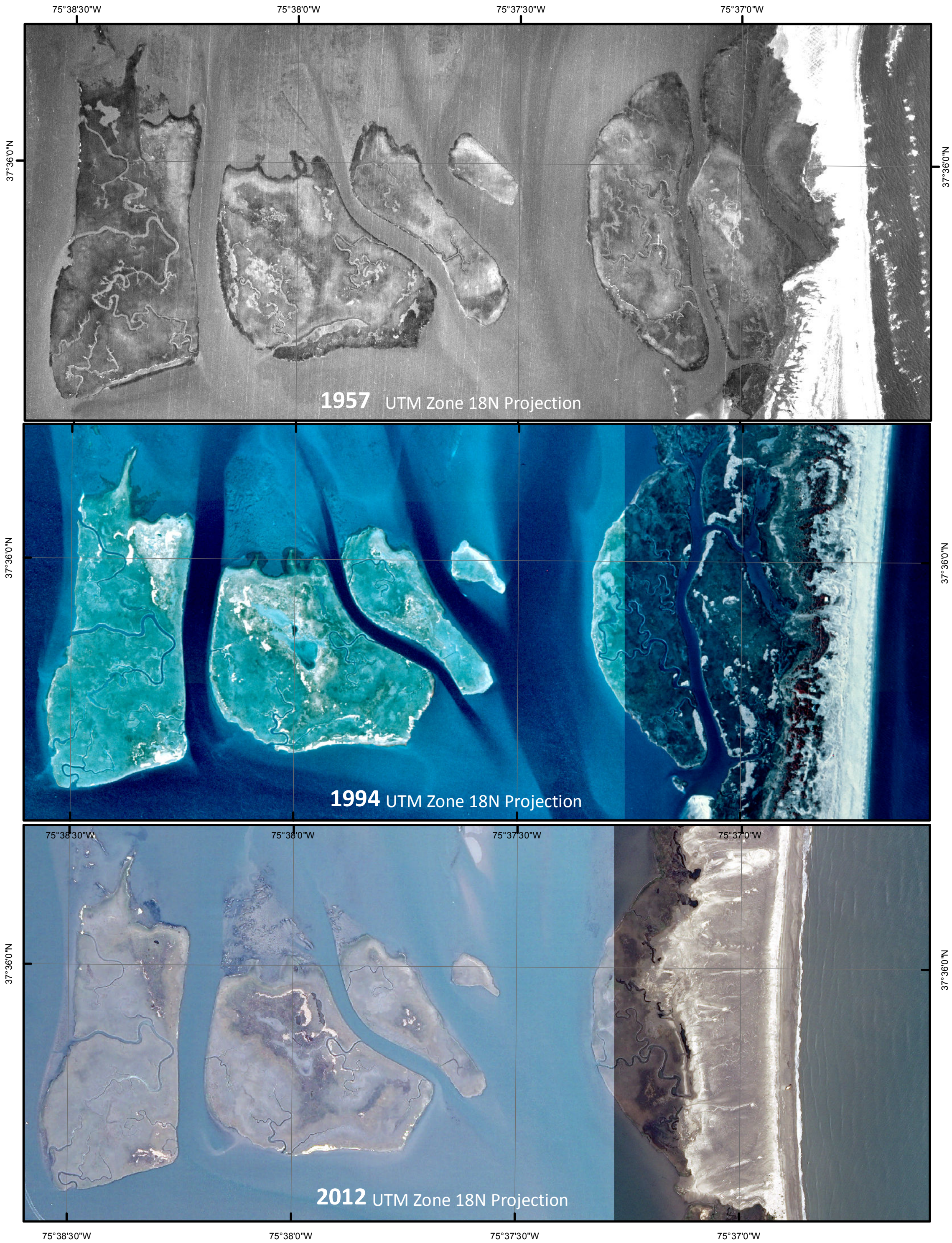

Figure 7. 1957, 1996, and 2012 aerial photograph samples

Image Pre-Processing

In order to compare year over year marsh extent, the aerial photographs needed to be in the same geographic coordinate system. The 1994 and 2012 dataset were already in the Universal Transverse Mercator (UTM) Zone 18N coordinate system, so that was chosen as the reference coordinate system. The 1957 unreferenced aerial photographs were converted into the Universal Transverse Mercator (UTM) Zone 18N coordinate system. Polynomial georectification was performed on each of the 13 photographs from the study area. Polynomial georectification converts photographic data file coordinates to a known geographic coordinate system by identifying ground control points (GCPs), computing an approximate transformation matrix, and resampling the image (Baily and Pearson, 2007).

GCPs were located and matched to the referenced 1994 dataset (Higinbotham et al., 2004). One of the photographs was unable to be referenced to the 1994 dataset because of a significant amount of change in the area. For this photograph, it was referenced to its overlapping, neighboring 1957 photographs after they were referenced to the 1994 dataset. Given the undeveloped nature of the study area, the GCPs were difficult to locate. Best practice in selecting GCPs is to use hard structures that do not move over time, but those do not exist in most of the study area. Instead natural GCPs were used such as the intersection of tidal creeks, tidal creek patterns, individual trees, and dredge spoil piles, which have been successful in other studies (Baily and Pearson, 2007; Cox et al., 2003; Higinbotham, 2004). It is believed that the lateral migration of these creeks is insignificant within the vegetated marsh (Cox et al., 2003). Even so, best judgment was used to choose tidal creek intersections that did not appear to be migrating, changing meander, or widening. GCPs were distributed widely across the photograph to provide 'stable warp' (Hughes et al., 2006), with the exception of one photograph that was mostly open ocean. The study area consists of intertidal zone with minimal topographical variation, and therefore a two-dimensional transformation is sufficient (Cox et al., 2003). Second order polynomial transformation was applied to the 1957 images to convert them into UTM Zone 18N coordinate system, with the exception of the photograph where the GCPs were not distributed completely across the photograph. For that photograph, first order transformation was used, this avoided unnecessary bending and curving that occurred when trying to transform the whole image based on the small area with GCPs. In order to minimize warp in the output rectified images, cubic convolution resampling was applied, chosen to smooth fluvial edges (Hughes et al., 2006). The root mean square (RMS) error was determined for the georectification process, with a target error of less than 5 m. RMS error is the difference in location between the GCPs on a transformed image and the base layer (Hughes et al 2006).

Table 5 shows the georeferencing details for each 1957 photograph. After georeferencing, adjacent images did not match up perfectly, but the shift was less than 10 m. The photograph edges were expected to have the greatest error and to the extent possible were not used in delineating the marsh.

Table 5. Georefencing details for the 1957 photographs

1957 photograph filename	1994 file(s) used for reference	Number of GCPs	Type of GCP	RMS error (m)	Resolution (m)
ANO_2T_167.tif	C3707528.NWS.728510.tif C3707527.NES.65847.tif	8	Tidal creeks and 2 hard structures	1.39	0.25
ANO_2T_188.tif	C3707527.NES.65847.tif	11	All tidal creek	3.22	0.24
ANO_2T_169.tif	C3707528.SWS.728511.tif C3707527.SES.65849.tif C3707528.NWS.728510.tif C3707527.NES.65847.tif	8	Tidal creeks, vegetation pattern, hard structures	1.64	0.26
ANO_2T_184.tif	C3707527.SES.65849.tif	7	Tidal creeks, vegetation patterns	1.83	0.25
ANO_2T_186.tif	C3707527.NES.65847.tif C3707527.SES.65849.tif	9	All tidal creek	3.00	0.26
ANO_3T_101.tif	C3707527.SES.65849.tif C3707527.SWS.65850.tif	8	All tidal creek	1.95	0.24
ANO_3T_99.tif	C3707527.SWS.65850.tif C3707527.SES.65849.tif C3707527.NES.65847.tif C3707527.NWS.65848.tif	9	Hard structure (roads, houses), tidal creeks	2.49	0.24
ANO_3T_97.tif	C3707527.NES.65847.tif C3707527.NWS.65848.tif	7	Hard structure (roads, houses), tidal creeks	0.68	0.24
ANO_2T_190.tif	C3707527.NES.65847.tif C3707519.SES.65845.tif	7	Hard structures, tidal creeks	0.24	0.26
ANO_2T_165.tif	Referenced to overlapping 1957 georeferenced images, the central area in this photo has changed dramatically so GCPs could not be located across both years	9	All tidal creeks and landforms, not well distributed	2.77	0.25
ANO_2T_163.tif	C3707520.SWS.65834.tif C3707519.SES.65845.tif	8	Mostly tidal creeks, one structure	1.75	0.24
ANO_5T_143.tif	C3707520.SWS.65834.tif	8	All tidal creeks, only around area of photograph in study area	3.2	0.25
ANO_3T_133.tif	C3707527.SWS.65850.tif C3707527.NWS.65848.tif	8	7 road intersections, 1 tidal creek	0.55	0.25

Marsh Delineation

Marsh extent for each year was determined by manually delineating the marsh boundaries from aerial photographs at a scale of 1:2,000. This method was chosen over automated classification because the 1957 black and white photographs do not include enough spectral information to allow for automated classification. In order to be consistent across all years, manual delineation was completed for the 1994 and 2012 datasets as well. Figure 8 shows example areas of the delineation decisions for each of the dataset years.

The gray scale tone, color, texture, shape, contrast, and pattern differences were used to interpret the marsh boundaries. The marshes on and around Cedar and Parramore Islands consist almost entirely of the *S. alterniflora* species, so marsh grass types were not differentiated (Hayden et al., 1995). The delineation involved drawing the boundary between marsh and water/mudflat and between marsh and upland. Limitations included the quality of some photos, time constraints, and the level of detail possible using the manual delineation method.

Delineation was started on the 2012 images because they were the highest quality and allowed for some spot verification with other recent datasets. This process also served as training on the types of patterns, tones, and texture that marsh vegetation exhibits in aerial photography. Landcover information from other studies and datasets was used for verifying some of the delineation decisions (Shao et al., 1998; Silberhorn and Harris, 1977; NOAA, 2015a).

In general, the water edge of the marsh in the study area was obvious, although in some areas where the marsh was degrading, the line was less obvious (see Figure 8). The delineation was conservative, and only areas where it was clearly apparent that no vegetation was present were counted as water. This means that many areas of degraded marsh were still counted as marsh, although they might have contained small mudflat areas. Only in small areas on the backside of Parramore Island and the mainland were the line between *S. alterniflora* and other vegetation difficult to delineate. In some instances in order to differentiate between the different vegetation types, a standard deviation texture transformation was run on the image. After the texture transformation, areas with more tonal variation are highlighted. The *S. alterniflora* has less tonal variation than the higher vegetation types, and the texture file was used to determine location of the edge between the two types.

The delineation included as much detail as possible, but because the salt marsh forms many small islands, only marsh creeks and channels over 10 m wide in at least one of the three years were delineated (see Figure 8). Creeks and channels narrower than 10 m were included as marsh. Interior marsh ponds were delineated only if they were larger than 0.5 ha (5,000 m^2); otherwise they were included as marsh.

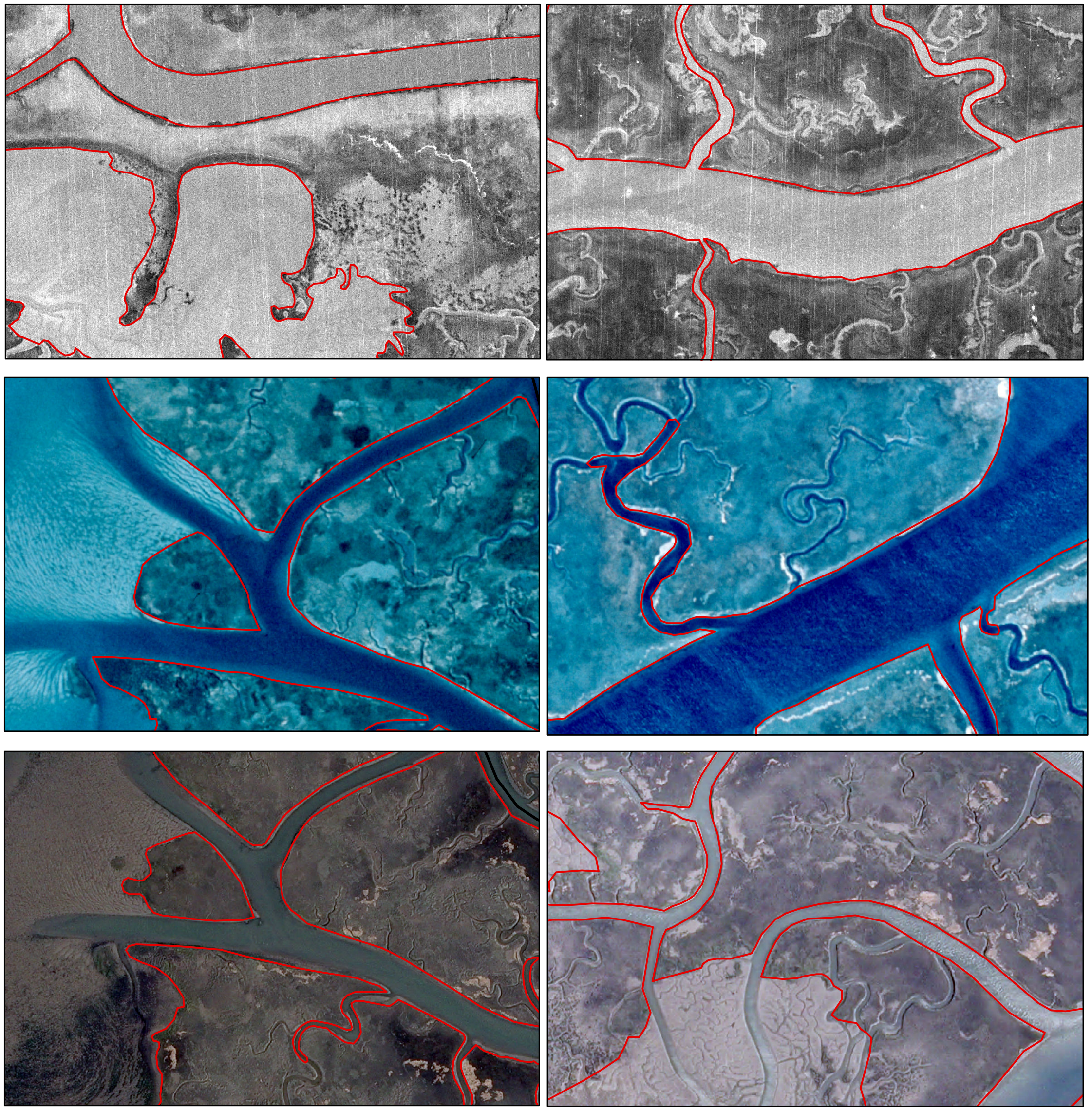

Figure 8. Marsh delineation (in red) on 1957 (top row), 1994 (middle row), and 2012 (bottom row) aerial photographs.

The delineated marsh area was calculated for each year using ArcGIS's 'calculate geometry' tool. Using those areas, a change rate was then calculated for the two subsequent incremental time periods (1957-1994 and 1994-2012), and the total time (1957-2012) using the exact number of days between the photograph dates. This process was repeated for each of the three marsh types (shown in Figure 3) to further differentiate the marsh change rates by location within the system. The marsh area for each of the three years were overlain in ArcGIS, and new files created showing the difference between each year created (using the 'erase' tool in ArcGIS). These difference files were used to create maps displaying the areas changed over each incremental time period.

Digitizing and classification error was determined by replicating the marsh delineation within a 2,025-hectare area subset (the approximate size of a doq photograph) (Figure 9) for each year. The area was selected to include both island marsh and fringe marsh, and span multiple photographs. The same subset area was used to create a second delineation for the 1957, 1994, and 2012 datasets. During the second delineation, for locations where an uncertain boundary occurred, an intentional effort was made to make the opposite decision as the original delineation. This ensured areas of uncertainty contributed to the error estimate. The spatially explicit difference between the marsh area in the second delineation, and the marsh area in the original delineation within the 2,025-hectare subset area was calculated for each dataset year. The percent difference was used as the error estimate percent for each dataset year, and applied to the total marsh area, and the separate marsh type areas to determine an error estimate in hectares. An upper bound and lower bounds of the marsh areas were calculated for each marsh type and dataset year using the error estimate, and subsequently used to calculate a range of the change rates. This range was used for the change rate error estimates.

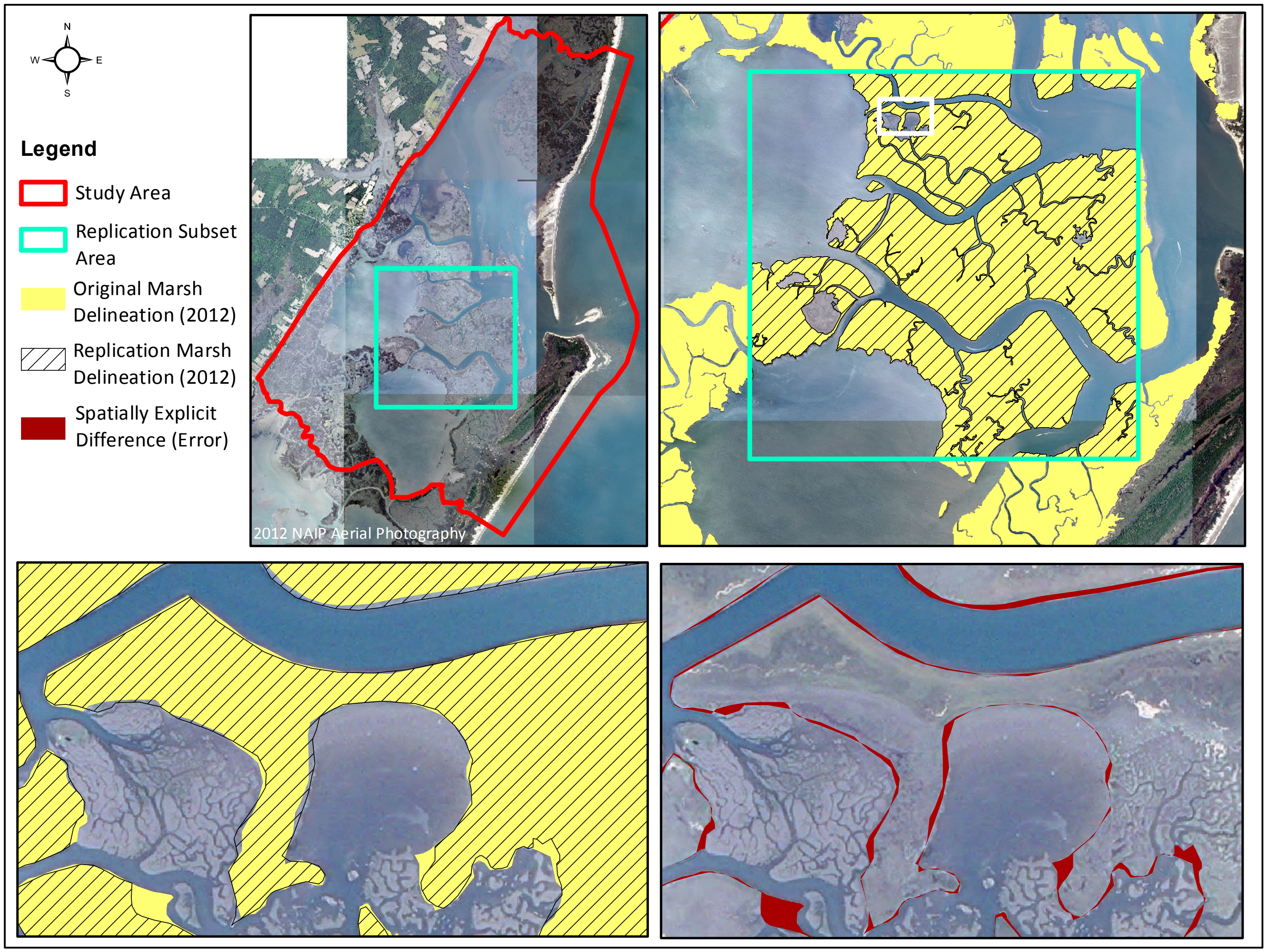

Figure 9. Replication subset area within study area(top left), replication delineation and original delineation(top right), portion of replication delineation and original delineation (bottom left), and portion with difference highlighted (bottom right).

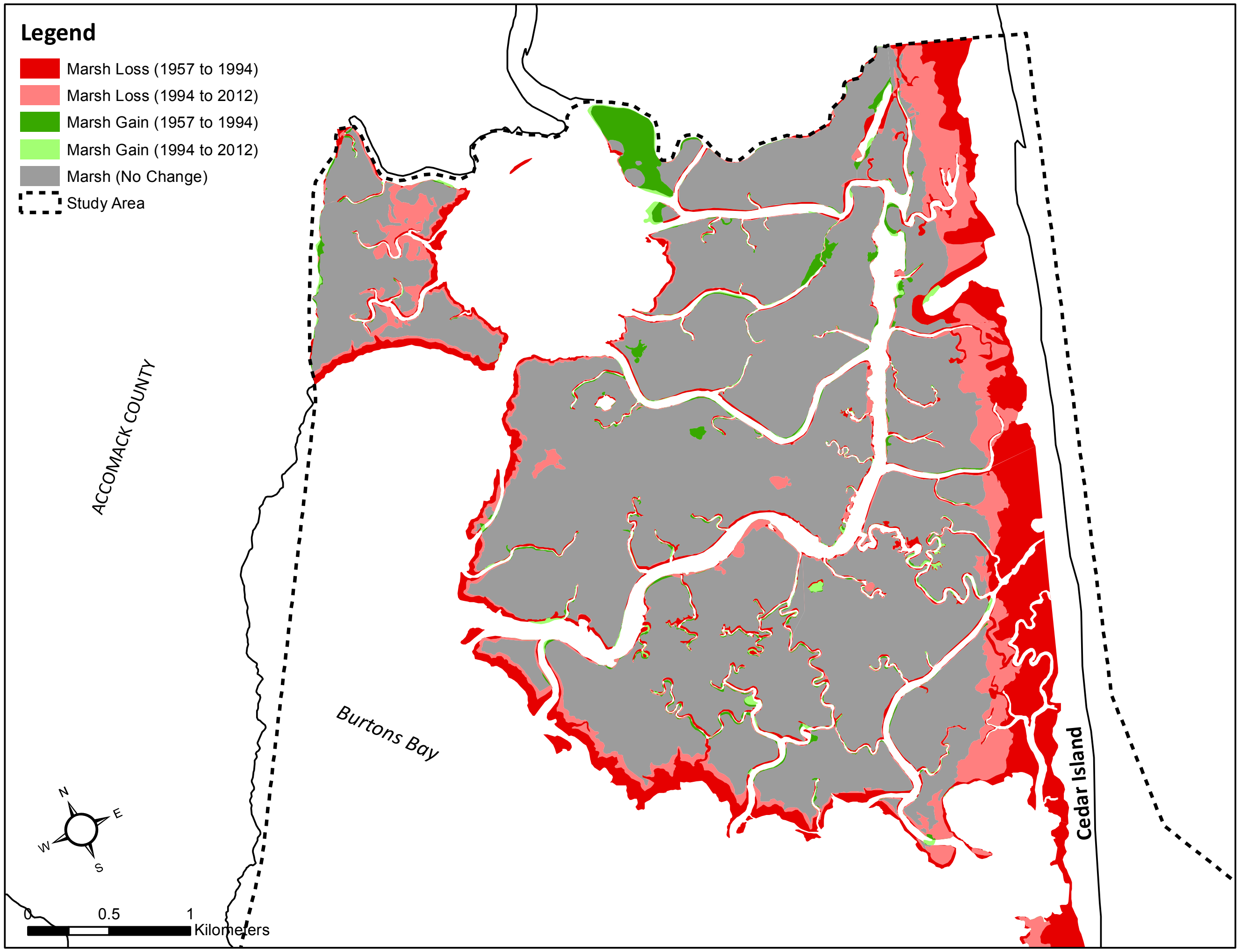

Figure 11B. Inset B from Figure 11A, showing marsh loss and gain in the Parramore and Cedar barrier-island system (1957–1994 and 1994–2012). (Loss/gain locations derived from USDA, 1957; USGS, 1994; USDA, 2012)

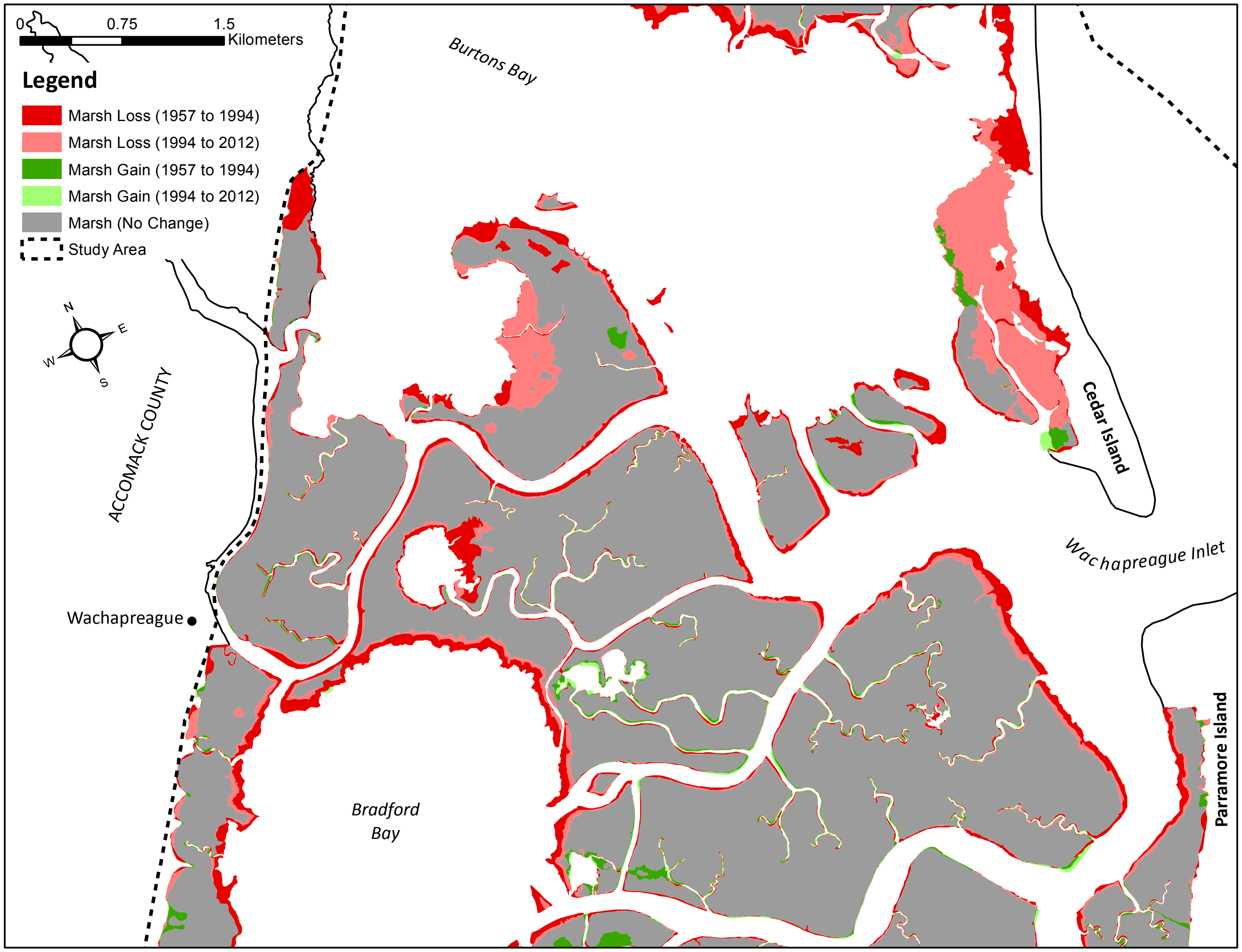

Figure 11C. Inset C from Figure 11A, showing marsh loss and gain in the Parramore and Cedar barrier-island system (1957–1994 and 1994–2012). (Loss/gain locations derived from USDA, 1957; USGS, 1994; USDA, 2012)

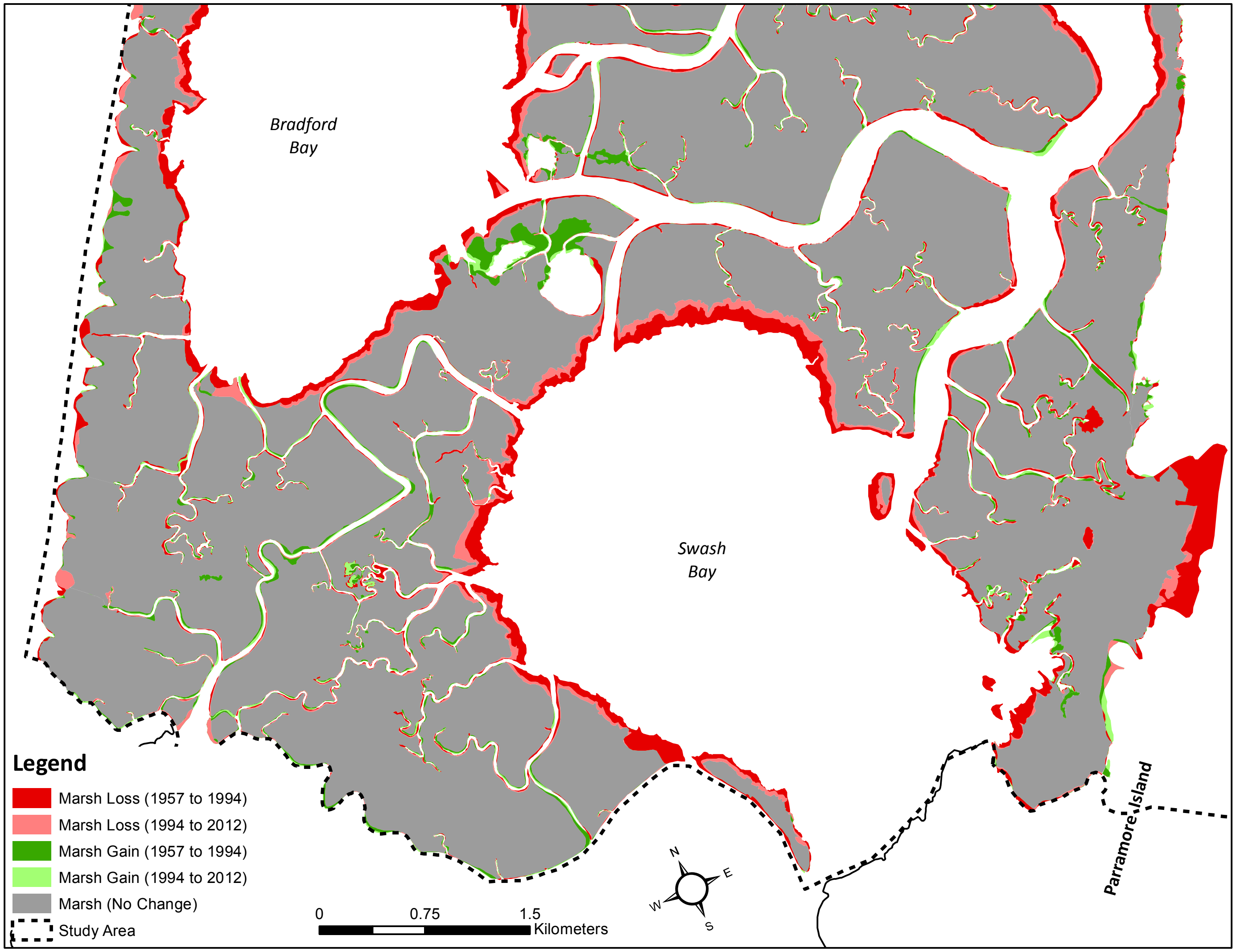

Figure 11D. Inset D from Figure 11A, showing marsh loss and gain in the Parramore and Cedar barrier-island system (1957–1994 and 1994–2012). (Loss/gain locations derived from USDA, 1957; USGS, 1994; USDA, 2012)

DISCUSSION

The island marsh loss rate in this study (0.17 ±0.02% yr^{-1}) was less than the Kastler and Wiberg (1996) island marsh sample area (0.27% yr^{-1}) over similar time periods; this would indicate that the island marsh sample area was not representative of the larger island marsh system. Kastler and Wiberg (1996) found a similar loss rate (0.93% yr^{-1}) for the 8-year period on the barrier fringing marsh as this study (0.95 ±0.01% yr^{-1}) for the recent 18-year period, indicating that the sample area is representative of the larger barrier fringe marsh system in the short-term. Kastler and Wiberg's (1996) island marsh loss rate may have been higher because the sample area location was directly opposite Quinby Inlet. For reference, Figure 12 provides the location of Kastler and Wiberg's (1996) study sample areas, just south of my study area, and Figure 13 displays the marsh gain and loss distribution of Kastler and Wiberg's (1996) island marsh. Table 10 shows a comparison between the current study results and the previous marsh change studies.

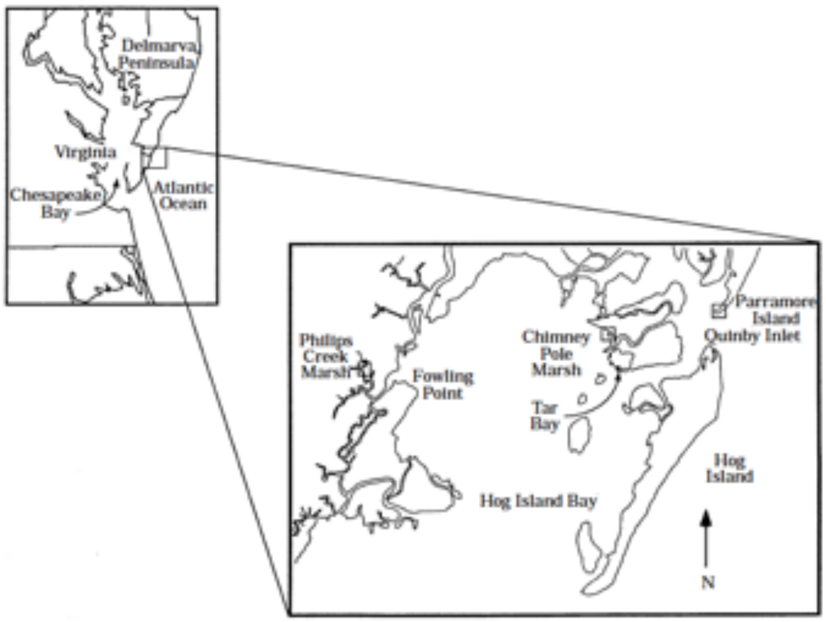

Figure 12. **Wiberg and Kastler (1996) study sample locations**

Figure 13. **Island marsh gain and loss from Kaster and Wiberg (1996). Solid black areas equal marsh gain, hatched equal marsh loss, white with grass equals no change.**

Table 10. Comparison of marsh change study results in the Virginia Coast Reserve

	Years Studied	Change Per Year* (%)
Whole Marsh		
Current Study	1957–2012	−0.24, ±0.02
Current Study	1957–1994	−0.20, ±0.02
Current Study	1994–2012	−0.33, ±0.01
Barrier Fringe Marsh		
Current Study	1957-2012	-0.55, ±0.02
Current Study	1994–2012	−0.95, ±0.01
Kastler and Wiberg (1996)	1982–1990	−0.93
Island Marsh		
Current Study	1957–2012	−0.17, ±0.02
Knowlton (1971)	1852–1962	−0.16
Kastler and Wiberg (1996)	1949–1990	−0.27

*averaged annual rate

The location of marsh loss in the system indicates that barrier island overwash and edge erosion are its biggest drivers. Large areas of barrier fringe loss have been caused by Cedar Island's landward migration, as documented by Gaunt (1991), Richardson and McBride (2011), Nebel et al. (2012), and Richardson (2012). On Parramore Island, only one barrier fringe marsh section was lost because of overwash processes. Parramore Island has a forested interior (maritime forest) separating the front barrier sand from the backbarrier marsh. The forested interior is degrading because of landward retreat related to increased salt-spray exposure, saltwater inundation through overwash processes, and subsurface saltwater intrusion (Hayden et al., 1995; Richardson, 2012); it is expected that further retreat will begin to affect the backbarrier marsh similarly to Cedar Island. The increase in barrier island overwash could be from an increasing rise in the relative sea level. As sediment is lost in the tidal inlets, barrier island erosion causes a decrease in island elevation, which makes the island more susceptible to overwash processes during storms. Alternatively, the increase in marsh loss because of overwash could be related to an increase in the number or intensity of storms (Nebel et al., 2012). The overwash-related marsh loss is consistent with the findings of Knowlton (1971) and Kastler and Wiberg (1996).

The edge erosion is likely caused by tidal processes and/or wave action. In southern New England, edge erosion of salt marshes has been attributed to intense crab grazing that is killing *S. alterniflora* (Smith, 2009). The literature does not show evidence of this being an issue in the Virginia Coast Reserve salt marshes. Rather, in the Virginia Coast Reserve, the major edge erosion occurs along the bays that are fed by major tidal creeks, indicating that tidal processes could be driving it (Kastler and Wiberg, 1996). The increased tidal prism caused by an increase in sediment trapping and relative sea-level rise could cause an increase in tidal current. FitzGerald et al. (2006) predicted in Stage 1 of their model that the increase in tidal flow will scour tidal creeks, as well as enlarge them. Increased wave activity increases sediment erosion and could be an additional factor in the increasing marsh loss (Kastler and Wiberg, 1996). Marsh edge erosion is occurring along the larger bays with large fetch, increasing the potential for wave action. In Burtons Bay and Swash Bay the edge erosion is not uniform along the shoreline and is greater along the northeast shore indicating that wind-driven waves from the southwest are contributing to the edge erosion. If it were only cause by tidal processes, the edge erosion would be more uniform around the bay shoreline.

The results did not document much interior marsh degradation, which could be because of the only-moderate negative balance between sedimentation and relative sea-level rise. It would be expected that as the difference between sedimentation and relative sea-level rise increases, interior marsh degradation would increase (Kastler and Wiberg, 1996). Erwin et al. (2006) found ponds in the Virginia Coast Reserve to be experiencing high sedimentation rates, and possibly to be filling in. They hypothesized that the marsh surface might level before the marsh is inundated by sea-level rise (Erwin et al., 2006). Additionally, the edge erosion that is occurring will increase the tidal prism, and in the future may cause an increase in interior marsh inundation.

The results of this marsh-change analysis showed the total marsh loss rate increased from 0.20 ±0.02% yr^{-1} to 0.33 ±0.01% yr^{-1} over the two incremental time periods. A long-term marsh-loss rate of 0.24±0.02% yr^{-1} for 1957 to 2012 was found. Knowlton's (1971) results from the earlier 110-year period show a lower marsh loss rate (0.16% yr^{-1}), which fits with the trend of increasing loss over time that was found for the study period.

This increase in marsh loss, along with the evidence of landward migration of both islands (Richardson, 2012) appears to support the FitzGerald et al. (2006) three-stage model. Tide gauge data for the region show the rate of relative sea-level rise increased during the study period from 3.03 mm/yr (1960–1984) to 3.98 mm/yr (1985–2009) (Sallenger et al., 2012). Higher rates (5.73 mm/yr from 1975 to 2006) occurred north of the study area in Ocean City, MD, and south of the study area at the Chesapeake Bay Bridge Tunnel, VA (6.02 mm/yr from 1976 to 2006) (NOAA, 2015b). The increase in relative sea-level rise and the increase in the marsh loss rate provide indications that the barrier-island system has entered Stage 1, Marsh Decline, of the FitzGerald et al. (2006) model.

However, when the marsh loss rates are evaluated by marsh type, it was recognized that all of the increase in marsh loss rate is being contributed by the barrier fringe marsh, primarily along the landward edge of Cedar Island (Figures 11b and c). Both island marsh and mainland marsh loss rates stayed nearly constant over our two incremental time periods, 0.17 ±0.02% yr^{-1} and 0.16 ±0.02% yr^{-1}, respectively. Additionally, the Island marsh loss rate (0.17 ±0.02% yr^{-1}) is similar to the island marsh loss rate found by Knowlton (0.16% yr^{-1}) for the time period prior to this study. With the increasing relative sea-level rise in the study area, an increase in the island marsh loss rate should also occur if relative sea-level rise is the primary driving factor.

The FitzGerald et al. (2006) model predicts that marsh loss from sea-level rise causes increased tidal prism, which would then cause retreat of the islands. As described, both islands already have retreating shorelines. Cedar Island is experiencing whole island retreat, and the retreat there is driving the increase in marsh loss rate from barrier island overwash, rather than vice versa. According to the location and trend in marsh loss, it cannot be attributed primarily to relative sea-level rise. The edge erosion is likely because of wind driven waves and tidal current. These factors contribute to evidence that the marsh loss in the study area does not support the behavior described in the FitzGerald et al. (2006) model.

Global Context

The Parramore and Cedar Island study area is unique in the global context of salt marsh loss because little human modification has occurred in the system. Globally, land conversion has caused the direct loss of 25-50% of coastal wetlands (salt marsh and mangroves) (Kirwan and Megonigal, 2013). Areas around the world that are experiencing the highest salt marsh loss, such as Louisiana, and Venice, Italy are caused by the indirect humans effects of increasing subsidence and/or decreasing sediment availability. It is uncommon to find salt marshes losses that can be directly attributed to sea-level rise, other factors are more likely responsible (Fagherazzi et al, 2012; Kirwan and Temmerman, 2009).

In coastal watersheds along the US Atlantic shoreline, it was estimated that the salt marshes lost 1.0% of their area between 1998 and 2004, and those in the Gulf of Mexico lost 1.8% of their area in the same time period (Stedman and Dahl, 2008). The US Atlantic coast losses occurred mostly in New York, New Jersey, Delaware, Maryland, and Virginia. Along the Gulf of Mexico coast losses were primarily documented in Mississippi, Louisiana, and Texas. Louisiana salt marsh losses have been attributed to canal and spoil bank construction, canal dredging, levees blocking migration, lack of sediment, land subsidence, and storm induced erosion (Kennish, 2001; Britsch and Dunbar, 1993; Sasser et al., 1986).

Comparing the study results to other research done around the world on similar coastlines, a wide range of marsh change values exist. Table 10 summarizes the results of a literature review of similar studies. Marsh change results ranged from +0.17 to -2.09%

yr^{-1}. The highest results are documented in the studies done in New York, Louisiana, and Central Southern England. These three areas are heavily impacted by human modifications. The Jamaica Bay location included the construction of John F. Kennedy Airport during the study period, and the Central Southern England is a highly developed port area where shipping traffic and dredging are common. These results show the substantial impact development can have on salt marshes when compared to the results from the uninhabited Parramore and Cedar islands. The Jamaica Bay study also showed an increase in marsh loss rates as the loss expanded from primarily edge erosion to the marsh interior. This may indicate that the Parramore and Cedar Island system may not experience marsh interior loss until the loss rate increases.

The remaining marsh loss rate findings in published literature are lower than the marsh loss rate finding for the Parramore and Cedar Island system. Of particular interest is the study from Great Egg Harbor Bay in New Jersey where a similar relative sea-level rise rate and time period result in much lower marsh loss rate. The Great Egg Harbor Bay is a flood-tide dominated barrier island system so this could be providing greater sediment supply into the back-barrier marshes when compared to the Parramore and Cedar Island system. The findings of marsh loss studies in the literature further indicates that local and/or regional processes (often human modification) are dominant in determining salt marsh survival and loss. None of the studies attributed marsh loss primarily to global sea-level rise.

Table 11. Comparison of Global Studies

Location	Coastal Setting	Marsh Type	Relative Sea-level Rise Rate (mm/yr)	Start Year	End Year	Time Period	Average Salt Marsh Change (percent/yr)	Contributing Factors	Source
USA									
Parramore and Cedar Islands, Virginia	Barrier Island System	whole marsh	3.48	1957	2012	55	-0.24	barrier island overwash, edge erosion	current study
Altamaha River Estuary, Georgia	River Delta	*S.alterniflora*	3.05	1953	1993	40	-0.13	n.d.	Higinbotham et al., 2004
Satilla River Estuary, Georgia	River Delta	*S.alterniflora*	3.05	1953	1993	40	-0.02	n.d.	Higinbotham et al., 2004
Great Egg Harbor Bay, New Jersey	Barrier Island System	island marsh	4	1940	1991	51	-0.09	low sediment input	Guo and Psuty, 1997
Barataria Bay, Louisiana	Barrier Island System		n.d.	1945	1980	35	-0.85	n.d.	Sasser et al., 1986
Jamaica Bay, New York	Barrier Island System	island marsh	2.7	1924	1999	75	-0.68	reduced sediment, dredging, boat traffic, relative sea-level rise	Hartig et al., 2002
Jamaica Bay, New York	Barrier Island System	island marsh	2.7	1974	1999	25	-1.52	reduced sediment, dredging, boat traffic, relative sea-level rise, high mussel populations	Hartig et al., 2002
Bloodsworth Island, Maryland	Estuary	low and high island marsh	3.1	1903	1992	89	-0.18	channel widening, edge erosion, interior ponding, storms, wave erosion, reduced sediment, sea-level rise	Downs et al., 1994
UK									
Langstone Harbour, Central Southern England	Harbour	*S.anglica*	3-5	1971	2001	30	-1.29	land reclamation, marsh front erosion, wave and tidal energy	Baily and Pearson, 2007

Chichester Harbour, Central Southern England	Harbour	*S.anglica*	3-5	1971	2001	30	-0.94	wave and tidal energy	Baily and Pearson, 2007
Portsmouth Harbour, Central Southern England	Harbour	*S.anglica*	3-5	1971	2001	30	-2.09	wave and tidal energy	Baily and Pearson, 2007
Pagham Harbour, Central Southern England	Harbour	*S.anglica*	3-5	1971	2001	30	0.17	abundance of sediment, no boats, no dredging	Baily and Pearson, 2007
Keyhaven and Lymington, The Solvent, Central Southern England	Estuary	*S.anglica*	3-5	1971	2001	30	-1.55	n.d.	Baily and Pearson, 2007
Calshot to Fawley Refinery, Southampton Water, Central Southern England	Estuary	*S.anglica*	3-5	1971	2001	30	-1.31	marsh front erosion, power station outflow	Baily and Pearson, 2007
Fawley Refinery to Hythe, Southampton Water, Central Southern England	Estuary	*S.anglica*	3-5	1971	2001	30	-0.98	marsh front erosion, power station outflow	Baily and Pearson, 2007

CONCLUSIONS

1. The marsh-loss rate increased from 9.3 ±1.2 ha yr^{-1} (0.20 ±0.02% yr^{-1}) for the period 1957 to 1994 to 14.0 ±0.63 ha yr^{-1} (0.33 ±0.01% yr^{-1}) for 1994 to 2012. Long-term marsh loss from 1957 to 2012 was 10.9 ±1.0 ha yr^{-1} (0.24 ±0.02% yr^{-1}).
2. The greatest marsh losses (0.55 ±0.02% yr^{-1}) are occurring in the barrier fringe marsh, primarily along the landward edge of Cedar Island, as a result of washover deposition and landward barrier-island migration. The losses that occurred in the island marsh (0.17 ±0.02% yr^{-1}) and mainland marsh (0.16 ±0.02% yr^{-1}) are primarily a result of edge erosion.
3. Kastler and Wiberg's island marsh sample area is over-representative of the marsh change as found in this study, and the fringe marsh is representative of the larger system in the short-term. The island marsh loss rate (0.17 ±0.02% yr^{-1}) we found is less than the Kastler and Wiberg (1996) island marsh sample area (0.27% yr^{-1}). The barrier fringe loss rate (0.95 ±0.01% yr^{-1}) found in this study is similar to the Kastler and Wiberg (1996) barrier fringe sample area loss rate (0.93% yr^{-1}).
4. Knowlton's (1971) island marsh loss rate (0.16% yr^{-1}) for 1852-1962 is similar to the island marsh loss rate (0.17 ±0.02% yr^{-1}) for 1957 to 2012. The island marsh loss rate is not increasing over time.

5. The data from our study do not support the FitzGerald et al. (2006) three-stage runaway transgression model for mixed-energy barrier islands at this time because marsh loss rates were found to be stable in two (island and mainland marshes) out of three marsh types during a time period of accelerating sea-level rise. And in the one marsh type that did show change (barrier fringe marsh), the change was driven by landward barrier-island migration. Marsh loss rates are not driven by primarily by sea-level rise but a combination of factors, including overwash processes, wave action, and tidal processes.

DEFINITIONS

Ebb-tidal delta: Arcuate to elongate-shaped shoal on the seaward side of a tidal inlet. Formed by ebb-tidal currents and modified by waves and flood-tidal currents (Davis and FitzGerald, 2004).

Flood-tidal delta: Horseshoe to multilobate shaped sand shoal located landward of a tidal inlet, formed by flood-tidal currents and modified by ebb-tidal currents (Davis and FitzGerald, 2004).

Georectification: process of registering an image to a reference data source. Converting the data file coordinates to a known geographic coordinate system by identifying ground control points, computing an approximate transformation matrix, and resampling the image (Baily and Pearson, 2007).

Ground Control Point (GCP): a location on the surface of the earth that can be identified on the imagery/photograph and located accurately on a map (Jensen, 2005).

Mixed-energy Barrier Island: Barrier island in which the morphology has developed through a combination of wave and tidal processes (Davis and FitzGerald, 2004).

Root-mean-square error (RMSE): difference in location between the ground controls points on a transformed image and the base layer. It is based on the Pythagorean theorem and calculated for each coordinate pair. The RMSE for the whole image is the sum of the error for each coordinate divided by the square root of the number of coordinate pairs (Hughes et al 2006).

Tidal Inlet: An opening in the shoreline through which water penetrates the land, thereby providing a connection between the ocean and estuaries (i.e., bays, lagoons, and marsh and tidal creek systems). The main channel of a tidal inlet is maintained by tidal currents (Davis and FitzGerald, 2004).

Transgression: landward movement of a shoreline (i.e., barrier island)

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