Topography, vegetation cover and below ground biomass of spatially constrained and unconstrained foredunes in New Jersey, USA

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Abstract

Space for dunes is often limited in developed areas, placing increased importance on human efforts to aid dune-building. This study assesses how different management strategies influence dune topography, surface cover and below ground biomass of vegetation on four dune segments in New Jersey in two successive years. Two segments are evolving without human actions, one with a cover of native vegetation (*Ammophila breviligulata*) and one with an invasive exotic (*Carex kobomugi*). Two segments are in developed areas and are maintained using sand fences, vegetation plantings and bulldozers; one of these segments uses bulldozers to bury a seawall.

The foredunes evolving naturally are wider than foredunes in the developed segments and have more topographic variability alongshore. Foredunes in the developed segments are narrower because sand blown or washed landward is recycled. The naturally evolving *A. breviligulata* dune segment had the sparsest vegetation cover; the segment maintained mainly by sand fences and vegetation plantings had the densest cover. The crest of developed dunes can be higher than the crest of natural dunes with the same vegetation type and similar beach widths, but sediment volume may be restricted if the dune cannot migrate inland. Planting programs hasten dune accretion and are especially valuable on the dune ramp following wave erosion. Species dependent on mobile dunes can be favored where landward infrastructure is not threatened; species dependent on stable dunes can be favored in developed areas. Dune veneers placed over seawalls are temporary, but seawalls can favor evolution of stable-dune species landward of them.

Keywords: developed coast; hybrid structures; managed dunes; shore protection; vegetation

1. Introduction

The coastlines of many countries are developed with buildings and infrastructure that are placed in locations susceptible to flooding and wave erosion. Development continues, even as the physical drivers of coastal change (sea level rise and storm frequency and magnitude) are projected to increase the likelihood of inundation and erosion (Webster et al., 2005; Bindoff et al., 2007; NRC, 2014). Beaches and dunes provide a natural buffer to protect human structures from these hazards. The protection provided by dunes is a function of their size and ability to survive erosion by waves and deflation by wind. The beach provides a buffer against wave attack, a source of sediment to the foredune, and a space for dunes to grow. Dunes play a key role in providing elevation to protect against flooding, but the limited space available for these landforms to build by natural processes in developed areas often restricts their size and longevity, placing increased importance on active management (Jackson and Nordstrom, 2011).

The location, size and stability of dunes can be enhanced using sand-trapping fences and vegetation plantings. These adjustments have a centuries-long history of use and have been subject to many investigations (e.g. Woodhouse, 1967; Schwendiman, 1977; Hotta et al., 1987, 1991; Skarregaard, 1989; Avis, 1995; Mendelssohn et al., 1991; Miller et al., 2001). The increasing need to overcome temporal and spatial constraints to natural dune building has placed emphasis on use of bulldozers to speed dune formation (Wells and McNinch, 1991; McNinch and Wells, 1992) and using hard cores within dunes that are not expected to survive for long (Nordstrom, 2014). These artificially constructed or maintained dunes are subject to reworking by natural processes (Conaway and Wells, 2005; Smyth and Hesp, 2015), leading to interesting nature-human hybrids. Recent emphasis on restoring native species in dunes previously stabilized by exotic species has complicated management decisions by suggesting restoration projects that create more mobile dune landscapes with greater ecological value but less value for protecting human structures (Hilton et al., 2005; Wooton et al., 2005; Walker et al., 2013; Pye et al., 2014; Konlechner et al., 2015).

Our study assesses the way alternative dune-building strategies influence dune morphology and vegetation characteristics by conducting topographic surveys and measuring surface cover, below ground biomass of vegetation, and sediment grain size. Data on these characteristics were gathered on four different dune segments in three jurisdictions on the developed shoreline of the State of New Jersey, USA (Fig. 1) in successive years in the autumn of 2015 and 2016. New Jersey was selected for study because foredunes are an important component of efforts to mitigate wave overwash and flooding there, and bulldozing, fencing and vegetation plantings are all used to maintain the dunes in developed areas. Dunes where sediment delivery is solely by aeolian sediment transport are found in parks and conservation areas.

Storms of different intensity and magnitude can have different levels of impact on beaches and dunes. Runup may be confined to the foreshore; runup may reach the dune and erode (scarp) the seaward portion; runup may overtop the dune (overwash) resulting in landward sediment transport; and storm surge may submerge the beach and dune (Sallenger, 2000). Post-storm management efforts may require totally rebuilding dunes (following the overwash scenario) or aiding recovery of a portion of the dune (such as following dune scarping). In some cases, elimination of the beach may reduce the potential for dune building to the point where the protection must be provided by shore-parallel walls.

The dunes evaluated here are in four shoreline segments that are managed at different levels of intensity. Two segments (both at Island Beach State Park) are evolving with little human action; one of these segments has a cover of native vegetation and one has an invasive exotic.

Two dune segments are managed more intensively. Dune growth and stabilization in one of these segments (Seaside Park) are aided by sand fences and vegetation plantings. Dune growth and stabilization in the other segment (Bay Head) are aided by bulldozing, sand fences and vegetation plantings. A seawall was built in Bay Head to provide additional protection. Dunes in all locations are fronted by sand beaches with a mean size in the range of medium to coarse sand. Previous studies in this region quantified amounts of aeolian transport and topographic changes (Gares, 1990, 1992; Gares and Nordstrom, 1995; Kaplan et al., 2016), and evaluated the vegetation types used for stabilization, with a special emphasis on the invasive species *Carex kobomugi* (Wooten et al., 2005; Charbonneau et al., 2016).

Management of beaches and dunes is governed by state law (N.J.A.C. 7:7E Coastal Zone Management Rules). Coastal management rules apply to natural dunes with no active management, dunes modified to provide a protective barrier or enhance ecosystem function, and dunes engineered according to a federal or state design template. The state Coastal Zone Management Rules encourage communities to manage foredunes as barriers to storm waves and flood inundation. New Jersey law adopted provisions by the US Federal Emergency Management Agency under the National Flood Insurance Program (NFIP) for creation of dunes for shore protection. According to NFIP Regulations, primary frontal dunes are not considered effective barriers to base flood storm surges and associated wave action if the cross-sectional area of the dune perpendicular to the shoreline above the 100-year still-water flood elevation and seaward of the dune crest, is less than 1,100 ft^2 (102 m^2).

Local communities receive a permit from the state to conduct beach and dune maintenance activities. Permitted activities that enhance the protective function of the dune include bulldozing sediment from the lower to the upper beach as part of an emergency post-storm restoration plan, placement and/or repair of sand fencing and planting and fertilizing dune vegetation. The Public Works Department of each municipality generally assumes responsibility for post-storm transfers of sediment to enhance dune recovery and placement of sand trapping fences to increase dune height and width. The Environmental Commission in each municipality is generally responsible for oversight of planting dune vegetation, based on a landscape plan submitted to the state. Vegetation planting should be diverse and limited to species native to the state. Use of American beachgrass (*Ammophila breviligulata*) is recommended for stabilization of foredunes.

2. Study area

Many of the former foredunes in this part of New Jersey were severely eroded by storm waves during Hurricane Sandy in October 2012. The dunes at Island Beach State Park and Seaside Park were scarped by wave erosion seaward of the crest. The dune in the segment at Bay Head that is analyzed in this study (Fig. 2d) was completely eliminated, and bulldozers were used to reconstruct it. Vegetation on all dunes is less dense than before Hurricane Sandy, in part because of the limited time for colonization of the dune ramp that formed seaward of the crest after the storm and because of burial of vegetation on the dune crest by aeolian transport across the beach and ramp.

Island Beach State Park (henceforth called Island Beach) is on a low barrier spit. Sand fences and vegetation plantings are not used to repair breaches in the dune in the northern portion of the park, where this study was conducted (Fig. 2a,b). Blowouts are common, and the dune is subject to considerable mobility through time (Gares and Nordstrom, 1995). The dune is active up to 80-90 m landward of the foredune crest. The nearest human facilities in the area studied here are maintenance buildings 110 m landward of the foredune crest. The most common native vegetation types on the foredune are *A. breviligulata* and *Solidago sempervirens* (seaside goldenrod). *Carex kobomugi* (Asiatic sand sedge) dominates dune vegetation in places. This invasive exotic species was first recorded in the USA just north of Island Beach in 1929, and it has spread through natural processes and human plantings along the coast from Massachusetts to North Carolina (Wooton et al., 2005). Studies at Island Beach have acknowledged the value of *C. kobomugi* for dune stabilization but they also identify the problems it can cause as an exotic (Wooten et al., 2005; Charbonneau et al., 2016). Accordingly, we selected one segment at Island Beach with predominantly *A. breviligulata* cover (Fig. 2a) and one with predominantly *C. kobomugi* cover (Fig. 2b).

Fences are on the seaward side of the dune at Seaside Park (Fig. 2c) and Bay Head (Fig. 2d) to increase sand volume and prevent trampling by visitors and at the sides of walkovers and on the landward side of dunes to control access and prevent sand inundation of nearby infrastructure. An additional fence is on the crest of the dune at Bay Head. The fences have wooden slats, creating a porosity of about 65%. Fences are all linear, except fronting the dune along the middle and northern portions of the segment at Seaside Park, where a zig-zag configuration is used. The fences during this study were about 1.3 m above the ground surface, except for the partially-buried fence fronting the dune at Seaside Park, which was about 0.6 m above the ground surface. The dunes in Seaside Park and Bay Head are artificially planted periodically using *A. breviligulata*. Any sand blown over the dune or washed through gaps at pedestrian access paths is bulldozed back to the beach and dune in both communities.

Seaside Park is on the same low barrier spit as Island Beach and the segment evaluated is 2.5 km north of the northern (*C. kobomugi*) segment at Island Beach. The dune at Seaside Park is backed by a boardwalk and road. The boardwalk was damaged by a storm in March 1962, but subsequent dune-building efforts have resulted in one of the most effective protective dunes in the state. About 10-12 m of retreat of the dune occurred during Hurricane Sandy, but about 18-19 m of dune width remained.

The dune at Bay Head is 20 km north of Island Beach. The site is located on a headland, but the elevation is sufficiently low that dunes are considered important in providing protection from wave inundation. Little sand accumulated at the fences or on the dune segment selected for this study because the site is within an enclave (Fig. 2d) set back between beachfront houses that shelter the dune from sand blown off the beach, especially during the strongest onshore winds that blow oblique to the shoreline (Kaplan et al. 2016). Houses along the shoreline adjacent to the enclave are located between the beach and shorefront road and are protected by a seawall. The seawall was extended alongshore after Hurricane Sandy to seal off the enclave and dune from wave attack. The seawall is periodically exposed by wave action and subsequently covered by aeolian accretion and bulldozing, creating a surface that mimics a natural dune when vegetated.

Activities in dunes in the two developed communities are regulated under Article III of Chapter 135 of the municipal code of Seaside Park and Article II of Chapter 75 of the municipal code of Bay Head. A principal difference in the two codes is recognition of the needs of shorefront residents in Bay Head, where houses are just landward of the beach. Visitor access is prohibited on the dunes in all three jurisdictions, except through demarcated pedestrian access ways. Walkways are located at shore-perpendicular street ends in Seaside Park and are maintained as gaps through the dune. One elevated walkway is allowed for each shorefront residence in Bay Head. Seaside Park has no private residences seaward of the shorefront road and boardwalk, and they have established a municipal dune development district there to build a dune with sand fences and vegetation plantings using municipal resources. Private owners in Bay Head are obliged to install fences and plantings to build up the height of dunes that become lower by natural or human causes. Scraping of the beach above high water to build up the height of the dune is allowed in Bay Head if a municipal permit is obtained. This activity helps maintain a sand veneer over the seawall. Native vegetation is specified in both municipalities, with no distinction made of how plants are introduced. Permitted species include *A. breviligulata*, *S. sempervirens*, and species more common landward of the crest, including *Myrica pensylvanica* (bayberry) and *Rosa rugosa* (Rugosa rose).

Beaches at Seaside Park and Bay Head are raked to remove litter, preventing growth of vegetation and incipient dunes seaward of the sand fences and seawall (respectively). Raking does not occur at Island Beach. The beach at Island Beach was artificially nourished in 1955 (152,000 m^3) and 1962 (45,600 m^3); Seaside Park was nourished in 1963 (103,664 m^3) and 1964 (144,400 m^3); Bay Head was nourished in 1963 (408,880 m^3) (Beach Nourishment Viewer, no date). These operations were sufficiently far in the past for the sediment grain size characteristics to be in equilibrium with local wave conditions.

3. Methods

Field data were gathered along three cross-shore transects on each segment at Island Beach (25 October 2015 and 19 November 2016), Seaside Park (5 October 2015 and 3 December 2016) and Bay Head (25 October 2015 and 11 December 2016). Segments at Island Beach are bounded by gaps at blowouts. Segments in the two developed municipalities are bounded by pedestrian access ways or, in one case at Bay Head, by a house built within the dune to the north (Fig. 2d). The center transect was selected by finding the middle of the segment by pacing from the two segment ends. The other two transects were located half way between the center transect and the segment ends. Topography was measured at breaks in slope, from the foreshore to a position landward of the foredune crest using a Leica NRTK-GPS system. The landward distances at Seaside Park and Bay Head were the boardwalk and shorefront roads. The dune at Island Beach extended far landward but was only surveyed to a distance similar to the two developed sites.

Sampling for vegetation cover, fine root mass and grain size characteristics was conducted at four cross shore subenvironments within the dune (Fig 3), including the lower dune ramp (just landward of sand fences, where present at Seaside Park and Bay Head), upper dune ramp, middle of foredune slope, and dune crest. All variables were measured in 2015. Topography and vegetation cover were sampled again in 2016. We conducted the study in late autumn to represent vegetation conditions close to the time when storm frequency and magnitude increase. Vegetation density would be even less in the winter, when change by aeolian processes would be more conspicuous, but we expect the relative differences between segments to be similar in autumn and winter.

Percent vegetation cover was estimated within three 1x1 m quadrats spaced at distances of 2 m alongshore at each sampling location in the dune (36 quadrats per segment). Photographic images of each quadrat were taken using a handheld digital camera (SONY 5100, 25 megapixels). Images were imported to Adobe Photoshop CS6 extended version 13.0 (Adobe Systems, Mountain View, CA) to estimate vegetation cover. Images were cropped along the quadrat frame and edited to eliminate shell hash and pebble lag and contrast vegetation from sand surface. Ratio of number of pixels representing vegetation to total number of image pixels was used to estimate vegetation cover. Differences in vegetation cover at the four segments were analyzed using two-factor ANOVA (Minitab 17). Data on vegetation cover were normalized using a log base 10 transform prior to analysis.

Information on roots was obtained using a 50 mm-diameter bulk corer. We analyzed fine roots (<2 mm in diameter), not rhizomes. Fine root biomass is concentrated within the top 0.10-0.20 m of the dune surface (Stevenson and Day 1996). Our cores were inserted to a depth of 0.30 m. Sample volumes were 589 cm^3. The corer was randomly inserted within 1 m of the designated center of the sampling location in each subenvironment along each transect (12 cores per segment). Core sediment samples were sealed in air-tight containers and analyzed for root characteristics. Core samples were dried; roots were then sieved from sediment, weighed and analyzed using WinRHIZO Pro 2004b software (Meng-Ben and Qiang 2009) to obtain values for total root length. Sand from the core taken at each subenvironment along the middle transect of each segment (4 cores per segment) in 2015 was washed, dried and sieved at 0.25 ϕ intervals and analyzed using graphic measures (Folk, 1974) to determine mean grain size (m_z) and sorting (σ_I).

4. Results

4.1 Topography

The foredune in the two segments at Island Beach (Figs. 4a,b) is wider than the dunes in the two developed segments and has the greatest topographic variability alongshore. The dune crest of the segment colonized by *C. kobomugi* is about 1.0 m higher and more peaked than the crest of the segment colonized by *A. breviligulata* and was subject to less geomorphic change between 2015 and 2016. Accretion occurred on the upper ramp on the *C. kobomugi* site over that annual interval, while the dune slope on the *A. breviligulata* site, which was poorly vegetated, had a net loss.

The crest of the managed dune at Seaside Park (Fig. 4c) is higher than the crest at the naturally-evolving *A. breviligulata* segment at Island Beach. The dune at Seaside Park has less volume than the unmanaged dunes at Island Beach because accretion on the landward side is eliminated by cleanup operations on the boardwalk and street. The dune ramp at Seaside Park is more prominent (higher and wider) than at Island Beach, especially in 2016, because the sand fence and vegetation plantings enhance accretion at that location (Fig. 5).

The bulldozed dunes at Bay Head (Fig. 4d) form two ridges that are lower than the crests at Island Beach and Seaside Park. The landward ridge is about as far from the berm crest as the foredunes at Island Beach and Seaside Park and would be well placed to survive annual storms. This ridge has undergone little change because wave action and aeolian accretion are prevented by the seawall and fences seaward of it. The bulk of the seaward ridge is a seawall covered by a veneer of sand bulldozed from the beach. The seaward side of the seawall was exposed in the 2015 survey but not in the 2016 survey, which was conducted after sediment was artificially placed over the seawall. No feature with a shape similar to the dune ramp exists on the seaward bulldozed ridge.

4.2 Sediment characteristics

Sediment grain size on the New Jersey beaches decreases from north to south (McMaster 1954). Sediment on the dune in Bay Head is the coarsest of the segments and the least well sorted (Table 1). These characteristics may be a function of creation by bulldozing rather than accretion by aeolian processes from a coarser source on the beach. The coarser, more poorly sorted sediment in Bay Head may make the dune surface somewhat less susceptible to accretion and deflation, contributing to the greater stability of the landward ridge (Fig. 4). Sediment differs less between the other three segments than between those three segments and Bay Head, presumably because of the proximity of Seaside Park to Island Beach. Sediment is coarser on the upper ramp of both Island Beach sites (and the mid slope of the *C. kobomugi* site), which were poorly vegetated in 2015 (Fig. 6) and thus subject to deflation.

4.3 Vegetation characteristics

Two-factor ANOVA revealed a significant difference in mean vegetation cover between segments and sub-environments and their interaction in 2015 [$F(9,128) = 3.62$, $p<0.001$] and 2016 [$F(9,128) = 5.43$, $p<0.001$]. The dune crest at the *C. kobomugi* segment at Island Beach had conspicuously more vegetation cover than the *A. breviligulata* segment in 2015 (solid bars in Fig. 6). *C. kobomugi* forms a dense root mat with a high blade density (Wooton et al., 2005), which is part of the reason for the more extensive cover. Cover at Island Beach and Seaside Park was greater on the dune crest than at other subenvironments. The relatively dense *C. kobomugi* cover on the crest in 2016 had the least amount of variation alongshore in any subenvironment in any segment (coefficient of variation in Fig. 6). The greater vegetation cover on the mid slope and upper ramp on the *C. kobomugi* segment in 2016 may be related to the lack of erosion at those locations and stability of the crest (Fig. 4), whereas deflation occurred on the mid slope of the *A. breviligulata* segment, with deposition on the crest.

The crest at Island Beach and Seaside Park was the only subenvironment unaffected by Hurricane Sandy, so the greater cover in 2015 and 2016 could be partly a function of the longevity of the plants. Cover may have been greater on the mid dune slope at the two developed segments than at Island Beach in 2015 because of greater stability of the dune due to deployment of sand fences. The total amount of vegetation cover was limited at all segments in 2015 but was greatest across the dune profile at Seaside Park, where greater attention had been placed on dune management in the past in fencing and planting programs.

Cover increased considerably at all sampling locations by 2016 ($t= 2.66$, $p=0.018$) (open bars in Fig. 6), except on the lower ramp at Seaside Park and Bay Head and on all locations on the *A. breviligulata* segment at Island Beach, which is the only segment evolving by natural processes unaffected by exotic vegetation. A conspicuous increase in vegetation cover occurred at all sampling locations in the *C. kobomugi* segment, where growth was unaided by human efforts. The greatest increase in total vegetation cover was at Seaside Park, with the greatest increase on the upper ramp, which was freshly planted prior to the 2016 survey (Fig. 5). The increase in the vegetation cover on the dune crest and mid slope at Bay Head was also due to planting just prior to the 2016 survey.

Root mass was higher at the dune crest in all segments (Table 2), reflecting the vigor of actively growing vegetation there. The *A. breviligulata* segment at Island Beach had the lowest root mass across all subenvironments. The *A. breviligulata* segment at Island Beach was the only segment where root length on the ramp was greater than at the crest. The greater length relative to the *C. kobomugi* segment and Bay Head could be related to the greater amount of surface cover revealed in the data for 2015 in Fig. 6. Seaside Park had the greatest percent surface cover on the ramp, and the upper ramp there had the greatest average root length. The dune crest at Seaside Park had far greater root mass than any other subenvironnment in any other segment, whereas the crest at Bay Head had far greater root length (Table 2). Both of these segments were artificially vegetated prior to sampling.

5. Discussion

5.1 Management implications at the study sites

Increases in human development of the shoreline and decreases in the amount of natural habitat make management decisions difficult where space is restricted. Options for developed areas will differ from natural areas because of these spatial considerations, but human actions can overcome some of the spatial constraints (Nordstrom et al., 2002). The foredune at both segments at Island Beach is wider than the foredune at the two developed segments because it is not truncated by infrastructure on the landward side. Sediment delivered landward of the crest at the two developed sites is mechanically moved back to the beach and dune, and the culturally prescribed landward limit prevents accretion by either natural or human processes on that side. Plantings at Seaside Park appear to have contributed to the density of the *A. breviligulata* there, increasing the potential to build up the height of the dune. The thin vegetation cover on the crest on the *A. breviligulata* segment at Island Beach and the lack of fences may allow greater amounts of sediment to pass over the crest and be deposited on the landward side, maintaining or increasing the volume of sediment within the dune field.

The limited vegetation cover and greater dynamism of the crest of the *A. breviligulata* segment at Island Beach than the crest at the other sites is not a management concern. The dune in this portion of the state park is allowed to undergo natural changes because human facilities are not immediately threatened. It has been speculated that dunes invaded by *C. kobomugi* may be lower because this species grows lower to the surface than *A. breviligulata* (Shisler et al. 1987 in Burkitt and Wooton 2011). *C. kobomugi* can be 0.15 – 0.30 m tall, whereas *A. breviligulata* often is taller than 1 m (Wooton et al. 2005). We cannot specify cause-effect on dune growth. It is not clear whether trapping by the *C. kobomugi* or a previous cover of *A. breviligulata* contributed to past evolution of the higher, more-peaked crest in that segment, but the denser cover of *C. kobomugi* that now occurs across the ramp and crest appears to have made the crest more stable.

Beach widths are similar at Seaside Park and Island Beach, and the seaward portion of the foredune is at about the same distance from the berm crest, indicating that the seaward sand fence and vegetation plantings at Seaside Park (Fig. 5) are well placed to favor accretion at a location in equilibrium with natural processes. There is no need to place sand fences farther out on the beach, where incipient dunes are almost certain to be eliminated by small storms. Sediment can be stored landward, where vegetation can colonize the deposits and remain in place to grow and increase dune resistance to deflation and wave runup.

Rodgers (2002) found that dunes modified by humans had less vegetation cover than natural dunes. The greater vegetation cover at Seaside Park, primarily by the native stabilizing species (*A. breviligulata*), is attributed to the proactive planting program. Visitor access to dunes is controlled at all segments (by posted signs at Island Beach, by sand fences and posted signs at Seaside Park and by sand fences at Bay Head). These controls greatly reduce the issue of trampling that damages vegetation cover. In a sense, the *C. kobomugi* segment is a human-modified dune, albeit unintentionally through introduction of an exotic species. The least human-modified dune (the *A. breviligulata* segment at Island Beach) had the least vegetation cover. Proactive planting programs can be effective in building and maintaining vegetation cover, but there is only a need for planting programs where dune stability is a key element in shore protection. *C. kobomugi* can reduce the abundance of many native plants significantly, so removal of that species would be desirable, as suggested by Wooton et al., (2005). The dune in the *C. kobomugi* segment at Island Beach is not required for shore protection, so any initial increased mobility associated with *C. kobomugi* removal should not be an issue. Allowing dunes in parks and reserves to be mobile becomes important in maintaining conditions for species dependent on active dunes as an ever-increasing number of dunes in developed areas are being stabilized (Pye et al., 2014). This consideration supports the management decision to restrict the use of fences to repair gaps in the dune at Island Beach.

Wave erosion of the bulldozed dune cover placed seaward of the seawall at Bay Head in 2015 indicates that the sediment placed there is too close to the active foreshore to survive wave attack by moderate storms. Pye and Blott (2016) found that significant dune erosion occurred where the upper beach was <25 m wide. The upper beach at Bay Head was less than this distance, even in the 2016 survey, when beach widths were wide in the other segments. The buried seawall provides protection against wave runup farther landward. Coastal vegetation under natural conditions is strongly related to zonation related to processes across the sea-land gradient as modified by erosion rates and frequency of wave inundation, but the characteristics of vegetation can be altered by human-induced changes (Moreno-Casasola, 1986; Roman and Nordstrom, 1988; Rodgers, 2002; Acosta et al., 2007). The protection provided by the seawall allows the bulldozed sand just landward of the seawall to become vegetated in a position closer to the water than would occur under natural conditions. The seaward side of the ridge is more dynamic and lacks the ramp and the characteristic morphology and vegetation found in that subenvironment at the other three segments.

The crest and mid slope of the landward dune ridge (the former foredune) at Bay Head are no longer as dynamic as the foredune at the other three segments. This landward ridge is no longer required to provide protection against wave erosion and overwash, but it can have nature value. Dunes in developed areas that are truncated by human infrastructure may lack the natural diversity found in the more stable backdune areas in natural systems (Nordstrom et al., 2011). The isolation of the landward ridge provides the opportunity for colonization by species more acclimated to stable, sheltered conditions, such as *Myrica pensylvanica* (Bayberry) and *Prunus maritima* (Beach plum). *Ammophila* degenerates when sand deposition diminishes (van der Putten, 1990; van der Putten and Peters, 1995; van der Laan et al., 1997), so backdune species may be a better choice than the recently planted *A. breviligulata*. Maintaining the fences at Bay Head may not be necessary, given the lack of mobility of the dune. If control of human trampling is the issue, not control of blowing sand, sand-trapping fences could be replaced by symbolic fences to reduce adverse impact on biota and increase aesthetic appeal (Grafals-Soto and Nordstrom 2009.

We made no attempt to core directly over dense vegetation, so our data cannot be compared with Charbonneau et al. (2016) who targeted ramets for coring. Nevertheless, our data indicating that *C. kobomugi* had greater biomass than *A. breviligulata* is in accordance with their findings, and lends support their conclusion that *C. kobomugi* may provide greater resistance to erosion. The high blade density and dense network of subsurface rhizomes and deep root system may make *C. kobomugi* an effective dune stabilizer, but as an invasive, it can reduce native diversity and potential resilience of the dune (Wootton et al. 2005; Burkitt and Wooton 2011). The New Jersey Department of Environmental Protection has already initiated a management strategy to eradicate this species (Wootton et al. 2005). The *C. kobomugi* cover is of questionable value in a portion of the state park where human resources are not threatened. *C. kobomugi* appears unnecessary in developed areas as well because changes at Seaside Park indicate that a high dune crest and accreting seaward slope can be built and maintained by planting the native *A. breviligulata* and deploying sand fences.

Few studies have dealt with spatial differences in root mass across the coastal dune gradient, but this variable is expected to vary across the shore (Imbert and Houle 2001). Greater root mass would be expected with landward distance because the greater dynamism on the seaward side would decrease the number of species and vigor of vegetation. Greater root mass was found on the dune crest, likely due to the longevity of plants there and the limited accretion of fresh sand yet to be colonized by vegetation. Sand that accumulates in the fall and winter, when plant growth is not active, is expected to yield few new roots (Imbert and Houle 2001) and reduce the ratio of old roots to the volume of sediment sampled. The artificial planting of the upper ramp at Seaside Park does not have the root mass that could be expected after several growing seasons but it exceeds the unplanted subenvironments seaward of the crest at all sites.

5.2 Management implications relative to spatial constraints

Table 3 presents management suggestions for dune building that are related to spatial constraints as manifested at the sites monitored here. Locations where space is unrestricted and management as natural preserves is possible are represented by the two Island Beach sites. Space is restricted at Seaside Park and minimal at the seaward dune ridge at Bay Head. The general concepts in Table 3 reflect conditions in these four study segments but can be interpreted as representative of dune environments elsewhere.

Foredunes not truncated by infrastructure on the landward side can have free interplay of natural processes and have value for maintaining natural diversity and providing opportunities for ecotourism. These locations should be managed to function naturally without human actions, except for replacement of exotic species with native species or elimination of human structures that no longer serve their original purpose. Protection of buildings and infrastructure is of overriding concern in developed areas, so increasing height and volume of the dunes is critical. Dunes in developed areas have additional value in providing a natural image and supplementing some of the advantages of nature preserves, including providing migration corridors and refuge areas for wildlife. Dunes also serve as reminders of the natural heritage that is often lost in the development process. The most naturally-compatible option in developed areas is to use native species to trap wind-blown sand and help stabilize the dune, but fences and bulldozing may be required to build an initial dune core more rapidly. Hard protection structures may be required where space is minimal, but a temporary sand cover mechanically emplaced over the structures can restore the appearance and some of the functions of a natural environment, such as maintaining habitat for invertebrates. Hard structures ensure stability landward of them and provide the opportunity for maintaining backdune species. Allowing natural processes to prevail is critical in maintaining natural gradients and diversity, so active attempts to manage sediment transfers should be restricted where possible. Bulldozers do not seem appropriate in natural areas but may be required in developed areas to repair storm-created breaches in dunes and cover exposed seawalls and bulkheads.

6. Conclusions

- The crest of a foredune can have greater density of vegetation than seaward portions of the dune because of its greater likelihood of survival during storms.
- Fencing and planting programs to hasten dune accretion and vegetation growth may be especially valuable on the dune ramp, which is a locus of accretion following wave erosion of the seaward portion of the dune.
- Dunes in natural areas that are unfettered by spatial constraints can be wider and have greater volume than dunes in developed areas that are truncated on the landward side by buildings and infrastructure.
- The crest of dunes in developed areas can be higher than the crest of natural dunes with the same dominant vegetation type and with similar beach widths, but the volume of the dune may be restricted if the dune is not allowed to migrate.
- Segments with foredunes built by bulldozing and sand fences can have a more consistent crest profile with distance alongshore than the crest in segments allowed to evolve by natural processes and native vegetation.

- Mobility of dunes and crest irregularities need not be a concern where dunes are not required for shore protection.
- Increased opportunity exists for favoring species dependent on mobile dunes in natural areas and favoring species dependent on stable dunes in developed areas.
- Seawalls can favor stable-dune species landward of them.
- Dune veneers can be placed over seawalls to mimic natural landforms and supplement natural habitat.
- Increases in human development of the shorefront and decreases in the amount of natural habitat make management decisions difficult where space is restricted, but restoration and use options can be tailored to fit these constraints.

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Table 1. Sediment characteristics of the four study segments in 2015.

Segment	Location	Mean (mm)	Sorting (ϕ)
Island Beach *A. breviligulata*	Dune Crest	0.36	0.41
	Mid Slope	0.36	0.41
	Upper Ramp	0.47	0.61
	Lower Ramp	0.37	0.44
Island Beach *C. kobomugi*	Dune Crest	0.38	0.41
	Mid Slope	0.44	0.46
	Upper Ramp	0.46	0.49
	Lower Ramp	0.43	0.53
Seaside Park	Dune Crest	0.41	0.46
	Mid Slope	0.42	0.50
	Upper Ramp	0.40	0.36
	Lower Ramp	0.40	0.38
Bay Head	Dune Crest	0.58	0.63
	Mid Slope	0.57	0.54
	Upper Ramp	0.63	0.54
	Lower Ramp	0.68	0.60

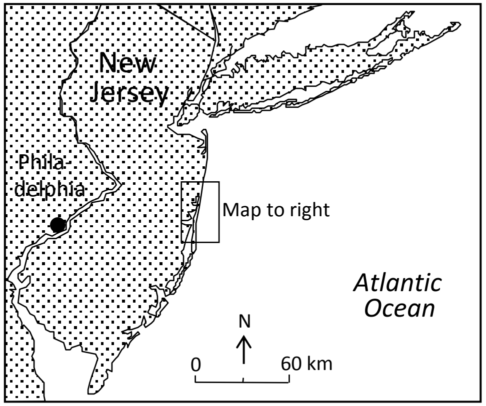
Table 2. Mean and standard deviation (s) of fine root mass and length from (volume) replicate sediment cores (n=3) across the foredune in 2015. Sample volumes were 589 cm^3.

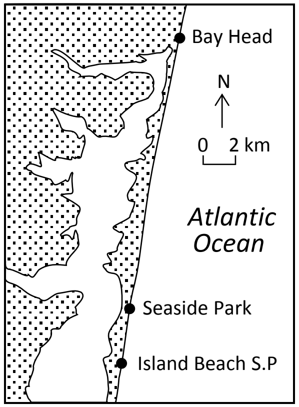
		Mass (g)		Length (mm)	
		mean	s	mean	s
Island Beach	Dune crest	0.026	0.04	15.97	14.6
A. breviligulata	Mid slope	0.003	0.00	3.09	5.4
	Upper ramp	0.004	0.00	29.65	24.9
	Lower ramp	0.010	0.00	56.60	19.7
Island Beach	Dune crest	0.074	0.05	135.55	165.2
C. kobomugi	Mid slope	0.020	0.02	68.63	85.9
	Upper ramp	0.041	0.07	7.67	13.3
	Lower ramp	0.009	0.02	6.64	9.0
Seaside Park	Dune crest	0.382	0.36	107.13	120.9
	Mid slope	0.021	0.02	134.42	163.5
	Upper ramp	0.068	0.10	86.66	86.3
	Lower ramp	0.000	0.00	0.67	1.2
Bay Head	Dune crest	0.040	0.03	550.70	266.4
	Mid slope	0.010	0.00	190.27	126.9
	Upper ramp	0.000	0.00	0.00	0.00
	Lower ramp	0.004	0.00	43.94	68.8

Table 3. Management suggestions for dune building on developed shores related to spatial constraints.

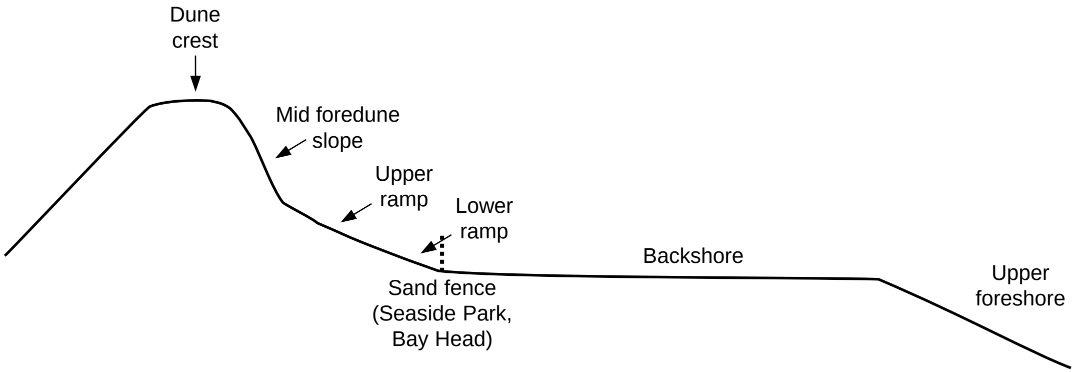
	Availability of space		
	Unlimited	**Restricted**	**Minimal**
Use value of dune	Habitat; nature protection; ecotourism.	Shore protection; natural image; supplemental habitat	Restore/retain natural appearance
Compatible options	Preserve and protect natural dune processes and forms	Enhance dune formation by human actions	Supplemental dunes with structures; use landward space for stable habitat
Ecological benefits	Natural gradients and diversity; maintenance of seed banks	Maintenance of corridors; seed banks	Protection of backdune species
Vegetation actions	Eliminate exotics, restore natives	Institute regular planting programs	Favor backdune species landward of structures.
Sediment management	Allow free interplay of processes	Build predictable dune height and volume with environmentally compatible methods.	Retain natural cover over structures.
Fencing actions	Use only signs or symbolic fences if visitor trampling is an issue	Sand trapping fences just seaward of dune	Sand trapping fences to control loose bulldozed sand
Bulldozing actions	None	Repair storm-created breaches and return overwashed sand	Cover hard structures for aesthetics and for protection against-storm wave runup

List of figures

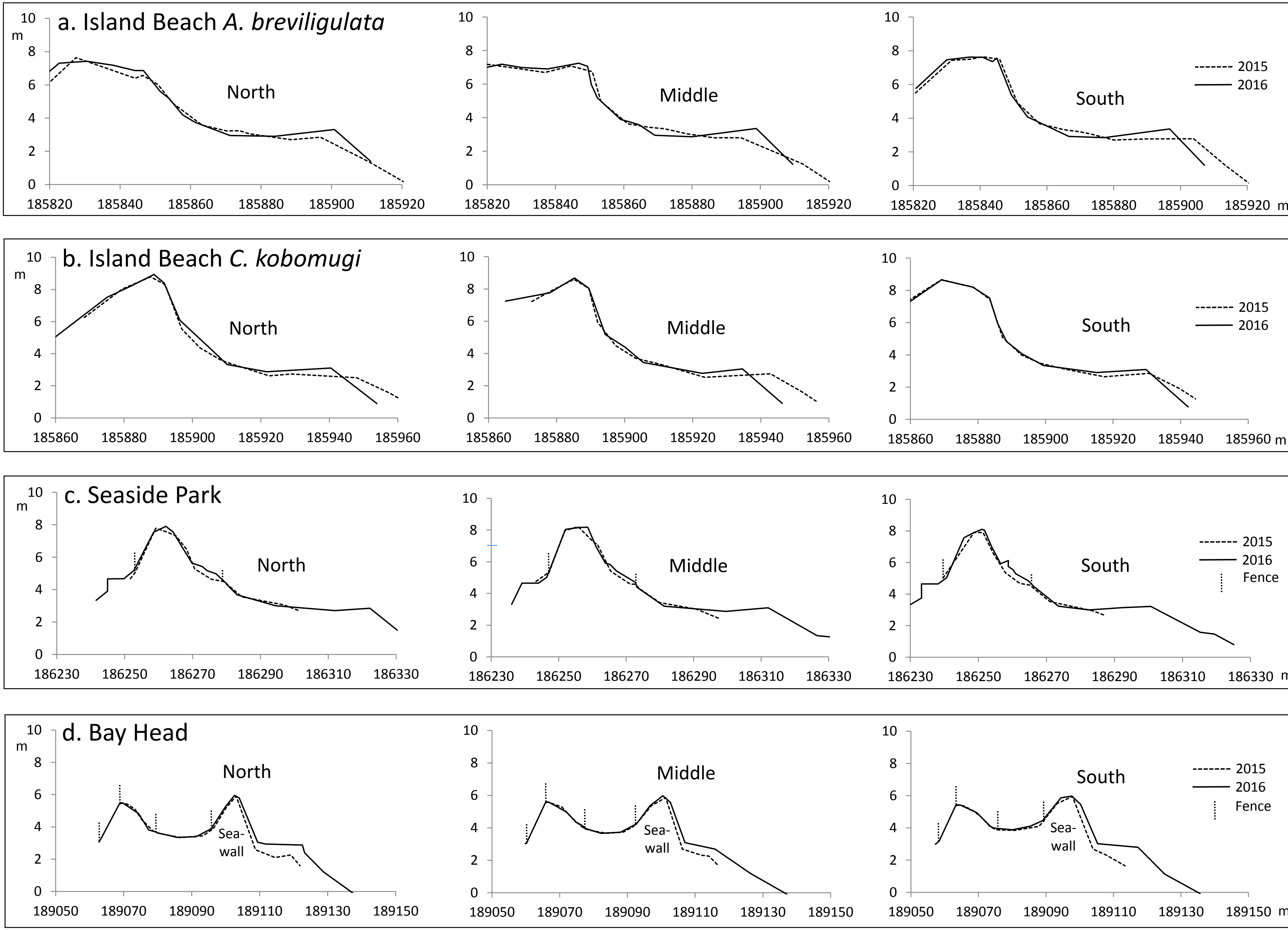

New
Jersey
Phila-
delphia
Map to right
Atlantic
Ocean
N
0
60 km


Bay Head
N
0
2 km
Atlantic
Ocean
Seaside Park
Island Beach S.P

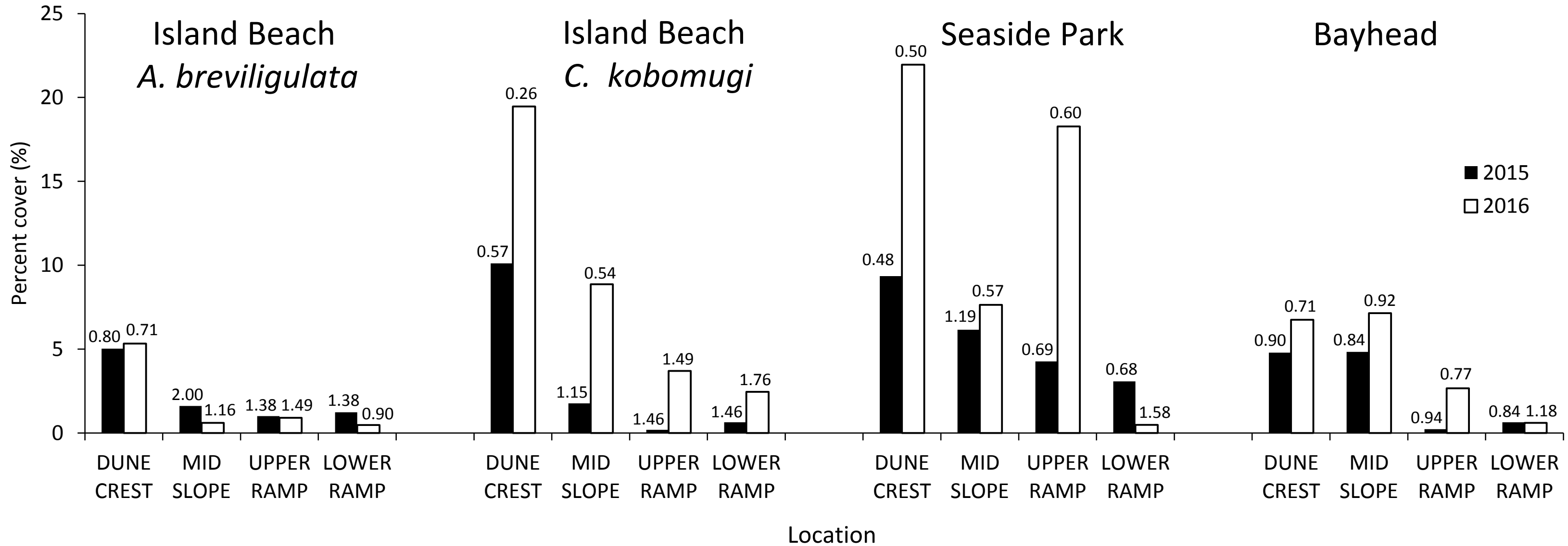

a. Island Beach (*Ammophila*)
b. Island Beach (*Carex*)
c. Seaside Park
d. Bay Head



Dune
crest
Mid foredune
slope
Upper
ramp
Lower
ramp
Backshore
Upper
foreshore
Sand fence
(Seaside Park,
Bay Head)



a. Island Beach *A. breviligulata*
North
Middle
South
b. Island Beach *C. kobomugi*
North
Middle
South
c. Seaside Park
North
Middle
South
d. Bay Head
North
Middle
South
Sea-wall
2015
2016
Fence
m



Island Beach
A. breviligulata
Island Beach
C. kobomugi
Seaside Park
Bayhead
2015
2016
Percent cover (%)
25
20
15
10
5
0
0.80 0.71
2.00 1.16
1.38 1.49
1.38 0.90
0.57 0.26
1.15 0.54
1.46 1.49
1.46 1.76
0.48 0.50
1.19 0.57
0.69 0.60
0.68 1.58
0.90 0.71
0.84 0.92
0.94 0.77
0.84 1.18
DUNE CREST
MID SLOPE
UPPER RAMP
LOWER RAMP
Location