2018

The role of vegetation-topographic interactions in a barrier island system: island migration in a changing climate

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at Virginia Commonwealth University.

by

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June 2018

Acknowledgment

The author wishes to thank several people. I owe so much to my advisor, Dr. Julie Zinnert, for her encouragement, always-supportive mentorship and for pushing me to do my best and believe in myself among much self-doubt. The personal and professional growth I have experienced in the past year would not have been possible without her mentorship. I thank the members of my thesis committee and my numerous undergraduate and graduate colleagues in the Coastal Plant Ecology Lab at VCU, especially Austin Tuley, Joe Brown, Lauren Wood and Eddie Long, for their help and direction with this project. I would like to thank my parents, Pete and Michele, for their unending love, support and patience during the past seven years and long-distance moves it has taken me to reach this point in my life. Last but not least, I would like to thank the Virginia Coast Reserve, an NSF LTER site, and The Nature Conservancy of Virginia for providing access to the pristine barrier islands of Virginia to complete this project.

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Abstract

THE ROLE OF VEGETATION-TOPOGRAPHIC INTERACTIONS IN A BARRIER ISLAND SYSTEM: ISLAND MIGRATION IN A CHANGING CLIMATE

By Benjamin P Nettleton, M.S.

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at Virginia Commonwealth University.

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Major Director: Dr. Julie Zinnert, Assistant Professor, Department of Biology

Islands have been characterized based on vegetation and topography as exhibiting different disturbance regimes - reinforcing or resisting. This study had two objectives: quantify barrier island upland migration and vegetation cover change over 32 years (1984-2016), and assess tolerance of two prevalent dune grass species, *A. breviligulata*, and *S. patens* to sand burial. Using Landsat imagery from the Virginia Coast Reserve, islands were categorized within the disturbance resistance/reinforcing framework based on dune elevation. Resistant areas were associated with woody cover and low marsh to upland migration while reinforcing areas had low vegetation cover and high rates of migration. System-wide, migration rates increased over time and large losses of upland and marsh, paired with expansions of woody cover occurred. In the field, each grass species was subject to repeated burials. *S. patens* was able to maintain biomass and height in high rates of burial, whereas *A. breviligulata* did not survive.

Introduction

Barrier islands provide many valuable ecosystem services such as sheltering the mainland from storms (Seabloom et al. 2013), protecting marshes and estuaries that support fishing and shellfish economies, as well as providing critical habitat for numerous other rare and endangered species (Masterson et al. 2014). Globally, barrier islands comprise 15% of coastlines and are found on every continent, less Antarctica. 30% of barrier islands are found along the United States coastline, one of the most extensively anthropogenically developed coastlines in the world. (Stutz and Pilkey 2001). Barrier islands cover 78% of the U.S. Atlantic coastline, protecting over 41.5 million people from the most significant impacts of hurricanes and nor'easters. (Wilson and Fischetti 2010; Zhang and Leatherman 2011; Arkema et al. 2013).

Barrier islands create ecologically important back-barrier marshes and tidal bays, previously mentioned for their economic importance, however they also have unique upland ecosystems that have received little attention relative to their back-barrier counter-parts (Feagin et al. 2009, Zinnert et al. 2016). Barrier island upland consists of multiple habitats including beach, dune/swale complex (grassland, shrubland, and maritime forest), and back-barrier marsh complex. These habitats are highly dynamic and exist along steep environmental gradients in resources, salinity, and disturbance susceptibility (Stallins and Parker 2003; Stallins 2005). Dune/swale vegetation creates feedbacks with island topography and influences the disturbance frequency and severity that inner island communities experience. (Stallins and Parker 2003; Stallins 2005, Miller et al. 2010).

Because of the tight coupling of island ecological processes and oceanic and atmospheric drivers of disturbance (e.g. hurricanes, nor'easters, sea level rise), barrier islands are at the forefront of global climate change (Zinnert et. al. 2011; Arkema et al. 2013). Barrier islands respond to long term presses, like sea level rise, by "rolling over" (i.e. landward migration of an island) often through sediment transport onto the back-barrier marsh platform via overwash (Hayden et al. 1980). Overwash occurs during storm events when waves and surge breach the foredune, washing sediment and salt water into the swales and island interior. Overwash can often reduce or temporarily eliminate local vegetation and in severe cases alter local topography by flattening dune structures (Stallins and Parker 2003; Gornish and Miller 2010, Miller et al. 2010). This migration via overwash results in the island maintaining elevation above sea level.

Previous studies used models to describe dunes as fitting into alternate morphological states: high and low (Vinent and Moore 2015). These models only accounted for dune elevation and did not consider vegetation feedbacks, the spatial arrangement of dunes and other interior characteristics of the barrier islands. To address this, recent work has introduced a more comprehensive concept of disturbance resisting and disturbance reinforcing stability domains, which cover the barrier island landscape from beach to marsh (Zinnert et al. 2017). While the dune models are relevant, my thesis will follow the broader scale definition introduced by Zinnert et al.

2017 due to the large scale nature of my questions. Disturbance reinforcing islands tend to have low elevation, sparse vegetation cover and have a high frequency of overwash, often leading to an active landward migration. Conversely, disturbance resisting islands are generally wider, more topographically diverse and less susceptible to overwash, thus remaining relatively stable over time (Zinnert et al. 2017).

Interactions between vegetation cover and elevation may play an important role in influencing the amounts and frequency of sediment washing onto the marsh, altering rates of island migration. At the ecosystem scale, major shifts in the upland vegetation communities of barrier island worldwide have been observed over the past several decades (Battaglia et al. 2007, Young et al. 2007, Isermann 2008, Lucas and Carter 2010). Across the Virginia barrier islands and the rest of the east coast, this has mainly been in the form of the rapid expansion of a few woody species and reduction in diversity of upland grasses and forbs (Battaglia et al. 2007, Young et al. 2007). Additionally, losses in island area have been observed, with a 29% loss of upland area at the Virginia Coast Reserve from 1984-2011, attributable to combined effects of erosion and sea level rise (Zinnert et al. 2016).

Several species of dune building grasses are particularly important in their ability to influence susceptibility to overwash disturbance by feedbacks with dune topography (Stallins 2005, Feagin et al. 2015). *Ammophila breviligulata* and *Spartina patens* are the two most common dune-building grasses along the Virginia barrier islands, differing in growth strategies and thus, dune-building. *Ammophila breviligulata* tends to build relatively long, unbroken dune ridges as a function of its guerilla rhizome morphology and response to sand burial (Maun and Lapierre 1984, Maun 1994). One study showed that *Ammophila breviligulata* can tolerate very high rates of burial, up to 1 m of sand per year, which significantly contributes to dune formation (Maun and Lapierre 1984). *Ammophila breviligulata* responds to one-time burial by decreasing above ground biomass and allocating resources to maintaining root mass (Brown et al. 2017). The long, unbroken dune ridges characteristic of *A. breviligulata* are typically several meters high and are relatively undisturbed except in some of the strongest storms. Areas with these dune ridges typically fit the disturbance resistant alternate state (Stallins 2005, Zinnert et al. 2017).

Alternatively, *S. patens* tends to build low, hummocky dunes or maintain topographically flat areas as a function of its phalanx rhizome morphology (Brantley et al. 2014). *Spartina patens* is generally not considered a dune building species and responds to burial by increasing and elongating leaves above the surface and decreasing root mass, likely to increase photosynthesis, rather than growing taller (Brown et al. 2017). The small, broken dunes with open space between them may be frequently disturbed as ocean water can easily overtop and/or move around the hummocky dunes during storm surge. Areas with these dune types are classified as fitting the disturbance reinforcing alternate state (Stallins 2005, Zinnert et al. 2017).

While much of the previous literature has considered the alternate stability domains at an island scale, because of the coupling with vegetation, we expect that these alternate states can exist at an intra-island scale. This is supported by elevation and distribution data of the two dune building grasses we focus on. While both species are commonly distributed across each island, *S. patens* occupies lower elevations with higher cover at lower elevation sites (unpublished data) relative to *A. breviligulata*. Differences in photosynthetic pathways has been linked to resource allocation post-burial for these two grasses (Brown and Zinnert, 2018), likely influencing distribution relative to disturbance. *Ammophila breviligulata*, a C- 3 grass or cool season grass, is not as water or nutrient use efficient as *S. patens*, a C-4 or warm season grass.

Depending on propagule availability after severe overwash disturbance, either *A. breviligulata* or *S.patens* could potentially recolonize and begin the dune-building process (Brantley et al. 2014). However, if *S. patens* colonizes first, it is unknown if it maintains disturbance reinforcing sites that inhibit growth of *A. breviligulata* because of feedbacks between vegetation growth and overwash frequency. Growth response to variation in the frequency of burial events has not been tested for either species. While previous literature shows that both species respond with growth to burial, I am subjecting plants to burial levels characteristic of an extreme event in-situ, a contrast to small incremental or one-time burials that have been conducted in previous studies. This could enhance existing coastal dune models to understand how strong storms and associated burial may affect the growth response of these common coastal grasses.

Given the observed changes in vegetation communities on barrier island systems and trends of migration and loss in island area, it is necessary to connect and specifically describe these patterns and the mechanisms by which the vegetation topographic feedbacks that influence them operate. Additionally, climate change models have predicted scenarios of more frequent and higher intensity storms in the Atlantic basin (Emanuel 2013); this may lead to a higher potential for more frequent and severe overwash disturbance than was historically observed. Our objective is to integrate remote sensing analysis and field experiments to understand these broad and local scale interactions in the context of the two stability domains.

Specific Questions and Hypothesis:

1. Is there a threshold of overwash burial frequency that inhibits the recovery of burial tolerant vegetation? Additionally, are there species-specific responses to these different rates of burial that influence their potential to assemble according to dominant disturbance regimes?

I hypothesize that increased burial frequency will limit recovery of any and all vegetation at the highest frequency of burial (3, 15cm events) due to 45cm of burial being an exceptional event. I predict that vegetation will emerge at the 1 and 2 time frequencies, but that species specific differences will be evident. Specifically, I predict that *A. breviligulata* will have reduced aboveground growth and emergence in response to repeated burial. Our high frequencies of burial may overwhelm this species and limit its capacity to photosynthesize due to *A. breviligulata's* nature of allocating below ground in response to burial. Conversely, *S. patens* will respond with increased biomass in all burial situations, allocating more resources aboveground. This will enable survival and above ground emergence of *S. patens* in our repeated disturbance scenario.

2. What are the general patterns of vegetation change occurring over the last several decades at the VCR? Additionally, how does stability domain (e.g. disturbance reinforcing, disturbance resisting) influence the historical (1984-2016) rate of marsh to upland conversion (as a measure for barrier island migration)? Do these stability domains and associated migration rates vary at a sub-island scale?

Based on previous studies, I hypothesize that woody vegetation has rapidly increased across the entire VCR and that the islands are extremely spatially and temporally dynamic in vegetation cover and land area, with overall trends toward loss of land area. Due to higher frequencies of overwash associated with disturbance reinforcing stability domains, I hypothesize that the marsh to upland conversion is faster when compared to disturbance resisting domains that have higher protecting foredunes and thus less overwash. I predict that migration rates and stability domains will vary at a scale finer than whole-island.

Methods

Burial Field Experiment

The field experiment was placed on Hog Island, VA (37° 23′ N, 75° 42′ W), located about 8 km off the coast of the eastern shore of Northampton County, Virginia (Figure 1). Hog Island is owned and managed by The Nature Conservancy as part of the Virginia Coast Reserve (VCR) and is part of an NSF Long Term Ecological Research (LTER) site.

To examine the effect of burial on dune-building grasses, roughly 2 x 2 m plots (n=5) were established behind the foredune that were approximately equal in cover of *A. breviligulata* and *S. patens*, each containing four treatments and one reference (Figure 2). These two species are common along dune ridges and have been selected for the distinct ways that they each build dunes and influence stability domains. Following Walters and Kirwan (2016), each bucket setup contained one plant of each species surrounded by 20 L plastic buckets with a 30 cm diameter to contain sand. The bottoms of the buckets were cut out to allow drainage and were cut longer than burial depth to allow 10cm of the bucket to be pushed into the sand for anchorage. A shovel was used around the placed bucket collar to sever rhizomes so that plants could not benefit from the shared nutrients of nearby unburied plants.

Treatments consisted of three frequencies of burials (three burials, two burials and one burial, each being distinct and two weeks apart) where 15 cm of sand was applied each time to replicate a natural burial disturbance from overwash. This amount coincides with literature derived burial depths which range from 5-10 cm for smaller storms recurring every couple years (Kochel and Dolan 1986) to over 50 cm for rare and intense storms such as hurricanes, which often have decadal scale intervals between recurrences for the mid-Atlantic region (Foxgrover 2009). The sand source was in front of the foredune in a non-vegetated area and dug from the near surface (within ~15cm) each time to maintain as similar as possible bulk density and water content. Sand was dumped onto the plants with a shovel and contained to a depth of 15 cm by the plastic bucket collars.

A reference was placed in each plot that consisted of the rim of a bucket, driven 10 cm into the ground, which received no burial treatments. To account for differences in growth strategies of the two species and the varying environmental conditions throughout the growing season, all final measurements were taken after treatments had four weeks to recover from the last burial. The experiment began well into the spring green-up, on June 6, 2017, with subsequent treatments on June 26 and July 14, and final measurements and collections occurred August 16 and 17.

Field Measurements

To quantify growth responses of both species, height, aboveground biomass and specific leaf area (SLA) were measured at the end of the experiment. Plant height was measured with a meter stick during the last treatment and again at the final harvesting to infer both a final height and a height change value for each plant. Measurements started at the sand surface and terminated at the end of the longest leaf of each species. Above ground biomass was collected by clipping all growth above the sand surface from each bucket, separated by species and weighed in grams using a digital scale. I collected and massed the below burial biomass, i.e. the biomass that was within the plastic collars but was not root tissue. SLA is the area of a fresh single-sided leaf divided by its dry mass and provides data that can be used to infer relative growth rates and photosynthetic rates of plants. (Pérez-Harguindeguy et al. 2013). SLA was measured from a 1 cm length leaf cutting from each of the live plants. Both the SLA and biomass samples were dried in an oven at 70°C for 72 hours prior to weighing.

Statistical Analysis

I used Chi Square tests to assess above ground emergence for each species across treatments. Due to the small sample size and non-normality of the data, Kruskal - Wallis nonparametric tests were used to test for the effect of burial on vegetation across the four treatments. Above burial biomass, total biomass, and height were compared among treatments. To determine species specific responses, ratios of *A. breviligulata:S. patens* within each treatment were calculated and compared across treatments using Kruskal - Wallis multiple comparisons for any significant results. I was unable to make statistical comparisons of SLA due to limited above ground emergence.

Historical Rate of Barrier Island Migration

Ten undeveloped Virginia barrier islands were used in this study: Metompkin, Cedar, Parramore, Hog, Cobb, Wreck, Ship Shoal, Myrtle Smith, and Fishermans, listed from north to south (Figure 1). Due to its unique circular shape and location at the mouth of the Chesapeake Bay, rather than a longitudinal Atlantic shore barrier, Fishermans Island was excluded from some analyses. Landsat TM5 satellite images were obtained from the USGS Global Visualization Viewer for the following dates: September 21, 1984, September 12, 1998, August 12, 2011 and September 12, 2016. Images were chosen from available dates within the growing season, cloud-free and at similar tide levels in order to minimize uncertainties due to heterogeneous natural conditions. Each imagery file was radiometrically corrected using ENVI 4.7 and predefined ENVI settings for Landsat calibration. Atmospheric correction was done to retrieve surface reflectance with ENVI QUAC. QUAC is a scene-based empirical approach used for the removal of atmospheric effects based on the radiance values of the image/scene. QUAC provides suitable reflectance spectra even when imagery does not have proper wavelength or radiometric calibration or when solar illumination intensity is unknown (Agrawal et. al 2011).

All Landsat scenes were subset to the Virginia barrier islands. Classifications of land use and cover for these historical Landsat images were provided from Zinnert et. al 2016 and included five classes: woody, grassland, sand/bare, water, and marsh. The classifications were exported to ArcGIS 10.4.1 (ESRI 2016). Total upland area was calculated from merging of the following classes: bare sand, woody, and grassland. Upland water (interior ponds) was not included as it was absent or less than 8 ha in total area during any given time.

Each island was subdivided into 1 km long polygons in ArcGIS that span the width of the island. We chose 1 km segments so that at least 3-4 polygons would be created for each island and to capture the variation in woody cover and island widths that occur on small spatial scales on some of the islands. Each of these subsections was then classified as disturbance reinforcing or disturbance resisting based on 2009 foredune elevation data obtained from Lidar (Oster and Moore 2009). Since disturbance reinforcing states are characterized by the low, hummocky dunes formed by *S. patens,* and disturbance resisting states by higher, unbroken dune ridges formed by *A. breviligulata,* disturbance resisting subsections have foredune elevation >1.0 m and disturbance reinforcing subsections will have foredune elevation <1.0 m, following literature derived model parameters for dune stability states (Duran Vinent and Moore 2015). We have field validation data for species composition on several islands for historical years (Young et al. 2011, Brantley et al. 2014; Brown, unpublished data). The 2016 data was field validated through aerial surveys and ground surveys done by the Coastal Plant Ecology Lab at VCU.

Change in land cover classes between years and overall were quantified by overlaying the class of interest from the initial year (e.g. marsh 1984) and the second class of interest from a different year (e.g. upland 1998) and extrapolating the intersection. The intersect sums overlapping areas for each pairwise comparison of cover classes. Of particular interest was the conversion of marsh to barrier island upland (i.e. barrier island migration). We calculated total class area (hectares) for each time period and class changes between time periods for whole islands and each island sub-section. Within the 1km sub-sections, ArcGIS was used to draw 3 cross-island transects (perpendicular to the shoreline) that divided the 1km subsection into equal thirds (Figure 3). We used these transects as consistent lines to measure the marsh and island upland widths, and the distance the marsh/upland boundary transgressed (i.e. the width of the marsh to upland intersection layer). Marsh to upland conversion rates and migration rates were calculated by dividing the area converted or distance the upland boundary transgressed, respectively, by the number of years in the time period of interest (e.g. 13 years for 1998-2011). This was done at both the whole island and sub-section scale. Whole islands were classified into similarity groups (parallel beach retreat, rotational instability, non-parallel beach retreat) based on historical shoreline retreat rates and geomorphologic characteristics according to Leatherman et al. (1982) (Figure 1).

Statistical Analysis

Significant differences in the distance of landward movement of the marsh/upland boundary (representing marsh to upland conversion) between the two stability domains was determined with a paired t-test. Non-linear regressions were used to determine if the available 2009 fore-dune elevation had a significant relationship with 1998-2011 marsh to upland migration and the 2011 woody cover.

Results

Burial Field Experiment

There was a significant difference in the aboveground emergence of *A. breviligulata* across the different treatments (Chi=15.791, p=0.0013). All *A. breviligulata* plants survived at the one time burial, but aboveground emergence was reduced to 40% at two time burial, and no plants emerged alive at the 3 time burial. Conversely, there was no difference in the aboveground emergence of *S. patens* across treatments (Chi=5.174, p=0.1595). *Spartina patens* maintained an 80% emergence rate at the 3 time burial (Figure 4).

Overall plant height (independent of species) was not significantly different at any burial treatment level (Chi=2.140, p=0.5438). The ratio of height between the species (*A. breviligulata:S. patens*) identified that *A. breviligulata* maintained the same height as *S. patens* at all frequencies of burial except 3 times (Chi=9.427, p=0.0241) due to no aboveground emergence in *A. breviligulata* (Figure 5). Burial did not have an effect on the total biomass by treatment (Chi=3.659, p=0.3007 (Figure 6)). However, at the species level, *S. patens* had marginally significantly higher biomass than *A. breviligulata* (Chi=8.065, p=0.0448) at the 45cm burial.

Historical Rate of Barrier Island Migration

Over the timeframe of this study, relative sea level rise was ~118.4 mm (~3.7 mm yr^{-1} (Boon and Mitchell 2015). From 1984-2016 across all islands, 12.8% of back barrier marsh and 27.4% of island upland area was lost. Despite reductions in upland area, large expansions of woody cover occurred (table 1). The Virginia barrier islands are highly dynamic with gains and losses in all the landcover types throughout each time period, demonstrating the transient nature of vegetation classes (Figure 7). The gain of woody vegetation was the most consistent vegetation change observed, expanding on almost all islands and increasing in the most recent time frames. The greatest total amounts of woody expansion occurred from 2011-2016 and occurred on Ship Shoal Island for the first time in our study time frame. In 2011-2016, the only island that did not have woody expansion was Myrtle.

Rate of marsh to upland conversion was variable across islands and time, ranging from 0.15 – 25.38 ha yr^{-1} (Figure 8) at the island scale. Across the VCR from 1984-2016, >1365 ha of marsh converted to upland, indicating the transgression of many of the islands. The average rate of marsh to upland conversion increased dramatically in the most recent time frame, from ~36 ha yr^{-1} (1984-2011) to 77 ha yr^{-1} (2011-2016). Northern and southern islands had higher rates of upland migration (ranging from 4.27 – 25.4 ha yr^{-1}), whereas the middle islands were relatively stable with migration rates(ranging from0.15 – 2.93 ha yr^{-1}). The exception was Cobb Island in the most recent time period (2011-2016). The rate of marsh to upland migration increased from 1.23 ha yr^{-1} in 2011 to 9.07 ha yr^{-1} in 2016.

When considered at the 1 km sub-island scale, intra-island variation became apparent (Figure 9). Rather than seeing uniform movement in a binary matter across an island, I found that the overall island migration is a function of great variation in marsh to upland conversion at the local scale. For example, Parramore and Cedar Islands have sub-sections that are among the fastest migrating areas in the system with other subsections showing relatively little migration (Figure 9). The pattern of increasing rates was also seen in the most recent time frame at the sub-island scale.

Using the elevations derived from model results (Duran Vinent and Moore, 2015) as guidance for placing island subsections within the disturbance resisting/reinforcing concept based on their 2009 foredune elevation, I found significant differences in the 1998-2011 marsh to upland migration rate ($t=2.644$ $p=0.0214$) between disturbance resisting and disturbance reinforcing subsections (Figure 10). My empirical data suggests that an elevation threshold of disturbance regime based on rates of marsh to upland migration exists ~ 2.0 m (Exponential function, AIC = 280.5, $r^2 = 0.39$, $y = 63.23 (-1.35)^2$. This is evidenced by the rate of change of upland migration at foredune elevations greater than 2.0 m (Figure 11). I also found evidence for a dune elevation threshold that determines woody cover presence or absence ~1.5 m (Quadratic function, AIC=354.4, $r^2=0.18$, $y = -44.74x^2 + 47.34x + -9.41$) (Figure 12). Woody cover is only found extensively in island sub-sections that have a foredune elevation above this height.

Smith and Parramore Islands serve as examples of bistability at the sub-island scale. The north end of Smith Island represents the disturbance reinforcing state with low dune elevations (0.9 - 1.7 m) and a large shift toward the mainland as a result of marsh to upland migration (0.74 -2.01 ha yr^{-1} in 1 km subsections). The south end of the island fits the stable disturbance resisting regime with dune/swale complex, high foredune elevations (1.6 - 3.5 m), little to no shoreline change or marsh to upland migration (0.0 - 0.67 ha yr^{-1}), and the presence of woody vegetation (Figures 13 and 14). Similar to Smith, the north end of Parramore Island represents a disturbance resisting regime with dune/swale complex, high foredune elevation (1.6 to 2.0 m) and extensive woody cover. This area has experienced shoreline erosion over the timeframe with little marsh to upland migration. Conversely, the south end of Parramore is rapidly migrating, with low foredune elevation (1.1 to 1.6 m) and a general lack of woody cover (Figure 13).

Discussion

Burial Field Experiment

My experiment demonstrates that the thresholds of burial tolerance are higher for *S. patens* than for *A. breviligulata*. *Spartina patens* is able to survive and sustain 3 15 cm burial events, whereas *A. breviligulata* cannot. This supports other findings that *S. patens* cover is an indicator of active overwash sites, where repeated burial most often occurs (Wolner et al. 2013, Brantley et al. 2014). The ability of *S. patens* to survive these higher frequencies of burial is likely due to above ground biomass allocation, leaf elongation, and increase in foliar nitrogen during burial events (Brown and Zinnert 2018). *Spartina patens* has shorter stature than *A. breviligulata* at the reference and low frequency burials, but this changes at the highest frequency. This is evidence that *S. patens* is stimulated by burial and responds by quickly increasing above ground growth. The tendency of *S. patens* to dominate low elevation areas of barrier islands and tolerate repeated disturbance, suggest that *S. patens* could be an indicator of overwash prone sites and outcompete other species in climates with high frequencies of overwash burial. Additionally, due to the dune building nature of *S. patens* (small hummocks rather than protecting ridges), high frequencies of overwash that repeatedly select for this species may lead to a feedback cycle where a disturbance reinforcing regime is maintained.

Ammophila breviligulata is known to be stimulated by burial (Disraeli 1984, Yuan et al. 1993, Brown 1997); however, some studies have shown little response (Maun and Lapierre 1984). *Ammophila breviligulata* has strong associations with dune ridges and higher elevation sites, as well as transitional areas of moderate disturbance (Wolner et al. 2013). Given sufficient time between disturbances, *A. breviligulata* can dominate and build higher dunes, but that threshold remains unknown and is an important determinant of island stability thresholds. I found that *A. breviligulata* was intolerant to repeated burial and unable to make a quick recovery of aboveground biomass above 2 burial treatments in the length of time I ran the experiment. This is supported by the lack of aboveground emergence with 3, 15 cm treatments and reduced height with 2 burial treatments (Figure 5). To my knowledge, our study is the first to test for a threshold of overwash burial in the field for either species.

These results suggest that there is a maximum threshold of burial frequency that is different for each species with levels lower for *A. breviligulata.* Storm and overwash frequencies that cross that tipping point of burial depth and exclude *A. breviligulata* have the potential to cause local scale stability shifts toward maintenance of low and disturbance reinforcing regimes (Stallins 2005, Wolner et al. 2013, Vinent and Moore 2015, Zinnert et al. 2017). This has implications for modeling efforts of barrier island resilience given the predictions of increased storm intensity and ongoing sea level rise that will increase overwash disturbance (Emanuel 2013). If more low, disturbance reinforcing areas develop on the barrier islands of Virginia, I would expect to see increased rates of barrier island migration and erosion.

Due to gaps in data collection during initial set up of this experiment, I was unable to make comparisons of height change over the time of the experiment. Intense heat and field conditions prevented me from collecting percent cover and other height measurements during the third application. I also did not anticipate as many treatments having no aboveground emergence. This limited the quantitative power of the data and prevented me from being able to assess traits like Leaf N and SLA. An additional growing season to allow plants to recover would likely resolve this situation. I also find myself with new questions regarding whether or not *A. breviligulata* can emerge and outgrow *S. patens* in extreme burial events, as some literature has suggested and if so, under what timeline. To address the holes in this experiment, as well as these new questions, another burial experiment with similar methodology has been placed on Hog Island. Burial responses will be assessed after one full year (a full seasonal cycle) for each species in this new design.

Historical Rate of Barrier Island Migration

My work shows that the Virginia barrier islands are undergoing rapid and significant state changes. The large losses in total upland (1580 ha) and marsh area (970 ha) over the 32-year time period, along with the expansion of woody vegetation fit trends seen on other Atlantic and Gulf of Mexico barrier islands (Battaglia et al. 2007, Morton 2008, Lucas and Carter 2010, Moore et al. 2014). It is also important to note that the increases in woody vegetation do not offset losses in other upland classes because it represents the encroachment into former grassland and bare soils rather than new upland area forming.

Changes in vegetation state may cause dramatic shifts in island stability and thus migration processes. For example, historically Cobb Island was classified as a rotational island with classic, drumstick morphology (Leatherman et al. 1982) that had minimal shoreline migration. During the interim periods of my study, woody vegetation rapidly expanded on Cobb (2.2 ha in 1984 to 71.9 ha in 1998), but island migration rates remained low (<1 ha yr^{-1}). After 2011, migration rates rapidly increased (1.0-4.5 ha yr^{-1}) once woody vegetation had eroded into the sea with the loss of nearly 150 ha of island upland. The dynamic nature of barrier island vegetation may affect vulnerability to large disturbances in the system and the impacts of disturbance may be exacerbated at times when the islands are in a state of dense vegetation that increases resistance (i.e. dense woody cover). Cobb Island is now able to migrate, but at the loss of significant upland area and no longer fits the Leatherman et al. (1982) classification. Cobb Island demonstrates that islands can cross critical thresholds and transition to an alternate state in a very short amount of time. In the case of Cobb Island, the erosion and loss of area has been so severe that the change is likely irreversible.

Some of the islands fit within the classifications by Leatherman et al. (1982). The parallel retreat northern islands (i.e. Metompkin and Cedar) are rapidly migrating, with low elevations (Oster and Moore 2009). Large portions of these islands exhibit the disturbance reinforcing state. Changes on Paramore Island suggest it may be shifting from a rotational stability island (Leatherman et al. 1982) as seen on Cobb Island. The north end of Parramore was historically stable, with high foredunes and extensive maritime forest; however, it has experienced rapid erosion (loss of 134 ha of upland) during the 32 year study period. On the ground, I have observed much of the maritime forest being washed into the ocean on the north end. On the south end, low foredunes and a lack of woody vegetation (Figure 13) have supported marsh to upland conversion and resulting transgression of that portion of the island towards mainland.

My study has demonstrated the importance of scale when classifying islands by disturbance regime and quantifying other geomorphic trends. At the whole island scale, processes are simplified and over-inflated, giving the appearance of a more binary situation where an entire island is either migrating or not (Figure 8). Using the whole island scale gives a large number due to the consideration of the entire island moving as one body and taking the sum of all the marsh to upland area. Considering upland conversion rates at the 1km sub-island scale, it becomes apparent that upland migration rates vary within each island (Figure 9). There is a critical elevation threshold ~2 m where marsh to upland conversion occurs. Identifying the dune height at which an island or sub-section fits into the disturbance reinforcing or a disturbance resisting domain is significant when considering thresholds to disturbance. If a disturbance resisting dune (≥2.0 m) is toppled by a significant event (i.e. catastrophic storm), a resisting island or sub-section could flip to a reinforcing state if colonization by *S. patens* dominates and/or additional disturbance occurs before sufficient time to rebuild a significant dune (Wolner et al. 2013, Vinent and Moore 2015). However, higher woody cover is also associated with disturbance resistant areas and reduced marsh to upland migration. This likely occurred because of both the physical blocking of the transfer of sediment to the island interior (i.e. blocking overwash) via tall dune ridges and complex, dense vegetation and root masses characteristic of woody vegetation.

The recent and rapid expansion of woody vegetation across the VCR indicates a potential macroclimatic shift that has enabled a regime shift on the islands (Huang et al. in press). The woody expansion observed has almost exclusively been the native shrub *Morella cerifera* (Young et al. 2007). Islands that previously had maritime forest are not regenerating that forest, and areas with current maritime forest are being invaded with *M. cerifera* or *Phragmites australis* (unpublished data). Over 30 years of ground observation on the north end of Hog Island have failed to document the succession of *M. cerifera* thickets to a more complex maritime forest (Bissett et al. 2016). If recent patterns hold, this regime shift and arresting of succession has likely implications for island stability and future response to sea-level rise. In many cases the capacity for a coastal wetland system to keep pace with sea level rise is dependent on the positive feedbacks between vegetation growth and inundation (Kirwan and Megonigal 2013, Krauss et al. 2014). *Morella cerifera* is a salt-intolerant species, so where it has expanded and dominated former grassland swales, there may be risk for a large storm (overwash) event to trigger the mass die-off and rapid erosion of these now-dead and de-stabilized shrub thickets.

Conclusion and Significance

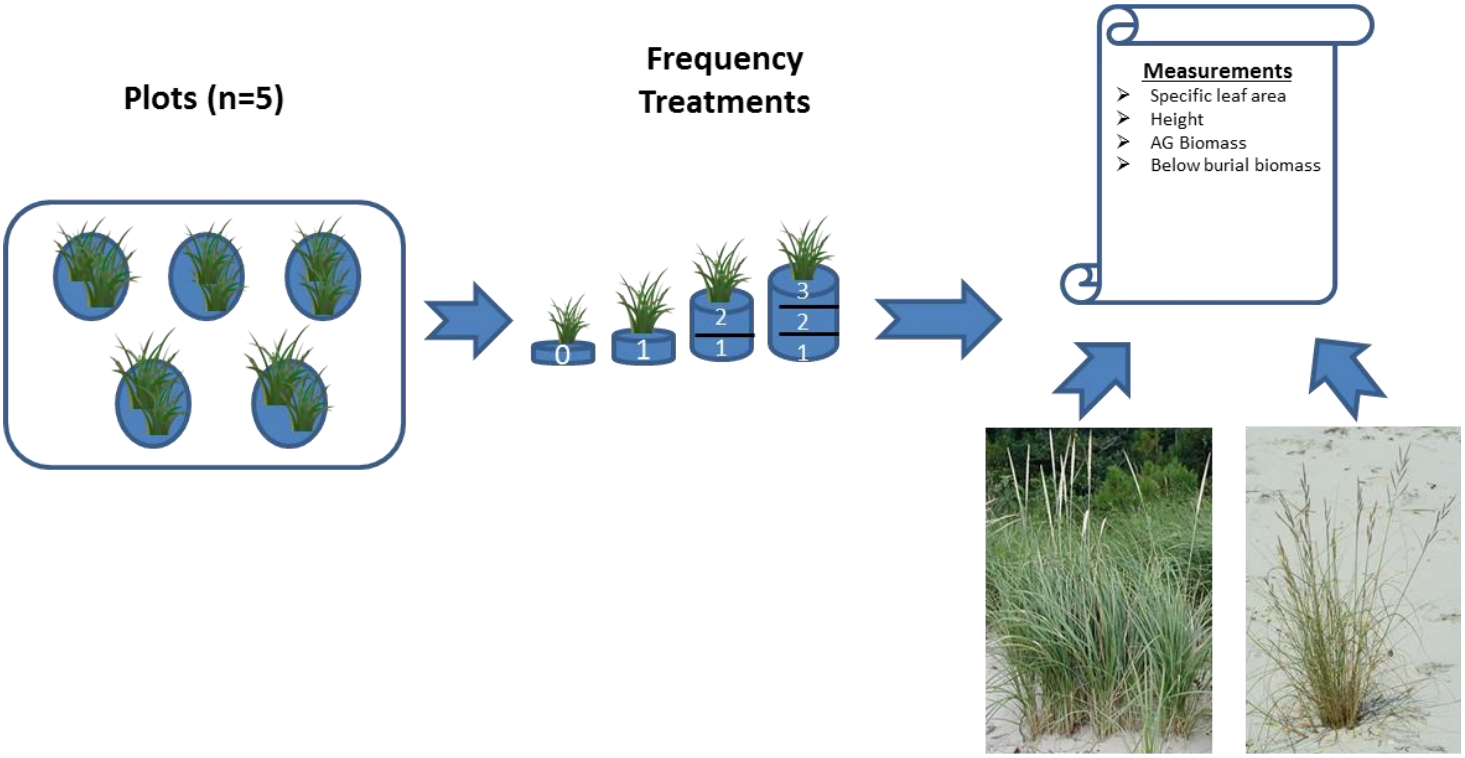
Determining the growth response and success of both dune building species after repeated overwash events will improve our understanding of the mechanisms underlying dune stability domains. If storm and overwash frequency surpass a species' threshold tolerance to burial, changes in stability domain states could occur and barrier island migration rates could be significantly affected. This research connects broad and local scale processes to better model and predict barrier island response to the factors of climate change (i.e. sea level rise and storms). Understanding how each of these species responds to overwash burial will help us to predict what island stability states might become dominant under specific models of future storm frequency. This will be of conservation interest, as we gain insight to species' tolerance to overwash frequency.

Across the system, at both the whole island scale and the 1km sub-section scale, we observed that the Virginia barrier islands are transgressing landward at an increasing rate and locations that were stable historically, have begun to show migration in the most recent time period of 2011-2016. This rapid rate of migration could be problematic in the future as island rollover could outpace development of new back barrier marsh and islands may fail to keep up with sea level rise. I did not observe significant marsh gains on any islands, and most islands were losing marsh area as a result of back-barrier erosion and conversion to upland. Marsh loss along the VCR is driven by anthropogenic factors like eutrophication and sediment starvation, in addition to sea level rise (Kirwan and Megonigal, 2013). Barrier island migration and the attendant narrowing of back-barrrier marsh are ecomorphodynamically coupled and as such, large-scale marsh loss may be inevitable as barrier islands equilibrate to accelerating sea level rise (Deaton et al. 2017). Without this marsh platform, islands will overwash into the lagoon and be lost to the sea. Tracking of island change at multiple scales provides critical insight into the rate of barrier island migration in different stability domains and helps us to better predict the future of barrier islands and their ability to keep pace and maintain elevation above sea level.

Table 1. Area change (ha) for Woody cover, Bare Sand, Grass, and Marsh between 1984 and 2016 at the Virginia Coast Reserve. Arrows indicate net gain (up), loss (down), or no change (side).

Island	Woody	Bare (sand)	Grass	Marsh
Metompkin	9.63	-177.13	68.25	-171.91
Cedar	-17.46	-45.14	-12.51	-325.9
Parramore	-110.25	-7.19	-298.4	-179.97
Hog	224.01	-276.45	-10.53	-16.37
Cobb	-0.09	-258.55	-131.49	-50.55
Wreck	19.62	34.42	-14.76	-74.31
Ship Shoal	6.66	-80.21	40.32	-43.49
Myrtle	0	-256.23	-49.86	-76.12
Smith	48.06	-183.06	-102.24	-31.41
Total	**180.18**	**-1249.54**	**-511.21**	**-970.03**

Figure 1. Satellite image of the Virginia Coast Reserve. Study island names are highlighted in yellow font with island classifications according to Leatherman et al. (1982).



Ammophila breviligulata

Spartina patens

Figure 2. Methods schematic for the dune grass burial experiment. Five plots each contained five buckets with roughly equal representation of *A. breviligulata and S.* patens, buried at 3 different treatment levels and a bucket collar receiving no burial as the reference.

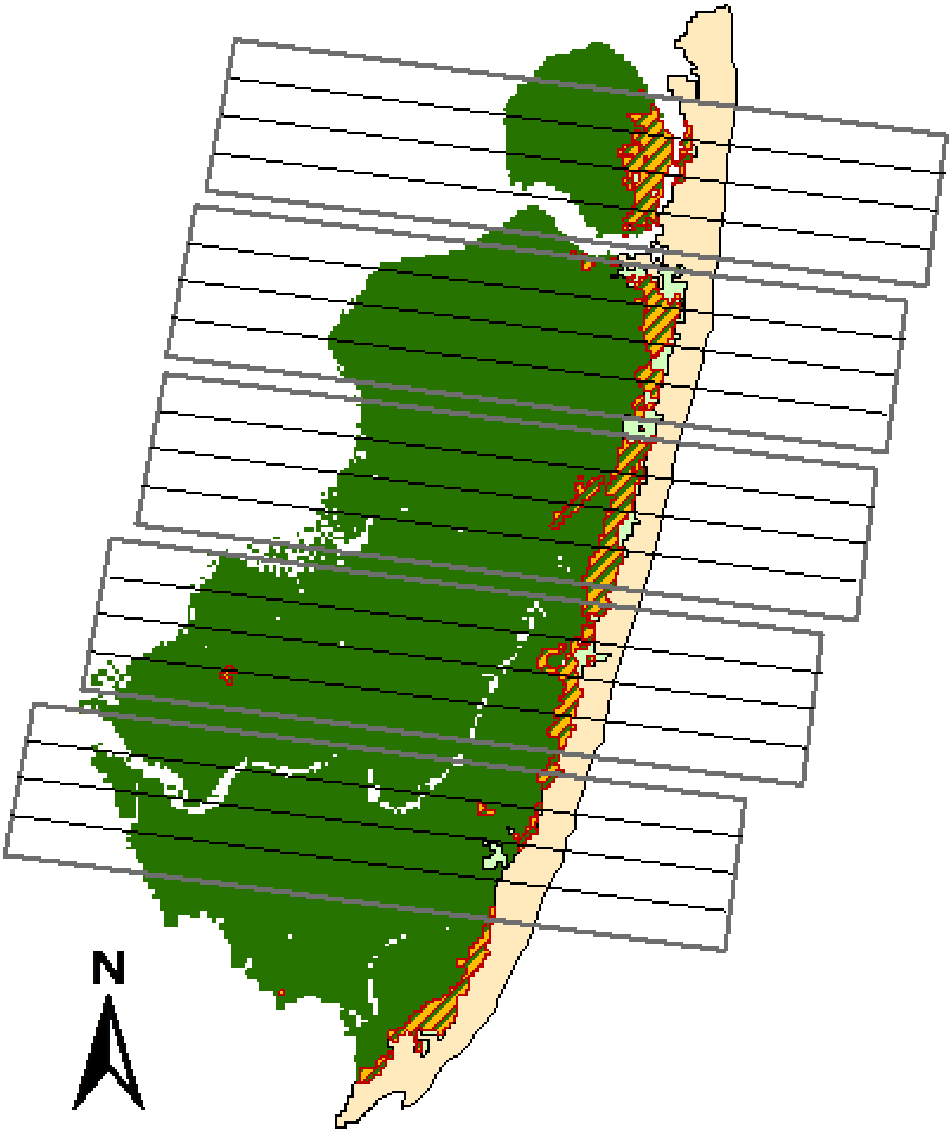


Figure 3. ArcMap screenshot of Cedar Island, VA showing 1 km sub-plots (boxed frames) and the 3 transects within in each sub-plot used for measurements. The map also shows the 1998 marsh (solid green) and 1998 upland (beige) with the 1998-2011 marsh to upland (orange hatched) representing the island migration for that time.

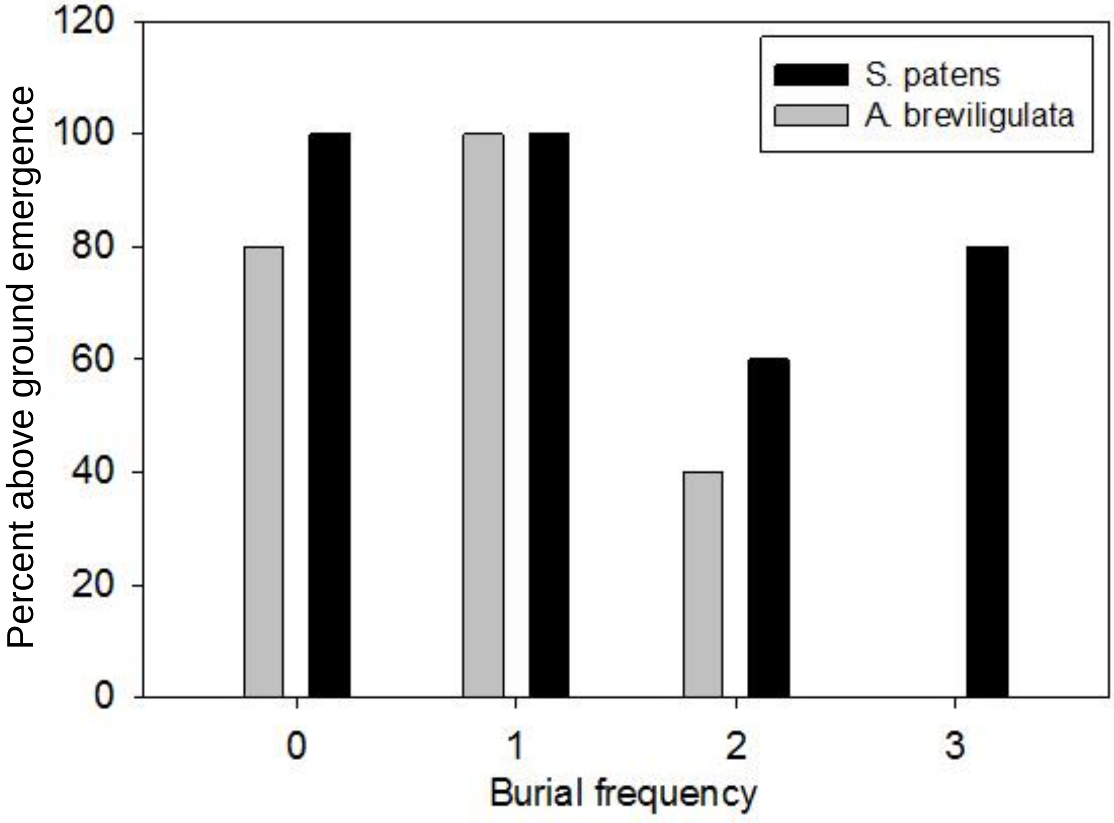


Figure 4. Percent above ground emergence, measured at the end of the experiment, of each species at the four treatment levels. No *A. breviligulata* emerged at the 3 time burial.

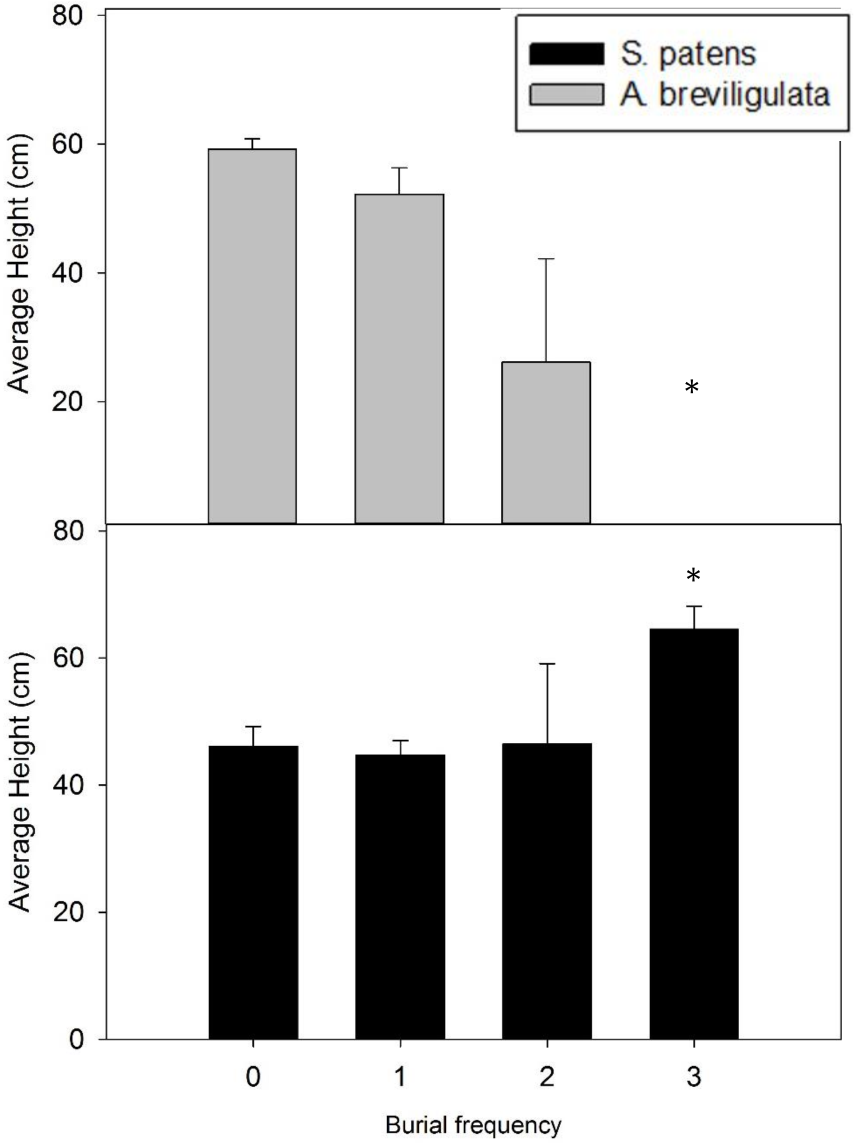


Figure 5. Final height of each species across the four treatment levels. Height was only significantly different at the 3 time burial, where no *A. breviligulata* emerged above ground.

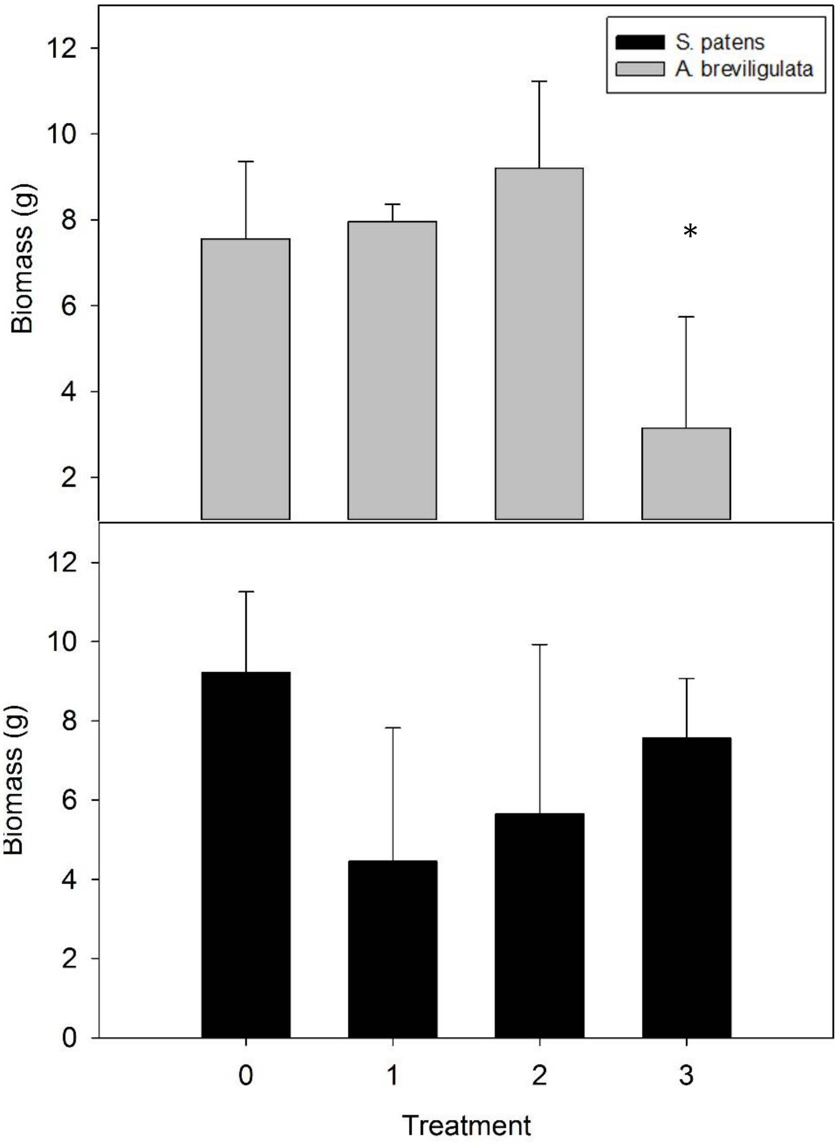


Figure 6. Final biomass of each species across the four treatment levels. *Spartina patens* was able to maintain similar levels of biomass at all levels, while *A. breviliguluta* had marginally significantly reduced biomass at the 3 time burial.

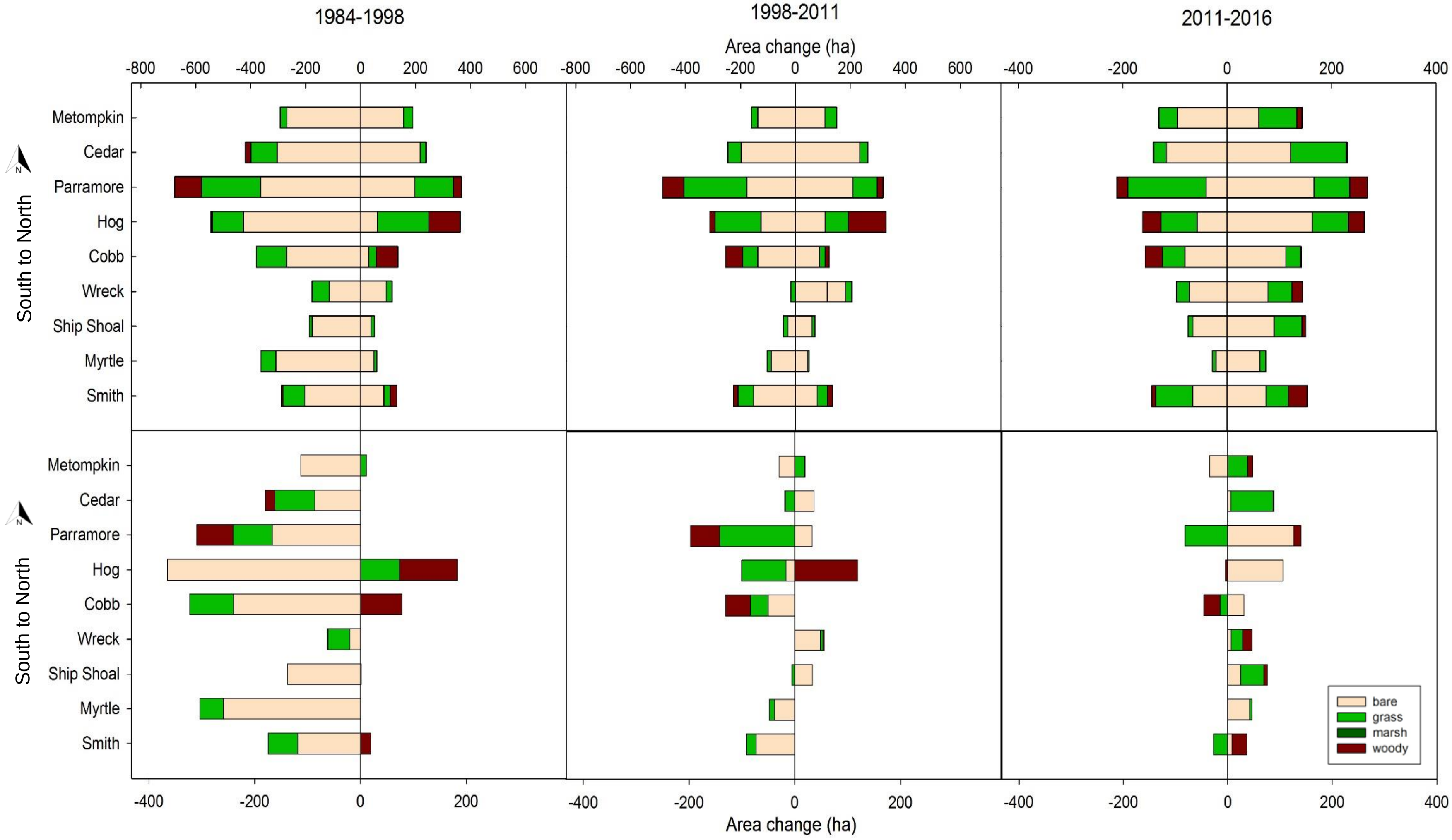


Figure 7. Gains and losses in area of each cover type during each time period (**a, b, c**) and overall net changes in cover type during each time period (**d, e, f**) for the Virginia Coast Reserve.

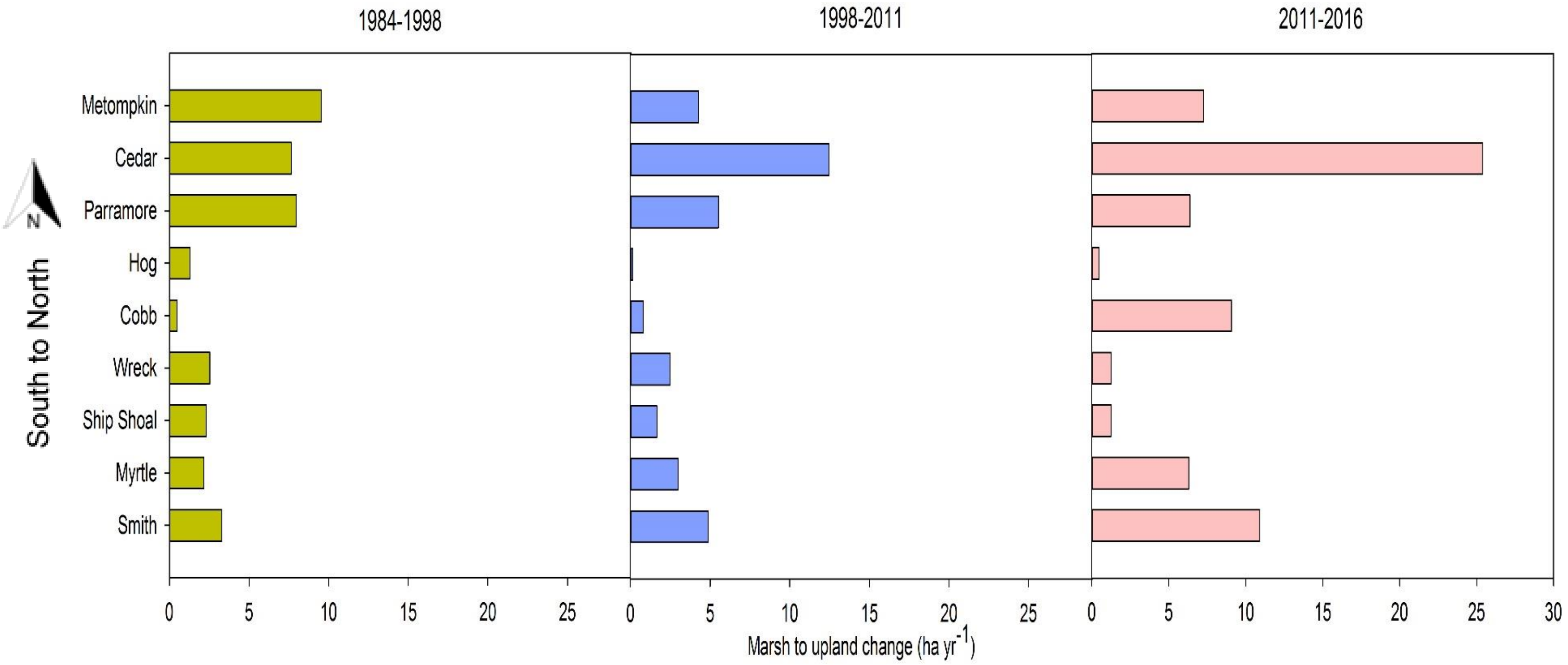


Figure 8. Marsh to upland conversion rate by whole island at the Virginia Coast Reserve for each interim time period during the 32 year study from 1984-2016.

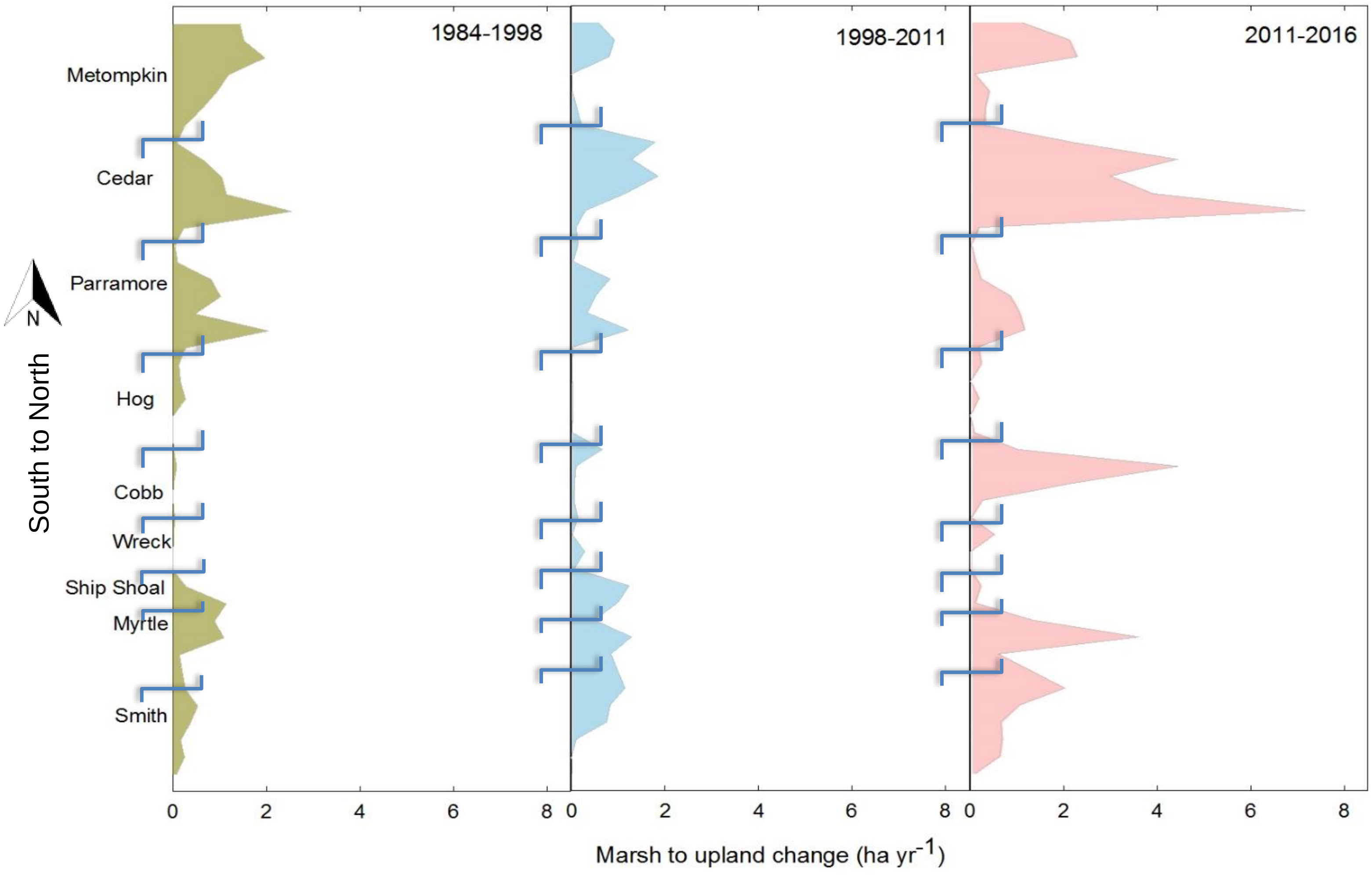


Figure 9. Marsh to upland conversion rate by 1km island sub-plots at the Virginia Coast Reserve for each interim time period during the 32 year study from 1984-2016.

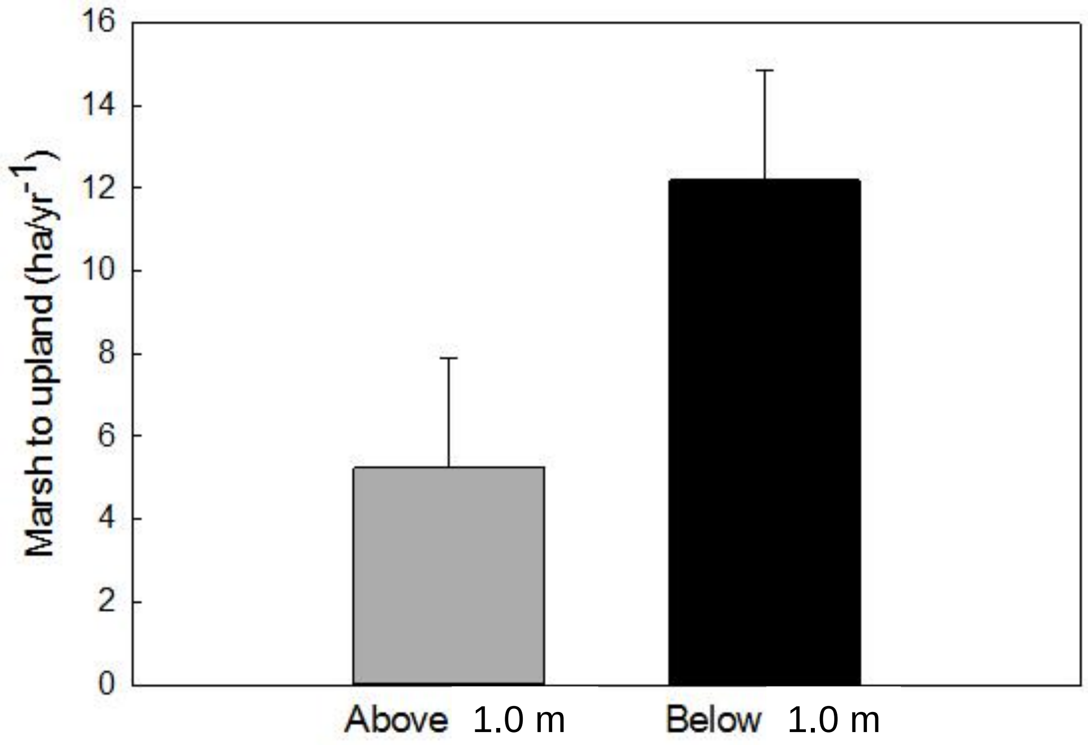


Figure 10. Mean marsh to upland conversion rates at each disturbance regime, above and below a foredune elevation of 1.0 m to show that marsh to upland migration occurs at a higher rate in the disturbance reinforcing regime (<1.0 m).

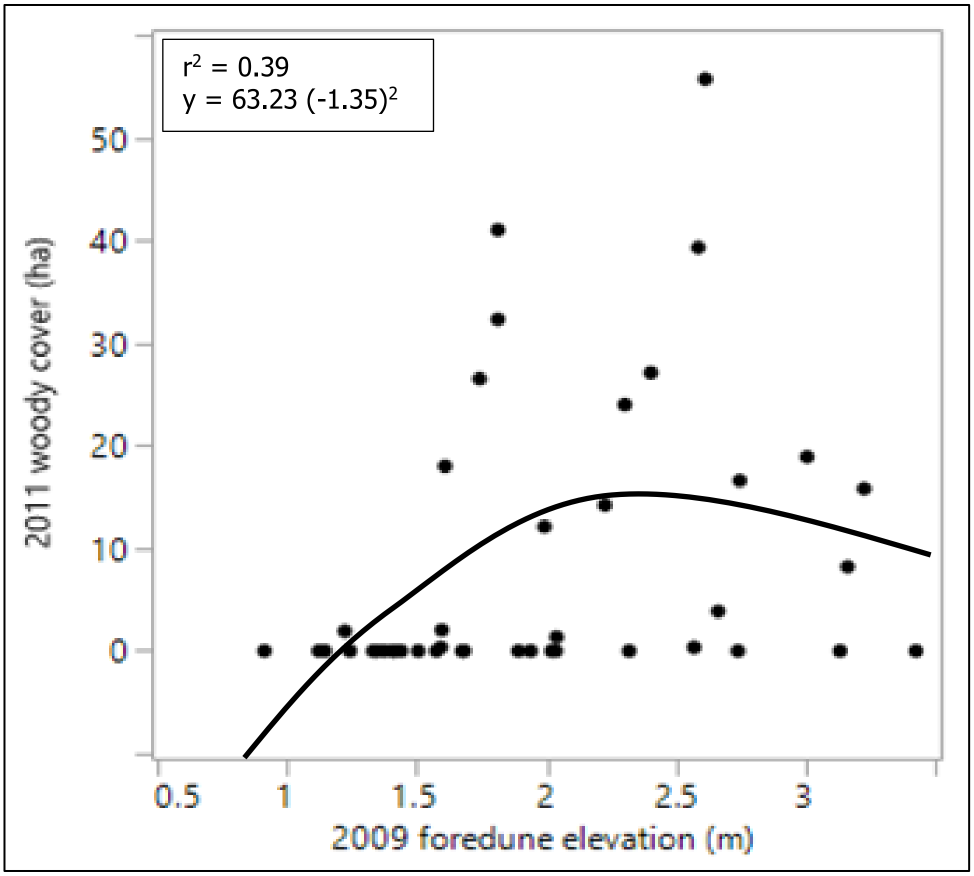


Figure 11. Scatterplot and non-linear regression of 1km island sub-plots of foredune elevations in 2009 and woody cover in 2011 at the Virginia Coast Reserve.

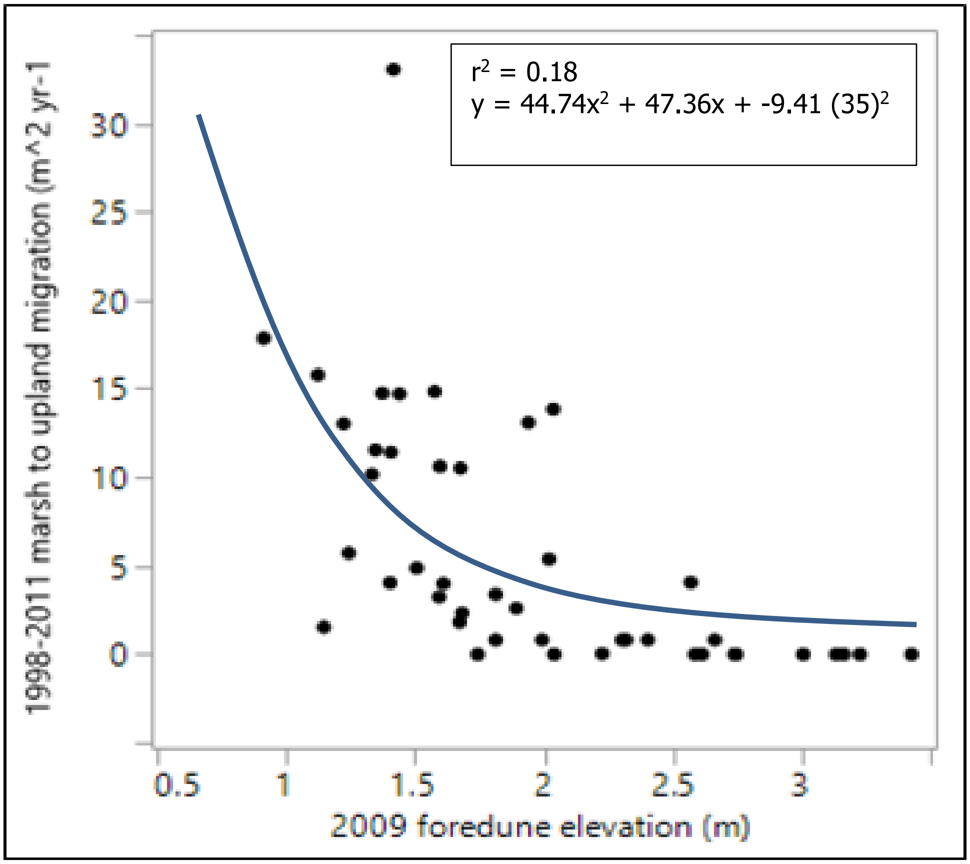


Figure 12. Scatterplot of 1km island sub-plot foredune elevations in 2009 and the marsh to upland migration rates from 1998-2011. The solid line identifies a potential threshold elevation where higher rates of upland migration fail to occur. I consider sub-plots to the right of the line disturbance resisting and to the left, disturbance reinforcing.

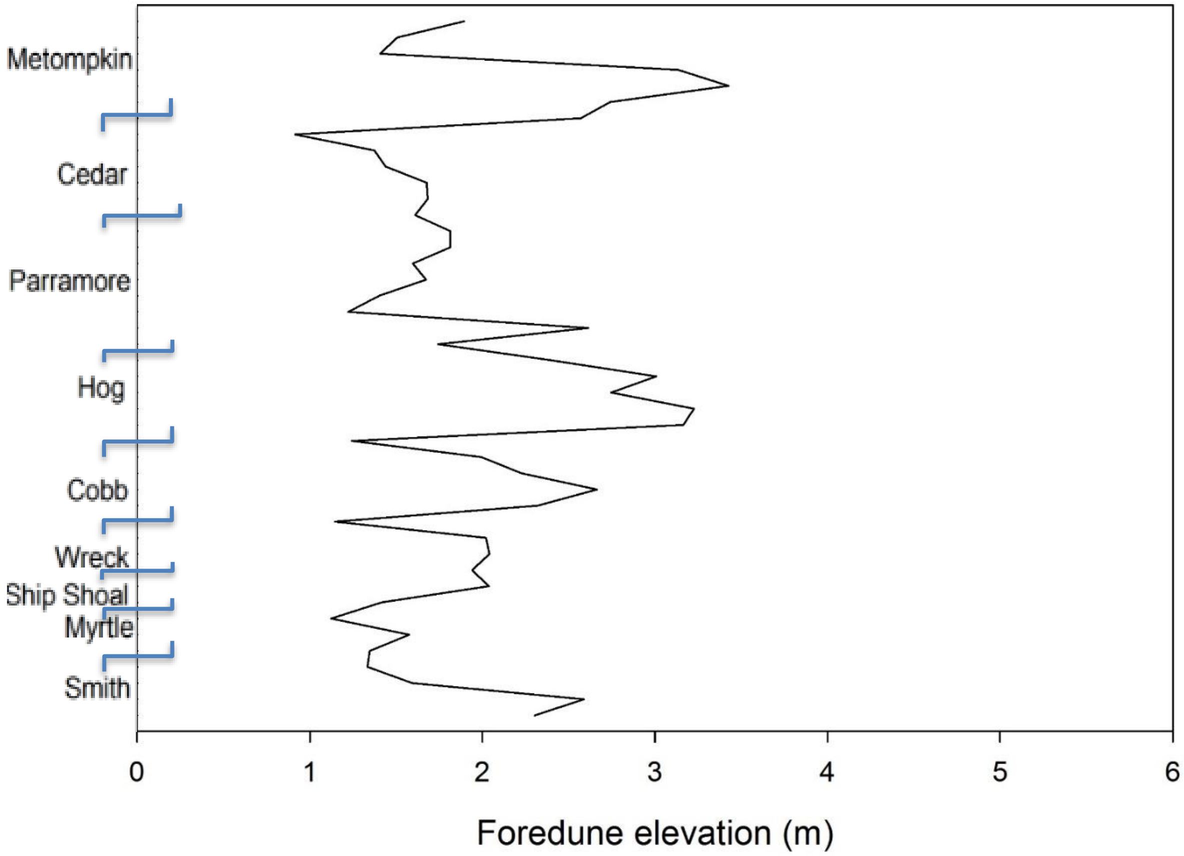


Figure 13. Line graph of foredune elevation by 1 kilometer transects in 2009 at the Virginia Coast Reserve.

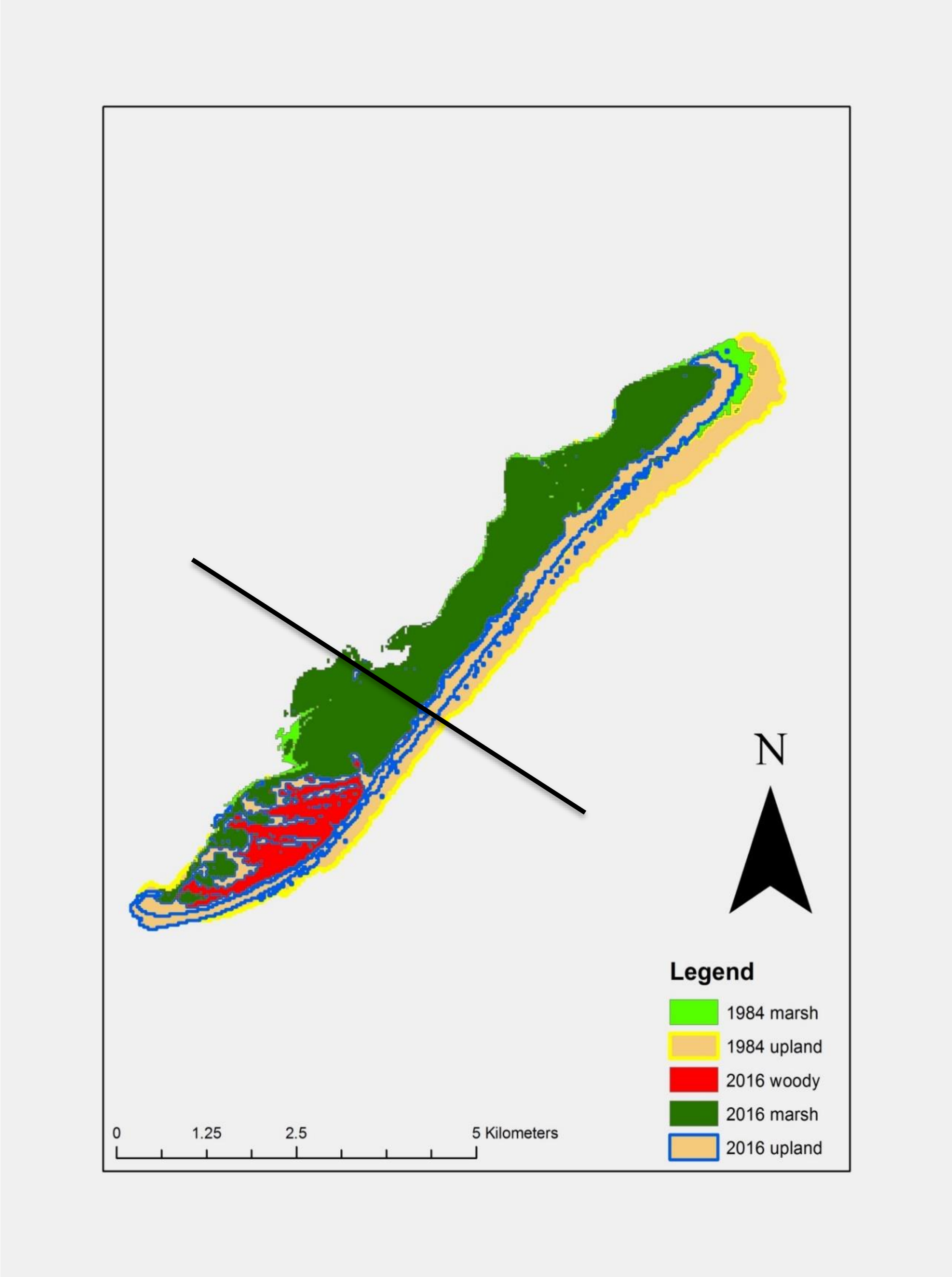


Figure 14. ArcMap image of Smith Island showing the 1984 upland and shoreline, marsh area and the 2016 upland and shoreline, marsh and woody area. The solid line represents a divide, where the island south of it has been classified as disturbance resisting and the north of it, disturbance reinforcing.

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Vita

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