

Ecomorphodynamic feedbacks and barrier island response to disturbance: Insights from the Virginia Barrier Islands, Mid-Atlantic Bight, USA

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ARTICLE INFO

Article history:

Received 19 November 2011

Received in revised form 14 March 2013

Accepted 15 March 2013

Available online 18 April 2013

Keywords:

Barrier islands

Ecomorphodynamics

Overwash

Coastal dunes

Climate change impacts

Virginia Coast Reserve

ABSTRACT

Ecomorphodynamic feedbacks play an important role in the susceptibility and response of barrier islands to disturbance by overwash. Dune-building grasses, like *Ammophila breviligulata*, can help to restore areas of high relief after overwash events (i.e., resist disturbance). If overwash recurs before dunes have reestablished, however, overwash-adapted “maintainer” species, like *Spartina patens* (upright variety), may preferentially survive. Maintainer species help to preserve low, flat topography, thereby increasing the likelihood of future overwash (i.e., reinforcing disturbance). Under frequent disturbance conditions, this positive feedback may lead to overwash persistence. We explore the potential influence of the maintainer feedback on two morphologically distinct barrier islands in the Virginia Coast Reserve (VCR), located in the Mid-Atlantic Bight of the U.S. East Coast. Combined topographic and vegetation surveys show that on Hog Island (high-relief, rotating), where dunes dominated by *A. breviligulata* are ubiquitous, overwash zones are currently limited in extent and related to beach width rather than dominance by *S. patens*. Historical aerial photos and stratigraphic evidence (ground-penetrating radar, cores) indicate that gradual recovery has taken place following overwash events on Hog Island, except where the beach is narrow and eroding. Conversely, on Metompkin Island (low-relief, transgressing), overwash is widespread and dominated by *S. patens*, particularly along the rapidly migrating northern half of the island, where shell armoring is also common. Overwash has generally been more prevalent and persistent here than on Hog Island. We present a new conceptual model of the response of barrier islands to disturbance incorporating ecological and physical processes. Our findings suggest that in barrier systems where both dune-building grasses and overwash-adapted maintainer species are common (like the VCR), the maintainer feedback is likely to be a more important dynamic on islands already susceptible to frequent disturbance because of physical factors. The maintainer feedback, therefore, has the potential to accelerate large-scale shifts from dune-dominated to overwash-dominated barrier morphologies as the effects of climate change (increased storm intensity, sea level rise) cause overwash to become more frequent.

Published by Elsevier B.V.

1. Introduction

1.1. Background

Barrier islands are characterized by low elevations, unconsolidated substrates, and high sensitivity to changes in sea level and storm activity. As a result, these coastal landscapes tend to be disturbance-prone, dynamic systems in which sediment is frequently redistributed and, consequently, ecosystems exhibit considerable variability. Physical parameters, such as elevation above sea level and distance from the shoreline, determine the frequency of overwash disturbance on barrier islands, which in turn influences the composition and distribution of the ecological communities that these landscapes support (e.g., Hosier and Cleary, 1977; Fahrig et al., 1994; Hayden et al., 1995; Young et al., 2011). As sea level

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rise accelerates (Church and White, 2006; IPCC, 2007) and storms potentially become more intense (Komar and Allan, 2007; Bender et al., 2010; Knutson et al., 2010), overwash events on barrier islands will likely become more common, with closely linked morphological and ecological implications (e.g., Houser and Hamilton, 2009; Gornish and Miller, 2010).

Overwash occurs when storm surge and wave runup combine to overtop the dune or berm crest (Sallenger, 2000), leveling the existing topography and spreading sediment into the backbarrier. The process of overwash is crucial in determining whether barrier islands will survive as sea level rises: sediment transport by overwash facilitates landward migration, which can help a barrier maintain its elevation relative to sea level (e.g., Hayden et al., 1980). If sea level rises too rapidly, sediment supply is insufficient, or topographic recovery is inhibited by recurrent overwash, a barrier island may not be able to adjust quickly enough, ultimately disintegrating as sea level rise progresses (e.g., FitzGerald et al., 2006; Moore et al., 2010).

Barrier islands vary in susceptibility and response to disturbance by overwash, depending in part on morphological and vegetative characteristics. High-relief barrier islands tend to be dominated by dune-building grasses like *Ammophila breviligulata* (Fig. 1a). Like other dune-building grasses, *A. breviligulata* thrives at higher elevations and aids vertical accretion by trapping sand as it grows upward through gradual aeolian deposition. In this way, *A. breviligulata* expands its own preferred habitat in a positive feedback, generally on the time scale of years. On the northeastern U.S. coast, for instance, *A. breviligulata* builds characteristically tall, continuous dunes, facilitated by the guerrilla growth style of its vertically- and laterally-propagating rhizomes. These *A. breviligulata* dunes restrict large-scale overwash to only the most severe storm conditions (i.e., resist disturbance). In the relatively rare event that overwash does occur, recolonization by *A. breviligulata* – particularly through the dispersal of seeds and rhizomes in wrack – gradually leads to the reestablishment of the dune horizon (Godfrey et al., 1979; Leatherman and Zaremba, 1987), given sufficient supply of sand.



Fig. 1. a) Tall, continuous dunes built by *A. breviligulata*. b) Overwash flats stabilized by *S. patens*.

In contrast, barrier islands that are characterized by low, discontinuous, or absent dunes are susceptible to frequent overwash. Where these low-relief barriers occur on the southeastern U.S. coast, the strand grass *Spartina patens* (upright variety) is common on the widespread overwash flats that result from recurrent disturbance (Hosier and Cleary, 1977; Godfrey et al., 1979; Ritchie and Penland, 1988; Fig. 1b). This variety of *S. patens* is especially well-adapted for survival in overwash zones: it can regenerate upwards through thick layers of sediment rapidly deposited by overwash (Ehrenfeld, 1990), is tolerant of saline flooding (Silander and Antonovics, 1979), and thrives in wetter soils (i.e., lower elevations on barrier islands). *S. patens* does not contribute significantly to dune building, but rather stabilizes low, flat topography (Godfrey and Godfrey, 1976; Stallins, 2005) with its turf-like mat of roots and rhizomes.

Godfrey et al. (1979) proposed that while the dominance of *A. breviligulata* in high-relief barrier systems contributes to disturbance resistance, the dominance of *S. patens* (upright variety) in low-relief barrier systems reinforces frequent disturbance by maintaining low topographic roughness. Similarly, Stallins and Parker (2003) and Stallins (2005) suggested a weak positive feedback in which overwash-adapted species that do not build significant dunes (e.g., *S. patens*) may be more successful under conditions of repeated disturbance. Such species, they argued, promote the maintenance of low-relief topography by stabilizing sediment and rendering it unavailable for dune building. The maintenance of low-relief topography increases the likelihood of overwash, further favoring the success of the overwash-adapted species.

Whereas physical factors (e.g., relative sea level rise rate, antecedent geology and topography, sediment supply, wave climate, shoreline orientation, etc.) may play a primary role in establishing the vulnerability of a barrier island to disturbance, the two ecomorphodynamic feedbacks described above also mediate disturbance via dune building and overwash maintenance. These feedbacks have been compared separately in distinct barrier systems (Godfrey et al., 1979; Stallins and Parker, 2003) that vary physically and ecologically as well as in disturbance-forcing conditions (e.g., hydrodynamics, climate). Until now, they have not been considered comprehensively within a single barrier island chain where *A. breviligulata* is the dominant relief-promoting species, but where *S. patens* (upright variety) is also common.

In such systems, we hypothesize that the dune-builder feedback is likely to be the primary ecomorphodynamic influence on barrier morphology when disturbance (overwash) is rare, because *A. breviligulata* can effectively (re)create high-relief habitat for itself in the absence of disturbance (generally on time scales of years). As the frequency of disturbance increases, we hypothesize that the influence of the maintainer feedback will increase as well. This is because overwash-adapted maintainer species are likely to preferentially survive when disturbance recurs at similar or shorter intervals than the time scale needed for dune-building grasses to reestablish topographic relief (as long as the recurrence interval does not become so short that *no* vegetation can survive). Although the time scale of dune recovery can vary between environments, we emphasize that it is the *relationship* between this time scale and the frequency of disturbance events that affects whether the maintainer feedback is likely to be at work (Fig. 2), rather than the absolute number of years.

Ultimately, dominance by maintainer species may effectively lengthen the time needed for dune recovery by decreasing the space available for dune-building grasses and limiting the availability of sand for aeolian transport. Over longer time scales (decades to centuries), the balance between the dune-builder and maintainer feedbacks will likely influence large-scale barrier morphology by contributing (along with physical processes) to the development or maintenance of topography, thereby modulating or intensifying the response of barrier islands to climate change.

Our objectives are to: 1) infer where and under what conditions the maintainer feedback is likely to be at work, 2) add insight into the mechanisms by which ecological and physical processes work separately and

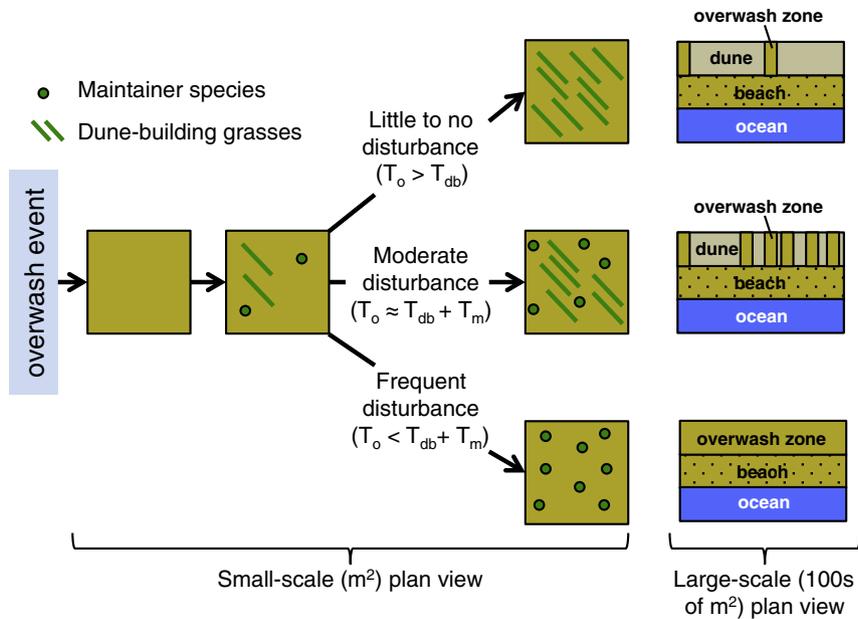


Fig. 2. Possible scenarios for ecomorphodynamic response to overwash when continuous dune builders and overwash-adapted maintainer species are present. T_o = time between overwash events, T_{db} = time needed for dune-building grasses to restore topographic relief, and T_m = time added to topographic recovery by the preferential survival of maintainer species. After overwash (left), both types of vegetation are likely to recolonize the area, but we hypothesize that the subsequent frequency of disturbance determines which species ultimately becomes dominant (small-scale plan view). The right-most column (large-scale plan view) shows the implications for barrier island morphology associated with each scenario.

Modified from Wolner et al. (2011).

synergistically, and 3) provide a conceptual ecomorphodynamic model for barrier systems in which dune-building grasses and maintainer species are both prevalent. To meet these objectives, we assess the relationship between morphology and the composition of vegetative species, as well as the spatial (100s of m to km) and temporal (decadal to centennial) persistence of overwash zones on two morphologically distinct barrier islands in the Virginia Coast Reserve (VCR), located in the Mid-Atlantic Bight of the U.S. East Coast.

1.2. Regional setting

The Virginia Coast Reserve includes the Virginia Barrier Islands and surrounding coastal landscape (Fig. 3). Currently a Long-Term Ecological Research (LTER) site, the VCR has been protected from anthropogenic development since the mid-20th century, providing a unique opportunity to observe a mid-Atlantic barrier island chain in its (nearly) natural state. *A. breviligulata* (as the dominant dune-building species) and *S. patens* (upright variety) are both common in the VCR. Island morphologies and patterns of change in shorelines in the VCR are highly variable (Dolan et al., 1979; Leatherman et al., 1982; Kochel et al., 1985). Here, we focus on two morphological end-members, Hog and Metompkin Islands (Fig. 3).

Hog Island is an infrequently disturbed, drumstick-shaped barrier characterized in most places by multiple continuous dune ridges (typically 3–4 m above the NAVD 88 datum, which is high-relief for the VCR). Over the last several hundred years (at least), this island has been undergoing rotational change in the position of the shoreline – i.e., alternation between accretion on the northern half/erosion on the southern half and vice versa, with generally clockwise rotation in this case since the late 1800s (Harris, 1992). The northern half of Hog Island is dominated by dune-swale topography, although small-scale overwash (10s of m) is evident along the seaward-most dune ridge. Excluding inlet-parallel beaches, large-scale overwash (100s of m) is limited to the rotational axis of the island, where shoreline oscillation has exposed a swale to wave action (Harris, 1992) and the beach is narrowest. The central portion of the island includes dunes and hummocky, lower-relief transitional areas. Relict overwash channels are apparent – now disconnected from

the active beach by continuous dune ridges – along the southern half of the island, where the shoreline has switched recently (ca. 40 years BP) from an erosional to an accretional regime.

Conversely, Metompkin Island is a frequently disturbed, linear island dominated by overwash zones (typically <2 m above the NAVD88 datum) and undergoing rapid parallel shoreline retreat (between 1.9 and 13.6 m/yr in the late 20th and early 21st century; Byrnes, 1988; O. Brenner, personal communication, 14 June 2011). The southern, lagoon-backed half of the island is separated from the northern, marsh-backed half by an offset in shoreline position at the site of a former ephemeral inlet. The southern half has historically migrated more rapidly than the northern half, but this trend reversed ca. 30 years BP, when the northern half began migrating (largely via overwash) up to 4 times faster than the southern half, reducing the magnitude of the offset (Byrnes and Gingerich, 1987; Byrnes, 1988). Consistent with this heterogeneity in the rates of migration, the southern half of the island is characterized by a discontinuous single dune line punctuated by overwash fans and channels as well as transitional areas in various stages of recovery, whereas the northern half consists entirely of coalesced overwash terraces.

Although Hog and Metompkin Islands represent end-members within the VCR, dichotomous terms for morphology (high-relief vs. low-relief) and disturbance (infrequent vs. frequent) are relative and depend on the spatial scale under consideration. Hog Island, for instance, would not necessarily represent a high-relief, infrequently disturbed *end-member* if compared to some coastal systems outside of the VCR (e.g., the Georgia Bight in the southeastern U.S. or the Columbia River littoral cell in the northwestern U.S.). These terms, therefore, should be considered within the context of the study area; however, this does not preclude our findings from providing general insight into disturbance-mediating ecomorphodynamic processes in other barrier systems.

2. Methods

2.1. Relating physical and ecological characteristics: transect surveys

Because the northern and southern halves of Hog and Metompkin Islands are each characterized by distinct morphological dynamics

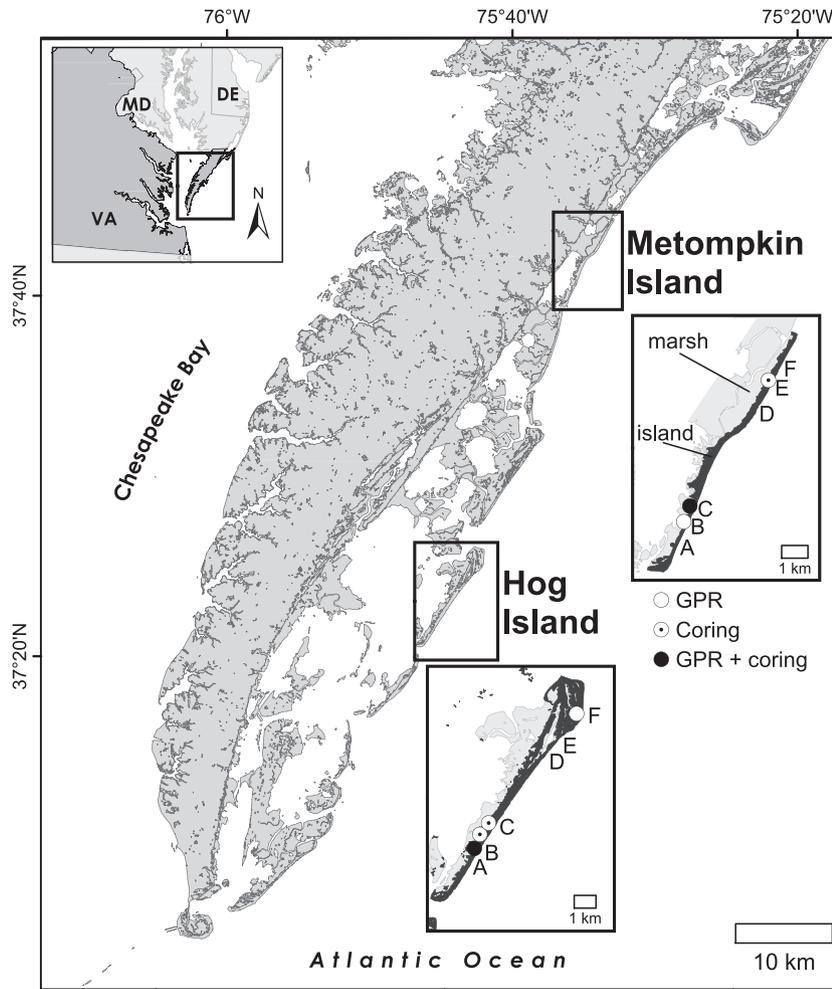


Fig. 3. The southern Delmarva Peninsula, showing the Virginia Barrier Islands on the Atlantic coast. Hog and Metompkin Islands (inset) represent morphological end-members within the barrier island chain. Representative sites, where transects were established on each island, are lettered A through F. Also shown are sites of ground-penetrating radar (GPR) surveys and vibracore collection.

(Byrnes, 1988; Harris, 1992; Fenster and Hayden, 2007), we focused on three representative sites in the north and three in the south of each island, for a total of six sites per island (Fig. 3).

We established one cross-shore and two alongshore transects at each site for collection of topographic, ecological, and sedimentological data. Cross-shore transects (extending 50–200+ m) began at the foredune toe or vegetation line – or, if absent, the estimated point where these would be expected to develop – and extended to the start of the stable island interior or backbarrier (e.g., shrub thicket, mudflat, marsh, or water). The two alongshore transects, included to capture community variability that may occur with changing distance from the shoreline and/or between the center and edges of overwash sites, intersected the cross-shore transect at 5 m and the midway point. Alongshore transects extended 50 m in either direction from the cross-shore transect, or less if the stable interior or backbarrier was encountered first.

At 5 m increments along transects, we paired high-resolution (cm-scale) GPS elevation measurements (R7/8 GNSS, Trimble Navigation Limited) with observations of the composition and percent cover of vegetation in a 0.5×0.5 m quadrat. Taxonomic identifications in the field followed Duncan and Duncan (1987) or Uva et al. (1997). When positive field identification was not possible, reference samples were returned to the lab and identified to the lowest possible taxonomic level (genus or species) according to Radford et al. (1968).

We recorded the morphologic environment of each paired sampling point as one of the following: overwash, transitional (e.g., partial or

recovering overwash, low hummocky topography), dune, swale (either interdunal or backing a single dune), or relict overwash (known instances of past overwash now cut off from the beach by accretional dunes). To capture topography in greater detail, we collected additional elevation measurements at any change or break in slope along a transect. Elevation measurements on the cross-shore transects also extended seaward to the water line. All elevation measurements were referenced to the NAVD88 datum and differentially corrected using the National Geodetic Survey's Online Positioning User Service (<http://www.ngs.noaa.gov/OPUS/>).

Our analyses of vegetation and environmental data focused on the primary dune-building and maintainer species, *A. breviligulata* and *S. patens*, respectively. We chose frequency of occurrence as the best metric for assessing relative dominance of species in each morphologic environment because the density of vegetation at our sites was moderate to low, our sampling units were small, and the spatial distribution of species, relative to disturbance, was our primary interest (McCune and Grace, 2002). We normalized frequency data by the number of observations in each morphologic environment (i.e., converted to percent frequency).

We used Indicator Species Analysis (ISA) to determine the strength and statistical significance of the observed relationships between vegetation and morphology (PC-Ord, MJM Software Designs). ISA is a community ordination technique that considers presence/absence and relative abundance of different plant species across a range of

categories (Dufrene and Legendre, 1997); in this case, the categories were morphologic environments. ISA assigns an indicator value (IV) of 0–100 to each species based on the relative strength of the relationship between that species and a given category (a strong IV is >25 ; Bakker, 2008). The threshold above which the maximum IV for a given species is statistically significant ($\alpha = 0.1$) based on a Monte Carlo test varies by species and between analyses, but was generally ~ 5 in this study for commonly occurring species when all sampling points were included (or ~ 20 on Hog Island and ~ 10 on Metompkin Island when only vegetated sampling points were included).

Because beach width can exert substantial control over dune (re) development by affecting the supply of sand to the dunes (e.g., Bauer and Davidson-Arnott, 2002), we also examined the potential influence of beach width on morphology. We calculated beach width at each site as the distance between the wet/dry line and the start of the cross-shore transect. We related beach widths and mean elevations of transects (as an inverse proxy for degree of disturbance) on each island using Spearman correlation, which tests for any monotonic relationship.

Shell armoring may also limit sand transport and, thus, inhibit dune recovery (e.g., Cleary and Hosier, 1979; Priestas and Fagherazzi, 2010). To assess shell armoring at each site, we collected surficial sediment samples every 10 m along all transects and calculated the percentage of each dry sample weight accounted for by shells >2 mm in diameter (separated by sieve). We compared percents by weight of shell gravel among sites using the Kruskal–Wallis test (non-parametric ANOVA analog).

2.2. Assessing overwash persistence: historical analyses

To examine overwash persistence on decadal timescales, we expanded a set of shapefiles digitized from orthorectified historical aerial photographs by Wilson et al. (2007). Similar to Hosier and Cleary (1977) and Kochel et al. (1985), Wilson et al. (2007) delineated the boundaries of overwash zones using the expected position of the foredune prior to destruction by overwash and the apparent landward/lateral extent of fresh sand deposition (inferred from the surrounding intact foredune and vegetation cover; M. D. Wilson, personal communication, 20 May 2010).

Wilson et al.'s (2007) dataset of photos and shapefiles covered Hog and Metompkin Islands for the years 1962, 1977, 1985, 1994, and 2002, and Metompkin Island only for the years 1949 and 1955. We extended this dataset to include 2007 and 2009 for both islands using recently released aerial imagery (VGIN Virginia Base Mapping Program, © 2007 and 2009 Commonwealth of Virginia) and comparable digitization techniques (ESRI ArcGIS). We digitized the area of the island – defined as the area between the wet/dry line and the island/backbarrier marsh boundary – for every photo in the dataset. We then calculated total overwash area for each photo as a percentage of the area of the island. As a measure of overwash persistence, we calculated the percent of the area of the island also overwashed in the antecedent photo of the same island (i.e., the “percent of overlap”). We compared results between islands using the Kruskal–Wallis test.

To assess overwash persistence on longer timescales (decades to centuries), we conducted ground-penetrating radar (GPR) surveys and collected sediment vibracores in select locations on each island (Fig. 3). We collected GPR profiles using a PulseEKKO Pro 200 MHz system (Sensors and Software; step size = 20 cm) integrated with the R7/8 Trimble GPS unit for topographic correction. Radar velocities were determined using the common midpoint method (CMP). We applied exponential gain compensation (SEC2) to all profiles.

Exploratory GPR surveys revealed that in many parts of the study area, and especially in active overwash zones, the saline water table causes attenuation of the GPR signal too near the surface to allow collection of substantive data. Surveys of a known relict overwash channel among dunes on the southern end of Hog Island (Site B), where surface elevations were higher, however, demonstrated that distinguishing between dune and overwash facies is possible if signal penetration is

sufficient. We limited our large-scale GPR surveys, therefore, to dune complexes where field reconnaissance and aerial photos suggested that overwash may have previously occurred.

We collected sediment vibracores ranging from 1 to 6 m in length (1.5 to 7+ m in total depth) using 3" aluminum irrigation piping and a portable vibracoring rig similar to the model described by Finklestein and Prins (1981). Because of the infeasibility of coring through thick sand deposits (dunes), we collected cores in overwash zones (active or relict), transitional areas, swales, or high marshes. Though our options were limited by access, we were able to obtain cores in areas of interest that either corresponded with GPR transect locations (e.g., relict overwash on Hog Island) or that could not be surveyed using GPR, such as active overwash zones and sites of historic large-scale overwash currently located within dense shrub thickets.

We visually distinguished overwash deposits, based on literature descriptions of typical characteristics observed in cores, including: moderately to very well sorted, fine to coarse sand and shells with parallel, planar heavy mineral laminations; the presence of shell hash and/or shell lag deposits; and textural indications of decreasing energy up-unit, such as normal grading (coarse shell lag to finer sand) or inverse grading (fine heavy mineral lag to coarser sand) (e.g., Schwartz, 1975; Leatherman and Williams, 1977, 1983; Leatherman et al., 1977; Sedgwick and Davis, 2003; Wang and Horwitz, 2007). Because the characteristic cross-stratification associated with aeolian deposition is difficult to preserve in the vibracoring process, potential aeolian deposits could not be identified with the same degree of certainty. We made tentative identifications based on the co-occurrence of the following features: well to very well sorted fine to medium sand; discontinuous, wavy, or cross-cutting heavy mineral laminations; and higher apparent proportions of frosted quartz grains (e.g., Margolis and Krinsley, 1971; Hayes, 1979; Byrne and McCann, 1990).

3. Results

3.1. Relationships between vegetation and morphology

Sites varied substantially in topographic relief and vegetation composition (Fig. 4). On both islands, *A. breviligulata* was dominant (i.e., occurred more frequently) on dunes as well as in low-lying transitional areas (Fig. 5a). *A. breviligulata* occurred more frequently than *S. patens* in overwash zones on Hog Island, although it should be noted that large-scale overwash was limited to a single area (Site D, parts of Site E) at the rotational axis of the island, and observed vegetation cover in this area was exceptionally sparse relative to other sites. *S. patens* was dominant in interdunal swales on Hog Island, consistent with the affinity of this species for lower elevations and wetter soils. Relict overwash was ecologically distinct from other morphologic environments in terms of overall species assemblage, but did not show any pattern with respect to *A. breviligulata* and *S. patens* (equal percent frequencies).

On Metompkin Island, percent frequencies for overwash were also low overall (largely because of an almost entirely bare, overwash-dominated site on the southern half of the island, Site A; Fig. 4). Nevertheless, *S. patens* was marginally dominant in overwash zones – a signal derived from the denser stands of vegetation present in the overwash terraces on the northern half of the island (Sites D, E, and F). *A. breviligulata*, rather than *S. patens*, was dominant in the open swales (backdune platforms grading into high marsh). No distinct relict overwash zones were present, likely because Metompkin Island has been transgressing too rapidly to preserve such features. *A. breviligulata* and *S. patens* appeared to be separated more sharply by morphologic environment here than on Hog Island, where frequencies were more comparable across environments.

ISA results (Fig. 5b) were broadly consistent with species frequency distributions. *A. breviligulata* was a strong and statistically significant indicator of dunes on both islands ($\alpha = 0.1$; $p = 0.04$). On Hog Island, *A. breviligulata* was also a strong indicator of transitional areas.

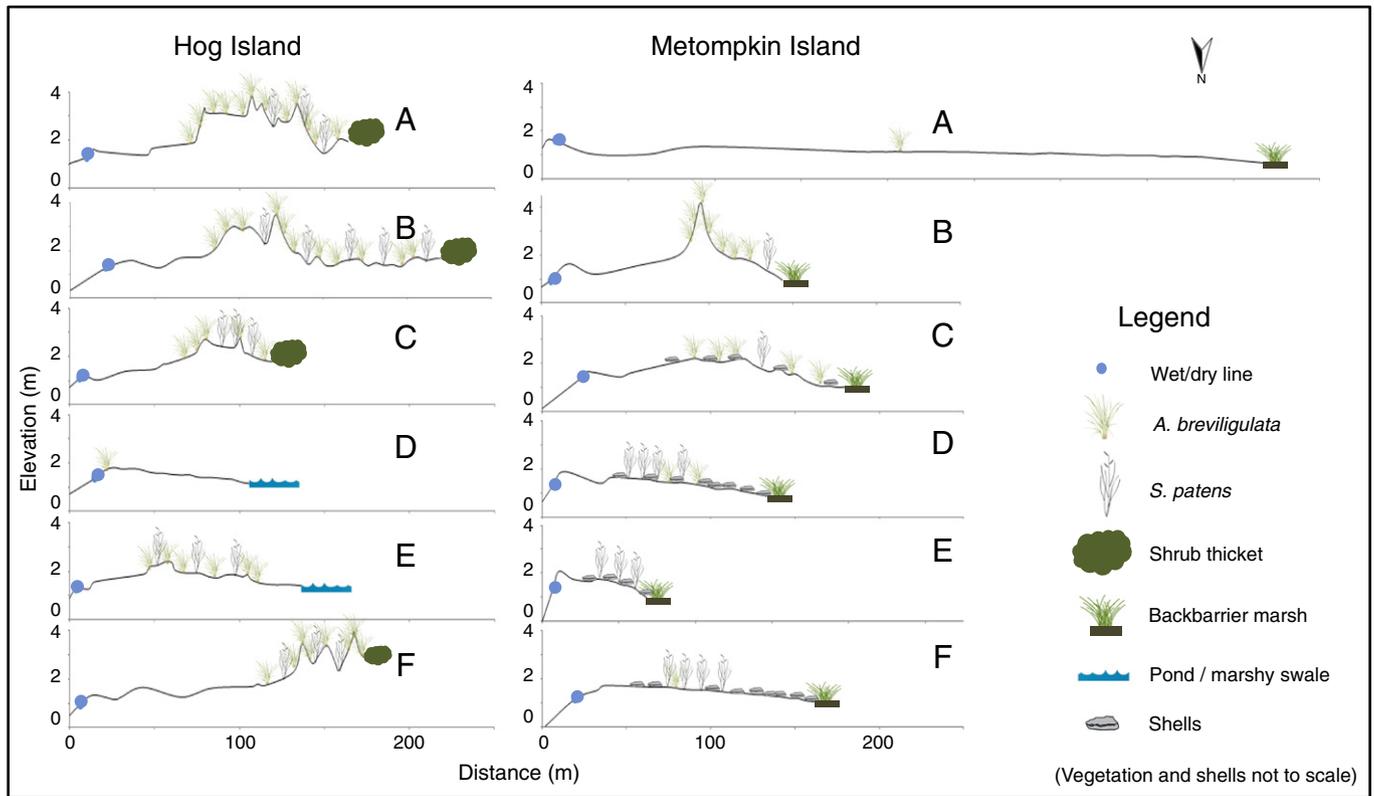


Fig. 4. Cross-shore transects from sites (A–F) on Hog and Metompkin Islands, from the water line (left) to the landward terminus (right – e.g., shrub thicket, backbarrier marsh). Only the key dune-building and maintainer species (*A. breviligulata* and *S. patens*, respectively) are shown. Although other species were observed (e.g., *Panicum amarum* and *distichum*, *Solidago sempervirens*, *Cakile edentula*), *A. breviligulata* and *S. patens* were typically dominant. Excluding other species does not affect the representation of relative vegetation cover.

S. patens was a significant indicator of swales ($p = 0.00$), although *A. breviligulata* also had a strong (but lower) IV. Neither species was a strong or significant indicator of overwash (likely because of low percent cover: only 11 of 74 overwash sampling points were vegetated) or of relict overwash.

On Metompkin Island, *S. patens* was a significant indicator of overwash ($p = 0.08$), although the largely bare overwash zone at Site A contributed to a relatively low IV. Neither species was a strong indicator of transitional areas, likely because the overall species assemblage

in this environment was more diverse than elsewhere. *A. breviligulata* was a strong indicator in swales.

Like the frequency data, the strong contrast in ISA results between dunes and overwash on Metompkin Island demonstrated a potentially sharper distinction between communities than on Hog Island, where values were more moderate and consistent across environments. This difference between the two islands became more apparent when bare sampling points were excluded from analysis (Fig. 5c). IVs for the species of interest on Hog Island were even more consistent across

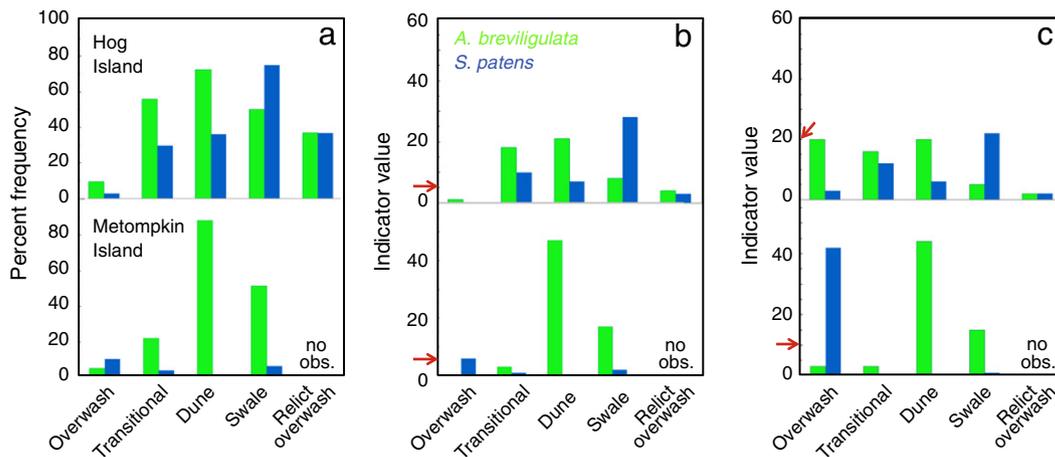


Fig. 5. a) Percent frequency, b) Indicator Species Analysis (ISA) results including all sampling points (335 on Hog Island, 363 on Metompkin Island), and c) ISA results including only vegetated sampling points (258 on Hog Island, 167 on Metompkin Island). Top and bottom panels show results for Hog and Metompkin Islands, respectively. Arrows indicate the value above which the maximum indicator values of commonly occurring species like *A. breviligulata* and *S. patens* were statistically significant ($\alpha = 0.1$). Modified from Wolner et al. (2011).

environments (generally between 5 and 20), especially for *A. breviligulata*. As a result, although *A. breviligulata* still had a higher IV than *S. patens* in overwash, transitional, and dune environments, it was no longer strong or significant ($p > 0.1$). On Metompkin Island, however, *A. breviligulata* remained a strong and significant indicator of dunes. *S. patens* became a dramatically stronger and more significant indicator of overwash ($p = 0.00$), and was the only strong indicator species in this environment.

3.2. Relationships between beach width, shell armoring, and morphology

Beach widths varied widely among sites on both islands (Fig. 4). On Hog Island, a strongly positive, significant correlation was apparent between beach widths (considered here as a proxy for supply of sand to the dunes) and mean elevations of transects (an inverse proxy for degree of disturbance; Fig. 6). This positive, significant correlation continued to exist even when an anomalous measurement (beach width = 1.2 m) was corrected using a 2009 aerial photo (maximum possible beach width from photo = 30 m). Beach width on Hog Island, therefore, was closely related to overwash distribution – i.e., narrower beaches were associated with lower mean elevations.

On Metompkin Island, beach width did not appear to be linked to the distribution of overwash. No significant relationship was evident between beach widths and mean elevations of transects (Fig. 6). The relationship remained insignificant even when an outlying measurement was excluded (beach width = 176 m, a value supported by the 2009 aerial photo).

Shell armoring was present on Metompkin Island only (Fig. 4), where percents by weight of shell gravel in sediment samples varied significantly among sites (Fig. 7). Mean percents by weight of shell gravel were greatest at the overwash-dominated northern sites (D, E, and F). At Site C (transitional), percents by weight of shell gravel were significantly lower than at the northern sites, but significantly greater than at Sites A and B, where shells were essentially nonexistent on the sampling transects.

3.3. Overwash occurrence through time

The prevalence and distribution of overwash during the period of record for aerial photos differed markedly between the two islands (Fig. 8). Overwash coverage, as a percentage of the area of the island, was significantly greater on Metompkin Island than on Hog Island

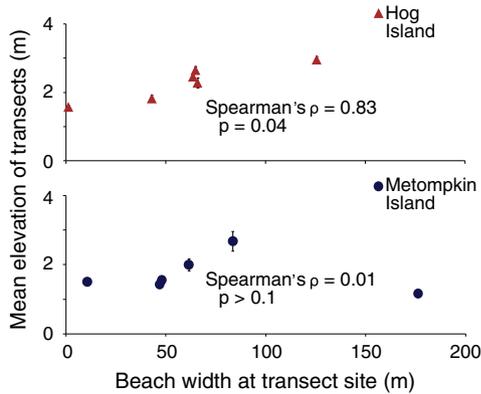


Fig. 6. Mean elevation of transects and beach width at each site, showing the correlation coefficient (ρ) and p value from Spearman correlation. Error bars represent 95% confidence intervals (not visible behind some markers). In a subsequent correlation analysis (not shown), the anomalous point on Hog Island (beach width = 1.2 m) was corrected to 30 m using 2009 aerial imagery; however, no changes occurred to the ρ or p values because Spearman correlation is a rank-order analysis. The correlation on Metompkin Island was still insignificant ($p > 0.1$) after removing the outlying point at beach width = 176 m (this value was corroborated by 2009 aerial imagery). Modified from Wolner et al. (2011).

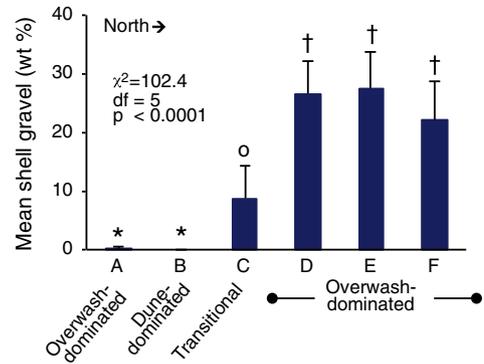


Fig. 7. Mean percents by weight of shell gravel for sediment samples collected at sites on Metompkin Island (no shell gravel observed on Hog Island). Error bars represent 95% confidence intervals. Kruskal–Wallis tests were used for overall and pairwise comparisons of sites. Sites that share a symbol were not significantly different in 15 pairwise comparisons (Bonferroni $\alpha' = 0.003$).

throughout the period of photo record (Fig. 9). The percent of island overwashed peaked for both islands in 1962, when the historic Ash Wednesday nor'easter impacted the VCR (Dolan and Davis, 1992). Although subsequent values were typically > 20% on Metompkin Island, values on Hog Island, however, remained near zero. Both islands had apparent lows in overwash coverage in 1977, but the quality of the 1977 photos was poor, making overwash zones particularly difficult to distinguish.

The percent of overlap, or percent of island also overwashed in the antecedent photo (as a measure of overwash persistence), was significantly greater on Metompkin Island through time (Fig. 9). Percent values of overlap were low on Hog Island overall; the highest values followed the 1962 Ash Wednesday storm. On the southern end of Hog Island, large-scale overwash apparently associated with this storm

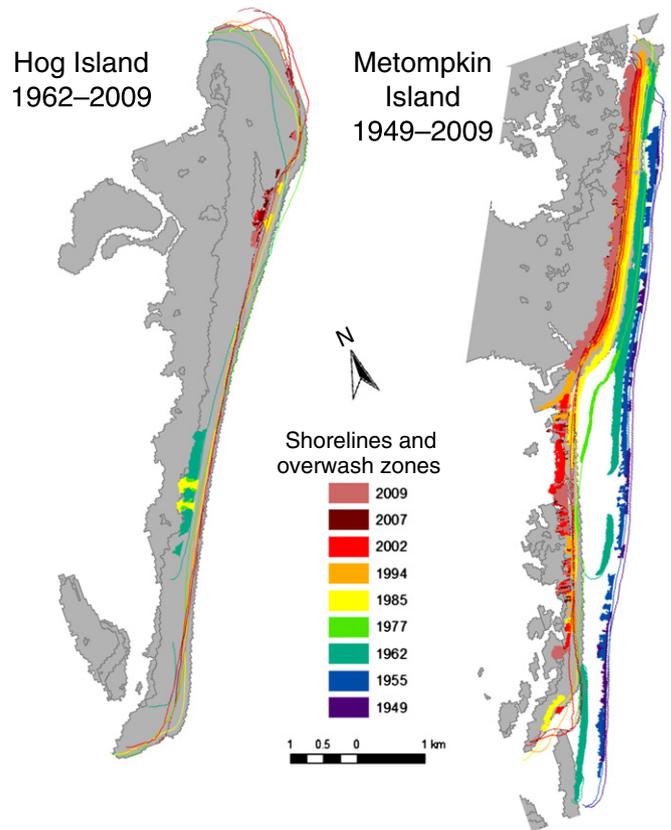


Fig. 8. Shorelines and overwash zones digitized from aerial photos (no data for Hog Island in 1949 and 1955). All shapefiles except 2007 and 2009 from Wilson et al. (2007).

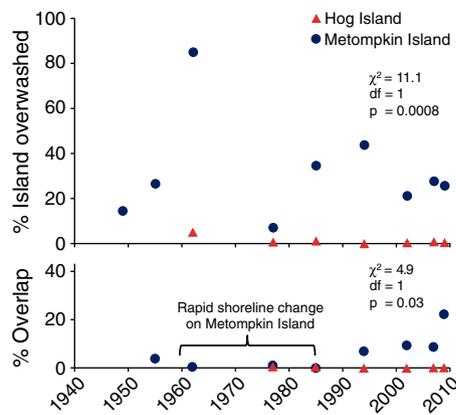


Fig. 9. Top: percent of the area of the island overwashed in each year (no data for Hog Island in 1949 and 1955). Bottom: percent of island also overwashed in the antecedent photo (i.e., percent of overlap). Rapid changes in the position of the shoreline on Metompkin Island likely limited percent values of overlap prior to 1994 because little overlap of the island itself occurred from image to image. Statistical differences between islands were determined using Kruskal–Wallis tests.

persisted through 1985, but gradually recovered as the southern shoreline became accretional (Fig. 8). Subsequent percent values of overlap on Hog Island were associated solely with the rotational axis of the island.

Metompkin Island appeared to have similarly low percent values of overlap between 1949 and 1994 (Fig. 9). During this time period, however, the position of the shoreline changed rapidly (100s of m between temporally consecutive photos), resulting in little overlap of the island itself from image to image. Once the changes in the position of the shoreline slowed (10s of m between temporally consecutive photos), the percent values of overlap were considerably higher than on Hog Island, indicating that rapid island translation likely limited percent values of overlap prior to 1994. Overall, the coverage and the spatial and temporal overlap of overwash zones were distinctly greater in scale and more general in distribution on Metompkin Island than on Hog Island.

3.4. Stratigraphic relationships

On Hog Island, flat-lying, evenly-spaced reflections (indicative of overwash facies; Møller and Anthony, 2003) beneath 1–2 m of inclined, cross-cutting, finer-scale reflections (indicative of dune facies; Havholm et al., 2004) suggested the recovery of overwash into dunes in the south (Site B; Fig. 10) and north (Site F; Fig. 11). The southern profile (Fig. 10) also captured the subsurface expression of a relict overwash channel, now part of a swale fronted by accretional secondary and foredune ridges.

Because of the limitations of GPR in low-lying environments, where the saline water table is near the ground surface, GPR surveys on Metompkin Island (not shown) were not as effective as on Hog Island, and did not resolve any evidence of overwash recovering into dunes. Analysis of historical aerial photos (Fig. 8) suggests that on northern Metompkin Island, at least, significant dune recovery between overwash events is not likely to have taken place.

Cores collected on Hog Island at Site B (along the GPR profile shown in Fig. 10) were short (1–2.5 m) and consisted of moderately to very well sorted, fine to medium sand with heavy mineral laminations. Stratigraphic units with slightly coarser shell hash and/or planar heavy mineral laminations at depth transitioned up-core to units of better sorted, finer-grained, often frosted sediment displaying wavy, discontinuous, and/or cross-cutting heavy mineral laminations, as well as bioturbation (massive bedding) near the surface (Fig. 12). We interpreted this sequence as mixed-energy overwash deposits underlying reworked sediments, possibly including aeolian lag deposits. The depth to the base of

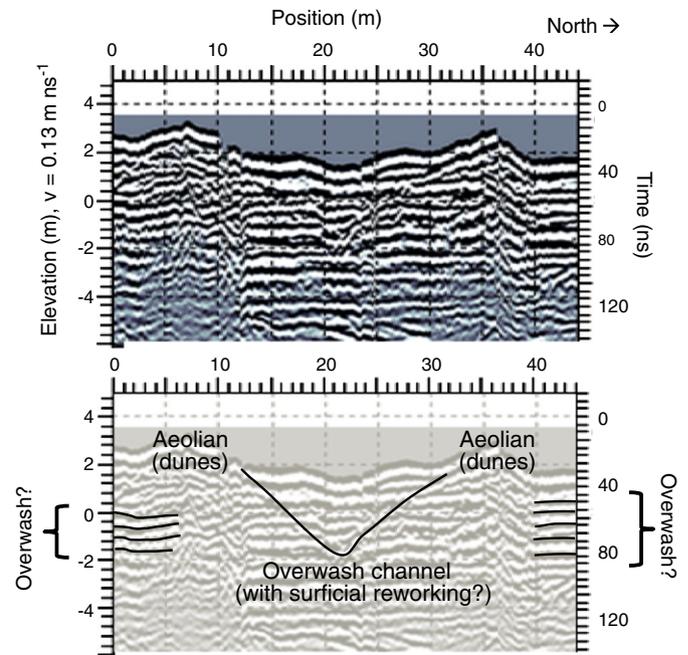


Fig. 10. Alongshore GPR profile through the relict overwash channel at Site B on southern Hog Island (top panel: uninterpreted profile; bottom panel: interpreted profile). Surficial reworking is indicated by the massive (possibly bioturbated) unit(s) near the surface. We obtained short cores (Fig. 12) between the 15 and 30 m alongshore positions on this profile.

the reworked/possible aeolian units (0.5–1.5 m, depending on the core and the extent of compaction) corresponded roughly to the depth of apparent surficial reworking in the GPR transect (Fig. 10).

Longer cores (1.5–6 m long, 2.5–7+ m deep), collected between Sites B and C on Hog Island (Fig. 3), were associated with locations known to have been affected by large-scale overwash during the 1962 Ash Wednesday nor'easter, when the shoreline was considerably landward of its current location. The characteristic pattern observed in these cores began with estuarine mud and intertidal deposits at the base, truncated by one to two pulses of planar-stratified, fine to medium sand, with disturbed heavy mineral laminations indicating reworking in the upper strata. We interpreted these planar-laminated sand units as overwash (possibly part of a spit-building succession). Reworking at the upper boundaries of these units graded into organic-rich mud and muddy sand containing roots, woody debris, and possible paleosols, which we interpreted as stable island interior facies (e.g., upland, swale, or high marsh). These facies were truncated by one to three units of clean, planar, fine to medium sand with heavy mineral laminations, sometimes exhibiting textural evidence of depositional energy decreasing up-unit (e.g., basal heavy mineral or shell lag deposits), indicating pulses of overwash. The uppermost of these overwash deposits graded into possible aeolian and biologically reworked units underlying the modern surface, typified by rooted, mottled, fine to medium sand, sometimes exhibiting cross-cutting heavy mineral laminations or massive (bioturbated) bedding (Fig. 13). Overall, the longer Hog Island cores encompassed a twice-repeated sequence of overwash facies recovering into stable interior environments.

In the single core obtained on northern Metompkin Island (Site E; Fig. 3), estuarine mud at the base was overlain by a backbarrier marsh facies (sandy, bioturbated mud containing roots; Fig. 14). This facies was truncated by three clean, planar units of fine to medium sand with basal heavy mineral or shell lag deposits, signifying a decrease in depositional energy up-unit (i.e., three stacked pulses of overwash).

In cores collected in a transitional area on southern Metompkin Island (Site C; Fig. 3), estuarine and intertidal facies at the base were truncated by overwash deposits (planar, shelly sand), which were overlain

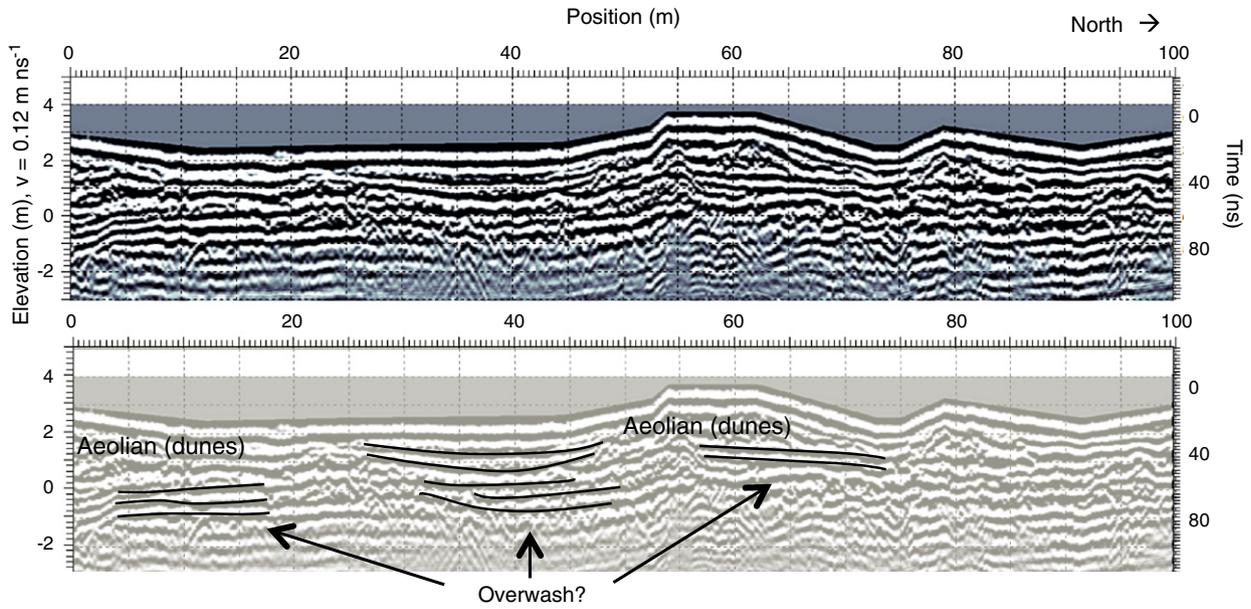


Fig. 11. Alongshore GPR profile along the secondary dune at Site F on northern Hog Island (top panel: uninterpreted profile; bottom panel: interpreted profile). Because of malfunctioning GPS, we applied topographic corrections using an estimated profile based on field notes and elevation data collected during vegetation surveys.

at the surface by about 0.5–1 m (depending on cross-shore position and degree of compaction) of possible aeolian deposition and/or aeolian or biological reworking. These uppermost units were characterized by wavy, discontinuous, cross-cutting heavy mineral laminations (possibly aeolian lag deposits) and/or bioturbation, with sediments commonly exhibiting quartz frosting. Like the northernmost core, the southern Metompkin Island cores were dominated overall by stacked overwash

deposits. Unlike the northernmost core, however, overwash deposits were interspersed with thin, muddy or organic-rich layers (including possible paleosols; Fig. 15).

4. Discussion

4.1. Vegetation dynamics

The co-occurrence of *A. breviligulata* and *S. patens* in most of the observed environments (Fig. 5) is not surprising: although both species usually reach maximum densities in specific habitats, they can also grow more sparsely under a range of conditions (Silander and Antonovics, 1979; Young et al., 2011). The critical issue for this investigation is not where each species occurs, but the environment conditions under which each species dominates, or with which it is most closely associated.

The strong association on both islands between dunes and *A. breviligulata* is consistent with the tendency of this species to thrive at higher elevations and to contribute to vertical accretion. The similar (albeit weaker) relationship between *A. breviligulata* and transitional areas, particularly on Hog Island, supports the role of this grass in topographic recovery following disturbance.

The key respect in which the two islands differ with regard to vegetation is the composition of species in overwash zones. The significant association between overwash and *S. patens* on Metompkin Island – which strengthened further when only vegetated sampling points were considered – supports our hypothesis that the maintainer feedback is more likely to play a role on this island, where disturbance is more prevalent. Conversely, on Hog Island, the marginal dominance of *A. breviligulata* in overwash zones (although not a significant association in ISA) suggests that this island may follow the post-overwash trajectory typical of disturbance-resisting systems in which the dune-builder feedback is the primary ecomorphodynamic process: gradual recolonization by vegetation, with the ultimate success of *A. breviligulata* contributing to vertical accretion and the eventual redevelopment of dunes (Godfrey et al., 1979; Fig. 2). The preservation of relict overwash channels on southern Hog Island does not appear to be a product of the maintainer feedback (no relationship with *S. patens* was apparent), but rather of local shoreline accretion and seaward dune development subsequent to channel incision (Harris, 1992).

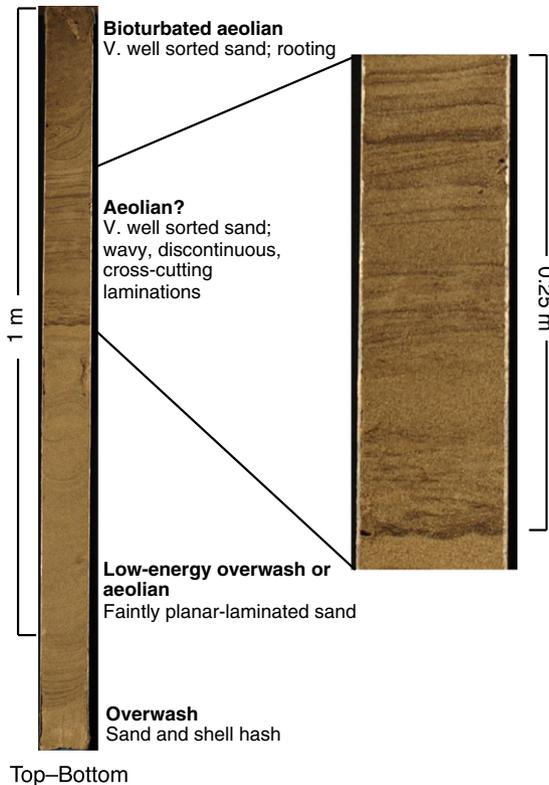


Fig. 12. Photo and interpretation of a characteristic short core from a relict overwash channel on southern Hog Island (Site B). Wavy, discontinuous, and cross-cutting laminations, interpreted as possible aeolian lag deposits, are enlarged in the right panel.

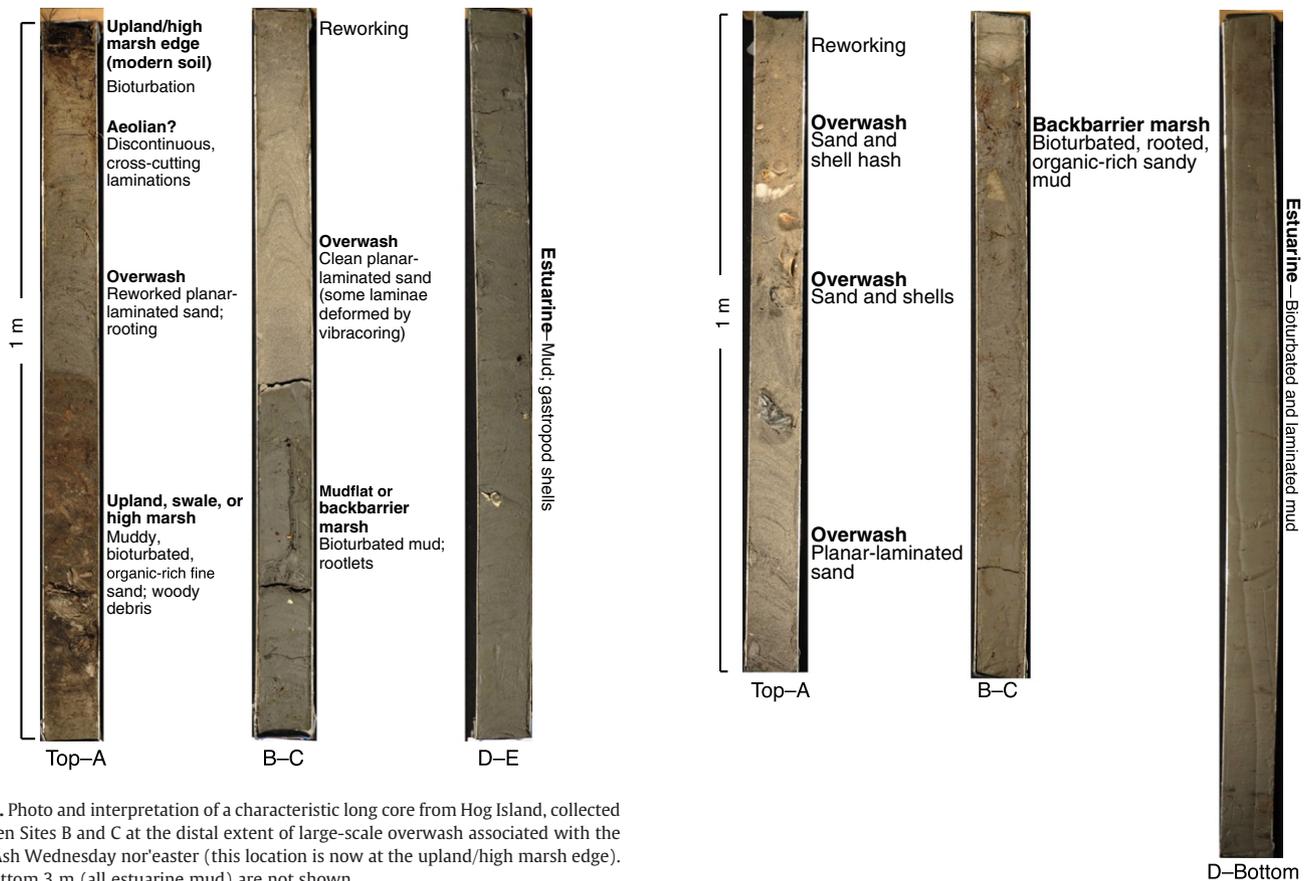


Fig. 13. Photo and interpretation of a characteristic long core from Hog Island, collected between Sites B and C at the distal extent of large-scale overwash associated with the 1962 Ash Wednesday nor'easter (this location is now at the upland/high marsh edge). The bottom 3 m (all estuarine mud) are not shown.

The difference in species dominance between swales on Hog Island and Metompkin Islands may be explained by differences in island morphology, and consequently in freshwater availability. Hog Island is a wide (~1 km) barrier with multiple shore-parallel dune ridges, and therefore, is likely to retain a large freshwater lens that discharges in interdunal swales, facilitating the growth of species like *S. patens* that thrive in wetter soils. In contrast, Metompkin Island is thin (<0.5 km), having only a single dune ridge (where dunes are present at all); as a result, its dune-backing swales are typically flat, open platforms running from the dune ridge to the marsh. Freshwater on this island is probably limited and not likely to pool in these swales, resulting in drier soils that facilitate the growth of *A. breviligulata*. Given the dominance of *S. patens* in swales on Hog Island, the maintainer feedback potentially could become a more important dynamic here than it currently appears to be if the frontal dunes were lost to erosion (thereby linking swales to the active beach). This scenario would likely arise first at the rotational axis of the island, where overwash is already beginning to encroach on a wide, marshy swale.

The sharper ecological distinction between morphologic environments on Metompkin Island relative to Hog Island (Fig. 5) may be the result of differences in disturbance regime (i.e., the frequency and spatial variability of disturbance by overwash). On Hog Island, the rarity of disturbance (both spatially and temporally) may allow grass communities to intermingle over time. When overwash does occur, seed dispersal in wrack and lateral encroachment by surrounding vegetation may determine the composition of the recovering community (e.g., Fahrig et al., 1993), as expected for a disturbance-resistant island where the dune-builder feedback is dominant (Godfrey et al., 1979). On Metompkin Island, disturbance is more heterogeneous. Frequent, widespread disturbance in low-relief overwash terraces on northern Metompkin Island may lead to the dominance of only the most overwash-adapted species (e.g., *S. patens*). In contrast, the patchy, infrequently disturbed dunes on southern Metompkin Island are isolated areas of high relief, occupied

Fig. 14. Photo and interpretation of a core from an overwash zone on Metompkin Island (Site E), collected near the vegetation line after augering ~1 m through shell gravel and sand similar to the uppermost layer of the core.

only by species that thrive at higher elevations and in drier soils (e.g., *A. breviligulata*). Metompkin Island, therefore, may be an example of a barrier in which both feedbacks play an important role: discontinuous but relatively tall dunes resist overwash *locally* (remaining dunes), whereas low elevations and the dominance of *S. patens* reinforce continued disturbance in widespread overwash zones, leading to distinct communities. In other words, although disturbance is more frequent overall on Metompkin Island, spatial heterogeneity within this disturbance regime may introduce greater compositional distinctions between morphologic environments.

4.2. Physical dynamics

On Metompkin Island, the correlation between low topographic roughness and the abundance of shells indicates that armoring may be suppressing topographic recovery (e.g., Cleary and Hosier, 1979; Priestas and Fagherazzi, 2010), particularly in the northern overwash terraces (Sites D, E, and F; Fig. 7). Shell armoring may be a factor in transitional areas as well: Site C was flanked by dunes and dominated by *A. breviligulata* (relative to *S. patens*), yet was low-lying – perhaps because shells were more prevalent here than elsewhere along the southern half of the island.

Elevation itself may also be an important variable in limiting topographic development on Metompkin Island. Priestas and Fagherazzi (2010) noted an association between exceptionally low elevations produced by scouring and inhibited recovery after overwash. Although certain species are tolerant of some flooding (e.g., *S. patens*; Silander and Antonovics, 1979), recolonization may be limited if inundation occurs too frequently. If sand is often or always wet, transport by wind is likely to be restricted. Aerial photos and field reconnaissance show that the

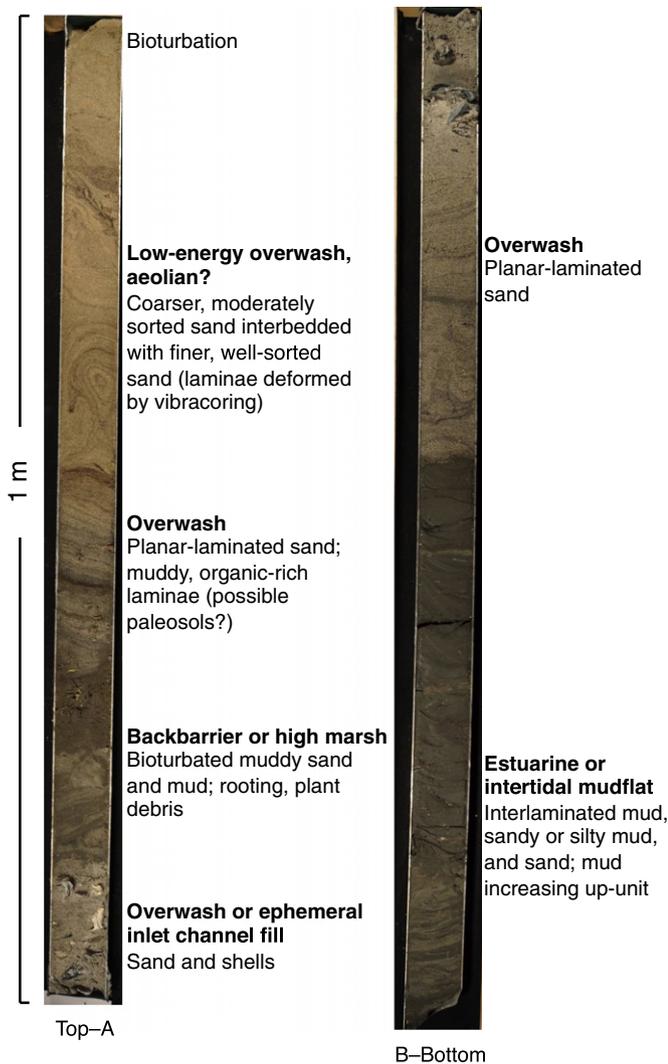


Fig. 15. Photo and interpretation of a characteristic core from a transitional area on Metompkin Island (Site C), collected near the landward edge of the island.

large, especially low-relief overwash fan at Site A on southern Metompkin Island (Fig. 4) – a site surrounded by dunes and located at the widest part of the beach – has been extant since at least 2007, without any apparent changes in dimension. Vegetation and shell cover were almost entirely absent at this site during field expeditions in 2009 and 2010, making it distinctive from the overwash-dominated sites on northern Metompkin Island (although it was representative of smaller-scale overwash zones observed elsewhere along the southern half of the island). The elevation of this site relative to the wet/dry line and the beach was lower overall than at other sites (Fig. 4), and during field visits, the surficial sand was generally wet. This suggests that relative elevations here may be low enough to allow flooding at high tides, either as a result of the freshwater lens rising with the saline water table (e.g., Hayden et al., 1995), or because of spillover from a frequently inundated runnel observed on the adjacent beach. This overwash fan, therefore, may have persisted not because of the presence of maintainer species or shell armoring (as in the north, where overwash terraces have persisted at least as long; Fig. 8), but rather because of recurrent flooding resulting from critically low elevations.

On Hog Island, the occurrence and persistence of overwash appears to be related principally to the dynamics of the shoreline. Large-scale overwash currently occurs only at the rotational axis of the island (Sites D and E; Figs. 3 and 4), where the beach has been narrowing over the last several decades (Fenster and Hayden, 2007) and is presently thinner

than at any other point on the island. This area has been the sole site of persistent overwash over the last several decades as the shoreline has eroded locally (Fig. 8). On southern Hog Island, the recovery of persistent overwash (apparently initiated during the 1962 Ash Wednesday storm) occurred in association with a local shift from shoreline erosion to accretion ca. 40 years BP. Overwash zones have recovered into dunes on northern and southern Hog Island (Figs. 10 and 11) in areas associated with recent local shoreline accretion (Fenster and Hayden, 2007). Overwash persistence on Hog Island, therefore, may be linked to narrow and eroding beaches, whereas overwash recovery is associated with wide and accreting beaches. This is unsurprising, given the importance of the supply of windblown sand and shoreline position in the (re)development of dunes (Bauer and Davidson-Arnott, 2002) and the determination of frequency of disturbance (Fahrig et al., 1993).

The characteristic, repeating succession of units in the longer cores from southern Hog Island (Fig. 13) generally resembles the pattern of overwash and aeolian units overlying organic-rich, muddy backbarrier strata observed by Godfrey et al. (1979) in a disturbance-resistant barrier system (Nauset Spit, MA). The alternation between overwash and stable interior/aeolian facies in our cores (collected in an area where the shoreline has oscillated) further supports the role of rotational change of the shoreline in overwash dynamics on Hog Island, suggesting that overwash may persist in the short term where the local shoreline is eroding, but gradually recovers into dunes or stable interior when the shoreline becomes accretional.

In contrast to Hog Island, overwash occurrence and persistence do not appear to be related to local beach width on Metompkin Island. Rather, overwash is spatially widespread and has been persistent on time scales of at least decades (Figs. 8 and 9). The absence of a relationship between beach width and overwash distribution (Fig. 6) suggests that factors affecting sand transport/supply other than beach width – such as the dominance of maintainer species (northern sites), critically low elevations (southern site), and/or the presence of shell armor (both northern and southern sites) – may be contributing to the occurrence and maintenance of low topographic roughness.

The stratigraphic succession in cores from Metompkin Island largely resembles the pattern identified by Godfrey et al. (1979) in a disturbance-reinforcing barrier system (Core Banks, NC): repeated high-energy overwash deposits, sometimes with organic-rich (possibly paleosol) layers associated with low or high marsh. Cores from southern Metompkin Island, which included possible aeolian/paleosol layers among overwash deposits (Fig. 15), indicate that periods of infrequent disturbance may occur in transitional areas. The core from northern Metompkin Island, characterized by stacked overwash deposits with no apparent evidence of paleosol development or lower energy conditions (Fig. 14), suggests that the present-day uniform morphology of overwash terraces may be representative of the past several decades for this part of the island.

4.3. Synthesis and implications

Though Hog and Metompkin Islands have evolved in response to a range of physical drivers (e.g., Leatherman et al., 1982; Byrnes, 1988; Harris, 1992; Oertel et al., 2008) that have established contrasting disturbance regimes on the two islands, ecomorphodynamic feedbacks (along with physical processes) have contributed to the continuation of these disturbance conditions. Building on the work of previous studies (Godfrey et al., 1979; Stallins and Parker, 2003) and informed by our findings from the VCR, here we present an ecomorphodynamic conceptual model synthesizing the contributions of physical and ecological factors in the response of barrier islands to disturbance (Fig. 16).

Hog Island appears to follow the disturbance-resistant model of barrier island vulnerability. Relatively high-relief, continuous dunes built by *A. breviligulata* resist overwash. In the apparently rare event that overwash does occur (e.g., during extreme storms or in association with narrow beaches), dune recovery happens gradually via

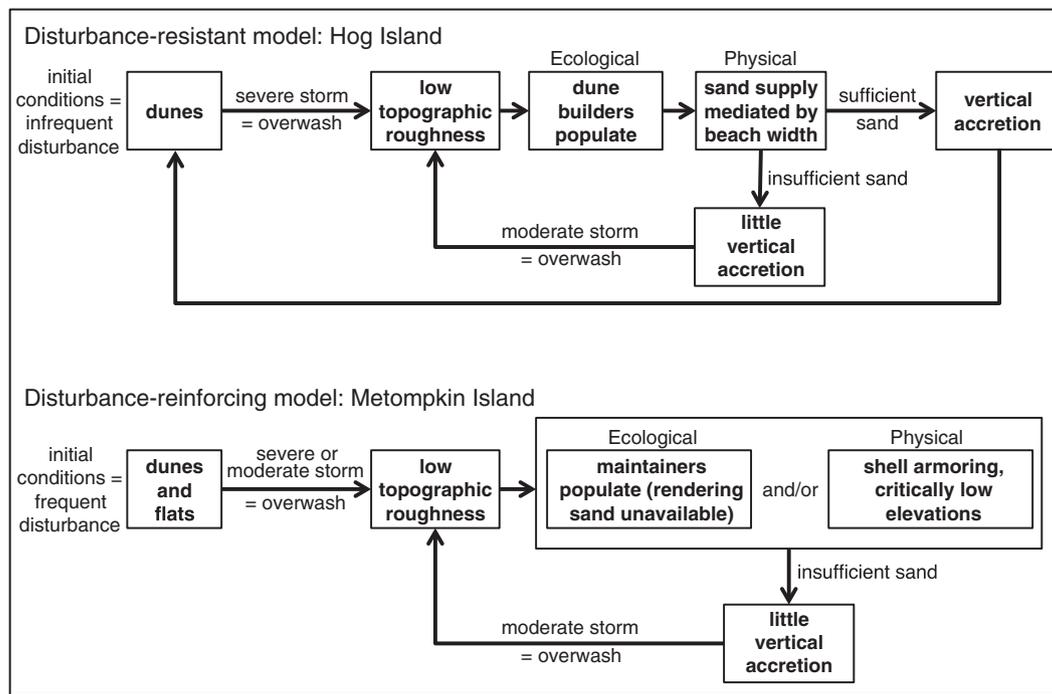


Fig. 16. Ecomorphodynamic conceptual model of barrier island susceptibility and response to overwash, based on results from the VCR. Initial conditions (disturbance regimes) are set by physical factors, such as the rate of relative sea level rise, antecedent geology and topography, supply of sand, wave climate, shoreline orientation, etc. In the bottom panel, insufficient supply of sand is caused by a combination of ecological and physical processes.

recolonization by *A. breviligulata*, except where physical conditions such as beach width (supply of sand) are prohibitive (Fig. 16). Overwash may persist where the beach is narrow and eroding, but where the beach is accreting, overwash recovers into dunes or stable interior environments, depending on distance from the prograding shoreline. The distribution and persistence of overwash on Hog Island does not appear to be a function of the maintainer feedback, but rather of the rotational dynamics of the shoreline and the supply of sand mediated by changes in beach width. As hypothesized, the dune-builder feedback appears to be the dominant ecomorphodynamic process on this island.

Metompkin Island, in contrast, may be classified overall as a disturbance-reinforcing system (although patchy dunes in the southern half of the island resist disturbance locally). Overwash occurs frequently on this low-relief barrier, driving the rapid landward migration of the island (Byrnes and Gingerich, 1987). Spatial and temporal persistence of overwash is considerably greater than on Hog Island. On the northern half of Metompkin Island – where overwash is more widespread and apparently more frequent than on the southern half – the presence of shell armoring and the dominance of *S. patens* may combine to reinforce continued disturbance, resulting in the development of persistent overwash terraces. On the southern half, some recovery may take place in low-lying transitional areas during periods of infrequent disturbance, but shell armoring may ultimately suppress the reestablishment of fully formed dunes. In addition, if overwash incises the island surface to critically low elevations, recovery of vegetation and topography may not be possible. Shell armoring and critically low elevations, thus, may result in the persistence of low, flat topography among the discontinuous dunes in the south.

The distribution and persistence of overwash on Metompkin Island, therefore, appears to be influenced by a combination of interacting physical and ecological factors: frequent disturbance, sedimentological and morphological characteristics, and disturbance-mediating ecomorphodynamic feedbacks. On this island, the dune-builder feedback (south) and the maintainer feedback (north) both appear to contribute to the development and maintenance of morphology,

resulting in vegetation compositions that are sharply distinct between morphologic environments.

Consistent with our hypothesis, the maintainer feedback appears to be more important on Metompkin Island as a whole than on Hog Island, although we emphasize that it is not the primary driver of or sole influence on overwash frequency. Rather, physical factors on Metompkin Island – such as shell armoring, critically low elevations, and initial conditions conducive to frequent disturbance – also play crucial roles in limiting the supply of sand for dune building and reinforcing persistent disturbance (Fig. 16). Maintainer species may have a greater impact in the presence of shell armoring, because these two factors are likely to reinforce the effects of one another (as long as armoring is not extensive enough to entirely suppress the recolonization of vegetation; e.g., Cleary and Hosier, 1979). Armoring may limit available space for recolonization, making the dominance of *S. patens* in those areas in which vegetation can grow even more impactful.

The Virginia Coast Reserve (VCR) can be characterized as an ecomorphodynamically diverse barrier system in which a range of disturbance-mediating conditions exists. In the VCR – as well as in other systems where continuous dune-building grasses and overwash-adapted maintainer species coexist – islands that are high-relief and infrequently disturbed (relative to the time scale of dune recovery) are likely to resist disturbance via the dune-builder feedback, and physical processes are likely to determine where overwash will be persistent. Conversely, on islands that are low-relief and frequently disturbed, the maintainer feedback is likely to be more influential (assuming the frequency of disturbance is not so high that all vegetation is suppressed), with physical and ecological processes controlling the occurrence of persistent overwash. To some extent, these findings are scale-dependent, in that relief and frequency of disturbance are relative concepts; furthermore, the disturbance-mediating models described may be broadly generalizable for a barrier island chain (e.g., Stallins and Parker, 2003) or vary between and even within islands. This must be considered when drawing comparisons to systems outside the VCR, but does not nullify the usefulness of such comparisons. Rather, future work on this subject would benefit from considering a range of scales to further dissect the

conditions governing generalizability versus localization of feedback effects.

Though quantifying the effects of the maintainer feedback is beyond the scope of this study, our findings have significant implications for barrier island evolution under changing climate conditions. As sea level rises and storms become more intense, the frequency of disturbance on barrier islands is likely to increase. Consequently, persistence of overwash may also increase in barrier systems like the VCR, especially if the maintainer feedback becomes progressively more important in reinforcing vulnerability. In combination with physical dynamics, this feedback may have the potential to intensify the response of barrier islands to climate change by accelerating large-scale shifts from dune-dominated to overwash-dominated morphologies (i.e., from the top scenario to the bottom scenario in Fig. 2) as the time needed for dunes to reestablish lengthens beyond the time scale of successive overwash events. Continued investigation of the effects of ecomorphodynamic feedbacks on barrier island evolution – across a range of coastal environments and spatial scales – will be necessary to develop a more quantitative understanding of the rates and conditions under which each feedback is likely to operate, especially as climate conditions change.

5. Conclusions

The Virginia Coast Reserve (VCR) is a morphologically variable mid-Atlantic barrier system in which the dune-building grass *A. breviligulata* and the overwash-adapted “maintainer” species *S. patens* (upright variety) are common. We consider the potential role of an ecomorphodynamic process that we have called the maintainer feedback – whereby frequent disturbance (relative to the time scale of dune recovery) is reinforced by the preferential survival of species that maintain low topographic roughness – in the context of two morphologically distinct islands within the VCR: Hog Island (high-relief, rotating) and Metompkin Island (low-relief, transgressing).

On Hog Island, continuous *A. breviligulata* dunes resist disturbance, except where the beach is narrowest and the shoreline is eroding (i.e., where the supply of sand is limited). Decadally persistent overwash is limited to these conditions; overwash recovers into dunes or stable interior environments where the shoreline is accreting.

On Metompkin Island, overwash is widespread and associated with the maintainer species *S. patens*, shell armoring, and/or exceptionally low elevations relative to the beach (all of which limit the supply of sand). These factors appear to reinforce disturbance, either separately or in combination, resulting in decadally persistent overwash.

Thus, in ecomorphodynamically diverse systems like the VCR, physical processes are likely to control overwash persistence on infrequently disturbed, high-relief islands, whereas both physical and ecological processes may contribute to overwash persistence on more frequently disturbed, low-relief islands. Relief and frequency of disturbance are relative and scale-dependent terms; therefore, we note that although our model can provide insight into other systems, patterns observed elsewhere may be affected by the scale and spectrum of conditions under consideration.

Overwash on barrier islands will likely become more common with the effects of climate change (sea level rise, increased storminess). As a result, the maintainer feedback may become increasingly important in reinforcing frequent disturbance, leading to increased overwash persistence. Although physical factors (e.g., supply of sand, dynamics of the shoreline, antecedent topography) are the central controls on barrier island evolution and response to climate change, the impacts of disturbance-mediating ecomorphodynamic feedbacks should not be overlooked. The maintainer feedback, though not necessarily the primary driver of overwash persistence, nevertheless may have the potential (in concert with physical processes) to catalyze and accelerate large-scale changes in morphology and vulnerability as climate changes and disturbance becomes more common.

Acknowledgments

This research was supported by the U.S. Department of Energy's Office of Science (BER) through the Coastal Center of the National Institute for Climatic Change Research at Tulane University. Additional funding for this work was provided by the Geological Society of America and the Department of Environmental Sciences at the University of Virginia. Access to field sites was made possible by the Virginia Coast Reserve Long-Term Ecological Research (VCR LTER) site, The Nature Conservancy, and U.S. Fish and Wildlife Services. The authors are grateful to Karen McGlathery, Pat Wiberg, and two anonymous reviewers for helpful comments on an earlier version of this manuscript. We also thank Chris Buck and the staff of the Anheuser-Busch Coastal Research Center, as well as Sean Fate and the staff of the Virginia Institute of Marine Science's Eastern Shore Laboratory, for extensive support in the field. We would like to thank the following people for essential field, laboratory, and figure assistance: Meredith Weakley, Owen Brenner, Luke Cole, Jared Austin, James Deemy, Kati Rubis, Sheri Shiflett, Dana Oster, and Nick Brockmeier. The aerial photo and shapefile database (1949–2002) was kindly provided by Michael Wilson and Bryan Watts at the Center for Conservation Biology, College of William and Mary.

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