

Effects of sand fences on coastal dune vegetation distribution

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ABSTRACT

Sand fences are important human adjustments modifying the morphology of developed shores. The effects of sand fences on sediment transport and deposition in their initial stages have been well studied, but little is known about the effect of deteriorated sand fences that have become partially buried low scale barriers within the dune, potentially benefiting vegetation growth by protecting it from onshore stress. Data on vegetation, topography and fence characteristics were gathered at three dune sites in Ocean City, New Jersey on September 2007 and March 2008 to evaluate the effect of fences within the dune on vegetation distribution. Variables include: distance landward of dune toe, degree of sheltering from onshore stressors, net change in surface elevation (deposition or erosion), vegetation diversity and density, presence of remnant fence, and distance landward of fence. Results for the studied environment reveal that 1) vegetation diversity or density does not increase near remnant fences because most remnants are lower than average vegetation height and can not provide shelter; but 2) vegetation distribution is related to topographic variables, such as degree of sheltering, that are most likely the result of sand accretion caused by fence deployment. Fence deployment that prioritizes the creation of topographically diverse dunes within a restricted space may increase the diversity and density of the vegetation, and the resilience and value of developed dunes. Managers should consider the benefits of using sand fences on appropriately wide beaches to create a protective dune that is also diverse, functional and better able to adapt to change.

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1. Introduction

Sand fences are important shore-parallel human adjustments modifying the geomorphology of developed coasts because in many locations they are permitted seaward of the dune crest; they are inexpensive, easy to emplace; and are commonly deployed on the dynamic boundary between beach and dune (Nordstrom, 2000). They contribute to dune formation by concentrating sediment deposition just downwind of the fence and are useful in controlling wind-blown sand, preventing the inundation of cultural features (Gares, 1990; Sherman and Nordstrom, 1994; Nordstrom, 2000). Use of sand fences is documented as early as the 15th Century in Europe (van der Laan et al., 1997), and they are presently deployed in many parts of the world (Hotta et al., 1987, 1991; Gómez-Pina et al., 2002; Bouaziz, et al. 2003). Sand fences' frequent occurrence on human-altered coasts requires their incorporation into prototype field investigations (Nordstrom et al., 2007b).

The geomorphic and engineering purposes of sand fences are well studied (e.g. Snyder and Pinet, 1981; Hotta et al., 1987, 1991; Mendelsohn et al., 1991; Miller et al., 2001). Many of these studies have evaluated the initial stages of sand fences and their effect on sediment transport and deposition. Nevertheless, little is known about

the effect of deteriorated sand fences that have become remnants within the vegetated dune. Fences within the dune are small-scale boundaries that influence rates of sand transport and create distinctive patterns of vegetation justifying more intensive study of their effects (Nordstrom et al., 2007a). The objectives of this study are (1) to characterize the distribution of vegetation density and diversity and relate it to sand fence presence within the dune and to the topographic characteristics of fence-created dunes; and (2) to identify the management implications of using sand fences to create dunes on vegetation distribution.

1.1. Sand fences, dunes and vegetation on developed coasts

Intense coastal development has resulted in the widespread modification of sandy ecosystems (Defeo et al., 2009). Developed coasts are often intensively built with narrow beaches truncated on the landward side by buildings, roads and shore-protection structures, limiting the space for dunes to form, evolve and survive (Nordstrom et al., 2000, 2006). Beach nourishment is often used to create a wider beach to reduce threats of building overwash and for recreation. Cleaning operations to improve the appearance of the beach for recreational use or to increase ease of access prevent natural dune growth on nourished beaches (Nordstrom, 2000).

The location of coastal foredunes landward of the beach and seaward of most human development has made these landforms subject to considerable human modification (Nordstrom and Arens, 1998). In

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some places, coastal dunes are artificially recreated using sand fences or vegetation plantings where the original dune features were eliminated. Dunes that are intentionally created by artificial means, hereafter developed dunes, are usually built for shore protection and provide specific utility functions of human needs (Nordstrom, 2000). Developed dunes are in fact much more common on many coastal areas than natural dunes, for example the U.S. east coast (Martinez et al., 2004), justifying the need to emphasize their importance in scientific studies. Developed dunes are usually small relative to natural dunes because landward growth is restricted by the presence of shorefront houses or hotels on their landward side, and seaward growth is prevented by frequent wave attack or mechanical beach cleaning (Nordstrom et al., 2000). The location of human structures determines the spatial distribution of the sand accumulations that leads to dune formation, whether the sediment is moved by humans or is trapped by sand fences.

Sand fences are common features of foredunes in developed coastal areas because they are intentionally used to build or stabilize dunes (Nordstrom et al., 2007b). In the USA, sand fences, also known as snow fences, commonly have an initial height of 1.2 m and porosity of 50% (Mendelssohn et al., 1991), which is the most effective porosity for sand trapping (Hotta et al., 1987) (Fig. 1). During the initial stages of the dune building process, sand fences are located at the high sediment transport backshore where they increase the rate of sand accumulation (Miller et al., 2001; Nordstrom et al., 2007b), causing deposition at a higher rate than any dune vegetation species. Sand fences cause accumulation of sediment just landward of the fence (creating a slope) and affect sediment transport and elevation change at locations farther downwind because the sediment deposition to their lee is not moved to those locations (Gares, 1990). Because sand fences determine the rates of deposition in different locations within the dune, changes in elevation and topography on dunes created with fences mainly depend on fence deployment.

The distribution of sand accumulation and the development of dune topography through the use of fences is a function of fence porosity, fence configuration, separation distance between fence rows, fence height, single or double fence row deployment, wind speed, and sand characteristics. Fence porosity determines the steepness of the slope, fence configuration (ie. straight or zig zag) defines the development and shape of the dune ridges (ie. straight or undulatory), and fence height controls the distribution of greatest sand entrapment landward of the fence (Snyder and Pinet, 1981; CERC, 1984; Hotta et al., 1991). Double fence rows create dunes with broad bases and are more efficient in trapping sand during strong winds than single fence rows. Double fence rows with separations up to four times their height have a tendency to collect greater sand volume than fences located farther apart (Hotta et al., 1991). If significant wind blown sand occurs, sand fences become buried after a sufficiently long time (Hotta et al., 1987).



Fig. 1. Common initial sand fence deployment for dune building purposes, New Jersey.

Sand fences will remain partially exposed and become remnants if their location in relation to the dune toe changes to a less active landward zone, which may happen if a new fence is deployed seaward, or if multiple fence rows are deployed simultaneously. Partially visible remnant fences have lower exposed heights than new fences. Lower height allows for sediment transport and deposition to occur farther landward in the dune (Hotta et al., 1991). Remnant fences have higher porosities than when initially deployed because many of the slats are weathered or missing (Nordstrom et al., 2007b). Sediment transport decreases landward of the dune toe at remnant fence locations limiting the amounts of sediment available for the fences to entrain.

Fences within the dune are small-scale boundaries that create distinctive vegetation patterns (Nordstrom et al., 2007a). They are present within dune vegetation (Fig. 2), at a variety of dune zones where different kinds and levels of onshore stresses occur (Table 1). Sediment transport is one of the primary stresses controlling dune vegetation types and the structure of plant communities because it has direct mechanical effects on erosion and burial (Moreno-Casasola, 1986; McLachlan, 1990). Burial in sand alters all aspects of the plant and the soil micro environment including soil temperature, soil moisture, bulk density, nutrient status, soil pH and oxygen levels (Maun, 2004). Exposure to salt spray hampers sapling establishment and growth (Remke and Blindlow, 2011). Exposure to high wind speeds leads to reduced leaf growth due to shaking, leaf damage due to collision with other plants, increased transpiration rates and water loss, and leaf tip burning (Hesp, 1991).

Exposure to onshore stress is reduced with distance from the shoreline (as topographic sheltering increases landward), being highest at the backshore and crests and lowest at the swale and backdune (Wilson and Sykes, 1999; Maun, 2009). As a consequence, different cross-shore habitats develop within the topography, eventually leading to the establishment of ecologically distinct zones that respond to different levels of stress (Table 1) and represent different stages in succession. These dune zones are discrete and occur in parallel series with species composition related to the ability of each species to withstand the environmental factors prevailing in that zone (Doing, 1985). Highest dune vegetation diversity occurs on the low, sheltered swales and backdunes, which have a more stable morphology (Miller et al., 2001). Plant density gradually increases in each zone with distance from the shoreline (Abuodha et al., 2003) as stress decreases and nutrients increase.

The existence of dune zones that are sheltered or exposed to onshore stress depends on topographic variability. Sheltered zones are protected against onshore stress by topographic barriers such as the seaward ridge. Sand fences are additional barriers that may shelter



Fig. 2. Remnant fence located landward of the foredune crest at the swale, New Jersey.

Table 1

Description of vegetation zones corresponding to dune succession stages and stress in a natural dune complex in New Jersey (Martin, 1959).

Vegetation community	Dune zone	Stresses	Species
Dunegrass	Seaward slope, crest and backslope of primary foredune or seaward ridge	High exposure to windborne salt spray and sediment transport, marked deflation (wind erosion) and deposition, low moisture content, and extreme temperature fluctuations	<i>Ammophila breviligulata</i> , <i>Cakile edentula</i> , <i>Euphorbia polygonifolia</i>
Heather	Seaward slopes of secondary foredunes	Less exposed to sand transport and windborne salt spray than dunegrass	<i>Hudsonia tomentosa</i> , <i>Panicum amarum</i>
Ticket or shrubs	Backslopes and swales	Exposed, at canopy height, to considerable amounts of salt spray, but they are not generally exposed to burial by sand	<i>Myrica Pensylvanica</i> , <i>Prunus serotina</i> , <i>Juniperus virginiana</i>
Woodland	Landward of secondary foredune (300 m landward of shoreline)	High intensity of salt spray only at canopy height	<i>Juniperus virginiana</i> , <i>Ilex opaca</i> , <i>Prunus serotina</i>

vegetation from sand blast, and promote a microclimate conducive to vegetation growth (Bofah and Ahmad, 1990). Increases in vegetation diversity adjacent to sand fences in specific dune zones have been related to possible seed trapping by fences within the dune (Nordstrom et al., 2007a).

Because sand fences have been deployed for dune building at the Jersey shore for decades (NJDEP, 1984), New Jersey was the selected study site. The municipality of Ocean City was chosen as a case study because its history of fence deployment for dune building has resulted in the presence of multiple remnant fence rows of different heights within different dune zones. While Ocean City – like any other field study location – has locally contingent, idiosyncratic aspects, it is representative of a large number of barrier islands on the Atlantic coast of the U.S. where sand fences have been deployed for dune building.

2. Study area

Ocean City is a developed barrier island in Cape May County generally characterized by a 60 m-wide (on average at low tide) un-vegetated beach; 35 m wide dunes, 2–3 m above the backshore; and a 4–12 m-wide un-vegetated trough landward of the dunes (Freestone and Nordstrom, 2001). On the northern side of the island a boardwalk is located landward of the trough followed by shorefront houses or hotels (Site 1) (Fig. 3), while on the southern side, the landward side of the trough is framed by a bulkhead followed by shorefront homes (Sites 2 and 3). Seaward of the bulkhead, two rows of 1.2 m-high wooden-slat sand fences with 50% initial porosity were deployed for dune construction in 1995 following beach nourishment (Nordstrom et al., 2007b). In the 5 m space between the fences, *Ammophila breviligulata* or Beachgrass was planted. Subsequent plantings occur annually as needed (Freestone and Nordstrom, 2001).

Two more rows of fences were added seaward of the initial ones after they were partially buried. At the time of this study, partially buried remnant fences had weathered and missing slats and were located at various dune zones including the swale and the foreslope of the landward ridge. Data were gathered at the developed dunes found at 21st Street (Site 1), where remnant fences are far landward

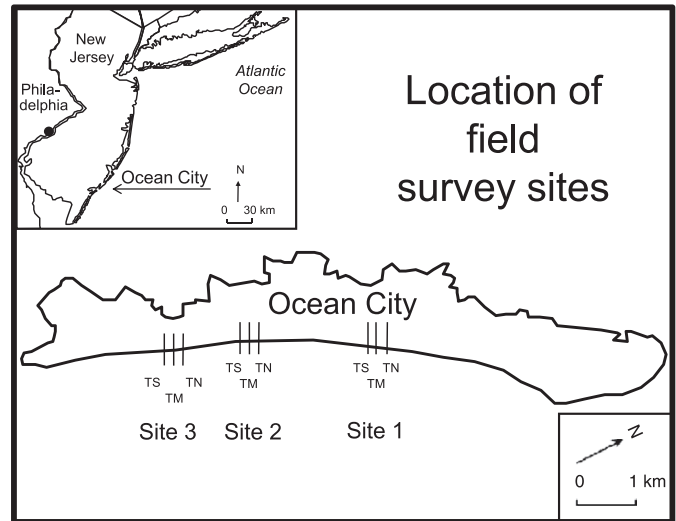


Fig. 3. Field survey sites in Ocean City, New Jersey.

of the dune toe, and at 38th and 41st Streets (Sites 2 and 3) (Fig. 3) where multiple remnant fence rows are visible along the dune gradient.

At Site 1, the topography seaward of the seaward-most fence and former dune toe was allowed to evolve naturally on a beach artificially widened by nourishment. Remnant fences are found at the foreslope of the second (landward) ridge and former dune toe (Fig. 4) because the natural foredune that formed 60 m seaward after nourishment trapped most sediment blown onshore and prevented transport farther landward. Site 1 is a hybrid dune system that incorporates natural and anthropogenic elements, in a wide space that could resemble that of a natural dune environment.

The dunes at Sites 2 and 3 were built through fence deployment and vegetation plantings. They were both originally built on narrow beaches and represent compressed dune gradients (c.f. Freestone and Nordstrom, 2001). Most fences at Site 2 are completely buried, and only one remnant fence row is visible between the ridges, while Site 3 has multiple visible remnant fence rows located at various zones within the dune.

3. Methods

Most field data were gathered September 8th to October 6th 2007 to account for maximum vegetation growth during months that were warm, but less crowded by tourists. Data were collected to produce topographic, vegetation and fence variables (Table 2). Each of these variables was identified along topographic transects perpendicular



Fig. 4. Remnant fences at former dune toe and foreslope of landward ridge in Site 1, Ocean City, New Jersey (looking seaward, east).

Table 2
Variables used in the correlation coefficient matrix.

Geomorphic variables
Distance landward of dune toe
Sheltering: degree of sheltering (S)
$S = \sqrt{[(q)(e)(d)]}$
q = quadrat depth (highest elevation seaward – quadrat elevation)
e = highest elevation seaward
d = distance of quadrat from dune toe
Net change in surface elevation (October 2007–March 2008)
Vegetation variables
Diversity: Simpson's diversity index (D)
$D = 1 / \sum_{i=1}^S p_i^2$
S = Total number of species in the quadrat
P = Proportion of total individuals in the i th species
Density: number of individuals
Fence variables
Fence presence/absence
Distance landward of fence (0–7 m)

to the shoreline. 1 m² quadrats were used to collect data on vegetation variables.

Cross-shore topographic data were collected every 3 m on three evenly spaced transects per site extending from the upper limit of swash (ULS) to the landward-most sand fence. Cross-shore transects at 3 m-interval survey points allow for the identification of most topographic and vegetation differences within the different dune zones and accounts for dune vegetation variability with distance landward of the beach. The transects were referenced to nearby locally defined points, such as a street post or bulkhead piling, which could be expected to be in a fixed position for several years thus serving as a datum.

Data on net change in surface elevation were collected by locating erosion pins on each transect at the 3 m-interval survey points. The exposed height of the pins was measured on October 4th 2007, and re-measured on March 2nd 2008, to account for the winter storm season when most sediment transport occurs. Because data collected with the pins represent surface elevation changes occurring after data on vegetation were gathered, elevation change data were not used to explain specific vegetation patterns but to identify deposition and erosion zones.

Replicated ordered sampling was used to measure vegetation characteristics. 1 m² quadrats (Fig. 5) were placed at survey points spaced every 3 m on each of the transects from the landward-most fence to the seaward-most vegetation. The 1 m² quadrat size is sufficiently detailed to evaluate fine scale patterns of vegetation and their relation to topography (Nordstrom et al., 2007a). Replicates were located 1 m north and south of the middle quadrat. Ten to 27 lines of quadrats with replicates were located across each transect, depending on the width of the dune.

Vegetation species were identified and counted in each quadrat to calculate diversity. Vegetation density was approximated by manually counting small clusters (5–10 individuals) and visually estimating the number of individuals in large clusters. The highest stalk of each vegetation cluster was measured with a measuring tape and averaged. Vegetation distribution patterns may be affected by sediment transport, salt spray, excessive heat, soil moisture, dryness, high light intensity and temperature, and wind exposure (Hesp, 1991; Costa et al., 1996; Wilson and Sykes, 1999; Maun, 2004) in addition to burial or deposition. Data for these variables were not collected in the field, but the cross-shore position of the transects accounts for the decreasing intensity of most of these physical stresses and the gradual increase in conditions favoring vegetation growth landward of the beach.

Remnant fences were identified and their exposed heights were averaged after measuring individual slats with a measuring tape. The distance of the fences from the closest quadrat was recorded.

Quadrat replicates and transects were aggregated per site to create a correlation coefficient matrix between topographic, vegetation and fence variables at a 95% confidence level. A correlation analysis was the most appropriate statistical test to determine whether and how strongly pairs of variables were related per site. Topographic variables include distance of quadrat landward of dune toe, elevation of each quadrat above the dune toe, net change in surface elevation and topographic sheltering. The dune toe was selected as the baseline for quadrat location because it is the seaward-most dune zone where onshore stress levels are highest. Net change in surface elevation identifies dune locations where erosion or deposition occurred. Sheltering considers topography as a main barrier against onshore stress, and distance from dune toe. It was calculated as the square root of the product of quadrat depth (quadrat elevation subtracted from the highest elevation seaward), highest elevation seaward and distance of quadrat landward of dune toe (Table 2).

Vegetation variables include vegetation diversity, vegetation density, Beachgrass density, and vegetation height. Simpson's Diversity Index was used to calculate diversity (Lubke, 2004), and to consider the number of species and number of individuals per species per quadrat (Table 2). Number of individuals per cluster was used as a measure of vegetation density. Beachgrass density was selected as a separate variable because it is the most abundant species in all sites and it is often planted for dune stabilization. Vegetation height was calculated by averaging the highest stalk in each vegetation cluster per quadrat.

Fence variables include fence presence, fence height, and distance of quadrat landward of fence. Fence presence and distance from fence identify fence location within the dune and the vegetation quadrats that may be affected by remnant fences. Because fences affect sediment mobility the most between at 3–7 times their initial fence height (CERC, 1984), only quadrats 0–7 m landward of remnant fences were considered when evaluating distance from fence. Fence height is an indicator of the barrier potential of the fence.

Based on results from the correlation analysis, a multiple regression analysis was conducted to study the relationship between vegetation diversity as the dependent variable and distance landward of fence, degree of sheltering and net surface change in elevation as independent variables. The regression analysis was used to evaluate the importance of the independent variables in determining diversity and creating a prediction model that explains their relationships. Critical values used for the model were calculated at a 0.05 confidence level.

Quadrat replicates were averaged to create figures that display topographic, vegetation and fence variables (Figs. 6–9). These figures are useful for comparing variable values considering their location within the dune and, the presence and height of fences. The middle transect was selected as the most representative because its location is least affected by the presence of walkways where pedestrian trampling could be an additional stress on dune vegetation distribution.

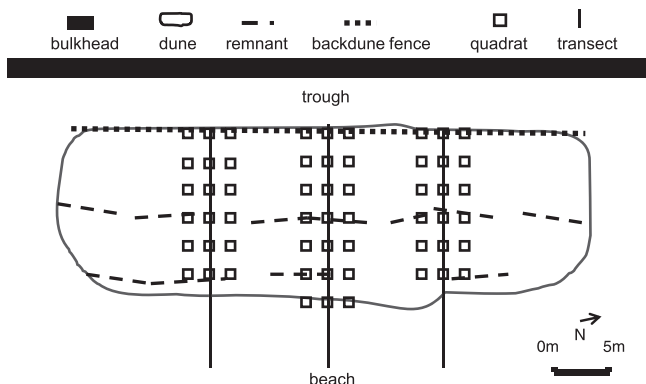


Fig. 5. Cross-shore data collection methods diagram.

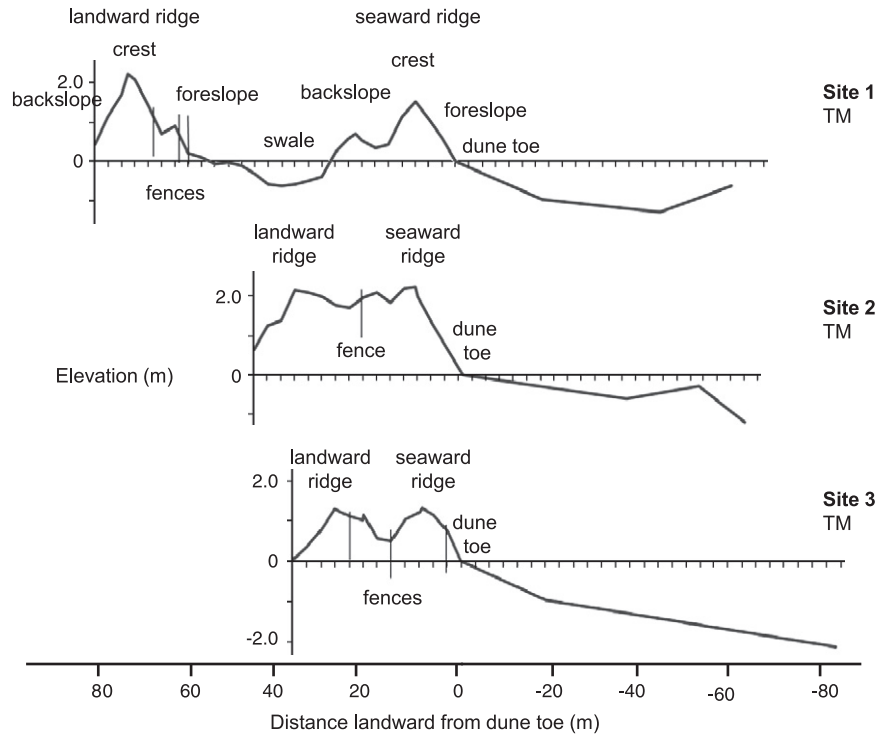


Fig. 6. Topography and fences in all sites aligned at the backshore/dune toe contact. Completely buried fences are not depicted. 0 m refers to the dune toe of each site.

4. Results

4.1. Fence characteristics

Remnant fences were found at different dune zones including: foreslope of landward ridge, swale, and backslope and foreslope of seaward ridge (Fig. 6). Most remnant fence rows (11 out of 18) were 0.25 m high or less. Forty-four of the 498 vegetation quadrats had remnant fences within them or within 1.5 m of the edge of the quadrat.

Remnant fences at Site 1 were located at the foreslope of the landward ridge and at the former dune toe (Fig. 6). The seaward-most fence has remained 0.9 m above ground because its burial was prevented by lack of landward sediment transport after the formation of the natural foredune, which replaced the fences as the main transport barrier. A single, 0.10 m-high remnant fence row is barely visible between the highest points at Site 2, while Site 3 has fences at the foreslope of the landward ridge, swale and foreslope of seaward ridge (Fig. 6).

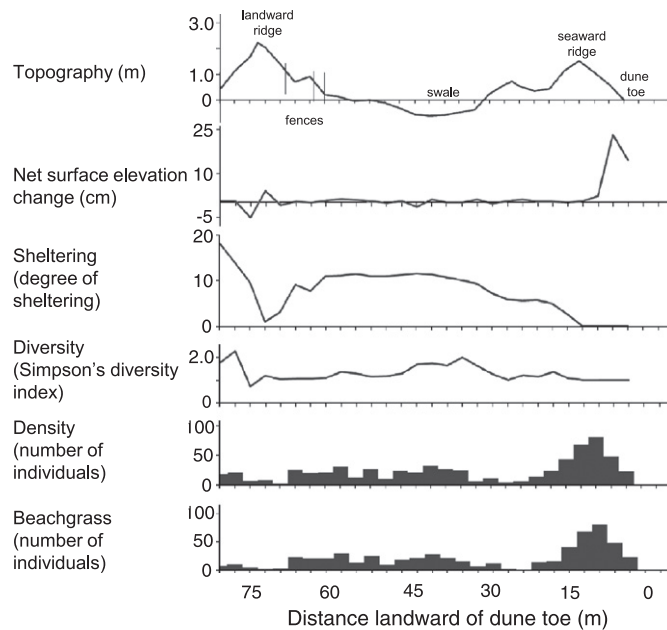


Fig. 7. Cross-shore distribution of variables landward of dune toe on Site 1 middle transect, landward of dune toe. Formulas for Degree of Sheltering and Simpson's Diversity Index can be found in Table 2.

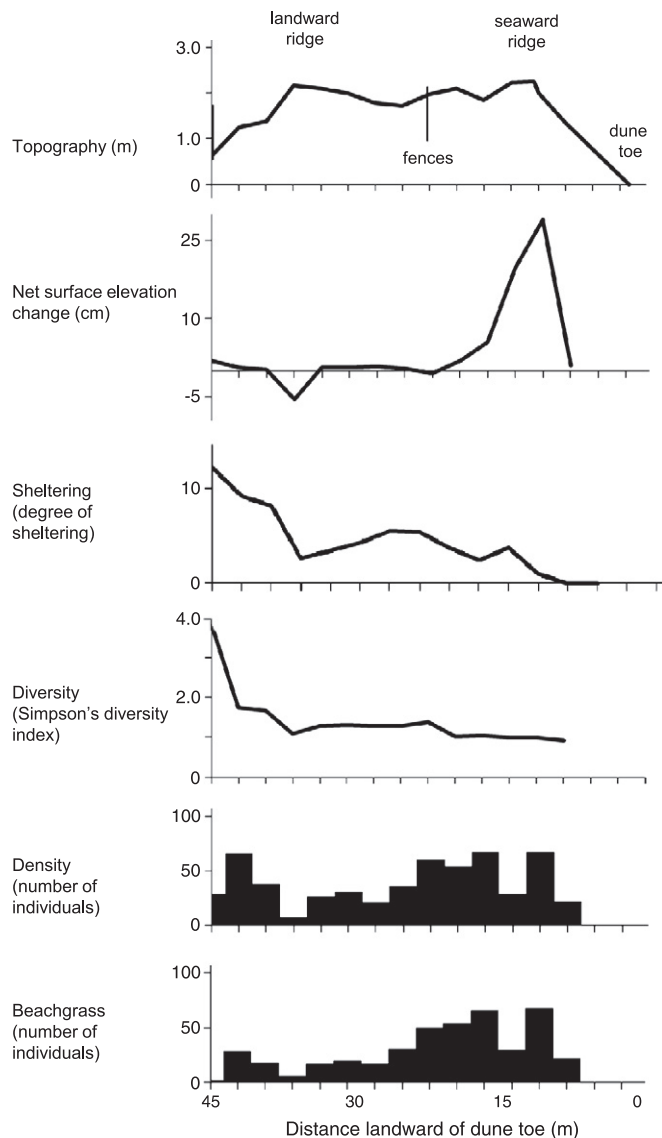


Fig. 8. Cross-shore distribution of variables landward of dune toe on Site 2 middle transect, landward of dune toe. Formulas for Degree of Sheltering and Simpson's Diversity Index can be found in Table 2.

4.2. Topographic characteristics

Dune width ranges from 33 to 88 m, dune height from 1.2 m to 2.2 m and beach width from 30 to 80 m (Fig. 6). Site 1 provides the greatest degree of sheltering (Fig. 7) of all sites at the backslope of the landward ridge because it has the widest dune and the highest landward ridge. An increase in sheltering occurs at the swale of Site 1 because it is 2 m lower than the seaward ridge which traps sediment transport, causing deposition on the vegetated seaward foreslope (Fig. 7).

Although Sites 2 and 3 were both created entirely with fences, they have very different morphologies. Site 2 has a narrow dune (45 m wide), with high sediment volume, low topographic variability and no swale (Fig. 8). Limited increase in sheltering occurs between the ridges where the elevation is only 0.5 m lower than the seaward ridge. Sediment deposition at Site 2 is the highest of all sites because the height of the vegetated seaward ridge allows it to trap great amounts of onshore sediment transport (Fig. 8).

Site 3 has the narrowest (38 m wide) and lowest dune (1.2 m) but great topographic variability because the swale is 0.8 m lower than the seaward ridge (Fig. 9). Sheltering increases only slightly at the

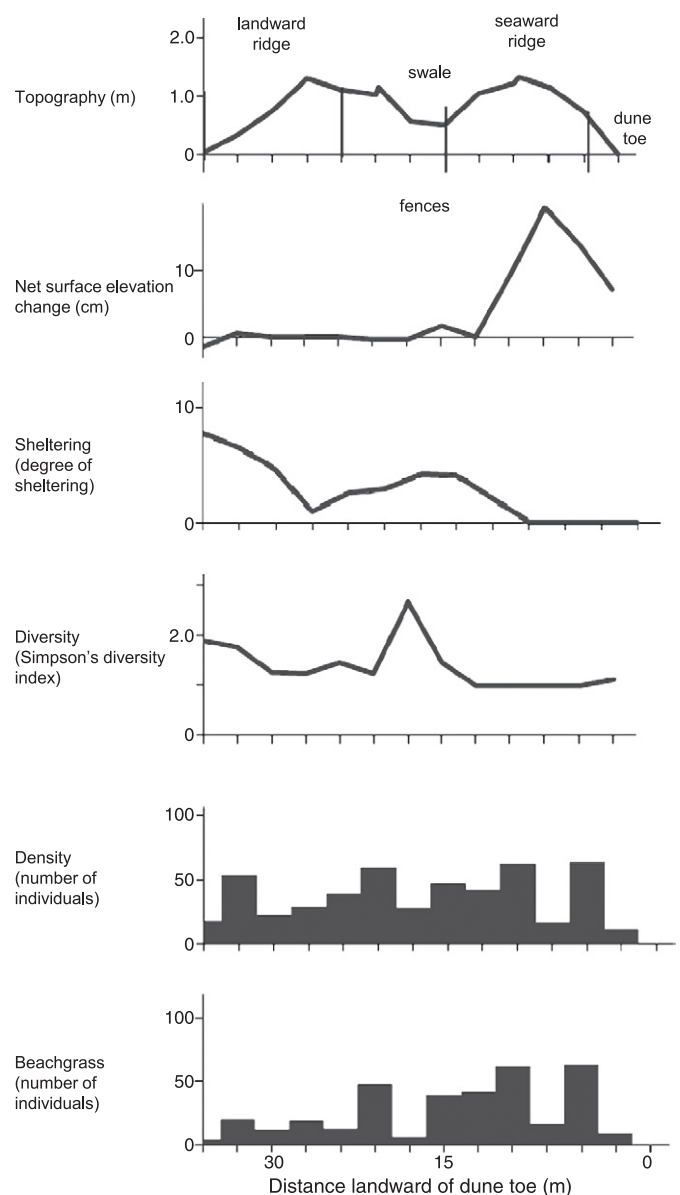


Fig. 9. Cross-shore distribution of variables landward of dune toe on Site 3 middle transect, landward of dune toe. Formulas for Degree of Sheltering and Simpson's Diversity Index can be found in Table 2.

swale, because the low seaward ridge is a less effective barrier against onshore stress than higher ridges allowing for stress to reach landward dune zones. Deposition at Site 3, for example, seems to be distributed farther inland than Site 1 and Site 2 (Fig. 9).

4.3. Vegetation characteristics

Fifteen vegetation species were identified in at least one of 12 transects (Table 3). Average vegetation height is 0.25 m. Beachgrass is the most common and abundant species. Japanese Sedge was the only invasive species found (Table 3). According to the Monmouth County Planning Board, this species is sometimes planted to stabilize the dune because it is tolerant to salt spray and sand blasting. Quadrats with unidentifiable species occurred in three transects, and most transects had quadrats with no vegetation, which generally occurred close to the highly stressed backshore.

Vegetation diversity is high in the backslope of the landward ridge (Figs. 7–9) and in low swales (Site 1 and 3), which is what would occur at a natural site (Doing, 1985; Stallins, 2002). The lack of swale

at Site 2 creates an exposed zone between the two ridges increasing the vulnerability of vegetation to onshore stresses and preventing an increase in vegetation diversity. High vegetation diversity occurs at the low swale of Site 3 despite the overall low sheltering at this site, possibly because of the high water table and increased soil moisture in the swale (i.e. [Lubke, 2004](#); [Maun, 2009](#)). Soil moisture gradient varies inversely with the topographic profile allowing low dune elevations to have greater moisture content of sand with increasing depth ([Martin, 1959](#)). The highest vegetation density occurs at the seaward ridge of each site where pioneer Beachgrass is the dominant species ([Figs. 7–9](#)) indicating the early successional stage of these dunes.

4.4. Variable inter-relationships

Correlation analyses of all variables for all sites and per site show no significant correlation between fence variables and vegetation variables (Table 4), perhaps because most remnant fences are just as high as or lower than average vegetation height (0.25 m) and cannot provide additional sheltering or create microhabitats that would benefit vegetation growth. Vegetation diversity is highly correlated with two of the topographic variables: distance landward of the dune toe and degree of sheltering (Table 4). These two variables are highly correlated to one another because the first is used to calculate the second (Table 2). Sheltering increases as distance from the source of onshore stress and topographic barriers increase.

At Sites 1 and 2, vegetation diversity is strongly correlated with sheltering (Table 4). Site 1 has great width and height, creating sheltered zones that favor diversity. Site 2 has great height and sediment volume, which provides shelter that benefits diversity at the back-slope but not between the ridges. Site 2 has the highest positive correlation between vegetation diversity and degree of sheltering, possibly as a consequence of vegetation plantings of species such as Japanese Sedge at the backslope. The correlation between vegetation diversity and sheltering at Site 3 is the lowest of all sites because its ridges are low, limiting their barrier potential against onshore stress, and because other variables, such as closeness to water table and moisture availability, may be stimulating diversity in the swale where sheltering is unexpectedly low.

Vegetation density and Beachgrass density are negatively correlated with distance landward of the dune toe and sheltering, and positively to deposition (Table 4) because Beachgrass is the most abundant species stimulated by burial occurring at the seaward ridge. Beachgrass is most abundant because the fast rate of dune development altered the succession sequence, and the limited space for dune formation in a developed coast prevented the establishment

of a dense successional species community landward of the seaward ridge.

In natural dunes, Beachgrass is the main sand-trapping barrier, and its growth is stimulated by burial of 17–28 cm (Martin, 1959). *Ammophila* decreases in vigor as deposition decreases, and with its decay, soil nutrients increase, benefiting the establishment of successional species (Hesp, 1991). Excessive burial beyond the positive stimulus threshold of Beachgrass in the initial stages of fence-created dunes limits its growth, giving it a secondary role in dune formation. In fence-created dunes, Beachgrass growth, decay and replacement by successional species does not occur simultaneously with dune growth. Succession takes longer because Beachgrass communities cannot thrive until the foredune has been initiated, fences become partially buried remnants and the enhanced sediment deposition rate decreases to a level that stimulates Beachgrass growth. The presence of shorefront property, boardwalks and bulkheads restricts the dune width, which limits the space where successional species can develop and leads to overall greater exposure to onshore stress when compared to wider dunes. Beachgrass is the most abundant species at Site 1, despite its greater width because the successional sequence was altered by the limited sediment transported landward of the new seaward ridge which prevented the establishment and later decay of pioneer species that should have resulted in the growth of a dense successional community landward of the seaward ridge.

4.5. Vegetation diversity prediction models

Multiple regression analysis for each site indicates that the independent variables (distance landward of fence, sheltering and net change in surface elevation) account for approximately 40% of the variability in vegetation diversity at Site 1 (adjusted $R^2 = 0.37$) and Site 2 (adjusted $R^2 = 0.43$), both significant at 0.05 confidence level (Table 5). Adjusted R^2 values were not significant at Site 3. Based on this model, sheltering is the common variable determining variability in the diversity of vegetation at Sites 1 and 2. The distribution of vegetation diversity at Site 3 may be responding to greater exposure to onshore stresses as a consequence of the small dimensions of the dune and to other variables controlled by the topographic profile, such as the availability of soil moisture. Sand moisture is closely and inversely associated with elevation, increasing at the low swale where the water table is closer to the surface benefiting vegetation growth at that zone since deficient amounts of soil moisture inhibit autogenic succession (Martin, 1959).

5. Discussion

Previous studies indicate that artificially creating and maintaining a dune for protection of human facilities against flooding and wind-blown sand may also provide protection to landward vegetation, resulting in greater species richness than would be possible in the restricted space available on developed coasts, allowing more natural cross-shore gradients of processes and vegetation types to occur (Nordstrom, 2008). This study explores the role of sand fences in this process. Given the specific developed dune environment studied here, results reveal that 1) vegetation diversity or density do not increase near remnant fences because most remnants are lower than average vegetation height and do not provide additional shelter, but 2) vegetation distribution seems to be responding to topographic characteristics that are most likely the result of sand accretion caused by fence deployment.

Because this study is based on a single location, some of the detailed results and conclusions may be site-specific. However, the general qualitative relationships (such as the association between topographic and vegetation diversity) are widely applicable to coastal dune environments. Some of the more specific findings (e.g., a critical visible

Table 3
Vegetation species present in each transect.

[illegible]

Table 4Pearson correlation coefficients and *r* critical values (directly under coefficient) of fence, topographic and vegetation variables at 0.05 confidence level.

	Dist. fence	Fence presence	Dist.toe	Sheltering	Surf. elev.	Diversity	Density
All sites							
N = 498 all but dist. from fence (N = 89)							
Fence presence	–0.863						
	0.212						
Dist. dune toe	0.094	0.195					
	0.212	0.090					
Sheltering	0.013	0.030	0.804				
	0.212	0.090	0.090				
Surface elevation	–0.117	0.003	–0.359	–0.325			
	0.212	0.090	0.090	0.090			
Diversity	–0.020	0.013	0.291	0.356	–0.065		
	0.212	0.090	0.090	0.090	0.090		
Density	0.029	0.085	–0.341	–0.300	0.281	0.042	
	0.212	0.090	0.090	0.090	0.090	0.090	
Beachgrass density	0.030	0.087	–0.400	–0.340	0.351	–0.284	0.846
	0.212	0.090	0.090	0.090	0.090	0.090	0.090
Site 1							
N = 251 all but dist. from fence (N = 49)							
Fence presence	–0.866						
	0.285						
Dist.dune toe	0.621	0.312					
	0.285	0.126					
Sheltering	0.094	0.013	0.729				
	0.285	0.126	0.126				
Surface elevation	–0.241	0.076	–0.345	–0.333			
	0.285	0.126	0.126	0.126			
Diversity	–0.175	0.004	0.384	0.523	–0.098		
	0.285	0.126	0.126	0.126	0.126		
Density	–0.043	0.158	–0.406	–0.353	0.202	–0.113	
	0.285	0.126	0.126	0.126	0.126	0.126	
Beachgrass density	0.046	0.175	–0.486	–0.450	0.222	–0.287	0.956
	0.285	0.126	0.126	0.126	0.126	0.126	0.126
Site 2							
N = 125 all but dist. from fence (N = 9)							
Fence presence	–0.856						
	0.667						
Dist.dune toe	0.999	0.007					
	0.667	0.179					
Sheltering	–0.468	0.078	0.793				
	0.667	0.179	0.179				
Surface elevation	0.413	0.086	–0.536	–0.422			
	0.667	0.179	0.179	0.179			
Diversity	–0.464	0.056	0.584	0.646	–0.152		
	0.667	0.179	0.179	0.179	0.179		
Density	–0.389	0.000	–0.266	–0.140	0.410	–0.021	
	0.667	0.179	0.179	0.179	0.179	0.179	
Beachgrass density	–0.340	0.023	–0.514	–0.389	0.531	–0.324	0.884
	0.667	0.179	0.179	0.179	0.179	0.179	0.179
Site 3							
N = 120 all but dist. from fence (N = 29)							
Fence presence	–0.866						
	0.372						
Dist.dune toe	0.337	0.119					
	0.372	0.183					
Sheltering	–0.006	0.063	0.773				
	0.372	0.183	0.183				
Surface elevation	–0.192	0.152	–0.369	–0.276			
	0.372	0.183	0.183	0.183			
Diversity	0.207	0.073	0.320	0.242	0.009		
	0.372	0.183	0.183	0.183	0.183		
Density	0.142	0.052	0.045	0.017	0.160	0.304	
	0.372	0.183	0.183	0.183	0.183	0.183	
Beachgrass density	0.048	0.113	–0.329	–0.225	0.288	–0.247	0.629
	0.372	0.183	0.183	0.183	0.183	0.183	0.183

fence height of 0.25 m) should be applicable to any coastal dune area with general floral and faunal assemblages similar to the study area.

The distribution of vegetation diversity and density in the fence-created dunes studied here is a function of sheltered and exposed, high and low dune zones resulting from topographic variability. Topography

controls the environmental gradients of intensity of onshore stresses (i.e. sand movement, wind-borne salt spray, and available soil moisture) to which vegetation responds (Martin, 1959). Fences are responsible for much of the topographic variability, but the relationship between observed fences and topography is not always direct because some

Table 5
Individual site models to predict variability in vegetation diversity.

	Site 1		Site 2		Site 3	
Dependent variable: vegetation diversity	Estimated coefficient	Prob > t	Estimated coefficient	Prob > t	Estimated coefficient	Prob > t
Dist. landw. fence	0.0009	0.9533	0.0056	0.8310	0.0086	0.6532
Sheltering	0.0554	0.0001	0.1477	0.0105	0.0033	0.9535
Net change in surface elevation	0.0823	0.0017	0.0795	0.5185	−0.0139	0.2198
Observations	68		23		46	
F	14.36		6.70		1.06	
Prob > F	0.0000		0.0026		0.3751	
Adjusted R ²	0.3708		0.4265		0.0040	

local high peaks are the result of fences that are now buried (Freestone and Nordstrom, 2001). The location and extent of different dune zones that determine the distribution of vegetation diversity is a function of the past deposition caused by both exposed and buried fences and beach nourishment, which often occur almost simultaneously. Past fence deployments have been made largely to increase the value of the dunes for shore protection, but careful fence deployment may provide the additional benefits of creating alternative types of dune environments with high morphological and vegetation diversity.

5.1. Management implications of fence deployment

The effect of remnant fences on dune morphology (i.e. shape, width and height of ridges and swales) is a function of the amount of sediment transport occurring at their initial deployment location. Use of fences, considering the effects that different fence configurations, number of rows and separation distance have on topography, can lead to creating the diversity of topographic features necessary for encouraging dune vegetation diversity. The variety of local relief in the ridge and swale topography creates small-scale differences in sheltering and proximity to the water table that enhances the variety of habitats over short distances across the shore (Nordstrom et al., 2007a). Sheltered dune zones are especially important because few species can tolerate living in the dynamic sections of the dune gradient and tend to disappear toward the more stabilized and sheltered locations, which show richer species composition (Moreno-Casasola, 1986). Growing on the inland-facing side of dune ridges or in low swales, species are protected from winds and salt spray (Martin, 1959; Doing, 1985; Stallins, 2002; Acosta et al., 2007).

Fences can create dunes with the topographic characteristics that benefit vegetation diversity (i.e. Fig. 9), such as sheltered zones and closeness to the water table, within a limited space. But they may also create dunes with low topographic variability and high sediment volume which takes away the benefits of a swale (i.e. Fig. 8). Therefore, fence deployment can lead to high or low topographic variability (Fig. 10). Multiple fence rows placed a short distance apart create a protective dune that maximizes dune volume but sacrifices topographic variability and geomorphic and vegetation diversity. Fewer fence rows at slightly greater distance apart create a dune that better represents the high topographic variability of natural dunes and has greater potential of developing diverse vegetation communities within a narrow space. Diverse vegetation and morphology make the dune system more resilient to changing conditions and increase the ecological value of dunes built primarily to protect human facilities (Martinez et al., 2004; Nordstrom, 2008).

State regulations need to be considered when planning for these alternative fence usages. For instance, legislative amendments to the State of New Jersey Coastal Area Facilities Review Act in 1993/94 allow for construction of sand-trapping fences but prohibit their

removal. Concerning regulations like these, a remnant fence height of 0.25 m or less could be acceptable because it allows the fence to blend into the landscape within the vegetation around it, large mammals (i.e. rabbits) can jump over it and small mammals and invertebrates can pass through the slats. But ideally, sand fences should be allowed to become completely buried, which decelerates the rate of deposition towards a more natural rate, creating a morphology that is more compatible with natural dune functions and vegetation successional sequences. Once the initial fence is completely buried, single fence rows may be deployed seaward of the dune toe to create a swale between ridges, leading to a variety of sheltered and exposed zones for diverse vegetation species to occur. Alternatively, fences could be made from bushes, in which case they would break down after they have accomplished their trapping functions (c.f. Nordstrom and Arens, 1998). Either way, if fences are used, they should be monitored through time and adaptive management implemented to ensure that they do not interrupt natural vegetation gradients (Nordstrom et al., 2007a). Preventing or restricting the use of sand-trapping fences after burial of the initial fence that is used to create the initial dune ridge, which then provides protection to human structures, is an option that could enhance values and allow vegetation to become the primary means of trapping wind-blown sand (Nordstrom et al., 2000).

Remnant fences with visible heights greater than 0.25 m represent ineffective or unnecessary deployments that may be aesthetically displeasing and may obstruct the movement of fauna within the dune. Managers should evaluate previous fence deployments by measuring and recording present remnant fence height to determine if past use of fences has been effective and prevent the future existence of highly visible remnant fences. Dune vegetation could be planted to disguise the fences as an alternative to fence removal. The vegetation species selected must have adaptations to survive in the specific dune zone where the fence remains so that it is able to thrive on its own. Because most remnant fences studied here have been weathered into broken and discontinuous segments (Fig. 5), it is likely that the plantings will resemble the patchiness of natural vegetation growth. These vegetation plantings would serve multiple purposes as they would be camouflaging the fence, creating habitat and increasing vegetation density landward of the seaward ridge.

5.2. Implications of beach nourishment as a potential dune restoration alternative

Beach nourishment is designed to widen the beach and reduce coastal flooding threats on buildings and coastal settlements, but it has the potential for restoring dune landforms and habitats by widening beaches and creating space for foredunes to evolve naturally, and has proven its effectiveness at specific locations when integrated with vegetation plantings (De Lillis et al., 2004; Nordstrom, 2008). Nevertheless, the creation of an excessively wide beach solely for protection or recreation will not automatically result in natural succession or a well-vegetated dune system (i.e. Fig. 7). Beach nourishment can be a tool for restoration if dune vegetation diversity and density are integrated in the nourishment objectives.

The problem with an overly wide beach is that as the dune develops, sediment transport will be blocked by the seaward-most barrier, initiating a ridge that will prevent landward sediment transport. The establishment of pioneer species landward of the initial ridge will be problematic because they need burial of 17–28 cm, which is unlikely landward of a seaward ridge. Even if Beachgrass is planted in this space, lack of appropriate amount of burial will limit its growth. Lack of Beachgrass changes the successional sequences, leading to low vegetation density landward of the seaward ridge. Deploying fences where managers want the dune to start may not work if the beach is so wide that natural barriers such as wrack or vegetation occur seaward of the fences. Managers could clean the beach up to the location where they would like the dune toe to be, to eliminate wrack and vegetation

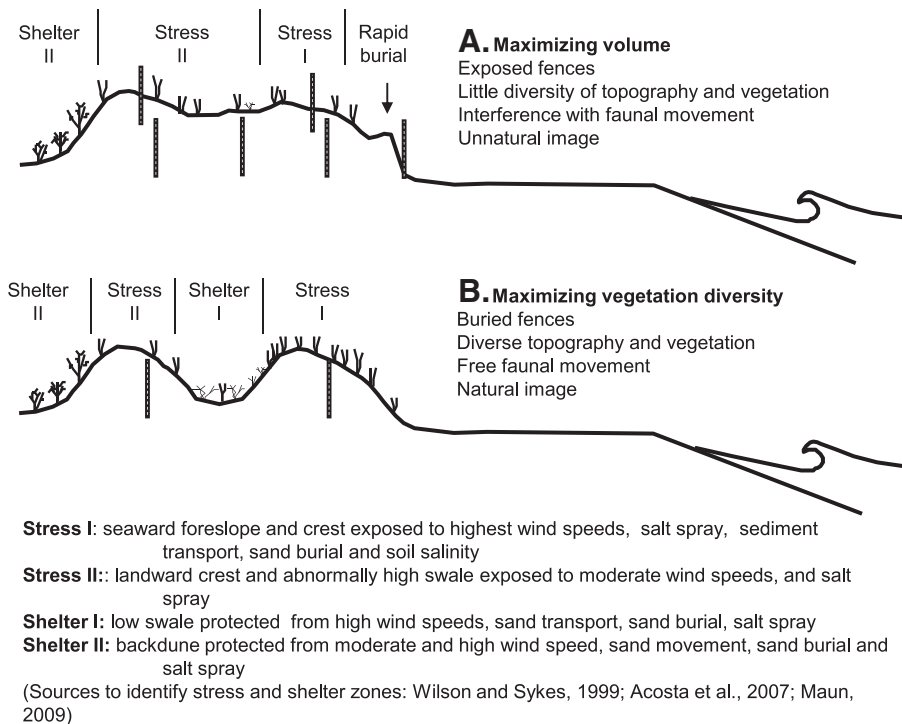


Fig. 10. Alternative options for sand fence deployment considering their potential to create a protective dune that has morphological and vegetation diversity.

seeds and prevent sediment deposition at seaward locations, but beach cleaning and eliminating biological material may be incompatible with the restoration approach.

Adequate beach width is necessary for incipient dunes to develop into naturally functioning systems (McLean and Shen, 2006), but the appropriate width is different for every beach and should be determined based on an approximation to the original beach width. Historic photographs and memories of long-time residents may help determine the adequate beach width for specific locations. Considering that cost effectiveness is an important factor determining the volume of nourishment projects, municipalities and managers should remember that investing in a naturally functioning dune habitat on a naturally wide beach may facilitate the creation of a system that is more resilient, better able to withstand change and adapt to a variety of circumstances, including extreme weather events, which may return their investment in the long run. Smaller scale, slow nourishment projects may also avoid detrimental effects on benthic habitats and killing fauna by excessive burial (Bilodeau and Bourgeois, 2004; Defeo et al., 2009).

6. Conclusions and management alternatives

The major conclusions of this study and management inferences can be summarized as follows:

- The distribution of vegetation diversity and density at the studied sites is not directly related to sand fence presence.
- Vegetation distribution is related to topographic variables, especially topographic sheltering from onshore stress.
- The fence-created dunes studied here exhibit a variety of topographic profiles that can be assumed to be primarily caused by sand accumulation due to fence deployment.
- Fence deployment could be used to create topographically diverse dunes with various sheltered and exposed zones similar to those found in nature but within a restricted space where different kinds of vegetation communities can develop.

- Managers should consider using sand fences and appropriate beach width to create a protective dune that is also diverse, functional and better able to adapt to change.

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