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Relationships between coastal sand dune properties and plant community distribution: The case of Is Arenas (Sardinia)

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Abstract

Coastal dune environments are selective ecosystems characterized by a close interaction between abiotic and biotic factors in a dynamic balance. The present study focused on the psammophilous geosigmetum, the most affected by the interactions between physical processes and biological and anthropic processes. The main purpose was to study the relationships between the abiotic properties of the dune and the presence of the various plant communities, combining morpho-sedimentological, geopedological, and geobotanical data. The study was carried out on the well-preserved dune system of Is Arenas (CW Sardinia) which is one of the most important in the Mediterranean area. The analyses revealed differences at the morphodynamic, sedimentological, and geopedological levels. The micro-topography of the dunes affects the values of the main abiotic variables, and determines the presence of various microhabitats of great heterogeneity. This work shows that the data on the geomorphological dynamics and the chemical–physical processes, correlated with the geobotanical analyses, might make it possible to identify the ecosystemic processes, and thereby plan adequate management and conservation strategies for this coastal dune system.

Keywords: *Coastal dunes, geomorphology, psammophilous vegetation, Sardinia, sedimentology*

Introduction

Coastal dune environments are complex, vulnerable and characterized by a close interaction between abiotic and biotic components. These ecosystems are highly variable because of shifting substrate, burial by sand, bare areas among plants, the porous nature of sands, and little or no organic matter, especially during the early stages of dune development (Maun 2009). Comparative sedimentological and geobotanical studies make it possible to highlight the relationships that exist among these components, verifying the incidence of the local micro-environmental factors (e.g., morphology and micro-topography of the dune, appearance, and structure of the plant communities, exposure to winds and marine aerosol, solid fraction, and aerosol transport) on the entire ecosystem, starting from the consideration that the morphological, sedimentological, and geobotanical properties are closely correlated to the beach type (Hesp 1991).

Multidisciplinary studies on coastal ecosystems have long been conducted in Europe, because of the growing interest connected with the increase in use by tourists and the resulting human-induced alterations (Hesp 1988; Frederiksen et al. 2006; Álvarez-Rogel et al. 2007; Nordstrom et al. 2007).

Coastal dune ecosystems consist of highly permeable and generally xeric substrates, soils that are pedogenetically uninvolved, and specialized psammophilous vegetation. They are mainly controlled by the interaction between the sediment transport processes and the ecological responses of plants (Baas & Nield 2007) such as the morphological adaptations of psammophilous species (life cycle, growth form, biological form, phenology, plant height).

Williams et al. (2001) highlighted among the factors that have the most impact on the morphology and evolution of dune systems, the influence of the sea, effects of the wind, vegetation, human activities, and kinds of sedimentary deposits. Hesp (2002)

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pointed out how plant density and the distribution, height, and cover of the biotic communities, together with wind speed and sand transport rates, influence the morphological development of dunes.

Dune systems are characterized by environmental gradients that determine the coexistence of different aspects of vegetation in relatively small spaces (Wilson & Sykes 1999; Frederiksen et al. 2006); in fact, one of the main characteristics of coastal dunes is their high environmental heterogeneity associated to the variability of the plant communities (Van der Maarel 2003), which form complex mosaics (Shanmugam et al. 2003; Acosta et al. 2005).

Coastal flora and vegetation are associated with a tolerance to the consistency and salinity gradient of sediments, wind, marine aerosol, and the presence of brackish water (Barbour & De Jong 1977). In well-preserved dune ecosystems, it is assumed that the typical vegetation zonation is closely connected with the geomorphological and sedimentological characteristics of the system (Aboudha et al. 2003). Any alteration of the morphology of dune systems causes the fragmentation of the vegetation zonation, with the replacement of the most common phytocoenosis and, in the most severe cases, the disappearance of the sensitive biocoenosis (Acosta et al. 2007; Zedda et al. 2010). The backdune (BD) vegetation should be progressively less exposed to the rigid conditions of the foredunes (FDs) and, therefore, less tolerant to salt spray, winds, and sand burial (Wiedemann & Pickart 2004; Acosta et al. 2009). However, since the abiotic factors act simultaneously and change rapidly, the fundamental causes of vegetation zonation are poorly understood (Forey et al. 2008).

The main objective of the study was to analyze, at the single morphological unit level, the ecological relationships between environmental variables and vegetation pattern in a coastal dune system, through the integration of morpho-sedimentological, geopedological, and geobotanical analyses. Our study focused on the dune system of Is Arenas (CW Sardinia), where the coastal dunes are well-conserved, due to the low level of human disturbance. The specific aims of the study were: (1) to compare areas of the dune system having different geomorphological characteristics; (2) to analyze the trend of the geopedological variables in relation to the distance from the coastline and the vegetation cover; (3) to compare the non-vegetated zone and that colonized by vegetation, in order to highlight the presence of ecological gradients, and verify their influence on the psammophilous zonation, and (4) to analyze the relationships between vegetation communities and the geopedological characteristics of the substrate. The study made it also possible to set up a network of permanent study areas, useful for monitoring the dune system for management purposes in the context of long-term habitat conservation.

Materials and methods

Study area

The dune system of Is Arenas (Figure 1), covering about 1000 ha in the northeastern sector of the Sinis Peninsula (CW Sardinia), is one of the most important and well-preserved coastal systems of the western Mediterranean basin. Geologically, the oldest outcrop limits refer to the Oligo-Miocene period, but the area mainly consists of Quaternary deposits that form a sedimentary complex; Holocene sandstones and aeolian sands form the upper limit of the succession (Carboni et al. 1998).

The beach, oriented in a perpendicular direction with respect to the northwest wind (Spano & Pinna 1956), presents a transverse profile, characterized by a submerged beach, an intertidal zone, a backshore averaging 20–40 m width (Spano & Pinna 1956), and a well-developed dune system. On the basis of the morphological characteristics, the beach can be classified among the intermediate multibar systems trending toward intermediate-reflecting to the North-East (NE) and intermediate-dissipative to the South-West (SW) (Carboni et al. 2003). Right behind the beach, the sands have accumulated into dune cordons, forming parabolic dunes that develop perpendicularly to the coastline, with irregular heights ranging between 20 and 40–45 m (Federici et al. 1995).

The hydrographic network is formed by the torrential Rio Pischinappiu, with a flow rate that essentially depends on the autumn and spring rainfalls, and the mouth of which opens onto the northern part of the beach.

Based on available climatic data (Riola Sardo, 10 m a.s.l.), the area has the typical Mediterranean annual trend of temperatures and precipitations. The annual mean temperature is 16.9°C, the coldest months are January and February, and the hottest are July and August. The annual mean rainfall is 536.7 mm, with a peak in November (94.8 mm) and a dry summer (lowest value in July with 3 mm). Bioclimatically this area is classified as oceanic pluviseasonal Mediterranean, with an upper thermo-Mediterranean thermotype and upper dry ombrotype (Fenu & Bacchetta 2008).

Data sampling

Two sites were selected along the backshore: one in the northern part and another one in the southern part of the dune systems. All together, six transects (three per site) were drawn running from the coastline to the BDs, as far as the limit of the wooded area (Table I). Along the non-vegetated zone of each transect, sediment samples were taken from the main morphological units [coastline, ordinary berm, storm berm, mid-beach, scarp toe, scarp crest, FD, and dune crest (DC)] every 3 months; all in all, considering the seasonal presence of each morphological unit, a total of 54 samplings were carried out (21 in June; 16 in September; 8 in December; 9 in March). In the embryo dune, the most affected by the morpho-sedimentological process, 25 (2 × 2 m) permanent plots were randomly established, and monitored on a quarterly basis. Within the plots, sedimentological and geopedological samplings, floristic inventories, and phytosociological relevés were carried out. Considering the low level of anthropic disturbance, human impacts were not considered in this study.

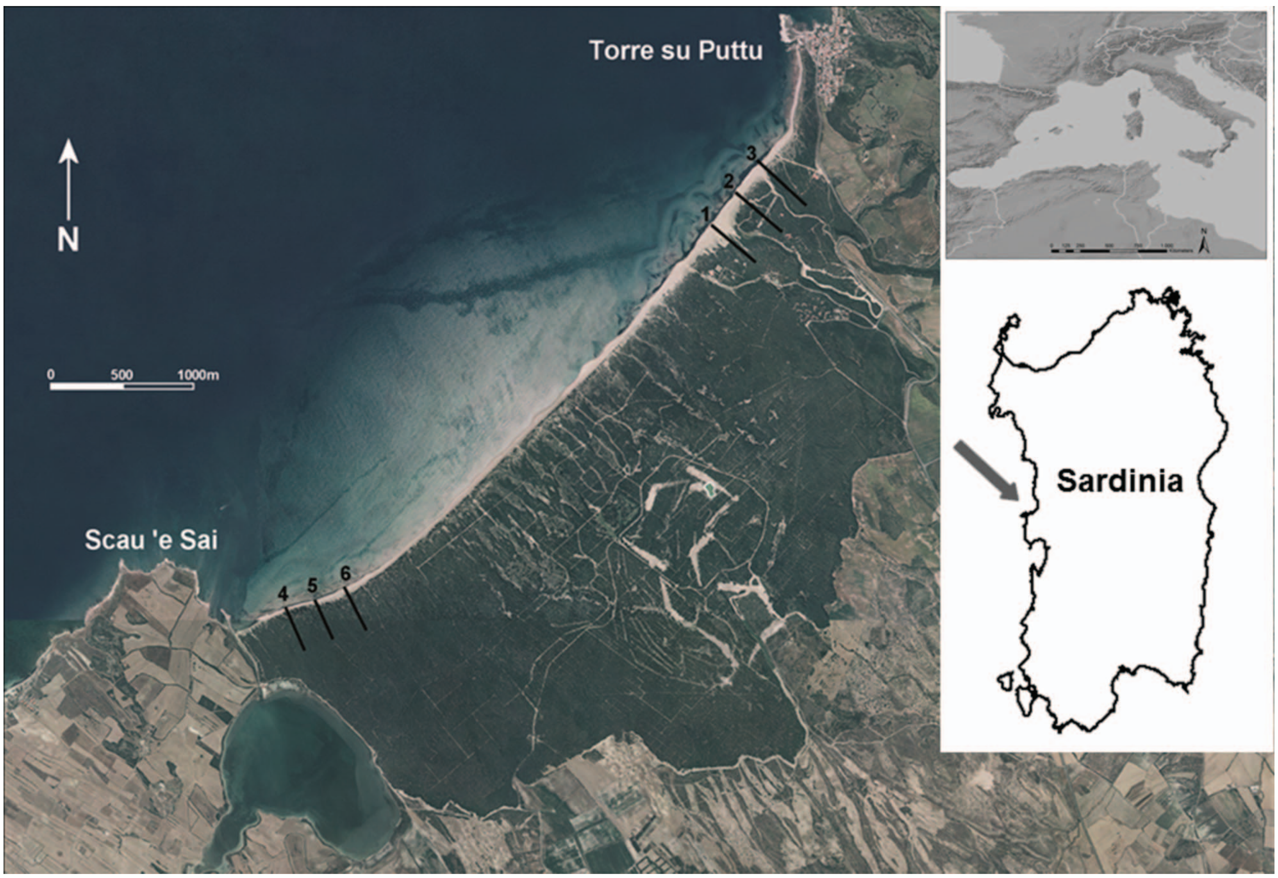

Figure 1. Aerial photograph of the study area; the black lines indicate the position of the sampling transects (see Table I).

Table I. General characteristics of transects, with coordinates, mean length of each transect (based on four seasonal measures), altitude range, aspect, slope, and number of permanent plots.

Transect	Zone	Coordinates	Mean length (m)	Altitude (m a.s.l.)	Aspect (°)	Slope (°)	No. of plots
T1	North	N – 40°04′497 E – 8°29′106	56.6	2–7	W270	5	6
T2	North	N – 40°04′539 E – 8°29′126	50.4	3–5	NW300	2–3	4
T3	North	N – 40°04′671 E – 8°29′264	42	1.5–3	N330	20	4
T4	South	N – 40°02′955 E – 8°26′810	19.4	0.5–2	NW330	5	3
T5	South	N – 40°02′960 E – 8°26′820	26.7	1–2	NW300	5–10	4
T6	South	N – 40°03′036 E – 8°27′098	17.6	1–3	N345	45	4

Morpho-sedimentological analyses

In the morpho-sedimentological sampling, the total length of each transect and the distances among the morphologies were measured, in order to verify the seasonal variations of the profile and the width of the beach.

The sediment samples, consisting of ca. 200 g of sand taken from the surface (between 0 and 5 cm depth) so as to represent a single sedimentation event, were dried at 110°C for 24 h, before being analyzed.

The grain size analyses were performed by dry sieving for 10 min, using a set of 32 sieves with mesh sizes ranging from 4 to 0.06 mm, following Wentworth (1922). The data was expressed graphically by grain size distribution curves and processed following Folk and Ward (1957) to determine mean grain size.

Geopedological analyses

The samples were air-dried and passed through a 2-mm sieve before laboratory analysis. For the analysis of pH, a sand sample of 20.00 ± 0.02 g in solution with 50 ml distilled water (ratio 1:2.5) was used; after shaking the solution for 5 min with a mechanical shaker, the pH reading was obtained using a PC510 multiparameter pH-meter, equipped with a Hamilton Polilyte Lab sensor.

Following the Dietrich–Fruhling method, the carbonate content of a sand sample (0.82 g) was assessed by acid attack using 20 ml of diluted HCl (ratio 1:1), using a Bernard's calcimeter (SISS 1985).

To estimate the organic matter content, the Walkley–Black method was used, based on the principle of oxidation of the organic substance by 10 ml of K_2Cr_2O in 20 ml of H_2SO_4 at 96%, at the temperature reached due to the effect of the sudden dilution of the sulfuric acid (SISS 1985).

For conductivity measurements, an aqueous extract was analyzed (water–sediment ratio 2:1), using an ASAL 711 orbital shaker at 120–140 cycles/min and a Eutech Instruments conductivity meter. A mixture of 10 g sand and 20 ml H_2O was shaken for 120 min and then left to rest overnight; after filtration of the aqueous extract, the conductivity value at 25°C, expressed in μS cm^{-1}, was measured.

Geobotanical analyses

All the plants present within the plots were recorded, and a floristic inventory was prepared. Phytosociological relevés were carried out (four times for each plot) according to the Sigmatist School of Zurich-Montpellier (Braun Blanquet 1965), resulting in a dataset of 100 surveys.

For the taxonomical identification of the specimens, the nomenclature, and the biological and chorological category, reference was made to Fenu and Bacchetta (2008).

Statistical analyses

Significant relationships between geomorphological parameters and the distance from the coastline were tested using Pearson's correlation coefficient. The mean values of the geopedological analyses obtained for the northern and southern sites of the beach were compared using the non-parametric Kolmogorov–Smirnov test. The mean values obtained for the three main morphologies (FD, DC, BD) were compared at first using the non-parametric Kruskal–Wallis test and then using the non-parametric Kolmogorov–Smirnov test.

The Mann–Whitney *U* inferential statistical test was applied to evaluate significant differences between sample medians of non-vegetated and vegetated zones.

From a phytosociological point of view, the relevés performed in each plot from March until June were selected and a matrix of "50 relevés × 58 species" was prepared, in which the values were transformed according to Van der Maarel (1979). The matrix was subjected to multivariate analysis using the average linkage hierarchical clustering algorithm; the dendrogram obtained from the cluster analysis made it possible to identify the main vegetation types, which were then compared with the plant communities described in previous studies (Bartolo et al. 1992; Mayer 1995). The values relating to the environmental parameters of the single plots were grouped together on the basis of the phytocoenoses identified; the results were analyzed by pairwise comparisons of the mean values of two contiguous plant communities, using the non-parametric Kolmogorov–Smirnov test. All statistical analyses were carried out using the Statistica 6.0 software (Statsoft, USA).

Results

Morpho-sedimentological analyses

The greatest mean beach width (Table II) was recorded in June (76.38 ± 37.76 m), while the lowest value was observed in September (65.63 ± 33.09 m). The seasonal measurements showed a greater width of the backshore in the northern area (Table II). In summer, the northern area had a linear shoreline and greater beach width than the southern part (114.76 ± 16.81 m and 38.00 ± 9.89 m, respectively). In autumn, a general retreating trend was observed both in the southern part (95.43 ± 16.18 m), with a cuspidate shoreline, and in the

Table II. Seasonal values registered for the backshore and for the northern and southern areas. In bold are the significantly different values between north and south ($p < 0.05$ by the Kolmogorov–Smirnov test).

		June		September		December		March	
	Variable	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Beach	Length (m)	76.38	37.76	65.63	33.09	74.33	30.10	67.53	33.91
	No. of vascular plant species	7.80	3.37	5.00	2.17	6.80	2.88	8.64	3.70
	Vegetation cover (%)	75.40	21.07	52.60	24.86	51.80	29.32	66.20	26.24
	Conductivity (μS cm^{-1})	1,387.63	2,209.19	1,498.66	2,523.85	1,019.57	1,808.85	877.85	1,738.97
	pH	8.72	0.30	8.43	0.31	8.40	0.43	8.41	0.43
	Organic matter (g kg^{-1})	2.42	4.51	2.82	5.25	2.14	5.60	1.69	3.36
	Calcimetry (g kg^{-1})	72.43	10.23	71.46	6.76	74.77	6.46	75.96	6.33
	Mean grain size (mm)	0.30	0.66	0.30	0.66	0.30	0.69	0.29	0.70
Northern area (north)	Length (m)	114.76	16.81	95.43	16.18	97.86	26.05	95.96	25.48
	No. of vascular plant species	7.71	3.39	4.71	2.02	6.29	2.28	8.07	3.61
	Vegetation cover (%)	73.93	20.01	46.43	24.38	49.29	30.05	63.93	25.65
	Conductivity (μS cm^{-1})	679.64	1,122.20	1,047.96	1,726.09	960.65	1,578.46	623.55	1,135.65
	pH	8.75	0.21	8.53	0.25	8.37	0.44	8.43	0.40
	Organic matter (g kg^{-1})	**0.89**	0.88	1.57	1.16	0.59	0.47	**0.74**	0.58
	Calcimetry (g kg^{-1})	**75.51**	9.90	73.26	7.37	**78.12**	4.86	**79.23**	4.91
	Mean grain size (mm)	**0.41**	0.80	**0.42**	0.83	**0.38**	0.81	**0.38**	0.87
Southern area (south)	Length (m)	38.00	9.89	35.83	12.34	50.80	5.09	39.10	5.84
	No. of vascular plant species	7.91	3.34	5.36	2.31	7.45	3.39	9.36	3.67
	Vegetation cover (%)	77.27	22.19	60.45	23.20	55.00	28.04	69.09	26.70
	Conductivity (μS cm^{-1})	2,488.94	2,919.06	2,074.56	3,179.75	1,110.23	2,111.62	1,241.14	2,297.23
	pH	8.67	0.40	8.30	0.31	8.44	0.41	8.37	0.48
	Organic matter (g kg^{-1})	**4.50**	6.28	4.40	7.52	4.85	8.62	**3.05**	4.89
	Calcimetry (g kg^{-1})	**67.63**	8.79	69.15	5.00	**68.89**	4.38	**71.28**	71.28
	Mean grain size (mm)	**0.19**	0.93	**0.19**	0.88	**0.19**	0.98	**0.19**	0.19

northern part (35.83 ± 12.34 m) where the shoreline remained straight. In winter, the shoreline in the northern part showed a new advancement compared to the previous season (97.86 ± 26.05 m), while in the southern part an anomalous increase in the width of the backshore was recorded (50.80 ± 5.09 m). In spring, a retreat of the shoreline was observed in both areas, with values of 95.96 ± 25.48 and 39.10 ± 5.84 m to the north and south, respectively.

The morphological structuring of the beach underwent considerable seasonal variations: in summer there were several morphologies (coastline, ordinary berm, storm berm, mid-beach, scarp toe, scarp crest, FD, and DC) while, during the remaining seasons, a progressive homogenization of the morphologies was observed.

Grain size varied from 0.30 ± 0.66 mm in June to 0.29 ± 0.70 mm in March (Table II). The two areas examined (Table II) showed significant differences in mean grain size of the sediments: the northern part was characterized by sands of medium grain size, while the southern part consisted of fine grain sands. The grain size curves reveal a mainly bimodal and unimodal distribution in the sediments of the northern and southern zone, respectively (Figure 2a, b).

Considering all samples ($n = 154$), mean grain size showed a general decrease with increasing distance from the coastline ($r = -0.586$; $p < 0.001$; Figure 3) and, consequently, significant differences were found between the non-vegetated and vegetated zones (Table III), but not among the consecutive morphologies (Table IV).

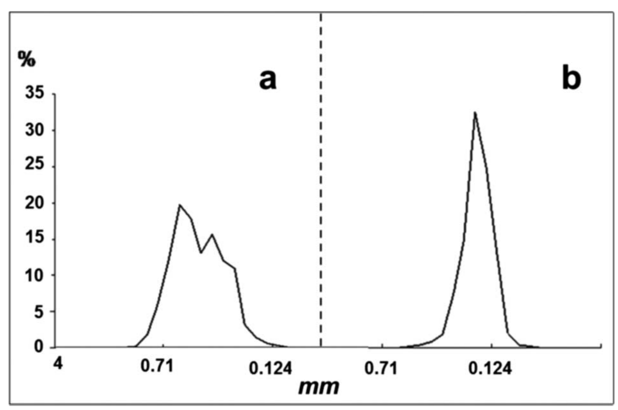

Figure 2. Grain size distribution curves obtained for the northern (a) and southern (b) areas of the beach.

Geopedological analyses

The highest conductivity values were measured in September, while the lowest ones in March (Table II). The range of variation in the single samplings was quite high, and fell between 26 μS cm^{-1} in March, and 13,800 μS cm^{-1} in September. Conductivity values underwent higher seasonal variations in the southern part of the beach,

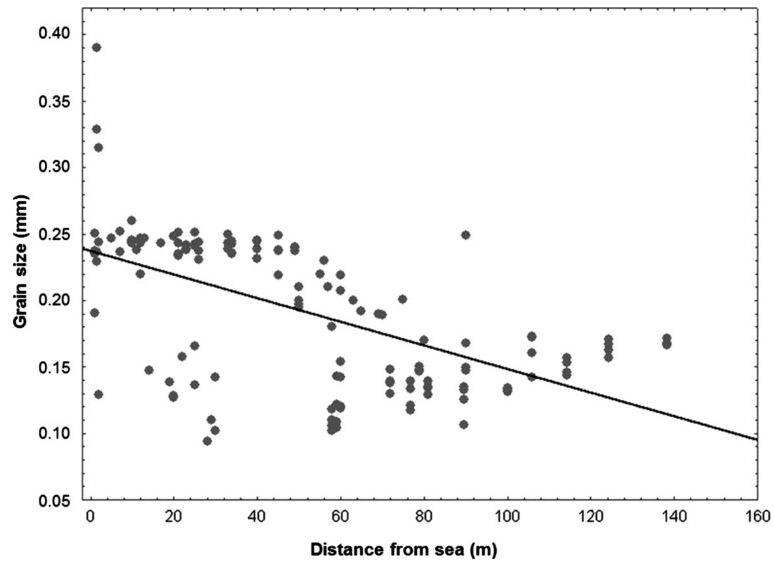

Figure 3. General reduction of average grain size with increasing distance from the coastline, considering all samples ($n = 154$).

Table III. Differences in the geopedological and sedimentological parameters between the non-vegetated and vegetated zones registered for the backshore, and for the northern and southern areas ($n = 154$, with 92 samples from the northern area and 62 from the southern area).

	Non-vegetated dunes		Vegetated dunes		Significance
	Mean	SD	Mean	SD	(Mann–Whitney *U* test)
Beach					
Conductivity (μS cm^{-1})	2,664.11	2,807.31	307.37	565.15	$p < 0.001$
pH	8.39	0.52	8.57	0.25	NS
Organic matter (g kg^{-1})	1.82	4.68	2.47	4.82	NS ($p < 0.05$ only in December)
Calcimetry (g kg^{-1})	73.59	8.58	73.29	7.61	NS
Mean grain size (mm)	0.34	0.65	0.28	0.70	$p < 0.001$
Northern area					
Conductivity (μS cm^{-1})	1,878.68	1,864.01	165.84	149.61	$p < 0.001$
pH	8.41	0.51	8.63	0.18	NS
Organic matter (g kg^{-1})	0.94	0.79	1.99	0.98	NS
Calcimetry (g kg^{-1})	76.65	7.90	76.15	7.69	NS
Mean grain size (mm)	0.45	0.09	0.38	0.06	$p < 0.001$
Southern area					
Conductivity (μS cm^{-1})	3,821.39	3,565.59	530.73	866.47	$p < 0.001$
pH	8.34	0.63	8.50	8.31	NS
Organic matter (g kg^{-1})	3.90	2.89	4.24	6.66	NS
Calcimetry (g kg^{-1})	69.88	8.50	68.84	5.50	NS
Mean grain size (mm)	0.29	0.16	0.19	0.02	NS

but these differences were not statistically significant (Table II). Conductivity also showed an ecological sea-inland gradient, with high values close to the shoreline (>1000 μS cm^{-1}), and lower ones toward the inland, with values dropping to ≤ 100 μS cm^{-1} and minimum value of 50 μS cm^{-1} (Table IV). The mean pH value for the beach remained similar throughout the seasons, with fluctuations ranging between 7.30 in March and 9.35 in June, and similar values in the two sites analyzed. The highest seasonal values were recorded in June and the lowest in December (Table II). The organic matter content was highest in September, and lowest in March, with fluctuations between 0 and 30.69 g kg^{-1} recorded in June/December and September, respectively. In all seasons, mean values were higher in the southern zone than in the northern one (Table II). The carbonate content was higher in March and lower in September; unlike organic matter, this parameter always showed significantly lower values in the southern part of the beach, with the exception of September (Table II).

The comparison between the non-vegetated and vegetated zones revealed large differences in conductivity and mean grain size, while pH, carbonate content, and organic matter content were similar

Table IV. Seasonal comparison of the main morphologies (values for plots). In bold are the values that are significantly different between FD and BD at $p < 0.05$ (by the Kolmogorov–Smirnov test).

		June		September		December		March	
	Variable	Mean	SD	Mean	SD	Mean	SD	Mean	SD
FD	Distance from sea (m)	34.40	20.57	40.67	23.43	38.50	20.90	38.50	20.90
	No. of vascular plant species	**4.00**	1.41	**3.16**	0.89	**3.83**	1.34	**4.83**	1.21
	Vegetation cover (%)	**42.00**	13.27	**27.50**	14.36	**23.33**	12.80	**35.83**	17.89
	Conductivity (μS cm^{-1})	1,580.00	1,409.89	1,006.50	948.08	**556.33**	312.72	**288.00**	91.33
	pH	8.81	0.11	8.43	0.43	8.50	0.33	8.53	0.16
	Organic matter (g kg^{-1})	0.94	0.27	1.04	0.55	0.74	0.54	0.70	0.42
	Calcimetry (g kg^{-1})	68.07	9.33	75.78	7.85	78.34	7.35	77.36	6.36
	Mean grain size (mm)	0.25	0.65	0.28	0.68	0.29	0.65	0.27	0.67
DC	Distance from sea (m)	47.62	25.53	47.61	25.52	49.78	26.91	47.61	25.52
	No. of vascular plant species	7.50	2.70	5.00	1.73	5.83	1.95	7.16	2.40
	Vegetation cover (%)	77.50	11.46	53.33	19.72	44.16	30.33	64.16	27.14
	Conductivity (μS cm^{-1})	159.33	73.36	244.33	130.00	196.16	109.76	173.16	112.71
	pH	8.41	0.33	8.61	0.09	8.58	0.13	8.53	0.20
	Organic matter (g kg^{-1})	3.47	5.99	3.67	6.37	5.07	9.77	3.72	7.03
	Calcimetry (g kg^{-1})	73.43	11.92	73.29	5.04	72.39	7.56	73.74	7.69
	Mean grain size (mm)	0.28	0.28	0.29	0.68	0.27	0.71	0.26	0.70
BD	Distance from sea (m)	79.18	36.63	79.73	35.89	79.73	35.89	79.73	35.87
	No. of vascular plant species	**9.28**	3.01	**5.84**	2.24	**8.61**	2.37	**11.07**	3.05
	Vegetation cover (%)	**86.42**	12.31	**63.84**	22.28	**68.46**	21.78	**82.69**	9.32
	Conductivity (μS cm^{-1})	160.57	87.05	129.08	84.32	**126.23**	95.82	**80.92**	38.69
	pH	8.52	0.18	8.59	0.15	8.63	0.26	8.60	0.23
	Organic matter (g kg^{-1})	2.65	4.55	2.50	2.07	2.54	5.30	1.82	1.86
	Calcimetry (g kg^{-1})	71.38	8.15	68.81	4.83	72.35	4.85	74.81	4.96
	Mean grain size (mm)	0.28	0.70	0.29	0.75	0.28	0.67	0.28	0.74

(Table III). The conductivity values were higher in the non-vegetated zone than in those colonized by the psammophilous vegetation. Mean grain size was significantly higher in the non-vegetated zone, and so was the organic matter content, but only in December.

The seasonal comparison among the morphologies is reported in Table IV. The mean distance from the coastline remained essentially constant throughout the year for the DC and the BD; the mean distance of the FD from the coastline ranged from 34.40 ± 20.57 m (June) to 40.67 ± 23.43 m (September). Conductivity values were remarkably higher in the FD at all samplings; significant differences were only found between FD and BD, but not between consecutive morphologies. The pH remained constant in all samplings, and the calcimetry measurements, unlike conductivity, did not show an evident decrease going from the shoreline toward the interior. The organic matter content was higher, but not in a statistically significant way, in DC, where higher values of organic carbon are generally recorded.

Geobotanical analyses

The floristic survey made it possible to draw up an inventory with 75 taxonomic units, including 46 species, 27 subspecies, and 2 varieties, belonging to 34 families and 65 genera. The biological spectrum revealed the high value of the therophytes (35%), followed by phanerophytes/nanophanerophytes (20%), chamaephytes, and geophytes (16%; Appendix I).

In terms of chorology, the floristic inventory was mostly made up of Mediterranean taxa (89%) and, within this group, the circum-Mediterranean taxa were prevalent (34), followed by western Mediterranean (8) and Mediterranean-Atlantic (6) ones. Endemic species accounted for 13% of the total (Appendix I).

The mean number of taxa per plot was 7.06 ± 3.36, with fluctuations from 2 to 17 taxa per plot; the highest number of taxa was measured in March, the lowest in September (Table II). Within the dune system, floristic richness (Table II) was greater in the southern zone (7.52 ± 3.52 taxa per plot) compared to the northern one (6.69 ± 3.19 taxa per plot). Along each transect, the number of species progressively increased, reaching the highest values in the BD. Significant differences were found between FD and BD, while no significant differences occurred among the intermediate morphologies (Table IV).

The annual mean value of the vegetation cover was 61.50 ± 27.38%, with higher values in June and lower ones in September and December; the vegetation cover was constantly higher in the southern zone of the beach, but this difference were not statistically significant (Table II). Along each transect, as previously detected for the number of taxa, the vegetation cover reached higher values in the BD (annual mean of 75.86 $\pm$ 19.79%), compared to the DC and FD (annual means of 57.91 $\pm$ 26.99% and 33.95 $\pm$ 18.04%, respectively). In this case as well, significant differences were found between the FD and BD, while among the intermediate morphologies there were no statistically significant differences (Table IV).

The phytosociological surveys (Appendix II) allowed to identify six plant communities (Table V). Four of them refer to the Sardinian psammophilous geosigmetum (Bacchetta et al. 2009), while the one dominated by *Ephedra distachya* has not well been syntaxonomically defined, even though it is very common along the western and northern coasts of Sardinia (Fenu & Bacchetta 2008). The last group consists of a phytocoenosis dominated by *Eryngium maritimum*, attributable to aspects of degradation of the main plant communities. The mean values of biotic and environmental variables for each plant community are reported in Table VI.

The number of taxa and vegetation cover increased progressively along the psammophilous succession; significant differences in number of taxa were found between AGR and CRU, EPH and JUN, and AMM and JUN ($p < 0.05$ by the Kolmogorov–Smirnov test). Similarly, an increase was observed in vegetation cover, with the lowest values in the geophytic communities, and the highest ones in the forest communities; significant differences were observed only between the geophytic (AMM, ERY, and AGR) and phanerophytic communities ($p < 0.01$ by the Kolmogorov–Smirnov test).

The ERY communities were generally closer to the coastline, while AMM, CRU, and EPH were the furthest away (>64 m), but the statistical analysis did not reveal significant differences for the communities studied.

Conductivity values were highest in ERY and AGR, i.e., closest to the shoreline, and lowest in CRU, farther from the shoreline. The organic matter content was highest in scrub/forest coenoses (EPH and JUN), while considerably lower values were recorded in the other plant communities (≤ 1 g kg^{-1}), in particular in AMM (0.47 $\pm$ 0.48 g kg^{-1}). The calcimetry measurements gave the highest mean values in AMM and the lowest in JUN, and significant differences occurred only

Table V. Plant communities recorded in the Is Arenas dunal system. For each plant community, the main life-forms are reported and the relative ponderate percent of cover (in brackets).

Plant association	Main life-form	Abb.[1]	Habitat
Sileno corsicae–Agropyretum juncei Bartolo, Brullo, De Marco, Dinelli, Signorello & Spampinato 1992	G (92.36%)	AGR	Open psammophilous herbaceous vegetation of embryo dunes
Sileno corsicae–Ammophilethum arundinaceae Bartolo, Brullo, De Marco, Dinelli, Signorello & Spampinato 1992	G (91.15%)	AMM	Closed psammophilous herbaceous vegetation of mobile dunes
Eryngium maritimum L. community	G (84.23%)	ERY	Open psammophilous herbaceous vegetation of embryo and mobile dunes
Pycnocomo rutifolii–Crucianelletum maritimae Géhu, Biondi, Géhu-Frank & Taffetani 1987	C (72.04%)	CRU	Chamaephytic vegetation of semi-stable dunes
Ephedro–Helicrysetum tyrrhenici Valsecchi & Bagella 1991 *corr.*	NP (68.90%)	EPH	Nanophanerophytic vegetation of semi-stable dunes.
Pistacio–Juniperetum macrocarpae Caneva, De Marco & Mossa 1981	P (75.46%)	JUN	Coastal juniper microforest of stable dunes.

Note: [1]Abb. = Abbreviation for this plant association considered in this study.

Table VI. Characteristics of the plant communities analyzed.

	Distance from sea (m)		No. of vascular plant species		Vegetation cover (%)		Calcimetry (g kg^{-1})		Conductivity (μS cm^{-1})		Organic matter (g kg^{-1})		pH		Mean grain size (mm)	
Abb.[1]	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
AGR	50.74	33.47	4.42	1.75	34.79	22.38	74.86	8.55	466.00	636.37	1.00	0.88	8.63	0.27	0.30	0.69
ERY	39.47	19.72	4.75	2.22	41.56	22.96	75.34	8.73	586.31	1,014.67	1.06	0.50	8.49	0.27	0.23	0.71
AMM	65.21	18.23	6.00	1.32	70.00	12.75	76.13	6.45	229.56	186.29	0.47	0.48	8.64	0.14	0.37	0.80
CRU	65.87	33.59	8.83	2.03	68.33	17.72	75.49	3.27	109.50	54.90	1.06	0.43	8.59	0.16	0.30	0.73
EPH	64.57	47.61	9.25	2.45	79.17	16.05	68.44	4.42	113.33	61.32	7.77	9.13	8.55	0.27	0.22	0.79
JUN	59.19	24.99	10.55	3.34	88.00	10.17	67.55	5.35	176.10	103.69	4.35	5.54	8.53	0.26	0.24	0.73

Note: [1]Abb. = Abbreviation for this plant association considered in this study.

between AMM and JUN and between CRU and JUN. The pH values remained constant in all plant communities, while mean grain size showed the highest values in AMM and the lowest ones in EPH, without significant differences among vegetation types.

Discussion

Morpho-sedimentological analyses

The periodic measurements showed a typical morpho-sedimentological pattern in the backshore dynamic process (Pranzini 2004). The greater width of the backshore in the northern part is due to the proximity of the Rio Pischinappiu mouth, which redistributes its sediments mainly in this area. The anomalous increase in width in the southern part, recorded in winter, is related to the accumulation of sizable deposits (called "banquettes") of beach-cast *Posidonia oceanica* seagrass litter. This confirms that beached *P. oceanica* plays a pivotal role in determining the geomorphological structure of beaches (De Falco et al. 2000), which attenuates the erosive action of the waves (Fonseca & Cahalan 1992; Granata et al. 2001). Moreover our results confirm the role played by *P. oceanica* in the dune formation process by entrapment of the fine sand (Hemminga & Nieuwenhuize 1990) and by contributing to the biogenic sediment (De Falco et al. 2003). In this context, the removal of the "banquettes" causes both a modification of the morphological structure and an alteration of the sedimentary balance of the beach (De Falco et al. 2008). In addition, the remains of *P. oceanica* constitute an important source of organic matter for psammophilous plants (Balestri et al. 2006; Cardona & García 2008).

Our results show a substantial lack of homogeneity between the two areas at the morpho-sedimentological level. The northern zone is generally wider, with lower conductivity, organic matter, and carbonate content, and a higher pH than the southern zone. On the other hand, the southern area is narrower and with finer grain sizes; however these differences do not correspond to significant variations in number of taxa and vegetation cover.

The morphological structuring of the beach shows important seasonal variations: in summer numerous morphologies were recorded, which allowed to classify the beach as a typically reflective type (Pranzini 2004). During the remaining seasons, with the progressive homogenization of the morphologies, a winter dissipative type profile is observed (Pranzini 2004), indicating an intense erosive action of the waves in winter. During the summer period, characterized by a calmer sea, the stretch of sand – in addition to being generally wider – is morphologically well structured, as expected in a microtidal Mediterranean context dominated by wave action (Pranzini 2004). The seasonal variations and shoreline trend suggest a disappearance or retreat of the upper limit of the *P. oceanica* meadow, which may determine a decrease in the beach slope and thus reduce the waterfront (Basterretxea et al. 2004).

The mean grain size decrease with increasing distance from the coastline is in accord with Ishikawa et al. (1995), who highlighted an increase in the percentage of fine sand as the distance from the shoreline increases. The sedimentological samples show a good class level and textural homogeneity, especially in the southern zone, where the impact of the sediments arriving from the stream is not felt directly. The bimodal distribution observed in the northern zone, compared to the unimodal one in the southern, is connected with the sedimentary deposits from the Rio Pischinappiu, which brings sediments of different grain size classes.

Geopedological analyses

The geopedological analysis showed that environmental variables shift along the typical sea-inland gradient: grain size and organic matter content increased toward the inland dunes, whereas pH and conductivity were highest in the exposed part of the beach and gradually decreased, as reported for other coastal dune systems (Averiss & Skene 2001; Isermann 2005; Forey et al. 2008; Houle 2008; Lane et al. 2008).

Our results indicate conductivity as one of the main factors limiting the distribution of plant communities, confirming that few plant species are able to tolerate a high salt concentration in the soil (Cutini et al. 2010). Conductivity values were high in the FD, which is directly exposed to waves and subjected to the constant arrival of salt from the sea (Frederiksen et al. 2006), while they progressively decreased toward the BDs. The conductivity values observed are in agreement with the dissipative model (Pranzini 2004) according to which, due to the effect of the presence of submerged morphologies, the waves break much farther offshore, arriving at the shoreline with less energy and thus transporting a lower salt concentration; moreover, the northern part of the beach is affected by the greater addition of fresh water, resulting from the abundant winter and spring rains, from the Rio Pischinappiu.

The organic matter shows high values in the BDs owing to the presence of shrub vegetation with the formation of structured and more evolved soils. In the BDs, higher values of organic carbon were recorded, presumably due to a greater accumulation of water and salt, elements that reduce the mineralization of organic matter in topographically depressed areas (Rhao & Pathak 1996; Álvarez-Rogel et al. 2007). The higher values observed in the southern zone are probably related to the sizable accumulation along the coastline of *P. oceanica* litter in the winter, resulting in an addition of organic substance transported by the wind toward the backshore (Cardona & García 2008). The lower values found in December in the non-vegetated zone, compared to the vegetated one, and in the FD can be attributed to the fact that most of the "banquettes" return to the sea (Mateo et al. 2003) and only a small part is carried by the wind toward the backshore (Cardona & García 2008).

The seasonal variations in pH are in keeping with the annual range of variation for coastal dune areas (Troelstra et al. 1990). The values were higher in the vegetated zone, compared to the non-vegetated one, confirming previous results that showed how, on a small scale, vegetation plays an important role in determining soil pH (Averiss & Skene 2001; Isermann 2005).

The calcimetry values did not show an evident decrease going from the shoreline toward the interior, as found in previous studies (Frederiksen et al. 2006). The high values in the northern area may be attributed to the presence of the outcropping carbonate bedrock and considerable bioclastic accumulations connected with the drift coastal currents (Federici et al. 1995).

Geobotanical analyses

The flora and vegetation distribution along the sandy waterfronts is regulated by the main environmental variables and this is particularly evident along the coastline, where the selective pressures of the marine environment are more intense.

The floristic inventory confirms the well-preserved status of the Is Arenas dune system. In the biological analysis, the high value of the therophytes confirms the Mediterranean climate of this area, and highlights the conditions of high xericity, typical of coastal dune ecosystems (Fenu & Bacchetta 2008); the percentage of phanerophytes and nanophanerophytes is related with the presence of the *Juniperus oxycedrus* subsp. *macrocarpa* microforest and the abundant phytocoenosis dominated by *E. distachya* throughout the area. The value of the chamaephytes is related with the high wind conditions, while the geophyte percentage represents a further evidence of the environmental xericity (Fenu & Bacchetta 2008).

In the chorological analysis, the high percentage of Mediterranean elements, and in particular the western Mediterranean and Mediterranean-Atlantic ones, highlights the floristic relationships between Sardinian and western Mediterranean territories, due to ancient paleogeographic connections, and validates the arrangement of this area in the western Mediterranean biogeographic subregion (Fenu & Bacchetta 2008). The percentage of endemic taxa, such as *Senecio transiens*, *Silene beguinotii*, *Lotus cytisoides* subsp. *conradiae*, *Torilis nodosa* subsp. *nemoralaris*, denotes the high naturalistic interest of the Is Arenas dune system, and confirms the low level of human-induced exploitation.

The highest number of taxa was recorded in March, concomitant with the germination of annual plants and the greater water availability, while the lowest was recorded in September, when the greatest water deficit occurs and the biological cycle of annual species is already over. Within the dune system, the greatest floristic richness found in the southern zone, classified as intermediate-dissipative, is in disagreement with Hesp (1988) for the pure dissipative type (Barbour & De Jong 1977). The vegetation cover was lowest when there were a lower number of taxa, and the weather and marine events that causing greater morphological variations of the beach occurred with the greatest frequency (i.e., September and December).

Both the number of taxa and vegetation cover increased progressively along the psammophilous succession: toward the BD, the vegetation was progressively less influenced by the main weather/marine agents and, therefore, gradually less tolerant to salt spray, winds, and sand burial (Wiedemann & Pickart 2004; Acosta et al. 2009). The non-significant differences between chamaephytic and phanerophytic/nanophanerophytic coenoses might be related to plot size (4 m^2), optimal for embryo dunes (Dierschke 1994) but probably undersized for forest or scrub formations. Acosta et al. (2009) reported that, for the coasts of the Molise region, the species richness differed significantly only between that part of the dune dominated by annual communities and the interior dune habitats; for Is Arenas, significant differences were observed even within the dune habitats, with the number of taxa increasing significantly between the embryo and semi-stable dunes and the dunes stabilized by forest formations, which are more highly structured and evolved.

Our results are consistent with previous ones in similar ecosystems (Acosta et al. 2005; Forey et al. 2008): the rapid variations at short distances of environmental factors determine the high heterogeneity of the system on which the mosaic vegetation distribution depends, according to the various micro-gradients of single depressions, more than a general distribution model depending on the distance from the coastline. The vegetation may only secondarily influence the morphology of the dune system, by trapping the sediments (between the leaves) and thus contributing to increasing the height of the dunes (Hesp 2002; Álvarez-Rogel et al. 2007).

The psammophilous communities are closely related to dune morphologies; nevertheless, significant differences in structure, floristic composition and environmental requirements are only recorded between phytocoenoses situated at the ends of the geosigmetum, while along the catenal seriation there are gradual and progressive variations of the parameters studied. In fact, the micro-topography of the dunes governs the abiotic variables (water supply, oxido-reduction potential, and salinity), and, therefore, establishes various microhabitats along the dune systems (Álvarez-Rogel et al. 2007).

Conductivity shows notable differences only between geophytic coenoses, those closest to the shoreline, and BD plant communities. However, the greatest differences in conductivity occurred between non-vegetated and vegetated areas, more than among phytocoenoses; they were distributed in a mosaic pattern and not bound to the distance from the coastline. As expected, the organic matter content was highest in the BD communities, due to the great lichen-moss cover and the relative slowness of the process of mineralization of organic substances (Rhao & Pathak 1996; Álvarez-Rogel et al. 2007). In the other plant communities, considerably lower values of organic matter were recorded, with higher values occurring in the inter-dune depressions as compared to the DC, mainly occupied by the *Ammophila arenaria* communities (Álvarez-Rogel et al. 2007). The increase in pH as the vegetation cover decreases confirms the notion that vegetation plays an important role in determining soil pH (Averiss & Skene 2001; Isermann 2005). Calcimetry showed a broader variation in the geophytic and chamaephytic communities due to the abundance of *P. oceanica* "banquettes", within which there is a considerable accumulation of carbonate sediments deriving from the epiphytic organisms and benthic invertebrates (De Falco et al. 2003).

Mean grain size becomes finer in more evolved formations, since the selective action of transport is greater in the BD areas (Karavas et al. 2005); however, the differences among plant communities were not statistically significant. Nevertheless, the transport and distribution of the sediments, influenced by numerous factors (Bauer & Davidson-Arnott 2002), require more detailed studies in order to explain the geomorphological development of the dune system and the distribution gradients of the sediment.

The present study has made it possible to set up a network of permanent areas for periodic monitoring of the dune systems. According to Bernatchez and Dubois (2008), the seasonal approach provides a better definition of the ongoing processes, allowing a more precise analysis of the dynamics taking place within a beach area. The periodic measurement of the parameters considered, together with other environmental variables (e.g., climate and submerged beach), may provide a general description of the processes affecting the beach, and may lead to an integrated monitoring of the entire ecosystem that can provide support for the decisions regarding its future management.

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Appendix I

Table IA. Floristic inventory for the Is Arenas dune systems.

Family	Taxonomic unit	Biological type	Chorological type
Cupressaceae	*Juniperus oxycedrus* L. subsp. *macrocarpa* (Sibth. *et* Sm.) Neilr.	P caesp	Circum-Medit.
Ephedraceae	*Ephedra distachya* L. subsp. *distachya*	NP	NW Medit.
Araceae	*Arum pictum* L. *f.* subsp. *pictum*	G rhiz	Endem. SA-CO
Posidoniaceae	*Posidonia oceanica* (L.) Delile	I rad	Medit.-Atl.
Alliaceae	*Pancratium maritimum* L.	G bulb	Circum-Medit.
Asparagaceae	*Agave fourcroydes* Lem.	P caesp	Nat. (C America)
	Asparagus acutifolius L.	G rhiz	Circum-Medit.
	Asparagus stipularis Forssk.	NP	Circum-Medit.
Orchidaceae	*Barlia robertiana* (Loisel.) Greuter	G bulb	Circum-Medit.
	Ophrys eleonorae Devillers-Tersch. *et* Devillers	G bulb	Endem. SA
Xanthorrhoeaceae	*Asphodelus ramosus* L. subsp. *ramosus* var. *ramosus*	G rhiz	Circum-Medit.
Smilacaceae	*Smilax aspera* L.	NP	Circum-Medit.
Poaceae	*Ammophila arenaria* (L.) Link subsp. *australis* (Mabille) Laínz	G rhiz	Circum-Medit.
	Catapodium balearicum (Willk.) H. Scholz	T scap	Circum-Medit.
	Dactylis glomerata L. subsp. *hispanica* (Roth.) Nyman	H caesp	Circum-Medit.
	Elymus farctus (Viv.) Runemark *ex* Melderis subsp. *farctus*	G rhiz	Circum-Medit.
	Hordeum marinum Huds.	T scap	Circumbor.
	Lagurus ovatus L. subsp. *vestitus* (Messeri) H. Scholtz	T scap	W Medit.
	Rostraria litorea (All.) Holub	T scap	Circum-Medit.
	Sporobolus virginicus Kunth	G rhiz	Circum-Medit.
Ranunculaceae	*Delphinium gracile* DC.	T scap	W Medit.
Amaranthaceae	*Salsola kali* L. subsp. *kali*	T scap	Circumbor.
Caryophyllaceae	*Silene beguinotii* Vals.	T scap	Endem. SA
	Silene coelirosa (L.) Godr.	T scap	W Medit.
Polygonaceae	*Polygonum maritimum* L.	Ch rept	Medit.-Atl.
Tamaricaceae	*Tamarix canariensis* Willd.	P caesp	SW Medit.
Santalaceae	*Thesium humile* Vahl	T scap	Circum-Medit.
Crassulaceae	*Umbilicus gaditanus* Boiss.	G bulb	Medit.-Trop.
Geraniaceae	*Geranium robertianum* L.	T scap	Circumbor.
Fabaceae	*Acacia saligna* (Labill.) H.L. Wendl.	P caesp	Nat. (W Australia)
	Dorycnium hirsutum (L.) Ser.	Ch suffr	Circum-Medit.
	Lotus cytisoides L. subsp. *conradiae* Gamisans	Ch suffr	Endem. SA-CO
	Medicago marina L	Ch rept	Medit.-Atl.
	Ononis variegata L.	T scap	Circum-Medit.
	Trigonella monspeliaca L.	T scap	Euro-Medit.
Euphorbiaceae	*Chamaesyce peplis* (L.) Prokh.	T rept	Euro-Medit.
	Euphorbia paralias L.	Ch frut	Medit.-Atl.
	Euphorbia peplus L.	T scap	Circumbor.
	Euphorbia terracina L.	T scap	Circum-Medit.
Rhamnaceae	*Rhamnus alaternus* L. subsp. *alaternus*	P caesp	Circum-Medit.
Brassicaceae	*Brassica tournefortii* Gouan	T scap	Medit.-Irano-Turan.
	Cakile maritima Scop. subsp. *maritima*	T scap	Circum-Medit.
	Lobularia maritima (L.) Desv. subsp. *maritima*	H scap	Circum-Medit.
	Matthiola incana (L.) R. Br.	Ch suffr	W Medit.
	Matthiola tricuspidata (L.) R. Br.	T scap	Circum-Medit.
Cistaceae	*Cistus creticus* L. subsp. *eriocephalus* (Viv.) Greuter *et* Burdet	NP	Circum-Medit.
	Cistus salviifolius L.	NP	W Medit.
Anacardiaceae	*Pistacia lentiscus* L.	P caesp	Circum-Medit.
Boraginaceae	*Echium arenarium* Guss.	H bienn	Circum-Medit.
Rubiaceae	*Crucianella maritima* L.	Ch suffr	Circum-Medit.
	Rubia peregrina L. subsp. *requienii* (Duby) Cardona *et* Sierra-Ràfols	P lian	Endem. SA-CO-ITM
Lamiaceae	*Prasium majus* L.	Ch frut	Circum-Medit.
Oleaceae	*Phillyrea media* L. var. *rodriguezii* P. Monts.	P caesp	Endem. SA-CO-BL
Orobanchaceae	*Orobanche amethystea* Thuill. subsp. *amethystea*	T par	Euro-Medit.
Plantaginaceae	*Plantago macrorrhiza* Poir.	H ros	W Medit.
	Veronica cymbalaria Bodard	T scap	Euro-Medit.

(*continued*)

Table IA. (*Continued*).

Family	Taxonomic unit	Biological type	Chorological type
Convolvulaceae	*Calystegia soldanella* (L.) Roem *et* Schult.	G rhiz	Cosmop.
Apiaceae	*Crithmum maritimum* L.	Ch suffr	Medit.-Atl.
	Daucus carota L. subsp. *carota*	H scap	Euro-Medit.
	Daucus carota L. subsp. *maritimus* (Lam.) Batt.	H bienn	W Medit.
	Daucus pumilus (L.) Hoffmanns. *et* Link	T scap	Medit.
	Eryngium maritimum L.	G rhiz	Medit.-Atl.
	Torilis arvensis (Huds.) Link subsp. *purpurea* (Ten.) Hayek	T scap	Circum-Medit.
	Torilis nodosa (L.) Gaertn. subsp. *nemoralaris* Brullo	T scap	Endem. SA-SI
Asteraceae	*Anthemis maritima* L.	H scap	W Medit.
	Cichorium endivia L. subsp. *pumilum* (Jacq.) Cout.	T scap	Circum-Medit.
	Helichrysum microphyllum (Willd.) Camb. subsp. *tyrrhenicum* Bacch., Brullo *et* Giusso	Ch suffr	Endem. SA-CO-BL
	Hypochaeris achyrophorus L.	T scap	Circum-Medit.
	Otanthus maritimus (L.) Hoffmanns. *et* Link subsp. *maritimus*	Ch suffr	Circum-Medit.
	Senecio transiens (Rouy) Jeanm.	T scap	Endem. SA-CO
	Sonchus bulbosus (L.) N. Kilian *et* Greuter subsp. *bulbosus*	G bulb	Circum-Medit.
	Sonchus oleraceus L.	T scap	Boreo-Trop.
Dipsacaceae	*Centranthus calcitrapae* (L.) Dufr. subsp. *calcitrapae*	T scap	Circum-Medit.
	Lonicera implexa Aiton subsp. *implexa*	P lian	Circum-Medit.
	Sixalix atropurpurea (L.) Greuter *et* Burdet subsp. *grandiflora* (Scop.) Soldano *et* F. Conti	H bienn	Circum-Medit.

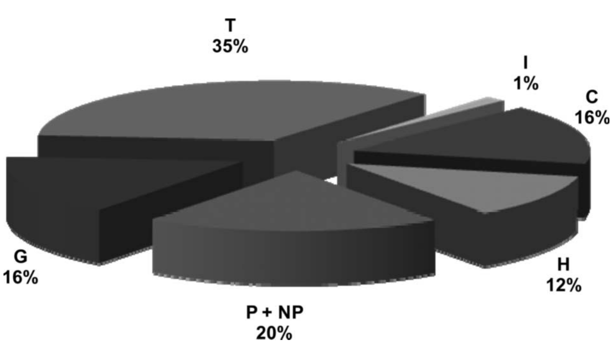

Figure 1A. Biologic spectrum of Is Arenas flora. Abbreviations: C = chamaephytes; H = hemicryptophytes; G = geophytes; NP = nanophanerophytes; P = phanerophytes; T = therophytes.

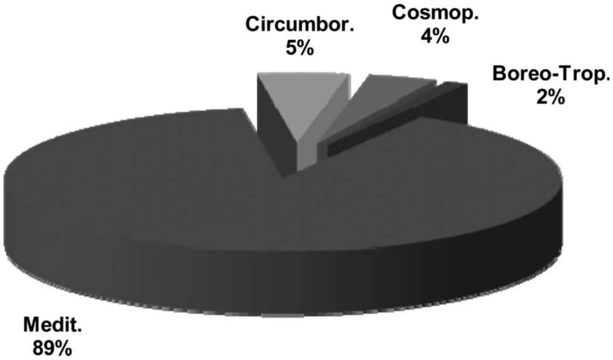

Figure 2A. General chorologic spectrum of Is Arenas flora.

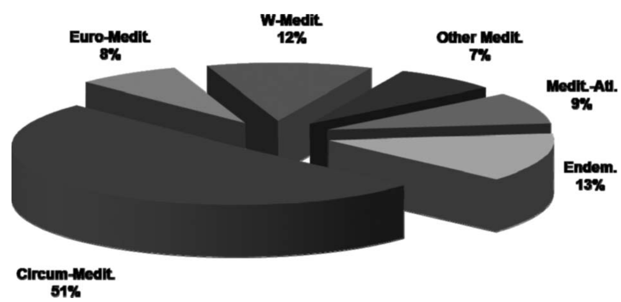

Figure 3A. Percentages of the chorologic units of the Mediterranean taxa.

Appendix II. Phytosociological relevés carried out in this study and used for analysis (n = 50; see Materials and Methods section).

Rel. no.	1	2	9	10	13	14	23	24	29	30	43	44	5	6	15	16	17	18	21	22	3	4	35	36	39
Group	AGR	AGR	AGR	AGR	AGR	AGR	AGR	AGR	AGR	AGR	AGR	AGR	AMM	AMM	AMM	AMM	AMM	AMM	AMM	AMM	ERY	ERY	ERY	ERY	ERY
Plot	T1 a	T1 a	T1 e	T1 e	T2 a	T2 a	T3 b	T3 b	T4 a	T4 a	T6 a	T6 a	T1 c	T1 c	T2 b	T2 b	T2 c	T2 c	T3 a	T3 a	T1 b	T1 b	T5 a	T5 a	T5 c
Date (1 = June; 2 = March)	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1
Altitude (m a.s.l.)	2	2	5	5	3	3	3	3	1	1	1	1	6	6	5	5	5	5	2	2	5	5	1	1	1
Aspect (°)	SW210	SW210	SW210	SW210	NW300	NW300	N330	N330	NW330	NW330	N345	N345	SW210	SW210	NW300	NW300	NW300	NW300	N330	N330	SW210	SW210	NW300	NW300	NW300
Slope (°)	5	5	5	5	3	3	20	20	5	5	45	45	5	5	3	3	3	3	20	20	5	5	30	30	30
Consistency (1–5)	2	2	4	4	2	2	3	3	2	2	1	1	4	4	3	3	4	4	2	2	3	3	1	1	4
Drainage (1–5)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Coverage (%)	20	20	90	80	50	30	60	40	60	60	40	15	80	70	80	80	90	80	70	60	65	15	40	30	90
Moss-lichen cover (%)	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average vegetation height (m)	0.03	0.03	0.03	0.03	0.15	0.15	0.25	0.25	0.4	0.4	0.4	0.4	0.8	0.8	0.7	0.7	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
No. of taxa	2	3	7	8	6	4	4	6	4	6	5	6	6	7	8	8	6	7	8	6	3	3	3	4	8
Elymus farctus subsp. *farctus*	2	1	4	3	3	2	3	2	2	2	2	+	2	1	2	1	2	2	+	2	1	1	2	2	+
Eryngium maritimum	1	+	3	1	1	+	1	1	3	1	+	+	3	2	2	1	+	+	3	1	4	1	3	1	4
Pancratium maritimum			1	1			1	1			1	1		+	+				+	+					1
Senecio transiens					+			+		+		+	+	+	+	+	+	+	+	+				+	
Ononis variegata			+	+																					+
Otanthus maritimus subsp. *maritimus*							2	1					+	+	+	+	3	4	+	+					
Cakile maritima subsp. *maritima*		1		+						+		+	+	1	+	1		1				+		+	
Juniperus oxycedrus subsp. *macrocarpa*																									+
Sonchus bulbosus subsp. *bulbosus*				+												+		+							
Matthiola incana																+	2	2							
Ephedra distachya subsp. *distachya*																									
Plantago macrorrhiza																									3
Brassica tournefortii													+	+			+	+							
Rubia peregrina subsp. *requienii*																									
Silene beguinotii				1																					
Euphorbia terracina																									1
Ammophila arenaria subsp. *australis*													4	4	3	4			3	1					
Medicago marina											+	+			1	1							+	+	
Silene coelirosa			1														+								
Catapodium balearicum											+														
Pistacia lentiscus																									
Rostraria litorea																									+
Salsola kali					+										+				+		+	+			
Sixalix atropurpurea subsp. *grandiflora*																									
Sonchus oleraceus																									
Asparagus stipularis																									
Helichrysum microphyllum subsp. *tyrrhenicum*																									
Lobularia maritima subsp. *maritima*																									
Matthiola tricuspidata			+	+	+	+																			
Ophrys eleonorae																									
Phillyrea media var. *rodriguezii*																									
Rhamnus alaternus subsp. *alaternus*																									
Crucianella maritima																									
Daucus pumilus																									
Hordeum marinum																									

(*continued*)

Appendix II. (*Continued*).

Rel. no.	1	2	9	10	13	14	23	24	29	30	43	44	5	6	15	16	17	18	21	22	3	4	35	36	39
Group	AGR	AGR	AGR	AGR	AGR	AGR	AGR	AGR	AGR	AGR	AGR	AGR	AMM	AMM	AMM	AMM	AMM	AMM	AMM	AMM	ERY	ERY	ERY	ERY	ERY
Plot	T1 a	T1 a	T1 e	T1 e	T2 a	T2 a	T3 b	T3 b	T4 a	T4 a	T6 a	T6 a	T1 c	T1 c	T2 b	T2 b	T2 c	T2 c	T3 a	T3 a	T1 b	T1 b	T5 a	T5 a	T5 c
Lagurus ovatus subsp. *vestitus*																									
Anthemis maritima																									
Asparagus acutifolius																									
Calystegia soldanella					2	2																			
Euphorbia paralias											3	1													
Euphorbia peplus	+	+																							
Hypochaeris achyrophorus																									
Lotus cytisoides subsp. *conradiae*																									
Orobanche amethystea subsp. *amethystea*																									
Polygonum maritimum																							1	+	
Prasium majus																									
Sporobolus virginicus					2	1																			
Acacia saligna																									
Arum pictum subsp. *pictum*																									
Chamaesyce peplis																			+						
Cichorium endivia subsp. *pumilum*																									
Crithmum maritimum																									
Echium arenarium			+																						
Geranium robertianum																									
Thesium humile			1																						
Torilis arvensis subsp. *purpurea*																									
Torilis nodosa subsp. *nemoralaris*																									
Trigonella monspeliaca																									

Rel. no.	40	45	46	7	8	25	26	37	38	11	12	31	32	47	48	19	20	27	28	33	34	41	42	49	50	
Group	ERY	ERY	ERY	CRU	CRU	CRU	CRU	CRU	CRU	EPH	EPH	EPH	EPH	EPH	EPH	GIN	GIN	GIN	GIN	GIN	GIN	GIN	GIN	GIN	GIN	
Plot	T5 c	T6 b	T6 b	T1 d	T1 d	T3 c	T3 c	T5 b	T5 b	T1 f	T1 f	T4 b	T4 b	T6 c	T6 c	T2 d	T2 d	T3 d	T3 d	T4 c	T4 c	T5 d	T5 d	T6 d	T6 d	
Date (1 = June; 2 = March)	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	
Altitude (m a.s.l.)	1	3	3	7	7	2	2	2	2	5	5	2	2	2	2	4	4	1	1	2	2	1	1	1	1	
Aspect (°)	NW300	N345	N345	SW210	SW210	N330	N330	NW300	NW300	SW210	SW210	NW330	NW330	N345	N345	NW300	NW300	N330	N330	NW330	NW330	NW300	NW300	N345	N345	
Slope (°)	30	45	45	5	5	20	20	30	30	5	5	5	5	45	45	3	3	20	20	5	5	25	25	45	45	
Consistency (1–5)	4	3	3	4	4	4	4	4	4	4	4	5	5	4	4	5	5	5	5	5	5	5	5	4	4	
Drainage (1–5)	5	5	5	5	5	5	5	5	5	5	5	4	4	5	5	5	5	5	5	5	5	4	4	5	5	
Coverage (%)	70	70	50	70	70	90	90	80	80	90	90	100	100	70	80	80	80	100	90	100	95	100	80	100	100	
Moss-lichen cover (%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Average vegetation height (m)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.25	0.25	0.3	0.3	0.4	0.4	0.4	0.4	1.3	1.3	1.5	1.5	1.5	1.5	1.5	1.5	2	2	
No. of taxa	9	6	7	11	9	10	13	8	8	11	12	12	11	10	12	13	15	13	12	14	17	6	9	11	14	Pres.
Elymus farctus subsp. *farctus*	1	1	1	2	2	2	2	2	2	1	1	2	2	2	2	1	1	+	+	+	1	+	1	+	1	50
Eryngium maritimum	1	4	2	2	1	+	+	2	1	2	2	2	1	+		2	1			4	1	1	+	+		46
Pancratium maritimum	1	2	2			2	2	1	+	+	+	1	+	2	1	+	+	1	+	1	1	1	+	+	+	34
Senecio transiens	+			+			+		+	+	1		+		+	+	+				+		+			25
Ononis variegata	+			1	1			1		1	+	1				+	+	+	+	+	+					16
Otanthus maritimus subsp. *maritimus*				+	+	1	2									+	+									16
Cakile maritima subsp. *maritima*			+							+	+				+											15
Juniperus oxycedrus subsp. *macrocarpa*	1					2	2								+	4	4	4	4	4	4	5	5	5	5	15
Sonchus bulbosus subsp. *bulbosus*	+		+		2		1		+	+	+		+		1						+					13
Matthiola incana				+	+	1	1									1	+	+	1							11

(*continued*)

Appendix II. (*Continued*).

Rel. no.	40	45	46	7	8	25	26	37	38	11	12	31	32	47	48	19	20	27	28	33	34	41	42	49	50	
Group	ERY	ERY	ERY	CRU	CRU	CRU	CRU	CRU	CRU	EPH	EPH	EPH	EPH	EPH	EPH	GIN	GIN	GIN	GIN	GIN	GIN	GIN	GIN	GIN	GIN	
Plot	T5 c	T6 b	T6 b	T1 d	T1 d	T3 c	T3 c	T5 b	T5 b	T1 f	T1 f	T4 b	T4 b	T6 c	T6 c	T2 d	T2 d	T3 d	T3 d	T4 c	T4 c	T5 d	T5 d	T6 d	T6 d	
Ephedra distachya subsp. *distachya*						1	1			4	4			4	4		+	+	1						1	10
Plantago macrorrhiza	2							1	1			1	1							3	2	1	1			10
Brassica tournefortii				+	+					+	+															8
Rubia peregrina subsp. *requienii*										+	1						+	+	+				+	2	1	8
Silene beguinotii				+	2		+			1	2						+		1							8
Euphorbia terracina								+	1			+	1							1		+				7
Ammophila arenaria subsp. *australis*																										6
Medicago marina																										6
Silene coelirosa														+		+	+	+								6
Catapodium balearicum		1	1											+	+											5
Pistacia lentiscus										+	+							2						+	+	5
Rostraria litorea	1																+			+	1					5
Salsola kali																										5
Sixalix atropurpurea subsp. *grandiflora*															+			+	+				+		1	5
Sonchus oleraceus		+		+										+	+									+		5
Asparagus stipularis				+	+													+	+							4
Helichrysum microphyllum subsp. *tyrrhenicum*				1	1													1	2							4
Lobularia maritima subsp. *maritima*						+	+					+	+													4
Matthiola tricuspidata																										4
Ophrys eleonorae						+	+					+	+													4
Phillyrea media var. *rodriguezii*																						+	+	+	+	4
Rhamnus alaternus subsp. *alaternus*																						+	+	+	+	4
Crucianella maritima				+		3	3																			3
Daucus pumilus														+	1										+	3
Hordeum marinum								+				+		+												3
Lagurus ovatus subsp. *vestitus*														+		+	+									3
Anthemis maritima																								+	+	2
Asparagus acutifolius																								+	+	2
Calystegia soldanella																										2
Euphorbia paralias																										2
Euphorbia peplus																										2
Hypochaeris achyrophorus																								+	+	2
Lotus cytisoides subsp. *conradiae*						1	+																			2
Orobanche amethystea subsp. *amethystea*		+	+																							2
Polygonum maritimum																										2
Prasium majus																								2	+	2
Sporobolus virginicus																										2
Acacia saligna																									+	1
Arum pictum subsp. *pictum*																									+	1
Chamaesyce peplis																										1
Cichorium endivia subsp. *pumilum*											1															1
Crithmum maritimum																							+			1
Echium arenarium																										1
Geranium robertianum																	+									1
Thesium humile																										1
Torilis arvensis subsp. *purpurea*																+										1
Torilis nodosa subsp. *nemoralaris*																		+								1
Trigonella monspeliaca						1																				1