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Designing ecosystems in degraded tropical coastal dunes[1]

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Abstract: Coastal dunes are prone to degradation and subsequent destruction by natural and human-induced disturbances. Worldwide, human disturbances have had a great impact on coastal dunes, resulting in loss of important ecosystem services (coastal protection). In the Port of Veracruz, Mexico, harbour expansion completely destroyed the dune area. A 2-km-long 10- to 20-m-high artificial and unstable dune, parallel to the coastline, was left. To revegetate this dune, we used 3 artificially created plant communities in which the dominant species had contrasting growth forms: *Opuntia stricta* (Cactaceae), *Panicum maximum* (tall grass), and *Paspalum* spp. (short grass). We monitored the vegetation and species turnover during 5 y. Plant cover reached almost 100% after only 1 y. Sand stabilization occurred at a faster rate on those locations covered by both grass types, but diversity of growth habits was highest at the *Opuntia* treatments. From 29 to 37% of the original dune species returned. The rehabilitated community was dominated by generalist herbs and vines (80%). Remnant patches with native vegetation played an important role in species turnover and promoted colonization by thicket and tropical dry forest species. The created ecosystems provided the required ecosystem service (prevention of shifting sand) and were self sustaining (at least over the 5-y period this study lasted), but with low diversity. When human disturbance is devastating, revegetation or even created ecosystems may be the only solution. However, restoration with native species should be promoted whenever possible.
Keywords: coastal dunes, designer ecosystems, Mexico, revegetation, succession, tropic.

Résumé : Les dunes côtières sont sensibles aux perturbations naturelles et anthropiques qui peuvent causer leur dégradation et mener à leur destruction. Les perturbations anthropiques ont eu à travers le monde des impacts majeurs sur les dunes côtières dont le résultat a été la perte d'importants services écologiques tel la protection des côtes. À Veracruz au Mexique, l'expansion du port a complètement détruit la zone dunaire. Une dune artificielle et instable de 10-20 m de hauteur et longue de 2 km a été laissée parallèlement à la côte. À partir des espèces disponibles pour la revégétalisation, trois communautés de plantes ont été créées artificiellement dans lesquelles les espèces dominantes avaient des formes de croissance contrastées : *Opuntia stricta* (Cactaceae), *Panicum maximum* (herbe haute) et *Paspalum* spp. (herbe courte). Nous avons suivi la végétation et le renouvellement des espèces pendant 5 ans. La couverture végétale a atteint presque 100 % après seulement un an. La stabilisation du sable a été plus rapide dans les sites où les 2 types d'herbes étaient présents mais la diversité des formes de croissance était plus grande dans les traitements d'*Opuntia*. De 29 à 37 % des espèces dunaires originales ont réapparu. Les communautés réhabilitées étaient dominées par des herbes généralistes et des vignes (80 %). Les parcelles restantes de végétation indigène ont joué un rôle important pour le renouvellement des espèces et ont favorisé la colonisation par des espèces de fourré et de forêt tropicale sèche. Les écosystèmes créés ont procuré les services écologiques requis (prévenir le déplacement du sable), ils sont maintenus dans le temps (au moins durant les 5 années de l'étude) mais avec une faible diversité. Lorsque les perturbations anthropiques sont dévastatrices, la revégétalisation ou même la création d'écosystèmes peut être l'unique solution. Cependant, la restauration à partir d'espèces indigènes devrait être favorisée lorsque possible.
Mots-clés : dunes côtières, ingénierie écologique, Mexique, revégétalisation, succession, tropique.

Nomenclature: Cronquist, 1988.

Introduction

Coastal dunes are aeolian landforms that develop in coastal locations where an ample supply of loose, sand-sized sediment is available to be transported inland by wind. They are distributed worldwide and are associated with sandy beaches (Nordstrom, Psuty & Carter, 1990; Carter *et al.,* 1992; Hesp, 2000). For a long time, coastal dunes have provided humans with important ecosystem services and goods, such as coastal defence, groundwater recharge, buffer against saltwater intrusion, agriculture, mining, housing, and tourism (Carter, 1991; van der Maarel, 1993a,b; Greipsson, 2002; Martínez *et al.,* 2007). The widespread marketing of coastal recreation in particular has increased drastically in the last 50 to 80 y, rendering substantial economic profits to humans (Martínez, Maun & Psuty, 2004). The calculated value of ecosystem services provided to human societies by coastal ecosystems represents from 40 to 70% of the value provided by the world's natural ecosystems (Costanza *et al.,* 1997; Martínez *et al.,* 2007).

Coastal dunes are considered fragile ecosystems that are prone to degradation and destruction. Natural disturbances such as high tides, storm surges, and hurricanes are particularly disruptive. Hurricanes can have a very large impact,

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and in the Gulf of Mexico, Barbour *et al.* (1987) report that recovery from hurricane damage may take 5 to 10 y. Furthermore, a large proportion of the worldwide human population (41%) lives within 100 km of the coastline (Burke *et al.,* 2001), and 21 of the 33 megacities (> 20 million inhabitants) of the world are located at the coast (Martínez *et al.,* 2007). Classification of coastal countries according to their ecological, economic, and social attributes along the coast reveals that many countries in tropical and subtropical latitudes have a relatively large percentage of well-preserved natural ecosystems, but the population growth rate of these countries ranges from moderate to very high. Tourism along the tropical coasts is an ever increasing activity. Thus, it is likely that degradation in these latitudes will increase in the coming decades. An already occurring consequence of the reduction and removal of natural coastal dune features (such as topography) is that the potential for storm surge damage has increased noticeably in the coastal zone (Nordstrom, Lampe & Vandemark, 2000; Nordstrom *et al.,* 2002). This is particularly important, especially considering that because of global climate change, the impact of storms and hurricanes is likely to become even more severe in the coming decades (Webster *et al.,* 2005). Restoration of tropical sand dune communities will become increasingly important.

Some of the processes in restoration ecology that Hobbs and Norton (1996) have considered essential include setting realistic goals for re-establishment of functional ecosystems, recognizing the ecological limitations on restoration and the socio-economic and cultural barriers to its implementation. In this sense, an important key step in restoration projects is defining the ecosystem attributes to be restored, namely, 1) composition; 2) structure; 3) pattern; 4) heterogeneity; and 5) functions (ecological processes such as nutrient or hydrological cycles; succession). Which are the important attributes to be restored? Can we restore structure and some of the ecosystem functions without necessarily restoring the same species composition? Clearly, the answers to these questions will in large part be determined by the objectives set for the restoration, and by the methodology followed.

An important (and increasingly frequent) problem arises when environmental degradation is extreme. What can be done in these cases? Or when there is a lack of species available for restoration or rehabilitation? Under these circumstances, creation of a complete replica of a pre-disturbance ecosystem is not realistic because much of the damage is practically irreversible, and all we can do is rehabilitate certain ecological functions through reconstruction of lost ecological structures (Choi, 2007). Ehrenfeld (2000) stated that in extreme conditions, revegetation may be appropriate and necessary, while Palmer *et al.* (2004) refer to "designed ecosystems" as an option to "create a well-functioning community of organisms that optimizes the ecological services provided by natural ecosystems to human society". Designed ecosystems can range from either manipulated slightly altered ecosystems to ones that are created *de novo*, when no alternatives are available or possible. The latter are artificially created to achieve specific goals (ecological, economic, or social or a combination of all).

Restoration, rehabilitation, and revegetation of coastal dunes has been undertaken in several temperate countries with sandy coasts, including the USA, the Netherlands, England, Spain, Iceland, Denmark, Scotland, and South Africa (Mitchell, 1974; Ritchie & Gimingham, 1989; Andersen, 1995; Avis, 1995; Hillen & Roelse, 1995; Lubke, Hertling & Avis, 1995; Greipsson & Davy, 1996; Pickart, Miller & Duebendorfer, 1998; Pickart *et al.,* 1998; Webb, Oliver & Pik, 2000; Nordstrom, Lampe & Vandemark, 2000; Greipsson, 2002; Nordstrom *et al.,* 2002). To our knowledge, there are only a few successful examples of these activities in tropical latitudes, namely Brazil (Freire, 1983; Carvalho & Oliveira-Filho, 1993; Miranda *et al.,* 1997; Zamith & Scarano, 2006) and Mexico (where *Opuntia stricta* var. *dillenni* and *Casuarina equisetifolia* have been used to stabilize the shifting substrate). Restoration of subtropical coastal dunes has also been addressed occasionally (Lubke & Avis, 1998; Maschinski & Wright, 2006; Wright *et al.,* 2006). In general, coastal dune restoration projects deal with the impact and removal of exotic species (Choi & Pavlovic, 1998; Pickart, Miller & Duebendorfer, 1998; Pickart *et al.,* 1998; Webb, Oliver & Pik, 2000; Zamith & Scarano, 2006); a few focus on community regeneration after intense disturbance (van Aarde *et al.,* 1996; Lubke & Avis, 1998; van Aarde, Smit & Claassens, 1998; Rozé & Lamauviel, 2004; Redi, van Aarde & Wassenaar, 2005) or deal with management aimed at restoration (Grootjans *et al.,* 1997; Spurgeon, 1998; Nordstrom, Lampe & Vandemark, 2000; Grootjans *et al.,* 2001; Nordstrom *et al.,* 2002; Zamith & Scarano, 2006) and reduction of biodiversity loss.

In this paper we report on a 4- to 5-y monitoring study of a revegetation project in a destroyed and artificially reconstructed coastal dune area located along the central Gulf of Mexico, in the Port of Veracruz. Because of the lack of availability of native species to restore, and the urgent social need to revegetate the area and stop sand blasting onto adjacent houses, artificially designed ecosystems were in this case appropriate and necessary. We thus sought to test whether 3 artificially created coastal dune communities with different community structure and species composition were able to provide ecological services (protection from sand-blasting caused by cold fronts, storms, and hurricanes) previously provided by natural ecosystems. Our working hypothesis was that if ecosystem attributes were restored (in terms of structure, pattern, and function) (Hobbs & Norton, 1996), then provision of our focal ecosystem services would be re-established. Additionally, we were interested in exploring whether these artificially created communities allowed the re-establishment of the original vegetation.

Methods

Study site and revegetation strategies

The study site is located in the northernmost area of the port of Veracruz (19° 12' 25.41" N, 96° 08' 09.52" W), along the central part of the Gulf of Mexico. The coast in this region changes direction and is slightly oriented east–west. It is severely impacted by strong northerly winds occurring during the winter months, from November through March. In 2000, nearly 600 000 people lived in the port of Veracruz. The dune system and the vegetation developing on this area are greatly appreciated by local inhabitants because they protect the bordering neighbourhoods from sand blasting and direct impacts of strong winds. In 1939, Miguel Angel Quevedo planted an artificial woodland of *Casuarina equisetifolia* on the dunes. Subsequently declared a protected area and this woodland was known locally as the "pine grove", la "pinera" (Siemens, Moreno-Casasola & Sarabia, 2006). In 1996, the harbour of the Port of Veracruz, one of the largest commercial ports of the country, was expanded to meet its commercial trade needs. Harbour expansion totally destroyed the dune area originally covered by natural dune vegetation and the "pinera". Dunes were flattened with bulldozers and vegetation was completely removed. A 2-km-long and 10- to 20-m-high artificial and unstable dune (no vegetation on the seaward slope but remnants of original vegetation on the landward slope), parallel to the coastline, was left, and the seaward mobile slope was steepened to gain more space for the port's storage activities. This large artificial dune was very mobile, and when the seasonal northerly winds ("nortes") struck, sand moved inland towards the bordering neighbourhoods. A revegetation project was necessary and thus implemented. This project sought to stabilize this extremely mobile remnant artificial dune and to determine which combinations of species would accelerate the colonization process in order to regain native plant cover. The vegetation objective was a self-sustaining and low-maintenance plant community that would a) maintain the artificial dune and thus protect inland houses from the impact of "nortes", storms, and hurricanes by dissipating the energy of these natural hazards; b) stabilize the shifting substrate; and c) create an artificial plant community that would naturally withstand the impact of strong winds and promote the arrival and colonization of native species by creating favourable conditions.

Owing to feasibility considerations and to the lack of nursery-grown dune plants that could be acquired commercially, 3 artificially created plant communities were developed using plants that could be obtained in sufficient numbers: 1) one based on the native dune cactaceae *Opuntia stricta* var. *dillenii*; 2) one based on the introduced tall grass *Panicum maximum*, which could easily be obtained from nearby dunes that were being grazed at the time the revegetation project started; and 3) one based on the short grasses *Paspalum lividum* and *Paspalum langei*, which were brought from grasslands used for cattle ranching. *Paspalum* spp. were brought in the form of strips that included all accompanying species from the grazing land and a 5-cm layer of soil, forming a carpet. It thus included a seed bank from other plant communities. Planting of the introduced species took place between 1997 and 1998. The first 3 months after transplant, the area was watered twice a week. Occasionally, 2-m stakes of *Casuarina equisetifolia*, *Gliricidia sepium*, and *Bursera simaruba* trees were planted within the 3 artificially created plant communites, subjected to the 3 treatments, but this was done mostly in the *Opuntia* treatment area because that was where revegetation started. Given the high mortality of these transplanted stakes, efforts to introduce more trees were stopped. This resulted in a higher number of trees in the *Opuntia* treatment, but only because planting effort was different among treatments.

Monitoring of vegetation and substrate mobility

Species composition and cover were determined before the expansion of the harbour (June 1997), so we had a reference point for the original vegetation prior to the destruction of the dune system. The success of each created ecosystem in re-establishing the ecological service of protection from sand blasting was assessed by monitoring 15 randomly placed 5- × 5-m squares in each artificial community. We made sure to cover locations on the upper and lower parts of the slopes as well as the crest of the artificial dune. In each square we placed 4 aluminum stakes to easily locate each plot on each monitoring date. Sand accretion and erosion were recorded every 6 months at each aluminum stake at the same time as vegetation was sampled. This gave us 4 sand-movement estimates per block for each observation period. On each occasion we recorded the level of sand in relation to a previously marked "zero line" according to the methods followed by Ranwell (1958) and Moreno-Casasola (1982; 1986). Strictly speaking, these measurements only denote the net 6-months balance of sand accretion and sand loss and do not necessarily correspond to the amount of sand movement. If during the 6-months period sand accretion exactly compensated for the amount of sand loss, we would detect a net balance of zero even though intense movement of sand might have occurred. Nevertheless, we think that the net changes we registered provide an approximate indication of substrate mobility, and the values were considered to be good estimates of sand movement. The created vegetation was surveyed every 6 months, at the onset of the rainy (May–June) and the "nortes" (October–December) seasons, over a 5-y period. On each occasion, species composition, total plant cover, percentage of bare sand, and abundance of each plant species per quadrat were estimated. Species abundance was estimated by means of the modified Braun–Blanquet scale (Westhoff & van der Maarel, 1978), where 1 = 1–2 individuals, covering < 5% of the sampled area; 2 = 3–10 individuals, covering < 5% of the sampled area; 3 = > 10 individuals, covering < 5% of the sampled area; 4 = numerous individuals, covering < 5% of the sampled area; 5 = plant cover 5–12.5%; 6 = plant cover 12.5–25%; 7 = plant cover 25–50%; 8 = plant cover 50–75%; and 9 = plant cover 75-100%. Individual trees were monitored to assess their survival.

Data analyses

Changes in species diversity were assessed by calculating Simpson's diversity and equitability indices (Magurran, 1988) for each artificial community and for every season during the 5-y period. We calculated Jaccard's Similarity Index in order to compare community composition among the 3 created communities and with that of the original community (Brower & Zar, 1977). We then calculated the relative frequency, relative cover (using the midpoint of each cover-abundance class), and importance values (as the sum of the first two) of the species found in the revegetated area. Finally, in order to summarize the changes in community composition occurring through time and in each rehabilitated area, we used Principal Component Analysis (PCA), using PC-ORD for Windows (McCune & Mefford, 1999). According to Kenkel (2006), when the "data do not encompass so great a range of environmental variation that species responses are non-linear" (as was our case), "biotic survey data are very often amenable to PCA". We carried out the PCA by combining the matrix from the first sampling date (1997 for *Opuntia* and 1998 for *Panicum* and *Paspalum* revegetation) and the last sampling date (December 2001).

Results

Sand movement and stabilization

The original vegetation before the expansion of the harbour of the Port of Veracruz showed a 90% plant cover, with 110 species and a Simpson diversity value of 0.36. Six months after the harbour expansion (and destruction of the original vegetation), the 3 created communities were successful at stabilizing the mobile sand, and practically the entire surface of the monitored plots was covered by vegetation (80-90%) (Table I). Substrate mobility was minimal. Throughout the 5-y monitoring period none of the plots lost its vegetation cover and the sand remained stabilized, except for a few spots with sporadic sand movement owing to human trampling.

Species composition and dynamics

The number of species in the created communities did not reach the number of species originally growing at the site (110 species) (Table I). Species richness varied greatly but in general increased throughout the 5-y monitoring period, especially in those plots revegetated with *Panicum* and *Paspalum*, where annual herbs grew well during the rainy periods. Diversity was also noticeably lower than that of the original vegetation (0.36) (Table I) throughout the study period. The dominance of a few species (*Panicum* and *Paspalum*) resulted in low diversity values even though species richness increased throughout. The most diverse plots were those revegetated with *Opuntia,* and the least diverse were those covered with *Paspalum*, although the latter reached a significant peak after 1 y. Over time, diversity increased slightly in *Opuntia*-covered plots but decreased in the other 2 treatments.

Jaccard's index, which was calculated to compare the different created communities with the original, revealed that less than 15% of the species originally growing at the site were shared with the subsequent communities (Figure 1a). Similarity with the original vegetation decreased noticeably in the *Opuntia*-dominated community after 3 y but increased slightly in the last years of monitoring. Seasonal fluctuations were observed in the *Paspalum* and *Panicum* communities owing to emerging annual herbs. The similarity between the *Panicum*-dominated community and the original vegetation increased during the "nortes" (November, October), while in the *Paspalum*-dominated community these similarity peaks were observed at the onset of the rainy periods (May–June) (Figure 1a). The 2 grass communities were more similar to each other than *Opuntia* was to either of them (Figure 1b). The *Opuntia*- and *Paspalum*-covered plots were the least similar lots throughout the 5-y period. Interestingly, similarity between the 3 treatments increased slowly over time.

The low diversity values calculated for the 3 created communities revealed reduced species richness, but this was mostly due to the dominance of a few species (Figure 2). In all cases, the created vegetation was dominated by the tall grass *Panicum maximum*, which invaded the entire artificial dune, along with some cosmopolite species such as *Bidens pilosa,* which is nevertheless a very common dune species in the region (Figure 2). The dominant species from the original community (*Randia laetevirens, Citharexylum ellipticum, Lantana camara*, *Chiococca coriacea*, and *Palafoxia lindenii*) were not found in the *Opuntia* community, except for *Palafoxia*, which arrived during our last observation. However, *Randia*, *Citharexylum*, *Lantana*, and *Ipomoea imperatii* appeared promptly and became established in the *Panicum* and *Paspalum* communities, although with smaller relative importance values than in the original community (Figure 2). *Chiococca coriacea* was not observed in any of the created communities. In the *Paspalum* community, the Mexican dune endemic *Palafoxia* became locally extinct, but it survived in the *Panicum*-community. By December 2001, *Panicum* and *Bidens* were the dominant species, and a few dune shrubs became important: *Coccoloba uvifera* in the *Opuntia* community and *Citharexylum* and *Lantana* in the *Panicum*- and *Paspalum*-dominated communities. *Paspalum langei* decreased its dominance, while *Panicum* invaded adjacent communities. In general, the composition of the new communities was dominated by opportunist species of environments different from coastal dunes.

The structure of the artificially created communities was somewhat similar to that of the vegetation originally growing in the system (Table II). Trees (such as *Bursera simaruba*, *Gliricidia sepium*, and *Casuarina equisetifolia*) remained relatively abundant in the *Opuntia* community,

TABLE I. Plant cover (%), total species richness, and Simpson Diversity Index throughout a 4- to 5-y monitoring period, in 3 mobile dune sites artificially revegetated with 3 dominant species, *Opuntia*, *Panicum*, and *Paspalum*, after the 1996 destruction of the original site.

Date	Cover			Species richness			Species diversity		
	Opuntia	*Panicum*	*Paspalum*	*Opuntia*	*Panicum*	*Paspalum*	*Opuntia*	*Panicum*	*Paspalum*
November 1997	80			39			0.1		
June 1998	84	89	90	29	37	31	0.11	0.08	0.08
November 1998	100	97	90	31	30	24	0.11	0.1	0.18
June 1999	97	88	90	47	31	35	0.11	0.09	0.16
November 1999	97	88	90	35	44	49	0.13	0.06	0.04
May 2000	90	91	90	37	41	43	0.13	0.06	0.05
October 2000	86	98	100	41	54	56	0.12	0.06	0.04
May 2001	90	97	100	42	37	41	0.11	0.07	0.05
December 2001	90	97	100	37	43	47	0.13	0.06	0.05

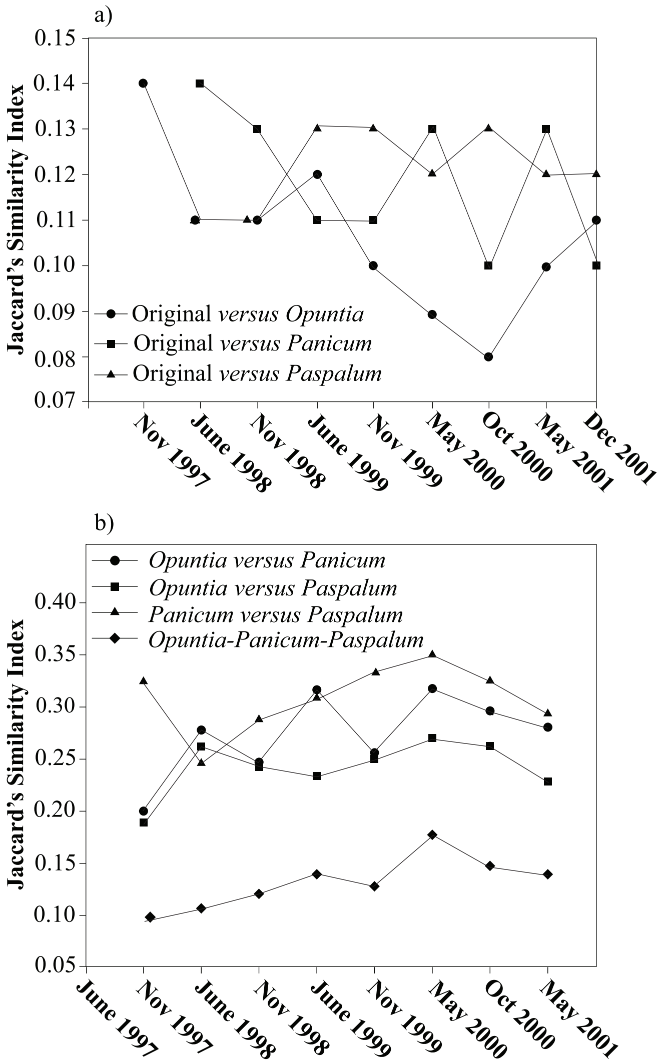

Figure 1. Jaccard's Similarity Indices calculated to compare the different revegetation techniques applied to an artificial mobile dune. a) Comparison with original vegetation; b) Comparison among the 3 dominant species used to rehabilitate.

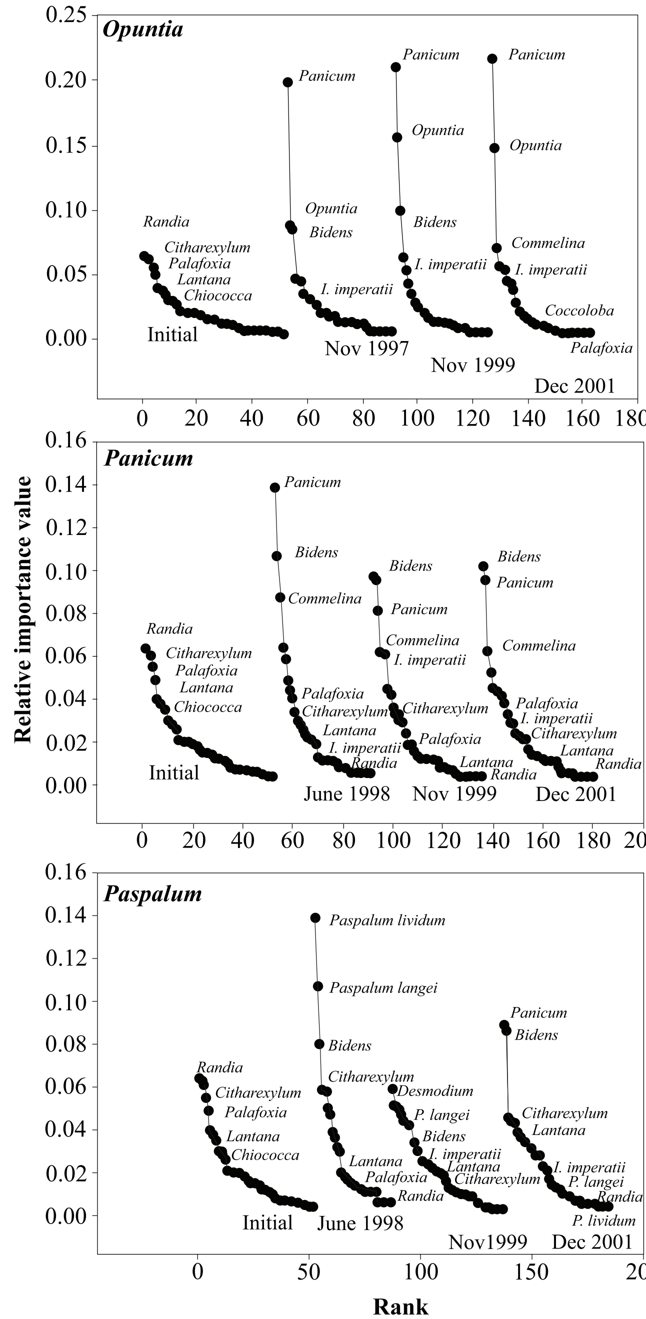

Figure 2. Changes in species dominance in 3 mobile dune sites revegetated with different combinations of species.

mostly owing to a larger number of trees planted in these plots, mainly *Casuarina*. By contrast, trees were scarce or even non-existent in the *Panicum* and *Paspalum* communities, mostly because fewer trees were planted in these communities. Shrubs (*Acacia cornigera*, *Crotalaria incana*) decreased noticeably in the *Opuntia*-dominated community but remained relatively abundant in the other 2 communities (*Acacia cornigera*, *Citharexylum ellipticum*, *Lantana camara*, *Trixis inula*, *Randia laetevirens*, *Erythrina herbacea*). Herbs (*Bidens pilosa*, *Baltimora recta*, *Cynodon dactylon*, *Desmodium adscendens*, *Cenchrus echinatus*, *Cnidosculus herbaceous*, *Schrankia quadrivalvis*, *Croton glandulosus*) remained equally abundant in all the treatments. In comparison with the original vegetation, vines (*Cissus sicyoides*, *Dalechampia scandens*, *Ipomoea batatas*, *I. imperatii*, *Merremia dissecta*, *Macroptilium atropurpureum, Passiflora foetida*, *Rhynchosia americana*, *R. minima*, *Stilozobium pruriens*) increased more than twofold in the 3 created communities.

Figure 3 shows principal component analysis for 2 sets of data: the first sampling in the monitoring study, performed in 1997 and 1998, and the last one in the study, performed in 2001. The first 2 axes explain 29.72% of the variance. Some of the 2001 *Opuntia* plots did not change significantly, remaining similar to the 1997 plots; these are shown close together in the ordination space. Other plots changed their composition, being located near the centre of the ordination space in 2001. The *Panicum* plots for the 2 dates remained very similar, showing little change. On the other hand, the *Paspalum* plots, which in 1998 appeared

TABLE II. Community structure of three mobile dune sites revegetated with different combinations of species (*Opuntia*, *Panicum*, and *Paspalum*). Values represent the percentage of species with listed growth form observed in each observation period.

Date	Trees (%)	Shrubs (%)	Herbs (%)	Vines (%)
ORIGINAL				
June-97	16	20	56	8
OPUNTIA				
Nov-97	5	18	59	18
June-98	7	3	66	24
Nov-98	6	10	58	26
June-99	17	11	47	26
Nov-99	11	3	57	29
May-00	14	3	62	22
Oct-00	12	2	61	24
May-01	12	5	60	24
Dec-01	11	8	57	24
PANICUM				
June-98	0	24	49	27
Nov-98	3	13	60	23
June-99	0	16	52	32
Nov-99	2	16	57	25
May-00	3	25	45	28
Oct-00	2	7	64	27
May-01	5	19	46	30
Dec-01	0	14	56	30
PASPALUM				
June-98	3	19	61	16
Nov-98	3	18	44	35
June-99	3	17	60	20
Nov-99	2	16	55	27
May-00	5	19	56	21
Oct-00	2	14	61	23
May-01	2	17	51	29
Dec-01	0	17	55	28

intermingled with the *Panicum* plots, had changed by 2001; many now appear in another part of the ordination space. One of the main changes was the reduction in frequency and plant cover of the 2 *Paspalum* species. The first axis can be interpreted as a temporal gradient. Most of the open figures (2001 sampling) for the 3 floristic compositions appear towards the right of the ordination graph, while 1997 plots are mainly located towards the left. The second axis can be interpreted as a gradient of sites and thus of species composition and vegetation structure.

Discussion

In this study we sought to test whether 3 artificially created communities could provide lost ecological services (protection from erosion and sand blasting), using 3 revegetation options that we had available at the time. This approach did not meet the definition of ecological restoration ("the process of assisting the recovery of damaged, degraded, or destroyed ecosystems"; SER, 2004), but it is similar to that of rehabilitation as defined by the Society of Ecological Restoration ("rehabilitation emphasizes the reparation of ecosystem processes, productivity and services" and does not include the "re-establishment of the pre-existing biotic integrity in terms of species composition and community structure"; SER, 2004, http://www.ser.

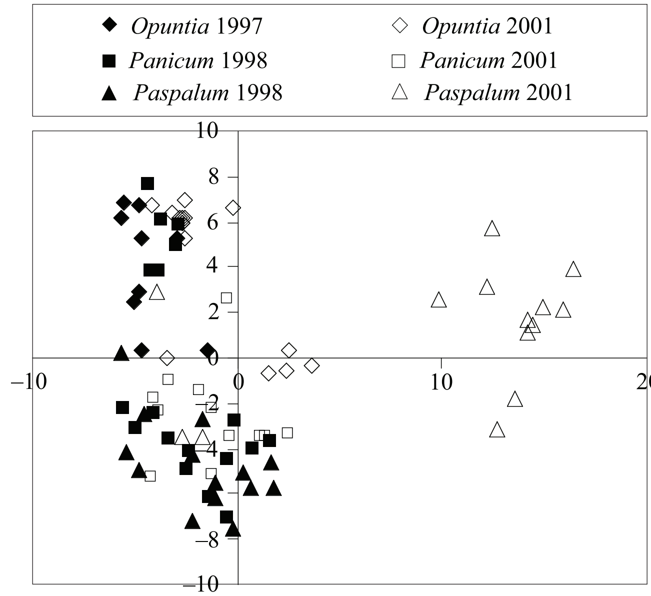

FIGURE 3. PCA ordination showing data for the first (1997 and 1998) and last (2001) monitoring surveys of the 3 areas.

org/content/ecological_restoration_primer.asp). The objectives of our revegetation project were appropriate for the conditions at our study site and the goals set for the project. Multiple restoration objectives, other than those of recovering damaged, degraded, or destroyed ecosystems, may be needed given "the tremendous diversity of both ecological conditions and the ways in which humans interact with nature" (Ehrenfeld, 2000). In this sense, it is important to acknowledge that restoration projects carried out to meet the goals of conserving species or entire ecosystems, of providing specific services, or of revegetating extremely damaged lands are all legitimate activities. None is superior or inferior to the other. Rather, they are appropriate under certain sets of conditions (Ehrenfeld, 2000).

How can we test whether we reached our goal? Hobbs and Norton (1996) suggest a set of criteria to assess success in ecological restoration. These criteria are largely focused on ecosystem attributes: 1) composition (species and their relative abundances); 2) pattern and structure (vertical and horizontal arrangement of vegetation and of system components); 3) heterogeneity (composition, pattern, and structure); and 4) function (performance of basic ecological processes, *e.g.*,, water, energy, nutrient transfers) and dynamics (successional processes, recovery from disturbance). These criteria might also apply to revegetation projects and even created ecosystems (as in our case).

COMPOSITION AND STRUCTURE

The literature reveals several successful restoration/rehabilitation projects on coastal dune communities, in which at least some taxa converge with the original communities (Grootjans *et al.,* 1997; Lubke & Avis, 1998; Pickart, Miller & Duebendorfer, 1998; Pickart *et al.,* 1998; van Aarde, Smit & Claassens, 1998; Grootjans *et al.,* 2001; Rozé & Lemauviel, 2004; Redi, van Aarde & Wassenaar, 2005; Wassenaar *et al.,* 2005; Zamith & Scarano, 2006). In general, these projects avoided growth of dense stands of a few dominant species, and patches with original vegetation were located in the vicinities of these sites. In our case, as we expected, initial species composition, diversity, and community structure (relative percentage of species with different growth forms) were not similar to the original community (the *Panicum* and *Paspalum* sites were grasslands, the first 80 cm high and the second 25 cm). However, these attributes changed over time, and the 3 created communities slowly came to resemble the original vegetation as time progressed. Several shrubs, such as *Lantana camara*, *Randia laetevirens*, and *Citharexyllum ellipticum*, managed to colonize the revegetated areas after a few years, thus increasing local biodiversity and adding complexity to community structure. The communities closer to the remnants of the original vegetation (*Panicum* and *Paspalum*) resembled more the original vegetation (Figure 1), although still with low values (< 15%), due to colonization by these shrubs. This makes it evident that remnant patches of original vegetation play a significant role in community restoration, rehabilitation, or revegetation (Grootjans *et al.,* 2001; Sawchik *et al.,* 2002; Redi, van Aarde & Wassenaar, 2005; Zamith & Scarano, 2006).

In addition to those species typical of coastal thicket and tropical rain forest, we also observed that many species typical of nearby communities soon appeared in the 3 revegetation treatments. *Bidens pilosa*, *Commelina erecta*, *Acacia cornigera*, *Macroptilium atropurpureum*, *Iresine celosia*, and *Cenchrus echinatus* are frequent inhabitants of stabilized dunes (Castillo & Moreno-Casasola, 1996; 1998). Others are frequent in pastures (*Sida rhombifolia*, *Setaria geniculata*) or in disturbed sites (*Ageratum conyzoides*, *Ipomoea batatas*, *Desmodium infractum*, *D. tortuosum*, *Trixis inula*, *Tridax procumbens*). A few typical sand dune species returned (*Erigeron myrionactis*, *Fimbristylis cymosa*, *Lantana camara*, *Randia laetevirens*, *Schrankia quadrivalvis*, *Citharexyllum ellipticum*, *Ipomoea imperatii*); these species are relatively tolerant to the harsh environment of exposed sand.

Changes in species dominance were very dynamic, and the importance values of species belonging to the original community increased over time. The relatively higher diversity values obtained in the *Opuntia* community can be explained by the growth form of these plants, which allows more empty space to be colonized by other plants and provides perching sites and food for local birds that may in turn disperse seeds from nearby communities, such as tropical rain forest (field observations). In contrast, there was little bare sand left to be colonized in the plots dominated by the grass species, *Panicum* and *Paspalum*. *Panicum* is a tall grass that expands quickly, taking over and producing an 80- to 100-cm-tall vegetation cover. *Paspalum* spp. are much shorter plants, but they also spread quickly (from 50–75% cover to 75–100%), and the strips used to cover the sand had a high vegetation cover from the very beginning (90%). Nevertheless, native shrubs managed to colonize (although in low numbers) these grass-dominated communities. However, the expansion of *Panicum* throughout the vegetated area may, in the long term, prevent further arrival of native species. Thus, growth of dense stands of this grass should be controlled to prevent the development of a nearly monospecific community.

Function

In local dunes, succession includes a grassland phase in which shrub species (*Randia laetevirens*, *Opuntia stricta*, *Citharexyllum ellipticum*, and *Lantana camara*)—all bird dispersed—start forming patches in the grassland matrix. With time, they form thickets that eventually constitute a tropical dry forest (Moreno-Casasola, 2004a,b). The presence of individuals of these species, although still in low numbers, is indicative of the beginning of a natural successional replacement.

Based on the above, we may state that the goals of the revegetation project were successfully achieved. Within the first year after revegetation, the 3 artificial communities accelerated the colonization and species turnover processes and withstood effectively the impact of strong northerly winds, thus preventing the occurrence of further erosion and sand blasting into adjacent houses. In terms of functionality and provision of ecosystem services (protection from sand blasting and encroachment), the 3 artificial communities were similar to the original.

Conclusion

In this study, the goals of the revegetation project concentrated on preventing the drifting sand from encroaching onto adjacent inland human populations were successfully achieved. Remnant patches with original native vegetation (coastal thickets and tropical dry forest) played an important role in species turnover and promoted colonization by thicket and tropical dry forest species. The presence of these dune shrubs dispersed by birds is probably facilitating the successional sequence and is indicative of an incipient reestablishment of the original vegetation in terms of vegetation structure and composition.

Human-induced disturbances may be in some cases so devastating that recovery is impossible. In these cases, rehabilitation or revegetation may provide the only possibility of “mending” the severely damaged ecosystem. However, it is very important to bear in mind that when possible, revegetation should not replace restoration with native species, which, in addition to offering sand-binding properties, provide biodiversity-related ecosystem services.

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Literature cited

Andersen, U. V., 1995. Succession and soil development in man-made coastal ecosystems at the Baltic Sea. Nordic Journal of Botany, 15: 91–104.

Avis, A. M., 1995. An evaluation of the vegetation developed after artificially stabilizing South African coastal dunes with indigenous species. Journal of Coastal Conservation, 1: 41–50.

Barbour, M. G., D. M. Rejmánek, A. F. Johnson & B. M. Pavlik, 1987. Beach vegetation and plant distribution patterns along the northern Gulf of Mexico. Phytocoenologia, 15: 201–233.

Brower, J. E. & J. H. Zar, 1977. Field and Laboratory Methods for General Ecology. Wm. C. Brown Company Publishers, Dubuque, Iowa.

Burke, L., Y. Kura, K. Kasem, C. Revenga, M. Spalding & D. McAllister, 2001. Coastal Ecosystems. World Resources Institute, Washington, DC.

Carvalho, D. A. & A. T. Oliveira-Filho, 1993. Avaliação da recomposição da cobertura vegetal de dunas de rejeito de mineração, em Mataracá/PB. Acta Botânica Brasílica, 7: 107–117.

Carter, R. W. G., 1991. Coastal Environments. Academic Press, London.

Carter, R. W. G, T. G. F. Curtis & M. J. Sheehy-Skeffington (eds.), 1992. Coastal Dunes: Geomorphology, Ecology and Management for Conservation. Proceedings of the 3rd European Dune Congress. Balkema, Rotterdam.

Castillo, S. & P. Moreno-Casasola, 1996. Sand dune vegetation: An extreme case of species invasion. Journal of Coastal Conservation, 2: 13–22.

Castillo, S. & P. Moreno-Casasola, 1998. Análisis de la flora de dunas costeras del Golfo y Caribe de México. Acta Botanica, 45: 55–80.

Choi, Y. D., 2007. Restoration ecology to the future: A call for new paradigm. Restoration Ecology, 15: 351–353.

Choi, Y. D. & N. B. Pavlovic, 1998. Experimental restoration of native vegetation in Indiana Dunes National Lakeshore. Restoration Ecology, 6: 118–129.

Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, S. Naeem, K. Limburg, J. Paruelo, R. V. O'Neill, R. Raskin, P. Sutton & M. ven den Belt, 1997. The value of the world's ecosystem services and natural capital. Nature, 387: 253–260.

Cronquist, A., 1988. The Evolution and Classification of Flowering Plants. The New York Botanical Garden, New York, New York.

Ehrenfeld, J. G., 2000. Defining the limits of restoration: the need for realistic goals. Restoration Ecology, 8: 2–9.

Freire, M. S. B., 1983. Experiencia de revegetacao nas dunas costeiras de Natal. Brasil Florestal, 53: 35–42.

Greipsson, S., 2002. Coastal dunes. Pages 214–237 *in* M. R. Perrow & A. J. Davy (eds.). Handbook of Ecological Restoration. Volume 2. Cambridge University Press, Cambridge.

Greipsson, S. & A. J. Davy, 1996. Sand accretion and salinity as constraints on the establishment of *Leymus arenarius* for land reclamation in Iceland. Annals of Botany, 78: 611–618.

Grootjans A. P., P. Jones, F. van der Meulen & R. Paskoff (eds.), 1997. Ecology and restoration perspectives of soft coastal ecosystems. Journal of Coastal Conservation, 3: 1–102.

Grootjans, A. P., H. Everts, K. Bruin & L. Fresco, 2001. Restoration of wet dune slacks on the Dutch Wadden Sea Islands: Recolonization after large-scale sod cutting. Restoration Ecology, 9: 137–146.

Hesp, P. A., 2000. Coastal Sand Dunes: Form and Function. Massey University, Auckland.

Hillen, R. & P. Roelse, 1995. Dynamic preservation of the coastline in the Netherlands. Journal of Coastal Conservation, 1: 17–28.

Hobbs, R. & D. A. Norton, 1996. Towards a conceptual framework for restoration ecology. Restoration Ecology, 4: 93–110.

Kenkel, N. C., 2006. On selecting an appropriate multivariate analysis. Canadian Journal of Plant Science, 86: 663–676.

Lubke, R. A. & A. M. Avis, 1998. A review of the concepts and application of rehabilitation following heavy mineral dune mining. Marine Pollution Bulletin, 37: 546–557.

Lubke, R. A., U. M. Hertling & A. M. Avis, 1995. Is *Ammophila arenaria* (marram grass) a threat to South African dune fields? Journal of Coastal Conservation, 1: 103–108.

Magurran, A. E., 1988. Ecological diversity and its measurement. Princeton University Press, Princeton, New Jersey.

Martínez, M. L., A. M. Maun & N. P. Psuty, 2004. The fragility and conservation of the world's coastal dunes: Geomorphological, ecological and socioeconomic perspectives. Pages 355–370 *in* M. L. Martínez & N. P. Psuty (eds.). Coastal Dunes: Ecology and Conservation. Springer-Verlag, Berlin.

Martínez, M. L., A. Intralawan, G. Vázquez, O. Pérez-Maqueo, P. Sutton & R. Landgrave, 2007. The coasts of our world: Ecological, economic and social importance. Ecological Economics, 63: 254–272.

Maschinski, J. & S. J. Wright, 2006. Using ecological theory to plan restorations of the endangered Beach jacquemontia (Convolvulaceae) in fragmented habitats. Journal for Nature Conservation, 3–4: 180–189.

McCune, B. & M. J. Mefford, 1999. PC-ORD for Windows: Multivariate Analysis of Ecological Data. Version 4.01. MjM Software Design, Gleneden Beach, Oregon.

Miranda, R. V., D. G. Barroso, C. S. Marinho & D. A. Carvalho, 1997. Estudo sobre a vegetação em dunas de rejeito de mineração no litoral norte do Estado da Paraíba. Revista Arvore, 21: 345–351.

Mitchell, A., 1974. Plants and techniques used for sand dune reclamation in Australia. International Journal of Biometeorology, 18: 168–173.

Moreno-Casasola, P., 1982. Ecología de la vegetación de dunas costeras: factores físicos. Biotica, 7: 577–602.

Moreno-Casasola, P., 1986. Sand movement as a factor in the distribution of plant communities in a coastal dune system. Vegetatio, 65: 67–76.

Moreno-Casasola, P., 2004a. Conservation and management of tropical sand dune systems. Pages 319–334 *in* M. L. Martínez & N. P. Psuty (eds.). Coastal Dunes: Ecology and Conservation. Springer-Verlag, Berlin.

Moreno-Casasola, P., 2004b. Playas y dunas del Golfo de México. Una visión de su situación actual. Pages 491–520 *in* M. Caso, I. Pisanty & E. Ezcurra (eds.). Diagnóstico ambiental del Golfo de México. SEMARNAT (INE)-INECOL-Harte Research Institute for Gulf of Mexico Studies.

Nordstrom, K. F., R. Lampe & L. M. Vandemark, 2000. Reestablishing naturally functioning dunes on developed coasts. Environmental Management, 25: 37–51.

Nordstrom, K. F., N. Psuty & B. Carter, 1990. Coastal Dunes: Form and Process. Wiley, Chichester.

Nordstrom, K. F., N. L. Nancy, M. S. Bruno & H. A. de Butts, 2002. Municipal initiatives for managing dunes in coastal residential areas: A case study of Avalon, New Jersey, USA. Geomorphology, 47(2–4): 137–152.

Palmer, M. A., E. S. Bernhardt, E. A. Chornesky, S. L. Collins, A. P. Dobson, C. S. Duke, B. D. Gold, R. Jacobson, S. Kingsland, R. Kranz, M. J. Mappin, M. L. Martínez, F. Micheli, J. L. Morse, M. L. Pace, M. Pascual, S. Palumbi, O. J. Reichman, A. L. Simons, A. Townsend & M. Turner, 2004. Ecology for a crowded planet. Science, 304: 1251–1252.

Pickart, A. J., L. M. Miller & T. E. Duebendorfer, 1998. Yellow bush lupine invasion in Northern California coastal dunes, I: Ecological impacts and manual restoration techniques. Restoration Ecology, 6: 59–68.

Pickart, A. J., K. C. Theiss, H. B. Stauffer & G. T. Olsen, 1998. Yellow bush lupine invasion in northern California coastal dunes, II: Mechanical restoration techniques. Restoration Ecology, 6: 69–74.

Ranwell, D. S., 1958. Movement of vegetated sand dunes at Newborough Warren, Anglesey. Journal of Ecology, 48: 83–100.

Redi, B. H., R. J. van Aarde & T. D. Wassenaar, 2005. Coastal dune forest development and the regeneration of millipede communities. Restoration Ecology, 13: 284–291.

Ritchie, W. & C. H. Gimingham, 1989. Restoration of coastal dunes breached by pipeline landfalls in north-east Scotland. Proceedings of the Royal Society of Edinburgh, 96B: 231–245.

Rozé, F. & S. Lemauviel, 2004. Sand dune restoration in North Brittany, France: A 10 year monitoring study. Restoration Ecology, 12: 29–35.

SER (Society for Ecological Restoration) International Science and Policy Working Group, 2004. The SER International Primer on Ecological Restoration. [URL] www.ser.org and Tucson: Society of Ecological Restoration International. [URL] http://www.ser.org/content/ecological_restoration_primer.asp

Sawchik, J., M. Dufrene, P. Lebrun, N. Schtickzelle & M. Baguette, 2002. Metapopulation dynamics of the bog fritillary butterfly: Modeling the effect of habitat fragmentation. Acta Oecologica, 23: 287–296.

Siemens, A., P. Moreno-Casasola & C. Sarabia, 2006. The metabolization of wetlands by the city of Veracruz, Mexico. Journal of Latin American Geography, 5: 7–29.

Spurgeon, J., 1998. The socio-economic costs and benefits of coastal habitat rehabilitation and creation. Marine Pollution Bulletin, 37: 373–382.

van Aarde, R. J., S. M. Ferreira, J. J. Kritzinger, P. J. van Dyk, M. Vogt & T. D. Wassenaar, 1996. An evaluation of habitat rehabilitation on coastal dune forests in northern KwaZulu-Natal, South Africa. Restoration Ecology, 4: 334–345.

van Aarde, R. J., A. M. Smit & A. S. Claassens, 1998. Soil characteristics of rehabilitating and unmined coastal dunes at Richards Bay, KwaZulu-Natal, South Africa. Restoration Ecology, 6: 102–110.

van der Maarel, E., 1993a. Dry Coastal Ecosystems: Polar Regions and Europe. Elsevier, Amsterdam.

van der Maarel, E., 1993b. Dry Coastal Ecosystems: Africa, America, Asia and Oceania. Elsevier, Amsterdam.

Wassenaar, T. D., R. J. van Aarde, S. L. Pimm & S. M. Ferreira, 2005. Community convergence in disturbed subtropical dune forests. Ecology, 86: 655–666.

Webb, C. E., I. Oliver & A. J. Pik, 2000. Does coastal foredune stabilization with *Ammophila arenaria* restore plant and arthropod communities in southeastern Australia? Restoration Ecology, 8: 283–288.

Webster, P., J. Holland, G. J. Curry & H. R. Chang, 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. Science, 309: 1844–1846.

Westhoff, V. & E. van der Maarel, 1978. The Braun–Blanquet approach. Pages 287–399 *in* R. H. Whittaker (ed.). Classification of Plant Communities. Junk Publishers, The Hague.

Wright, S. J., A. Frances, K. Griffin & J. Maschinski, 2006. Propagation protocol for *Jacquemontia reclinata* House, a federally endangered species of south Florida. Native Plants Journal, 7: 301–306.

Zamith, L. R. & F. R. Scarano, 2006. Restoration of a restinga sandy coastal plain in Brazil: Survival and growth of planted woody species. Restoration Ecology, 14: 87–94.