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Plant Diversity as a Suitable Tool for Coastal Dune Vulnerability Assessment

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ABSTRACT

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The investigation reported here is concerned with the use of plant diversity measures for coastal dune monitoring. The original set of recorded plant species on dune systems was broken into 3 functionally homogeneous groups, which allow ecological comparisons among foredune vegetation on a much wider sense than traditional taxonomic approaches. Plant diversity was measured both, as species richness and as the rate of species number increase with area. Plant diversity values were tested as a dependent variable of a coastal dune vulnerability Index. Increasing coastal dunes vulnerability, caused by natural or human events, lowered the rate of species increase with area within the plant functional type associated to prograding foredunes. Results suggest that plant diversity within this functional type, measured as the slope of the species-area curve, may be used as a management tool for predicting coastal dune vulnerability.

ADDITIONAL INDEX WORDS: *Foredune, management, plant functional type.*

INTRODUCTION

Coastal sand dunes are increasingly perceived as areas worthy of sustainable development. They provide a cost-effective natural means of coastal defence as well as a range of habitats for a diverse community of highly specialised animal and plant species (CARTER, 1991). Coastal dunes are particularly vulnerable to anthropogenic erosion and many of the dune systems in Europe are under threat from a wide variety of different human pressures (WILLIAMS, 1998). In this context, there is a need for provision of suitable tools for periodic measurement that will help in coastal dune management.

According to this, a series of indices, enclosing a wide number and types of variables, have been developed for assessing the vulnerability or sensitivity of coastal dunes to the various environmental changes which occur, both natural and human (ALVEIRIHNO-DIAS *et al.,* 1994; ARENS and WIERSMA, 1994; BODERE *et al.,* 1994; DAVIES *et al.,* 1995; WILLIAMS and BENNETT, 1996). However, these complex, multidisciplinary and multivariate data involve a main problem for any coastal dune management program, since managers have to handle with physical, biological and human variables (KEPNER and TREGOE, 1976).

On the other hand, diversity measures are integrated expressions of the community composition and may be easily quantified, having been widely proposed as an indicator of the condition of the ecosystems (MAGURRAN, 1989). According to this, and because of the close links between foredunes dynamics and foredunes vegetation (VAN DER MAAREL *et al.,* 1985; HESP, 1984; STUDER-EHRENSBERGER *et al.,* 1993; EISMA, 1997, among others) our aim was to evaluate the plant diversity patterns of foredunes, as an alternative tool for coastal dune managers to assess coastal dune condition.

STUDY AREA

The study area was the Gulf of Cadiz (SE Portugal- SW Spain), a semidiurnal mesotidal coast with mean tidal ranges of 2.1 m and variations to 0.45 m between successive flood or ebb tides (BORREGO and PENDÓN, 1989). Waves have medium intensity energy, 75% of the waves being ≤5m in height (ZAZO *et al.,* 1992). The most prominent dynamic feature is the active longshore drift towards east and southeast, generated by prevailing SW winds (DABRIO and POLO, 1987). This coastline is characterised by extensive sandy beaches prone to drifting sand and fringed by dune fields. Foredunes average 6 m in height and 75 m in width (FLOR, 1995).

The area has a Mediterranean type climate under oceanic influence. Winter temperature average of 9.3°C in the coldest months (January and December) and 23.9°C during the warmest summer month (July). Annual rainfall average 550 mm, 80% of which falls between October and March. Summer drought is severe, with no precipitation during July and August and little rainfall in June and September. Prevailing winds have a southwest component favouring a net inshore movement of sand.

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Table 1. *Plant functional types in foredunes (GARCÍA MORA* et al., *1999).*

Plant Trait	PFT_I	PFT_{II}	PFT_{III}
Life span	Winter annual	Perennial	Perennial or summer annual
Vegetative height	Below 15 cm	Indifferent	Above 15 cm
Underground structures	Shallow fibrous or thin tap	Thick spreading or deep	Thick spreading or deep
Leaf adaptations to coastal environmental stress	Absent	Present	Present
Capability of withstanding deep sand burial	Absent	Absent	Present
Seawater dispersion capability	Absent	Absent	Present

METHODS

30 dune systems of the Gulf of Cadiz, from Caños de Meca, close to the Straits of Gibraltar, to Loule Velho in Portugal (300km long stretch), were selected covering a wide range of dune types and forcing. Dune condition was assessed according to a Dune Vulnerability Index (VI) developed by BODERE *et al.,* (1991). The index is designed to determine the vulnerability of dune systems to multiple impacts through the application of a checklist, and provides an important measure of the manner in which coastal dune respond to imposed change (WILLIAMS and BENNETT, 1996). The vulnerability of a dune is defined as a reduced ability to adapt to change (WILLIAMS *et al.,* 1993). Four characteristics of the checklist, combining 43 variables give the Dune Vulnerability Index (Appendix I): *(A)* Site and Dune Morphology, 8 variables; *(B)* Condition of the Beach, 9 variables; *(C)* Surface Character of the Seaward 200 m, 12 variables and *(D)* Pressure of Use, 14 variables.

In essence each variable is associated with a five point sliding scale grading from zero to four. Summation of variables ranking within each variable class, expressed as a percentage of the total available for each section, let calculate the vulnerability accounted for each characteristic of the checklist. Summation of all raw data expressed as a percentage of the total available allows a VI to be calculated. The Vulnerability Index ranges between 0 and 1, and as the index increases, the ability of the dune system to withstand further interventions decreases.

The application of this Vulnerability Index proved to be useful in the assessment of the condition of coastal dunes, at least in England (WILLIAMS, 1998), France (BODERE *et al.,* 1991), Portugal (ALVEIRIHNO-DIAS *et al.,* 1994; MATIAS *et al.,* 1998) and Spain (GARCÍA MORA *et al.,* 1997).

A matrix with the vulnerability values of the four characteristics of the checklist for the 30 sampled sites was subjected to a classification analysis using between group average clustering (UPGMA by SPSS *v.6.0* software package). The square euclidean distance was used as the measure for association.

VI was assigned to every classified site, and two foredune condition classes where established from the main clustering dichotomy.

The composition of vegetation at each sampled foredune was recorded between October 1996 and September 1998. At each dune site a 62,5 × 4m plot was marked along the sea-facing slope of the frontal dune with the long axis parallel to the shore, avoiding the inclusion of secondary dunes or inland deposits of any nature. With a nested sampling approach we recorded the number of vascular plant species in 40 0,25m^2; 20 2,5m^2; 10 25m^2 and 1 250m^2.

Most foredunes hold a small number of plant species with low plant densities (CARTER, 1995), and the use of traditional diversity indexes such as Simpson or Shannon (PEET, 1975) failed to provide a useful diversity measure for monitoring the coastal dunes. In the present study plant diversity was computed as species richness in 250m^2 plots and as the slope of the species/area curve in the log-log space (*Z*), since diversity pattern described by the species-area curves has more evidence to support it than any other about species diversity (ROSENZWEIG, 1996).

Anyhow, as pointed out by HUSTON (1996) biological diversity is better understood when considering functional groups of species (*i.e.* plant functional types). The mechanisms controlling the number of plant functional types (PFTs) on a community are almost always different from the mechanisms that influence the number of functionally analogous species within a functional type. In this sense, an increasing number of analogous species within the more tolerant PFT to the current dominant stresses should be associated to an increased stability and continuity of the ecosystems, in the face of disturbance or environmental change. Moreover, plant functional types have been widely proposed as an ecological alternative to traditional taxonomic entities (*i.e.* species), in assessing the impacts of potential environmental changes in ecosystems (LEISHMAN and WESTOBY, 1992; BOUTIN and KEDDY, 1993; CHAPIN *et al.,* 1996; SHAO *et al.,* 1996; SKARPE 1996; GUITAY and NOBLE, 1997).

According to this, and for the purpose of this paper, we divided foredune vegetation into three specific functionally based subsets of species (Table 1), according to foredune dynamics and the main environmental stresses, as described by GARCÍA MORA *et al.,* (1999). Functional types are here defined as sets of species sharing similar structural and functional attributes, exhibiting similar responses to environmental conditions, that can usefully be lumped into groups by multivariate classification, with which ecosystem behaviour can be interpreted and predicted (GARCÍA MORA *et al.,* 1999). The three plant functional types, named Type I, II and III, cooccur in many European foredunes but their relative dominance depends on local environmental conditions. Dominance of Type III plants characterises prograding foredunes; Type II plants dominate receding foredunes and a larger proportion of Type I plants is a characteristic of stable foredunes or dunes subjected to intense human influence (GARCÍA MORA *et al.,* 1999).

For computing the diversity indexes, the recorded plant

Table 2. *Analysis of Variance of the pattern of species richness increase with area considering the total set of species and within each PFT (dependent variables) by Vulnerability Index (factor).*

		D.F	F Ratio	F Prob.	Group	N	95% Conf. Int. for Mean
Total	Between gr.	1	5.6081	0.0250	VI < 0.49	16	0.2529 To 0.3409
	Within gr.	28			VI ≥ 0.49	14	0.3201 To 0.4199
PFT_I	Between gr.	1	1.83	0.1949	VI < 0.49	9	0.4340 To 0.7949
	Within gr.	16			VI ≥ 0.49	9	0.2909 To 0.6424
PFT_{II}	Between gr.	1	0.0092	0.9245	VI < 0.49	12	0.3501 To 0.5633
	Within gr.	23			VI ≥ 0.49	13	0.3440 To 0.5562
PFT_{III}	Between gr.	1	16.4737	0.0004	VI < 0.49	16	0.2081 To 0.2819
	Within Gr.	28			VI ≥ 0.49	14	0.3171 To 0.4183

species were substituted for their functional type (Appendix II), and plant species diversity was calculated for the complete set of species and functional types.

The various plant species diversity values were treated as the dependent variable of the condition of the foredunes in a One Way ANOVA.

The Dune Vulnerability Index values were plotted against the slope of the species/area curve within PFTs when the pattern of species accumulation was found to be statistically different among sites of different vulnerability index range.

RESULTS

The 30 sampling sites were split in two groups according to the main clustering dichotomy. Group I showed medium to high resilience values, VI ranging between 0.16 and 0.47. Group II showed lower resilience values, VI ranging between 0.49 and 0.72.

A total of 55 vascular species, belonging to 49 genera and 22 families were recorded. Specific richness ranged from 3 to 25 species per 250m^2. No statistical differences in total species richness or in number of species within each functional type were apparent among sites of different vulnerability conditions.

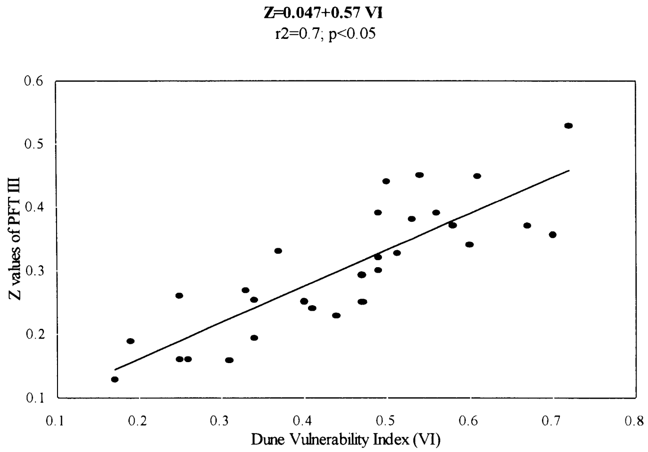

Figure 1. Linear regression of Type III plant diversity (measured as Z) against foredune condition (Vulnerability Index). As the Vulnerability Index grows due to increased disturbance the values of Z also rises, indicating a decrease in plant diversity values.

The species-area relationship at all sites fitted with a linear log-log model:

$$\log S = \log c + Z \log A \qquad (r > 0.9; p < 0.01).$$

Where log c is the S-intercept for species richness (*i.e.* diversity) when area is 1 m^2 and Z, the slope, describes the rate of diversity increase with area (ROSENZWEIG, 1996). Both, log c and Z, are fitted constants.

The patterns of species accumulation within the total set of species and, to a higher extent, within Functional Type III was found to be statistically different among sites of different vulnerability index range (VI ≥ 0.49 and VI < 0.49) but not when considering Plant Functional Types I or II (Table 2).

This is further shown in the linear positive relationships which was found between the rate of species increase with area within Type III plants and the values of Vulnerability Index (Figure 1).

DISCUSSION

In coastal dunes most environmental changes are reflected in the vegetation performance. The plant community is altered by a selective dieback of the less tolerant species and through a rapid temporal succession of opportunistic species (CARTER, 1995). In general, these changes in the community structure are brought together with a shift in the dominant plant functional type, favoured by the contemporary environmental stresses.

According to HUSTON (1996), the species diversity within each functional type should exhibit contrasting patterns in response to varied dune conditions. Also the abundance of species belonging to a particular functional type may increase while another may decrease in response to the same environmental changes. Changes in PFT_{III} species diversity, as estimated from the rate of species increase with area, fit well with this assumption since higher diversity values (*i.e.* lower Z values) are related to increasing dune resilience (*i.e.* lower VI).

The total number of species per plot and within type species richness do not change in response to the different coastal dune conditions. These results suggest that the main effects of increasing dune vulnerability to the vegetation performance are not predominantly related with invasion-extinction processes but with changes in plant species distribution. These changes in plant species distribution mainly concern type III plants, largely including species particularly associated to dynamic foredunes. Under conditions of natural disturbance in highly resilient foredunes there is not much habitat heterogeneity and vegetation becomes evenly distributed. As an average, all sites sustain a similar vegetation cover with a dominant percentage of Type III plants (García Mora *et al.,* 1999). As human influence increases or dune resilience level decreases, the habitat heterogeneity evolves into a mosaic of contrasted patches. Each foredune patch can be regarded as a short-term environmental island separated from others by high disturbance corridors. In these modified dune patches, Type III plants are more sensitive to disturbance, and are either partially removed or replaced by the other two functional types, although when considering the whole sampling plot the total species richness may remain unchanged. Increasing dune vulnerability increases the rate of Type III species accumulation with area, because the species/area curve rises by pulses when including isolated non-disturbed patches. Under low vulnerability conditions the species/area curve within PFT$_{\mathrm{III}}$ increases smoothly, as plant species tend to exhibit random spatial distributions and the total number of species of the area may be encountered in a wide range of the nested sampling plots.

Plant Functional Type III species are key factors in foredune development. It is the vulnerability of this plant functional type what makes the dunes sensitive to impact. Loss of foredune resilience can be understood in terms of a decrease in Functional Type III plants diversity. Thus, in order to preserve the state of natural dune system, management measures must be focused on natural maintenance of Type III plant populations.

For the purpose of coastal dune monitoring, the diversity of PFT$_{\mathrm{III}}$, measured as the value of the species/area slope, has proved to be a useful biological indicator of the degree of disturbance within the foredune habitat. For the Gulf of Cadiz, dune resilience levels may be inferred from Z values using a simple lineal model and PFT$_{\mathrm{III}}$ diversity may be used for monitoring the condition of coastal dunes.

This biological indicator may also be of applicability in other dune systems, as plant functional types used in this approach are based on foredune dynamics and the main coastal stresses affecting foredune habitats, regularly perturbed by the same major environmental stresses all over the world (Barbour *et al.,* 1985; Clark, 1986; Seelinger, 1992). Anyhow further research is needed in order to know whether the relation among VI and Z holds for a wider geographical context and whether it will be feasible for each biogeographical region constructing a regression line to tell dune condition from plant diversity.

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Appendix I: *Coastal Sand Dune Vulnerability Checklist (from BODERE* et al. *1991).*

		Scores				
		0	1	2	3	4
	Section A: Site and dune morphology					
1	Orthogonal fetch	short [ ]		medium [ ]		long [ ]
2	Surface area of dunes (ha)	>500 [ ]		>100 [ ]		<100 [ ]
3	Length of dune coast (km)	>20 [ ]	>10 [ ]	>5 [ ]	>1 [ ]	>0.1 [ ]
4	Width of dune belt (km)	>5 [ ]	>2 [ ]	>1 [ ]	>0.1 [ ]	<0.1 [ ]
5	Maximum height of dunes (m)	>25 [ ]	>10 [ ]	>5 [ ]	>1 [ ]	<1 [ ]
6a	If ridged: number of major ridges	>10 [ ]	5–9 [ ]	3–4 [ ]	2 [ ]	1 [ ]
6b	If plastered to slope: slope steepness	moderate [ ]		gentle [ ]		steep [ ]
6c	If perched on cliff: cliff height (m)	<2 [ ]		2–5 [ ]		>5 [ ]
7	Relative total area of wet slacks	moderate [ ]		small [ ]		none [ ]
8	Particle size in foredunes	[ ]	[ ]	[ ]	[ ]	[ ]
	Compare particle size with Phi sizes	≤−1	0	+1	+2	+3
	Total score/percentage:					
	Section B: Condition of the beach					
1	Width of inter-tidal zone (km)	>0.5 [ ]	>0.2 [ ]	>0.1 [ ]	>.05 [ ]	<0.05 [ ]
2	Sand supply input	high [ ]		moderate [ ]		low [ ]
3	Pebble cover as % of surface	0 [ ]	<5 [ ]	>5 [ ]	>25 [ ]	>50 [ ]
4	% foredunes cliffed by the sea	0 [ ]	<25 [ ]	>25 [ ]	>50 [ ]	>75 [ ]
5	Dune cliff as % dune height	0 [ ]	<25 [ ]	>25 [ ]	>50 [ ]	>75 [ ]
6	Breaches in seaward face	none [ ]		some [ ]		many [ ]
7	Width of breaches in seaward face	<2 [ ]		2–10 [ ]		>10 [ ]
8	Seaweed on upper beach	much [ ]		some [ ]		none [ ]
9	Colonisation by vegetation in zone between Dune face and HWSM	much [ ]		some [ ]		neg [ ]
	Total score/percentage:					

Appendix I: *Continued.*

		Scores				
		0	1	2	3	4
	Section C: Surface character of seaward 200m					
1	% system surface unvegetated	<10 [ ]	>10 [ ]	>20 [ ]	>40 [ ]	>75 [ ]
2	Blowouts as % of system area	<5 [ ]	>5 [ ]	>10 [ ]	>20 [ ]	>40 [ ]
3	Sand blown inland from system	little [ ]		some [ ]		much [ ]
4	Saltwater invasion of dunes	none [ ]		some [ ]		much [ ]
5	% new dunes along seaward edge	>50 [ ]	>25 [ ]	>5 [ ]	<5 [ ]	0 [ ]
6	% breaches with new dunes	>75 [ ]	>50 [ ]	>25 [ ]	>5 [ ]	0 [ ]
7	% seaward dune front vegetated	>90 [ ]	>60 [ ]	>30 [ ]	>10 [ ]	<10 [ ]
8	If recent sand deposition assess colonisation by	much [ ]		some [ ]		none [ ]
9	% impenetrable cover	some [ ]		little [ ]		none/much [ ]
10	Frontal change since 1940	advance [ ]		oscil. [ ]		retreat [ ]
11	Vegetation change since 1940	inc. [ ]		oscil. [ ]		decr. [ ]
12	Relic quarries in frontal 200m	none [ ]		small [ ]		large [ ]
	Total score/percentage:					
	Section D: Pressure of Use					
1	Visitor pressure	low [ ]		moderate [ ]		high [ ]
2	Road access	none [ ]		moderate [ ]		good [ ]
3	On-dune driving	none [ ]		some [ ]		much [ ]
4	Horse riding	none [ ]		some [ ]		much [ ]
5	Path network density	low [ ]		medium [ ]		high [ ]
6	Paths incised	little [ ]		moderate [ ]		deep [ ]
7	Commercial camping	little [ ]		some [ ]		much [ ]
8	Dispersed camping	little [ ]		some [ ]		much [ ]
9	Housing	little [ ]		some [ ]		much [ ]
10	Owners	one [ ]		some [ ]		many [ ]
11	Main owner/manager	protect [ ]		public [ ]		priv. [ ]
12	Commercial/random extraction	none [ ]		some [ ]		much [ ]
13	Grazing by cattle/sheep/goats	none [ ]		some [ ]		much [ ]
14	Rabbit population	small [ ]		moderate [ ]		large [ ]
	Total score/percentage:					
						Vulnerability score and index:

Appendix II. *Non phylogenetic plant species groupings of the recorded species according to GARCIA MORA* et al. *(1999).*

PFT$_{I}$	PFT$_{II}$	PFT$_{III}$
Anacyclus radiatus	*Armeria pungens*	*Ammophila arenaria*
Arctotheca calendula	*Artemisia crithmifolia*	*Arundo donax*
Bromus diandrus	*Carpobrotus edulis*	*Cakile maritima*
Bromus rigidus	*Crucianella maritima*	*Calistegia soldanella*
Carduus meonanthus	*Helychrysum picardii*	*Cyperus capitatus*
Chenopodium album	*Linaria lamarkii*	*Elymus farctus*
Chenopodium murale	*Linaria pedunculata*	*Eryngium maritimum*
Cutandia maritima	*Lotus creticus*	*Euphorbia paralias*
Emex espinosa	*Malcolmia littorea*	*Euphorbia peplis*
Erodium cicutarium	*Ononis variegata*	*Medicago marina*
Hedypnois cretica	*Pycnocomon rutifolium*	*Otanthus maritimus*
Hypochaeris glabra	*Reichardia gaditana*	*Pancratium maritimum*
Lagurus ovatus	*Silene ramosissima*	*Polygonum maritimum*
Malva hispanica	*Thymus carnosus*	*Salsola kali*
Medicago littoralis		*Sporobolus pungens*
Medicago minima		
Paronichia argentea		
Plantago coronopus		
Pseudorlaya pumilla		
Rumex tingitanus		
Scolymus maculatus		
Senecio vulgaris		
Solanum nigrum		
Sonchus oleraceus		
Sonchus tenerrimus		
Vulpia alopecurus		