

**BLUE CARBON IN FRESHWATER / BRACKISH MARSHES ON
THE BARRIER ISLANDS OF VIRGINIA: ABOVEGROUND NET
PRIMARY PRODUCTIVITY AND CARBON POOLS**

by

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B.S. May 2011, Elon University

A Thesis Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirement for the Degree of

MASTER OF SCIENCE

BIOLOGY

OLD DOMINION UNIVERSITY
MAY 2015

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ABSTRACT

BLUE CARBON IN FRESHWATER / BRACKISH MARSHES ON THE BARRIER ISLANDS OF VIRGINIA: ABOVEGROUND NET PRIMARY PRODUCTIVITY AND CARBON POOLS

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“Blue carbon” is a relatively new concept describing carbon distributed tidally and sequestered via net production within coastal ecosystems, including seagrass beds, mangrove forests, and salt-water marshes. These systems sequester carbon at least 10 times faster than terrestrial systems. Fresh to brackish wetlands that receive irregular tidal influence due to overwash and storm events have not been typically studied as blue carbon systems. My objective was to quantify carbon pools within four interdunal fresh to brackish marshes on Hog Island, Virginia to determine their blue carbon potential. Marshes 1 and 2 were farthest from the ocean, below and above a berm respectively. Marshes 3 and 4 were closest to the ocean, below and above a trail berm respectively. Marshes 1 and 2 were hypothesized to be more accessible to overwash events than Marshes 3 and 4. Aboveground primary production was determined via harvests throughout 2013. No significant differences in production were found among marshes ($F = 1.116$; $p = 0.355$). Values for primary production ranged from $156 \text{ g C m}^{-2} \text{ yr}^{-1}$ (marsh 3) to $284 \text{ g C m}^{-2} \text{ yr}^{-1}$ (marsh 2). Belowground biomass was measured with cores extracted in August, 2013. Marsh 2 had significantly more belowground biomass than all the other marshes ($F = 9.425$; $p < 0.0005$). Decomposition was measured with litterbags collected throughout the year. All marshes exhibited slow exponential decay ($k = 0.0007$,

0.002, 0.001, 0.001). Soil carbon values were highly variable with marsh 4 storing the most carbon. Carbon sequestration potential was calculated using auxiliary belowground data. These values do not include carbon exported from the marshes but suggest that carbon could be sequestered at high rates, similar to blue carbon systems.

ACKNOWLEDGMENTS

Countless people were involved with the success of this project and I would like to extend a heartfelt thank you to many people. Firstly and most importantly, I would like to thank Dr. Frank Day for his endless support and patience throughout all the stages of this project. Secondly, I would like to thank my committee members, Dr. Eric Walters and Dr. Rebecca Bray for their guidance regarding the completion of this project.

Countless people have helped me in the field, including Nathan Sedghi, Matt Smith, Leah Gibala-Smith, Dane Jensen, Dr. Ray Dueser and Dr. John Porter. I greatly appreciate the staff at the Anheuser – Busch Coastal Research Center, particularly Virginia Coast Reserve project site manager, Dr. Art Schwarzschild, Chris Buck and David Boyd for transportation to and from the island. I would also like to thank Dr. Margie Mulholland and her lab manager Peter Bernhardt for allowing me to use their mass spectrometer for the carbon analysis. I would never have been able to complete this project without the support of my parents, Rick and Teresa Adams, who always encouraged me to follow my dreams. I would also like to thank my undergraduate advisor Dr. Brant Touchette for providing me with incredible undergraduate research opportunities that helped me determine this career path. This research was funded by subcontract GA11020-142301 on the University of Virginia's NSF grant DEB-1237733.

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INTRODUCTION

The Intergovernmental Panel on Climate Change 5th Assessment report indicated that the years 1995 and 1997 through 2006 were the warmest on record since 1850 (Hartmann et al. 2013). This report also states that this century's global mean sea level is rising at a rate of 3.2 mm per year, which is double the rate of sea level rise from the previous century (Hartmann et al. 2013; Church et al. 2013). Record breaking global surface temperatures and rising sea level are a direct result of increasing concentrations of atmospheric greenhouse gases, particularly CO₂, from anthropogenic activities such as the burning of fossil fuels and land use changes. Currently, the concentration of CO₂ in the atmosphere is 401 ppm. This value is the highest in the past 800,000 years; as far back as ice core data are available. The mean rate of increase in the concentration of atmospheric CO₂ is also the highest in the past 20,000 years (Ciais et al. 2013). The consequences of these increases include extreme weather events, extended periods of drought, shifts in species ranges and migration patterns, increased coastal flooding and higher storm surges, and economic distress associated with individuals having to adapt to climate change effects (Hartmann et al. 2013). These issues will be exacerbated in the future if mitigation strategies are not implemented (Walther et al. 2002)

Obvious mitigation strategies include reducing the amount of CO₂ released into the atmosphere by developing and using alternative and renewable fuel sources, increasing energy efficiency, and reducing consumption of energy (Lal 2008). These strategies are important but are currently unpopular, particularly in the United States and developing nations, making them difficult to implement, especially on a global scale. A

less obvious strategy includes taking advantage of natural and technological carbon sequestration processes (Hallegatte 2009).

Carbon sequestration is the transfer of atmospheric carbon to alternative, long-lived pools (Lal 2008). These pools can be biotic or abiotic and include oceanic pools, pedologic, or soil, pools, biotic pools, or geologic strata (Figure 1) (Lal 2008)...

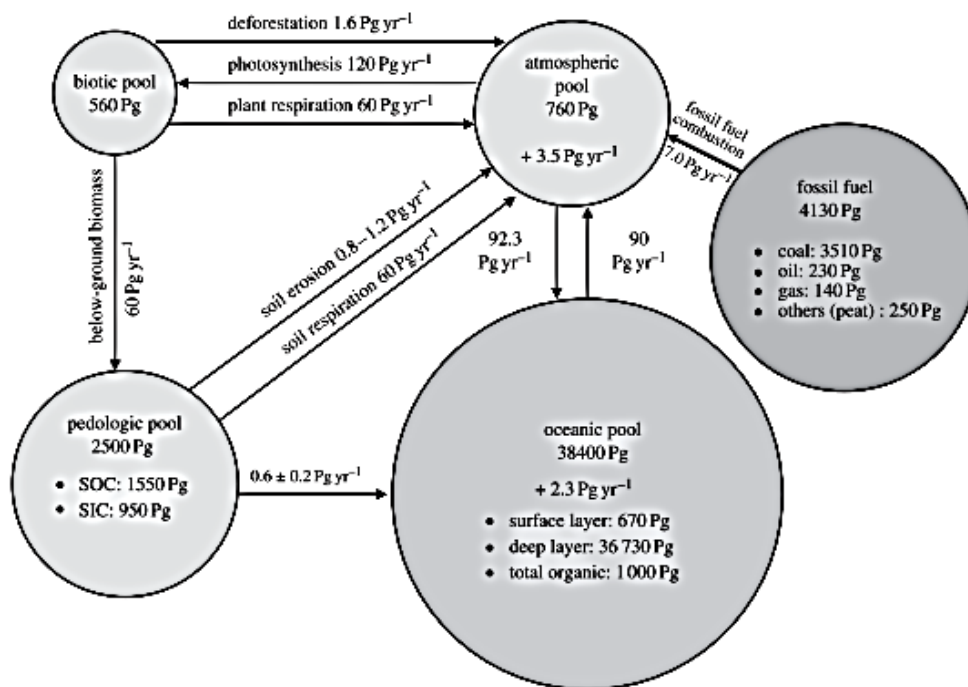


Figure 1. Global carbon pools including the fluxes between them (Lal 2008).

Current engineering technologies are being explored that could sequester carbon for the long term in abiotic pools. These strategies include oceanic injection, where pure CO_2 is injected deep into the ocean, and geologic injection, where industrially produced CO_2 is captured and injected deep within geological strata, coal seams, old oil wells, or saline aquifers (Klara et al. 2003). The maximum capacity for carbon capture is not understood and these technologies will likely not be available until 2025. These technologies also have serious leakage and cost concerns (Lal 2008). Another technology includes mineral

carbonation, where the natural transformation of CO₂ into mineral carbonates is mimicked in a laboratory setting, trapping the carbon within stable mineral compounds such as CaCO₃ and MgCO₃ (Park et al. 2003). This method is incredibly slow and increasing the rate of reaction is energy intensive and expensive, reducing its effectiveness. Biotic carbon sequestration, however, is low cost and immediately available (Lal 2008).

Biotic carbon sequestration has already been responsible for sequestering approximately half of the carbon emitted since the beginning of the industrial revolution (Battin et al. 2009). Biotic carbon sequestration involves plants and microorganisms removing CO₂ from the atmosphere through processes such as photosynthesis and burial of organic material within sediments (Lal 2008). It has been estimated that 0.5 – 2.7 Gross ton C yr⁻¹ of carbon is being released back into the atmosphere due to land use changes (Forster et al. 2007; Fourqurean et al. 2012). Thus 8-20% of anthropogenic greenhouse-gas emissions are due to prevention of biotic carbon sequestration from destroying ecosystems that are carbon sinks (Forster et al. 2007; Fourqurean et al. 2012).

Prior studies on global carbon budgets have focused primarily on terrestrial ecosystems; however, wetlands actually play a larger role in carbon sequestration (Chmura et al. 2003). Recent research has also concluded that tidal wetlands are sequestering carbon at a rate orders of magnitude higher than any other terrestrial system (Figure 2) (Mcleod et al. 2011). These highly productive, tidally based systems are now known as “blue carbon” systems and are beginning to receive attention for their potential to mitigate climate change (Nellemann et al. 2009).

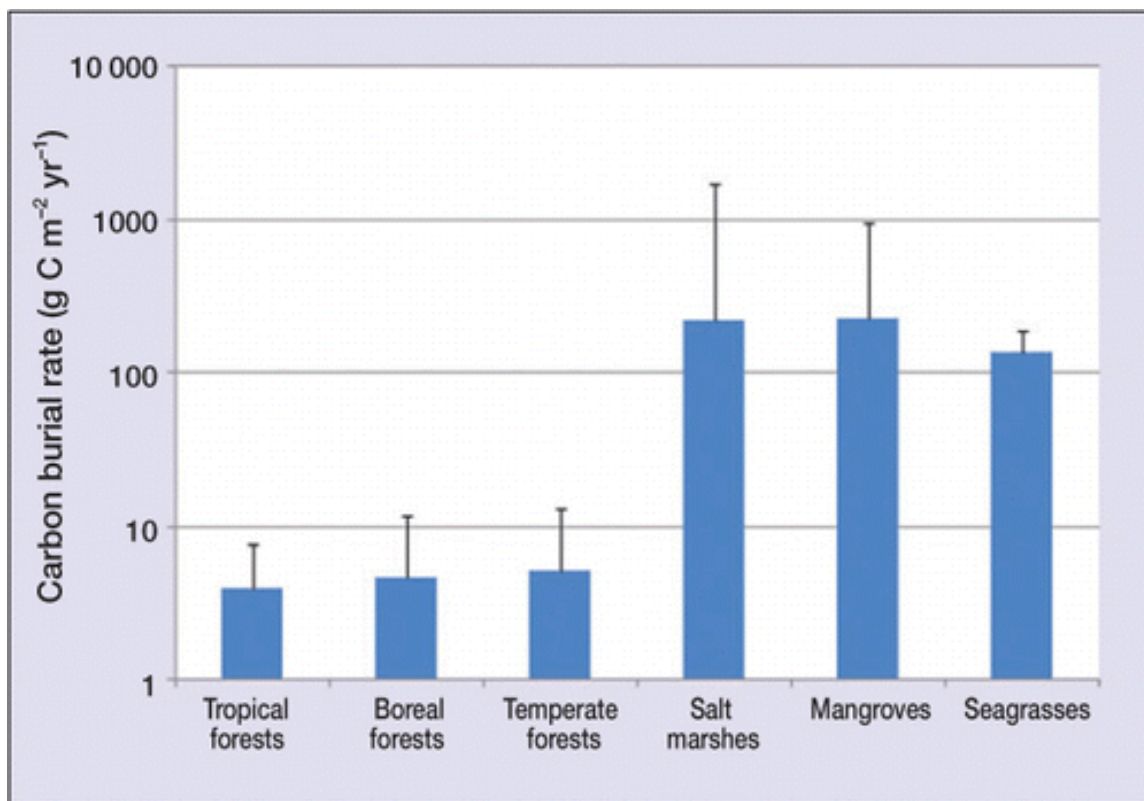


Figure 2. Mean long-term rates of C sequestration ($\text{g C m}^{-2} \text{yr}^{-1}$) in soils in terrestrial forests versus vegetated coastal systems. Bars indicate maximum rates of accumulation (Mcleod et al. 2011).

The vast majority of blue carbon research has focused on seagrass beds, mangrove systems, and salt-water marshes (Kennedy et al. 2010; Donato et al. 2011; Hopkinson et al. 2012; Duarte et al. 2013). Seagrasses alone occupy approximately 0.2% of the ocean surface, but are estimated to sequester $27.4 \text{ Tg C yr}^{-1}$, which is approximately 10% of the carbon buried in the oceans per year (Duarte et al. 2005; Fourqurean et al. 2012). Seagrass beds store carbon within above and belowground biomass and organic rich soils (Kennedy et al. 2010; Fourqurean et al. 2012). Dense stands of seagrass can also filter out organic particulate matter from the water column and store the organic matter within the sediments (Duarte et al. 2005). The anaerobic soil

conditions from inundation slow decomposition rates and allow organic carbon to accumulate and persist for millennia (Mateo et al. 1997; Fourqurean et al. 2012). This accumulation has been documented in organic soil deposits up to 11 m thick (Fourqurean et al. 2012). Current whole-ecosystem carbon stock is estimated to be 128 Mg C ha^{-1} (Alongi 2014). Unfortunately, since the beginning of the 20th century, 29% of seagrass beds have been destroyed worldwide (Fourqurean et al. 2012). This loss is continuing at a rate of 1.5% per year (Waycott et al. 2009; Fourqurean et al. 2012). The rate of carbon reentering the atmosphere due to seagrass bed destruction is exacerbated by the oxidation of organic matter stored in the soils (Fourqurean et al. 2012). This has led to an estimated 63-297 Tg C yr^{-1} reentering the atmosphere (Hopkinson et al 2012). Assuming the rate of loss remains the same, destruction of seagrass beds is contributing approximately 10% of land use change related to carbon release (Fourqurean et al. 2012). Fortunately, evidence from a seagrass bed restoration has indicated that these restored seagrass beds are sequestering carbon at a rate similar to those of natural beds (Greiner 2013).

Mangrove forests have a small spatial extent, approximately 0.5% of the global coastal area; however, they store the most carbon per unit area of any other ecosystem, estimated at 867 Mg C ha^{-1} , making them an important blue carbon ecosystem (Alongi 2014). Carbon is stored within biomass and soils in these systems. Mangroves produce a significant amount of belowground biomass to stabilize the trees in the waterlogged soils (Alongi 2014). Thus, the majority of carbon stored in mangrove systems is produced *in situ* and located belowground (Alongi 2014). Carbon is imported due to complex plant morphologies trapping suspended matter within the forest (Alongi 2014). Carbon is also produced by the diverse plankton communities that mangrove forests support (Alongi

2014). Biomass produced *in situ* or imported is allowed to persist after senescence due to anaerobic soil conditions slowing the decomposition process. The majority of this carbon is stored within the soils, at depths ranging from 0.5 m to greater than 3 m (Donato et al. 2011). The total global carbon burial rate for these systems is approximately 31-34 Tg C yr⁻¹ (Mcleod et al. 2011). These systems are also under threat from coastal development, aquaculture, and erosion (Donato et al. 2011). The global extent of mangroves has decreased by as much as 50% in the past 50 years (Donato et al. 2011). This deforestation generates 90 to 970 Tg C yr⁻¹, which is greater than the current rates of storage (Alongi 2014). Restoration efforts are important in order to improve ecosystem functions, but are not likely to increase global carbon storage by a significant amount, due to their small spatial extent (Alongi 2014).

Salt marsh systems occupy up to 400,000 km² globally and have 538 Mg C ha⁻¹ stored (Chmura et al. 2003; Duarte et al. 2005; Alongi 2014). Salt marshes have high primary productivity but these rates are variable, correlating with latitude. Salt marshes at low latitudes tend to have the highest rates of primary productivity, while salt marshes at higher latitudes have lower rates of primary productivity (Chmura 2013). Salt marshes also allocate a significant amount of biomass belowground (Turner 2004). Organic matter accumulates due to slow anaerobic decomposition processes as well as sediment deposition (Chmura 2013). The deposition of organic material has led to carbon deposits as thick as 6 m (Chmura 2013). Salt marshes are also declining rapidly due to landscape conversion and increasing sea level rise (Chmura 2013; Macreadie et al. 2013). This decline has been approximated to be a 25% loss since the 1800s (Macreadie et al. 2013). Salt marshes also have the potential to become carbon sources rather than carbon sinks,

releasing any carbon sequestered back into the atmosphere after disturbances (Macreadie et al. 2013).

Seagrass beds, mangrove forests and salt-water marshes have high primary production rates, low decomposition rates, high sediment deposition rates, and organic rich soils (Duarte et al. 2013). They also have the ability to accrete vertically with rising sea level and tidal action, allowing the soils to avoid carbon saturation (McLeod et al. 2011). It is also obvious that there is high variability of measurements of carbon burial and sequestration in these systems due to a limited number of studies. There is also a lack of consensus on how to measure carbon sequestration within these systems and a lack of consideration for other coastal ecosystem types (Grimsditch et al. 2013).

The Nature Conservancy's Virginia Coast Reserve is home to two types of blue carbon systems, salt-water marshes, and seagrass beds (Hayden et al. 1995; Carr et al. 2012).

Both of these ecosystem types are located between the Delmarva Peninsula and the Barrier Islands of Virginia (Figure 3). Barrier islands are some of the most dynamic ecosystems in the world (Hayden et al. 1991). They are found worldwide, typically along coasts that have small to moderate tidal range (Figure 4) (King 1972). Barrier islands are estimated to cover 13% of the world's coastline, with the longest chain along the eastern shore of the United States and the Gulf of Mexico (King 1972). They are typically found parallel to the shore with a bay, lagoon, or marsh separating them from the mainland and have a wide range of morphological features (Hoyt 1967). The distance of a barrier island from shore is variable. They typically are only a few kilometers wide but can range from 2 to over 100 kilometers long (Hoyt 1967). The number of parallel dune ridges is related to the width of the island and serve as indicators of shoreline position (Hoyt 1967). These

ridges vary in height, ranging from just higher than high tide to over 30 m in elevation (Hoyt 1967). More recently, barrier islands have been influenced by human development, which has led to increasing habitat loss (Ray and Gregg 1991).

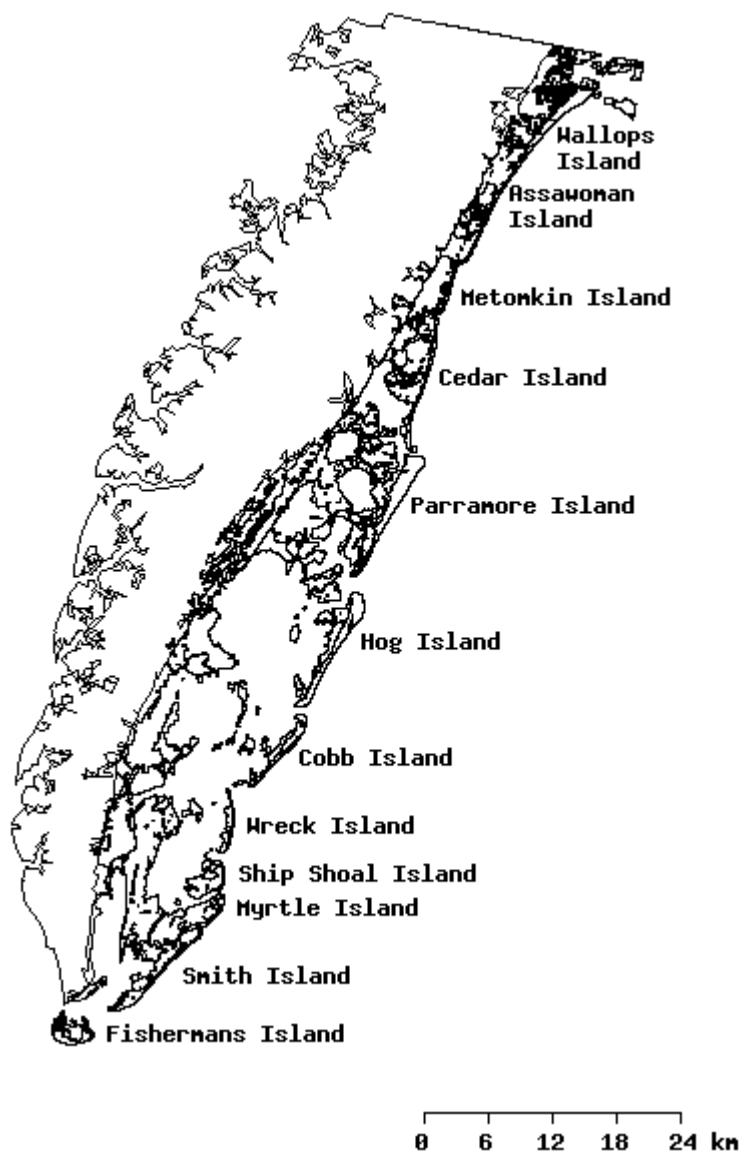


Figure 3. The Delmarva Peninsula of Virginia (VCR LTER).

Wide barrier islands can support fresh to brackish water marshes within the swales between dune ridges (Rheinhardt and Faser 2001). These marshes are highly

dynamic ecosystems that can fluctuate from a freshwater ecosystem to a saline ecosystem (Rheinhardt and Faser 2001). This fluctuation depends on several factors: these marshes are predominantly freshwater fed via the freshwater lens that forms under barrier islands (Röper et al. 2013). During precipitation events, rainwater can move easily through the sandy substrate and will float on top of the more dense saline water below the island surface (Figure 4) (Reilly and Goodman 195). During periods of high rainfall, this lens can inundate the swale (Rheinhardt and Faser 2001); however, storm events can cause saltwater intrusion into these interior marshes (Hayden et al. 1991). Thus, the amount of precipitation, the frequency of storms, the severity of the storm and the openness of the marsh to overwash will determine how fresh or brackish the marsh is at any given point in time. The Barrier Islands of Virginia in particular are some of the most dynamic areas in the world and are regularly affected by storm events, making the salinity of a marsh unpredictable (Hayden et al. 1991).

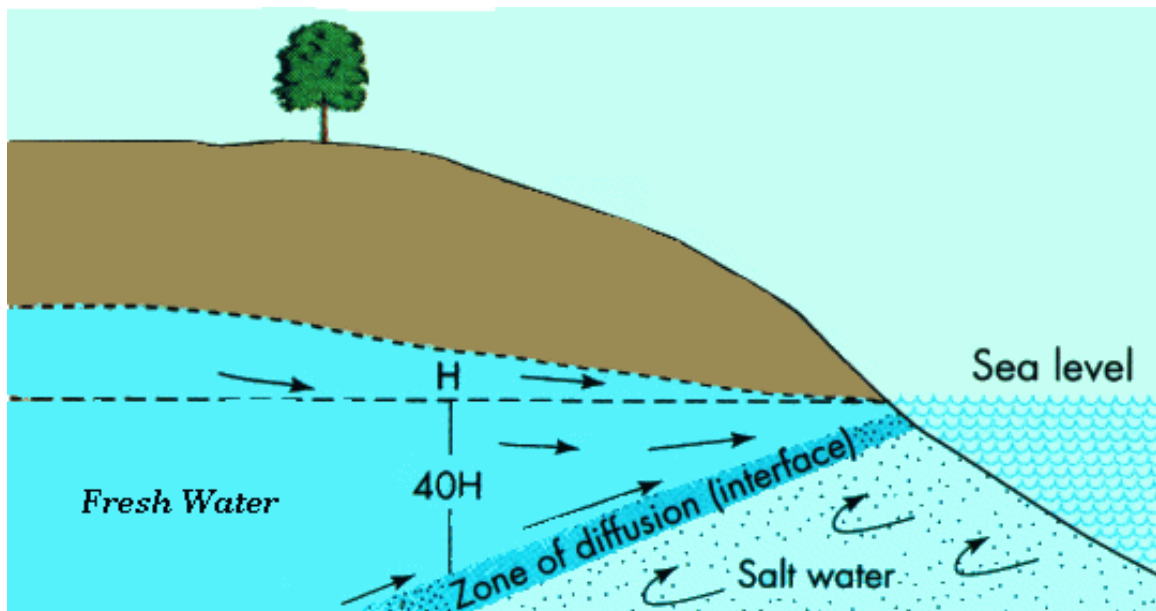


Figure 4. Diagram of a freshwater lens underneath a barrier island (Barlow 2003).

Current blue carbon research has focused largely on mangrove forests, seagrass beds, and salt water marshes. Generally, fresh to brackish water wetlands that are tidally influenced have not been included in these studies. Research including barrier island freshwater marshes is also scarce. The amount of carbon sequestered in the fresh to brackish water interior marshes on Hog Island, one of the Barrier Islands of Virginia, has not been quantified. The fresh to brackish water marshes on the barrier islands of Virginia are not tidal; however, they receive irregular tidal inundation during storm and overwash events (Hayden et al. 1995). Thus, I sought to quantify the carbon pools in aboveground vegetation, belowground vegetation, and in the soil for four marshes on Hog Island. These pools were used to determine the blue carbon potential of Hog Island marshes. The four marsh sites represented marshes that are protected from overwash events to different degrees. The primary objective of this study was to measure aboveground parameters in order to calculate aboveground primary production in these marshes. The four marsh sites were compared to determine how overwash events affected the aboveground carbon pools for each marsh. The Hog Island carbon pools were also compared to blue carbon systems. I hypothesized to find that the location of the marsh, its proximity to the ocean and its elevation, would be useful indicators in determining blue carbon potential. I also hypothesized to find that these marshes would be storing carbon at rates less than salt marshes, due to a lack of daily tidal action.

METHODS

Study Area

The Nature Conservancy's Virginia Coast Reserve (VCR) encompasses the largest chain of undisturbed barrier islands along the East Coast of the United States (Ray and Gregg 1991). The barrier islands of Virginia are a part of the VCR, which is one of the National Science Foundation (NSF) Long Term Ecological Research (LTER) sites and owned by The Nature Conservancy (TNC) (Hayden et al. 1991). The VCR includes 14 islands of various sizes to the east of the Delmarva Peninsula (Figure 5) (Shao et al. 1996).

Several different plant communities are present on the barrier islands of Virginia. The communities on Hog Island are among the more well studied of any of the VCR islands (37°40'N, 75°40'W). Hog Island is 11.3 km long x 0.8 km wide island 14 km off the coast of Virginia's Delmarva Peninsula in Accomack County (Hayden et al. 1991). The mean annual temperature on the island is 14.2 °C and mean annual precipitation is 105 cm (Hayden et al. 1991). Hog Island has been eroding on the southern end and accreting at the northern end. The northern end includes 3 dune ridges that run parallel to the shore, with low-lying swales in between. Communities on this island include salt-water marshes dominated by *Spartina alterniflora* on the western lagoon side (Shao et al. 1996; Carr et al. 2012). Also present are dune plant communities dominated by *Ammophila breviligulata*, *Spartina patens*, *Schizachyrium scoparium*, and *Panicum amarum* (Day et al. 2001). In many cases, the dunes provide shelter for other types of communities to exist within the low lying swales. These can include shrub-scrub

communities dominated by *Morella cerifera* and freshwater marshes dominated by *Spartina patens* and *Schoenoplectus americanus* (Shao et al. 1996).

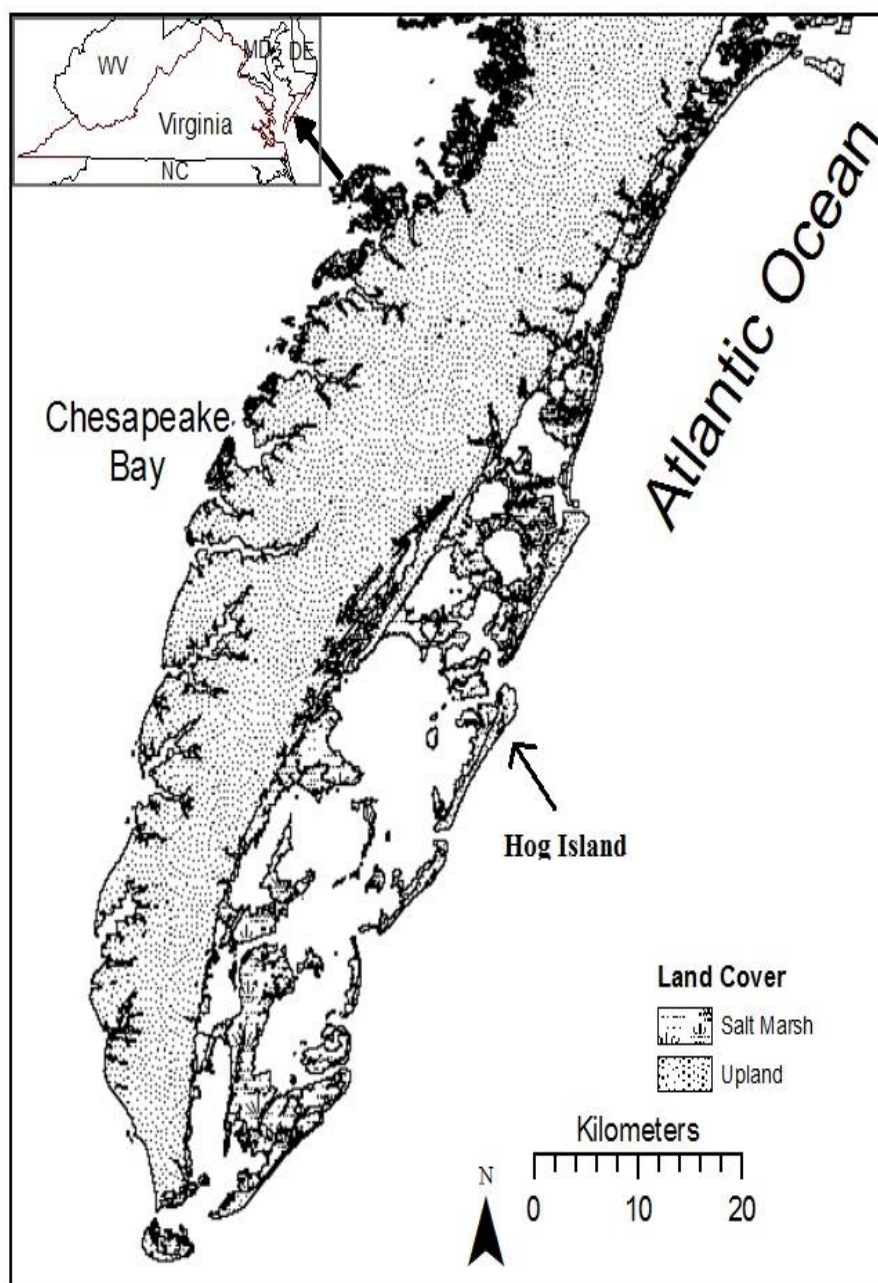


Figure 5. Map of the Delmarva Peninsula with Hog Island noted (VCR LTER).

During the course of this study, occurring during from February to November 2013, four interdunal freshwater to brackish water marsh sites were monitored (Figure 6). A trail berm, approximately 1.44 m above sea level, running from east to west on the island separated the sites into two northern sites and two southern sites. Among the northern sites, one was located closest to the beach (marsh 4), while another was more inland to the west (marsh 2). Among the southern sites, a site was closer to the beach (marsh 3), while the other was inland to the west (marsh 1). The western sites were located close to an overwash fan, where seawater could flow into the sites. The eastern sites did not have an overwash fan and had less exposure to seawater. Each site also had a pond area and three of the sites had wells to monitor groundwater levels. The marsh areas were dominated by *Spartina patens* and *Schoenoplectus americanus*, but *Phragmites australis* (Cav.) Trin. had begun to invade some parts and continued its expansion throughout the study. Previous studies from 1994 and 2012 on the interior marshes on Hog Island have established salinities to be between 0 and 2 ppt, indicating that these marshes have been predominantly freshwater to slightly brackish (Conn 1994; Blecha 2010).

The goal of this study was to estimate the carbon pools found in aboveground vegetation, belowground vegetation and the soil in order to estimate carbon sequestration potential. This was accomplished by measuring aboveground biomass via harvesting events throughout the growing season, belowground biomass via a single harvest event at the peak of the growing season, soil carbon pools via a coring event at the peak of the growing season, and aboveground decomposition via litter bags filled with standing dead culms of *Spartina patens*. Salinity and water table depth were also monitored at each site.

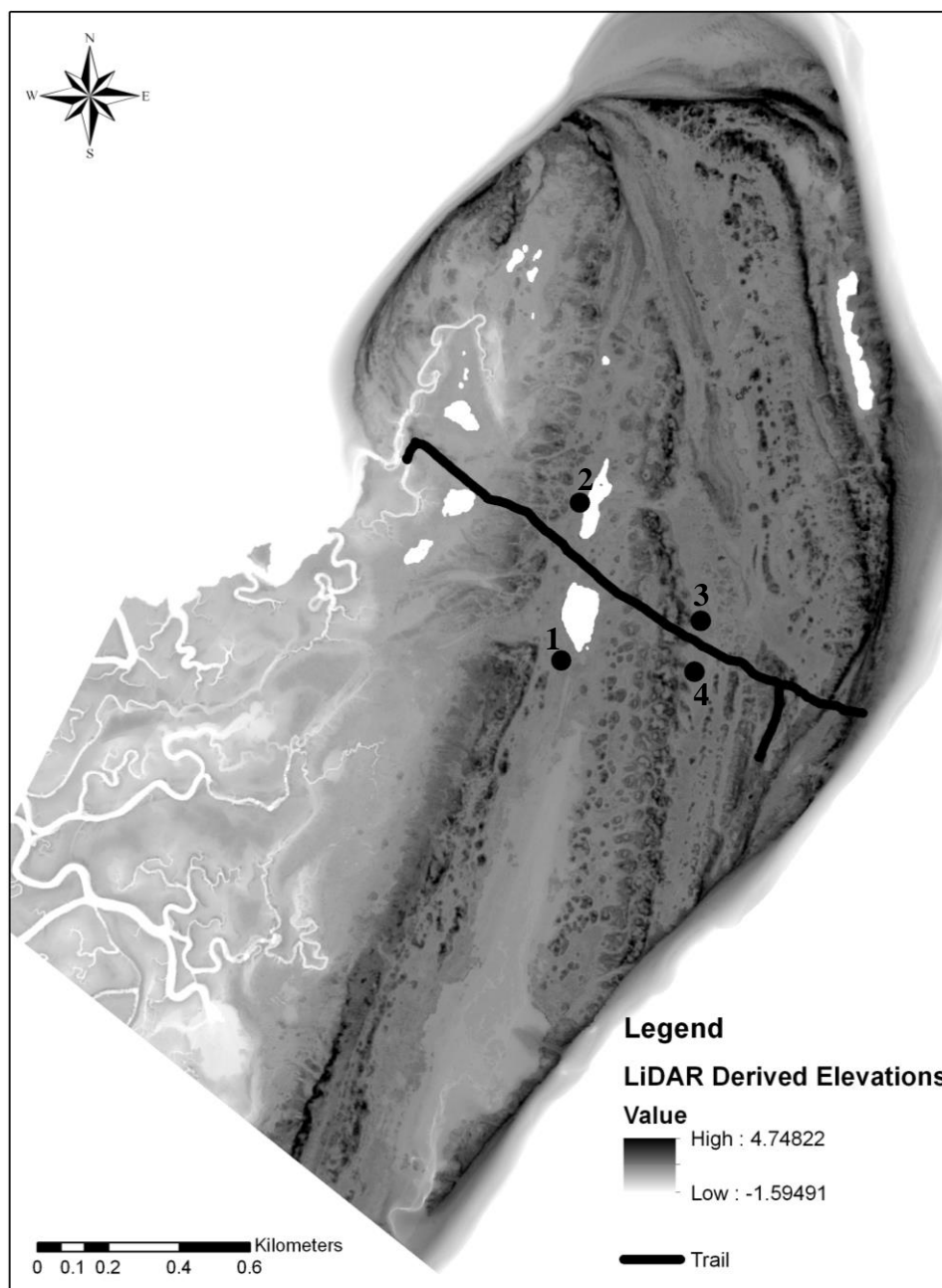


Figure 6. LiDAR derived elevations for northern Hog Island, Virginia. The trail and the locations of the marshes are noted.

Aboveground Biomass Production and Carbon Pools

Aboveground biomass was measured via four sampling events that encompassed the growing season of the predominant species, *Spartina patens* (Windham 2001). The aboveground plant parts were harvested in ten 0.25 m² plots per marsh site in February and April (representing pre- to early growing season), in August (representing peak-growing season), and in November (representing post-growing season) (Windham 2001). Special care was taken to avoid the quadrants that had been previously harvested. The aboveground plant parts were placed in paper bags and transported back to Old Dominion University where they were sorted into live plant material and standing dead plant material. The live material was further sorted by species. After sorting, all plant material was oven dried at 70°C for 48 hours and weighed to determine biomass. Aboveground net primary production was calculated by determining the change in live biomass from April to August (Fahey and Knapp 2007). This is likely an underestimate, as the shedding of plant parts and herbivory are difficult to determine and were not directly measured in this study (Ovington 1963).

The carbon concentrations in the plant tissues were determined with a Europa 20/20 isotope ratio mass spectrometer with an ANCA preparation unit. Reference samples were run every 8 samples and blanks were run at the beginning and end of every batch. The standards were ammonium sulfate for nitrogen and sucrose for carbon. Two tissue samples per species per marsh were run in the mass spectrometer and averaged to determine the percent carbon in each species for each marsh.

Belowground Biomass and Soil Carbon Pools

During the month of August, ten paired soil cores per marsh site were taken to a depth of 1 m. The location of each core was determined using a grid. The grids were made as large as possible while maintaining plant species homogeneity. A buffer of various sizes surrounding each grid was implemented to keep *P. australis* out of the grids. *P. australis* is an invasive species and was not considered for this study. A random number generator was used to determine the coordinates for the location of each sampling event. Each pair was approximately 50 cm apart. A 7 cm diameter bucket auger was used, and each core was separated into 10 cm zones (Powell and Day 1991).

The cores were brought back to the lab and refrigerated until they were processed. The roots from one paired core were separated from the soil using a wet sieving technique (Robertson et al. 1984). The roots were oven dried at 70 °C and weighed to determine biomass. The other paired core was used to determine carbon and nitrogen content of the soil. Percent carbon and nitrogen in the soils was determined using a Europa 20/20 isotope ratio mass spectrometer with an ANCA preparation unit as described above. Three cores per marsh were chosen randomly from the 10 collected to be analyzed in the mass spectrometer. These cores were consolidated into 3 depth profiles: 0-30 cm, 30-60 cm and 60-100 cm. Duplicate samples per depth profile were analyzed to determine the percent carbon present. The percent organic matter was also determined using the combustion method in a muffle furnace on additional subsamples (Allison 1965).

Decomposition of Aboveground Litter

Decomposition rates were determined by deploying 15 cm by 15 cm litter bags at ground level in February. The litter bags were constructed of nylon netting with a 0.79375 mm square mesh and were filled with standing dead stems of *Spartina patens* collected from the marshes in November, 2012. A subsample of the material collected in November was weighed before and after being oven dried in order to determine the air dry/oven dry conversion factor. Each of the four marshes had 5 sites with 6 bags at each site for a total of 120 bags. The locations for the bags were determined using the same grid as the belowground biomass measurements. Care was taken to avoid placing bags at the same coordinates. One bag from each site was collected in April, May, June, August and November and oven dried at 70°C for 48 hours. Decay curves were determined for each marsh site based on percent mass remaining after applying the air dry/ oven dry conversion factor to the stems placed in the litter bags before deployment. Percent carbon lost was determined by multiplying the weight of collected material by the percent carbon determined for *Spartina patens* using the mass spectrometer.

Environmental Measurements

Groundwater measurements for each site were taken in hand dug holes to accompany the well data. LiDAR or Light Detection And Ranging data were provided by the ABCRC. LiDAR data are remotely sensed elevation data determined by analyzing the reflected light of a laser fired to the ground. These elevations were measured in 2010 and provide a digital elevation model for Hog Island with a horizontal spatial resolution

of 1 m and a vertical spatial resolution of 3.05 m (VITA 2011). Salinity measurements were taken at each pond area at each sampling event using a refractometer.

Data Analysis

SPSS and SigmaPlot statistical packages were used to analyze the data. A mixed ANOVA was used to test for differences between salinity values, water table values, elevations, and decomposition rates in each marsh over time. All of these metrics failed the normality and homogeneity of variance tests. There were not any transformations that allowed the salinity data, water table data, or elevation data to comply with the normality test or the homogeneity of variance test and those mixed ANOVAs were performed on ranks. A negative exponential regression model was used to determine decomposition rates. The decomposition rates were transformed using the arcsin transformation. The dependent variables were salinity, water table, elevation, or percent mass remaining, the within subjects factor was time, and the between subject factor was marsh site. A one-way ANOVA was used to test for differences or variation among sites for aboveground production, belowground biomass, and total soil carbon between sites.

Carbon Sequestration Potential

Actual carbon sequestration rates could not be determined in this study because export, or losses, from the system through herbivory, methane emissions, and tidal influence were not measured; thus, carbon sequestration potential was estimated. Sequestration potential represents the maximum possible sequestration rate for these

systems. An estimation of the carbon sequestration potential for these systems was calculated by incorporating unpublished sedimentation rates, belowground net primary productivity, and belowground decomposition data from a study occurring at the same marshes, within the same time frame, as this study. The percent mass remaining after 365 days was determined using the decomposition rates for one year. Assuming steady state in the aboveground live compartment, (annual net primary production = mortality and mass loss in one year) this percentage was applied to aboveground net primary productivity to represent the amount of dead aboveground plant mass that would persist after 1 year. The same method was applied to belowground decomposition and primary production data provided by Sedghi (2015). The estimates of persistent dead plant mass were added to sedimentation rates provided by Sedghi (2015) to determine the carbon sequestration potential for each marsh.

RESULTS

Aboveground Plant Carbon Pools

The majority of the carbon stored in these systems was in standing dead material, particularly for marsh 3 (Figure 7). While no significant differences in standing dead plant material among marshes were observed (ANOVA, $F = 1.601$, $p = 0.206$), the pattern within the data suggests that marsh 3 had a larger pool of standing dead material compared to the other marshes. Significant differences in live plant material were also not observed (ANOVA, $F = 0.180$, $p = 0.909$); however, the pattern suggest marshes 1 and 2 had a larger live carbon pool than marshes 3 and 4.

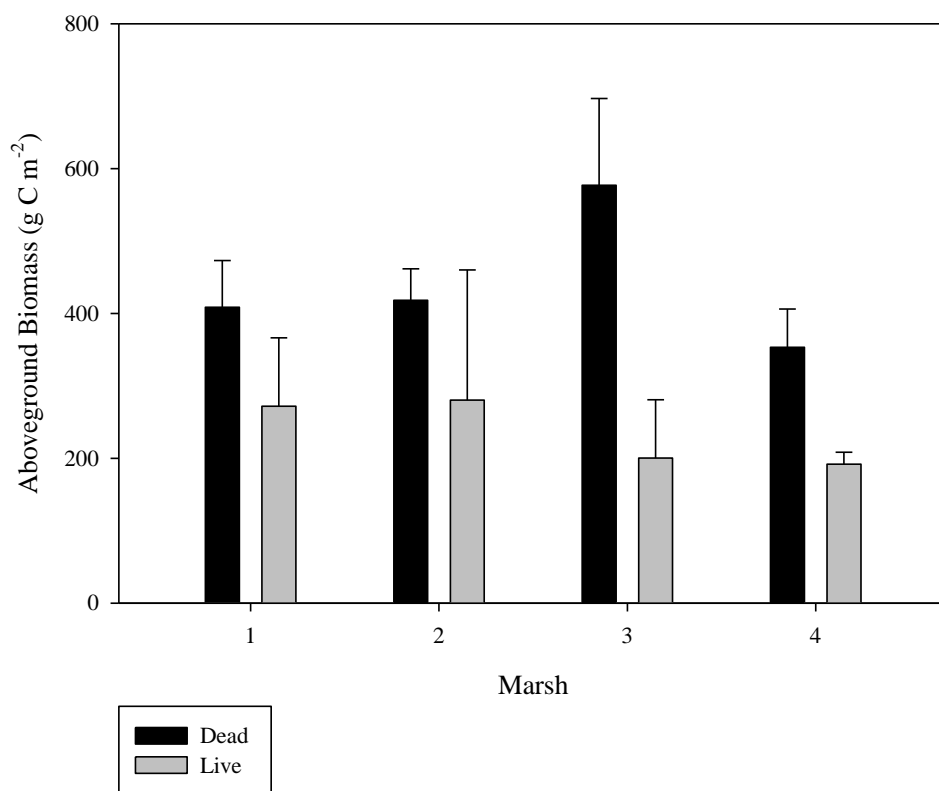


Figure 7. Aboveground carbon pools of live and dead plant material for the month of August.

Aboveground Net Primary Production

Aboveground net primary production values did not yield statistically significant differences among marshes (ANOVA, $F = 1.486$, $p = 0.235$). The trends among the marshes suggest that marsh 2 had the highest production values while marsh 4 had the lowest (Figure 8). Marsh 1 had the second highest while marsh 3 had the second lowest.

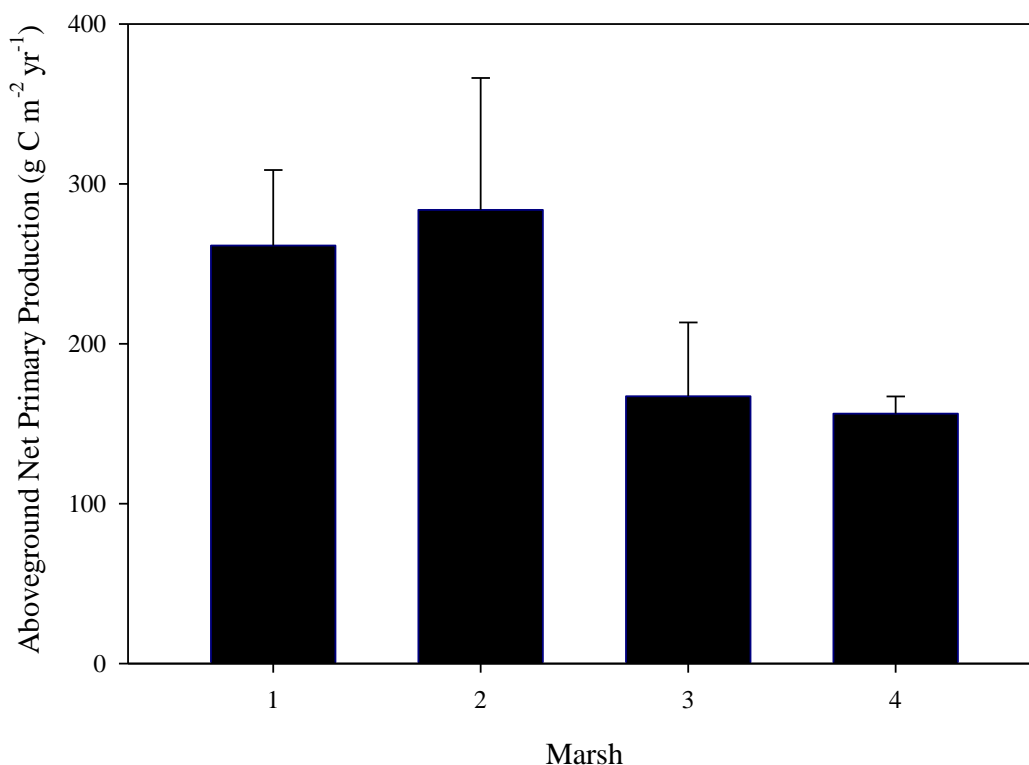


Figure 8. Aboveground net primary production in carbon units for the four marshes. Error bars indicate one standard error. No significant differences were observed among marshes.

Aboveground net primary production, partitioned by species, indicated that the species compositions for the marshes were different. Marshes 1 and 2 were dominated by *Spartina patens*. *Distichlis spicata* was also present in Marshes 1 and 2. Marsh 2 had small amounts of *Schoenoplectus americana*. Marshes 3 had approximately equal

amounts of *S. patens* and *S. americana*, while marsh 4 was dominated by *S. americana* with less *S. patens*. Marshes 3 and 4 had small amounts of *D. spicata* and marshes 2, 3 and 4 had small amounts of *Phyla lanceolata* (Figure 9).

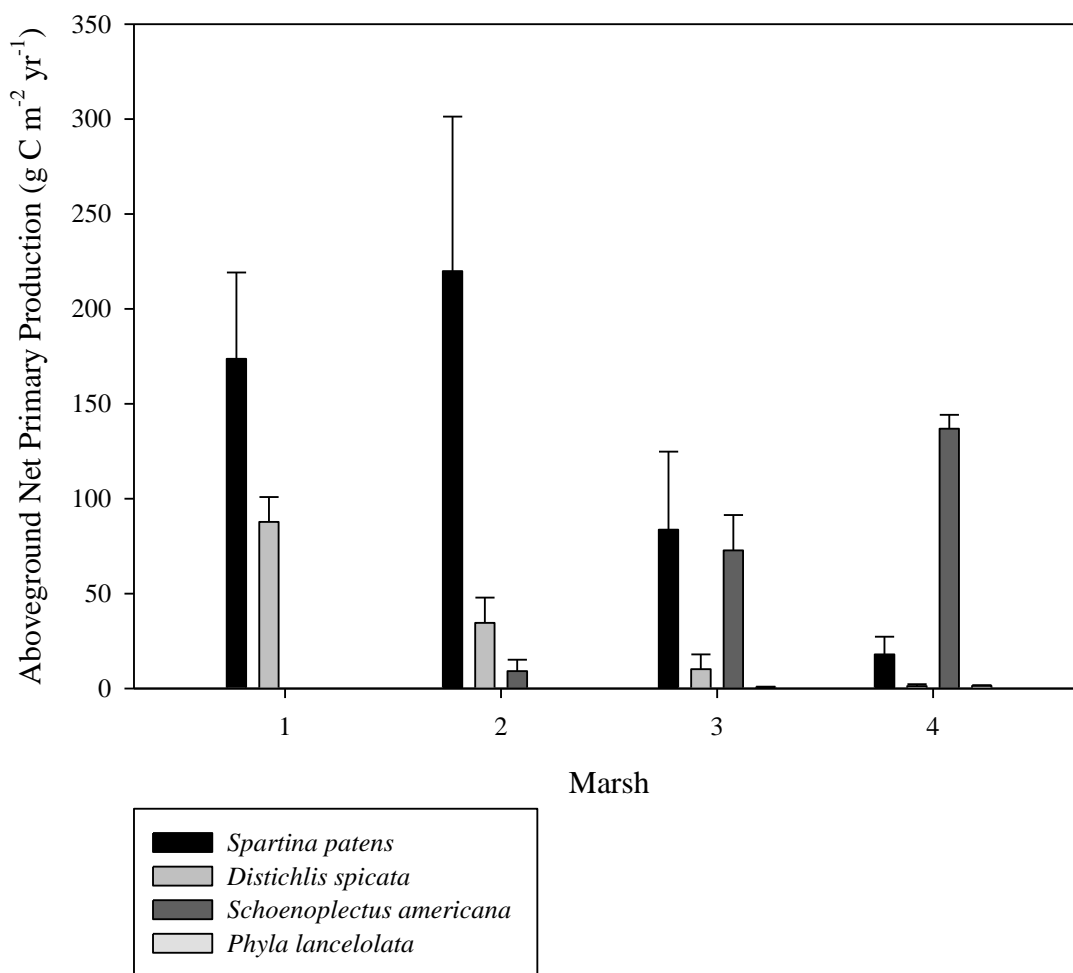


Figure 9. Aboveground net primary production by species in carbon units. Error bars represent one standard error.

Decomposition of Aboveground Litter

Aboveground decomposition exhibited a negative exponential decay curve (Figure 10, Table 1). Significant differences were found among marshes (ANOVA, F =

18.118, $p < 0.0005$). Marsh 1 had the slowest decay rate, while marsh 2 had the fastest decay rate; marshes 3 and 4 had the same decay constant (Table 2).

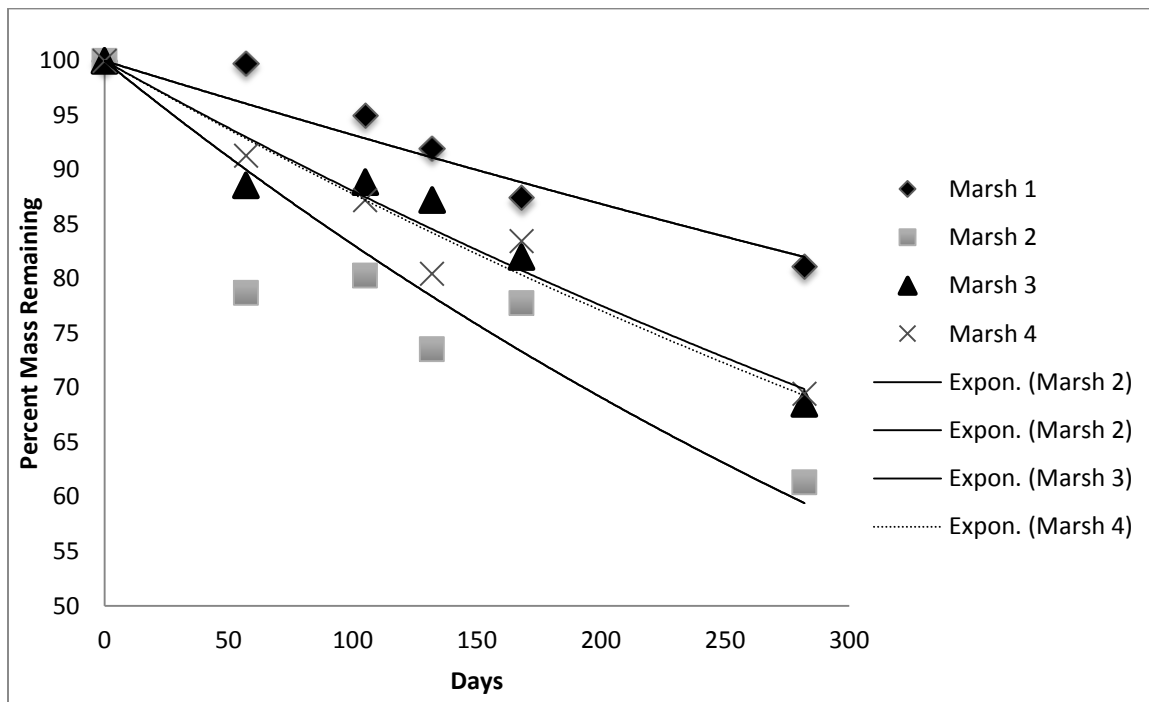


Figure 10. Mass loss over the course of the study. Negative exponential curves represent the best fit for the marshes.

Table 1. Decay equations for the four marsh sites; y = percent mass remaining, x = days in the field, k = the decay constant, R^2 = correlation coefficient.

<i>Marsh</i>	<i>Decay Equation</i>	<i>k</i>	<i>R²</i>
<i>1</i>	$y = 100e^{-7E-4x}$	<i>0.0007</i>	<i>0.9268</i>
<i>2</i>	$y = 100e^{-0.002x}$	<i>0.002</i>	<i>0.7807</i>
<i>3</i>	$y = 100e^{-0.001x}$	<i>0.001</i>	<i>0.9505</i>
<i>4</i>	$y = 100e^{-0.001x}$	<i>0.001</i>	<i>0.9466</i>

Table 2. Significance values (p-values) derived from the Tukey test for testing differences between marshes for decomposition rates.

Marsh	2	3	4
1	0.0005	0.011	0.009
2		0.019	0.010
3			0.999

Belowground Plant Carbon Pools

There were significant differences in belowground carbon pools among sites (ANOVA, $F=5.523$, $p < 0.003$). A Tukey pair wise multiple comparisons test revealed marsh 2 had significantly more biomass than all other marshes (Table 3). The remaining marshes were not statistically different from each other. There was a trend indicating marsh 1 with the second largest carbon pool and marshes 4 and 3 with the least, respectively (Figure 11).

The root to shoot ratios indicate that approximately half the biomass was stored belowground in marshes 2 and 4 while marsh 1 and 3 stored approximately 40% belowground (Table 4).

Soil Carbon Pools

The soil carbon pools to a depth of 1 m were highly variable in each marsh; no significant differences among marshes were found (ANOVA, $F = 1.073$, $p = 0.383$). There was a trend suggesting that marsh 4 had more carbon stored in the soils, followed by marshes 2, 1, and 3 (Figure 12).

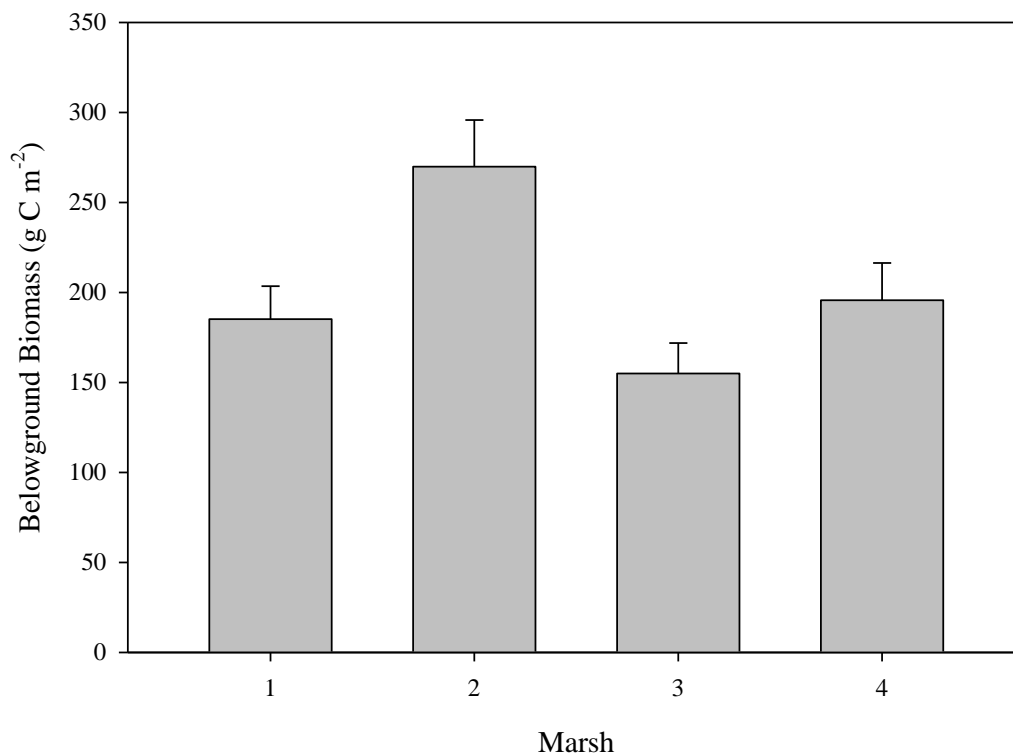


Figure 11. Belowground carbon pools measured in August to a depth of 1 m. Error bars represent one standard error.

Table 3. Significance values (p-values) derived from the Tukey test for testing differences in belowground biomass between marshes.

Marsh	2	3	4
1	0.032	0.735	0.984
2		0.002	0.072
3			0.517

Table 4. Root to shoot ratios for each marsh.

Marsh	Root: Shoot
1	0.68
2	0.96
3	0.77
4	1.02

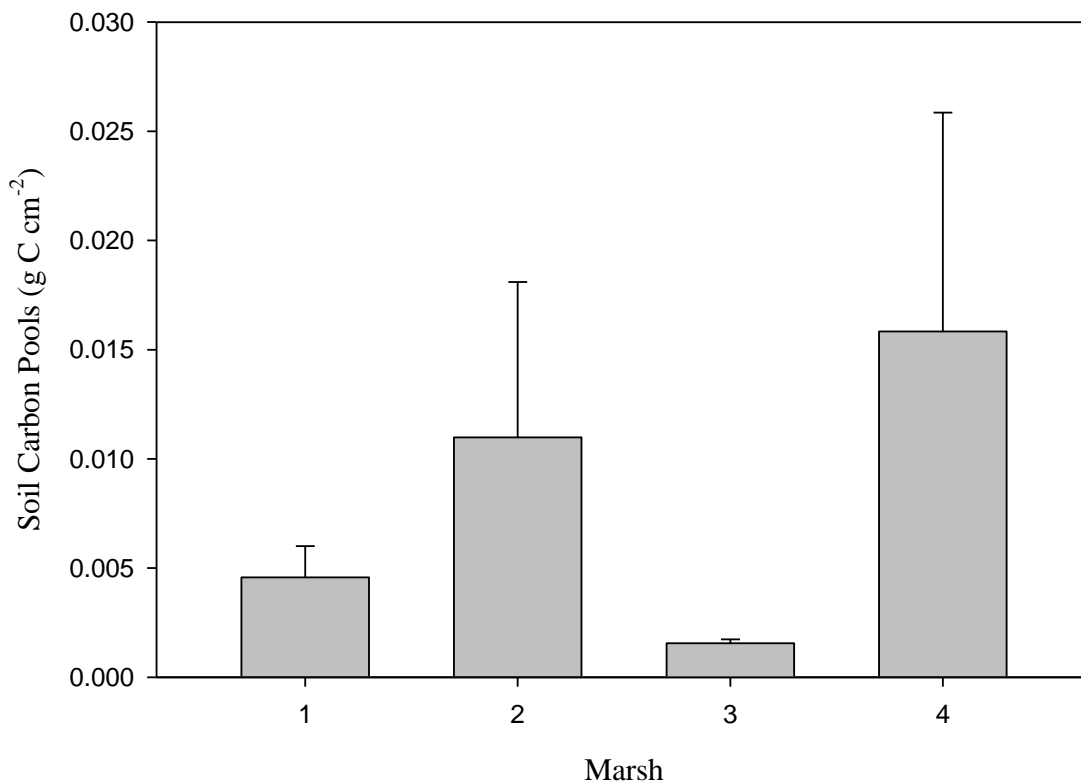


Figure 12. Soil carbon pools to a depth of 1 m in each marsh. Error bars indicate one standard error. No significant differences were found among marshes.

Soil Organic Matter

Percent organic matter by depth varied greatly. The majority of the organic matter was in the top 10 cm (Figure 13). Marshes 1 and 2 had significantly more organic matter than marsh 3 (ANOVA, $F = 56.513$; $p = 0.0005$, Table 5). No other statistical differences were observed. The data did exhibit some trends; marsh 2 had a higher percentage of organic matter than all other marshes, followed by marsh 1 and marsh 4. Marsh 3 had the lowest percentage of organic matter.

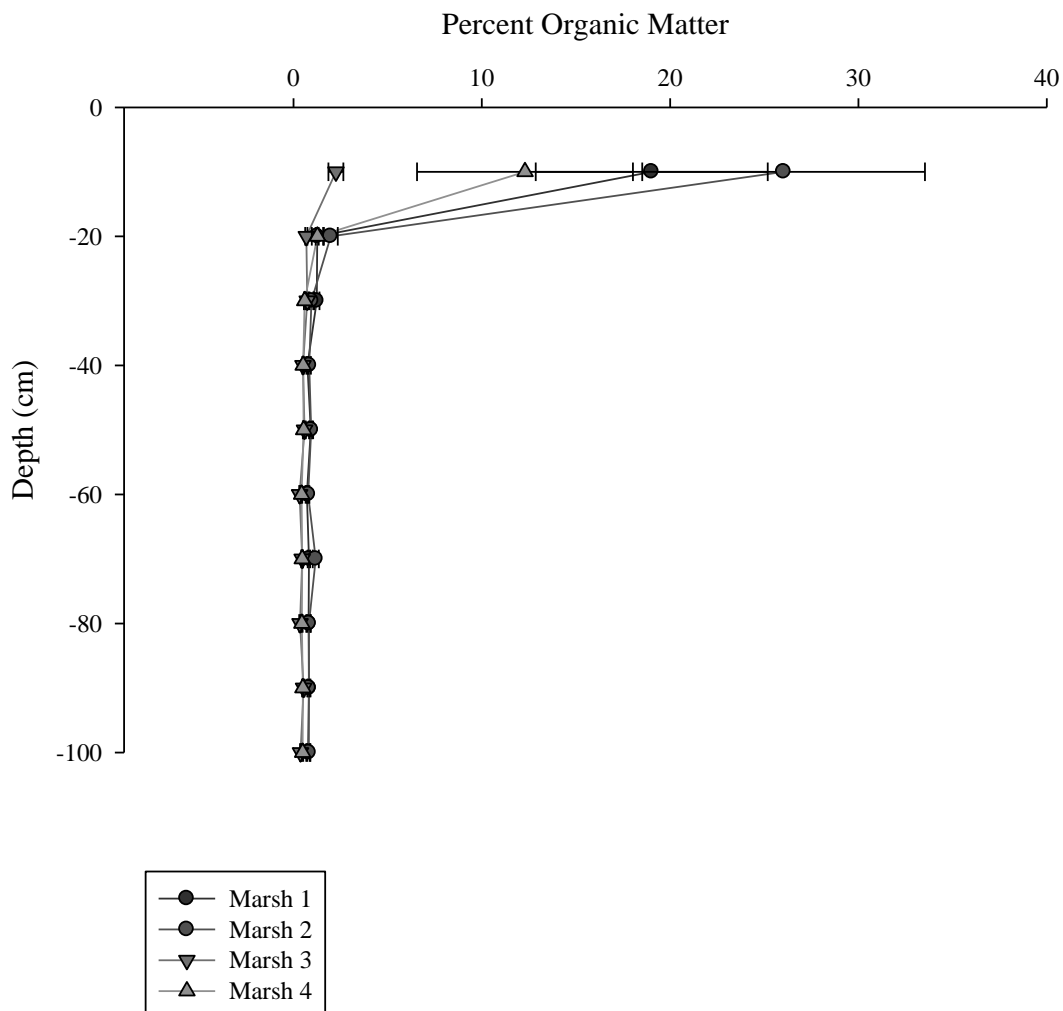


Figure 13. Percent organic matter by 10 cm depth increments for each marsh. Error bars represent one standard error.

Table 5. Significance values (p-values) derived from the Tukey test for testing differences in percent organic matter between marshes.

Marsh	2	3	4
1	0.751	0.074	0.636
2		0.008	0.163
3			0.568

Carbon Sequestration Potential

Carbon sequestration potential calculations suggest that marsh 1 had the highest sequestration potential, followed by marshes 2, 3 and 4 respectively (Figure 14).

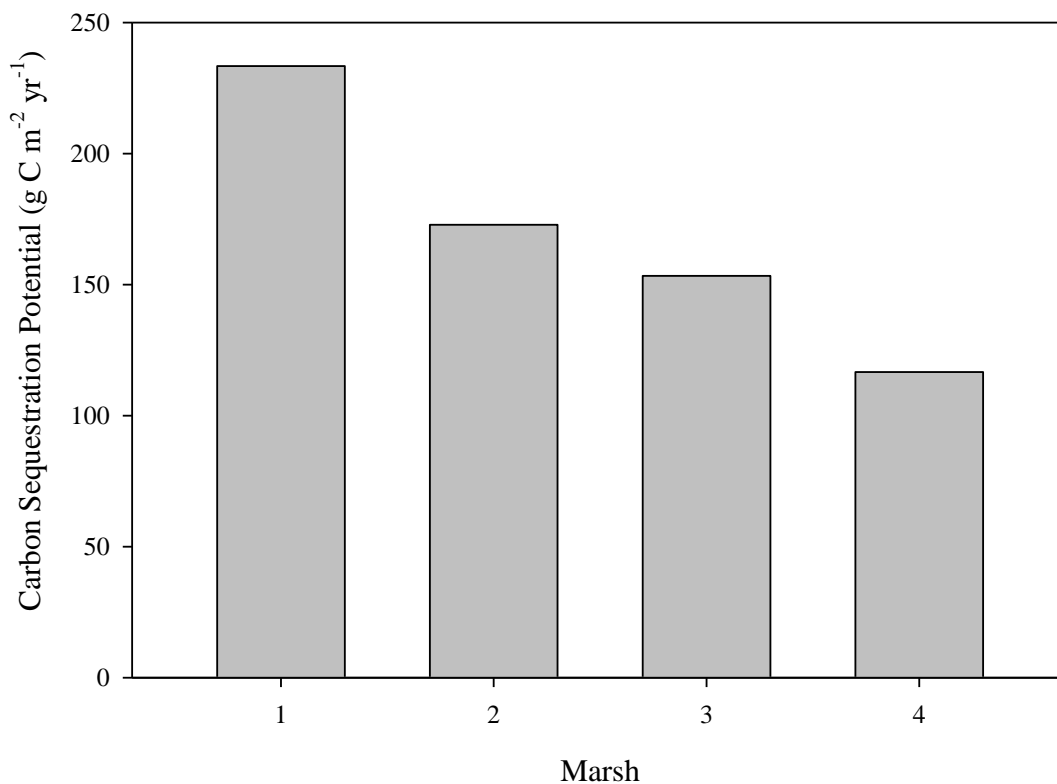


Figure 14. Carbon sequestration potentials for each marsh.

Environmental Measures

There were significant differences in salinities among marshes over time (ANOVA, $F=35.092$, $p < 0.0005$). Marshes 1 and 2 were significantly more saline than marshes 3 and 4 (Table 6 and Table 7). There was a wide range in salinities over time and generally these marshes were more saline than recorded in earlier studies on the same sites (Blecha 2010; Conn 1994). The values recorded for marshes 1 and 2 in August and

November were considerably higher than any other values reported for these marshes, (past and present) and likely represent a small overwash.

Table 6. Mean salinity values (ppt) for each marsh through the course of the study.

Marsh	February	April	May	June	August	November
1	14	20	15	12	25.7	36.7
2	13.7	16.7	15	11.3	26.3	30
3	14	11.3	11.7	10	11.3	15
4	11	12	10.3	8	14.3	16.3

Table 7. Significance values (p-values) derived from the Tukey test for testing differences in salinity between marshes.

Marsh	2	3	4
1	1.000	0.031	0.028
2		0.035	0.031
3			1.000
4			

The mixed ANOVA results indicated that there were significant differences among marshes (ANOVA, $F = 19.389$, $p = 0.002$). The Bonferroni pairwise comparison test showed significant differences between marshes 1 and 2, marshes 1 and 3, marshes 2 and 3, and marshes 3 and 4 (Table 9).

Table 8. Mean water table heights (cm) in relation to soil surface for the study period.

Marsh	February	April	May	August	November
1	2	1.3	0	-21	0.83
2	15	11	5.4	-16	0.5
3	17	15	1.4	-15	-14
4	12	11	2.7	-14	-28

Table 9. Significance values (p-values) derived from the Bonferroni pairwise comparison for differences between marshes for the water table.

Marsh	2	3	4
1	0.002	0.033	0.256
2		0.053	0.009
3			0.676
4			

LiDAR derived elevations for each marsh indicated that marshes 1 and 2 were lower in elevation than marshes 3 and 4 (Table 10 and Table 11). The Kruskal-Wallis one way analysis of variance, performed on ranks indicated significant differences ($F = 5.573$, $df = 3$, $p = 0.03$). The Bonferroni pairwise comparison indicated marshes 1 and 2 were statistically lower than marshes 3 and 4 (Table 11).

Table 10. LiDAR derived elevations (m) for each marsh. Marshes 1 and 2 were statistically lower than marshes 3 and 4.

Marsh	Elevation \pm Standard Error
1	1.315 \pm 0.029
2	1.327 \pm 0.017
3	1.401 \pm 0.011
4	1.422 \pm 0.023

Table 11. Significance values (p-values) derived from the Bonferroni pairwise comparison for differences in elevation between marshes.

Marsh	2	3	4
1	1.000	0.039	0.035
2		0.044	0.039
3			1.000
4			

The mean elevation of the trail berm was 1.44 ± 0.026 . The Kruskal-Wallis one way analysis of variance on ranks was statistically significant (ANOVA, $F = 3.939$; $df = 4$; $p = 0.006$). The Bonferroni pair wise comparison test revealed statistically significant differences between marshes 1, 2 and the trail berm. No statistical differences were found between the trail berm and marshes 3 and 4 (Table 12).

Table 12. Significance values (p-values) derived from the Bonferroni pairwise comparison for differences in marsh elevations and the trail elevation.

Marsh	p-value
1	0.088
2	0.085
3	1.000
4	1.000

DISCUSSION

Carbon Pools

The aboveground carbon pool data indicate that the amount of carbon stored in aboveground biomass ranges from 550 to 780 g C m⁻² at peak season. Approximately one third of this was live biomass depending upon the marsh. A similar range of values was reported along a salinity gradient in marshes on the Georgia Coast where the freshwater marshes were approximately 600 g C m⁻², the brackish marshes were 700 g C m⁻² and the saline marshes were 500 g C m⁻² (Wieski et al 2010). This pattern indicates that brackish marshes may be storing the most carbon compared to fresh and saline marshes. The Georgia Coast findings are particularly interesting in the context of the salinity data gathered for my study. Previous studies in these Hog Island marshes reported a range of salinities between 0 and 2 ppt (Blecha 2010; Conn 1994); where as I found salinities to be highly variable and typically between 8 and 20 ppt, indicating that these marshes may be becoming more brackish with time. A study of the evolution of a similar barrier island marsh in Georgia illustrates this pattern: Booth et al (1999) found that the barrier island freshwater marshes have undergone many substantial changes throughout their history due to storm tides continuously altering hydrology and salinity. They also reported the highly unstable nature of these barrier island wetlands (Booth et al 1999). The increasing salinities seen on Hog Island are likely due to island instability; however, it is also likely that the higher values up to 36 ppt were outliers influenced by salt water intrusion from a coastal storm. The increasing salinities at the Hog Island sites are likely increasing their carbon sequestration potential. It has been shown that brackish to saline marshes emit the

lowest methane compared to sites of lower salinities and total carbon stocks have been shown to be greatest at brackish stages of a marsh compared to saline or fresh water stages (Poffenbarger et al 2011, Wieski et al 2010).

In the current study, belowground biomass carbon pools ranged from 155 to 270 g C m⁻² to a depth of 1 m. These values are much smaller than those previously reported for salt marshes in Delaware and Maryland. Elsey-Quirk et al (2011) reported 5119 g C m⁻² of belowground carbon in a *S. patens* dominated marsh to a depth of 30 cm. This discrepancy may be explained by the age of the Hog Island marshes. Marshes 1 and 2 are approximately 70 years old while marshes 3 and 4 are approximately 30 years old (Harris et al 2007). The immaturity of the Hog Island marshes would explain the lack of accumulation of belowground biomass that older marshes have developed. The root: shoot ratios in the Hog Island marshes were similar to previously studied salt marshes in Louisiana (Edwards and Mills 2005). Recent research suggests that high root: shoot ratios may not be indicative of soil carbon storage capacity, thus this metric is not as useful of an indicator for carbon sequestration potential compared to other metrics utilized for my study (Unger 2013).

Differences Among Marshes

The LiDAR, water table and salinity data support the idea that marshes 1 and 2 are more susceptible to overwash events than marshes 3 and 4. Thus marshes 1 and 2 should have higher net primary production rates, higher belowground biomass, lower decomposition rates, higher concentration of carbon within the soil and thus the higher blue carbon potential. The plant species composition also supports the idea that marshes 1

and 2 are more susceptible to overwash events. Marshes 1 and 2 were dominated by *Spartina patens*, but also had *Distichlis spicata*, a salt tolerant species, indicating that marshes 1 and 2 receive more salt water input throughout the year (Lonard et al. 2013). Marshes 3 and 4 were dominated by *S.patens* and *S. americanus*. *S. patens* and *S. americanus* are fresh to brackish water species that would be expected in this environment (Howard and Mendelsohn 1999; Lonard et al. 2010).

Despite the lack of statistical significance, the data did show trends that support the hypothesis regarding increased carbon sequestration potential with increased susceptibility to overwash. Marshes 1 and 2 had the higher aboveground production, belowground biomass, and soil organic matter compared to marshes 3 and 4.

Decomposition rates and soil carbon pool data did not support the hypothesized trend that the marshes most susceptible to overwash would have the slowest decomposition rates and the densest soil carbon pools. In general, the decomposition rates for all the marshes were slower than rates reported for other salt marsh systems, allowing for high sequestration potential overall. These marshes are young, approximately 70 years old for marshes 1 and 2, and 30 years old for marshes 3 and 4; as the marshes age, it is likely the soil carbon pool will increase (Harris et al 2007).

During the course of this study, there were no major storm or overwash events that could have resulted in differences among marshes. In order to determine if differences in sequestration rates among marshes exist, further data should be collected, including a time period when overwashes occur.

Metrics for Predicting Carbon Sequestration Potential

Aboveground net primary production in carbon units ranged from 156 to 284 g C m⁻². These values fall within the range of reported aboveground net primary productivity values for salt marshes. Northern Canadian and Alaskan marshes were 60 g C m⁻² yr⁻¹ while north central Gulf of Mexico marshes, some of the highest salt marsh values for North America, were 812 g C m⁻² yr⁻¹ (Chmura 2013). According to Drexler et al (2013), tidal freshwater marshes have been found to store carbon at rates equal to, or in some cases higher than, brackish or saline tidal marshes. However, they are also capable of high methane emissions (Drexler et al 2013), which were not considered as a part of this study. High aboveground net primary production will lead to high sequestration potential (Mcleod et al. 2011).

All marshes exhibited slow aboveground decomposition rates. The rates exhibited by these marshes were slower than rates published for a New Jersey salt marsh. The New Jersey salt marsh study reported findings suggesting that *S. patens* was more resistant to decomposition compared to *S. alterniflora* exposed to the same conditions (Frasco and Good 1982). Slow decomposition rates are essential for high carbon sequestration potential (Mcleod et al. 2011). Slow aboveground decomposition allows for more aboveground biomass to be buried, increasing the total sediment carbon pool (Mcleod et al. 2011).

Higher percentages of organic matter are indicative of lower decomposition rates, which would lead to accumulation of organic material within the soil (Pant et al. 2003).

The increase of organic matter accumulation rates would increase the amount of carbon stored within the system, increasing the marsh's blue carbon potential. A study on *S. alterniflora* dominated marshes exposed to different salinities determined that freshwater marshes had 17 to 20% organic matter, brackish water marshes had 25 to 50% organic matter and saline marshes had 12 to 24% organic matter in the top 50 cm of soil (Nyman et al. 1990). Marshes 1 and 2 fell within the fresh to brackish water category, while marshes 3 and 4 were below the range reported for my study. As stated previously, the Hog Island marshes are becoming more saline with time. It is important to note that the majority of the organic matter was found within the top 10 cm of the sediment. A salt water marsh study located between Delaware and Maryland found organic matter percentages as high as 28.4% in the top 22.5 cm of soil (Elsley-Quirk et al. 2001). This lack of organic matter below 10 cm depth may indicate that carbon is not being stored in the Hog Island Marshes at the same capacity as other blue carbon systems; however the Hog Island marshes are young and may not have had the time to accumulate carbon. The increases in salinity and age of the Hog Island marshes will likely increase the carbon sequestration potential.

Soil carbon density for the Hog Island marshes ranged from 0.00155 to 0.0158 g cm⁻³. Average soil carbon density for salt marshes is reported to be 0.039 ± 0.003 g cm⁻³ (Chmura et al. 2003). This value is higher than the values determined for this study, indicating that Hog Island marshes are not storing carbon in the soil at rates similar to salt water marshes. The majority of carbon stored in wetlands is typically stored within the sediments (Bridgham et al. 2006). The low carbon density values in Hog Island marshes could be indicative of low carbon sequestration potential because soil carbon is a product

of carbon sequestration; however, it could also be due to marsh age as discussed previously. Soil carbon density will likely increase as these marshes age (Harris et al 2007).

Blue Carbon Implications

Carbon sequestration potential was calculated for this study because carbon export was not directly measured. Sequestration potential represents the maximum possible burial rate since carbon losses have not been considered. Actual carbon burial rates will likely be lower due to herbivory, methane emissions and tidal influence, but their exact influence is not known. The sequestration potentials among the marshes followed the trend I hypothesized, with marsh 1 having the highest potential, followed by marshes 2, 3, and 4. The sequestration potential for these marshes ranged from 116.6 to 233.4 g C m⁻² yr⁻¹. Mean salt marsh carbon sequestration rates have been reported to be between 194 and 242 g C m⁻² yr⁻¹, mean mangrove sequestration rates to be between 187 and 265 g C m⁻² yr⁻¹ and mean seagrass sequestration rates to be between 100 and 176 g C m⁻² yr⁻¹ (McLeod et al. 2011).

Tidal import and export will vary with the frequency and severity of storm systems, which will change with global climate change (Hartmann et al. 2013). Due to the lack of storm overwash events during the course of this study, it is difficult to predict how storms will actually affect the carbon storage capabilities of these marshes. Export in particular, was not directly measured but needs to be considered when addressing sequestration rates.

Methane emissions along tidal gradients tend to be higher in less saline systems (Poffenbarger et al 2011). The introduction of *Phragmites australis* increases methane

emissions (Mozdzer and Megonigal 2013). *Phragmites* had begun to invade the Hog Island marsh sites and thus methane emissions need to be monitored at these sites in order to evaluate carbon sequestration.

The data from aboveground net primary production, belowground biomass, and decomposition rates suggest that the Hog Island marshes are potentially sequestering carbon at rates similar to salt water marshes. However, data from percent organic matter in the soil and soil carbon pools suggest that the Hog Island marshes do not bury carbon at similar rates to salt water marshes. This is likely due to the age of the marshes and will increase with time. No major storm or overwash events occurred during this study, which may have contributed to lower soil carbon values. Laterally imported carbon from overwash events is important for blue carbon systems, contributing to a larger carbon sink (Mcleod et al. 2011). Future work should attempt to quantify sediment deposition during storm events to determine if lateral carbon import is occurring at a level consistent with other blue carbon systems. Climate change models forecast increasing storm frequency and severity, possibly increasing sediment deposition to these marshes, assuming they keep pace with sea level rise (Hartmann et al. 2013). Further work must also consider export from these systems in order to accurately determine a realistic sequestration rate. While the potential to sequester carbon in these systems was determined to be high, the lack of understanding of export limits the ability to compare this study to other blue carbon studies.

REFERENCES

- Alongi DM (2014) Carbon cycling and storage in mangrove forests. *Annual Review of Marine Science* 6: 195-219.
- Barlow, PM (2003) Ground water in freshwater – saltwater environments of the Atlantic coast. USGS Circular: 1262.
- Battin TJ, Luysaert S, Kaplan L, Aufdenkampe AK, Richter A, Tranvik LJ (2009) The boundless carbon cycle. *Nature Geoscience* 2: 598-600.
- Blecha SB (2010) Inter-island variability in above and belowground plant biomass in interior marshes on the Virginia Barrier Islands. Master's Thesis. Old Dominion University. Norfolk, VA
- Booth RK, Rich FJ, Bishop GA, Brannen NA (1999) Evolution of a freshwater barrier-island marsh in coastal Georgia, USA. *Wetlands* 19: 570-577.
- Bridgham SD, Megonigal JP, Keller JK, Bliss NB, Trettin C (2006) The carbon balance of North American wetlands. *Wetlands* 26: 889-916.
- Carr J., D'Odorico P, McGlathery KJ, Wiberg PL (2012) Stability and resilience of seagrass meadows to seasonal and interannual dynamics and environmental stress. *Journal of Geophysical Research* 117: 1-12.
- Chmura GL (2013) What do we need to assess the sustainability of the tidal salt marsh carbon sink? *Ocean and Coastal Management* 83: 25-31.
- Chmura GL, Anisfeld SC, Cahoon DR, Lynch JC (2003) Global carbon sequestration in tidal, saline wetland soils. *Global Biogeochemical Cycles* 17: 1-12.
- Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, Levermann A, Merrifield MA, Milne GA, Nerem RS, Nunn, PD, Payne AJ, Pfeffer WT, Stammer D, Unnikrishnan AS (2013) Sea level change. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, and Midgley PM (eds.) *Climate Change 2013: The physical science basis, contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 1137-1216.
- Ciais P, Sabine C, Bala G, Bopp L, Brovkin V, Canadell J, Chhabra A, DeFries R, Galloway J, Heimann M, Jones C, Quere L, Myneni RB, Piao S, Thornton P (2013) Carbon and other biogeochemical cycles. In: Stocker TF, Qin D, Plattner

- GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley (eds) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA pp 465-570.
- Conn, CE (1994) The role of nitrogen availability, hydroperiod and litter quality in root decomposition along a barrier island chronosequence. Ph.D Dissertation. Old Dominion University. Norfolk, VA.
- Dame RF, Kenny P (1986) Variability of *Spartina alterniflora* primary production in the euhaline North Inlet estuary. *Marine Ecology* 32: 71-80.
- Day FP, Crawford ER, Dilustro JJ (2001) Aboveground plant biomass change along a coastal barrier island dune chronosequence over a six-year period. *Journal of the Torrey Botanical Society* 128: 197-207.
- Donato DC, Kauffman JB, Murdiyarso D, Kurnianto S, Stidham M, Kannien M (2011) Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience* 4: 293-297.
- Drexler JZ, Krauss KW, Sasser MC, Fuller CC, Swarzenski CM, Powell A, Swanson KM, Orlando J (2013) A long-term comparison of carbon sequestration rates in impounded and naturally tidal freshwater marshes along the lower Waccamaw River, South Carolina. *Wetlands* 33: 965-974.
- Duarte CM, Kennedy H, Marba N, Hendricks I (2013) Assessing the capacity of seagrass meadows for carbon burial: Current limitations and future strategies. *Ocean and Coastal Management* 83: 32-38.
- Duarte CM, Middelburg JJ, Caraco N (2005) Major role of marine vegetation on the oceanic carbon cycle. *Biogeosciences* 2: 1-8.
- Edwards KR, Mills KP (2005) Aboveground and belowground productivity of *Spartina alterniflora* (Smooth Cordgrass) in natural and created Louisiana salt marshes. *Estuaries* 28: 252-265.
- Elsley-Quirk T, Selskar DM, Sommerfield CK, Gallagher JL (2011) Salt marsh carbon pool distribution in a Mid-Atlantic Lagoon, USA: Sea level rise implications. *Wetlands* 31: 87-99.
- Fahey T, Knapp AK (2007) Principles and standards for measuring primary production. Oxford University Press, New York, NY, USA.

- Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga R, Prinn R, Raga G, Schulz M, Van Dorland R (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA pp 129-234.
- Fourqurean JW, Duarte CM, Kennedy H, Marba N, Holmer M, Mateo MA, Apostolaki ET, Kendrick GA, Krause-Jensen D, McGlathery KJ, Serrano O (2012) Seagrass ecosystems as a globally significant carbon stock. *Natural Geoscience* 5: 505-509.
- Frasco BA, Good RE (1982) Decomposition dynamics of *Spartina alterniflora* and *Spartina patens* in a New Jersey salt marsh. *American Journal of Botany* 69: 402-406.
- Gabriel BC, Cruz AA (1974) Species composition, standing stock and net primary production of a salt marsh community in Mississippi. *Chesapeake Science* 15: 72-77.
- Greiner J (2013) Assessing the importance of seagrass habitat restoration to “blue carbon” sequestration in shallow coastal waters. Master’s Thesis, University of Virginia. Charlottesville.
- Grimsditch G, Alder J, Nakamura T, Kenchington R, Tamelander J (2013) The blue carbon special edition – introduction and overview. *Ocean and Coastal Management* 83: 1-4.
- Hallegatte S (2009) Strategies to adapt to an uncertain climate change. *Global Environmental Change* 19: 240-247.
- Harris, M., G. Shao and J. Porter (2007) Landscape Age Map for Hog Island, Northampton, Co., Virginia. 1852-1985. Virginia Coast Reserve Long-Term Ecological Research Project Data Publication.
- Hartmann DL, Klein Tank AMG, Rusticucci M, Alexander LV, Bronnimann S, Charabi Y, Dentener FJ, Dlugokencky EJ, Easterling DR, Kaplan A, Soden BJ, Thorn PW, Wild M, Zhai PM (2013) Observations: Atmosphere and surface. In: Soler TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the*

Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 159-254.

- Hayden, BP, Duesser RD, Callahan JT, Shugart HH (1991) Long-term research at the Virginia Coast Reserve. *Bioscience* 41: 310-318.
- Hayden BP, Santos MCFV, Shao G, Kochel RC (1995) Geomorphological controls on coastal vegetation at the Virginia Coastal Reserve. *Geomorphology* 13: 283-300.
- Hopkinson CS, Cai W-J, Hu X (2012) Carbon sequestration in wetland dominated coastal systems – a global sink of rapidly diminishing magnitude. *Current Opinion in Environmental Sustainability* 4: 186-194.
- Howard RJ, Mendelssohn IA (1999) Salinity as a constraint on growth of oligohaline marsh macrophytes. I. Species variation in stress tolerance. *American Journal of Botany* 86: 785-794.
- Hoyt JH (1967) Barrier island formation. *Geological Society of America Bulletin* 78: 1125-1136.
- Kennedy H, Beggins J, Duarte CM, Fourqurean JW, Holmer M, Marba N, Middelburg JJ (2010) Seagrass sediments as a global carbon sink: Isotopic constraints. *Global Biogeochemical Cycles* 24: 1-8
- King CA (1972) *Beaches and Coasts*. Edward Arnold, Wisconsin, USA.
- Klara SM, Srivastava RD, McIlvried HG (2003) Integrated collaborative technology development program for CO₂ sequestration in geologic formations – United States Department of Energy R&D. *Energy Conservation and Management* 44: 2699-2712.
- Lal R (2008) Carbon sequestration. *Philosophical Transactions of the Royal Society B: Biological Sciences* 363: 815- 830.
- Lonard RI, Judd FW, Stalter R (2013) The biological flora of coastal dunes and wetlands: *Distichlis spicata* (C. Linnaeus) E. Greene. *Journal of Coastal Research* 29: 105-117.
- Lonard RI, Judd FW, Stalter R (2010) The biological flora of coastal dunes and wetlands: *Spartina patens* (W. Aiton) G.H. Muhlenberg. *Journal of Coastal Research* 265: 935-946.
- Macreadie PI, Hughes AR, Kimbro DL (2013) Loss of “blue carbon” from coastal salt marshes following habitat disturbance. *PLoS One* 8:e69244. Doi: 10.1371/journal.pone.0069244.

- Mateo MA, Romero J, Perez M, Littler MM, Littler DS (1997) Dynamics of millenary organic deposits resulting from the growth of the Mediterranean seagrass *Posidonia oceanica*. *Estuarine, Coastal and Shelf Science* 44: 101-110.
- McLeod E, Chmura GL, Bouillon S, Salm R, Bjork M, Duarte CM, Lovelock CE, Schlesinger WH, Silliman BR (2011) A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO₂. *Frontiers in Ecology and Environment* 9: 552-560.
- Mozdzer TJ, Megonigal JP (2013) Increased methane emissions by an introduced *Phragmites australis* lineage under global change. *Wetlands* 33: 609-615.
- Nellemann C, Corcoran E, Duarte C, Valdes I, De Young C, Fonseca L, Grimsditch G (2009) Blue carbon, the role of healthy oceans in binding carbon. A rapid response assessment. Birkeland Trykkeri AS, Norway.
- Nyman J, Delaune RD, Patrick WH (1990) Wetland soil formation in the rapidly subsiding Mississippi River Deltaic Plain. Mineral and organic matter relationships. *Estuarine and Coastal Shelf Science* 31: 57-69.
- Pant HK, Rechicigl JE, Adjei MB (2003) Carbon sequestration in wetlands: Concept and estimation. *Food, Agriculture and Environment* 1: 308-313.
- Park A-HA, Jadhav R, Fan L-S (2003) CO₂ mineral sequestration: Chemically enhanced aqueous carbonation of serpentine. *Canadian Journal of Chemical Engineering* 81: 885-890.
- Poffenbarger HJ, Needleman BA, Megonigal JP (2011) Salinity influence on methane emissions from tidal marshes. *Wetlands* 31: 831-842.
- Powell SW, Day FP (1991) Root production in four communities in the Great Dismal Swamp. *American Journal of Botany* 78: 288-297.
- Ray GC, Gregg WP (1991) Establishing biosphere reserves for coastal barrier ecosystems. *Bioscience* 41: 301-309.
- Reilly TE, Goodman AS (1985) Quantitative analysis of saltwater-freshwater relationships in groundwater systems – a historical perspective. *Journal of Hydrology* 80: 125-160.
- Rheinhardt RD, Faser K (2001) Relationship between hydrology and zonation of freshwater swale wetlands on lower Hatteras Island, North Carolina, USA. *Wetlands* 21: 265-273.

- Robertson J, Thomas CJ, Caddy B, Lewis, Arlette JM (1984) Particle size analysis of soils – a comparison of dry and wet sieving techniques. *Forensic Science International* 24: 209 – 217.
- Roper T, Greskowiak J, Freund H, Massmann G (2013) Freshwater lens formation below juvenile dunes on a barrier island (Spiekeroog, Northwest Germany). *Estuarine and Coastal Shelf Science* 121-122: 40-50.
- Sedghi NM (2015) Blue carbon in coastal freshwater/brackish marshes on the barrier islands of Virginia: Belowground carbon pools. Master's Thesis. Old Dominion University. Norfolk, VA.
- Shao G, Shugart HH, Hayden BP (1996) Functional classifications of coastal barrier island vegetation. *Journal of Vegetation Science* 7: 391-396.
- Turner RE, Swenson EM, Milan CS, Lee JM, Oswald TA (2004) Below-ground biomass in healthy and impaired salt marshes. *Ecological Research* 19: 29-35.
- Unger V (2013) Carbon accumulation in salt marsh soils: A comparison of a coastal plain and coastal lagoon estuary in the mid-Atlantic U.S. Master's Thesis. Drexel University. Philadelphia, PA
- VITA 2011. LiDAR-based Digital Elevation Model for Northampton and Accomack Co., VA, 2010. Virginia Coast Reserve Long-Term Ecological Research Project Data Publication
- Walther, GR, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin JM, Hoegh-Guldberg O, Bairlen F (2002) Ecological responses to recent climate change. *Nature* 416: 389 – 395.
- Waycott M, Duarte CM, Carruthers TJB, Orth, RJ, Dennison WC, Olyarnik S, Calladine A, Fourqurean, JW, Heck KL, Hughes AR, Kendrick GA, Kenworthy WJ, Short FT, Williams SL, Paine RT (2009) Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proceedings of the National Academy of Science* 106: 12377-12381.
- Wieski K, Guo H, Craft CB, Pennings SC (2009) Ecosystem functions of tidal fresh, brackish, and salt marshes on the Georgia coast. *Estuaries and Coasts* 33: 161-169.
- Windham L (2001) Comparison of biomass production and decomposition between *Phragmites australis* (common reed) and *Spartina patens* (salt hay grass) in brackish tidal marshes of New Jersey, USA. *Wetlands* 21: 179-188.

APPENDIX

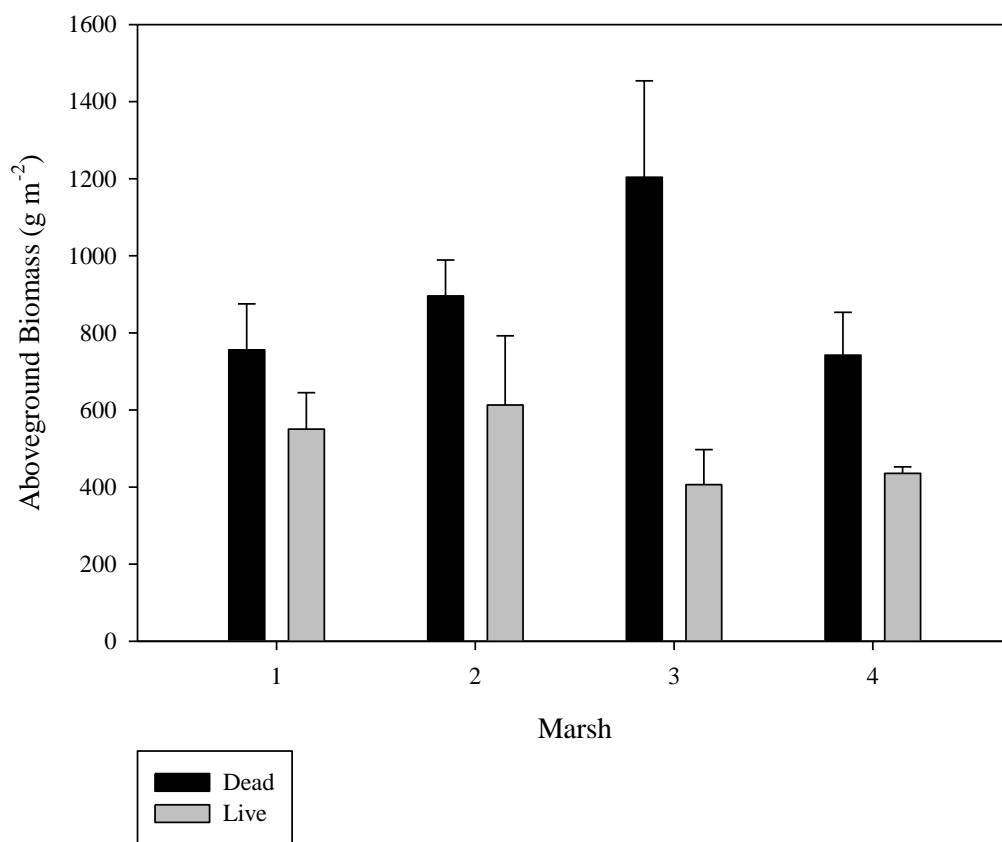


Figure 15. Peak aboveground biomass of live and dead plant material for the month of August.

Table 13. Peak aboveground biomass of live and dead plant material for the month of August

Marsh	Standing Dead Biomass (g m ⁻²)	Live Biomass (g m ⁻²)
1	756 ± 119.1	550.4 ± 94.3
2	896 ± 92.9	612.9 ± 179.7
3	1204 ± 249.8	406.3 ± 90.6
4	742.4 ± 111	435.6 ± 16.5

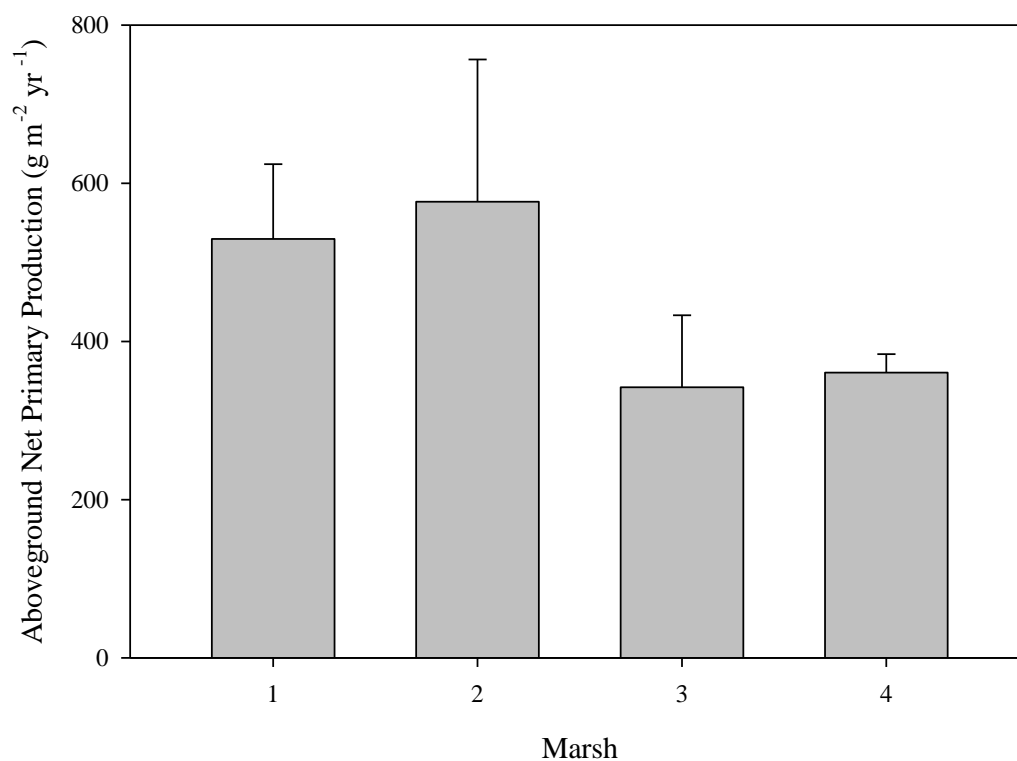


Figure 16. Aboveground net primary production for each marsh. Error bars indicate one standard error.

Table 14. Aboveground net primary production for each marsh.

Marsh	Aboveground Net Primary Productivity (g m⁻² yr⁻¹)
1	529.3 ± 94.5
2	576.6 ± 180
3	341.9 ± 91.2
4	360.6 ± 23.3

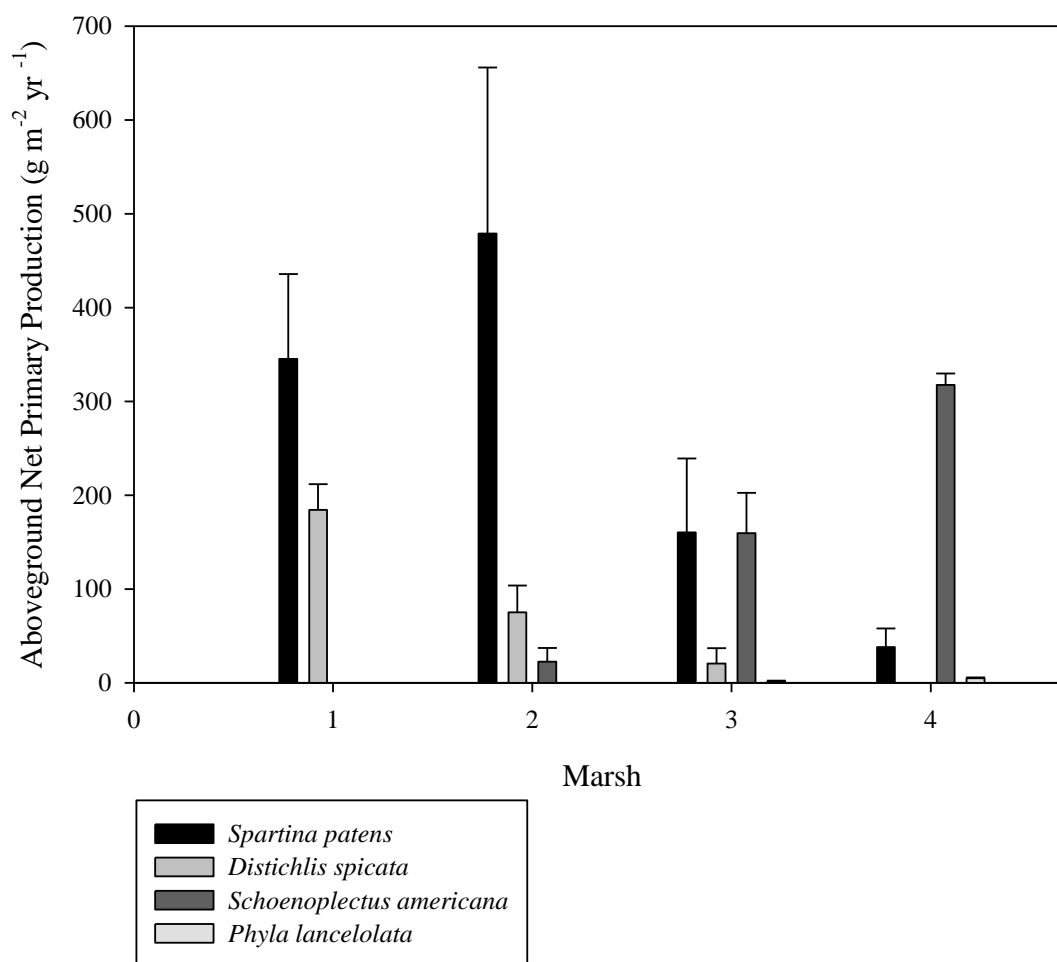


Figure 17. Aboveground net primary production by species. Error bars indicate one standard error.

Table 15. Aboveground net primary production by species ($\text{g m}^{-2} \text{ yr}^{-1}$).

Marsh	<i>Spartina patens</i>	<i>Distichlis spicata</i>	<i>Schoenoplectus americana</i>	<i>Phyla lanceolata</i>
1	345.2 ± 90.4	184.1 ± 27.4	0	0
2	478.9 ± 177	75.1 ± 28.7	22.6 ± 14.5	0
3	160.4 ± 78.8	20.5 ± 16.5	159.6 ± 42.9	1.4 ± 1
4	38.1 ± 19.8	0	317.6 ± 12.2	4.9 ± 0.9

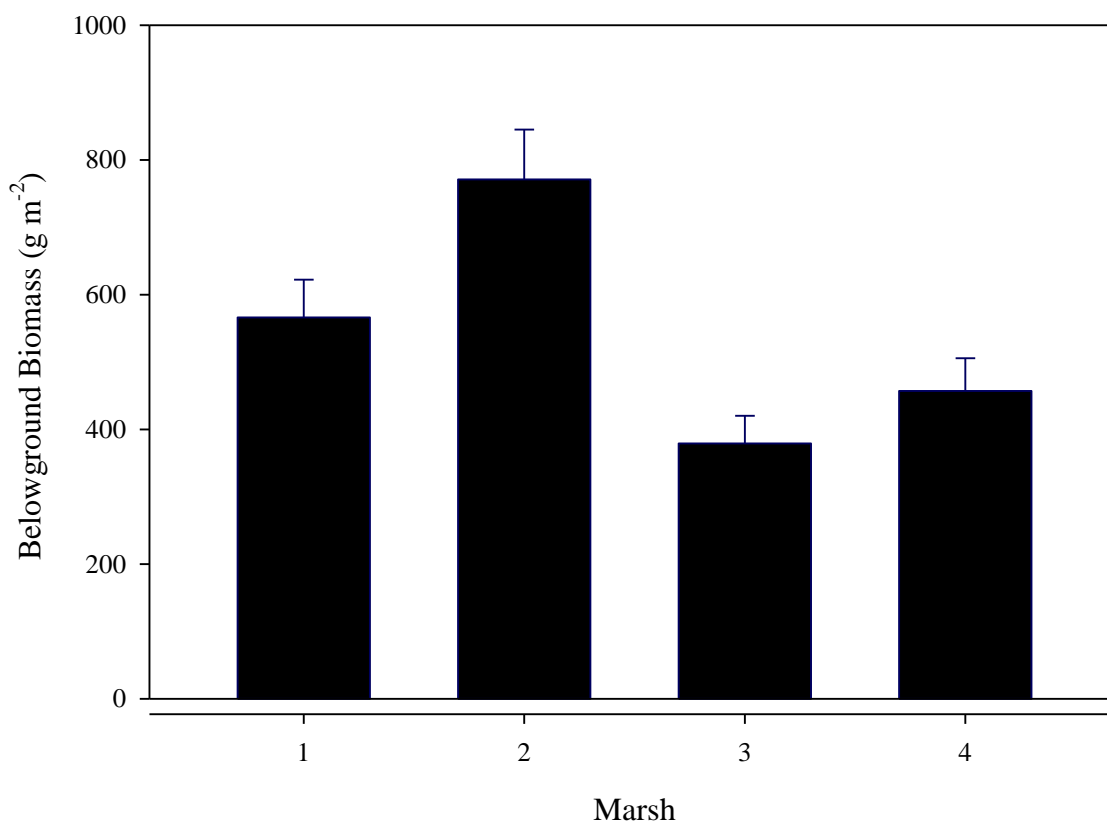


Figure 18. Belowground biomass for each marsh. Error bars indicate one standard error.

Table 16. Belowground biomass for each marsh.

Marsh	Belowground Biomass (g m⁻²)
1	566.1 ± 56.1
2	771 ± 74.1
3	378.9 ± 41.2
4	457 ± 48.5

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Touchette BW, Adams EC and Laimbeer P (2012) Age specific responses to salinity in salt marsh plant black needle rush (*Juncus roemerianus* Scheele) as determined through polyphasic chlorophyll *a* fluorescence transients (OJIP). *Marine Biology* 159: 2137-2147.

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